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Integration of large-scale wind power and use of energy storage in the Netherlands' electricity supply

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Abstract: The use of energy storage for increased operational flexibility is commonly regarded as a logical complement for systems with large amounts of wind power. The authors explore, the opportunities for energy storage for the integration of large-scale wind power into a future lay-out of the Dutch generation system, for which minimum-load problems are foreseen with high wind power penetrations. A central unit commitment and economic despatch model is extended with models for three large-scale energy storage technologies: pumped hydro accumulation storage (PAC), underground PAC and compressed air energy storage. Furthermore, an alternative solution is investigated, comprising the installation of heat boilers at selected combined heat and power locations (CHP) in order to increase the operational flexibility of these units. Results are shown for different wind power penetrations and scenarios. A cost–benefit analysis shows that the operation cost savings from energy storage increase with the amount of wind power installed. Taking into account the large investment costs, energy storage units are however unlikely to have a profitable exploitation. The installation of heat boilers at CHP locations is found to be more efficient and a promising solution for the integration of large-scale wind power in the Netherlands. A notable result is that for the Dutch system, the use of energy storage increases the system's overall CO_2 emission levels because energy storage allows storing power from cheap coal plants for substitution of expensive gas during peak. Even though often proposed as a solution for wind power integration, energy storage in fact partly annuls CO_2 emission savings by wind power.

1 Introduction

The share of wind power in European electricity supplies has increased significantly in the past decade. With the recently set ambitious European targets for future shares of renewables, the growth of wind power can be expected to continue. The development of wind power into an energy source of significance will have substantial impacts on the operation of power systems. The variability and unpredictability of wind cause power fluctuations in the system that are much more difficult to manage than load variations including load-forecasting errors. In particular, wind power influences the need for the regulation of power and calls for reserves in the minute to hour timeframes [1], which are often provided by conventional (coal and gas-fired) generating units. Therefore wind power must be taken into account in the commitment and despatch of other units in the system and, consequently, will have an influence on the operational revenues of other generation technologies.

It is often suggested that wind power and energy storage form a natural combination. Often, wind power and energy storage are regarded in a back-to-back configuration, for example, in [2–4]. Wind power is used to fill up storage reservoirs during high wind periods, and the stored energy may be used for electricity generation during calms. It should be noted that a back-to-back approach neglects all cost and market price aspects governing the operation of power systems in markets. Furthermore, large-scale wind power will become part of the existing power system. Therefore the cumulative technical capabilities of the existing system will determine technical constraints, if any, for integrating wind power. Consequently, the technical and economic benefits of energy storage facilities for wind power should be considered integrally by taking into account the system that both wind power and energy storage are integrated into. A system approach furthermore opens up a wider range of possible solutions for wind power integration.

In case a significant part of generation capacity is heat-demand constrained combined heat and power (CHP) such as the case in the Danish [5] and the Netherlands' [6] power systems, wind power may have to be curtailed at moments of low load and high wind. Meibom *et al.* [7] investigate the introduction of heat pumps or electric boilers in the Danish system, thereby decoupling the generation of heat and power to allow a reduction in wind power curtailment. The flexibility of CHP-dominant systems to integrate wind power could also be significantly increased by a more electricity price-based operation philosophy according to Lund [5]. The system-oriented approach is also applied in [8] to investigate the net benefits of wind power under different generation portfolios. Results are provided on total system operation costs and CO_2 emissions for different wind power penetration levels. Swider [9] asesses the benefits of the system integration of compressed air energy storage (CAES) in a case study from Germany using a stochastic electricity market model. It is found that the benefits of CAES are partly, but not solely, driven by installed wind power capacity.

In the Netherlands, 1.7 GW of wind power has been installed to date, serving over 3% of annual Dutch electricity demand, with governmental targets including 4 GW onshore capacity installed in 2011 and 6–9 GW offshore in 2020. Interestingly, no large-scale energy storage facilities are available in the Netherlands, mainly because of the absence of geographically favourable locations in this flat country. The possibilities of energy storage facilities have, however, been a subject of research since the 1980s [10, 11]. The most important reasons for research in energy storage technologies at the time were the possible contributions of energy storage for the optimisation of the operation of the Dutch generation system as a whole, for the future integration of recurring energy sources such as wind power and for the provision of fast power reserves. It was found that the use of energy storage was in particular beneficial in combination with a high share of base-load units (nuclear and coal units planned at that time), whereas the dedicated use of storage as reserve for wind power was found to be unprofitable. The large shares of heat-demand constrained CHP developed in the last decades and distributed generation (DG) unavailable for despatch, however, challenge the integration of wind power [6], and research into energy storage in the Netherlands has been resumed.

In this paper, the central unit commitment and economic despatch (UC-ED) optimisation model PowrSym3 is applied for the determination of the benefits of energy storage for the large-scale integration of wind power in the Dutch power system. PowrSym3 is a multi-area, multi-fuel, chronological production cost simulation model for CHP systems, which has been jointly developed by Operation Simulation Associates, Inc. and the former Netherlands Utility, SEP. Its database is continuously updated by TenneT TSO, the Netherlands [12]. PowrSym3 is discussed in more detail in Section 3.1. It can be noted that other system-planning models, such as those developed in [13], have been used for the exploration of solutions for wind power integration as well. Also, stochastic-based methods have been developed and applied for such exercises [7, 9] which may offer a better integration of the stochastic nature of wind power forecasts into UC-ED [14]. The method applied in this paper, however, offers important, additional insight into the chronological operation of power systems on a day-to-day and hour-to-hour basis, which is crucial for a correct understanding of the impacts of wind power on generation unit schedules and marginal system generation costs. Furthermore, the focus of this work is not limited to technical or economical aspects of wind power integration and the use of energy storage, but it also incorporates the environmental aspects connected with these, in particular CO_2 emission levels. Only such an integral approach captures the system insight needed for a correct assessment of possible synergies between energy storage and wind power integration. Uniquely, the PowrSym3 model offers the possibility to model variable head-pumped hydro storage units, which is essential for a correct assessment of the benefits of surface pumped hydro accumulation storage (PAC) in the Netherlands.

For this work, three large-scale energy storage technologies are modelled: surface PAC, underground PAC (UPAC) and CAES. The possibilities of energy storage are compared with a base-case, in which an equivalent capacity of combined cycle gas turbines (CCGT) are installed, and another alternative, investigating the installation of natural gas-fired heat

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boilers at selected CHP locations. The impacts of wind power on system operation and the opportunities of energy storage and heat boilers for a integration of larger amounts of wind energy are explored for different wind power levels. Four scenarios are applied to explore the sensitivity of the simulation results for different assumptions regarding international exchange and fuel and emission prices.

This paper is organised as follows. First, a theoretical framework of the relationship between energy storage, wind power and short-term marginal generation costs (Section 2) is provided. Then, the simulation method (Section 3) and setup (Section 4) are described, including the technical characteristics of the energy storage technologies and heat boilers. In Section 5, the results are presented for each storage technology, and a global cost–benefit analysis is provided in Section 6. Overall conclusions are presented in Section 7, and a reflection on this paper and recommendations for further research are presented in Section 8.

2 Energy storage, wind power and marginal generation cost

Energy storage provides a number of opportunities for the operation of power systems. Because of the need for a continuous power balance between generation and load, generation must be able to follow the load at all times. Energy storage provides additional flexibility for the system: at moments of low load, energy storage may be used to increase the overall system load by storing energy, whereas the stored energy can be delivered to the system at moments of high load. From a market perspective, this means that energy will be stored at moment of low prices (usually low load) and generated at high prices (usually peak load). Energy storage thereby has an impact on the short-run marginal generation cost in the system, defined here as the marginal operational costs for the most expensive unit in operation assuming a fixed generation portfolio.

In Fig. 1, the vertical axis represents the short-run marginal generation cost, whereas the horizontal axis represents electricity production level. The short-run marginal cost curve (striped grey) shows that the higher the production level, the higher is the marginal generation cost: operational costs are high during peak moments and low during off-peak. On the left, units with a must-run status with corresponding low marginal costs are represented, and on the right are the peak load units. Only during peak load, these units will be in operation and marginal generation costs will be high (C_2), whereas off-peak generation costs are far lower (C_1).

The benefits of energy storage in terms of short-run marginal cost benefits are that it reduces peak loads while it increases base-load hours. In Fig. 1, energy storage moves the off-peak load curve to the right and the peak load curve to the left, increasing the off-peak cost (market price) from C_1 to C_3 and reducing the peak cost (market price) from C_2 to C_4. Clearly, energy storage reduces the differences between peak and off-peak short-run marginal costs. The total benefit of the energy storage unit then depends on the market price difference between C_4 and C_3, the turn-around efficiency of the energy storage unit and the energy volumes bought and sold.

In case wind power is added to an existing system, wind power will shift the short-run marginal generation cost curve to the right at moments of high winds (Fig. 2) because of its very low marginal cost. As a result, short-run marginal generation cost will change from C_5 to C_7 during off-peak and from C_6 to C_8 during peak moments. The extent to which wind power indeed lowers the short-run marginal cost curve of the system as a whole depends on a number of factors. Most importantly, these are the technical flexibility of the system in which wind power is integrated into and the extent to which the market allows an efficient exploitation of this technical flexibility. Because of its low marginal cost, large amounts of wind power may reduce short-run marginal system costs and thereby spot market prices, as has been reported for some countries with

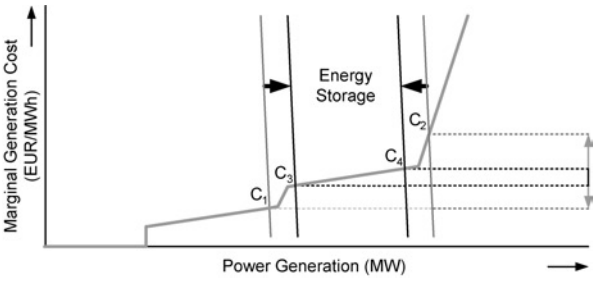

Figure 1 *Short-term marginal cost curve with peak and off-peak load curve and the impact of energy storage*

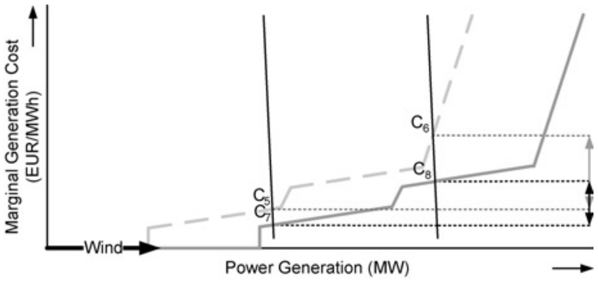

Figure 2 *Short-term marginal cost curve with peak and off-peak load curve and the impact of wind power*

significant wind power penetrations such as Denmark [15] and Germany [16]. This effect is incorporated by the simulation model: optimisation of UC-ED is based on marginal costs, taking into account the need for additional power reserves, decreased operational efficiencies of conventional units and so on.

For the Dutch system foreseen for 2012, with its high percentage of CHP (Table 1), the use of heat boilers at CHP locations increases the operational flexibility of the system. Because of heat demand schedules, electricity is generated also during moments of low load and sold for low prices. With the addition of large-scale wind power, prices drop even further during moments of low load, and minimum load problems may occur such as reported in [17]. The installation of heat boilers allows the shut-down of selected CHP-units during such hours, increasing the technical flexibility of the system.

The extent to which energy storage and heat boilers indeed allow a more efficient operation of the Dutch system with increasing amounts of wind power will be explored in the simulations performed below.

3 Simulation model

Unit commitment decisions are typically assessed only once or twice a day, whereas generation unit output changes may be carried out continuously during the day (despatch). With the reasonable predictability of system load, intra-day calculations for unit commitment are in principle necessary only when unexpected, significant changes occur in generation (i.e. outages) or demand. With the integration of significant amounts of wind power, the partial unpredictability of the wind requires unit commitment and despatch calculations to be carried out more often, using updated wind power forecasts, to minimise system operation costs.

Table 1 Generation technologies in 2012, excluding wind power

Generation technologies in 2012	Capacity	
	GW	%
natural gas-fired	12.1	53
coal-fired	4.1	18
nuclear	0.4	2
other	1.3	4
distributed generation	5.3	23
total installed of which CHP	22.9	100
		55

3.1 Model aspects

For the simulations performed here, the chronological UC-ED simulation program PowrSym3 has been used to simulate system operation and to estimate its costs and emissions, using heuristic algorithms. Optimisation of UC-ED is performed on a central basis; it is assumed that electricity markets function well. The UC-ED is calculated using the equal marginal cost method, in which the objective function is the total cost for generating both heat and power. Decremental despatch and de-commitment costs are calculated for all units included in the simulation. PowrSym3 includes six Monte Carlo based simulation modes for forced outages. A random Monte Carlo method has been applied for the simulations, ensuring a realistic representation of outage events including energy storage [12]. Spinning and operating reserves are derived from firm online units and firm transactions, with operating reserve additionally including idle quick-start units. Both spinning and operating reserves are specified for each simulation, but PowrSym3 also integrally assesses reserve requirements looking ahead at load and wind power input profiles. The costs of provision of sufficient reserves (possibly additional reserves because of wind power) are part of overall system operation cost. A perfect wind power forecast has been assumed, since the simulation results based on incorporation of hourly updated wind power forecasts in the hourly re-calculation of UC-ED more or less converge to the results obtained using a perfect wind power forecast [6].

The modelled system consists of a total of three areas, representing the Netherlands, Belgium/France and Germany. The Dutch area consists of a possible future lay-out of the Dutch generation system (Table 1). A notable aspect of this system is the high percentage of CHP generation. Also, it can be noted that the Netherlands presently imports about 18% of its annual electricity demand from Belgium/France and Germany. The simulation model comprises 80 detailed unit models based on empirical data for coal, gas, coal- and gas-fired CHP and nuclear units, including a number of units planned for installation, heat boiler models and different wind power penetration levels. Interconnections have been modelled as single connections with a maximum (MW) capacity. Inter-area exchanges are simulated as part of overall system operation cost optimisation using a transport algorithm, assuming all feasible transactions are made.

3.2 Simulation objective

UC-ED is regarded as a multi-criteria optimisation problem, where the operating cost function (including emission cost) is minimised within the boundary conditions of serving system load and local heat demands and maximum possible integration of wind power into system operation. The UC-ED formulation includes typical generation unit parameters such as minimum up- and downtimes, ramp rates, CHP operating constraints and unscheduled outage rates. Unit commitment and despatch are optimised on an hourly basis to achieve the minimum operating cost while all technical constraints are met: system load, heat demand in all heat areas, ramping capabilities of thermal units and minimum up- and downtimes. Wind power is curtailed as a last resort only to prevent the possible minimum load problems.

3.3 Model development

The model's generation unit database of the Dutch system has been expanded with energy storage unit models of aboveground PAC, UPAC and CAES. Energy storage is sized for a weekly cycle, during which daily cycles of pumped operation and generation are taken into account. The operation mode of energy storage is determined by the marginal system generation cost at each hour of operation (system operation cost optimisation) while incorporating international exchanges as part of the UC-ED schedule. PowrSym3 then calculates the operation of pumped energy storage based on a value-of-energy approach (trading high cost generation against low cost off-peak pumping energy while continuously taking into account the reservoir constraints) [12]. The modelled parameters for each storage option and the boiler option are based on historical case studies [10] and are shown in Table 2.

3.3.1 PAC model: PAC has been modelled using available data from case studies into large-scale surface PAC [10, 18]. The concept consists of two large reservoirs with a variable head of 50–70 m, connected through a number of hydro turbines. Because of the relatively small height difference between the two reservoirs, the generating efficiency varies with the head. As a result, the maximum generating capacity varies with the head height as well and lies between about 1 and 1.9 GW, with generating and pumping efficiencies ranging between 84% and 90% and 86% and 91%, respectively (turn-around efficiencies between 72% and 81%). The head level H is determined by

$$H = \sqrt{\frac{L_R + B}{A}} \tag{1}$$

where L_R is the reservoir level and A and B are constants. Generating and pumping efficiencies vary with the head level and are modelled as a six-point piece-wise linear curve, based on [18].

As an example of the relationship between operating efficiencies and reservoir level, Fig. 3 shows the despatch of PAC for 1 simulated week. The upper graph clearly shows a day–night despatch pattern, storing cheap off-peak electricity (power < 0) and generating electricity during peak. The lower figure shows the reservoir level of PAC during the same week: despatch on a weekly basis results in an empty reservoir on Friday night, to be filled using low marginal costs during the weekend. The relationship between generating efficiency, pumping efficiency, maximum generation level and reservoir head level is clearly visible. It can be noted that high storage efficiency does not reduce the maximum power consumed by PAC for storing energy, but only the amount of energy actually stored in the reservoir.

3.3.2 UPAC model: The modelling of UPAC is based on available literature on past plans for underground energy storage in the Netherlands [19, 20]. A large,

Table 2 Technical parameters for the simulated technical alternatives

Technical parameters	Technology				
	CCGT	PAC	UPAC	CAES	Boilers
nominal capacity, MW	1400	1900[a]	1400	1400	1800[b]
storage capacity, MW	—	1400	1400	1400	—
minimum generating power, MW	100	0	0	100	0
reservoir size, GWh	—	20	20	20	—
efficiency, %	55	81[a]	77	181[c]	95
planned maintenance, %	7	7	4	7	0
unplanned maintenance, %	7	7	5	7	0

[a] Maximum capacity and turn-around efficiency, both vary with reservoir head level, [b] Thermal capacity, replaces ~1000 MW of CHP-base-load, [c] With addition of 4.1 GJ natural gas/MW h

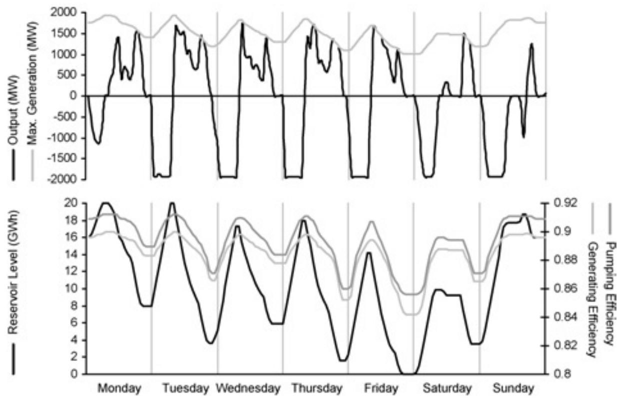

Figure 3 *Despatch of the PAC on a weekly basis*

fixed height difference between the upper and lower (underground) water reservoirs is assumed, resulting in a fixed turn-around efficiency of 77% and a fixed generation capacity. Additional technical parameters of the UPAC can be found in Table 2.

3.3.3 CAES model: The CAES has been modelled in a similar way as the UPAC pumped storage, but with a round-trip electrical efficiency of 181%. This means that for each MW h stored, sufficient air is compressed to generate 1.81 MW h under the consumption of 4.1 GJ of natural gas. This comes down to an overall energy efficiency [(natural gas + pumping energy)/electricity generation] of 60%. This efficiency is based on the application of present CCGT technology with an efficiency of ~57%; the increased efficiency of CAES compared with CCGT lies in the fact that air compression has been decoupled from unit operation and that the compressor is directly, electrically powered.

3.3.4 Heat boiler models: Heat boiler models have been modelled using the existing heat boiler models for Dutch and other heat locations in the database. PowrSym3 applies the following equation for modelling unit efficiency

$$\eta = A + P_e(B + CP_e) + D_{th}(D + ED_{th}) + FP_eD_{th} + GI_{th} \qquad (2)$$

where A, B, C, D, E, F and G are input coefficients, D_{th} the district heat production level, I_{th} the industrial heat production level and P_e the electric production level. For boiler models, P_e equals zero and either a district or industrial heat level is applicable (low or high temperature, respectively). A maximum operating efficiency of 95%, typical for state-of-the-art boilers, has been assumed. It can be noted that, even though the operation of heat boilers implies a lower overall energy efficiency (heat supply only, compared with heat and power supply from CHP), the operation costs for heat boilers instead of CHP unit are considerably lower. This is because of the very high efficiencies of the boilers and the fact that the revenues from electricity production from CHP are very low at moments of low load and high wind.

3.4 *Load and wind power data*

An estimated load pattern has been composed from the observed load pattern for parts of the years 2004 and 2005, based on measurements by Dutch transmission system operator (TSO) TenneT. An hourly load pattern for a future year of the Dutch power system is developed by scaling and extrapolation using an average annual load growth of 2%, based on historical load growth.

Future wind power production has been modelled for different wind power scenarios using weather data and park-aggregated speed–power curves. Wind speed data for 1 year were obtained from the Royal Dutch Meteorological Institute (KNMI), comprising 10 min wind speed averages with a resolution of 0.1 m/s for 18 locations in the Netherlands, both on- and offshore. Wind speed time series for the study period at planned wind park locations are created such that the spatial correlation between the sites is taken into account [6, 21]. Wind speed data are then transformed into wind power data using aggregated wind park wind speed–power curves and turbine availability rates. Because of the combination of wind speed and system load data from the same periods, any possible correlations between load and wind power (i.e. weather conditions) are automatically taken into account and are not further considered here.

4 Simulation setup

Simulations of UC-ED are performed for a 1-year period, with an hourly resolution, for different installed wind power capacities, taking into account the unscheduled unit outages and wind turbine availability rates. The simulation model applies a steady-state approach; UC-ED are optimised for each hourly state taking into account the past states (minimum up- and downtimes, ramp rates etc.) and load. To this base-case, five different wind power penetrations are added starting with 2 GW onshore and ending with 2 GW onshore and 8 GW offshore. This total of six cases is then run for a number of scenarios. The scenario approach used in this paper allows an assessment of the relative merits of the energy storage and heat boiler options compared with an equally installed capacity of CCGT, for different wind power penetrations. This way, the relationships between the different options and installed wind power capacity can be clarified.

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4.1 Scenarios

For this paper, a total of 120 simulations have been run, comprising any combination of the following cases:

- wind power penetration: 0 GW (base-case), 2, 4, 6, 8 and 10 GW;

- capacity alternatives: CCGT (base-case), PAC, UPAC, CAES, CCGT with heat boilers;

- sensitivity analysis: flexible exchange (base-case), fixed import schedule, high gas price, low CO_2 price.

The simulated alternatives allow the assessment of synergies between wind power and energy storage and heat boiler options. For the largest wind power penetration investigated here (10 GW), wind power would supply ~27% of annual electricity demand in the Netherlands. The additional sensitivity analyses allow a comparison of the benefits of the different capacity alternatives for a more constrained operation (in this case, international exchanges are fixed independently from wind power), a higher gas price and a lower CO_2 price.

4.2 Assumptions

For the simulations, central UC-ED (i.e. a perfectly operating electricity market) is assumed. It is assumed that wind power does not replace conventional generation. Since total installed capacity between the different options is equal for each wind power penetration level, however, a comparison of energy storage alternatives can be made on an equal system adequacy basis. It is assumed that no grid congestions are present within the Dutch network: no additional technical constraints exist apart from the technical parameters of the generation units. The simulation program calculates an optimal maintenance schedule for the simulated year on beforehand and determines unscheduled outages using Monte Carlo, also for the added energy storage units. The commitment and despatch of energy storage and heat boilers is based on the minimisation of overall operating costs. The prices for coal, gas, uranium and CO_2 for the base-case scenario have been determined by the authors using forward-prices and planning scenarios [22, 23] and set to 5 €/GJ, 2 €/GJ (dependent on distance to sea ports), 1 €/GJ and 20 €/ton. For the sensitivity analyses, the high gas price and low CO_2 price have been determined at 8 €/GJ and 0 €/ton, respectively. An overview of prices can be obtained from Table 3: all are from 2007 prices. Fixed operation and maintenance costs for both storage technologies have been estimated at 25 million euros per year, a figure comparable with the typical costs associated with CCGT. Finally, the decremental cost of wind power has been set to zero. Wind power will therefore be ramped down only as a last resort (i.e. wasted wind for fulfilling minimum output constraints of must-run units).

Table 3 Prices For The Sensitivity Analyses For Gas And CO_2 prices

Variable	Price	
	Low	High
coal, €/GJ	2	2
gas, €/GJ	5	8
uranium, €/GJ	1	1
CO_2, €/ton	0	20

5 Results

The simulation results include a number of parameters. Most importantly, overall system operation costs are considered for the assessment of costs and benefits of the different technological alternatives. Additional information on the characteristics of this system is gained from a CO_2-emission analysis.

5.1 Base-case

In this paper, the possibilities of energy storage for the integration of higher amounts of wind power in the Dutch system are explored, in particular for the reduction of minimum load problems requiring wind power curtailment. As can be seen from Fig. 4, all options considered here indeed reduce the amount of wind wasted in the Netherlands because of minimum-load problems. Energy storage and heat boilers all increase the flexibility of the Dutch system and thereby enable larger amounts of wind energy to be integrated, with PAC as the option with the highest potential for this. For the higher wind penetration

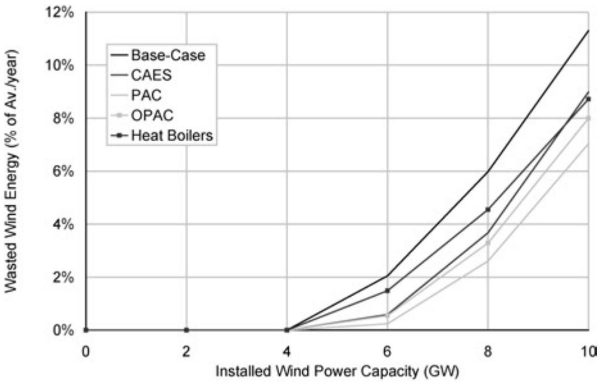

Figure 4 *Wasted wind energy because of minimum-load problems for the different options*

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levels, however, none of the options can separately prevent wasting wind energy altogether.

In Section 2, it was argued that the use of energy storage for system operation cost optimisation would stabilise short-term marginal costs. The simulation results show that operation cost variations indeed decrease in case energy storage is applied. In Fig. 5, hourly operational costs of the Dutch system for the same week with and without energy storage are shown as an example of this (PAC in this case). This effect can be reported for all energy storage technologies for all weeks throughout the year. For heat boilers, the effect is less clearly identifiable, since heat boilers operate merely to prevent minimum load problems (low load, high wind) as a result of CHP unit operation constraints. Therefore heat boilers simply create additional technical space to integrate wind power (less wasted wind) which in turn results in cost savings.

As followed from Section 2, wind power would bring down total system short-run marginal costs (system operation costs). This can be observed from Fig. 6 (the bump in the graph is caused by the lower capacity factor of the first 2 GW installed capacity which is located onshore). At 10 GW installed capacity, wind power is capable of saving up 25% of total system operation costs. Clearly, the relative cost savings gained from wind power decrease as the amount of wind power installed increases; technical flexibility comes at a price. This can be explained by limits in the operational flexibility of conventional plants, leading to sub-optimal despatch, reduced operating efficiencies and, ultimately, increased wasting of available wind resources. A similar explanation holds for CO_2 emissions for the base-case. Wind power saves significant amounts of CO_2 (up to 28% or 17 Mton annually) by saving fossil fuels and thereby also saving operation costs, as CO_2 emission costs are part of the overall operation costs. It should be noted that the CO_2 emission levels presented here include emissions as a result of imports.

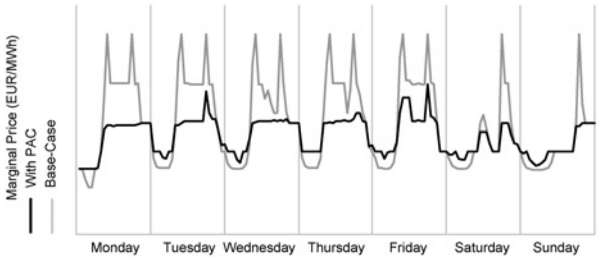

Figure 5 *Marginal cost for 1 simulated week with and without energy storage*

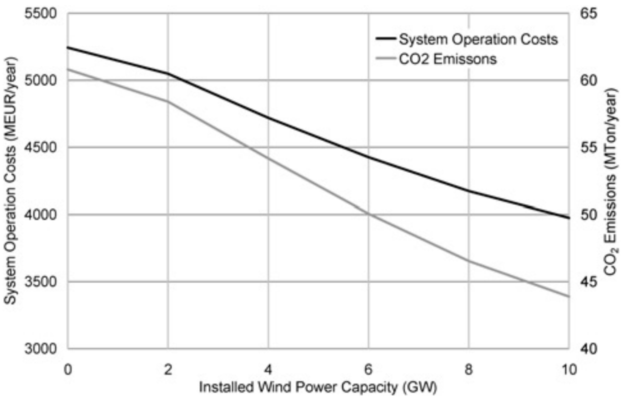

Figure 6 *Total system operation costs and CO_2 emissions for the base-case at 0, 2, 4, 6, 8 and 10 GW wind power installed capacity*

5.2 Operational cost savings

The simulation results in Fig. 7 clearly show that the operation cost savings by energy storage and boilers increase with the amount of wind power installed. Energy storage in the Dutch system amounts to savings between 1 million euros (CAES) and 9 million euros (PAC) annually for the amount of wind power presently installed, increasing to 29–73 million euros annually for 10 GW installed capacity. The annual economic benefits of heat boilers in the Dutch system are estimated to be 28 million euros. For all options investigated here, there is a positive correlation between the operational cost savings and wind power capacity.

When comparing the energy storage options, it can be observed that PAC allows the highest operation cost savings followed by UPAC and CAES. This can be explained by the fact that PAC has the highest maximum pumping capacity, increasing the opportunities for large-scale energy storage at the lowest costs, compared with UPAC. CAES has a

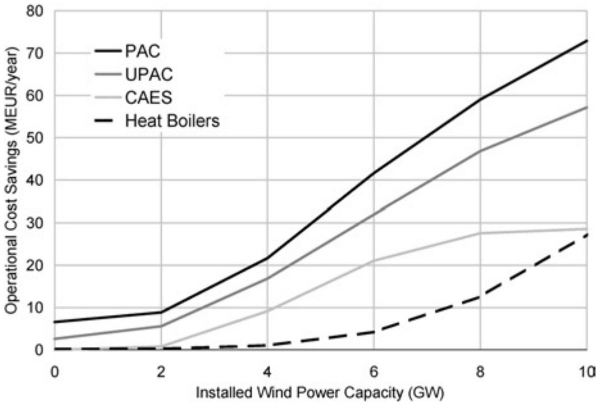

Figure 7 *System operational cost savings for the different options compared with the base-case for different wind power penetration levels*

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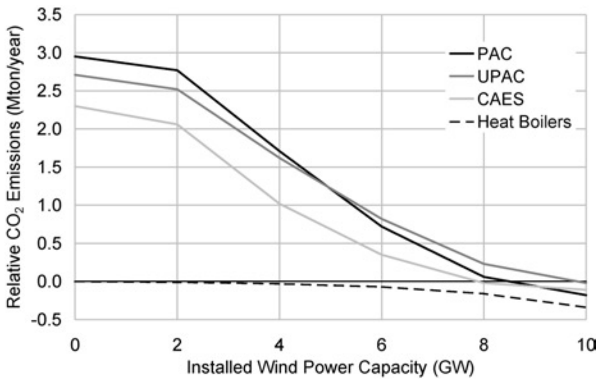

Figure 8 *Relative CO_2 emissions of the system for the different options compared for the base-case*

relatively small reservoir (Table 2, electrical efficiency of CAES), which limits its overall impact and possible synergies with large-scale wind power. Heat boilers are not put into operation until the first minimum-load problems occur at ∼4 GW installed wind power; from then on, the operational cost savings of this solutions increase rapidly.

5.3 Relative CO_2-emission levels

In Fig. 6, it is shown that system CO_2 emission levels are reduced with the integration of large-scale wind power. Fig. 8 shows the emission levels of CO_2 for energy storage and heat boilers compared with the base-case. Interestingly, the simulation results show that the application of energy storage in the Dutch system increases overall CO_2 emissions. Additional emissions with energy storage are highest at low wind power penetrations for PAC (3 Mton/year or a 5% increase).

The additional emission of CO_2 can be explained by two factors. First, it must be understood that energy storage is operated to minimise the system operation cost, within the technical possibilities of the system. For cost optimisation, the storage reservoirs are filled when prices are low, and to be emptied for generating electricity when prices are high. In the Dutch system, energy storage in fact substitutes peak-load gas-fired production by base-load coal-fired production: cheap coal is used for energy storage during off-peak while energy storage replaces expensive gas during peaks. Since coal emits more CO_2 on a MW h basis than gas, the net coal-for-gas substitution by energy storage increases the overall amount of CO_2 emitted by the Dutch system. Second, energy storage brings about conversion losses, which must be compensated by additional generation from thermal units, which again increases CO_2 emissions, especially since this is done by coal-fired units as well, being the cheapest option. For this system, it applies that from a CO_2 perspective, energy storage is an option only for very high wind penetration levels, when energy storage prevents substantial amounts of wasted wind.

Notably, the use of heat boilers not only saves operation costs (Fig. 7), but also some CO_2 emissions. Since the use of heat boilers at CHP locations specifically tackles minimum load problem as a result of CHP-unit-operating constraints, heat boilers reduce the amount of wasted wind. Since the CO_2 emissions of boilers and wind power together are lower than CO_2 emissions of CHP-units and wasted wind, boilers reduce the overall amount of CO_2 emitted by the system.

5.4 Sensitivity analysis

Operational cost savings by energy storage and heat boilers depend upon a number of assumptions, determining the technical capabilities of the system and operational costs of different generation technologies. The sensitivity analysis performed here considers international exchanges and gas and CO_2 prices.

5.4.1 International exchange: Fixed-schedule international exchange levels limit possibilities for wind power integration, since exchanges cannot be adjusted using updated wind power forecasts. Also, international exchanges (in particular cheap imports) are no longer available for energy storage in the Netherlands. From the simulations, it can be concluded that fixed international exchanges reduce price differences in the Dutch system and thereby the operational cost savings by energy storage. At high wind power penetrations, energy storage, however, has higher operation cost savings since it relieves the additional technical constraints of the Dutch system.

5.4.2 Gas price: In the Netherlands, the revenues from energy storage are heavily dependent on the generating cost difference between coal-fired (base load) and gas-fired (peak load) units. At a gas price of 8€/GJ, the operational cost savings of energy storage are higher since the generation cost difference between base-load coal and peak-load gas is higher. As the installed wind power capacity increases, savings by energy storage increase less compared with the base-case.

5.4.3 CO_2 price: Besides the gas price, the price for CO_2 is also an important determinant for the price difference between coal and gas. At a CO_2 emission cost of zero, generation costs of coal are lower compared with the base-case resulting in a higher cost difference between gas and coal. Simultaneously, it can be noted that the operational cost savings of wind power are less as well, since avoided CO_2 emissions do not save operational costs. As a result, the benefits

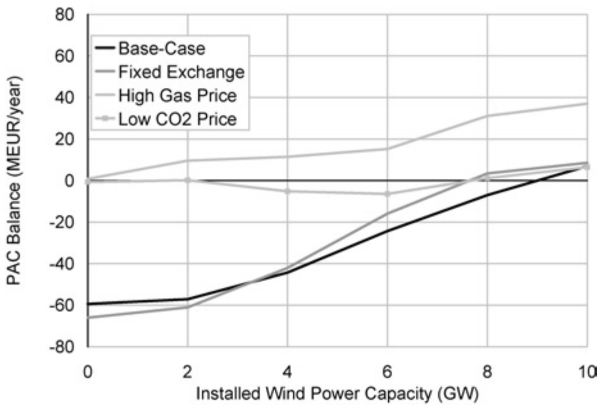

Figure 9 *Annual balance of PAC*

of energy storage do not vary significantly with the amount of wind power installed.

The results of the sensitivity analysis are shown in detail for each option as part of annual revenues (Section 4.1) in Figs. 9 (PAC), 10 (UPAC), 11 (CAES) and 12 (heat boilers).

6 Cost benefit analysis

Now that the operational cost savings by energy storage and heat boilers have been quantified, a comparison can be made between the different options by taking into account their associated investment costs. This will be done while taking into account the sensitivity of the results to assumptions regarding international exchange schedules, gas price and CO_2 price.

6.1 *Investment costs*

On the basis of the operational cost savings, an estimate of the total benefits of energy storage and heat boilers in the Dutch system can be made. The total costs for such units then need to be quantified to enable a cost–benefit analysis. In Table 4, the parameters of the cost–benefit analysis are shown. Capital cost savings by the different options are taken into acount as part of the overall benefits. As an example, the benefits and overall balance for the presently installed wind power capacity in the Netherlands are shown.

For this analysis, it has been assumed that both PAC and OPAC substitute a total of 1600 MW of CCGT,

Table 4 Cost–benefit analysis for CCGT, energy storage and heat boilers

	CCGT	PAC	UPAC	CAES	Heat B
nominal capacity, MW	1400	1925[a]	1400	1400	1800
capacity credit r.t. CCGT, MW	1400	1600	1600	1400	0
time to build, year	4	8	8	8	2
investment costs, M€	700	1700	1667	875	70
interest, M€	70	340	333	88	2
activation costs, M€	770	2040	2000	963	72
debited in 25 years	770	1020	1000	770	72
debited in 50 years	—	1020	1000	193	—
debit interest, %	5.0	5.0	5.0	5.0	5.0
annuity 25-year part, M€/year	55	72	71	55	5
annuity 50-year part, M€/year	—	56	55	12	—
costs, M€/year	55	128	126	67	5
avoided investment in CCGT, M€/year		62	62	55	0
avoided fixed O&M cost, M€/year		0	0	0	0
avoided variable O&M cost, M€/year		0	0	0	0
operational cost savings, M€/year[b]		8	5	1	0
benefits, M€/year		70	67	56	0
balance, M€/year		−58	−59	−11	−5

[a] Maximum power, varies between 1000 and 1925 MW, [b] Example for 1.6 GW wind power and flexible exchange scenario

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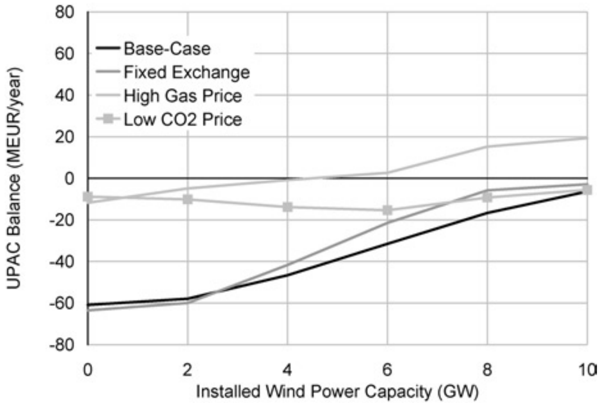

Figure 10 *Annual balance of UPAC*

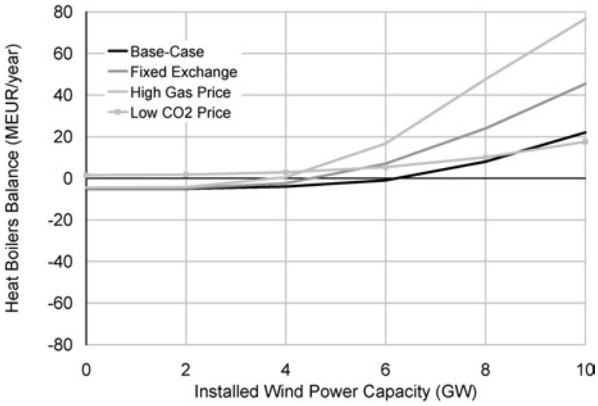

Figure 12 *Annual balance of heat boilers*

because of the higher availability rates of pumped hydro compared with CCGT. CAES replaces a total of 1400 MW since it is largely similar technology with comparable planned maintenance and forced outage rates. The time to build and total investment costs for energy storage has been estimated based on earlier Dutch research [10, 11], and the investment costs for heat boilers have been obtained from [24]. For the calculation of the annual expenses, it has been assumed furthermore that all civil investments for the energy storage options have technical lifetime of 50 years and is written down for depreciation in 50 years, whereas all electro-mechanical installations use a depreciation time of 25 years, with a debt interest rate of 5% annually (real interest at 0 inflation, all prices at 2007 level). The annual revenues and balance are shown for one simulated scenario only (base-case, 0 GW wind power installed).

6.2 Balances

In Figs. 9–12, the overall balance (total revenues minus total costs) for each option is shown for the base-case (black line) and the three investigated sensitivity variants. On the basis of these figures, it can be concluded that for the base-case only heat boilers and CAES are positive for wind power penetrations of 6 GW and upwards. PAC and UPAC do not seem to be cost-efficient, even at very high wind power levels of 10 GW. For all solutions, the balance improves in case a higher gas price is applicable. A low CO_2 price is especially beneficial for the revenues of PAC, OPAC and CAES for the lower wind power penetrations. From a return on investment perspective, heat boilers seem to have the highest potential for the integration of large-scale wind power into the Dutch system, although a different design of CAES (power against reservoir size) could result in a better business case.

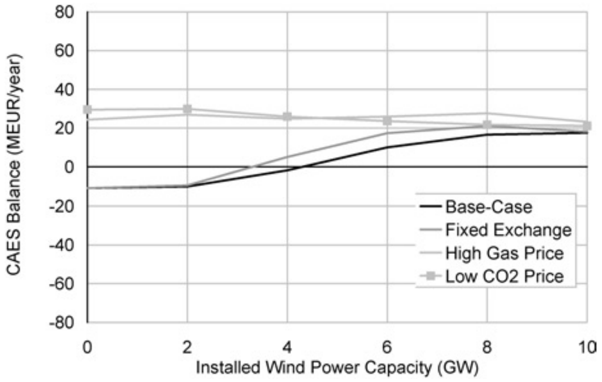

Figure 11 *Annual balance of CAES*

7 Conclusions

This paper has explored the opportunities of energy storage and heat boilers for the integration of wind power in the Dutch system. PAC, UPAC, CAES and the use of heat boilers at selected CHP locations provide a number of benefits for wind power integration. The integral approach of this paper allows a system-wide assessment of technical, economical and environmental aspects relevant for the exploration of possible synergies between wind power and energy storage when these are integrated into existing power supplies.

It has been shown that all investigated options decrease the amount of wasted wind energy as a result of minimum-load problems in the Dutch system, although significant amounts of available wind power are wasted still at high wind power penetrations. Furthermore, all solutions provide significant operational cost savings for the system as a whole, increasing with the amount of wind power installed. A notable result is that energy storage significantly increases the overall emissions of CO_2 of the Dutch system, especially at low wind power penetrations. This is because energy storage is used for substituting clean, peak-load gas generation for base-load coal generation and conversion losses inherent to the use of energy storage. Thus, even though proposed as a solution for wind power integration and a more sustainable power supply, in the Dutch system, energy storage would in fact annul part of the CO_2 emission savings by wind power. Heat boilers provide some additional CO_2 emission savings with amounts increasing with wind power installed capacity.

It can be concluded that energy storage, which has been often suggested as a logical partner for wind energy, is not the most efficient solution for the integration of large-scale wind power for penetrations up to 10 GW in the thermal system investigated. The cost–benefit analysis performed here shows that neither PAC nor UPAC is likely to have a positive balance, even at very high wind power penetrations, which is mainly due to the very large investment costs associated with these options. CAES has limited synergies with wind power because of its small energy storage capabilities. For the Dutch power system, the use of heat boilers at CHP locations seems to provide the highest potential for efficiently creating additional technical space for the integration of large-scale wind power.

8 Reflection

The results obtained here have proved the feasibility of heat boilers for increasing the operational flexibility of Dutch CHP plants. Although this solution is promising, as it specifically addresses one cause for minimum-load issues, it is not sufficient for the prevention of wasting available wind resources altogether and therefore only a necessary first step. Therefore efforts should be made to explore to what extent this solution can be extended to other CHP locations as well. Furthermore, research is needed into other solutions optimising the generation mix to remove minimum-load problems, in particular by making base-load coal and system load more flexible.

In this study, only the existing system interconnections of the Netherlands with Belgium/France and Germany have been taken into account. Later this year (2008), a 700 MW HVDC link to Norway (NorNed) will be in operation, and another HVDC link to the UK (BritNed) is being planned as well. Such interconnections increase the possibilities for international exchange and thereby for integrating wind power. In particular, the use of interconnections to Norway may provide an interesting alternative for costly energy storage solutions in the Netherlands.

One of the objectives of this paper was to explore a number of possible solutions for wind power integration into a future Dutch system. Uncertainties in the assumptions for this study (fuel prices, CO_2-emission prices) are significant, and these increase exponentially when explorations further ahead would be attempted. Furthermore, the future holds additional uncertainties, which may be more fundamental, such as the development of new generation and/or demand side management technologies, the size of the system and the market design. It is therefore recommended that an analysis such as this one is repeated in future to confirm whether the conclusions made here are still valid.

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