Optimization of Generation Plant Mix with the Integration of Large-Scale Wind Power

B.C. Ummels
Power Systems Laboratory, TU Delft
b.c.ummels@ewi.tudelft.nl
T +31 15 2784051
F +31 15 2781182

M. Gibescu
Power Systems Laboratory, TU Delft
m.gibescu@tudelft.nl

W.L. Kling
Power Systems Laboratory, TU Delft
Power Systems Laboratory, TU Eindhoven
Transmission Operations Department, TSO TenneT
w.l.kling@tudelft.nl

G.C.Paap
Power Systems Laboratory, TU Delft
g.c.paap@tudelft.nl

Abstract

With the growth of wind power, wind power's variability and unpredictability increases the need for power reserves in the minute to hour time-frames. Because these are often provided by conventional generating units, wind power must be taken into account in the commitment and dispatch generation of these units in the system. In this paper, impacts of wind power on the existing generation system and the opportunities for base-load coal, fast gas turbines, and different energy storage options are explored. Results include information on energy storage operation cycles, total operating cost, wasted wind power resources and emissions. It is shown that the feasibility of different generation options is dependent on the amount of wind power installed in the system. The value of base-load coal and gas-fired combined cycle decreases with the amount of installed wind power, whereas the value of underground pumped accumulation storage increases, although unlikely to become profitable. In this case, the use of heat boilers at combined heat and power locations appears to have the most potential for efficiently creating additional technical space for wind power integration.

Keywords: Power system operation, wind power, system integration, enery storage, cost optimization

1 Introduction

The development of wind power into an energy source of significance has substantial impacts on the operation of power systems. The variability and unpredictability of wind causes power fluctuations in the system that are much more difficult to manage than load variations including load forecasting errors and therefore complicate the task of balancing generation and demand in real-time. In particular, wind power influences the need for regulation power and calls for reserves in the minute to hour timeframes, which are often provided by conventional (coal, gas) generating units. Therefore, wind power must be taken into account in the operation of the other units in the system.

Optimization of the scheduling of conventional generation units can be divided into unit commitment and unit dispatch. Unit commitment calculations (unit is on or off) are typically performed months to days ahead based on long-term maintenance scheduling, fuel contracts and supply contracts. Unit dispatch (MW production for units in operation) is commonly calculated for the timescale of days to hour-ahead. In the unit commitment and dispatch, power reserves needed for balancing wind power variability and unpredictability must be taken into account. As the amount of wind power increases, so do the impacts of wind power on the operation of the rest of the system, such as investigated in [1], [2].

It is often suggested that wind power and energy storage form a natural combination, for example in references [3], [4] [5]. These studies consider wind power and energy storage in isolation, which may lead to conclusions different from studies in which a more system-oriented approach is adopted. As large-scale wind power will most often become part of larger, interconnected systems, it becomes part of existing generation portfolios. The cumulative technical capabilities of the existing system then determine technical constraints, if any, for integrating wind power, and, consequently, the benefits of energy storage facilities.

The impacts of wind power as part of larger systems has been examined for a number of European systems, such as the German [1] and the Irish [6]. In the Netherlands, the use of energy storage facilities has been a subject of research since the 1980's [7], [8]. The most important reasons for research in energy storage technologies were the possible contributions of energy storage to the optimization of the operation of the entire generation system, to the integration of recurring energy sources and a decreased need for reserve power. It was found that the use of energy storage was in particular beneficial in combination with a high share of base-load units (nuclear or coal), while the dedicated use of storage as reserve for wind power was found to be unprofitable at that time.

In this paper, a system-wide approach is applied for a foreseen future Dutch generation mix, to which then different wind power penetrations are added as well as different power generation and energy storage facilities. The simulation tool applied includes detailed models, based on empirical data, for all major units for a realistic future lay-out of the Dutch generation system. The opportunities of new units, in particular fast gas turbines and energy storage (underground pumped accumulation storage, UPAC, and compressed air energy storage, CAES), are explored for the optimization of the generation system including different wind power penetrations.

This paper is organised as follows. First, different power generation and storage technologies are shortly described (Section 2). Then, the simulation set-up is described, including the simulation model and different aspects of existing generation units as well as scenarios to be simulated (Section 3). Simulation results include system operation costs for different wind power penetration levels, energy storage impact on operating costs and emissions (Section 4). Overall conclusions can be found at the end of this paper (Section 5).

2 Generation Technologies

Different generation technologies have different technical characteristics, each affecting total operation costs, system emissions and the system's technical contstraints for the integration of wind power. Below, the different electrical and heat production technologies explored in this paper are shortly described.

2.1 Coal

Ever since the emergence of electrical power systems, coal has been a crucial pillar of the electric utility industry. Conventional coal-fired power plants combust pulverized coal in order to heat water. The high-pressure steam produced is used to power the steam turbine, thereby generating electricity. Modern coal power plants incorporate additional features, such as a feedwater heaters and air pre-heaters. The most advanced coal plants have efficiencies of approximately 45% and capacities up to 1000 MW [9]. With coal supplies in large long-term supply, a re-emergence of coal-fired generation could provide an answer to increasing demand for electric power, although a reduction of its emissions will be required.

2.2 CCGT

Combined Cycle Gas Turbines (CCGT) have become a generation technology of significance only in the past decades. The working principle of CCGT comprises the intake of preheated air, which is then mixed with natural gas and burnt. The expanded gas flow powers a turbine to produce electricity, after which the exhaust gasses are re-used to heat the input air. Advanced CCGT have efficiencies of approximately 55%. Generally, CCGT have a number of advantages over other options. In particular with respect to coal, CCGT units have low capital cost, low emission levels and a short construction time. Furthermore, the technology of CCGT allows faster unit start-ups and shorter shut-downs than conventional fossil-fueled technologies, which may be advantageous for the integration of renewable energy sources. The fuel cost of CCGT are however significantly higher compared to coal.

2.3 Pumped Water Storage

Pumped hydro (Pumped Accumulation Storage, PAC) uses hydro-turbines and water reservoirs for electricity production and energy storage. Electricity is generated by using the water flow forces from the higher into the lower reservoir, while energy storage is facilitated by pumping the water from the lower into the higher reservoir. The total generating-and-pumping efficiency of the energy storage, or *turn-around efficiency*, which depends mostly on the height difference between the reservoirs. For the Netherlands, large height differences can only be achieved by using underground cavernes as the lower reservoir (Underground PAC or UPAC), leading to turn-around efficiencies of 77% [10].

2.4 Compressed Air Energy Storage

Another energy storage facility is compressed air energy storage (CAES), which uses air instead of water as the storage medium. CAES effectively is a CCGT with an electrical compressor: during periods of low electricity prices, the compressor is used to store energy. The stored, compressed air is then later used as inflow for the CCGT. CAES also makes use of underground cavernes, which in this case store air instead of water. It should be noted the amount of energy stored by CAES only needs to be relatively small in order to produce large amounts of electricity: air is used in combination with natural gas as the fuel, making CAES in fact more of a generation rather than a storage unit. The benefits of CAES in combination wind power have been investigated by [11].

2.5 Heat Boilers

In a number of European power systems, such as the Danish, Finnish and Dutch, combined heat and power (CHP) has a prominent place as part of the total generation mix [12]. The CHP unit's generation schedules are usually heat-(or steam-) demand dependent and can therefore often be regarded as base-load units. With regard to wind power, CHP-units may pose additional technical bottlenecks, such as shown for the Dutch power system in [13]. The presence of heat boilers adds extra flexibility to CHP-units: during low heat demand, heat boilers may take over the supply of heat or steam in order to enable unit shutdown, while during high demand both the unit and the boiler will be in operation. With respect to wind power, the presence of heat boilers enables a temporarily shut-downs of CHP-units during moments of high wind power and low load, and may therefore facilitate the integration of additional wind energy.

3 Simulation Set-up

For the simulations, a chronological unit commitment and economic dispatch simulation (UC-ED) program has been used. UC-ED can be regarded as a multi-criteria optimization problem, where the operating cost function is minimized within the boundary conditions of serving system load and local heat demands, and maximum possible integration of wind power. The UC-ED formulation includes typical generation unit parameters such as minimum up- and down-times, ramp rates, combined heat-and-power operating constraints and unscheduled outage rates. Unit commitment and dispatch are optimized on a hourly basis to achieve minimum operating cost, while all of the following constraints are met:

- Electricity demand
- Heat demand in all heat areas
- Ramping capabilities of generation units
- Minimum up- and down times of generation units

An existing generation unit database, including models for coal, gas, coal- and gas-fired CHP and nuclear units, has been expanded with energy storage unit models and a number of heat boiler models for different CHP-locations. For the development of energy storage models, two parameters are of particular importance: the size of the energy storage reservoir (GWh) and the size of the pumping/generating capacity (MW). The purpose of the storage facility is determined largely by the combination of these two: for a day-night cycle, for example, a reservoir size of 6-10 hour equivalent of full production capacity would be an obvious choice. The models developed here are sized for a weekly cycle, during which daily cycles of pumped operation and generation are taken into account. A number of technical parameters for the various alternatives are shown in Table 1.

Parameter		**Technology**				
		Coal	CCGT	UPAC	CAES	Boilers
Nominal Capacity	MW	1400	1400	1400	1400	1800*
Storage Capacity	MW	-	-	1400	1400	-
Min.generating power	MW	500	100	0	100	0
Reservoir size	GWh	-	-	20	20	-
Efficiency	%	45	55	77	181#	95
Planned maintenance	%	7	7	4	7	0
Unplanned maint.	%	7	7	5	7	0

**Thermal capacity, replaces ~ 1000 MW of CHP-must run*
 # with addition of 4.1 GJ natural gas /MWh

Figure 1: Technical parameters for the simulated technical alternatives

3.1 UPAC Model

The modelling of UPAC is based on available literature on past plans for underground energy storage in the Netherlands [10], [14]. A large, fixed height difference between the upper and lower (underground) water reservoirs is assumed, resulting in a turn-around efficiency of 77%. The flexibility of the unit is estimated to allow a full ramp between 0 MW output and nominal output is possible within the hourly simulation step of the simulation program. Additional technical parameters of the UPAC can be found in Fig. 1.

3.2 CAES Model

The CAES has been modelled in a similar way as the UPAC, but with a round-trip electrical efficiency of 181%, at a consumption of a natural gas of 4.1 GJ/MWh. This comes down to a total efficiency - (natural gas + pumping energy) / electricity generation - of 59.5%. This efficiency is based on the application of present CCGT-technology with an efficiency of approximately 55%: the increased efficiency of CAES lies in the fact that air compression has been de-coupled from unit operation and that the compressor is directly, electrically powered.

3.3 Heat Boilers

Heat boiler models have been modeled using existing heat boiler models in the database, but using a higher operating efficiency of 95%, which is typical for state-of-the-art boilers. It is furthermore assumed that these boilers need not to be serviced, as the failure rates of the boilers are commonly very low and assumed to be zero here. It can be noted that, even though the operation of heat boilers implies a lower overall energy efficiency (heat supply only, compared to heat and power supply from CHP), the operation costs for heat boilers instead of CHP- are considerably lower. This is because at moments of low load and high wind, the revenues from electricity production from CHP tend to be very low.

3.4 Load Data

For the investigation of the impacts of wind power on *system* operation, the output of wind power must be regarded in combination with system load. As was shown in [2], large-scale wind power will have a significant impact on conventional generation unit commitment. Wind power variations may counter-balance or amplify load variations, requiring reduced or increased amounts of regulating power, respectively. Also, wind power reduces the share of system load to be covered by other generation units. For the simulations, a specifically developed load pattern for a future year of the Dutch power system has been used. The 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 TenneT and extrapolated by assuming an average annual load growth of 2%, based on historical load growth.

3.5 Wind Data

Future wind power production has been modeled for different wind power scenarios using weather data and park-aggregated speed-power curves. Wind speed data for one year have been obtained from the Royal Dutch Meteorological Institute (KNMI). The data concerns one year of 10-minute 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 [2], [15]. By combining the wind power data with system load data for the same period, also any possible correllation between load and wind power (i.e. weather conditions) are taken into account.

3.6 Delineations and Assumptions

A realistic future make-up of the Dutch generation park is used, including a number of units planned to be installed for all scenarios. For the simulations, central unit commitment and economic dispatch (or a perfectly operating market) are assumed. Furthermore, no grid congestions within the Dutch network are assumed: no additional technical constraints exist apart from the technical parameters of the generation units. A constant operating reserve of 1200 MW is assumed.

Power exchanges of the Dutch system with neighboring systems (Belgium and Germany) are assumed to be predetermined (long-term fixed schedules based on contracts). This assumption allows the calculation of the benefits of the different power or heat generation options for the Dutch system separately. The simulation program calculates optimal maintenance schedule for the simulated year and determines unscheduled outages using the Monte Carlo technique, also for new generation units.

The prices for coal, gas, nuclear and CO_2 have been determined on the basis of forward-prices and/or estimates by the authors to 5 EUR/GJ, 2 EUR/GJ (dependent on distance to sea ports), 1,00 EUR/GJ and about 20 EUR/ton. Fixed operation and maintenance costs for both storage technologies have been estimated at 25 million per year. 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 in minimum output constraints).

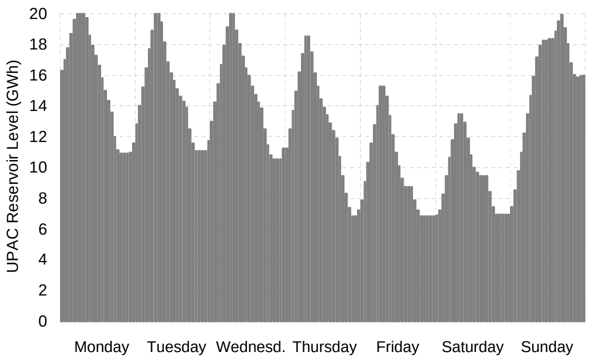

Figure 2: Reservoir level of UPAC during week 1, scenario without wind power

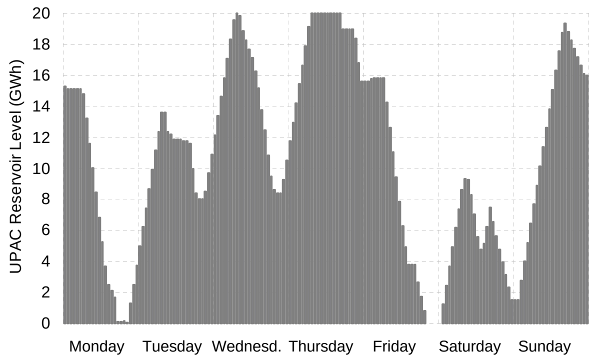

Figure 3: Reservoir level of UPAC during week 1, scenario with 8 GW wind power

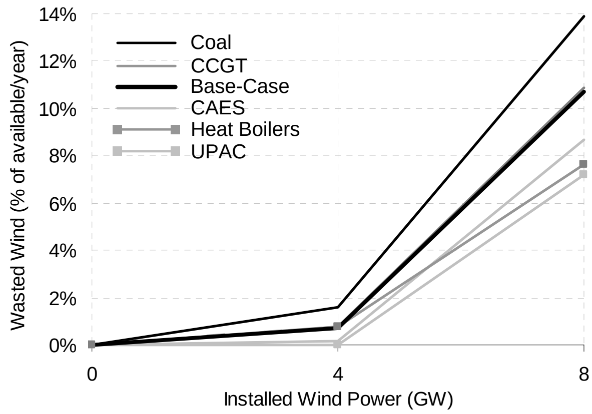

Figure 4: Percentages of wind energy wasted as a result of minimum load problems for the different options

3.7 Scenarios

In total, 30 different simulations have been run:

- Wind Power: 0 GW, 4 GW, 8 GW
- Alternatives: Base-case, new coal, new CCGT, UPAC, CAES, heat boilers
- Heat Boilers: in combination with new coal, new CCGT, UPAC and CAES

It can be noted that 8 GW wind power would supply about 22% of annual electricity demand in the Netherlands. The simulated alternatives allow the assessment of interdependencies of wind power integration and four generation alternatives and one heat boiler option, relative to a base-case with comparable generation adequacy. It can be noted that the addition of wind power *does* increase the installed adequacy (i.e. it is assumed that wind power does not replace conventional generation). The additional investigation of the heat boiler scenario allows the assessment of the benefits of the use of heat boilers at CHP-locations for all other alternatives and all wind power penetrations.

4 Simulation Results

Results include information on energy storage operation cycles, total operating cost, wasted wind power resources and emissions. All results will be discussed in detail below.

4.1 Operation of Energy Storage Units

The application of energy storage has profound implications on the operation of other generation units in the system. In Fig. 2, the reservoir level of UPAC is shown for one week. Clearly, both a daily and a weekly cycle can be observed. At moments of low prices (low load during the night and weekend), UPAC will pump up water and increase its reservoir level, in order to produce at moments of high prices (i.e. peak load during weekdays).

The daily operation cycle of energy storage is changed in case large-scale wind power is added to the system. In Fig. 3, the reservoir level of UPAC is shown for the same week as in Fig. 2, but now with the addition of wind power variations for 8 GW installed capacity. At moments of high wind, electricity prices are likely to be low and energy storage units in the system will be used to pump up water or compress air. When the wind drops and prices increase, the stored energy is sold. The variable nature of wind power partly determines the operation cycle of energy storage units, with a correllation increasing with the amount of wind power installed.

4.2 Wasted Wind Power

Previous work has shown that for the system investigated here, minimum-load problems can be foreseen to provide a binding technical constraint for the integration of wind power [2]. During these moments, imports, base-load thermal, and CHP-units generation cannot be decreased and threaten to exceed load minus wind power. As a result, wind power is regulated downwards and available wind resources cannot be harvested.

The amounts of wasted wind power differ between the different scenarios, as can be seen from Fig. 4. For the base-case scenario (not shown), the amount of wasted wind power is about 11% at 8 GW installed wind power. Due to its long start-up and shut-down times, coal-fired generation will operate at all times (base-load) with power output varying between minimum and maximum power. The minimum power level of additional coal increases the amount of base-load power and thereby increases the amount of wasted wind power to 14%. The impacts of additional CCGT on the amount of wasted wind is neglegible due to its flexible operation, allowing unit shut-down at moments of low prices (or high wind). Energy storage and heat boilers provide additional room for the intergration of wind power, resulting in lower amounts of wind power wasted: energy storage by increasing system load (pump operation), heat boilers by decreasing the base-load generation level.

4.3 Operation Costs

The costs for the operation of the system presented above include variable costs (fuel costs, variable operation and main-

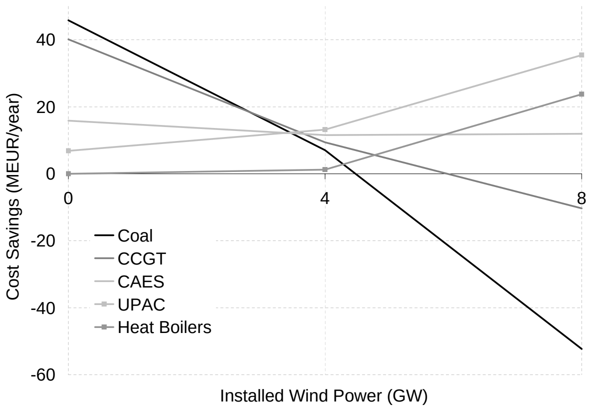

Figure 5: Operation cost savings by new conventional generation (coal, CCGT), energy storage (UPAC, CAES) and heat boilers.

tenance) as well as fixed operation and maintenance costs. Capital costs have not been included here. In Fig. 5, the total savings on operation costs for the investigated system are shown for the different options. From Fig. 5 it follows, that the operation cost savings of the generation and heat boiler options vary with the amount of wind power installed.

4.3.1 Coal and CCGT

Base-load coal generation is the most profitable option with 0 MW wind power, but its profits decline rapidly as the amount of wind power installed increases. This can be explained by the fact that this option has high fixed operation and maintenance costs, and low variable operation (fuel) cost. Because more wind power reduces the amount of full load hours for this unit, its profitability drops significantly. A similar explanation applies for CCGT, although its fixed operation and maintenance costs are lower and its fuel costs are higher. Furthermore, CCGT are capable of a more flexible operation, which explains the modest additional costs for CCGT compared to the base-case.

4.3.2 Energy Storage

The benefits of both energy storage options (UPAC and CAES) are modest at low wind power penetrations, with UPAC rising to a total annual benefit of about EUR 35 million at 8 GW of wind power. UPAC allows the integration of larger amounts of wind power (less wasted wind compared to the base-case), which in turn reduces total system operation cost. The cost savings by CAES are most and first decrease with the amount of wind power installed, but as the amount of wind power increases further, CAES modestly reduces the amount of wasted wind power and its benefits do not decrease further.

4.3.3 Heat Boilers

Fig. 5 clearly shows a positive relationship between the amount of wind power installed and the cost savings by the installation of heat boilers. Because minimum load problems in the system are reduced, higher amounts of wind power can be integrated into the system. The operating cost savings are EUR 25 million at 8 GW of wind power for this option. The robustness of this option is underlined by the fact that its revenues are dependent mostly by the back-to-back operation with CHP and the amount of wind power installed, and not by the other options for the generation mix, as can be seen from Fig. 6.

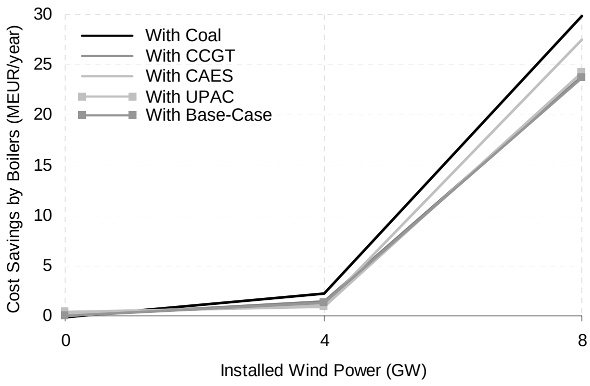

Figure 6: Operation cost savings by heat boilers with coal, CCGT, UPAC and CAES and for the base-case.

4.3.4 Cost-Benefit

Although a detailed cost-benefit analysis falls outside the scope of this paper, a first comparison between the most promising options for the integration of large-scale wind power (UPAC and heat boilers) can be made. Using literature research, a first comparison of the capital investment costs associated with heat boilers [16] and UPAC [10] shows that the cost of the heat boilers investigated here seem to be considerably lower.

4.4 Emissions

The integration of large-scale wind power in the power system investigated here significantly reduces CO_2, SO_2 and NO_X emissions. In Fig. 7, the emissions for the system as a whole are shown (emissions as a result of scheduled imports not considered here). System emissions drop by approximately one quarter for 8 GW of installed wind power: wind power then supplies 22% of Dutch demand.

In Fig. 8, the additional CO_2 output for the different generation options are presented, relative to the base-case. Clearly, the installation of additional coal-fired generation results in additional CO_2 emissions, because cheap coal replaces more expensive, but cleaner, gas-fired generation. Furthermore, installation of CCGT brings in more fuel and cost-efficient gas-fired generation, replacing more expensive and less efficient older gas units. As the amount of wind power increases, the amount of electricity produced by CCGT (and gas in general) decreases and the CO_2 savings decrease.

Notably, the use of energy storage and heat boilers increases CO_2 emissions for wind power penetrations up to 4 GW. Because the operation of UPAC and CAES is driven by price differences, UPAC and CAES allow a better exploitation of cheap, base-load coal, at the expense of gas, resulting in slightly higher CO_2 emissions. As the amount of wind power increases, the use of these energy storage units allows the integration of more wind energy (less wasted wind, Fig. 4), resulting in lower overall CO_2 output relative to the base-case. The use of heat boilers, finally, increases emissions because of efficiency losses (separate heat production instead of CHP), but this changes as the amount of installed wind power increases.

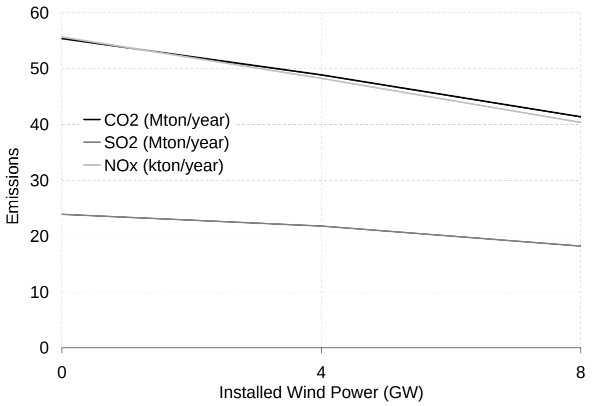

Figure 7: CO_2-output by the system for the base-case scenario

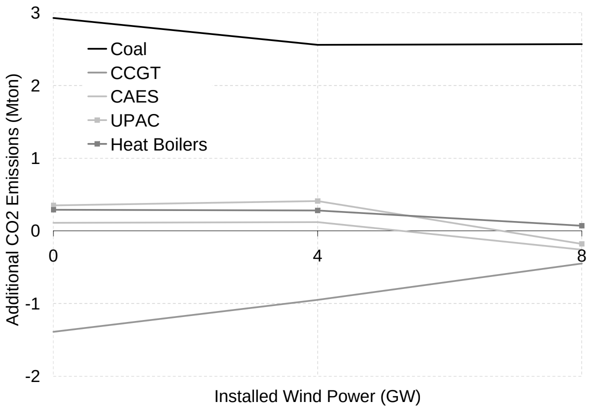

Figure 8: Additional CO_2-output by the system for the different options

5 Conclusions

In this paper, the opportunities for different generation technologies are explored for a future mix of the Dutch power system, with different amounts of wind power installed. Equivalent capacities of coal-fired and gas-fired generation and energy storage options as well as heat boilers have been added to the base-case and simulated for one year of operation. It has been shown that the business-cases for especially coal, but also gas deteriorates with the amount of wind power installed.

The paper shows that the use of energy storage, which is often suggested as a logical partner for wind energy, is not the most efficient solution for the integration of large-scale wind power. It is concluded that for this particular system, the use of heat boilers at combined heat and power plant locations seems to provide the most potential for efficiently creating additional technical space for wind power integration.

6 Acknowledgements

This work is part of the project PhD@Sea, which is funded under the BSIK-programme of the Dutch Government and supported by the consortium We@Sea, http://www.we-at-sea.org. The valuable comments and experience of Engbert Pelgrum, TenneT TSO, the Netherlands, are greatly acknowledged. The authors acknowledge the use of system data from Dutch TSO TenneT.

References

[1] G. Dany, “Power Reserve in Interconnected Systems with High Wind Power Production,” in *Proc. IEEE Porto PowerTech Conference*, Sep. 10–13 2001, p. 6.

[2] B. C. Ummels, M. Gibescu, E. Pelgrum, W. L. Kling, and A. J. Brand, “Impacts of Wind Power on Thermal Generation Unit Commitment and Dispatch,” *IEEE Transactions on Energy Conversion*, vol. 22, no. 1, pp. 44–51, March 2007.

[3] C. Bullough, C. Gatzen, C. Jakiel, M. Koller, A. Nowi, and S. Zunft, “Wind Power Trading Options in Competitive Electricity Market,” in *Proc. European Wind Energy Conference EWEC*, Nov. 22-25 2004, p. 9.

[4] O.A. Jaramillo, M.A. Borja, J.M. Huacuz, “Using hydropower to complement wind energy: a hybrid system to provide firm power,” *Renewable Energy 29*, pp. 1887–1909, 2004.

[5] E.D. Castronuovo, J.A. Peças Lopes, “Bounding active power generation of a wind-hydro power plant,” in *Proc. 8th International Conference on Probabilistic Methods Applied to Power Systems, Iowa State University*, Sep. 12-16 2004, p. 6.

[6] R. Doherty and M. J. O’Malley, “Quantifying Reserve Demands due to Increasing Wind Penetration,” in *Proc. IEEE Bologna PowerTech Conference*, June 23–26 2003, p. 5.

[7] Commission for Electricity and Storage (COE), “Opslag van Elektriciteit in Nederland: Haalbaar en aanvaardbaar? (in Dutch),” Dutch Ministry of Economic Affairs, Den Haag, Tech. Rep., 1988.

[8] “Evaluatie van de toepassing van energieopslagsystemen voor de Nederlandse elektriciteitsvoorziening (in Dutch),” N.V. Samenwerkende Elektriciteits-Produktiebedrijven (SEP), Arnhem, Tech. Rep., 1988.

[9] T. J. Ratajczak and M. Shahidehpour, “Emerging Technologies for Coal-Fired Generation,” in *IEEE Power Engineering Society General Meeting*, June 18-22 2006, p. 9.

[10] R. J. Rots, “Ondergrondse Pomp Accumulatie Centrale - Kosten-Baten Analyse (in Dutch),” AVECO / Koninklijke Volker Stevin, Delft, Tech. Rep., 1987.

[11] K. Burges and C. Nabe, “Compressed Air Energy Storage - Perpectives for Wind Integration,” Ecofys Germany GmbH, Köln, Tech. Rep., 2006.

[12] T. van Eck, *A New Balance for the Energy Sector*. Industrielinqs Pers en Platform, ISBN 978-90-788-8901-4, 2007.

[13] B. C. Ummels, M. Gibescu, E. Pelgrum, and W. L. Kling, “System Integration of Wind Power in the Netherlands,” in *Proc. IEEE PES General Meeting*, June 18–22 2006, p. 7.

[14] “Ondergrondse Pomp Accumulatie Centrale in Nederland - Vooronderzoek (in Dutch),” TH Delft, HASKONING, Koninklijke Volker Stevin, Tech. Rep., 1980.

[15] M. Gibescu, B. C. Ummels, and W. L. Kling, “Statistical Wind Speed Interpolation for Simulating Aggregated Wind Power Production under Unit Commitment and Dispatch,” in *Proc. 9th International Conference on Probabilistic Methods Applied to Power Systems*, June 11-15 2006, p. 7.

[16] T. Jóhannesson and T. Ólafsson, "Meeting the Annual Heat Demand," *Geo-Heat Center Bulletin*, no. 1, pp. 13–17, Dec. 2003. [Online]. Available: http://geoheat.oit.edu/bulletin/bull24-4/art4.pdf