3. Wind energy, electricity and hydrogen in the Netherlands

3.1. Introduction

Non-renewable and non-exhaustible resources have different dynamics because they belong to different resource types (see Table 3.1). The influence of the different dynamics of the resource types on overall systems performance is studied in this Chapter.

Table 3.1: non-renewable energy vs. non-exhaustible energy

<table>
<thead>
<tr>
<th>Resource type</th>
<th>Non-renewable</th>
<th>Renewable (exhaustible)</th>
<th>Non-exhaustible</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resource use</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Materials (non-dissipative)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Energy (dissipative)</td>
<td>Fossil fuels</td>
<td></td>
<td>Wind energy</td>
</tr>
</tbody>
</table>

Note: simplified version of Table 1.1

The substitution of fossil fuels by renewable energy sources is a mitigation strategy that is advocated by NGOs (EWEA/Greenpeace 2003), research institutes (OECD 2001a), and can be found in concrete policy goals (EC 1997 p10; Rowlands 2005 and references therein). The prospects for increasing the use of renewable energy are much better in the electricity generation sector than other sectors. The six main modern renewable energy technologies that produce electricity are: small hydropower, solar photovoltaics, concentrating solar power, biomass, geothermal power, and wind energy (IEA 2003). Wind energy has – in general – benefits over the other technologies because:

- solar photovoltaics is extremely expensive, has high indirect CO\textsubscript{2} emissions and a low ‘energy payback ratio’ compared to other renewable energy technologies (Gagnon et al. 2002; Goralczyk 2003; Hondo 2005; IEA 2003),
- concentrating solar power, small hydropower, biomass and geothermal power require special geographical circumstances (IEA 2003) and the global potentials are often limited (Sørensen 2000).

Therefore wind energy is expected to be the electricity generating renewable energy source with the largest installed capacity worldwide in the near future (IEA 2003).

---

66 Co-authors: José Potting, Henri C. Moll, and René M.J. Benders.
Submitted in slightly different form to: Energy.
67 An updated version of: (EWEA/Greenpeace 1999).
68 In non-OECD countries biomass is often used for heating and cooking, however with little prospects to increase the share of renewables. In Brazil biomass successfully penetrated the automotive sector.
69 When these special circumstances are present these technologies are often the cheapest options.
70 Currently small hydropower and biomass have more capacity installed, but as mentioned above available land and sites are scarce and slow down growth.
Wind energy is, however, no reliable energy source since its electricity production depends on the often variable weather conditions. Therefore wind energy has limited options to regulate its load to the grid. When the wind blows and wind energy delivery to the grid increases, power plants – with fuel combustion – decrease their output and (fossil) fuel is saved in this way. This strategy is effective when wind energy penetration rates are low. At higher wind energy penetration rates three classes of problems may arise.

First, when actual wind energy production is lower than expected based on weather forecasts electricity companies may face temporary capacity shortages. Improved forecasting techniques and international trade in electricity contribute significantly in reducing the size of this issue (Giebel 2000). Second, periods with high wind energy may heavily load the high-voltage grid and cause blackouts. Improving the high-voltage grid and improved protocols are options to reduce the risk of blackouts due to over-load of the grid to acceptable levels. Third, over-all system-efficiencies decrease because the remaining fossil fuelled power plants need to adjust their operating policies, which cause losses. This adjustment of operating policies results in less efficient operation of the system hereafter referred to as ‘system losses’. This effect is further explained in Section 3.2.2.

This research focuses on energy inefficiencies due to system losses. There are several potential solutions to (partly) overcome the problem of system losses associated with renewable energy sources. They come in three categories: temporary storage, isolated hydrogen production, and integrated hydrogen production.

Temporary storage. Most solutions are in the direction of temporary storage in times of excessive wind energy supply (Bathurst & Strbac 2003) and the use of hydropower to complement wind energy (Bélanger & Gagnon 2002; Jaramillo et al. 2004). Pumped hydro is often used as an intermediate between peak and off-peak electricity and is an obvious storage medium for wind energy. This solution considers the electricity producing sector as an isolated system.

Isolated hydrogen production. The direct production of hydrogen from wind or solar energy sources is an option often mentioned (even as a core reason to aim to develop a so-called ‘hydrogen economy’). All wind and solar energy is converted to hydrogen and not delivered to the grid. Therefore this solution prevents the ‘unreliable’ energy sources from interfering with the electricity system. Isolated hydrogen production is, however, not an efficient way to utilise renewable energy because the precursor is electricity (Ogden 1999). Electricity produced from wind or solar can be more efficiently utilised by direct delivery to the grid.

Integrated hydrogen production. The production of hydrogen from off-peak electricity stems from scenarios with very high penetration rates of nuclear power (Linden 1996; Ogden 1999). The basic idea is that power plants operate less efficiently at lower loads. Therefore the marginal fuel costs of electricity production decrease at lower loads and consequently the efficiency of hydrogen production from hydrolysis increases. In the system described here wind energy partly delivers electricity to the grid and partly produces hydrogen (see also: Gonzalez et al. 2004).

This research identifies the potential energetic benefits of integrated hydrogen production in electricity systems with high wind energy penetration. A modelling
approach is used to compare the over-all efficiency of integrated hydrogen production with the over-all efficiency of the current system where all wind energy is directly delivered to the grid and hydrogen is produced from methane steam reforming. The methodology and model presented in this Chapter is applied to the Netherlands.

This Chapter is structured as follows. Section 3.2 describes the regarded system and section 3.3 describes how the system is modelled. Next, section 3.4 deals with model implementation and addresses technical details of the model (data, equations, algorithms, and etceteras). Finally, section 3.5 shows the results of the model, section 3.6 discusses the interpretation of the model results, and in section 3.7 conclusions are drawn.

3.2. Description of the electricity production system including wind and hydrogen

This section describes the regarded system. Firstly, the characteristics of electricity demand and electricity production are described. Secondly, the effects of high wind energy penetration on the system are explained.

3.2.1. Load types and power plants

In electricity production three types of load are can be identified: base-load, mid-load, and peak-load (see e.g. Hitchin & Pout 2002). Electricity demand follows a daily pattern during weekdays: low demand during the night, peak demand in the morning, followed by slight decline, peak demand in the evening (after sunset), and again low demand in the late evening. As a result electricity production differentiates between different types of load. Base-load is produced continuously over long periods, mid-load starts up in the morning and shuts down during the night and thus runs for a few hours a day, and peak-load covers peak demand and consequently only runs for very short periods. Starting-up and shutting-down power plants is referred to as scheduling in this Chapter.

The total capacity of running power-plants is in practice always higher than the momentary electricity demand. Therefore at least some power-plants have to produce less electricity than their capacity would allow. Increasing or decreasing the output of a single power-plant is in this Chapter referred to as load-regulation.

Different types of power plants were developed because of the different load types and regulation possibilities. The main types used in this research are steam-turbine, gas-turbine, combined-cycle, and cogeneration. Steam-turbine power plants are often large and require quite some time to heat up completely. The possibility for load regulation is more limited than e.g. gas-turbines. A clear benefit is that anything that can produce heat can drive a steam turbine, also nuclear, solar-thermal, and combustible waste.

---

71 This type of load is also referred to as ‘shoulder’ or ‘cycling’ load.
72 The actual pattern is country dependent.
73 This type of power-plant is also referred to as ‘open-cycle’ power-plant.
74 This type of power-plant is also referred to as STAG (steam and gas) power-plant.
75 This type of power-plant is also referred to as combined heat and power (CHP) power-plant.
Gas-turbines are less efficient and limited to (expensive) gaseous or light liquid fuels. Therefore gas-turbines are more expensive to operate. Because they have no boiler their start-up time can be very short and load-regulation is rather flexible. Therefore peak-load power-plants are often gas-turbines.

Combined-cycle power plants are a combination of a gas-turbine and a steam-turbine where the hot exhaust-gasses from the gas-turbine are used to produce steam to drive the steam-turbine. Combined-cycle power plants are the most efficient electricity plants. They are, however, limited to gaseous or liquid fuels. About 2/3 of the output is delivered by the gas-turbine module and 1/3 by the steam-turbine module (de Biasi 2000). Operating flexibility depends on size and design. Low part-load operation is often possible, but results in significantly lower efficiencies.

Cogeneration is the utilisation of waste heat from power plants for industrial processes or municipal heat. The over-all efficiency of cogeneration is very high, but a drawback is that electricity generation is driven by heat demand, which results in low operation flexibility from the electricity generation perspective.

3.2.2. The effects of high wind energy penetration

As more wind turbines are installed the fossil fuel plants must adjust their operations strategies in order to deal with the mismatch between actual wind energy supply and electricity demand. This adjustment of the operations strategies results in less efficient production of electricity from fuel combustion because 1) more wind energy leads to less base-load production and more peak-load production, and 2) power plants operating at lower part-loads (Hirst 2002; Jong & Thomann 1983; Kennedy 2005; Lund 2005; Sørensen 2000 p681).

3.2.3. Comparing integrated hydrogen with BaU

Figure 3.1 gives a schematic representation of the focus of this research, i.e. the energetic benefits of the production of hydrogen from the ‘system losses’.

System I shows the current situation: wind energy is used to produce only electricity, fossil energy sources are used to produce both electricity and hydrogen. System II shows a possible future situation – a part of the renewable energy is used to produce hydrogen, while the rest of the system is not altered. This research reveals the potential fossil fuel reductions as a result of shifting from system I to system II.

In order to be able to compare the systems I and II in Figure 3.1, the fossil production of hydrogen must be taken into account. Methane steam reforming is taken as a reference and hydrogen is only produced from wind when this results in a reduction of the total fossil fuel costs in monetary terms. The over-all system efficiency is calculated in terms of avoided primary energy consumption.

76 Coal and biomass can be gasified and then combusted in a combined-cycle plant.
77 This is known as ‘topping’, the opposite – ‘bottoming’ – is the utilisation of the waste heat of very-high temperature industrial processes to produce electricity, which is less common.
78 Currently hydrogen is primary used in the petrochemical industry.
79 Because this is actually a form of part-load distribution, see sections 3.3.3 and 3.4.8.
3.3. Modelling of the electricity production system including wind and hydrogen

This section describes the methodology used to model the system described in section 3.2.

3.3.1. Chronological hourly modelling

Section 3.2 showed that the fossil fuel savings depend on the interaction between wind energy production and different types of power plants. Daily, weekly and annual dynamics of electricity demand determine power plant scheduling and operating, and thus the over-all system performance. Wind does interfere with the system in a chaotic manner – e.g. not following the same pattern every day – and therefore the appropriate approach to calculate the effects of wind energy on the over-all system
efficiency has to be modelled chronologically\textsuperscript{80} on an hour-to-hour base over a long period (Giebel 2000; van Wijk 1990).\textsuperscript{81,82}

3.3.2. Scheduling optimisation

The focus of this model is on energy efficiency. However, when optimising on energy solely, natural gas would be the preferred fuel over coal and the system would not behave realistic. Fuel prices reflect mining-costs, transportation-costs, politics, energy-content, and so forth. These are factors that can be expected to remain relatively constant over time. We chose to optimise on fuel costs rather than energy consumption because this allows the model to behave more closely to real-world behaviour. For the model absolute prices are of no importance, only the relative prices matter.

Scheduling of start-up / shut-down decisions is optimised based on operating costs, start-up costs,\textsuperscript{83} and shut-down-costs. In practice this means that coal-fired steam-turbines will be scheduled for long periods because of their high start-up costs and low fuel costs. Gas-turbines on the other hand will be scheduled for short periods because of their low start-up costs and high fuel costs. Scheduling of power plants is influenced by the required amount of spinning reserve (Section 3.3.3) and thus the capacity credits for wind energy (Section 3.3.4).

3.3.3. Spinning reserve

Because of the high interconnectivity of the electricity supply system, a single power plant breakdown can cause system-wide electricity blackouts far beyond national borders. Therefore, when a power plant breaks down, other power plants have to cover the lost supply directly. In order to do so, the other power plants must have reserve capacity available in case of emergency. This reserve capacity is referred to as spinning reserve and normally equals the largest running power plant. The left-hand side of Figure 3.2 shows how the total running capacity of power plants equals the momentary electricity production plus an amount of spinning reserve.\textsuperscript{84}

3.3.4. Capacity credits for wind

Wind energy is not a reliable source of electricity. However, because of the large number of individual wind turbines and their geographical dispersion some reliability can be attributed to wind turbines. This reliability of wind energy is referred to as the “capacity credits” for wind.

Figure 3.2 shows what happens to the electricity production system when wind energy is added to the system. First, electricity production from power plants is lowered,

\textsuperscript{80} This type of modelling is also referred to as ‘unit commitment’ (for a review see: Sheble & Fahd 1994)

\textsuperscript{81} Compared to other scheduling and operating optimisation problems.

\textsuperscript{82} It should be noted that techniques have been developed to assess the output of wind energy with so-called ‘residual load duration curves’ (Kennedy 2005). That method is, however, not precise at high wind energy penetration rates, and not able to determine the potential benefits of hydrogen production.

\textsuperscript{83} Reflecting the time needed to heat the plant and the energy requirements do so.

\textsuperscript{84} In actual systems different types of reserve are distinguished depending on respond times (van Asseldonk 2004)
resulting in energy savings. Next, spinning reserve is adjusted to the new situation, depending on the capacity credits of wind.

![Diagram showing electricity output and spinning capacity in situations with and without wind energy.](image)

Figure 3.2: electricity output and spinning capacity in situations with and without wind energy

### 3.3.5. Part-load distribution

Due to the requirement of spinning reserve not all power plants will be able to run at full-load. The distribution of the spinning reserve over a set of power plants is called part-load distribution.

Part-load distribution is based on part load efficiencies (PLE) and fuel prices. As a result coal-fired steam-turbines are likely to run at full-load whenever possible, while natural-gas-fired plants are likely to reduce their load sooner.

### 3.4. Model implementation

This section deals with the implementation of the methodology as described in the previous section. It describes assumptions, data sources, equations, algorithms and etceteras as used in the model.
3.4.1. General model dimensions
The model is run over a full year (8760 hr) in order to level out seasonal differences in wind energy supply and electricity demand. Seasonal effects tend to be quite strong – regarding both electricity demand and wind energy – in the Netherlands.

This model emphasises energy efficiency optimisation and energy prices are solely included to capture aspects of energy sources that cannot be expressed in Joules, for example differences in combustion properties of gaseous fuels and solid fuels.

3.4.2. Geographical focus
This research is limited to the case of the Netherlands because of our knowledge of the Dutch system (Benders 1996; de Vries et al. 1991), data availability, and contacts with energy companies (Battjes & de Kler 2004). The Netherlands lacks ‘special’ energy resources (like mountains for hydro, large area for biomass, sufficient solar, geothermal, etc) to produce renewable energy, and lacks the opportunity to store energy in pumped hydro. Therefore the conditions in the Netherlands are in favour of integrated hydrogen production. Moreover, the Netherlands is considered to have good wind resources (Junginger et al. 2004; Troen & Petersen 1989).

3.4.3. Hourly electricity demand
This model is limited to central electricity production. Therefore electricity demand equals central production and net imports. Hourly electricity demand data is calculated from (van Wijk 1990) and scaled-up to represent the 1998 situation (latest available data before liberalisation of the sector). During the scaling process both peak demand and total electricity demand were considered. Peak demand is 12,055 MW, and total demand is 72,062 GWh (Sep 1999).

3.4.4. Hourly wind energy electricity production
Hourly wind energy electricity production data is taken from Van Wijk (van Wijk 1990). The dataset represents the Dutch situation with 1GW of wind energy installed. This 1GW of wind energy installed produces 2,043 GWh electricity, equalling a load factor of 23%, while the current load-factor is 23-25% (EWEA/Greenpeace 1999; EWEA/Greenpeace 2003). Runs with alternative amounts of wind energy installed use linear up-scaling of this dataset.

3.4.5. Primary energy prices
Prices of primary energy are related to the Dutch situation and based upon (Sep 1996). This model assumes 2.33 €/GJ for coal, and 3.76 €/GJ for natural gas. As mentioned in section 3.3.2 only the ratio of coal and natural gas prices matters for the model. The ratio of prices influences scheduling and part-load distribution.

3.4.6. Power plant data
The power plant data is taken from the PowerPlan model (de Vries et al. 1991) and updated (Battjes & de Kler 2004). Load-regulation abilities (see section 3.2.1) are accounted for by minimum-loads. Part load efficiencies (PLE) are constructed from
typical Relative Net Plant Efficiency (RNPE)\textsuperscript{85} values (Chuang & Sue 2005; de Biasi 2000; Kim 2004).

3.4.7. Power plant scheduling

Power plant planning consists of two parts: starting-up plants on when required, and shutting-down plants off when no longer needed. In order to be able to make decisions on the planning the planner needs to have some information on the electricity demand and wind energy production in the near future. In this model there is a time-window of 168 hours (one week) wherein both electricity demand and wind energy production are known.\textsuperscript{86}

The spinning reserve required to equal the largest running power plant is 600 MW in this model.

The capacity credits of wind energy are based on a study on the capacity credits of wind energy in the Netherlands. This study finds a capacity credit of 20\% for 5\% of demand covered and a capacity credit of 13\% for 15\% of demand covered (Halberg as cited in Giebel 2000 p59).\textsuperscript{87} This model uses a linear relation between the percentage of demand covered and capacity credits.

The algorithm used to determine which power plant to turn on is straightforward. Figure 3.3 is used to explain how start-up scheduling is optimised. When additional capacity is needed (point A) all non-running power plants are evaluated for start-up. The algorithm is as follows:

- The participation factor in the forecast-window (from point A to B) is determined. This represented by the grey area in Figure 3.3.
- The total costs of starting-up the plant are determined using Equation 3.1. The start-up costs are allocated over the time the power plant is required.
- The cheapest power plant to start-up – based on Equation 3.1 – is selected for start-up.
- The process repeats itself until sufficient power plants are switched on.

\[
FcPpCosts = FuelCosts + \frac{\text{StartupCosts}}{FcWindow \times ParticipationFactor} \tag{Equation 3.1}
\]

With:

- \(FcPpCosts\) = Forecasted costs of starting-up the power plant
- \(FuelCosts\) = the fuel costs to generate 1 MWh
- \(StartupCosts\) = the costs per MW capacity to start-up the plant
- \(FcWindow\) = forecast window size; the number of hours taken into consideration
- \(ParticipationFactor\) = the full-load hours of the power plant in the forecast-window divided by the number of hours in the forecast-window, represented by the share of grey in the rectangle between A and B in Figure 3.3.

\textsuperscript{85} index, full-load = 100\%

\textsuperscript{86} Perfect foresight assumption.

\textsuperscript{87} For an overview of available literature see: <http://www.drgiebel.de/WindPowerCapacityCreditLit.htm>
The participation factor enables the model to weight the start-up costs and fuel costs of different power plants with respect to the size of the power plant.

The forecast-window size influences the forecasted fuel costs as can be seen in Equation 3.1. The minimal size of the forecast-window is determined by the dominance of the fuel costs over the start-up costs when the participation factor is one. In other words, when the power plant is expected to run for a long period the power plant with the cheapest fuel should be selected and thus have the lowest forecasted costs. A forecast-window of one week (168 hours) was chosen because of the weekly pattern in electricity demand, and because in our dataset fuel costs are dominant for all power plants regarding start-up decisions when this period is chosen.

**Figure 3.3: power plant planning**

Shutting-down power plants is a bit more complex than starting them up. Again Figure 3.3 is used to explain how shut-down scheduling is optimised. When more capacity is running than required (point C) all running power plants are evaluated for shut-down. The algorithm is as follows:

- The number of hours the power plant is not needed (from point C to D) is counted.
- The costs of shutting-down the power plant are compared to the costs of not shutting down the power plant using Equation 3.2. The higher \( F_{cP} \) Costs, the higher the refund of shutting-down the plant.
- The power plants are sorted according to the value of \( F_{cP} \) Costs.
- The most expensive running plant is shut-down using selection criterion: \( F_{cP} \) Costs is positive; the refund of shutting-down the power plant must be positive.
• The process repeats itself until no more power plants are available for shut-down.

\[ F_{cPp\text{Costs}} = F_{\text{Fuel\text{Costs}}} \cdot t - Shutdown\text{Costs} \]  
\textbf{Equation 3.2}

With:
\[ F_{cPp\text{Costs}} = \text{forecasted costs of running the powerplant} \]
\[ F_{\text{Fuel\text{Costs}}} = \text{the fuel costs to generate 1 MWh} \]
\[ t = \text{the number of hours the power plant's capacity is not needed} \]
\[ Shutdown\text{Costs} = \text{the costs per MW capacity to shut-down the plant} \]

It should be noted that the shut-down costs should not be taken too literally. They (partly) include the costs of starting-up after the shut-down period, because shutting-down implies starting-up and \textit{vice versa}.

3.4.8. \textit{Part load distribution}

Part-loads are distributed in the most efficient way when the marginal fuel costs of all power plants are equal. This means that power plants with higher fuel costs are regulated down before power plants with lower fuel costs.

Power plants are the most efficient at full-load or just below. Efficiencies decrease at lower loads and power plants also have minimum loads under which operation is not possible. Only fuel costs are considered because this Chapter focuses on energy efficiency. Therefore marginal costs are defined as marginal fuel costs as shown in Equation 3.3.

\[ M_{C}(PL) = \lim_{\Delta \rightarrow 0} \frac{\Delta \text{FC}}{\Delta \text{PL} \cdot \text{Cap}} = \frac{\partial}{\partial \text{PL}} \cdot \frac{\text{FC}(PL)}{\text{Cap}} \]  
\textbf{Equation 3.3}

With:
\[ M_{C} = \text{marginal costs (€/MWh)} \]
\[ PL = \text{part-load (％)} \]
\[ \text{Cap} = \text{capacity} \]
\[ \text{FC} = \text{fuel costs (€)} \]

The part-load efficiencies are functions of the part-loads; in notation PLE(PL). In reality PLE(PL)'s can be very complex functions, especially when power plants are an assembly of different compounds. E.g. reducing the load in combined-cycle plants – from full load to minimum load – leads to stepwise shutting down individual turbines until only one gas-turbine is running in the end. Therefore the PLE(PL) will look like a sawn-shaped graph rather than a smooth curve (Chuang & Sue 2005). For practical reasons, however, a polynomial of the second order is used to approach the PLE(PL) relationship.

A non-linear PLE(PL) relationship implies that the relation between power plant output and fuel consumption is also not a linear one. Consequently the marginal costs as a function of power plant output are not constant! Marginal costs are lower at lower part-loads and even become zero when minimum loads are reached.

Equation 3.4 shows how the total fuel costs are calculated. Equation 3.5 shows the result of the first derivative of the total fuel costs, which describes the marginal costs as a function of part-loads.
\[ MC(PL) = \frac{\partial}{\partial PL} \left( FP \cdot 3.6 \cdot PL \cdot Cap \right) \cdot \frac{FP \cdot 3.6 \cdot PL \cdot Cap}{Eff_{full} \cdot RNPE(PL) \cdot Cap} \]

Equation 3.4

\[ MC(PL) = FP \cdot 3.6 \left\{ \frac{1}{Eff_{full} \cdot RNPE(PL)} - \frac{PL \cdot \frac{\partial}{\partial PL} RNPE(PL)}{Eff_{full} \cdot (RNPE(PL))^2} \right\} \]

Equation 3.5

With:
- \( RNPE(PL) \) = relative net plant efficiency (index, full-load = 100%)
- \( Eff_{full} \) = plant efficiency at full load (%)
- \( MC \) = marginal costs (€/MWh)
- \( PL \) = part-load (%)
- \( Cap \) = capacity
- \( FP \) = fuel price (€/GJ)

Notes:
- Equation 3.5 is only valid when the part-load efficiencies are approached with a polynomial of the second order.
- The time-frame is 1 hour regarding all formulas.
- \( PLE(PL) = Eff_{full} \cdot RNPE(PL) \)

In the model the marginal costs are increased or decreased until the total electricity production meets total electricity demand. Therefore the power plant’s part-loads need to be a function of marginal costs, i.e. the inverse of Equation 3.5. When \( RNPE(PL) \) is approximated with a second order polynomial – as is done in our model – then the inverse of Equation 3.5 becomes unmanageably large. Moreover, these functions would lead to discontinuous relations between marginal costs and part-loads and cause power plants to allocate spinning reserve discontinuously amongst power plants, which is unrealistic behaviour. Therefore the relation between part-load and marginal costs is approximated with a fuzzy-logic approach in this model, which allows fast optimisation. Figure 3.4 shows the approximated relation between marginal costs and part-load.

Point \( c \) is determined by taking the average marginal costs associated with increasing the power plant output from minimum-load to full-load. Points \( b \) and \( d \) are determined by the difference in MC at minimum-load and MC at full-load. On the trajectories between points \( a \) and \( b \), and between points \( d \) and \( e \) the part-loads are kept constant at minimum-load levels and full-load levels respectively.

3.4.9. Hydrogen production

Both steam reforming of natural gas and water electrolysis are mature hydrogen production processes (Momirlan & Veziroglu 2002). The energy conversion efficiency of large-scale methane steam reforming is 75-80% HHV (Ogden 1999). In this model 75% efficiency is assumed. Water electrolysers are typically 70-85% efficient on a higher heating-value (HHV) basis (Ogden 1999). In this model 80% efficiency is assumed.
In this model hydrogen is produced when costs to produce hydrogen from electrolysis (based on marginal costs of electricity production) is lower than the costs to produce hydrogen from methane steam reforming. The fuel price for gas is assumed to be 3.76 €/GJ (see section 3.4.5). Therefore the benchmark costs of hydrogen are 5.01 €/GJ based on a conversion efficiency of 75% for steam reforming. This benchmark equals 14.44 €/MWh marginal costs based on a conversion efficiency of 80% for electrolysis. Therefore hydrogen production will only start when electricity prices drop below 14.44 €/MWh.

In this model hydrogen production from electrolysis is modelled as a power plant with negative output. A fuzzy approach was used to regulate hydrogen production similar to the power plants (see section 3.4.8).

3.5. Results

The model was run several times. A first set of model runs, with different wind energy capacities (50MW step-size) and no electrolysis, shows the relation between installed wind energy capacity and net avoided primary energy. A second set of model runs, with different wind energy capacities (1000MW step-size) and different electrolysis capacities, shows the ancillary benefits of hydrogen production.

---

88 Only fuel costs are considered; capital costs are not included.
3.5.1. Fossil fuel savings

Figure 3.5 shows the relation between wind energy capacity and avoided fossil energy consumption. On the left-hand side of the graph each added wind-turbine results in a proportional amount of avoided fossil energy consumption because there are no system losses involved. On the right-hand side of the graph each added wind-turbine results in a lower amount of avoided fossil energy consumption than the previous wind-turbine due to the system losses involved. The system losses shown here are low compared to similar analyses in other countries due to the relatively flexible power-plant – very low nuclear and conventional coal share, and high gas-fired combined-cycle – park of the Netherlands.

![Figure 3.5: net energy savings from wind energy](image)

*Note*: results from model runs with increasing wind energy capacity (step-size = 50MW).

Figure 3.6 shows the relation between wind energy capacity, hydrogen production capacity from electrolysis, and net avoided fossil energy consumption. As can be seen, hydrogen production from system losses is of almost no help at 6 GW or less of wind energy in terms of improving over-all system efficiencies. At higher wind energy penetration rates hydrogen production can significantly contribute to the system. The additional avoided use of primary energy steadily increases as wind energy increases from 7 to 12 GW. As the horizontal line in Figure 3.6 shows, the amount of avoided primary energy use from point from 10 to 11 GW wind is less than going from 10 GW wind to 10 GW wind + 500 MW electrolysis capacity. However, at 6 GW of wind energy capacity – the Dutch policy goal for 2020 – hydrogen production does not significantly increase over-all system efficiency.
**Figure 3.6: net energy savings from wind energy and hydrogen production**

*Note: the values for no hydrogen production correspond with the values in Figure 3.5*

**Figure 3.7: hydrogen produced**
3.5.2. **Hydrogen produced**

Figure 3.7 shows the amount of hydrogen produced at different wind energy capacities and different hydrogen production capacities. At 6 GW of wind energy and 1000 MW of electrolysis capacity, the number off full-load hours is 927 hr which corresponds with a load factor of 11%.

![Figure 3.7](image)

**Figure 3.7**: Amount of hydrogen produced at different wind energy capacities and different hydrogen production capacities.

3.5.3. **Stabilising effect of hydrogen production**

Figure 3.8 shows the marginal costs over a period of 500 hours for a situation without wind energy, with wind energy (6 GW), and with wind energy and hydrogen production (1000 MW). As can be seen the production of hydrogen has a dimming effect on the marginal costs when wind energy production is abundant.

Without wind energy the marginal costs follow a daily pattern with narrow canyons during off-peak hours. At A wind energy is almost zero and therefore the MC patterns overlap. At B is shown how wind energy production reduces the MC costs of electricity production during the day. At C is shown how wind energy production deepens the canyon of low MC during the night. At D is shown how wind energy – without hydrogen production – can cause the MC to drop to zero. This happens mostly during the off-peak hours when the power-plants are already running at low part-loads. At D is shown that hydrogen production can dim the effects from high wind energy production during off-peak hours. Finally at E is shown that a hydrogen production capacity of 1000 MW does not always prevent MC against reaching the bottom. Without hydrogen production MC dropped to the bottom during 642 hours; with hydrogen production MC dropped to the bottom during 256 hours, which is a reduction of 60%.

**Figure 3.8**: Hourly marginal costs for different scenarios

*Note*: hour 2600 corresponds with April 19; hour 3100 corresponds with May 10; the 6GW/0MW line overlaps with the 6GW/1000MW line most of the time.
As mentioned in section 3.1, wind energy may cause problems by heavily loading the high-voltage grid at times of abundant wind energy. Hydrogen production from hydrolysis has a potential to decrease the load from wind energy to the high-voltage grid.

3.6. Discussions

3.6.1. Geographical focus
The Dutch electricity producing system is characterised by relatively low nuclear capacity and relatively high combined-cycle capacity. The potential benefits of integrated hydrogen production are higher in countries with a more rigid power plant park, e.g. more nuclear capacity.

In our model the Netherlands is a closed country, while in reality electricity is imported from and exported to nearby countries. Trade in electricity increases the flexibility of the system and therefore decreases the potential benefits of integrated hydrogen production.

3.6.2. Model assumptions
Our model assumes perfect foresight regarding power-plant scheduling. Due to this assumption the running capacity shall often be lower than the real-life situation would be. Therefore, the potential benefits of integrated hydrogen production are underestimated.

Load-regulation abilities of power-plants are limited.\(^{89}\) This limitation is not included in this model because this limitation falls mostly within the resolution of our model. The main reasons are: 1) the Dutch power-plant park is dominated by gas-fired combined-cycle plants who can adjust their load unlimitedly within one hour, the resolution of our model, and 2) operators of a 600MW coal plant assured us that their coal plant can change its output from minimum load to full load within one hour, the resolution of our model.

The energy needed for starting-up power plants is not included in this model. The main reason is that in this model hydrogen production does not influence the power plant scheduling and therefore the number of power plant start-ups is equal with or without hydrogen production. In reality electrolysis capacity will influence power plant scheduling and therefore the potential benefits of integrated hydrogen production are underestimated.

3.6.3. Wind energy growth rate
Wind energy capacity in the Netherlands is increasing fast (see Figure 3.9). The implementation of the BLOW-covenant in mid 2002 (EZ 2004) altered the institutional framework and caused a sharp increase in wind energy capacity growth rates.

\(^{89}\) This is also referred to as ‘ramping’.
The Dutch policy goal for 2000 of 1 GW was not met, in spite of the enormous growth since 1990. The policy goals for 2010 and 2020 are 1.5 GW and 6 GW respectively. Because of successful modification of the institutional framework, the policy goals for 2010 and 2020 are more likely to be met. This implicates that the scenarios modelled cover the near future and beyond in terms of installed wind energy. Therefore measures must be taken to anticipate to these situations.

### 3.6.4. Alternative uses for hydrogen

The hype about the so-called hydrogen economy and the fast growth of wind energy triggered this research. Without doubt the establishment of a hydrogen economy would point focus on the efficient production of hydrogen and on the production of hydrogen from system losses. However, also if the hydrogen economy does not develop, hydrogen production from wind energy would still be a high potential option to aid the exploration of renewable resources. Hydrogen cannot not only be used to fuel fuel-cells, but hydrogen is also an important input for the (petro)-chemical industries (Czuppon et al. 1998). For reason of comparison the amount of hydrogen needed for fertiliser production in the Netherlands is calculated.\(^\text{90}\)

The consumption of nitrogenous fertilisers\(^\text{91}\) in the Netherlands in 2001 was 290 kilo tonnes (OECD 2004a), which requires 98.6 million kg ammonia (NH\(_3\))\(^\text{92}\) which

\(^{90}\) Data is readily available for fertiliser production. Fertiliser production is normally the largest hydrogen consumer in an economy, followed by oil-refineries (Czuppon et al. 1998).

\(^{91}\) For a comprehensive analysis on fertilisers see: (Davis & Haglund 1999).

---

Figure 3.9: total electricity production and wind energy electricity capacity

*Source:* (CBS 2005; ECN 2005)

*Note:* 2004 is preliminary
requires 17.4 million kg of hydrogen.\textsuperscript{93} This amount of hydrogen represents 2.5 PJ (HHV).\textsuperscript{94}

As Figure 3.7 shows, the amount of hydrogen produced at wind energy capacities of 6 GW and hydrogen electrolysis capacities of 2 GW is less than the amount of hydrogen needed for fertiliser production. At higher wind energy capacities hydrogen production becomes larger than the amount of hydrogen needed for fertiliser production and (finally) larger than the total amount of hydrogen needed for the chemicals industries. Therefore the supply of demand potentially outnumbers the demand. On the other hand it is likely that a vast production of hydrogen will create additional demand for hydrogen (e.g. fuel cells).

3.6.5. Dynamics of electricity generation capital stock
The electricity sector is very capital intensive and the lifetime of the capital stock is 25-40 years (de Vries et al. 1991). Therefore the electricity capital stock tends to change very slowly (see e.g. IEA 2002c, p130) and legitimates the use of the current power plant park for scenarios with a time frame of a few decades.

3.6.6. Relieving the grid
As shown in section 0, hydrogen production potentially relieves the high-voltage grid from heavy loads due to high production of wind energy. This is very important, because the Dutch high-voltage grid is expected to have a maximum of 3GW wind energy capacity connected (Tenent 2002). Therefore the potential benefits of “integrated hydrogen production” may be both relieving the grid and increasing the over-all system efficiency.

3.6.7. Policy relevance
Because of 1) high investment costs, 2) long lifetime of the capital stock, 3) danger of lock-in situations, and 4) high growth rate of wind energy capacity explorative research with a timeline of several decades is relevant for decision makers. Although the electricity markets are liberalised in the Netherlands, the role of the government is still influential. This research directs policy makers to think about the consequences of increasing wind energy and allows them to take action before problems arise.

This research shows that improvement of over-all system efficiency by coupling of currently separated systems can significantly contribute to avoided fossil fuel consumption, which is in line with previous research (Gielen 1995; Kram et al. 2001). As Figure 3.6 shows, the equivalent of avoided fossil fuel consumption from 11 GW wind energy can be met with 10 GW wind energy and 500 MW hydrogen production capacity.

\textsuperscript{92} 1 kg of nitrogenous fertilisers requires 340 g ammonia (Kramer 2000 p50).
\textsuperscript{93} according to: \(3 \text{H}_2 + \text{N}_2 \text{(from air)} \rightarrow 2 \text{NH}_3\) (Davis & Haglund 1999).
\textsuperscript{94} 1 kg of H2 \(\approx 141.9\) MJ (HHV) (Ogden 1999).
3.7. Conclusions

3.7.1. Hydrogen can be produced from wind
This research shows that the use of system losses for hydrogen production via electrolysis is beneficial in situations with ca. 8 GW or more wind in the Netherlands. Therefore, from a systems-efficiency perspective hydrogen production will only be beneficial at very high wind energy capacities. The 2020 goal of 6 GW will not benefit from hydrogen production in terms of systems-efficiency.

3.7.2. Relieving the grid
Relieving the grid is – according to this research – an ancillary beneficial effect of coupling hydrogen production with wind energy. In practice this means that electrolysis capacities should be located near places where large wind energy production facilities – like off-shore wind parks – are coupled to the grid.

3.7.3. Planning new capital is important
The planning of new electricity production capital can be important for the over-all efficiency of the system. More flexibility for less design-load efficiency may be profitable in systems with more renewable energy sources.

Diversity of renewable energy sources may also be a sensible tactic. Biomass for example is less favourable in terms of conversion efficiency compared to. However, because biomass conversion routes include gasification it may be used to fire reliable, efficient and flexible combined-cycle plants and thus contributes to the over-all system efficiency.

Key findings

- Increasing wind energy capacity generally results in decreasing fossil fuel consumption.
- The benefits of wind energy suffer from diminishing returns due to losses when the wind blows at times of low electricity demand.
- The production of hydrogen from (discarded) wind energy can help to reduce these losses.
- Reducing the losses would require much electrolysis capacity, and sophisticated regulation.
3.8. Acknowledgements

Coos Battjes, Kornelis Blok, Gregor Giebel, David Grote Beverborg, Peter de Jong, René Kleijn, Robert de Kler, Sander Lensink, Sanderine Nonhebel, Bas van Ruijven, Ton Schoot Uiterkamp, and Detlef van Vuuren are acknowledged for their contributions to this Chapter.