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ENERGY SYSTEM ANALYSIS OF CAES TECHNOLOGIES IN THE DANISH ENERGY SYSTEM WITH HIGH PENETRATION OF FLUCTUATING RENEWABLE ENERGY SOURCES

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Abstract

Wind power supplies 20% of the annual electricity demand in Denmark, while 50% is produced by combined heat and power (CHP). The installed wind turbine capacity in Western Denmark exceeds the local demand at certain points in time. So far, excess production has been exported to neighbouring countries. However, plans to expand wind power locally and in the neighbouring countries could restrain the export option and create transmission congestion challenges. This results in a need to increase the flexibility of the local electricity system. Compressed Air Energy Storage (CAES) has been proposed as a potential solution for levelling fluctuating wind power production and maintaining system balance. Compared to other electricity storage technologies, CAES provides a large storage capacity using readily available technologies. Results from this paper, however, show that in order to have a significant effect on reducing excess electricity production, the storage capacity of CAES has to be increased significantly compared to current technology. It is thus concluded that, seen from a local energy system balance perspective, CAES has little potential for reducing excess electricity production and facilitating high wind power penetration. The study did not, however, consider other possible benefits of a CAES plant such as e.g. providing regulating power.

1. Introduction

In 2004, wind energy provided 32% of the electricity consumption in Western Denmark. The current total installed wind turbine capacity is 2400 MW, of which 213 MW is offshore. This compares to an electricity consumption that varies between 1,150MW and 3,800MW. With high wind velocities, wind power production can exceed the local electricity demand. Moreover, the changing wind velocity gives rise to a great need of fast reserve capacity to regulate the power imbalances. The ability of the electricity system to accommodate this high level of wind energy is further complicated by the high percentage of decentralized small-scale CHP power plants with a total capacity of 1593 MW.

The system operator in Western Denmark (Energinet.dk) has so far been able to deal with these challenges by using both local thermal resources and connections to neighbouring electricity systems. Following a new legislation, major CHP plants exceeding 5 MW are gradually operating on market conditions. As an initial result, this operation has shown an improved system balance. Such CHP plants used to operate in accordance with a triple tariff system which was not influenced by system unbalances coming from e.g. wind power [1]. However, as neighbouring countries have plans to increase their wind production in the future, this could reduce the regulating capacities available from abroad. From the perspective of socio-economy and security of supply, local reserves are preferred; especially since excess wind power is sold at low prices and bought again later at higher prices.

To solve the problem on a long term with even more wind power in the system, one will have to combine a variety of different technologies [2-6]. Electricity storage is one of the possible solutions to the challenges mentioned above. However, very few technologies tend to be economical on a utility scale. At a local level in Denmark, one of the potentially feasible technologies available nowadays is *compressed air energy storage* (CAES).

Compressed air energy storage (CAES) is a modification of the basic gas turbine (GT) technology, in which low cost electricity is used for storing compressed air in an underground cavern. The air is then heated and expanded in a gas turbine to produce electricity during peak demand hours. As it derives from GT technology, CAES technology is readily available and reliable. Two plants have been constructed in the world so far; one in Germany and one in the USA of 390 MW and 110 MW turbine capacities, respectively.

Several papers have been published on the Wind/CAES hybrid system. In a paper published in 2004, Bullough et al. analyse the technical development and economic feasibility of an Advanced Adiabatic CAES (AA-CAES) system in various European countries with reference to the EU target of reaching 20% renewable energy by 2020 [7]. In another study prepared by the Lower Colorado River Authority in the USA, CAES was analysed as the technical solution to the curtailment and reactive power problems resulting from the transmission line congestion connecting the wind power rich McCamey area in Texas [8]. In his paper, Denholm suggests a fully renewable base load power plant using a combination of Wind power, CAES, and biofuels [9]. Several business-economic feasibility studies for CAES plant investment have been performed in various countries over the past 35 years [10,11].

This paper analyses the potential impact of a CAES plant on the electricity system in Western Denmark. In particular, the paper focuses on the issue of dealing with excess electricity production. The analysis is performed using the EnergyPLAN model, and the results show that for a 100% wind power energy system, the required CAES capacity is too large to be realistic.

2. The EnergyPLAN model

The large-scale integration of wind power has been analyzed by modelling the western Danish collective energy system (electricity and district heating) on the EnergyPLAN computer model. The EnergyPLAN model is a deterministic input/output simulation model. General inputs are demands, capacities and a number of optional different regulation strategies, emphasising import/export and excess electricity production. Outputs are energy balances and resulting annual production, fuel consumption and import/export. For a detailed description of the model, please consult [12]

The energy system in the EnergyPLAN model includes heat production from solar thermal, industrial CHP, CHP units, heat pumps, and heat storage and boilers. District heating supply is divided into three groups of boiler systems and decentralised and centralised CHP systems. Additional to the CHP units, the systems include electricity production from renewable energy, i.e. photovoltaic and wind power input divided into onshore and offshore, as well as traditional power plants (condensation plants).

The model is simple in the respect that it aggregates all units in each of the mentioned types in the modelled region into one unit with average properties. This means that the differences among the single units and the transmissions among them are not considered. On the other hand, the model is advanced in the respect that it uses detailed hourly distributions of heat demands, electricity demands, wind production etc. to analyse the behaviour of the entire system hour by hour for a whole year. Various constraints, operational strategies and changes to the system can be imposed and compared.

The inaccuracy caused by the aggregation has been evaluated by testing the effect of replacing the single CHP unit with ten different interconnected units each with properties related to actual Danish plants with differences in size, amount of heat storage etc. The difference between these two situations was found to correspond to changes in the specifications for the CHP unit of app. 3%, and such differences are now being compensated in the EnergyPLAN model

The model requires four sets of input for the technical analysis. The first set is the annual district heating consumption, and the annual consumption of electricity, including flexible demand and electricity consumption from the transport sector, if any. The second set is the capacity of photovoltaic and wind power, including a moderation factor in order to adjust the relationship between the wind capacity and the correlating electricity production. This part also defines solar thermal, industrial CHP heat production inputs to district heating. The third set consists of capacities and operation efficiencies of CHP units, power stations, boilers and heat pumps. And the last set specifies some technical limitations; namely the minimum CHP and power plant percentage of the load required in order to retain grid stability. Furthermore, it includes the maximum heat pump percentage required of the heat production in order to achieve the specified efficiency of the heat pumps.

The model emphasises the consequences of different regulation strategies. Basically, the technical analyses distinguish between the two following strategies:

- *Regulation Strategy I: Meeting Heat Demand:* In this strategy, all units produce solely according to the heat demands. In district heating systems without CHP, the boiler simply supplies the difference between the district heating demand and the production from solar thermal and industrial CHP. For district heating with CHP, the units are given priority according to the following sequence: Solar thermal, industrial CHP, CHP units, heat pumps and peak load boilers.

- *Regulation Strategy II: Meeting both Heat and Electricity Demands:* When choosing strategy II, the export of electricity is minimised mainly by replacing CHP heat production by boilers or by the use of heat pumps. This strategy increases electricity consumption and decreases electricity production simultaneously, as the CHP units must decrease their heat production. With the use of extra capacity at the CHP plants combined with heat storage capacity, the production at the condensation plants is minimised by replacing it with CHP production.

In all strategies, the model takes a number of restrictions into consideration, such as:

- the system needs a certain degree of grid-stabilising capacity
- bottlenecks in external transmission capacity
- strategies for avoiding critical surplus production
- maximum percentage of heat production from heat pumps

3. Energy System Description

The reference energy system scenario is based on the current day Western Danish electricity system (Table 1). The assumed wind turbine capacity includes plans to expand the offshore capacity up to 500 MW. For the purpose of analyzing the excess electricity production (EEP), the system is isolated from neighbouring systems by removing any transmission capacity.

Table 1: Main inputs for the reference energy system scenario in the EnergyPLAN model.

Heat Demand	23.51	TWh
Fixed El. Demand	24.87	TWh
Decentralized CHP	1450	MW
Decentralized Boiler	7000	MJ/s
Dec. Heat Storage	15	GWh
Centralized CHP	1300	MW
Cent. Condensing	3200	MW
Cent. Boiler	7000	MJ/s
Cent. Heat Storage	10	GWh
Onshore Wind	2500	MW
Onshore Prod.	6.05	MWh
Offshore Wind	500	MW
Offshore Prod.	2.11	MWh
Annual Wind %	33	%

The alternative scenario is the addition of a CAES plant to the system. The CAES plant considered is comprised of a 214 MW compressor train and a 361 MW expansion train. The cavern size is 700,000m^3 corresponding to 1478 MWh. The compressor efficiency is 69%, resulting in a 10-hour compression starting from an empty storage. The expansion requires 149 MWh of compressed air energy in combination with 434 MWh of fuel firing for producing 361 MWh of electricity. This, in turn, translates into around 10 hours of expansion capacity starting at a full storage.

4. Simulation Results

Figure 1 shows the annual power balance for the reference energy system (without CAES). The figure is generated by increasing the offshore wind turbine capacity from 500 MW to 4500 MW, which corresponds to a scenario in which 100% of the 25 TWh fixed electricity demand is met by wind power. The figure shows that, as the wind penetration increases, the production of both CHP and condensing power plants (PP) decreases, while the excess electricity production (EEP) increases. The decrease in CHP production is a result of following regulation strategy 2 in the EnergyPLAN simulations, which leads to the replacement of CHP production by boilers for meeting the heating demand. If regulation strategy 1 was followed instead, the CHP production would have stayed constant, thus leading to even higher EEP.

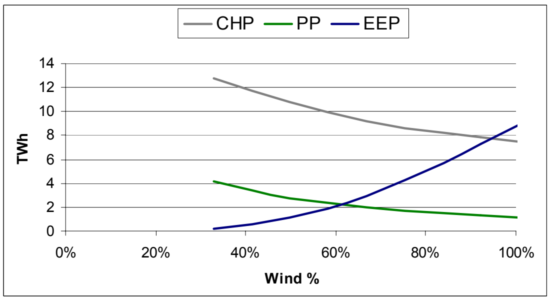

Figure 1: Power balance for the reference energy system at various wind power penetrations for a fixed annual electricity demand of 25 TWh

The same simulation is repeated for a system including the CAES plant described in section 3, and the resulting EEP is shown in Figure 2. It can be seen that adding the CAES plant is almost negligible in terms of reducing the EEP. The compressor/turbine operation is shown in Figure 3. Note that while the operation increases with the wind percentage it tends to peak towards the end and decrease again.

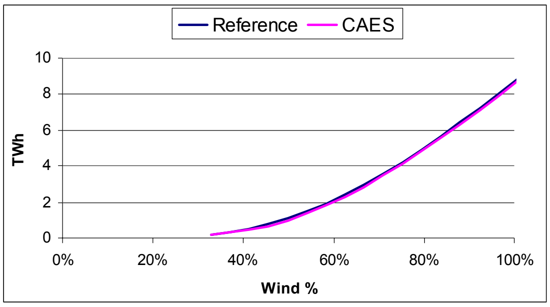

Figure 2: EEP for the reference system compared to adding the CAES, HP, and vehicle components.

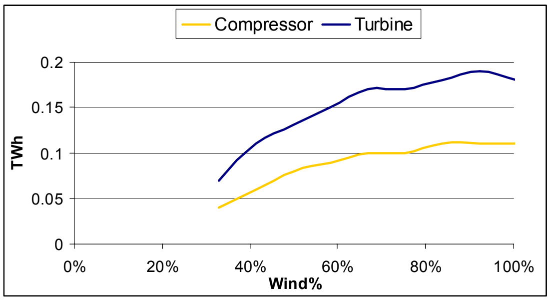

Figure 3: CAES compressor and turbine operation at various wind power penetrations.

Examining the hourly behaviour of the CAES plant shows that the relatively low operation is a result of two main factors:

- The limited amount of EEP at low wind penetration leading to an empty storage during hours of potential CAES turbine production.
- The excess amount of EEP at high wind penetration leading to a full storage during hours of potential CAES compression.

Figure 4 shows the potential compressor/turbine operation in both hours and MWh. The potential compression hours (PCH) are the hours with full storage and an EEP above 0. The corresponding potential compression operation (PCO) is the sum of the EEP during those hours. The potential expansion hours (PEH), on the other hand, are the hours with an empty storage and a condensing power plant (PP) production above 0. The corresponding potential expansion operation (PEO) is the sum of the PP production during those hours. It can be seen that, at low wind power penetration, the limiting factor is the emptiness of the storage at hours of potential expansion. As wind penetration increases, the limiting factor becomes the saturation of the storage during hours of compression.

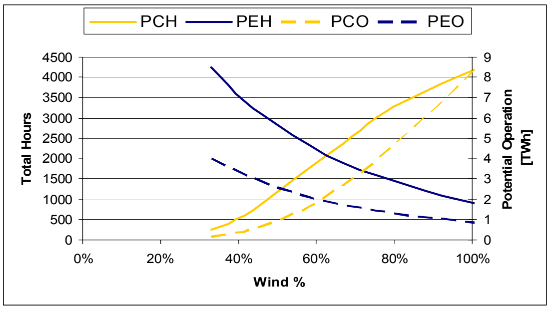

Figure 4: Potential compression and expansion hours and operation.

5. CAES/Electricity System Design

The results above were used for defining an optimum CAES/electricity system combination that minimizes the EEP. Given the compressor/turbine efficiencies, it is found that the electricity ratio of the CAES system is 0.6. In other words, every 0.6 MWh compressor consumption produces 1 MWh electricity output.

With the aim of replacing the condensing power plant (PP) production, the first step in designing the optimum system is to ensure that the total annual EEP is 60% of that of the PP production. This is found to be the case at a wind penetration of 55% (2500 MW and 1780 MW installed wind capacity onshore and offshore, respectively).

The next step is to determine the CAES plant capacity that could fully eliminate the EEP and PP production. Figures 5 and 6 show the CAES plant operation, EEP, and PP operation for two different CAES systems with varying storage capacity. It is assumed in this case? that the CAES plant efficiencies do not change with the changing capacities. The first CAES system is the same as the one discussed above, in section 3, whereas the second system has a compressor/turbine capacity of 2600MW/2700 MW, respectively, corresponding to the maximum EEP and PP values in the reference system.

It can be seen that for the smaller system, increasing the storage above 80 GWh has no effect on the CAES plant operation. For the larger CAES system, however, it is possible to fully eliminate the EEP and PP production by increasing the storage up to 600 GWh.

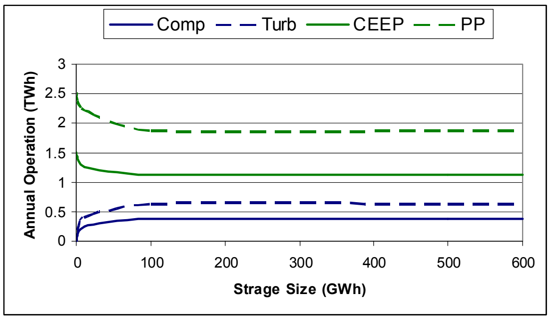

Figure 5: Performance of a 214/361 compressor/turbine system at various storage sizes

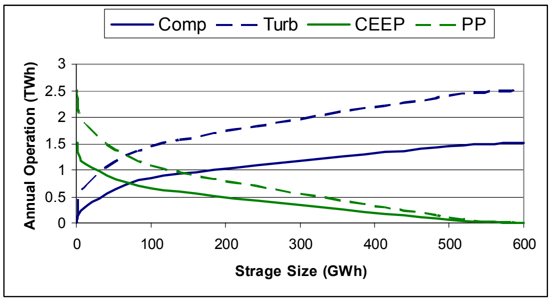

Figure 6: Performance of a 2600/2700 compressor/turbine system at various storage sizes

6. Conclusion

The ability of CAES to eliminate excess electricity production from wind power in the Danish energy system was analyzed using the EnergyPLAN computer model. It was found that a standard CAES plant capacity in the range of the plants existing in Huntorf and Alabama has negligible effects in improving the energy system balance at all ranges of wind penetration. For low wind penetration, the main CAES operational barrier is the lack of excess electricity, while for high penetration, the main barrier is the lack of discharging hours in a system with high CHP capacity.

An optimum CAES/electricity system combination was found. The optimum system is to have around 55% wind penetration. However, the storage value required for CAES to fully eliminate condensing power plants operation is found to be over 500 GWh. Compared to the fact that a 1,478 GWh storage corresponds to 700,000m^3, a 500 GWh storage could be too big to be realistic.

It is therefore concluded that, seen from a system balance perspective, CAES alone is not able to eliminate excess production. The study, however, did not consider the importance of a CAES plant for providing regulating power, an issue to be studied later on.

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