ECN-E--08-063

Conversion of excess wind energy into hydrogen for fuel cell applications

A system analysis within the context of the Dutch energy system

Gerard Kraaij

Marcel Weeda

September 2008

A		
B		
Made by: G.J. Kraaij	Approved: M. Weeda	ECN Hydrogen and Clean Fossil Fuels
Checked by: J.W. Dijkstra	Issued: F.A. de Bruijn	

Acknowledgement/Preface

The KNMI is acknowledged for providing the wind speed data.
Marcel Weeda is thanked for commenting on the report.

Abstract

For reduction of greenhouse gas emissions, an increased use of renewable energy sources in the electricity sector is planned. The amount of excess wind power from an increase of offshore wind power capacity is calculated for an isolated Dutch society. The excess wind power is converted into hydrogen by electrolysis and the subsequent use of the hydrogen in residential applications as well as transport applications is investigated for economic, environmental and storage aspects. At an equivalent of 8 GW offshore wind power in 2020 the wind power contributes around 20% to the electricity demand, with an excess wind power amounting to approx. 4% of the Dutch electricity consumption. Excess wind occurs during 20% of the time. Conversion of this electricity to hydrogen requires 6 GW of electrolyser capacity with an average load factor of 10%, leading to high depreciation costs of the electrolysers and subsequent high hydrogen costs. For economic as well as environmental reasons the use of hydrogen in transport applications is more beneficial than in residential applications.

Contents

Figures

Summary

Large-scale offshore wind power can lead to the situation that more electricity is available (including the base load electricity supply) than needed in the Netherlands. Excess wind power is defined as the effect that the production from the base load power plants and the wind power plants exceeds the electricity demand. This study investigates the characteristics of excess wind power and the conversion of this excess wind power to hydrogen by electrolysis. The hydrogen can be used in fuel cells for residential micro cogeneration of electricity and heat (μ-CHP) or for transport applications.

The political ambition for 2020 is to have 6 GW offshore and 2-4 GW onshore wind power. The effect of this ambition on the hourly power production is simulated as 8 GW offshore wind power equally divided over 3 locations. The wind power is simulated using hourly wind speed data from 2004 and turbine characteristics for wind power production. The hourly power demand in 2020 is extrapolated using the 2004 electricity demand data.

Currently about 1.6 GW of wind power capacity is installed. The study shows that excess wind power develops at a wind power capacity effectively above 4 GW offshore for a base load of 8.7 GW, no export of power or further demand side management. The results for 8 GW installed wind power are:

- The excess wind power is around 4.5 TWh.
- This can provide 80.000 ton of hydrogen/year.
- This amount of hydrogen is sufficient to supply 500.000 households with a fuel cell μ-CHP unit operating in electricity following mode. Alternatively, the amount of hydrogen is enough to supply 800.000 “average” cars.
- The capacity of the required storage (excluding cushion gas) is 20.000 ton of hydrogen.

The result of this study is that this wind power – electrolysis - H_2 -μ-CHP electricity production process is a possibility to convert excess electricity into hydrogen and back to electricity. Assuming electricity load following operation about 50% of the energy is lost, 31% is recovered as electricity and 17 % as heat. For full load operation the electrical efficiency is 28% and the thermal efficiency 31%. In neither case the μ-CHP unit can cover the complete heat demand of existing or future houses. For stationary applications the operation of the μ-CHP unit at periods of excess wind power is excluded.

For the cost calculations future targets for system components are used. The cost of electricity (without taxes or profit) for residential μ-CHP at 8 GW offshore wind capacity is at least 0.40 €/kWh, which is twice the present day mean consumer electricity price (including taxes and profit) of 0.20 €/kWh. The minimum electricity cost is calculated as 0.24 €/kWh at 25 GW installed wind capacity.

The production of hydrogen for transport applications starting with excess wind electricity also suffers from the low load factor for the electrolysers and therefore initial high hydrogen costs as in the stationary case. The minimum cost estimate for 8 GW installed offshore wind capacity for minimum APX electricity cost (i.e. 0.02 €/kWh) excess wind (4.5 TWh) energy conversion to H_2 is 4.4 €/kg.

A second option for transport applications is the dedicated conversion of 28.3 TWh wind energy from an 8 GW offshore wind farm to hydrogen. This amount can fuel 4-5 million cars with hydrogen. The minimum cost estimate for large-scale dedicated wind power

conversion to H_2 is 5 €/kg, using a mean electricity cost from offshore wind power of 0.08 €/kWh.

The CO_2 emission reduction for H_2 production by electrolysis of wind power and subsequent use in residential fuel cell CHP systems is about 1/3 of the reduction when the electricity would be used directly. The CO_2 reduction for using the H_2 in fuel cell transportation vehicles is about 2/3 of the reduction when the electricity would be used directly.

The perspective of excess wind energy via H_2 to μ-CHP for household applications is therefore very low based on low efficiency, high cost and low CO_2 emission reduction characteristics.

The conversion of excess wind energy to hydrogen for transport applications is a more likely market opportunity for economic (higher value for hydrogen) as well as environmental reasons (higher CO_2 reduction possibility) than stationary applications.

1. Introduction

Large-scale offshore wind power can lead to the situation that more electricity is produced (including the base load electricity supply) than needed in the Netherlands. A solution to keep the balance in the electricity is the conversion of the excess electricity into hydrogen (H_2). This study investigates the characteristics of excess wind power and the conversion of this excess wind power to hydrogen by electrolysis. The hydrogen can be used in fuel cells for residential micro cogeneration of electricity and heat (μ-CHP) or for transport applications.

The objectives of this study are:

- To investigate the amount of excess wind power as a function of the installed offshore wind power capacity.
- To calculate the efficiency of the conversion from excess electricity to hydrogen and back to electricity.
- To estimate the amount of households or cars that can be supplied with hydrogen from excess wind electricity.
- To determine the hydrogen storage requirements and size due to the seasonal and stochastic variation in wind energy,
- To estimate the cost of H_2 and of electricity as a function of the installed wind power.
- To estimate the CO_2 reduction capability for the stationary and transport applications.
- To assess the perspective of conversion of wind energy to H_2 for stationary or transport applications.

The year 2020 will be used as the year of reference. The electricity use for 2020 is based on the forecasts from the Globe Economy scenario.

2. Hydrogen applications

For the Netherlands the case of conversion of non-deployable or excess wind power to hydrogen via electrolysis is considered. The hydrogen can be used in households for electricity and heat production using µ-CHP as shown in Figure 1. Alternatively, the hydrogen can be used in passenger cars for mobile applications as shown in Figure 2.

2.1 Stationary application

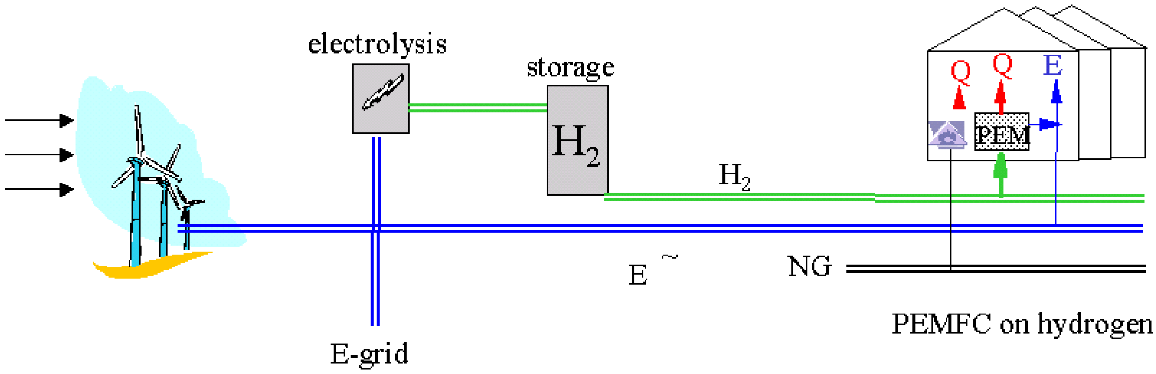

Figure 1: *System with excess wind electricity and µ-CHP fuel cells on hydrogen.*

The excess wind hydrogen system for households with use of hydrogen for µ-CHP is shown in Figure 1. Wind energy is converted into electricity by offshore wind turbines, which are connected to the Dutch electricity grid. In case the wind power plus electrical base load power exceeds the electricity demand, the excess electricity is converted to hydrogen using an electrolyser. This hydrogen is compressed and stored. The storage is connected to a hydrogen grid that supplies hydrogen to houses. When the electricity demand exceeds the wind power plus base load power, hydrogen from a hydrogen grid is converted into electricity and heat in a household µ-CHP unit. The houses are connected to the electrical grid for their regular or additional electrical needs and feed-in of surplus electricity from the µ-CHP unit. As the CHP unit only produces heat when the national electricity demand exceeds the wind power + base load power an additional facility is required to provide heat when the CHP unit is not in operation or producing an insufficient amount of heat. It is assumed here that a natural gas burner provides the additional heat requirements.

The main assumptions for this part of the study are:
1. Export of excess wind power to other countries is not considered.
2. Excess (offshore) wind power is converted to H_2 by electrolysis and stored.
3. H_2 is used in 1 kW_e µ-CHP FC in households for electricity and heat generation
4. An average Dutch household uses 4550 kWh of electricity/year in 2020.
5. µ-CHP units operate only in on hours without excess wind power (otherwise the electricity produced by the fuel cell from hydrogen would be directly converted into hydrogen and heat, which means a destruction of exergy) and are not operated in low tariff time hours, i.e. between 23.00 and 07.00 hrs and during the weekends.

The following aspects are investigated:
1. The number of households that can be supplied.
2. H_2 storage requirement to match the seasonal variation in wind electricity
3. Cost of electricity (CoE) from wind-H_2 fuelled µ-CHP as a function of the amount of excess wind electricity produced.

4. The influence of seasonal wind power variation on the hydrogen storage requirement.
5. Optimisation of CoE and efficiency through changing the way of operating the µ-CHP units in electrical load following operation (no feed-in) or full load operation up to the yearly electrical demand (feed-in). In the latter situation µ-CHP electricity produced may exceed the momentarily demand of electricity, so electricity needs to be exchanged with the grid.

2.2 Transport application

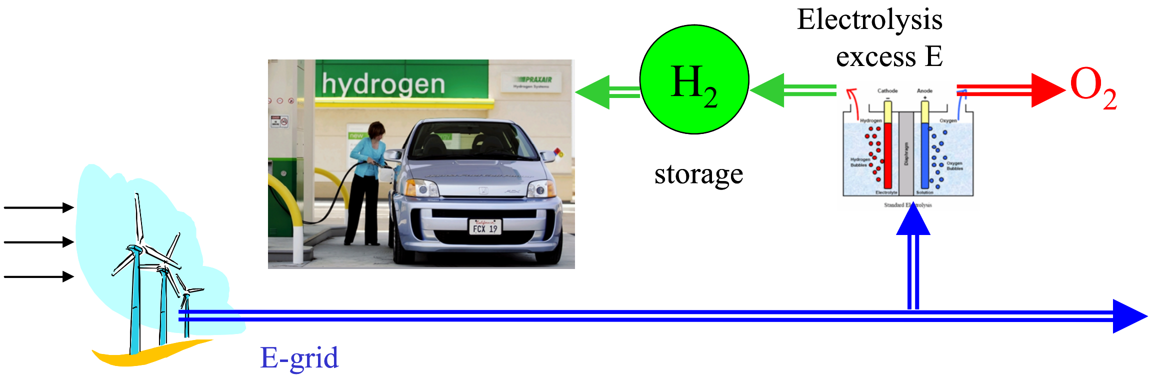

Figure 2: *System of excess wind energy to hydrogen for transport applications.*

The excess wind hydrogen system with use of hydrogen as fuel for passenger cars is shown in Figure 2. Wind energy is converted into electricity by offshore wind turbines and connected to the Dutch electricity grid. In case that the wind power plus electrical base load power exceed the electricity demand, the excess electricity is converted to hydrogen using an electrolyser. This hydrogen is compressed and stored. The storage is connected to a hydrogen grid that can supply hydrogen to filling stations. Alternatively the electrolyser is located at the filling station. Hydrogen is compressed to above the pressure required for the hydrogen storage tanks used in the vehicles (350 or 700 bar) and stored. When a hydrogen fuelled car arrives for refuelling, the hydrogen is dispensed into the tank of the vehicle.

The main assumptions for this part of the study are:
1. Export of excess wind power to other countries is not considered.
2. Excess (offshore) wind power is converted to H_2 by electrolysis.
3. The average passenger car drives 15500 km/year (as in 2004, CBS) and the hybrid fuel cell powered car drives 144 km/kg H_2. [1]

The following aspects that are investigated are for this system:
1. Number of cars that can run on H_2 from excess wind power
2. The influence of seasonal wind power variation on the H_2 storage requirement.
3. Cost of hydrogen (CoH2) as a function of installed wind power capacity and thus the amount of excess wind power produced.
4. Cost of hydrogen from dedicated wind parks for H_2 production.

For this application only the production costs of hydrogen will be calculated. Transportation and storage costs for hydrogen at refuelling stations are not taken into account in this study.

3. Electricity demand in the Netherlands

The electricity demand profile for the year 2020 is obtained in the following way:

- The electricity demand profile for 2004 is obtained on a 15 min. basis from Tennet [2].
- The 15 min. data are averaged into hourly data, since the wind speed data are available on an hourly basis. This also reduces the amount of data.
- The demand profile for 2020 is estimated by multiplying the demand profile for 2004 with the ratio of the expected electricity demand for 2020 and the electricity demand for 2004. The expected electricity demand for 2020 uses the Global Economy scenario from [3] and is 473 PJ or 131 TWh, an increase of 2.1% per year from the electricity demand of 2004, which is 94 TWh or 339 PJ.

3.1 Electricity demand pattern

The profile of the electricity demand in the Netherlands is shown in Figure 3 and Figure 4. Figure 3 shows that in the weekends the electricity demand is lower than on weekdays and during the night the demand is lower than during the day. There is a steep rise in the electricity demand in the morning that has to be provided by the flexible electricity production. Figure 4 shows the average daily electricity demand, where the weekly pattern can be clearly observed as well as the lower demand on the extra holidays. These figures are obtained for 2004.

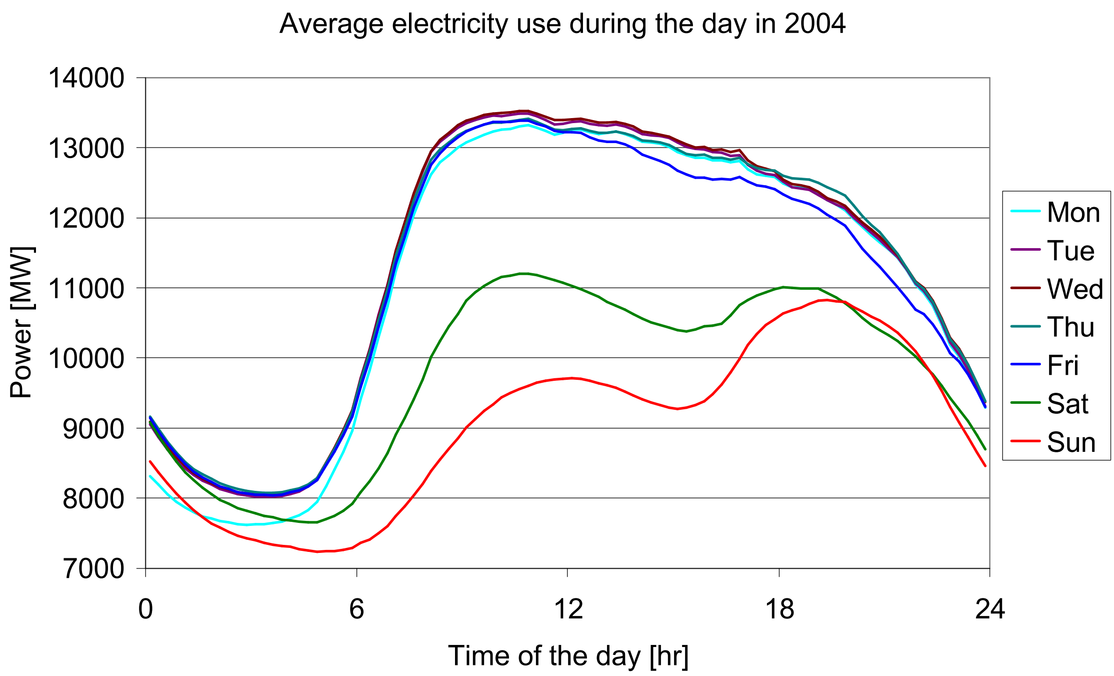

Figure 3: *Average hourly electricity demand for every weekday in 2004.*

The hourly electricity demand data of 2004 are multiplied by 131/94 to obtain the electricity demand load curve for 2020, as shown in Figure 5. The curve is obtained by sorting the hourly electricity demand of 2020 in ascending order. The minimum electricity demand is normally provided by base load power plants like nuclear or coal power plants that have limited dynamic response. The assumed base load power production of 8.7 GW in 2020 is also shown in Figure 5.

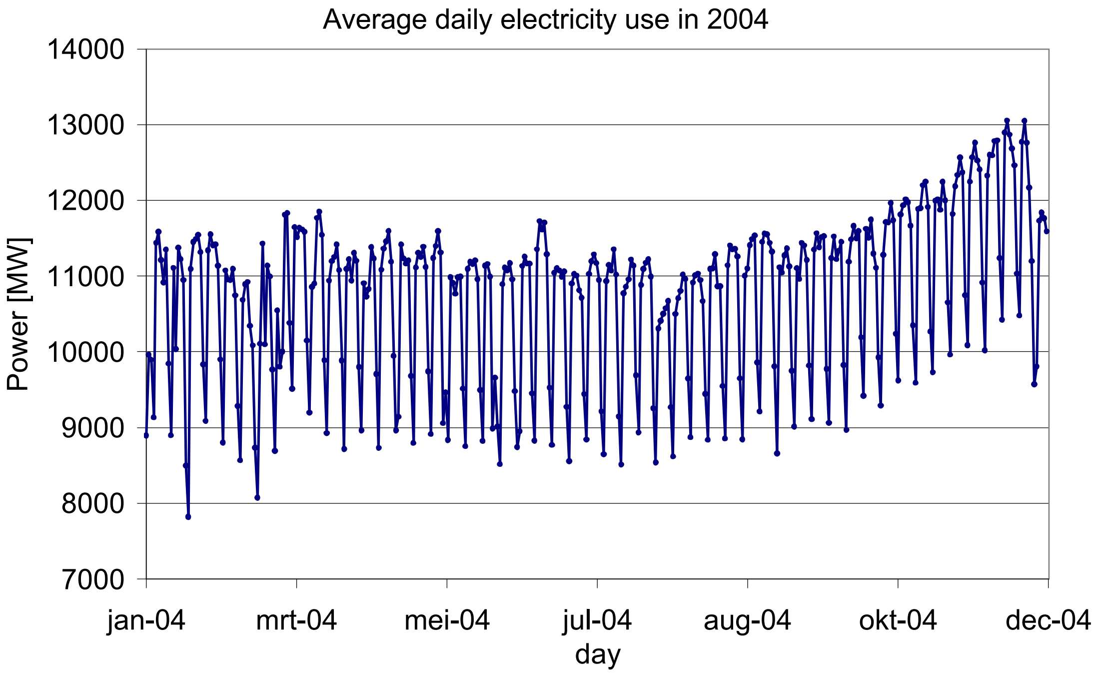

Figure 4: *Average daily electricity use in the Netherlands in 2004.*

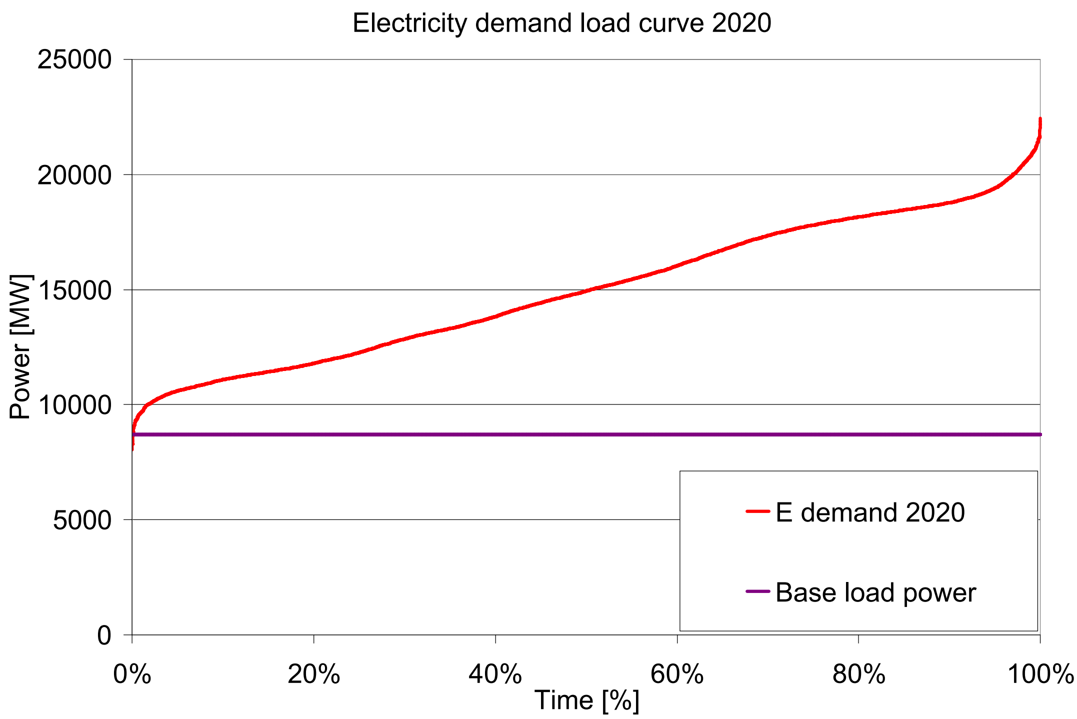

Figure 5: *The extrapolated electricity demand load curve for 2020 and the electricity produced by base load power plants (8.7 GW).*

4. Wind power production

For the analysis of offshore wind power production, the measured wind speed data of various locations are used. These locations, K13, Noordwijk and Texel, are shown Figure 6.

Figure 6: *Wind measurement stations in the Netherlands. The 3 named stations are used.*

Hourly time series of wind speed on these 3 off shore locations were imported from the KNMI wind speed data website [4] for the year 2002, 2003 and 2004. The average wind speed for these years were at resp. 102%, 84% and 98% of the average wind speed for the period 1996-2005 [5]. The capacity diagram of Figure 7 for a Vestas V90 3 MW wind turbine [6] was used to convert the wind speed into power production. For this conversion the program "HOMER" [7] was used that also corrects for the height at which the wind speed is measured. The hub height of the turbine was set to 70 m. The same hub height and wind turbine are used for the wind farm at Egmond aan Zee. By using wind speed data from 3 locations some spatial variation in the location of future wind parks is taken into account in the power production. For the analysis it is assumed that at each location 1/3 of the total capacity is installed.

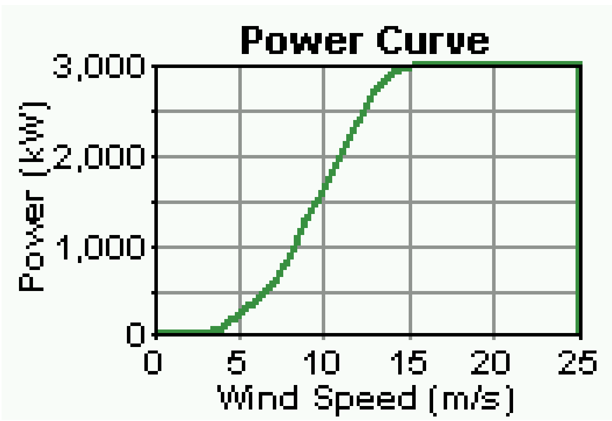

Figure 7: *Capacity curve of Vestas V90 3 MW wind turbine.*

The Dutch government has set a goal of 20% renewable power production in 2020. Part of this should be realised by an increase of the installed wind capacity. The currently installed wind power is approximately 1.5 GW onshore and 0.2 GW offshore. Policy ambitions for 2020 are 6 GW offshore wind power on top of the onshore wind power of 2-4 GW. For this study 8 GW installed wind capacity from the 3 offshore locations indicated in Figure 6 are used to simulate this ambition. The power production corresponds to 6 GW offshore and 3 GW onshore installed wind power capacity, as onshore the production is approximately 2/3 of the offshore production for the same wind turbine capacity.

The “Vijfde Nota Ruimtelijke ordening“ indicates that approximately 30 GW of offshore wind parks can be realised in the preferential area’s. The total potential for offshore wind energy is estimated by de Noord [8] as 150 GW for the Dutch territorial waters.

The hourly wind power production for the assumed 8 GW installed wind power capacity is shown in Figure 8 for the first 10 weeks of the year. This clearly shows the stochastic nature of wind power. The average offshore load factor for this wind turbine is approximately 45% at 100% availability. In this study we assume a 90% net energy due to turbine and park availability, power losses and aerodynamic losses due to wake effects in the wind farm, leading to an average load factor of 40% and a maximum power of 7.2 GW. This corresponds well to the average load factor for the offshore wind farm Q7 which is expected as 41% [435 GWh/yr at 120 MW installed] [9]. The wind power production is sorted in descending order for showing the load factor in Figure 9 for the complete year.

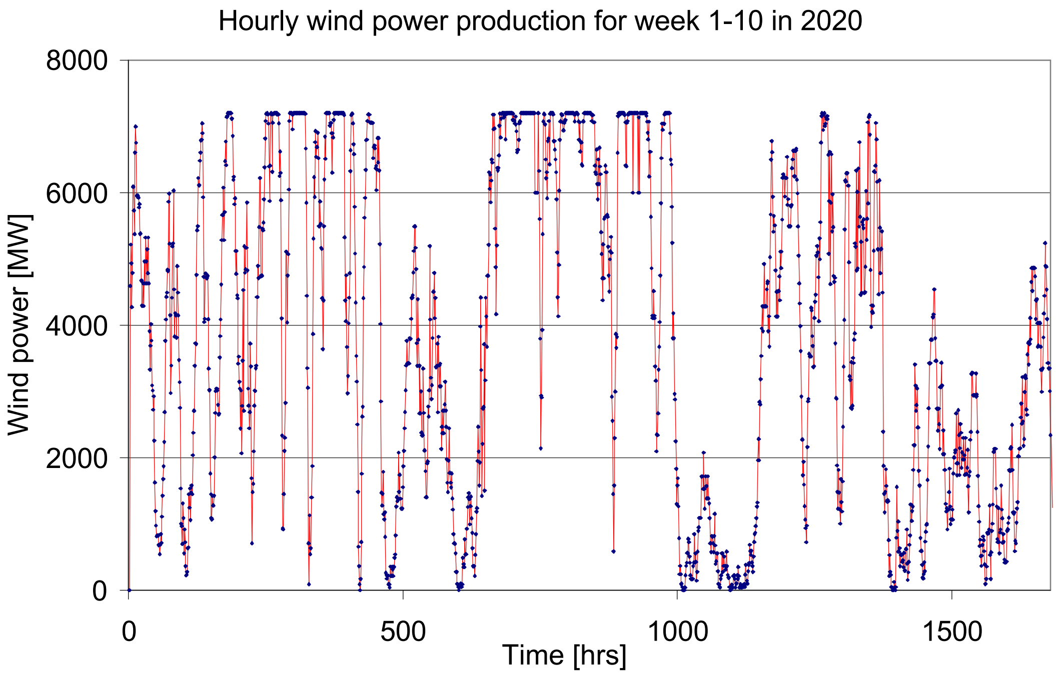

Figure 8: *Simulation of wind power production for the first 10 weeks of 2020 for 8 GW wind power capacity using the wind speed data of 2004.*

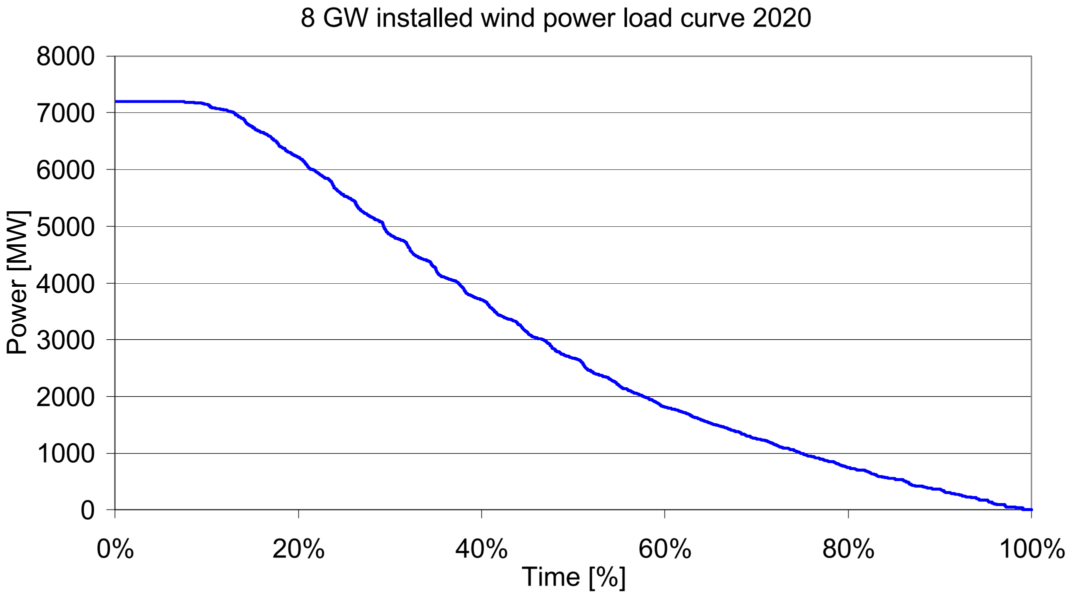

Figure 9: *Simulation of a load curve for 8 GW installed offshore wind power using 2004 wind speed data.*

5. Excess wind power determination

Whether or not excess wind electricity is produced or reserve capacity[1] is required to meet the electricity demand can be determined by subtracting from the demand (Figure 4 and Figure 5) the base load power (8.7 GW; see Figure 5) and the amount of wind power electricity produced (Figure 8 and Figure 9).

Excess wind power = Demand – Wind production –Base load (If < 0)
Reserve capacity = Demand – Wind production –Base load (If > 0)

The results for 8 GW wind power capacity are shown in Figure 10 and Figure 11. When the result is negative, this is the amount of excess wind power. When the result is positive, this is the required production from the reserve capacity. The reference year 2004 is used for both the electricity demand profile and the wind speed data[2] and extrapolated to the year 2020.

In Figure 11 the load curve for the hourly electrical demand for 2020 is presented (red line). By subtraction of the produced wind power from the electrical demand for each hour, the electrical power production from non-wind sources is obtained (pink line for 8 GW installed wind power). For the determination of the excess wind power a base load electricity generation of 8.7 GW is assumed (purple line), corresponding also to the minimum annual load as shown in Figure 11. The area under the purple base load line is denoted as excess wind power. With this assumption the excess wind power for the 8 GW wind power case is 4.5 TWh.

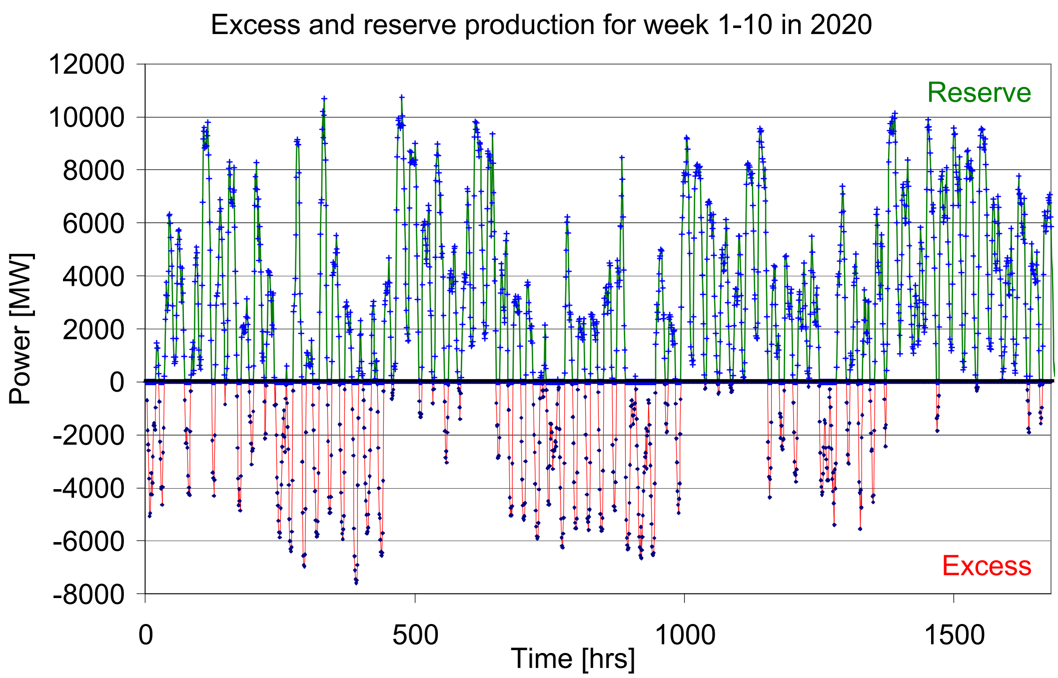

Figure 10: *Estimated excess wind power production and reserve power production for the first 10 weeks of 2020 at 8 GW installed wind power capacity and 8.7 GW base load.*

[1] In this study with reserve capacity is meant the capacity that is used to dynamically follow the demand either fast (primary or secondary control) or slow (tertiary control; stand-by power). This only excludes the base load power.
[2] The same year is used for power demand and wind speed data, although this is not necessary since it is found that a correlation between these data is absent.

In the TenneT study "Integrating the wind power into the system" [2] the main difference of calculating the excess wind power is that in their study excess power occurs when the dynamic response of the (in 2012 existing) power plants is insufficient to cope with the varying power demand, whereas in this study a constant baseload is assumed. The TenneT study assumes 2 GW onshore wind (load factor 25%) and 6 GW offshore wind (load factor 46%) and calculated the excess wind energy as 4.9 TWh/year.

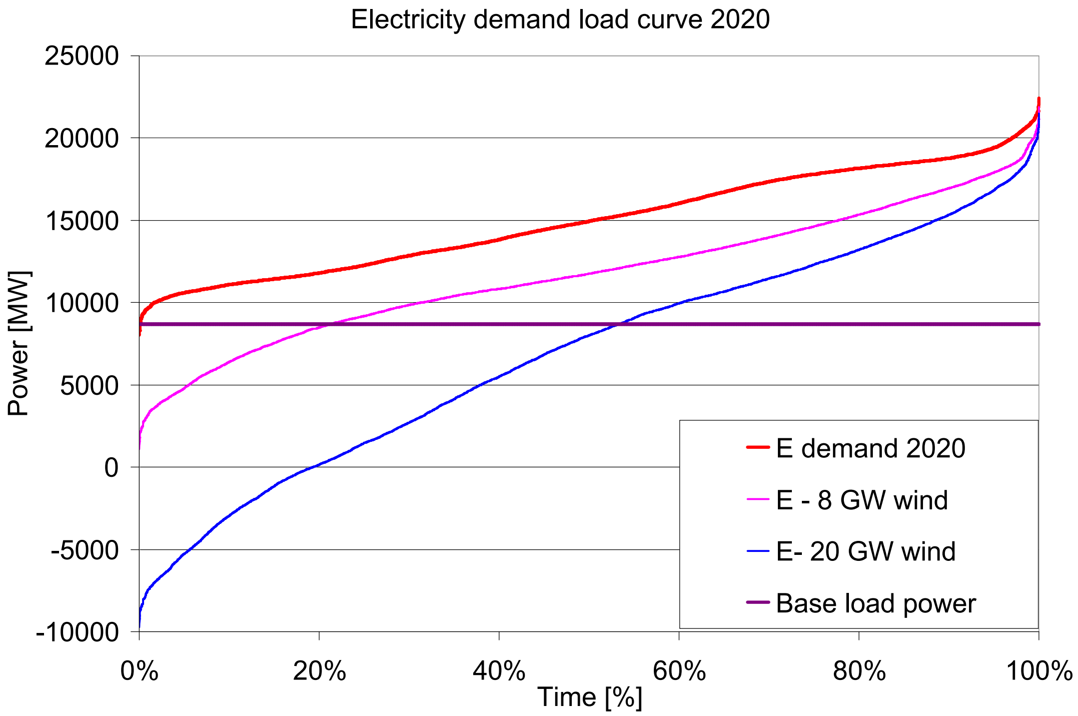

Figure 11: *Estimated electrical demand for the Netherlands in 2020 and the resulting demand when the produced wind power from an 8 or 20 GW wind park is subtracted.*

In Figure 11 also the non-wind electricity demand for 20 GW installed wind power capacity is shown (blue line). For this situation the amount of excess wind power (33.1 TWh) exceeds the amount of power required from the reserve capacity (17.5 TWh). This Figure also shows that the required reserve capacity (the points on the right axis) only slightly decreases with an increase in wind power capacity.

In Figure 12 the wind power production, the excess wind power and the required reserve power are presented as a function of the installed wind power. The installed wind power is varied from 0 to 40 GW. The potential for wind power in the Exclusive Economic Zone of the Dutch part of the North Sea is even larger, up to 150 GW [8]. The electricity demand is kept at the year 2020 level. This figure shows that from 4 GW onwards, excess wind electricity starts to arise. At 8 GW 16 % of the produced wind power can be defined as excess wind power and for 22 GW half of the wind power is excess wind power. This means that alternative uses for the excess wind electricity have to be found. The required amount of reserve power decreases from 55 TWh without wind power to 10 TWh at 40 GW of installed wind power.

The influence of the wind power capacity on the required reserve capacity is further elaborated in Figure 13. This Figure shows that the decrease in reserve capacity, compared to the reserve capacity required without wind power, is small (8%) for an increase in installed wind power up to 40 GW. The average operating time that the reserve capacity is used decreases from nearly 50% without wind capacity to 10% at 40 GW installed wind power. This means that the dynamic operation of the reserve capacity needs to be much faster than needed today since it has to cope with both changes in demand as well as changes in wind power production. This is further elaborated in Appendix C. Secondly, the cost per kWh of electricity from the reserve capacity will increase strongly since the investment costs of the reserve capacity per produced kWh increase five-fold going to 40 GW installed wind power. In this Figure the time that excess wind power is produced is also provided showing that above 20 GW installed wind power excess wind power occurs for more that 50% of the time. A table with the wind power production, excess wind production and reserve power production is provided in Appendix A.

With each additional wind park, the direct use of electricity from this wind park in the Netherlands electricity grid reduced, as is further elaborated in Appendix B.

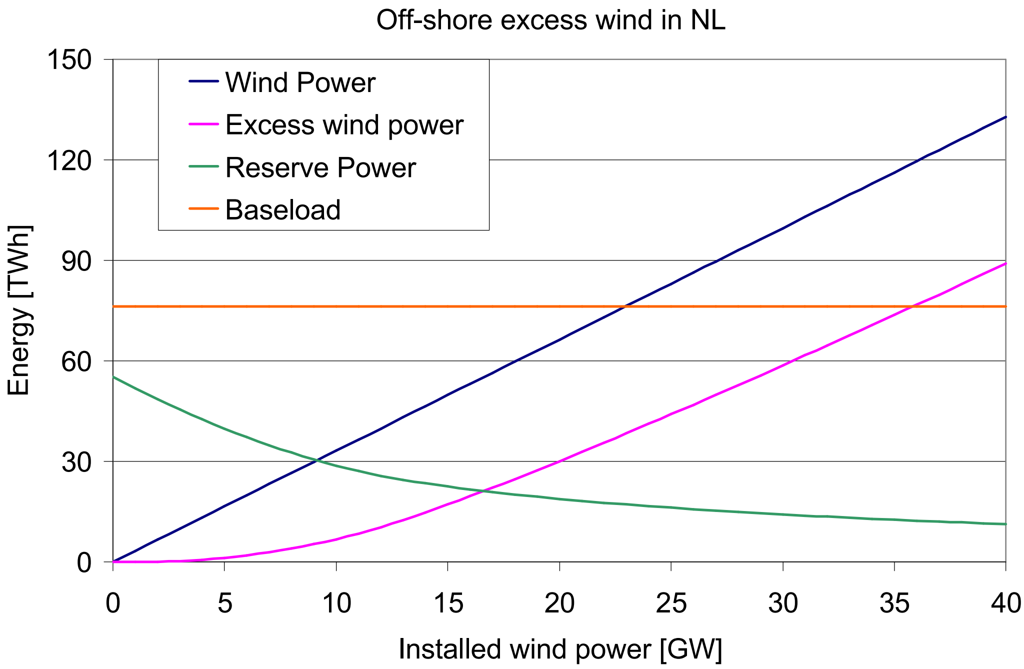

Figure 12: *Variation of produced wind power, excess wind power, reserve capacity power vs. the installed wind power capacity at constant base load.*

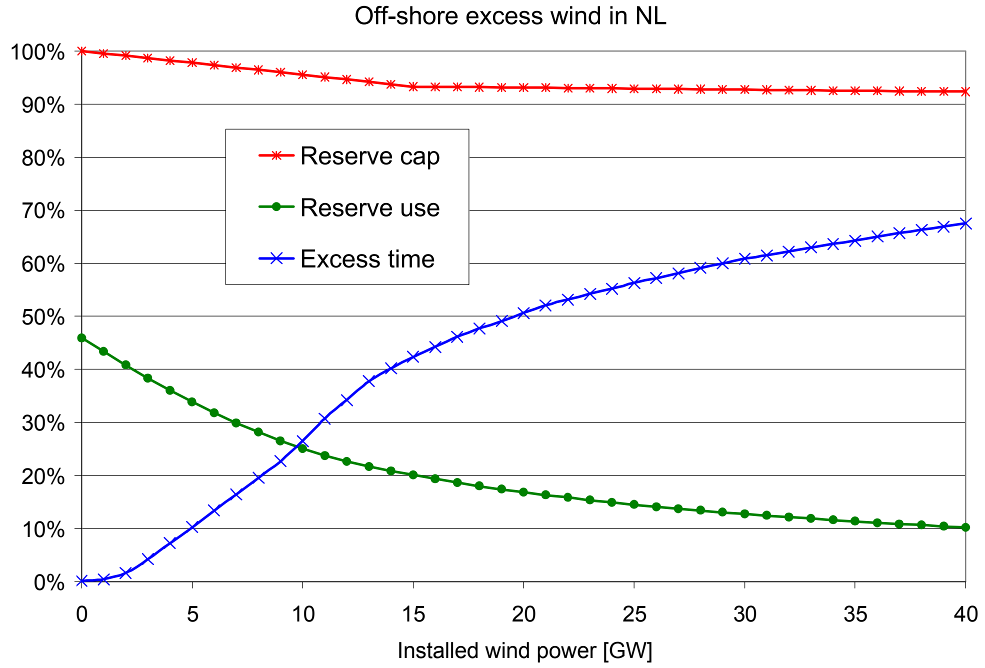

Figure 13: *Variation of reserve electricity capacity (reserve cap), reserve electricity use (reserve use) and time of excess wind power (excess time) vs. the installed wind power capacity.*

6. Use of excess wind power

6.1 Electrolysis and hydrogen distribution

The excess wind power can be converted to H_2 by electrolysis. Alkaline electrolysers are the present day choice. The electrolyser efficiency used in this study is 68% on the LHV (lower heating value) basis of H_2 which is 81% on the HHV (higher heating value) basis and the electrolyser output pressure is set to 13 bar.[3] The cost of large-scale electrolysers is assumed to be 500 €/kW$_e$, a target value commonly found in literature [10] and the target of the EU HYSTRUC project. In order to cope with the seasonal variation in wind energy, the hydrogen has to be compressed and stored. It is assumed here that the compressor capacity is equal to the electrolyser capacity and that the output pressure is 60 bar (comparable to the NG transport infrastructure). The hydrogen storage size requirements and associated costs due to the unbalance in H_2 production and usage are investigated in chapter 6.6.

One option is that the H_2 from the storage will be inserted in a hydrogen grid and transported to the houses for residential use in a μ-CHP unit providing heat and power to the house. The cost for the hydrogen infrastructure is estimated from the present transport and distribution costs for natural gas, for an average household using 1700 m^3/year natural gas (NG) this amounts to 170 €/year. For the hydrogen grid a double amount of 340 €/year will be assumed since a new grid has to be made with stricter requirements.

Another option is that the hydrogen will be used in fuel cell vehicles for transport application. The hydrogen can be generated by electrolysis at the filling station directly and stored, or at a central location, stored and distributed. Distribution of the hydrogen for transport has several options:

- Compressed hydrogen truck
- Liquid hydrogen truck
- Hydrogen pipeline

The heat produced by the electrolyser is not used and has no value in the analysis. In principle it can be fed into heating grids.

6.2 μ-CHP fuel cell system

For the μ-CHP fuel cell system a 1 kW$_e$ PEMFC system operating on H_2 in electrical load following mode is assumed since the feed-in tariff for electricity is only in the order of a few €ct/kWh (exception see chapter 6.4) in the Netherlands and it is therefore not economical to size the unit for grid delivery. The voltage-current density curve for a PEMFC operating on H_2 of Figure 14 is used. For the analysis of the μ-CHP system in this report the current density is arbitrary, for the 1 kW$_e$ operating point a mean cell voltage of 650 mV$_{dc}$ is assumed.

Thermal and electrical losses for the system are assumed, leading to the electrical and thermal power depicted in Figure 15 and efficiencies depicted in Figure 16

The maximum total efficiency at 1 kW$_e$ system power is set to 90%, the maximum value that can be found also in literature for these small systems [11]. From Figure 16 can be

[3] This amounts to 4.4 kWh/Nm^3 H_2 for the electrolyser system. Literature values vary between 4.3 and 4.8 kWh/Nm^3 H_2. The use of electrolysers with variable (and often zero) input poses extra requirements on the electrode materials used and reduces the efficiency of the electrolyser (a value of 2% is described, reference Dutton 2000). The output pressure of electrolysers from Norsk Hydro is 13 bar.

seen that the total efficiency reduces at part load due to the power independent losses in the system.

Two operating modes for the µ-CHP units are considered:

1. Electrical load following operation (no feed-in to the grid)
2. Full load operation up to the yearly electrical demand (with feed-in to the grid).

In the latter situation µ-CHP electricity produced may exceed the momentarily demand of electricity, so electricity needs to be exchanged with the grid.

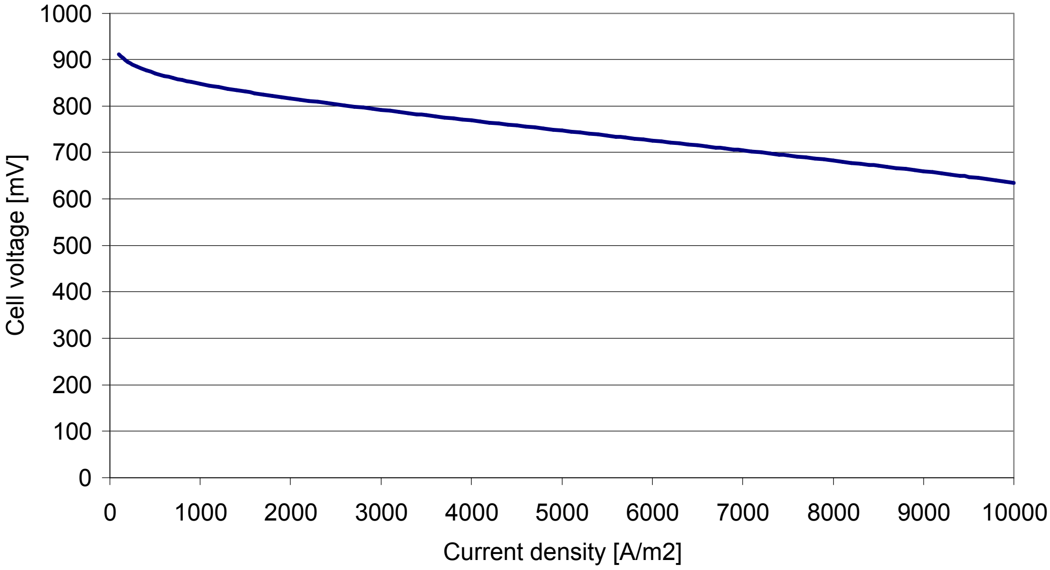

Figure 14: *Voltage-current density curve for a PEMFC on H2 used for modelling.*

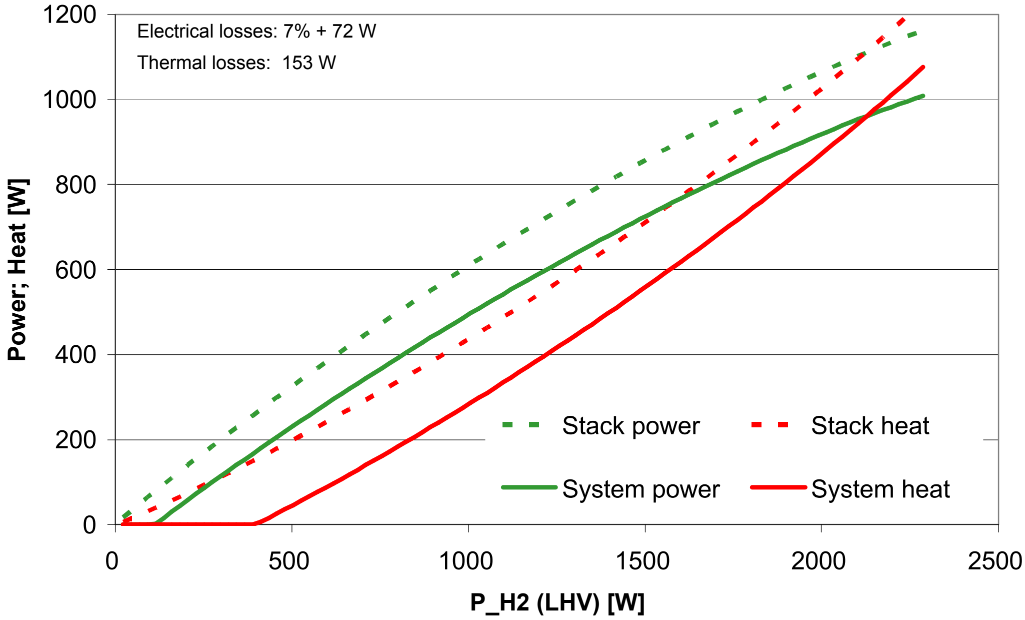

Figure 15: *Net electrical and heat output of a 1 kWe µ-CHP PEMFC system and gross stack output as a function of the H2 power input in LHV.*

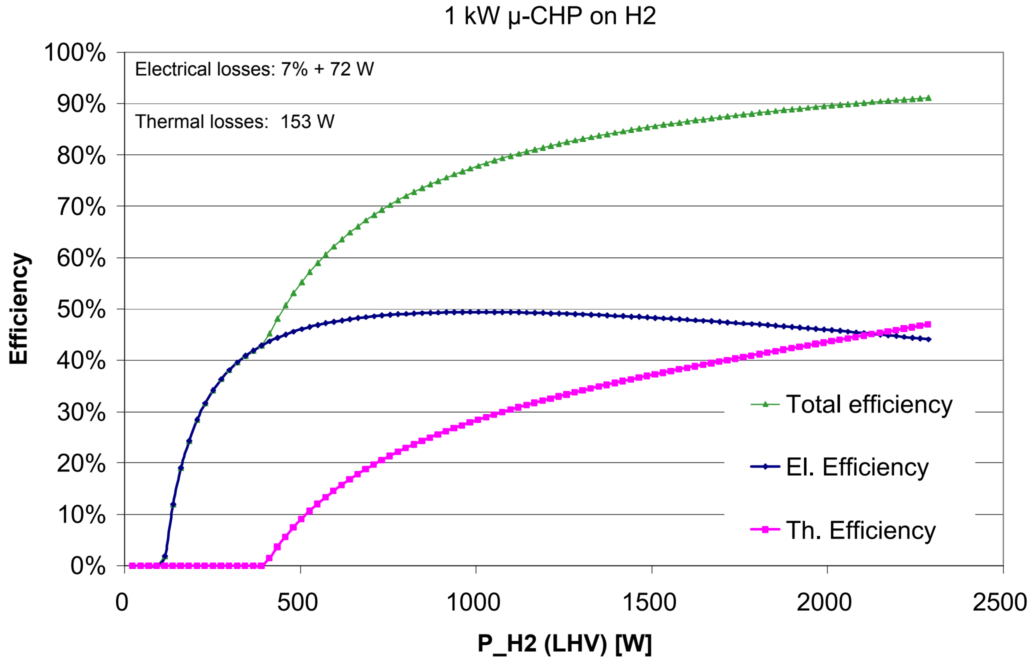

Figure 16: *Total, electrical and thermal efficiency for the 1 kWe µ-CHP system as a function of the H2 power input in LHV.*

6.3 Electrical load following mode

In the electrical load following operation in a household, the µ-CHP system can provide a part of the electrical load, as can be seen in Figure 17. An average household electrical load of 4550 kWh in 2020 is used (Global Economy scenario), together with a measured daily load profile, assuming that the µ-CHP system produces no electricity during low tariff electricity periods, i.e. from 23.00 hr in the evening to 07.00 hr in the morning.

In the arrangement according to Figure 17, 71 % of the demand can be provided directly by the µ-CHP unit. 14% of the demand can't be provided since the demand is larger than 1 kW_e, 7% can't be provided since the demand is loo low and the system will be shut-down for technical as well as economical (efficiency) reasons and 8% for no 23.00-07.00 hrs production. Here it is assumed that the system operates between 20% and 100% electrical power. The typical daily dynamic operation profile for the fuel cell system according to Figure 17 is shown in Figure 18, assuming that the µ-CHP system produces no electricity during low tariff electricity periods, i.e. from 23.00 to 07.00 hrs. Other non-producing electricity periods can be expected when large wind energy production is obtained.

The electrical load following operation is also the reason that the system operates most of the time in part load. The mean overall efficiency for the average household is calculated as 82%, of which 48% is electrical and 34% thermal. The useful heat from the fuel cell system is approximately 2170 kWh, which is 70% of the energy needed for tap water.[4] This means that also other heat supply is needed for the household for the additional tap water needs and space heating needs[5]. The tap water will be heated using a heat exchanger with the cooling system for the PEM fuel cell. The temperature of the hot water from the PEM fuel cell system is also low (max. 60 °C) and the tap water probably requires extra heating before it can be used.

[4] Average natural gas use for tap water is 350 m^3/yr, which corresponds to 3080 kWh.
[5] The average space heating need in 2006 was 10600 kWh/yr; for the Netherlands new house with EPC = 0.6 this reduces to 5800 kWh/yr. The space heating need is concentrated in the winter season.

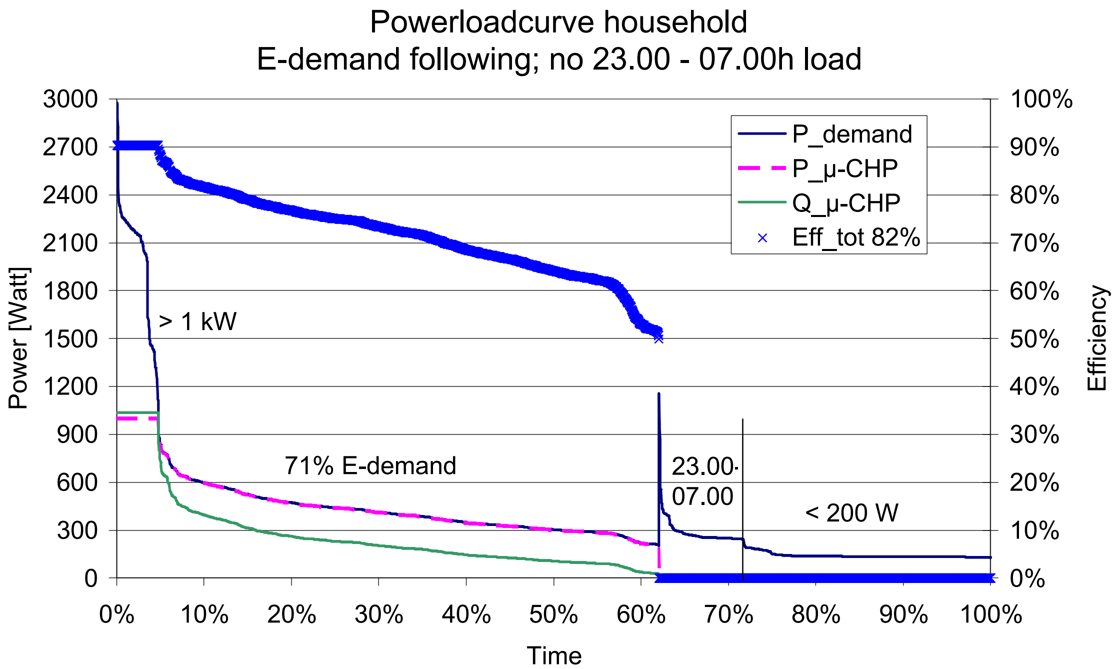

Figure 17: *Characteristic electrical load following operation for average household showing the power demand (P_demand), power supply (P_µ-CHP) and heat supply (Q_µ-CHP) by µ-CHP, together with the total efficiency (Eff_tot) of the µ-CHP unit.*

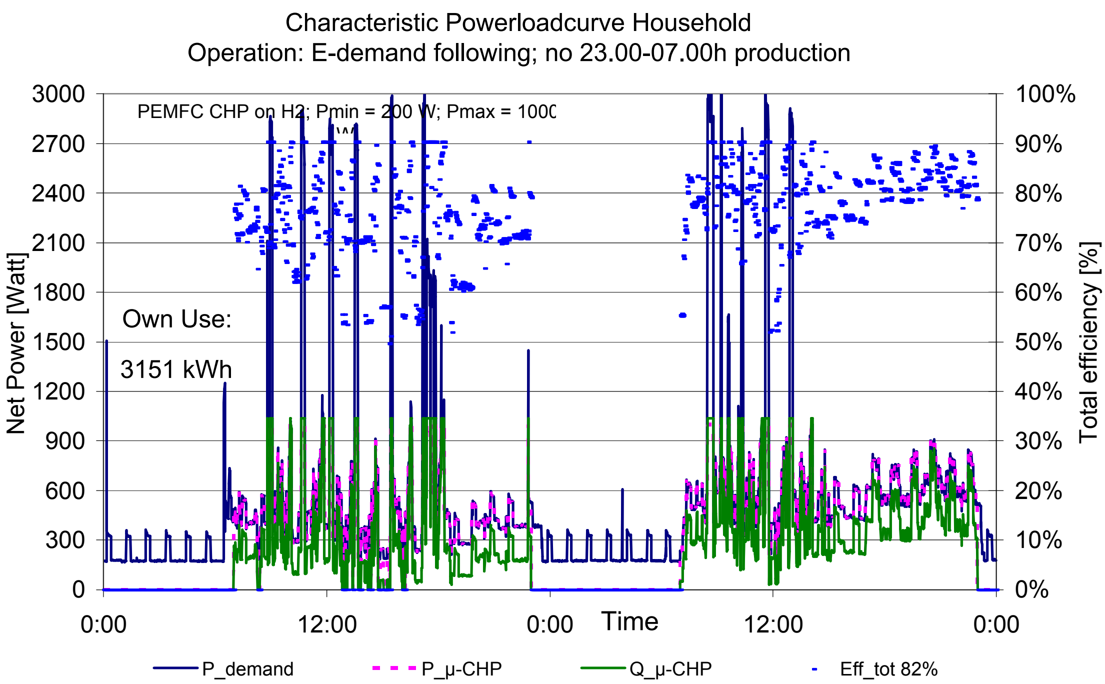

Figure 18: *Typical daily dynamic operation for the load following µ-CHP fuel cell system showing the power demand (P_demand), power supply (P_µ-CHP) and heat supply (Q_µ-CHP) by µ-CHP, together with the total efficiency (Eff_tot) of the µ-CHP unit.*

The cost of the 1 kW_e µ-CHP system is assumed as 1000 € above the cost of a central heating boiler, a target value often quoted for stationary applications.

6.4 Full-load operational mode

Another operational mode is that the fuel cell system produces on average the same amount of electricity as the yearly household demand. This means that electricity is exchanged with the grid. This operation mode is based on the Dutch feed-in tariff regulation for renewable energy (based on PV systems) up to 2006, which equals the consumer price (0.2 €/kWh), if:

- The amount of feed-in is lower than 3000 kWh and
- No net production of electricity into the grid (balancing electricity exchange with the grid for supply and feed-in).

In all other cases the Dutch feed-in tariff is approx. 0.03-0.04 €/kWh. The operating strategy for the fuel cell system would be to produce maximum power only in periods without excess wind power and in total providing the yearly domestic electricity demand as shown in Figure 19. This strategy minimises the amount of electricity to be purchased from the grid to 0 kWh/yr and at the same time maximises the heat production. The average heat from the fuel cell system (4650 kWh) now exceeds the average tap water needs (3080 kWh), providing room for some further optimisation or partial use for space heating. In Figure 20 a possible operation profile is provided assuming heat demand driven operation where most hot tap water is needed in the morning (for showering etc.). This example shows that also electricity is produced during hours of low electricity demand. Furthermore, the operation profile is strongly household specific. In this example 56% of the produced electricity is used directly and 44% of the produced electricity is exchanged with the grid. A full analysis on an hourly basis taking into account full load µ-CHP operation in non-excess wind hours and matching of supply and demand of heat for tapwater is however not done in this study. So it is not clear whether the situation of Figure 19 and Figure 20 is possible, but it represents an optimised case from an efficiency and cost point of view. The load factor in this operation is 52%, which means that maximum 18 GW wind power can be installed according to Figure 12.

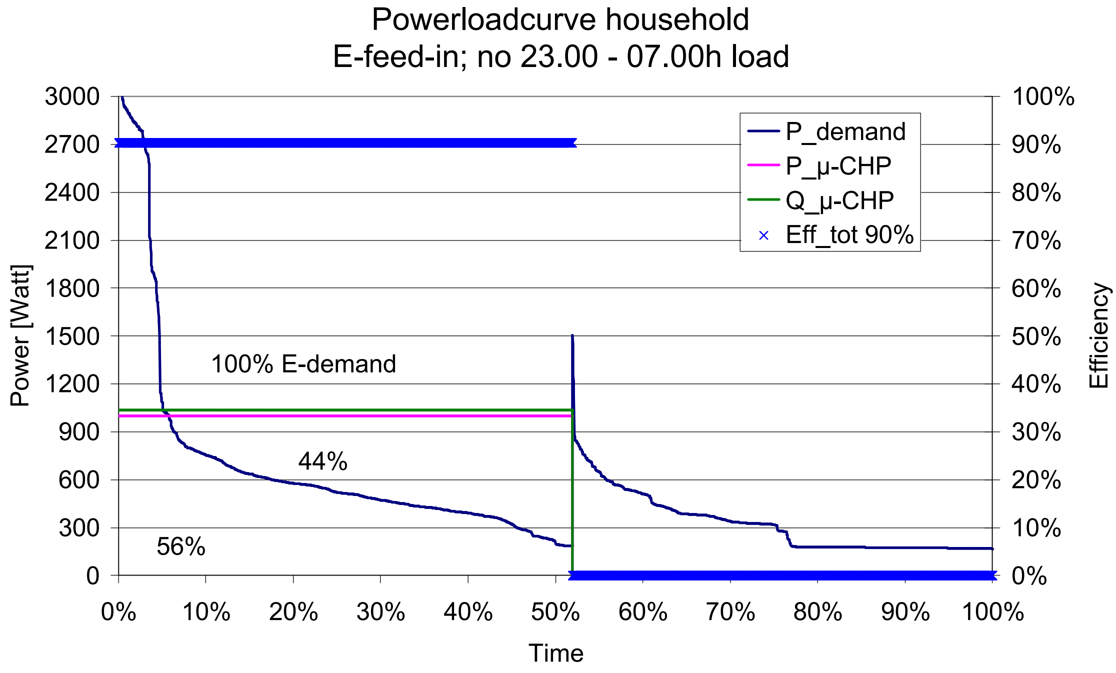

Figure 19: *Optimal µ-CHP operating strategy for present day feed-in arrangement showing the power demand (P_demand), power supply (P_µ-CHP) and heat supply (Q_µ-CHP) by µ-CHP, together with the total efficiency (Eff_tot) of the µ-CHP unit.*

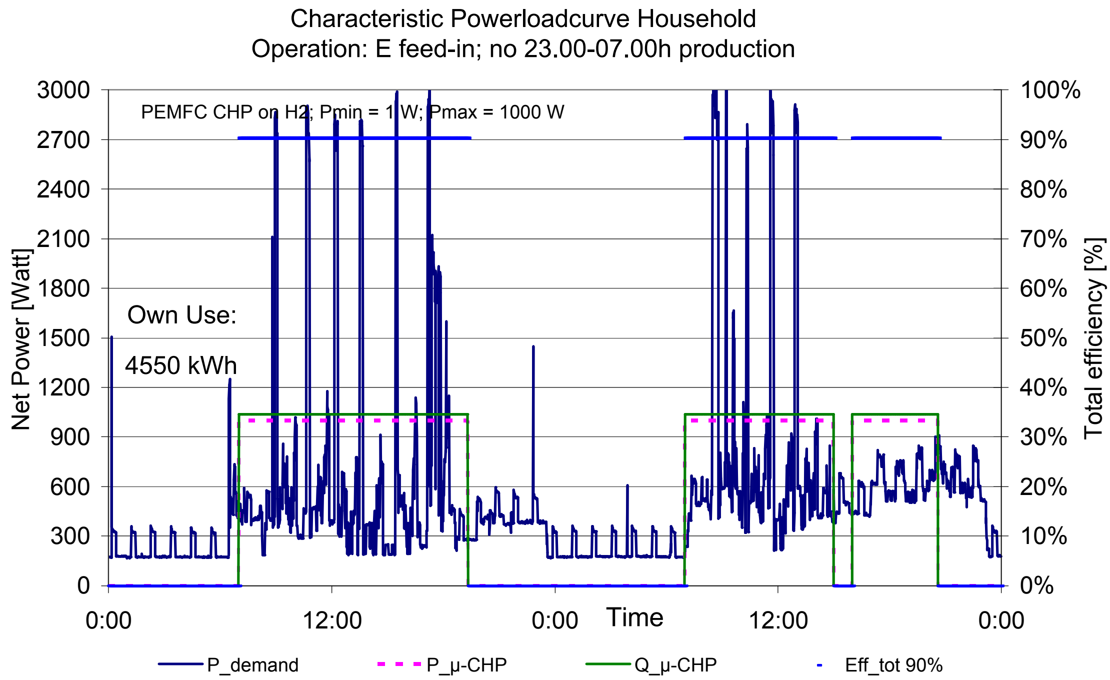

Figure 20: *Possible operation profile for heat demand driven operation and electrical feed-in showing the power demand (P_demand), power supply (P_µ-CHP) and heat supply (Q_µ-CHP) by µ-CHP, together with the total efficiency (Eff_tot) of the µ-CHP unit.*

6.5 Number of units supplied by hydrogen

The amount of households or passenger cars that can be provided with the hydrogen produced by excess wind power is presented in Figure 21.

For the µ-CHP system operating on H_2 coming from excess wind power electrolysis it is assumed that it only operates when there is no excess wind power and that the control signal for this is provided through the grid. In this way it is prevented that the µ-CHP unit makes extra power when there is already excess electricity. For the arrangement that electricity is fed back into the grid, the electricity production is 4550 kWh/yr up to an installed capacity of 18 GW, and becomes lower above 18 GW because the maximum operating time for the µ-CHP unit reduces due to the increasing time of excess wind electricity. For the µ-CHP without feed-in to the grid, the maximum electricity production is 3150 kWh/yr and starts to decrease gradually due to the increasing time of excess electricity.

Passenger car refuelling is independent from the time of excess wind energy. The average mileage for cars in the Netherlands is 15500 km/yr, the future fuel cell vehicles are expected to drive 144 km/kg H_2, which leads to an average H_2 use of 108 kg/yr. The total amount of households in the Netherlands in 2007 is 7.0 million and the total amount of passenger cars is 7.2 million.

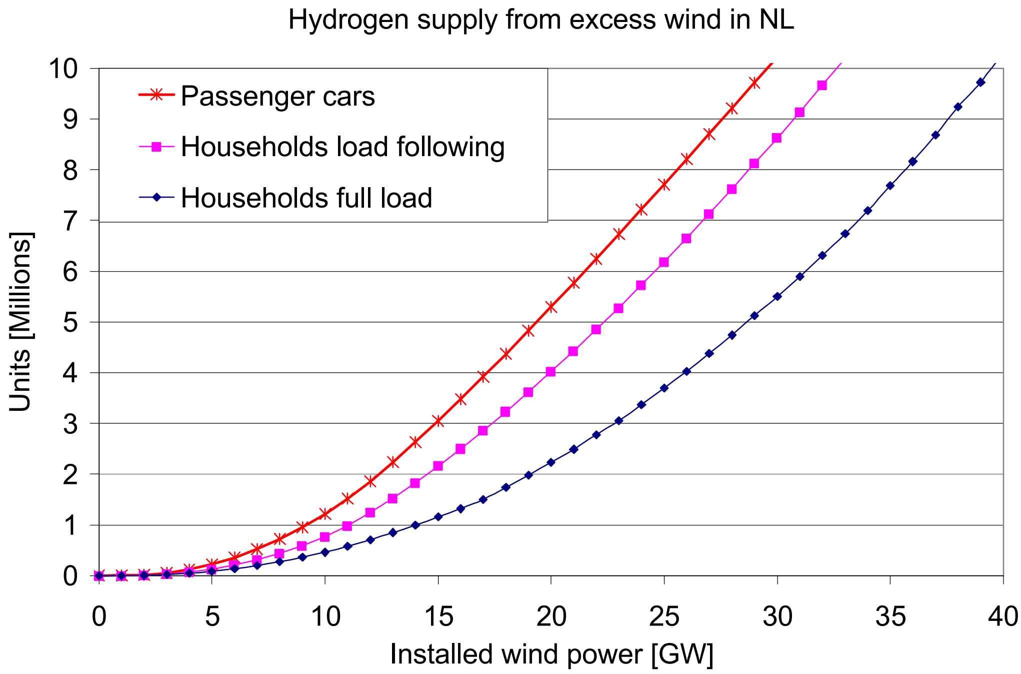

Figure 21: *Number of households for the electricity load following and full load operation, and number of cars that can be supplied with the hydrogen from excess wind power in relation to the installed wind power capacity.*

As an example, the 4.5 TWh/yr excess wind energy at 8 GW installed wind power capacity are converted by electrolysis to 80 kton/yr of H_2 and 0.6 Mton/yr of O_2. The further use of this O_2 should be investigated; Appendix E addresses briefly this issue.

6.6 Large-scale hydrogen storage

The hydrogen storage requirement for the 8 GW case due to seasonal variation in the wind power is depicted in Figure 22 (2004 wind data) and Figure 23 (2002, 2003 and 2004 wind data). It is assumed that all hydrogen produced in one year is also used in that year.

Two cases are distinguished:

1. Electricity production from hydrogen only during periods without excess wind power and not in the low price period (weekend and 23.00-07.00 hrs)
2. Time independent hydrogen use for passenger cars.

For both figures the storage requirement (without any strategic storage) is on the order of 20.000 tons of hydrogen except for the year 2003. Using the wind speeds of that year also the excess wind energy is half of the excess wind energy of the other 2 years. The 0.8 million cars that could be supplied by the hydrogen could store approximately 2500 ton of H_2, one order of magnitude less than the storage requirement. Pressurized storage at 80 bar (the pressure of the high pressure natural gas main transport pipelines) would require 5000 km of 1 m diameter high quality steel. For the amount of 20.000 tons of hydrogen geological storage should be investigated as an alternative. In the USA and UK storage in salt caverns is used. As an example, *the "ChevronPhillips Clemens Terminal" cavern has been in service > 20 years, storing ~2,500 net tons of GH_2 at up to 140 bar. Several solution-mining industry contacts estimated construction of such caverns at \$US 10 - 15 M. Therefore, a conservative estimate of a new cavern construction is \$US 15 M, plus the cost of GH_2 "cushion gas" at ~\$5M. The hydrogen leakage is probably very small [13].* For the Netherlands storage in empty gas field is another option (although they are not really empty) and should be compared to the salt cavern solution.

Large-scale liquid hydrogen storage is an alternative. The advantages of this option are:

- The purity of the hydrogen.
- In case of truck transport , a LH_2 truck transports approximately 10x as much energy as a compressed gaseous H_2 truck.
- Flexibility in infrastructure build-up.
- No pipeline infrastructure is required.

The disadvantages are:

- The energy requirement for liquefaction (10-12 kWh/kg LH_2)
- Preferably the liquid hydrogen containers (dewars) are kept cold since cooling down the dewars requires a large cooling capacity.
- Preferably, a liquefier plant is operated continuously since starting-up requires a long time and a lot of energy. So it also consumes electricity during no excess wind hours.
- The boil off for the storage (e.g. boil-off of 0.3%/day is reported for a 270 m^3 LH_2 tank at liquefaction plant in Ingolstadt and 0.025%/day for the worlds largest, 3200 m^3 LH_2 or 225 ton tank at NASA Kennedy Space Centre)

For the storage of 20.000 tons of liquid hydrogen about 100 tanks of the size at NASA are required. The boil-off from these tanks would be 5 ton/day and the liquefaction of this boil-off requires 2 MW continuously or 0.5% of the excess wind power.

When taking into account that only the amount of hydrogen is liquefied that is not used within one day, an electricity demand of approximately 15% of the excess wind energy is needed for the liquefaction process, neglecting the stochastic nature of the supply.

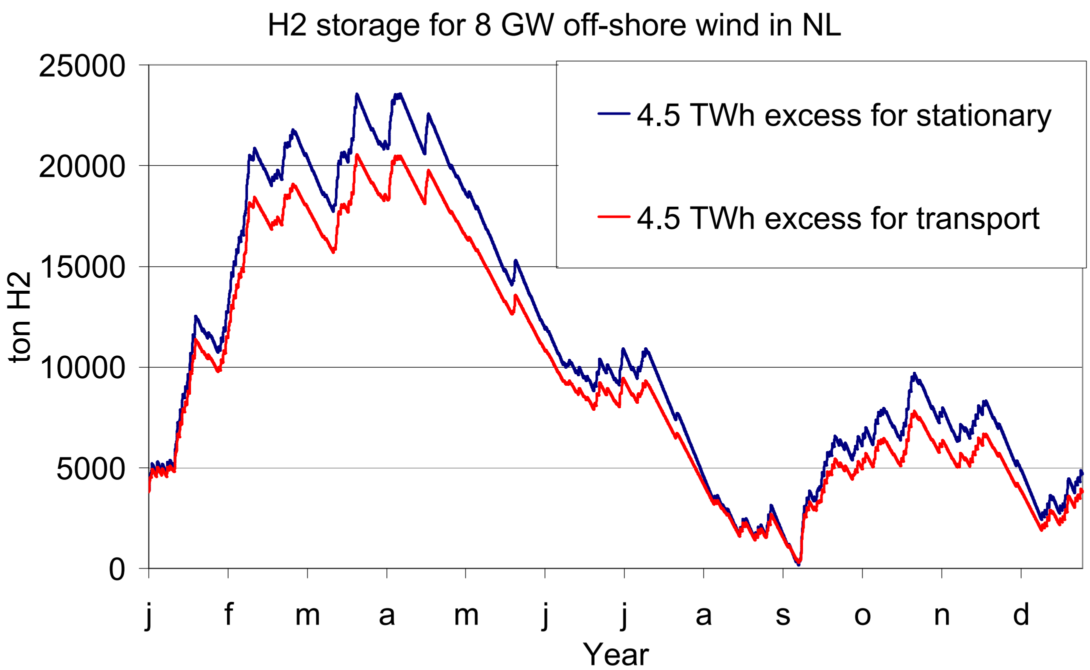

Figure 22: *Storage requirement for hydrogen for transport and μ-CHP applications due to seasonal variation in wind power (2004) for 8 GW installed wind power capacity.*

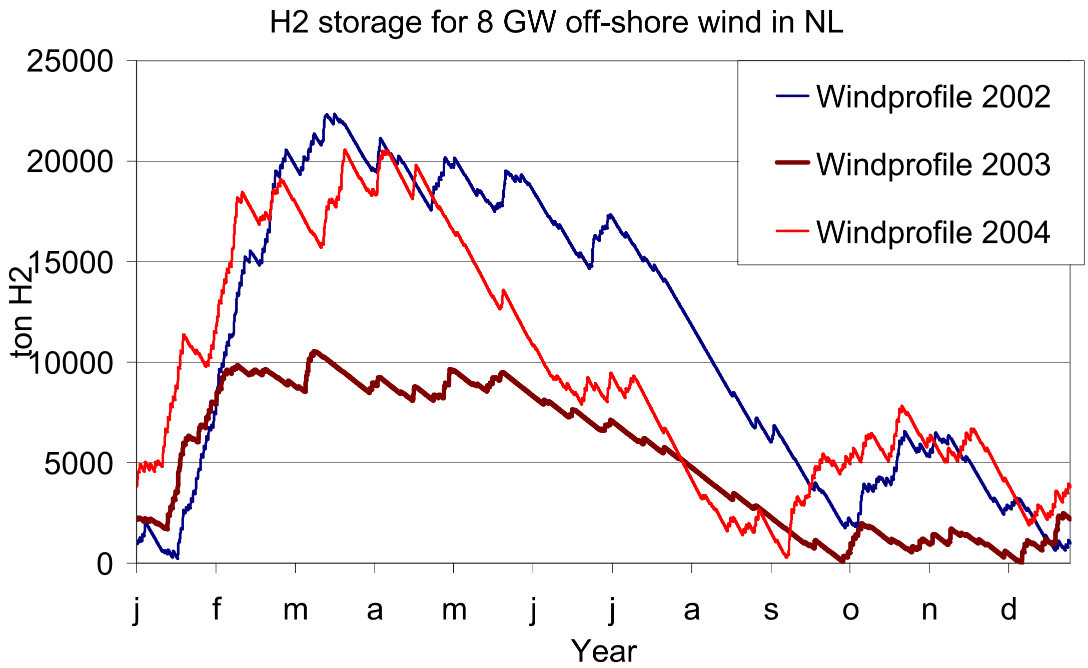

Figure 23: *Storage requirement for hydrogen for transport due to seasonal variation in wind power using wind data of 3 different years for 8 GW installed wind power capacity.*

6.7 Cost of hydrogen and electricity

First the cost of hydrogen production will be calculated. The hydrogen can be used either for transport applications or for stationary applications. Then the cost of the electricity produced by the μ-CHP household system for stationary applications will be calculated. The hydrogen cost depends mainly on the investment costs for electrolysers, the efficiency of the process, the time of excess wind energy and the cost of the excess electricity. For the cost of μ-CHP electricity (CoE) also the investment costs for the H_2 infrastructure and the fuel cell system are considered.

The assumptions made on the future investment costs, efficiency etc. are:

- Electrolyser investment cost is 500 €/kW$_e$ (this is a target set by the EU HYSTRUC project; the DoE target = 300 \$/kW$_e$)
- Fuel cell based μ-CHP investment cost is 1000 € above central heating boiler cost for a 1 kW$_e$ system.
- Offshore wind turbine investment cost is set to 2200 €/kW installed[6].
- Hydrogen grid cost is 340 €/household/year
- Interest rate of 5% and component specific technical lifetime assumptions (10-30 years).
- The minimum cost of excess electricity is set to 0.02 €/kWh$_e$ or 5.56 €/GJ. This is the minimum spot market price for electrical energy in the Netherlands and comparable to the price of natural gas for very large consumers (0.18 €/m^3 in 2006), based on the same energy content.
- The value of the useful heat from the fuel cell system is set equal to the consumer unit energy price for natural gas (0.59 €/m^3 = 0.067 €/kWh$_{th}$). All heat can be used.

[6] Airtricity proposed to build a 10.000 MW offshore wind park between England. Germany and the Netherlands at a cost of 22 billion Euro. This as a first step for a secure energy supply, protection of the environment and long term price stability.

From the previous paragraphs the following results are used:

- The electrical efficiency of the fuel cell is 48% and the thermal efficiency 34% for the electrical load following case
- The electrical efficiency of the fuel cell is 44% and the thermal efficiency 46% for the full-load operation case
- The time of excess wind energy is 20 % in the 8 GW installed wind power case, which corresponds to approx. 10% full load hours for the electrolysers.

When 8 GW wind power is installed, the size of the electrolyser will be maximum 6 GW, as can be concluded from Figure 11. The minimum investment costs for the 8 GW installed wind power case are then estimated as:

Inverter (6 GW)	300 M€
Electrolyser (6 GW)	3000 M€
Compressor	250 M€
Geological storage	200 M€
H_2 infrastructure	1400 M€
Fuel cell systems (0.4 Million)	400 M€
Total	5550 M€

These inputs are used in a spreadsheet model to calculate the cost of hydrogen and the cost of µ-CHP electricity. An example for the full-load operation case including feed-in of µ-CHP electricity is provided in Appendix F. For each consecutive step in the process the remaining energy is calculated as well as the cost of the energy carrier up to this step. The round-trip efficiency in this full-load operating example is 28% electrical and 29% thermal. Figure 24 visualises the development of cumulative cost and efficiency along the process or energy chain. The cost does not include profit or taxes for the feed-in operation of the fuel cell system. The process step "Fuel cell heat" shows the effect of the use of the heat from the fuel cell on cost and total efficiency. In this case the cost of µ-CHP electricity of 118 €/GJ or 0.45 €/kWh$_e$ is already higher than the present consumer price for electricity including taxes, profit etc. Due to the efficiency losses, the cost of electricity from the µ-CHP increases by 0.03 €/kWh$_e$ for every 0.01 €/kWh$_e$ increase of the cost of excess electricity from the grid.

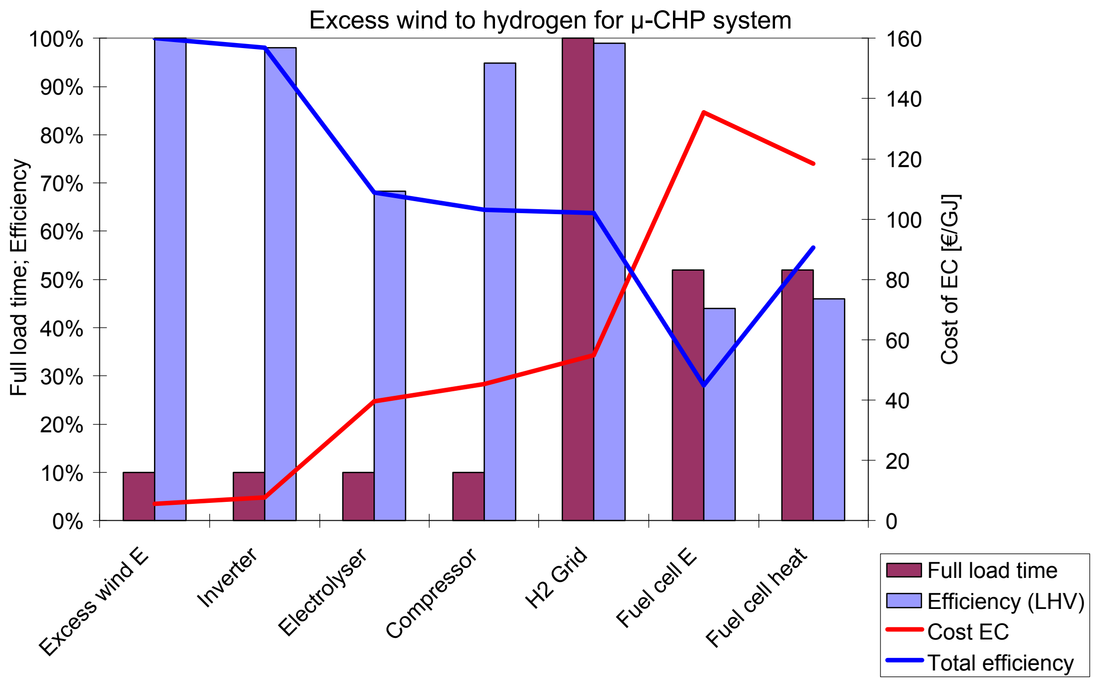

Figure 24: *Full load time, efficiency and cost at the different process steps for the 8 GW wind power case with feed-in. EC = energy carrier (either electricity or hydrogen)*

The cost of hydrogen from offshore wind power via electrolysis will depend on the cost of the electricity from the wind park and the load factor of the electrolyser. This is depicted in Figure 25. The cost of hydrogen used here is taken after the electrolyser as depicted in Figure 24. If excess wind is available from wind parks set up for mainly electricity production (up to about 8 GW installed power) the excess wind electricity price can be as low as 0.02 €/kWh, the present minimum price on the APX electricity market, leading to the cost of hydrogen of 4.4 €/kg. For much larger wind power production the offshore wind parks are assumed to be (mostly) set-up for H_2 production and then the price for the wind electricity to be used for the electrolysis is approximately 0.08 €/kWh. The minimum cost of H_2 is then 0.14 €/kWh or 5 €/kg, as can be seen from Figure 25.

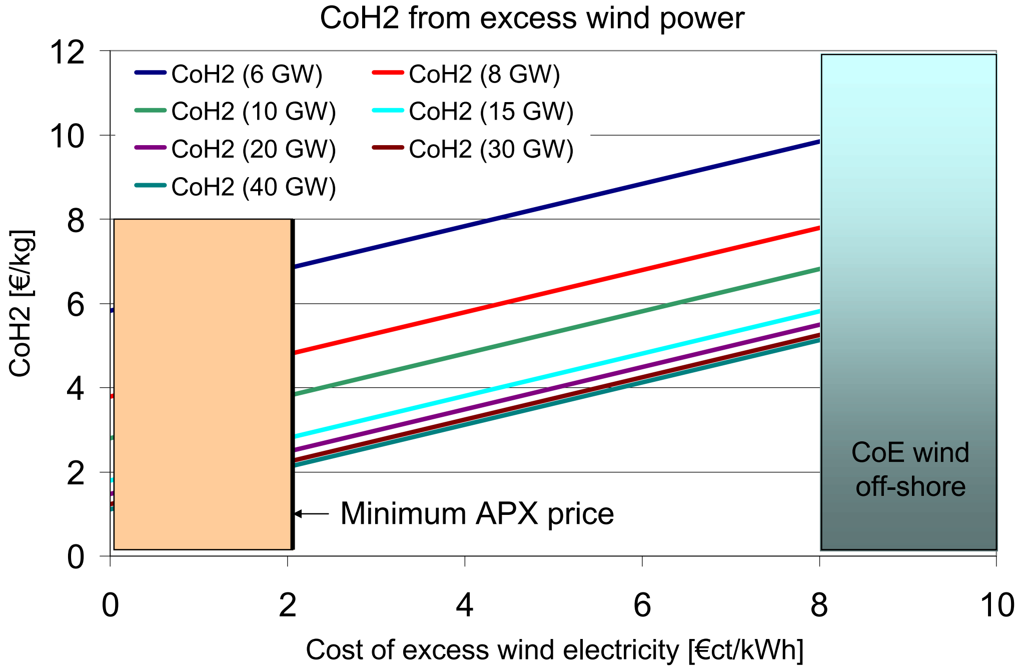

Figure 25: *Cost of hydrogen as a function of the cost of excess wind electricity and the amount of installed wind power capacity.*

In the calculations, the time of excess wind energy is varied between 10 and 90% and the results are depicted in Figure 26 and Figure 27. These figures show that the minimum CoE is at an excess wind energy part for about 50% of the time, corresponding to an installed wind power of around 30 GW. In Figure 26 the minimum cost of electricity is calculated for the load following operating strategy for the fuel cell system from Figure 18. At the left part of Figure 26 the CoE is high because the electrolyser operating time is low and at the right side the CoE is high because the fuel cell operating time is low since it will only operate during non-excess wind hours. In Figure 27 the minimum cost of electricity is calculated for the economic optimal full-load operating strategy for the fuel cell system from Figure 19. In this last figure the minimum cost of electricity is 0.04 €/kWh$_e$ lower than in Figure 26. In both figures the excess wind energy operating time from Figure 13 is used for estimating the required amount of installed offshore wind power. The calculation at 8 GW is the same calculation point as shown in Figure 24.

In Figure 28 the CoE for the case without feed-in is shown for variation in cost of excess electricity and installed wind power. With the assumptions mentioned above, the CoE is at least 5 times the cost of excess electricity.

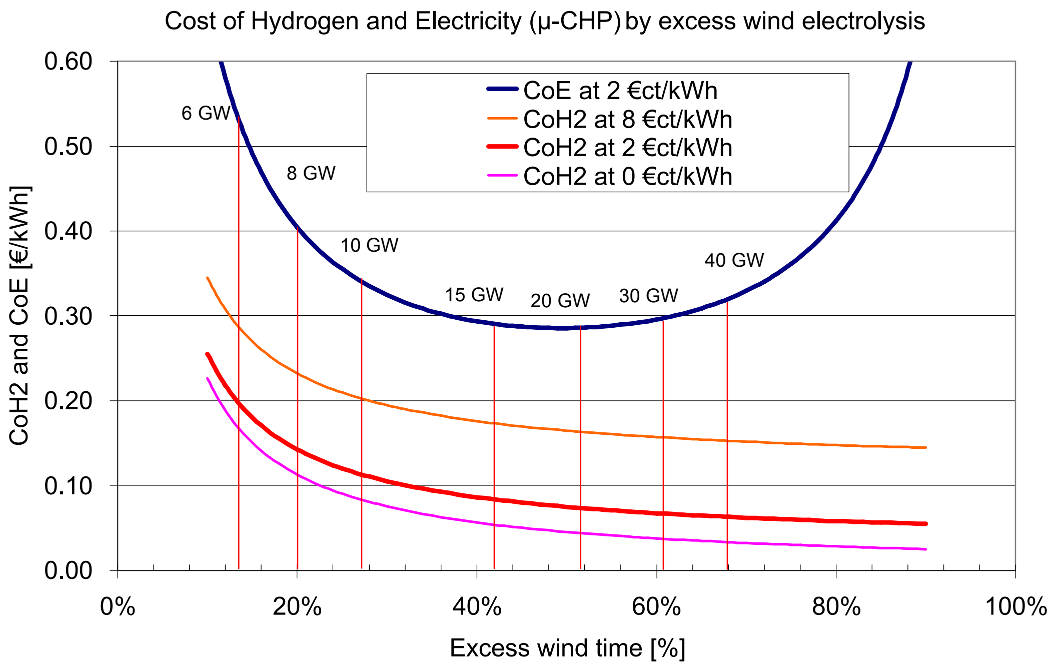

Figure 26: *Cost of hydrogen (CoH2) and cost of electricity (CoE) from H2 fuelled μ-CHP with variation of excess wind time (from Figure 13) and no feed-in. For CoH2 in €/kg, multiply by 33.6. For CoH2 in €/GJ, multiply by 278.*

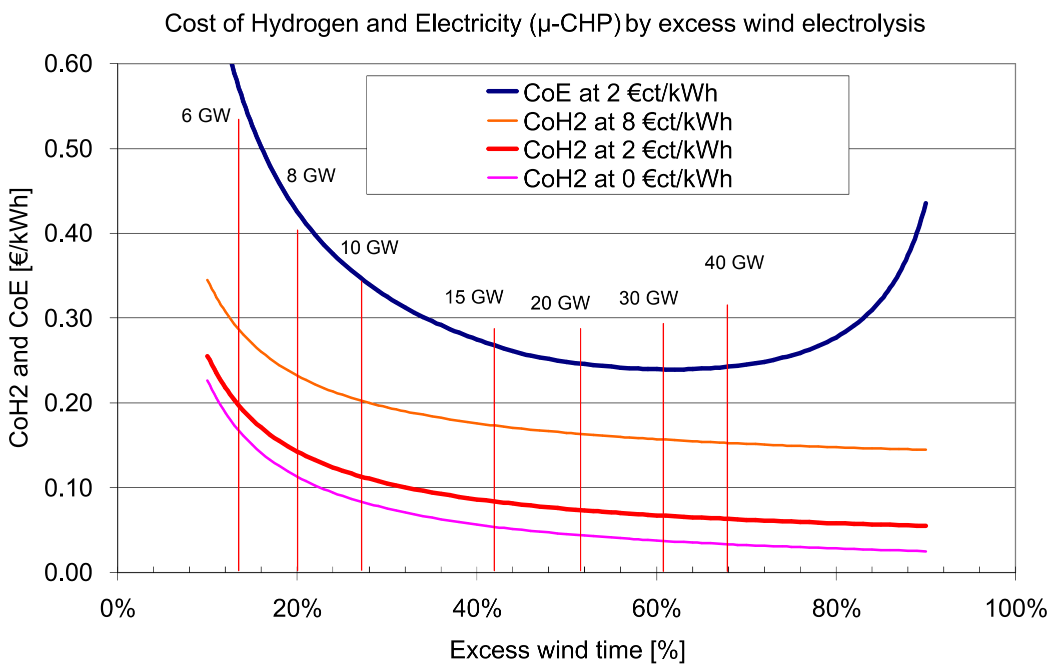

Figure 27: *Cost of hydrogen (CoH2) and cost of electricity (CoE) from H2 fuelled μ-CHP with variation of excess wind time (from Figure 13) and where the optimal operation of the fuel cell with present day feed-in arrangement is used from Figure 19.*

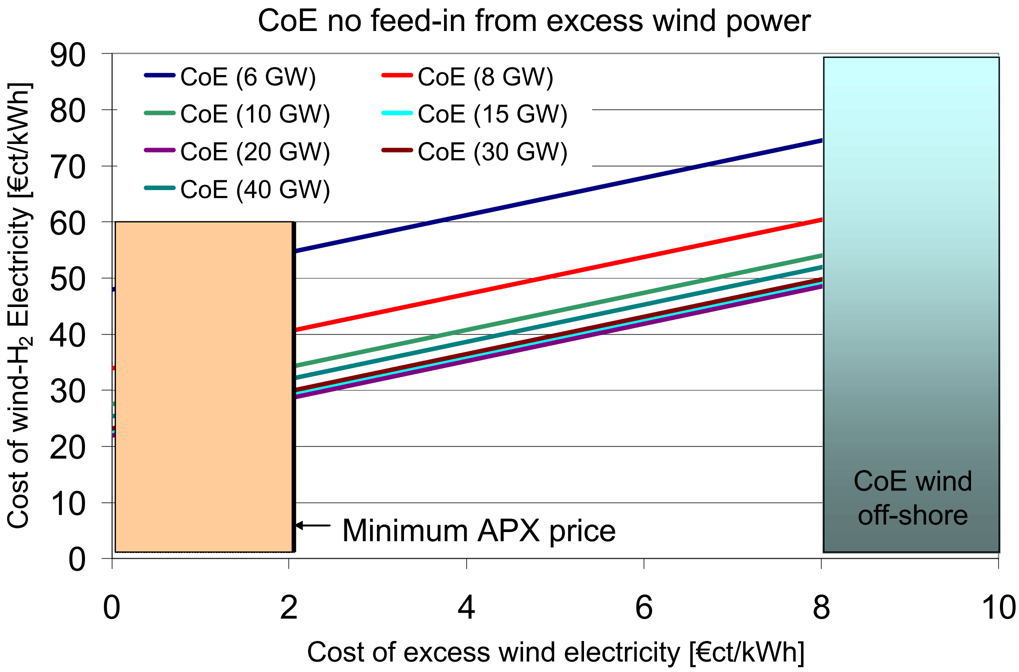

Figure 28: *Cost of Electricity for the μ-CHP case without feed-in of electricity as a function of the cost of excess wind electricity and the amount of installed wind power.*

6.8 Dedicated wind farm for transport application

Another option for the wind park is that it is dedicated to hydrogen production for transport, which leads to a much higher load factor, about 40%, for the electrolyser. Assume that an 8 GW off shore wind farm is established for this purpose. The electricity production is approx. 28.3 TWh/yr. As electricity the 28.3 TWh correspond to 20% of the Dutch electricity demand.

Assuming a constant demand throughout the year, matching supply and demand will require storage. This required storage capacity due to the seasonal variation in wind energy for dedicated and excess wind power from 8 GW installed offshore wind capacity is depicted in Figure 29. The cost of the hydrogen from the dedicated wind park and delivered to the fuelling station by pipeline is estimated as 5 €/kg H_2. These costs do not include the potential costs for large-scale storage.

The driving range of a fuel cell car on 1 kg H_2 is approximately 144 km. The 28.3 TWh dedicated wind for hydrogen can fuel 5 million cars (70% of the cars in 2006) driving on hydrogen using fuel cells, from excess wind it is sufficient for approximately 10% of the cars.

The fuel cost without duty and taxes, storage, distribution or foreground costs for such a fuel cell car amounts to 0.035 €/km. The fuel costs including all taxes, foreground costs etc. for present day highly efficient diesel cars start at 0.06 €/km. Only taking into account the crude oil and refinery costs, the cost starts at 0.025 €/km.

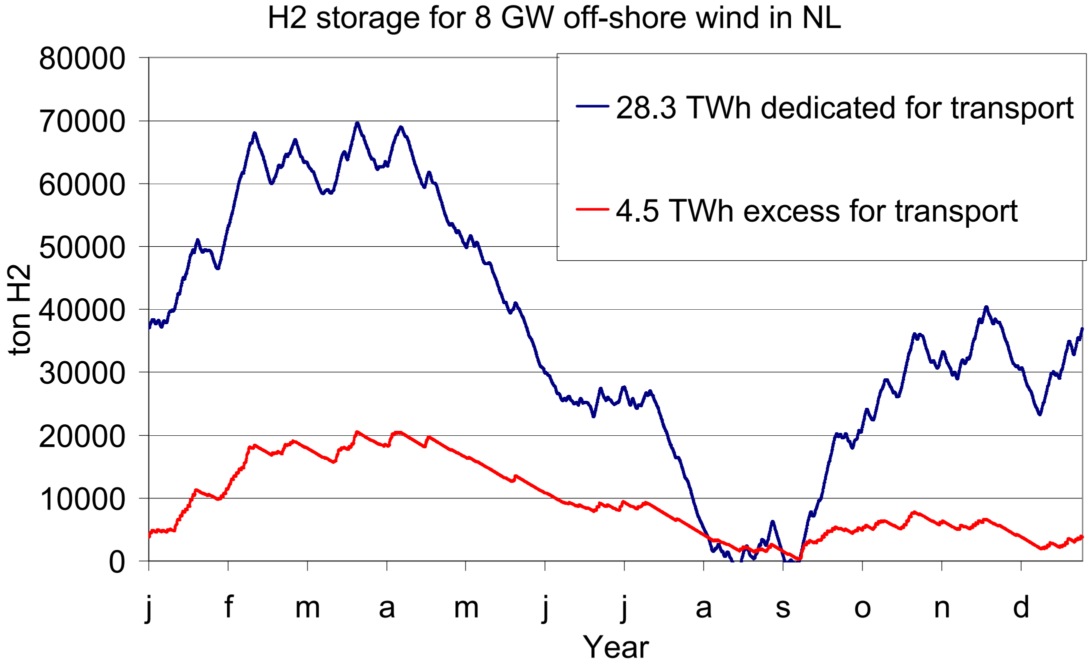

Figure 29: *Hydrogen storage requirement for 8 GW off shore wind power.*

6.9 CO_2 reduction comparison

The CO_2 reduction for transport applications is estimated as follows:

The driving range of a hybrid fuel cell car on 1 kg H_2 is assumed as approximately 144 km. A similar hybrid vehicle with an internal combustion engine uses approximately 3.6 kg/100km [1]. The CO_2 production is 3.2 kg CO_2/kg fuel. The avoided CO_2 emission for 1 kg H_2 is then 1.44 * 3.6 * 3.2 = 16.6 kg CO_2

The CO_2 reduction for μ-CHP is estimated as follows:

For the μ-CHP full load operation strategy, 1 kg of H_2 provides 14.8 kWhe and 15.4 kWhth. For the Dutch electricity production the CO_2 emission is 0.45 kg CO_2/kWhe. 1 Nm^3 of natural gas provides 8.8 kWh and emits 1.77 kg CO_2. The avoided CO_2 emission for 1 kg H_2 is 9.8 kg CO_2.

This means that the CO_2 reduction when H_2 is used for transport is almost twice the CO_2 reduction if the H_2 is used for residential applications.

The production of 1 kg H_2 from wind energy by electrolysis requires approximately 50 kWh of electricity. The avoided CO_2 production when the electricity would be used directly is approximately 22.5 kg CO_2.

7. Discussion

At this moment 1.6 GW of wind power capacity is installed in the Netherlands and until the equivalent of 4 GW offshore wind power is installed there will be no excess wind energy. Above this value options for the use of the excess wind energy are required. Several options are possible to use the excess wind energy. The option investigated in this report is the conversion of excess wind electricity into hydrogen, hydrogen storage and then use of hydrogen in residential CHP systems or for transport applications using fuel cells.

Alternative large energy storage systems with round trip electrical efficiency around 70% or higher are redox flow batteries, Compressed Air Energy Storage (CAES) and pump accumulator for water. The latter 2 options require specific geological conditions. Royal Haskoning investigates the pump accumulator system option for Limburg (Born). The underground storage capacity is made by drilling caverns of 20 m diameter at 1400 m depth in stone layers. The storage capacity of 2.5 Mm^3 equals 8400 MWh storage capacity[7] and the turbine size has 1400 MW peak power. An efficiency of 85% is claimed [14]. Combined with the 8 GW installed wind energy case, this option can supply approximately 1.5 TWh during non-excess wind power periods using 1.7-1.8 TWh of wind energy. The dynamic behaviour is very good, from zero to full capacity in 8 minutes. Several pump accumulator systems using water reservoirs at different heights are in operation in Europe.

Other options to use directly the increasing amount of variable renewable electricity are export of electricity and demand site management. The latter option also needs to be developed.

The use of hydrogen from wind electricity for transport applications has a higher likelihood that the use for stationary applications due to better economics and higher CO_2 reduction.

In the case of stationary applications the efficient way is to use electrolysers as soon as excess wind electricity develops. However, due to the small load factor of the electrolyser the hydrogen and thereby the electricity produced by residential CHP systems are very expensive even if the excess electricity is very cheap. The other starting option is the dedication of a wind farm to hydrogen production. Using this hydrogen for residential electricity production means that the electricity cost is at least 3 times the electricity cost using the electricity from the wind turbine directly and because the overall chain electricity production efficiency is only 30% and the heat production maximum 25%, the CO_2 savings are also less than 50% of the savings compared to direct use of wind electricity, even when for short times the wind electricity production would be stopped in order to prevent overproduction of electricity. Hydrogen grids for residential applications do not exist and need to be established. Legislative and safety issues should be solved for this application.

The production of hydrogen for transport applications starting with excess wind electricity also suffers from the low load factor for the electrolysers and therefore high hydrogen costs as in the stationary case above. A dedicated wind farm for hydrogen production for transport applications can produce hydrogen at a cost of 5 €/kg which is near to competitiveness with gasoline costs at high oil prices on a per km basis. In [15] the cost of hydrogen for such a dedicated wind farm is calculated as 6.7 €/kg using 0.091 €/kWh for electricity costs and 720 €/kW for the electrolyser. The CO_2 reduction for using H_2 in fuel cell transportation vehicles is about 2/3 of the reduction when the electricity would be used directly. For transport applications

[7] The same size of the caverns can hold approximately 30.000 ton of hydrogen.

arguments like local air quality and security of supply are in favour of H_2 as a transportation fuel.

The hydrogen storage option needs to be developed, either in salt caverns, empty gas fields or as liquid hydrogen, in order to cope with the seasonal variation in wind power. The seasonal storage requirement caused by the stochastic behaviour of wind energy is on the order of 2 months use, excluding strategic storage. Geologic storage is the most likely solution, either in empty gas fields or salt caverns. For the first solution mixing with the remaining natural gas and subsequent purification of the hydrogen has to be investigated. For the second solution the caverns must be made. This last solution is also used for natural gas storage and it will probably also be the preferred solution for hydrogen storage.

An integrated system of electrolyser, coal gasification and CO_2 sequestration using also the oxygen from the electrolyser is envisaged as a possible future system (Appendix E). The oxygen from the electrolyser is used for oxyfuel combustion of the coal for gasification. In this way the efficiency of the coal gasifier is increased because no air separation unit is needed for the oxygen production. This plant can produce either electricity or hydrogen, depending on demand. This option would also decrease the demand for hydrogen storage. This option can be investigated further.

8. Conclusions

8.1 Excess wind to hydrogen for µ-CHP systems

Excess wind power is defined as the effect that the production from the base load power plants and the wind power plants exceeds the electricity demand. In the Netherlands excess wind power develops at a wind power capacity effectively above 4 GW offshore for a base load of 8.7 GW, assuming no export of power or further demand side management.

The political ambition for 2020 for 6 GW offshore and 2-4 GW onshore wind power is simulated as 8 GW offshore wind power equally divided over 3 locations. The wind power is simulated using hourly wind speed data from 2004. The hourly power demand is extrapolated from the 2004 electricity demand profile. The results for 8 GW installed wind power are:

- The excess wind electricity is around 4.5 TWh.
- This can provide 90.000 ton of hydrogen/year.
- This amount of hydrogen is sufficient to supply 500.000 households with a fuel cell µ-CHP unit operating in electricity following mode. Alternatively, the amount of hydrogen is enough to supply 800.000 “average” cars.
- The capacity of the storage required (excluding cushion gas) is 20.000 ton of hydrogen.

Large-scale integration of excess wind energy via electrolysis to H_2 production and storage, to be applied in residential fuel cell CHP systems for households is a possibility to solve the unbalance of electricity supply and demand in time. In the process about 50% of the energy is lost, 31% is recovered as electricity and 17 % as heat assuming electricity load following operation.

The cost of electricity (without taxes or profit and neglecting hydrogen storage costs) produced by the µ-CHP household system operating in electricity demand following mode at 8 GW installed offshore wind power is calculated as 0.40 €/kWh. The minimum cost is calculated as 0.28 €/kWh at an installed wind capacity of 25 GW. These costs are higher than the present day mean consumer electricity price (including taxes and profit) of 0.20 €/kWh.

Alternatively, full load operation of the fuel cell system with power exchange with the grid is investigated. The net power from the grid is put to zero. The cost of electricity at 8 GW wind power is with 0.42 €/kWh_e slightly higher than the case above, at 30 GW wind power the cost decreases to 0.24 €/kWh_e due to increased production at nominal power which also increases the heat production compared to the electricity following mode. The total efficiency increases to 57% (28% electrical and 29% thermal).

With the µ-CHP system neither the complete electrical demand, nor the complete heat demand can be covered. This means that the house needs to be connected to the electrical grid and the remaining heating requirement should be solved e.g. by natural gas, heat pumps and/or solar collectors.

The CO_2 reduction for this system is a factor 3 lower than by direct use of the electricity.

The perspective of excess wind energy via H_2 to µ-CHP for household applications is very low due to high cost and decreased CO_2 reduction compared to direct use of the electricity.

Considering above conclusions, market development of excess wind energy via electrolysis to H_2 production and storage for fuel cell μ-CHP for household applications is inappropriate for the Netherlands for the next decennia. This statement is backed by Energinet [15] for the Danish market, *"The hydrogen option only makes sense if hydrogen fuelled vehicles come onto the market. Even then, the cost of the electrolysis plant needs to be taken into account. Energinet does not suggest using the hydrogen as a storage medium, with a view to feeding electricity back into the system. That would necessitate additional plant, such as fuel cells, and incur significant losses, so it is unlikely it would be economic."*

8.2 Excess wind to hydrogen for transport applications

The production of hydrogen for transport applications starting with excess wind electricity also suffers from the low load factor for the electrolysers and therefore initial high hydrogen costs as in the stationary case. The minimum cost estimate for 8 GW installed offshore wind capacity for minimum APX electricity cost (i.e. 0.02 €/kWh) excess wind (4.5 TWh) energy conversion to H_2 is 4.4 €/kg.

A second option for transport applications is the dedicated conversion of large-scale offshore wind power to hydrogen. Using a mean electricity cost from offshore wind power of 0.08 €/kWh, the minimum cost estimate for large-scale dedicated wind power conversion to H_2 is 5 €/kg.

The CO_2 emission reduction for electrolysis and subsequent use of the H_2 for transport applications will result in approximately 60% larger CO_2 reduction compared to the μ-CHP application. The CO_2 reduction for using H_2 in fuel cell transportation vehicles is about 2/3 of the reduction when the electricity would be used directly. For transport applications arguments like local air quality and security of supply are in favour of H_2 as a transportation fuel.

Excess wind energy to hydrogen for transport applications is a more likely market opportunity for economic (higher value for hydrogen) and environmental reasons (higher CO_2 reduction possibility) than stationary applications.

9. References

[1] WELL-TO-WHEELS ANALYSIS OF FUTURE AUTOMOTIVE FUELS AND POWERTRAINS IN THE EUROPEAN CONTEXT TANK-to-WHEELS Report Version 2c, March 2007

[2] TenneT; "Integrating wind power into the Dutch system"; MR 05-373 (2005)

[3] Referentieramingen energie en emissies 2005-2020; ECN-C--05-018

[4] KNMI HYDRA PROJECT

[5] windaanbod windresource website

[6]V90-3MW product brochure from Vestas

[7] http://www.nrel.gov/homer/

[8] Potentials and costs for renewable electricity generation. A data overview; ECN-C--03-006 (2004); de Noord

[9] http://www.offshorewindenergy.org/

[10] FROM HYDROPOWER TO HYDROGEN; H.P. Schiffer

[11] according to the old website from Ballard: http://www.ballard.com/be_a_customer/power_generation/fuel_cell_powergen/1kw_residential_cogeneration_system

[12] J. Schindler, R Wurster, M. Zerta, W. Zittel Woher kommt die Energie fur die Wasserstofferzeugung (2006)

[13] Running the World on Renewables: Hydrogen Transmission Pipelines with Firming Geologic Storage; W. Leighty; Spring 2007 Conference, Basel, Switzerland

[14] http://www.technischweekblad.nl/13277_Waterkrachtcentrale_op_veertienhonderd_meter_diepte.lynkx

[15] Realistic costs of wind-hydrogen vehicle fuel production, J. Linnemann, R Steinberger-Wilckens; Int. J. of Hydrogen Energy; 2007(32) p. 1492-1499

[16] No limits to high wind penetration Windpower monthly (22) 9; 2006

[17] IPCC report "Carbon dioxide capture and storage", 2005, Cambridge University Press

Websites last visited August 2008.

Appendix A Table of wind power and excess wind power

Wind GW	Wind Power TWh	Excess wind power TWh	Reserve Power TWh
0	0.0	0.0	55.2
1	3.5	0.0	51.7
2	7.1	0.1	48.2
3	10.6	0.3	44.9
4	14.2	0.7	41.8
5	17.7	1.4	38.9
6	21.2	2.2	36.2
7	24.8	3.3	33.7
8	28.3	4.5	31.4
9	31.9	5.9	29.3
10	35.4	7.6	27.3
11	39.0	9.5	25.7
12	42.5	11.6	24.3
13	46.0	14.0	23.1
14	49.6	16.5	22.1
15	53.1	19.1	21.1
16	56.7	21.8	20.3
17	60.2	24.5	19.5
18	63.7	27.3	18.8
19	67.3	30.2	18.1
20	70.8	33.1	17.5
21	74.4	36.1	16.9
22	77.9	39.1	16.4
23	81.4	42.1	15.9
24	85.0	45.2	15.4
25	88.5	48.2	14.9
26	92.1	51.4	14.5
27	95.6	54.5	14.1
28	99.1	57.6	13.7
29	102.7	60.8	13.3
30	106.2	64.0	13.0
31	109.8	67.2	12.6
32	113.3	70.4	12.3
33	116.9	73.7	12.0
34	120.4	76.9	11.7
35	123.9	80.2	11.4
36	127.5	83.5	11.2
37	131.0	86.7	10.9
38	134.6	90.0	10.7
39	138.1	93.3	10.4
40	141.6	96.7	10.2

Appendix B Effect of additional wind parks on grid connection

Under the assumption of a constant base load of 8.7 GW and no export of electricity the amount of electricity that can be adsorbed by the Dutch consumers for each additional offshore wind park is calculated. The power that can be adsorbed will decrease and above 13 GW installed capacity also the maximum power from the wind park that can be absorbed in the grid becomes smaller due to the spatial coupling of the wind speeds. This is shown in Figure 30.

From this figure can be concluded that for the installation of new wind parks above 4-5 GW either the base load capacity should be more flexible, export of electricity be possible, demand side management introduced, storage systems installed or new applications for the electricity like hydrogen production developed. Otherwise the amount of electricity that can be sold to the grid becomes too low and the investment for grid improvement and coupling of the wind power to the grid becomes too high.

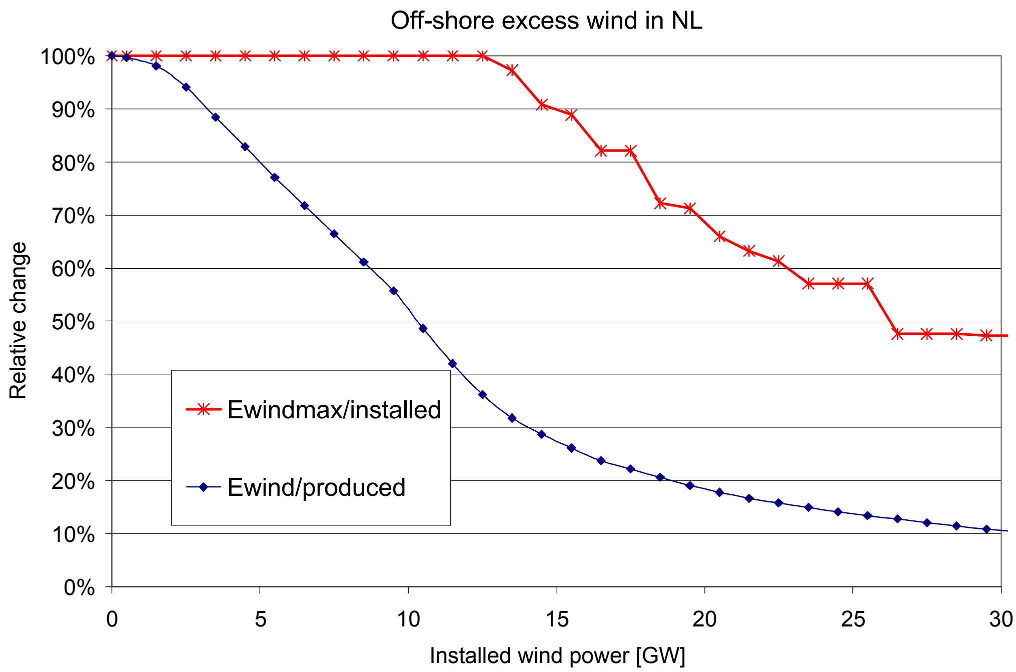

Figure 30: *The relative mean power (Ewind) and maximum power (Ewindmax) that can be adsorbed by the Dutch consumers for additional increase in the installed wind power.*

Appendix C Dynamic demand on reserve power capacity

Figure 31 shows the dynamic response of the reserve capacity with and without 8 GW installed wind power together with the dynamic change of hourly sorted wind power. With this wind power the dynamic changes are somewhat larger that need to be controlled with an even smaller reserve capacity. The data presented here are on an hour basis, the demands on dynamic changes are on a 15 min. basis and that subject is addressed in the Tennet study [1].

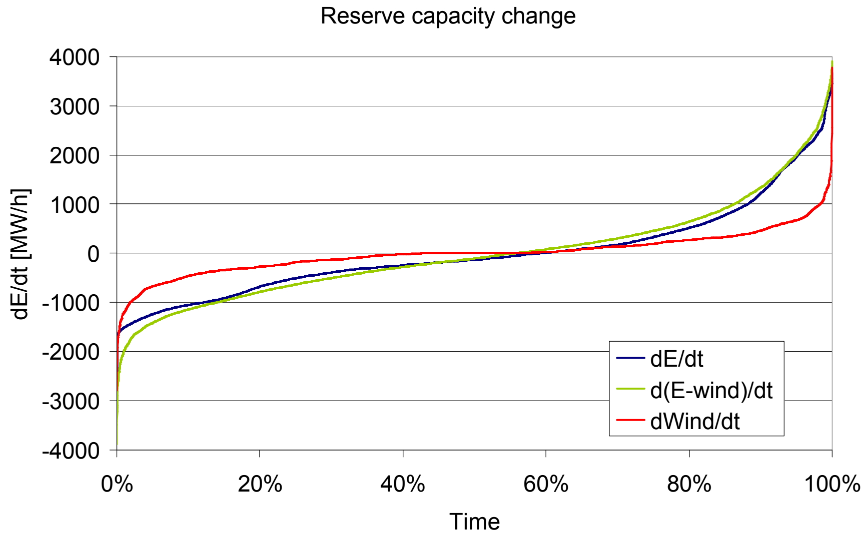

Figure 31: *The dynamic response from the reserve capacity without (blue) and with (green) 8 GW installed wind power. The red line denotes the dynamic change in wind power.*

The situation changes drastically when going to 30 GW installed wind power. The dynamic demand on the reserve capacity increases by a factor 4 from no wind power to 30 GW installed wind power, as can be observed from Figure 32 and follows more or less the changes in the wind power production. The required reserve capacity hardly reduces if no export or import is assumed.

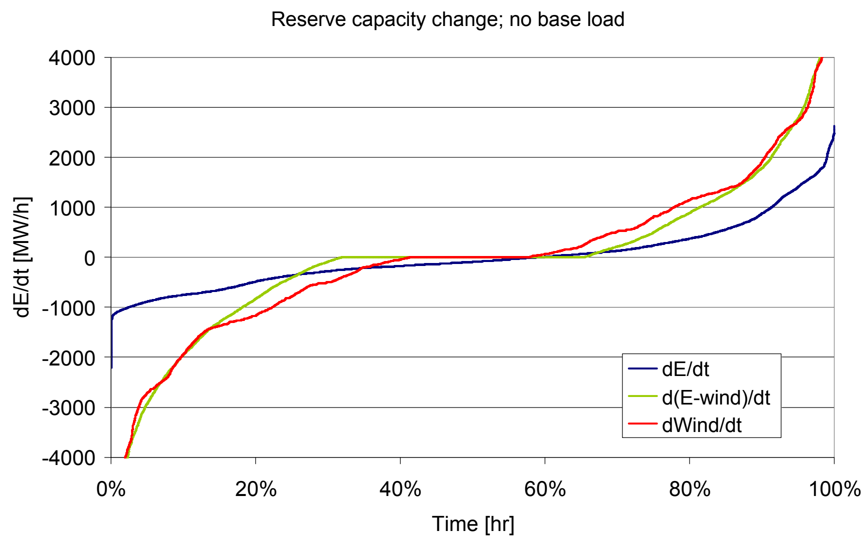

Figure 32: *The dynamic response from the reserve capacity without (blue) and with (green) 30 GW installed wind power. The red line denotes the dynamic change in wind power.*

Appendix D Effect of excess wind pay-back on electricity cost

In Figure 33 the effect of an increase of the installed wind power on the mean cost of electricity is shown. The mean cost of electricity is obtained from coal power plants in base load operation up to 8.7 GW, gas power plants for the dynamic operation and the stochastic wind power. With the increase of the installed wind power, the capacity of the base load park is reduced in the calculations. The increase in the cost of electricity is caused by two effects; the pay-back price of excess wind power and the reduction of the load factor for the reserve capacity (cf Figure 13). The effect of the reduction of the load factor of the conventional power plants is the curve for 0.0796 €/kWh selling price (= wind power production cost). The variation on the selling price for excess electricity for 0 (no value, very unlikely), 0.02 (minimum present APX price) and 0.079 €/kWh (cost price of wind electricity) is shown in this figure. The effects of CO_2 taxes or credits are not taken into account in this figure. In [7] the extra costs for this variability are estimated as 0.015 €/kWh at an equivalent of 30 GW installed wind power and an excess wind electricity price of 0.048 €/kWh, in close agreement with the figures shown here.

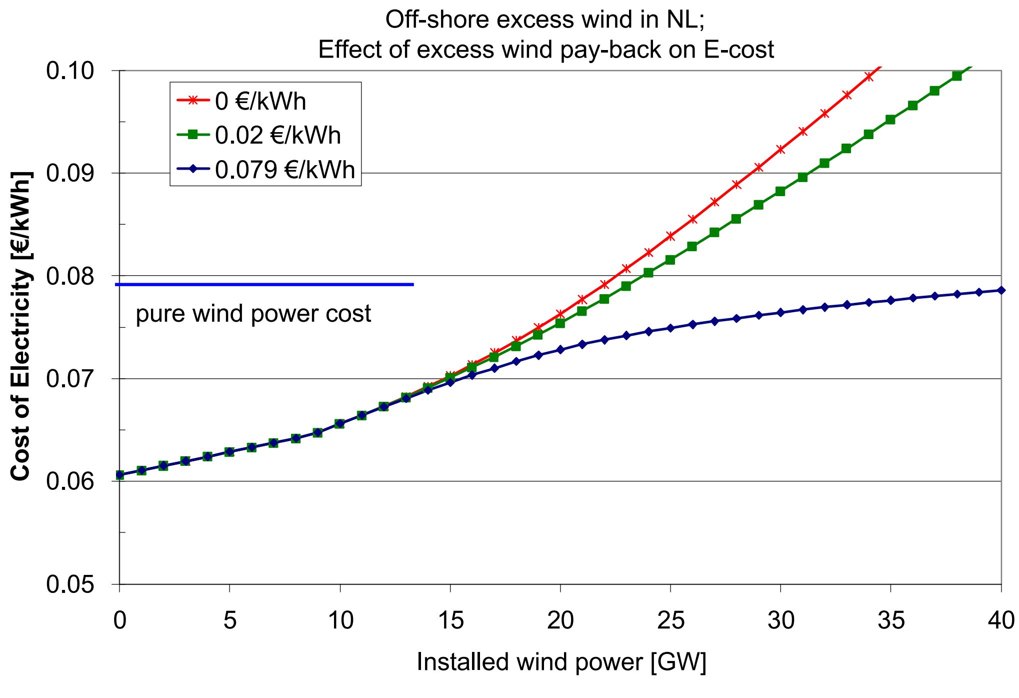

Figure 33: *The effect of the excess electricity pay-back tariff on the mean cost of electricity for an increase of the installed wind power.*

Appendix E   Future systems using the oxygen

To make the electrolysis process for hydrogen production more economically viable, an application for the produced oxygen is required. The most important application is primary metal production. The second large-scale application of oxygen is production of chemicals and gasification. In this second application there is methanol production from natural gas and oxyfuel gasification. An interesting option is the application for oxyfuel gasification of coal. This application can then also provide carbon capture and storage for sustainable energy production. For this application oxygen is produced by liquefaction of air and subsequent distillation. The efficiency penalty for this is approx. 4% (or ≈ 10% of the electricity produced)

The future wind-hydrogen system could be like Figure 34. First, demand side management of electricity needs to be established for reduction of the amount of excess wind electricity. The reason is that H_2 production via electrolysis (80%) and electricity production from carbon containing fuels (50%) is less efficient compared to H_2 production from carbon containing fuels (75%) and direct use of electricity from wind (100%) for the same amount of H_2 and electricity. Then excess electricity is converted to H_2 for transport applications and O_2 for oxyfuel gasification of coal together with carbon capture and storage (CCS). Both H_2 and O_2 need to be stored in order to cope with the varying supply. The gasification plant has flexibility in the rate of H_2 production versus electricity production. For electricity production during low wind energy periods, natural gas can be added before the gas turbine in order to increase the electrical output from the gas turbine.

As an example for excess wind energy of 7.6 TWh/yr from 10 GW installed wind power, the amount of produced oxygen from electrolysis (1.1 Mton/yr) is sufficient for approx. 600 MWe coal gasification plant (using 0.75 kg O_2 /kg C for the gasification process). The energy saving by not using oxygen from air separation is approx. 0.5 TWh/yr. The CO_2 capture potential is 3.2 Mton CO_2/yr.

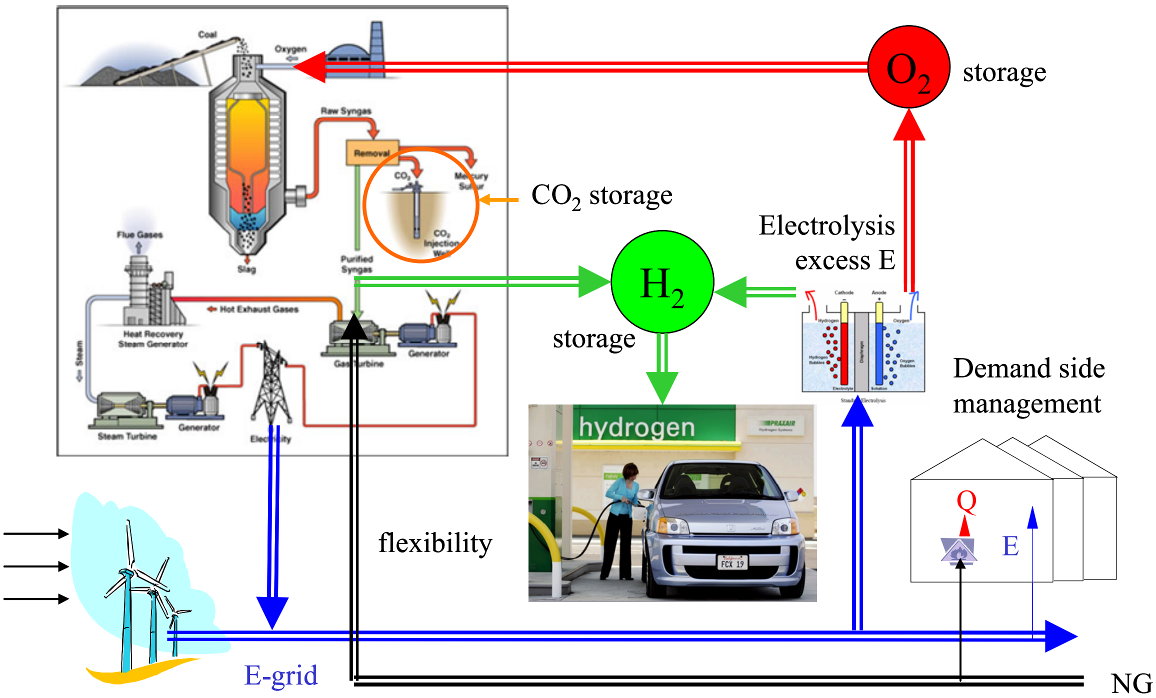

Figure 34: *Future wind-hydrogen system with coal gasification.*

The seasonal storage requirement for H_2 and O_2 for excess wind energy is 30 kton of H_2 and 250 kton of O_2. For liquid storage this means 440000 m^3 of LH_2 and 220000 m^3 of LO_2. As an example for pressurized storage for H_2 this would mean 6000 km of a 1 m diameter cylinder filled up to 100 bar. For O_2 the cylinder would be half that size. Demand side management and optimisation of operation of the plants should be used for storage requirement reduction. Intermittent operation of a liquefier will also reduce the efficiency of the liquefier.

The system of Figure 34 increases the storage requirement since the gasification unit will mainly produce hydrogen during excess wind energy hours. If we assume that a 500 MW unit is part of the electricity base load system, the base load for wind power feed-in is reduced from 8700 MW to 8200 MW. This leads to less excess wind power (6.4 TWh instead of 7.6 TWh, fitting with the 500 MW). Assume that the electrical efficiency of this system is 45% and the H_2 production efficiency is 70%, then the amount of H_2 produced is equal to the amount from 2.8 TWh of wind power. The result is that the coupling of H_2 production with electricity production produces 30.000 ton H_2 more and the same amount of electricity compared to a coal power plant that is only used for base load electricity production and a wind park of 11 GW.

Appendix F Result cost calculation spreadsheet

Component	Capacity	Investment cost	Lifetime	Full load time	Maintenance	Efficiency (LHV)	Energy	Energy carrier EC	Energy carrier EC	Pressure	Efficiency heat	Total efficiency	Mech. Eff.	Cost EC
	kWe or equivalent	€/kWe	year	%	% of investment cost per year	%	GJ/year	Input	Output	bar	%	%	%	€/GJ
☑ Grid electricity	6000			10%		100%	18921.6	Grid	Electricity AC		0%	100%		€ 5.56
☐ Wind turbine	6000	2200	20	40%	5%	100%	75686	Wind	Electr. DC/AC		0%	100%		€ 0.00
☐ WE subsidy	6500		10	19%		100%	39780				0%	100%		€ 1.39
☑ Inverter	5786	50	10	10%	1%	98%	18543	Electr. DC/AC	Electricity DC		0%	98%		€ 7.75
☑ Electrolyser	5670	500	20	10%	5%	68%	12666	Electricity DC	Hydrogen	12	0%	68%		€ 39.64
☐ liquefaction	387	629	20	100%	5%	77%	12666	Hydrogen	Hydrogen	1	0%	68%		€ 39.64
☑ Compressor	4078	60	10	10%	5%	95%	12005	Hydrogen	Hydrogen	60	0%	64%	70%	€ 45.36
☐ LH2 storage	387	231	30	100%	1%	99%	12005	Hydrogen	Hydrogen	60	0%	64%		€ 45.36
☐ Truck transport	761	50	10	50%	15%	95%	12005	Hydrogen	Hydrogen	60	0%	64%	50%	€ 45.36
☐ Expander	423	50	10	90%	5%	102%	12005	Hydrogen	Hydrogen	50	0%	64%	50%	€ 45.36
☑ H2 grid	377	3500	30	100%	2%	99%	11885	Hydrogen	Hydrogen	2	0%	64%		€ 54.91
☑ Fuel Cell	319	1000	10	52%	5%	44%	5229	Hydrogen	Electricity AC	1	46%	28%		€ 135.39
☑ Value heat				*52%*		*46%*	*5229*	*Electricity AC*	*Electricity AC*		*100%*	*57%*		€ 118.33