On the potential of coupling renewables into energy pools

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Abstract

The objective of this paper is to combine wind power with a renewable energy storage system and thereby to simulate a scheduled power unit. This is demonstrated with an optimization, targeted to produce periods with constant generation. As an example application a pumped hydro storage plant in combination with approximately one third of the total installed German wind power is used. As long as there is a mixture of coal and gas generation this remains a future scenario, because there is no incentive to follow a predefined schedule other than the forecast of the wind power generation. An indication on the ratio between installed wind power and required storage capacity to deliver constant generation for certain time periods will be provided. Wind power predictions are generated with a multi-scheme weather ensemble prediction system, allowing for day-ahead optimization of hydro power operation. The optimum daily operation strategy is found with an hourly-discretized optimization algorithm. In an application of the proposed method it is shown that optimized coupling of wind and hydro power allows for considerable reduction of output power fluctuations and that time period-wise constant power delivery to the grid is feasible.

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Introduction

Wind power is considered one of the most important renewable energy sources in the near future. For example, in the past years the number of wind farms in Germany increased strongly, with a total installed capacity of 19764 MW by the end of 2006. However, the varying output of wind energy could destabilize electricity grids, if no precautions are taken. Hence, it is of great importance to develop strategies that aid in smoothing the altering wind generation levels. This becomes even more evident, when future offshore projects, for example in Germany with anticipated output power of 20000-25000 MW until 2025/2030, are taken into consideration. Whether intermittency poses technical limits on renewables in the future is certainly also of concern for other forms of renewable energy sources[3], since for OECD (Organisation for Economic Cooperation and Development) Europe, IEA's (International Energy Agency) World Energy Outlook[4] projects up to 23 % market share of non-hydro renewable energy by 2030. Since natural variations of resource availability do not necessarily correspond with the (also varying) need of the consumers, balancing supply and demand is a critical issue, potentially requiring backup by other means of energy supply. The variations can occur at any time scale: hourly changes in output require balancing of short-term fluctuations by the so-called operational reserve, while days with low output require balancing of longer-term output fluctuations by so-called capacity reserves. Conversely, exceptionally windy days or rainy seasons can produce a surplus of supply and there might be an issue of handling excess capacity, where grids are not sufficiently interconnected. Transmission system operators (TSOs) are forced to buy balance or reserve capacity in advance to ascertain secure grid operation. Hydro power resources are uniquely capable of addressing these grid-integration issues, due to the characteristics of the generators (fast response times and low operation costs) and the built-in large scale energy storage that accompanies hydro impoundments. Hydro facilities may aid in realizing economic benefits through provision of ancillary services and potentially use the wind energy to improve the operation of hydro facilities beyond energy production[5].

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[3] See IEA (2005).

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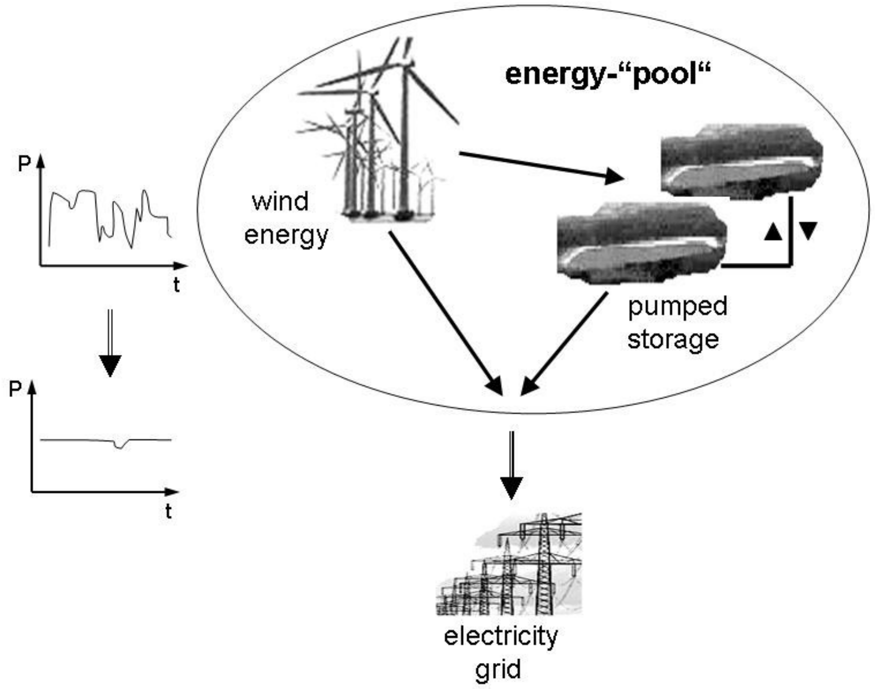
[5] See Acker (2005).

Method and data

Approaches to couple wind and hydro power

Coupling of renewable energy sources in a systems-approach has not yet received widespread attention as a basic alternative for energy production. In earlier work, Millham[6] studied the possibility of equilibrating wind power production through the complementary use of hydro power. In this study Millham investigated whether 51 spatially widespread hydro power stations in the North-West of the USA could aid in smoothing unstable and unreliable wind power output and therefore generating secure power to the system. Ackermann[7] investigated the applicability of a hybrid wind-hydro system for climate conditions in New Zealand. In a simulation study Kaldellis and Kavadias[8] and Kaldellis[9] studied the potential of coupled systems of several wind power stations and a small pumped hydro power station for Aegean Sea islands'. It has been found that under the prevailing favorable wind conditions and for small power network dimensions, the proposed coupling gave promising results. Several other studies investigated the usefulness of a coupled wind and hydro power system for islands.[10] These reports discuss specific case studies and generally indicate that integrating wind energy on grids with hydro power offers some economic advantages due to the flexibility of the hydro system and its ability to store energy and water. The U.S. Department of Energy is sponsoring several case studies directed at understanding the issues, opportunities, costs, and barriers to wind and hydro power integration.[11] In a study tailored towards the Mexican power market, Jaramillo et al.[12] developed a solution to provide firm power with a hybrid wind and hydro power system. Castronuovo und Peças Lopes[13] propose an optimization algorithm for daily operation of a coupled wind and hydro power station in Portugal. Hereby both technical and economic aspects of such a combined power system have been considered, also accounting for the uncertainty due to the strongly varying character of wind power by employing Monte-Carlo Simulations.

Figure 1: Sketch of the wind and hydro power system ("energy pool") and its connection to the grid.



The goal of this study is to combine wind power with a renewable energy storage system and thereby to simulate a scheduled unit. This is demonstrated by adapting the optimization approach put forth by Castronuovo and Peças Lopes for Germany, targeted to produce periods with constant generation. A pumped storage hydro facility is used to balance a certain percentage of German wind power. Furthermore, we apply ensemble data of wind power generation from a multi-scheme ensemble prediction system to model the actual situation of the day-ahead and hour-ahead market. This provides the possibility to verify the uncertainty of the forecasts and to adjust the predictions of the production according to the consumption/market prices by applying the upper or lower limits. Note that this is a possible future scenario, since there is little incentive to follow a predefined schedule other than the forecast of the wind power generation as long as a mixture of coal and gas generation exists. The study presented here will give an indication on the required ratio between installed wind power and storage to deliver a time period-wise constant generation.

Principle of the wind and hydro pool and formulation of an optimization function

Castronuovo and Peças Lopes developed their approach for the remuneration tariffs for wind energy in Portugal, with larger remuneration during peak hours. This in turn significantly affects the optimum operation plan of a

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[6] See Millham (1985).

[7] See Ackermann (1997).

[8] See Kaldellis/Kavadias (2001).

[9] See Kaldellis (2002).

[10] See e.g. Bakos (2002); Protopapas/Papathanassiou (2004); Bueno/Carta (2006).

[11] See Acker (2005).

[12] See Jaramillo/Borja/Huacuz (2004).

[13] See Castronuovo/Peças Lopes (2004a,b,c).

wind and hydro power system. During weak demand it is more profitable and/or necessary to pump and hence to store wind energy. On the other hand it is advantageous and/or necessary to release water from the reservoir during peak demand hours, with higher remuneration. When adopting the model by Castronuovo and Peças Lopes for the German energy market it was important to take into consideration that there is a fixed feed-in tariff in Germany, regulated by the German Renewable Energy Sources Act EEG ("Erneuerbare-Energien-Gesetz", implemented in 2000; updated in 2004). Hence there is no incentive for wind generators and wind park owners to store energy. However, the incentive lies on the side of the TSOs due to the fact that they are required to balance the varying wind power in the system. TSOs therefore anticipate smooth power output in the form of base loads. Balancing is in general costly (in particular with the less flexible conventional/thermal energy) and the optimization of combined wind and other renewables such as hydro power may lead to cost and CO_2 reductions. Large energy systems operate with little storage capacities, with a guiding principle to balance demand and supply continuously and hence replacing capacity within very short lead times by ancillary services. Here we propose coupling of wind and hydro power in a "first-order energy pool", similar to a hybrid energy system. Power is then delivered to the grid from those energy pools (see Figure 1). This differs from current practice, where according to the separation between production and dispatch e.g. hydro power must be bought by the TSOs from a vendor to balance wind power. Note that currently such energy pools are only used by the market-dominating power producers to enable them to deliver their produced power in a variable and most cost effective way. Also, hydro power is generally used to supply additional energy during peak hours, but the potential for smoother, increased and hence more profitable deliverable power through energy "pooling" has not yet been investigated thoroughly. The following analysis of a coupled wind and hydro power system takes this situation as a starting point to show the potential of such an energy pool system from an environmental and economic point of view. Therefore, the economic principle, that less input effort (here: balance capacity) results in lower costs, whereby the profit increases for constant output (here: delivered power), has formed the basis in this study. In addition it is anticipated to transform the fluctuating wind power into base loads (smoother power output). This results in the following fundamental optimization principles:

1. The difference between the upper (b) and lower (a) power delivery boundaries of the entire system P_i must be set such that the remaining fluctuations in the interval i will be minimized.
2. The power output of the entire system P_i must at all times be as high as possible.
3. The usage of pumps P_{Pi} must be minimized, to avoid additional internal costs.

Based on those 3 principles a multi-target system can be set up, whereby it is feasible to vary the individual targets according to their importance for the outcome through weighting factors. Based on the model by Castronuovo and Peças Lopes we can now formulate an adapted model, suitable for the German energy market:

Min.

$$nc_s(b-a)+\sum_{i=1}^{n}(-c_p P_i + c_{Pp} Pp_i) \qquad (1)$$

with

$$P_i = Pw_i + Ph_i \qquad (2)$$

$$Pv_i = Pw_i + Pp_i \qquad (3)$$

$$E_{i+1} = E_i + t\left(\eta_p Pp_i - \frac{Ph_i}{\eta_h}\right) \qquad (4)$$

$$E_1 = E_1^{esp} \qquad (5)$$

$$E_{n+1} = E_{n+1}^{esp} \qquad (6)$$

$$a \le P_i \le b \qquad (7)$$

$$0 \le b \le Pg^U \qquad (8)$$

$$Pg^L \le (Pw_i + Pp_i) \le Pg^U \qquad (9)$$

$$Ph^L \le Ph_i \le \min\left(Ph^U, \eta_h \frac{E_i}{t}\right) \qquad (10)$$

$$Pp^L \le Pp_i \le Pp^U \qquad (11)$$

$$0 \le E_i \le E^U \qquad (12)$$

$$c_s + c_p + c_{Pp} = 1 \qquad (13)$$

$$a \ge 0 \qquad (14)$$

where the vectors (hourly time step) P are power delivered to the grid by the wind and hydro system, Pw and Ph are power delivered by the wind and hydro generator, respectively, Pp is power required by the pumping system and E is the energy storage level in the reservoir. The parameters a and b describe the lower and upper output limit, respectively. Pv is the available wind power, Pg^L and Pg^U are the lower and upper power output limits of the wind farm, Ph^L and Ph^U are the lower and upper power limit of the hydro turbine, Pp^L and Pp^U are the lower and upper power limit of the hydro pump, c_S is a target weight factor for limiting fluctuations of the power delivery of the system, c_P is a target weight factor for the level of power delivery of the system, c_{Pp} is a target weight factor (pump operation cost) for usage of hydro pumps, E^U is the maximum reservoir storage capacity, E_1^{esp} and E_{n+1}^{esp} are the initial and final energy level of the reservoir, η_p and η_h are the efficiency factor of the hydro pump/pipe system as well as the efficiency factor of the hydro turbine/generator, t is the duration of time interval i (here: $t = 1$ h) and n is the number of discrete time intervals i (here $n = 48$).

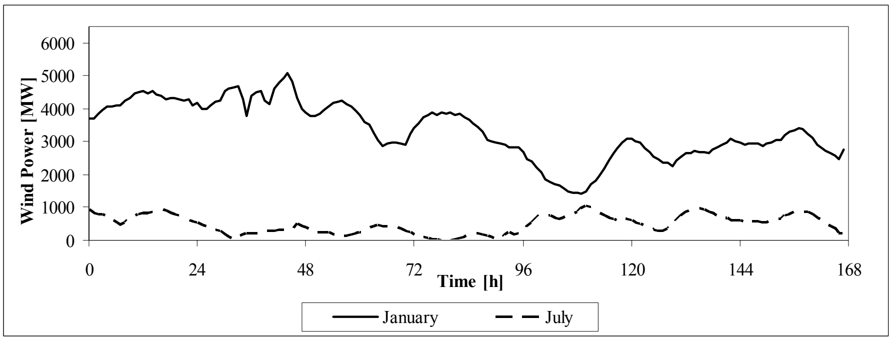
Wind power is normally considered a non-scheduled unit, but in combination with hydro power it could become a scheduled unit. The first order target is therefore to meet a fixed generation, rather than what the wind power forecast had predicted. The first term of the objective function (Equ. 1) describes the output power fluctuations, which must be minimized for all time periods *n*. The second term represents the maximization of the output power and in the third term hydro pump usage is minimized.

Equation (2) defines the output as sum of the deliveries of wind and hydro power. The former is however fed only partially direct into the system; the remaining portion is dedicated for pump operation, in case it is advantageous to retain the energy for later time periods [Equ. (3)]. Otherwise the produced power from wind is always to be used entirely. Equation (4) describes the energy balance of the water reservoir. What has been pumped and/or generated additionally by the turbine in the *i*-th interval is the quantity that is available at the beginning of the next interval (*i*+1). The initial level is known in the optimization scheme, as it is the final level of the previous day. The optimal final level of the current day is however unknown and depends on the optimal mode of operation of the system [Equs.(5) and (6)]. In order to determine this storage level, the simulation horizon is extended to 48 hours, even though only the first 24 hours are used. The output of the wind-hydro power facility has to remain within the maximum feasible output range [Equ. (7)]. Parameter *b* must not be larger than the capacity of the wind park, which is stipulated in Equ. (8). Equations (9) to (12) define the operational ranges of the wind park, the turbine, the pump and the energy storage. As can be seen from Equ. (10), the efficiency of the turbine depends on the technical design or the energy available in the reservoir. Equation (13) ascertains the standardization of the multi-target system. The starting values chosen were $c_s = c_p = c_{Pp} = 0.333$, thus an equal weighting of all target criteria. The optimization problem (1) – (14) has been solved with linear programming by the simplex algorithm.

Table 1: Parameters of the pumped hydro storage facility used in this study. Efficiencies have been estimated.

t [h]	Ph^U [MW]	Pp^U [MW]	Ph^L Pp^L [MW]	E^U [MWh]	E_1^{esp} E_{n+1}^{esp} [MWh]	η_h [-]	η_p [-]
1	1076	1028	0	8224	4000	0.9	0.9

Figure 2: Wind power forecast from 07 January to 13 January 2005 and from 11 July to 17 July 2005 for the balance region of RWE.



Data

The German balancing market is divided into four zones operated by E.ON Netz, RWE Transportnetz Strom, Vattenfall Europe Transmission and EnBW Transportnetze. In the present study we used the RWE zone, where as of 2006, due to the EEG, 37.3 % of the total wind power in Germany have to be balanced. Hourly wind power forecasts for the time period from 03 January 2005 to 21 July 2005 were generated by WEPROG (Weather & wind Energy PROGnoses) with their operational multi-scheme ensemble prediction system (MSEPS[14]). The forecast horizon chosen was 24 h to 48 h ahead, starting at 00:00 hours on the previous day. To verify the algorithm, synthetic measurements of wind power that resemble actual measurements in a statistical sense have been generated, based on short term predictions. This procedure is equivalent to the common field verification practice used in meteorology. WEPROG's multi-scheme ensemble prediction system (MSEPS) is a limited area ensemble prediction system that generates 75 different numerical weather predictions, based on different parameterization schemes of physical and dynamical schemes within the numerical core model. The MSEPS is coupled with a wind power prediction module (WPPM). This WPPM differs from traditional power prediction tools since it is designed to provide an objective uncertainty of the power forecast due to the weather uncertainty. The results from individual ensemble members are integrated with a probabilistic multi-trend filter.[15]

We used the pumped hydro storage facility "Goldisthal" in Thuringia, Germany, as reference pumped hydro storage facility, which is operated by Vattenfall Europe. The characteristic technical values of the pumped hydro storage facility are given in Table 1.[16]

Application of the optimization scheme

Analysis of system behavior

Two representative time periods have been selected, for which the analysis was performed. The first time period during winter (7 – 13 January

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[14] See Möhrlen/Jørgensen (2006).

[15] See Möhrlen/Jørgensen/Pahlow/Entekhabi (2007).

[16] See Vattenfall Europe (2003).

Figure 3: System behavior for the January-week.
Upper plot: Wind power output and system output power.
Lower plot: Power used by the pump and produced by the generator as well as the energy (water) level in the reservoir.

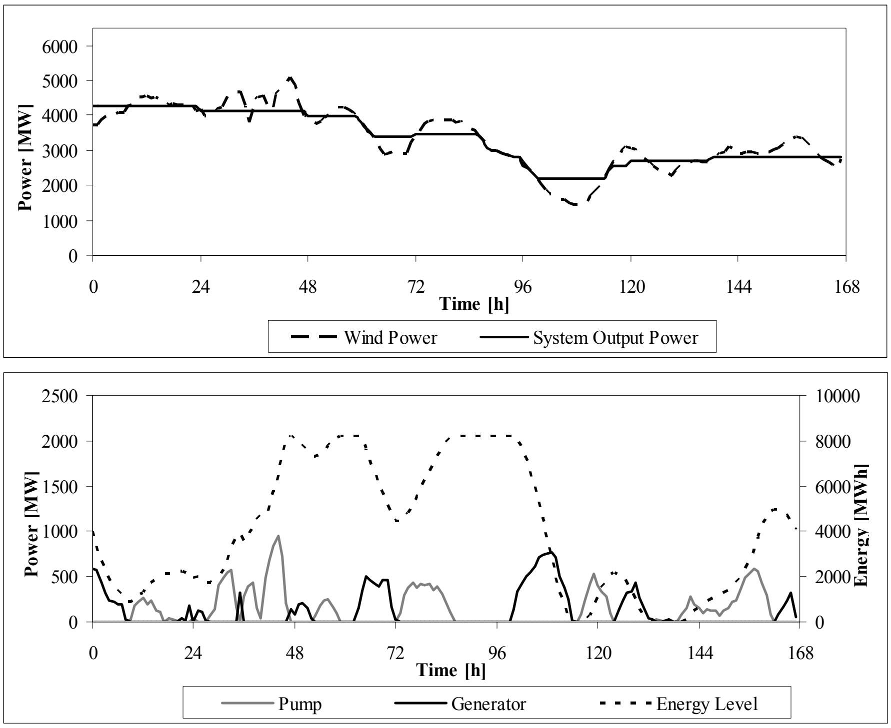
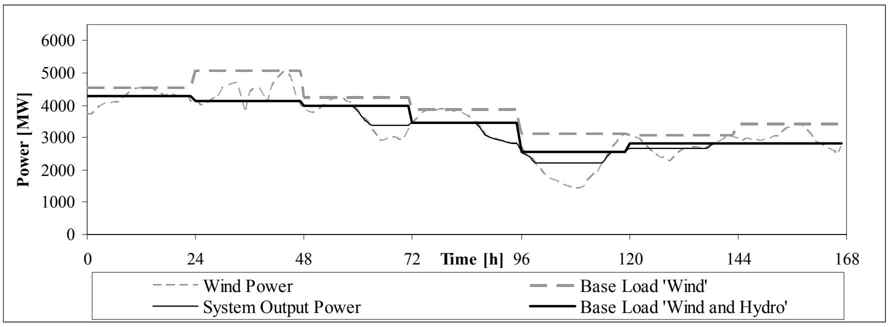


Figure 4: Base load for “wind” and “wind and hydro” for the January-week. Also shown are the wind power and system output power.



2005) had high wind speeds, whereas the second time period during summer (11 – 17 July 2005) had low wind speeds, which is common for this region (see Figure 2). The winter and summer time periods differ in both the maximum and the range of wind power. However, it will become clear later on, that not the level, but solely the range of output power is crucial for the system behavior. The span of generated output during the winter week is 1429 MW (23.0 %) to 5070 MW (81.7 %), i.e. a range of 58.7 % of the total output of 6203 MW of the TSO RWE (based on the total installed capacity in Germany of 16629 MW by the end of 2004). In the selected summer week the power generation rises maximally to 1047 MW, i.e. 16.4% of the July maximum of 6390 MW; the smallest output was 8 MW (0.001%) thus spanning a range of 16.4 % (based on the total installed capacity in Germany of 17132 MW by the end of June 2005).

Winter-week

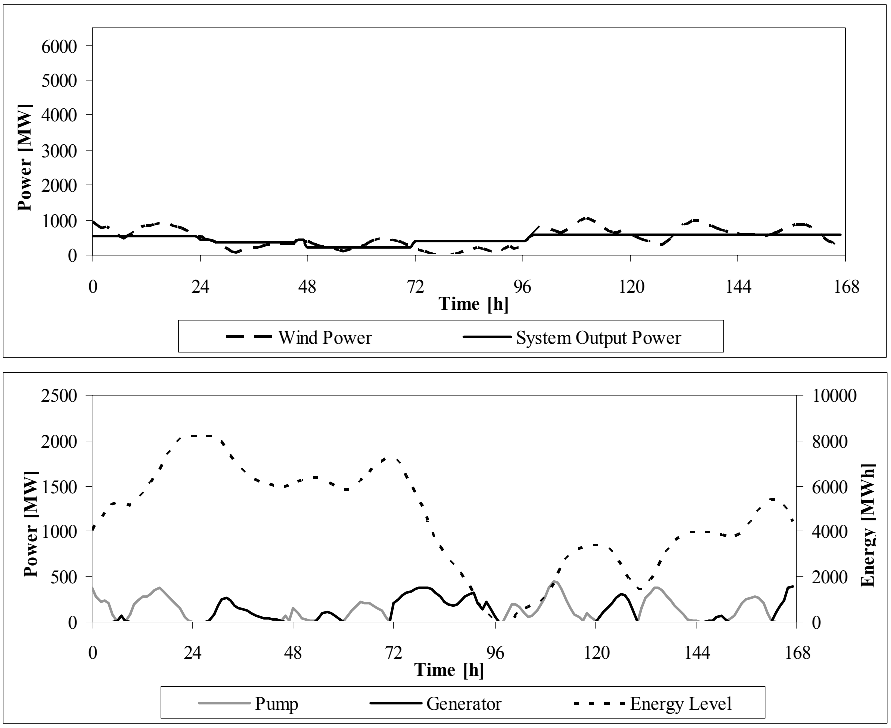
Figure 3 shows the simulation results for the first time period (January-week). The well balanced and smooth power delivery of the coupled wind and hydro system, when compared with wind power usage only, can clearly be seen. The absolute fluctuation (variation) is reduced to 33.7 % of the total power, a reduction of 42.6 %. Furthermore, on simulation days 1, 2, 6 and 7 nearly constant power delivery is provided, hence the desired constant power delivery is nearly reached. However, it should be noticed, that the delivered power follows the actual wind power closely during the transition from day 4 to day 5. This is due to the rapid decline of wind power from 4000 MW to 1500 MW within 24 hours. Such an enormous drop in power can not be compensated by the storage system due to insufficient storage capacity. Hence the storage height remains at the highest level. The optimization model rather seeks to counterbalance the next power decline on day 5. This illustrates, that the limiting factor in this case is the optimization target that tries to keep the production constant and reaches a limit, where the hydro facility does not have enough capacity. Alternatively, the algorithm could be set to reduce the production before reaching the limit or to increase the storage capacity to a larger storage reservoir. Hence, the maximum storage capacity and/or the amount of power that should be delivered relatively constant are the limits of the wind and hydro power system. A different behavior can be observed on day 2, with several short power peaks, which can not be compensated by the system due to the storage level. Given the expected power decline at the end of day 3, it is therefore necessary to limit the power delivery during peak periods and to fill the storage reservoir using the available energy to pump the water into the reservoir. Otherwise the power level would drop further at the end of day 3, which in turn results in sub-optimal system performance. A common observed feature during the transition from one day to the next is a step-wise decline or increase of the level of power delivery. This can be explained by considering that a specific optimization model structure with 48 hour-intervals is used, i.e. the evolution of the second day is generated by simulating day 2 and 3, which enables the system to consider the decline in power level at the end of day 3 to lower the power delivery accordingly in advance. Otherwise the power level would drop more drastically between the second and the third day. This foresighted aspect of the optimization is an advantage of the approach used here. Moreover, the adaptation of the optimization algorithm over time will further improve with a longer forecast horizon.

Next a reference base load was used to compare the two options “wind only” and “combined wind and hydro”. Note that this base load must be balanced. In the present example the maximum power delivery within a particular day is anticipated for the base load. Hence, no renewable energy remains unused, in compliance with the German Renewable Energy Sources Act. Figure 4 shows the base load for the two scenarios “wind” and “wind and hydro” for the January week. The hourly fluctuations are clearly reduced through optimized coupling of wind and hydro power. Thereby, the need for additional balancing power (reserve capacity), which otherwise has to be purchased from other sources, can be decreased by 78.0 %, i.e. by 889 MW per day. The reduction in base load for the “wind and hydro” scenario is 12.1 % when compared with the “wind” scenario. Table 2 summarizes the results for both scenarios. Note that for the “wind” scenario expensive balancing reserve is frequently necessary in order to reach the daily base load and to balance the forecasting error. On the other hand, “wind and hydro” has less time periods where balancing is necessary. It may even be considered whether additional reserve is necessary, since the fluctuations are controllable and therefore no grid issues may arise.

Table 2: Balancing requirements (reserve) to reach base load for the two scenarios „wind“ and „wind and hydro“ for the January-week.

	WIND		WIND and HYDRO			
day	**base load** [MW]	**reserve** [MW]	**base load** [MW]	Δ [%]	**reserve** [MW]	Δ [%]
1	4556	850	4290	-5.8	0	-100
2	5070	1279	4114	-18.9	0	-100
3	4242	1360	3984	-6.1	598	-56.0
4	3885	1060	3453	-11.1	628	-40.8
5	3101	1672	2570	-17.1	396	-76.3
6	3090	832	2814	-8.9	129	-84.5
7	3406	920	2814	-17.4	0	-100
Ø	**3907**	**1139**	**3434**	**-12.1**	**250**	**-78.0**
% of total power	**63.0**	**18.4**	**55.4**		**4.0**	

Figure 5: System behavior for the July-week.
Upper plot: Wind power output and system output power.
Lower plot: Power used by the pump and produced by the generator as well as the energy (water) level in the reservoir.



Summer-week

In Figure 5 the simulation results for the July-week are shown. The delivered total output of the coupled wind and hydro system has a more consistent character when compared with the winter-week due to lower wind power penetration. In this case the wind-hydro system can almost always produce a base load without reserve capacity. Compared with the “wind” scenario, the range and deviation are reduced by 65.0 % and 51.3 %, respectively. The maximum reservoir level is reached only once at the beginning of the second day. The model is able to foresee the low level trend for the third day and hence the water in the reservoir is not being released completely, despite reduced output. A complete reservoir release is not adequate at the beginning of the third day where the output power continues to drop nearly to zero. The reason for this is that at the beginning of day 4 a power output increase is expected for day 5.

Therefore, it becomes beneficial to then release the total stored energy, firstly because a smooth transition between day 4 and day 5 should be achieved and secondly because a rise in reservoir level is expected thereafter.

Pumps and generators are only used up to 40 % of their capacity, which shows that these would be clearly over-dimensioned, if the weather conditions were not to change.

The comparison of the two scenarios „wind“and „wind and hydro “ is shown in Figure 6. The additional maximum balance requirement, which must be acquired from other power stations, can be lowered by the system coupling of wind and hydro power in relation to the exclusive use of the wind energy in the July-week by 91.9 % (467 MW on average). The reduction in base load for the “wind and hydro” scenario is 33.1 % when compared with the “wind” scenario. Table 3 summarizes the comparison of the two scenarios for the summer week.

Sensitivity analysis

In this section two aspects of the coupled wind-hydro optimization model are examined. It is of interest to what extent the capacities of pump and turbine, as well as the maximum reservoir level, affect the simulation results. In particular, the upper limit of the reservoir level has been found to be a limiting factor for reaching the goal of constant power output of the wind and hydro system. Therefore it is useful to test the model with unrestricted storage capacity in order to determine the optimum system performance. As a second measure the weighting factors of the three target criteria (constant power output, level of power output and pump capacity) are varied, so that the effects of the different parameter constellations can be evaluated in terms of the model behavior.

Figure 6: Base load for „wind“ and „wind and hydro“ for the July-week. Also shown are the wind power and system power output.

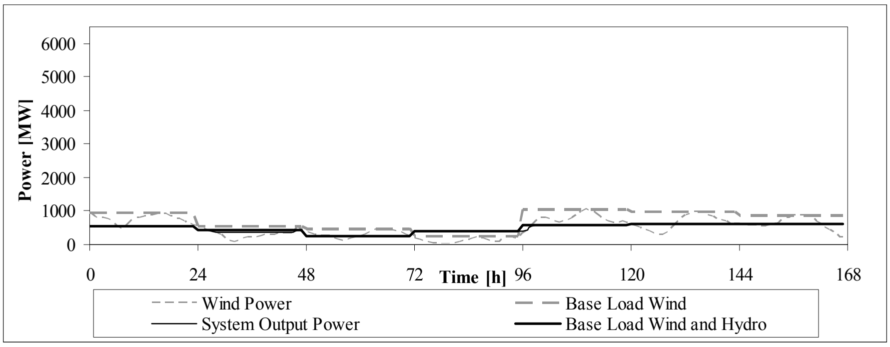


Table 3: Balancing requirements (reserve) to reach base load for the two scenarios „wind“ and „wind and hydro“ for the July-week.

	WIND		WIND and HYDRO			
day	**base load** [MW]	**reserve** [MW]	**base load** [MW]	Δ [%]	**reserve** [MW]	Δ [%]
1	938	454	555	-40.8	0	-100
2	532	446	431	-19.0	76	-83.0
3	458	333	237	-48.3	0	-100
4	251	243	385	53.4	0	-100
5	1047	714	599	-42.8	214	-70.0
6	983	682	601	-38.9	0	-100
7	886	681	601	-32.2	0	-100
Ø	**728**	**508**	**487**	**-33.1**	**41**	**-91.9**
% of total power	**11.4**	**7.9**	**7.6**		**0.6**	

Figure 7: System behavior for unlimited storage, pump and turbine power during the January-week.

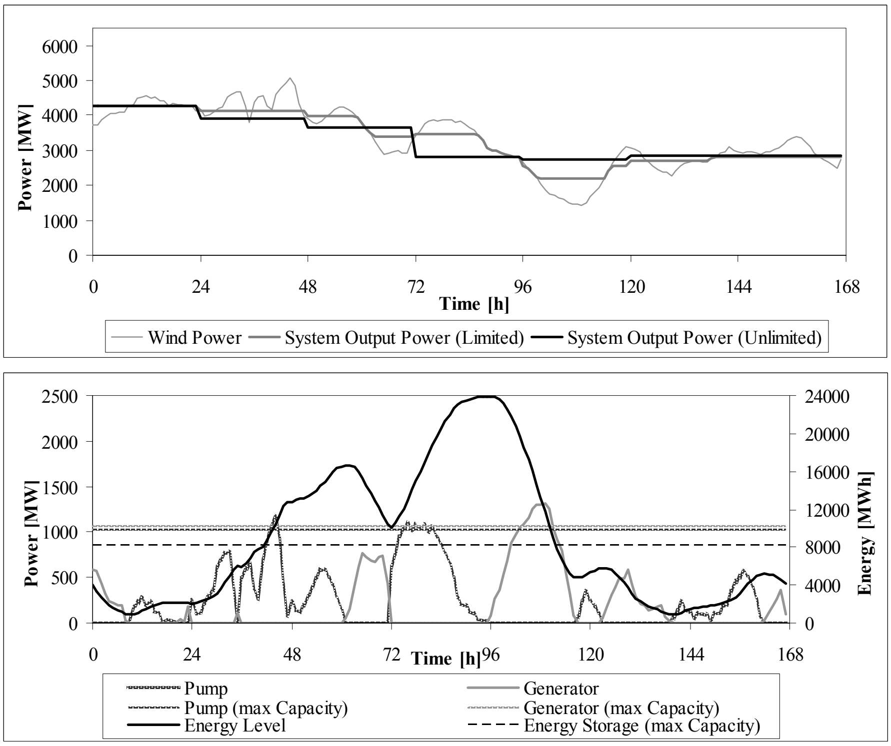


Table 4: Reserve requirements to reach base load for limited conditions („Initial Conditions“) and conditions without limitations („Unlimited Conditions“) for the January-week.

	INITIAL CONDITIONS		UNLIMITED CONDITIONS			
day	**base load** [MW]	**reserve** [MW]	**base load** [MW]	Δ [%]	**reserve** [MW]	Δ [%]
1	4290	0	4290	0	0	0
2	4114	0	3903	-5.1	0	0
3	3984	598	3655	-8.3	0	-100
4	3453	628	2799	-18.9	0	-100
5	2570	396	2747	6.9	0	-100
6	2814	129	2849	1.2	0	-100
7	2814	0	2849	1.2	0	0
Ø	**3434**	**250**	**3299**	**-3.9**	**0**	**-100**
% of total power	**55.4**	**4.0**	**53.2**		**0**	

Figure 8: System behavior for unlimited storage, pump and turbine power during the July-week.

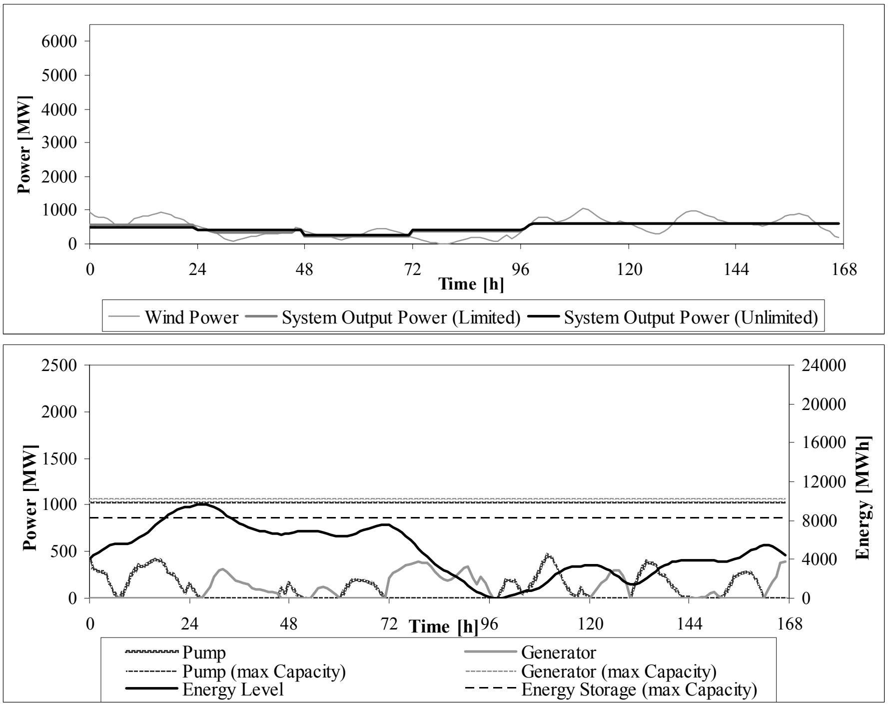


Table 5: Reserve requirements to reach base load for limited conditions („Initial Conditions“) and conditions without limitations („Unlimited Conditions“) for the July-week.

	INITIAL CONDITIONS		UNLIMITED CONDITIONS			
Day	**Base Load** [MW]	**Reserve** [MW]	**Base Load** [MW]	Δ [%]	**Reserve** [MW]	Δ [%]
1	555	0	500	-9.9	0	0
2	431	76	397	-7.9	0	-100
3	237	0	250	5.5	0	0
4	385	0	397	3.1	0	0
5	599	214	599	0	214	0
6	601	0	601	0	0	0
7	601	0	601	0	0	0
Ø	**487**	**41**	**478**	**-1.9**	**31**	**-24.4**
% of total power	**7.6**	**0.6**	**7.5**		**0.5**	

Unlimited storage, pump and turbine capacity

In Figure 7 the simulation results for the case of unlimited reservoir storage and in addition unlimited pump and turbine capacity are shown for the January-week. The coupled wind and hydro system allows for base load on every day. However, it becomes also clear, that this in turn requires substantial excess storage capacity.

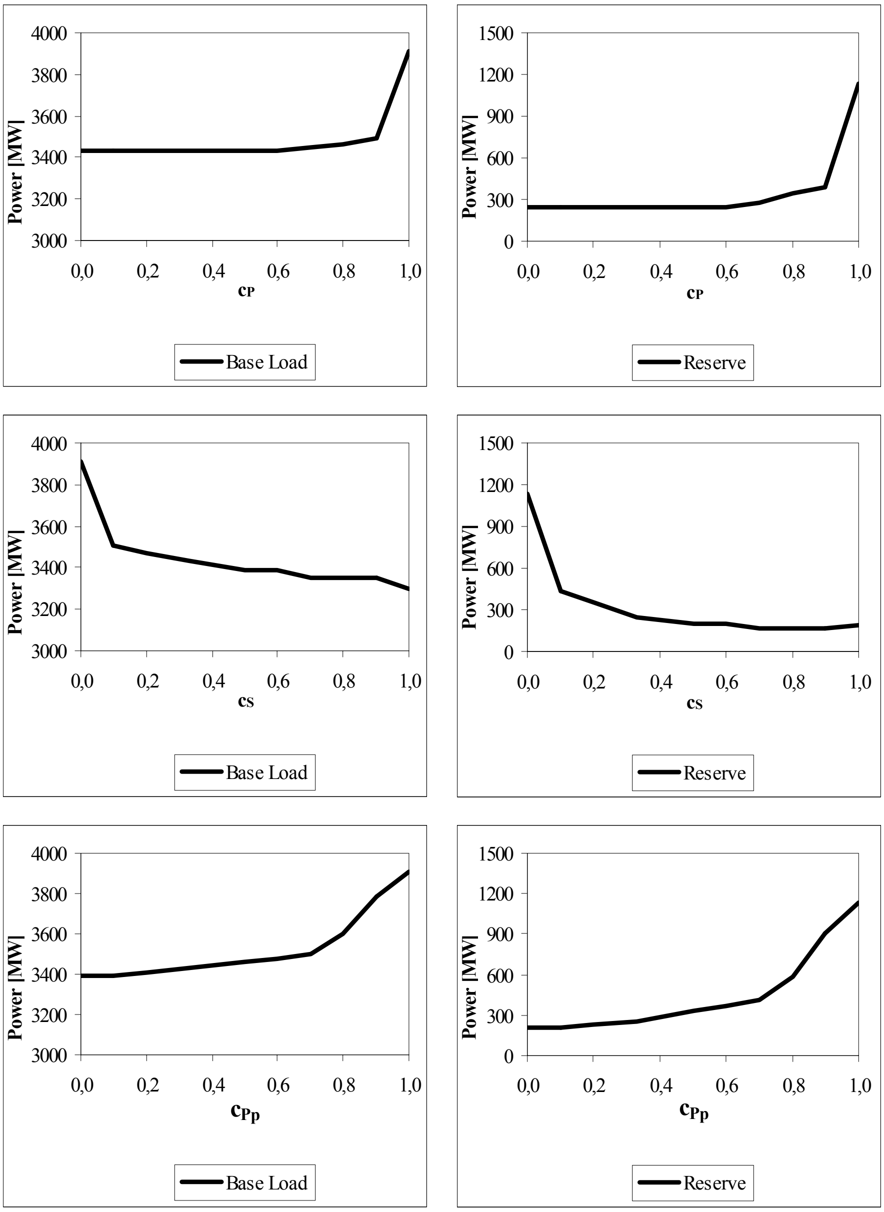
The initial maximum reservoir storage of 8224 MWh is almost tripled to 23931 MWh (note the different energy scale when compared to Figures 3 and 5). Furthermore, storage in excess of the initial 8224 MWh lasts for 69 time steps or about three days. This would mean that three pumped hydro storage facilities, such as the one considered here, were necessary. From Figure 7 it can also be seen that the pumps and turbines are only briefly used beyond their capacity, i.e. these do not impose a strong limiting factor. With one single pumped hydro storage facility such as the one outlined in Table 1, the purchase of 78 % reserve capacity can be avoided (see Table 2). Adding two such additional facilities to the coupled wind and hydro power system is by no means justifiable and neither ecologically nor economically sound. Table 4 has a summary of this comparison.

For unlimited reservoir storage, pump and turbine capacity during the July-week, hardly any changes in system behavior can be observed compared to the case with limited capacity (see Figure 8). This could be expected, since base load has nearly been reached before with system limitations (see Figure 5). The results are summarized in Table 5. Since the reduction of the balance requirements remains very small, additional pumped storage would therefore be uneconomical. Pumps and turbines remain clearly over-dimensioned.

Variation of the target weight factors

Earlier it has been justified why it is difficult to set concrete cost factors for

Figure 9: Sensitivity of base load and the maximum reserve on variation of target weighting factors c_P, c_S and c_{Pp} for the January-week (upper plots: c_P, middle plots: c_S, lower plots c_{Pp}).



the three target function criteria. Therefore, the parameters were not restricted for the simulations. It is however interesting to investigate to what extent the system performance is affected by different parameter constellations. Next, one of the weighting factors at a time was varied. Regardless, the condition $c_s + c_p + c_{Pp} = 1$ must hold. The results are shown only for the January−week, since the results from the July period reflect the same tendencies. During the variations, the sensitivity was analyzed with respect to daily power output and reserve. The optimization results are summarized in Figure 9. To recall, the factor c_P describes the adequate consideration of the absolute level of the power to the grid P_i and P_i is to be maximized. The output power of the system approaches the "wind"-scenario level (base load 3907 MW and reserve power 1139 MW) for large values of c_P, since P_i and base load are maximized (Figure 9, upper plots). This in turn results in a strong increase of reserve capacity. It may seem inadequate that this behavior occurs for large c_P only, whereas the power does not decrease even for small c_P. Note that the pump power P_{Pi} is considerably smaller than the total delivered power to the grid P_i, whereas $n(b\text{-}a) = P_S$ [see Equ. (1)] is similar to P_i. Hence, c_S and c_{Pp} become large for small c_P due to $c_s+c_p+c_{Pp}=1$. The system behavior is not altered due to similar order of magnitude of P_i and P_S. The parameter Pp_i can be neglected when compared to P_S. Therefore P_i can be assigned a small weight, as long as P_S has a large weight. For small weight on P_S one would have to choose c_{Pp} large, which is not advantageous, as can clearly be seen in Figure 9. Variation of c_S (Figure 9, middle plots) shows the opposite behavior to variation of c_P, since P_S is to be minimized [see Equ. (1)]. Base loads and reserves are on average smaller for large values of c_S, since the criterion to maximize P_i is softened in favor of P_S, i.e. to provide constant output. Lastly the variation of the pump-coefficient c_{Pp} is shown in Figure 9 (lower plots). This term has less influence on overall system behavior and therefore a variation of c_{Pp} induces system changes mainly by simultaneous decrease in the other two weighting factors. For large c_{Pp} it can be seen that less pumping occurs. This is explained by the fact that pumping becomes increasingly expensive. Usage of pumps becomes less, due to the condition that Pp_i is to be minimized. For $c_{Pp} = 1$ pumping ceases and the system would be driven by wind only. Our results suggest that it is beneficial to put strong weight on the criterion to deliver constant output (P_S) and to have less weight on absolute output power. Pumping is of less importance and can be assigned a smaller weight. Castronuovo and Peças Lopes (2004a) used $c_{Pp} = 1.5$ €/MW, $c_S = 500.0$ €/MW and $c_P = 103.8$ €/MW (peak hours) and 54.0 €/MW (off peak hours), considering Portuguese remuneration, which is confirmed by the tendencies found here.

Discussion

The diurnal cycle of the demand and the wind power generation tends to correlate with highest generation and demand during daytime and lowest generation and demand at night time. This is the typical pattern for most of the wind power installed in continental regions, whereas the offshore wind power has comparably little variation between day and night generation patterns. The correlation between demand and wind power generation is however not perfect. The diurnal cycle of the demand is to a first order approximation governed "by the clock" with some weather dependency and some weak day dependency. The wind generation would also be clock-driven, if the cloud cover would be the same every day. Under normal conditions, there exists therefore a varying phase difference between the demand and the wind power generation. This difference tends to cause a sudden need for regulation at least twice per day. Hydro power is most suitable to handle this difference, due to fast response times.

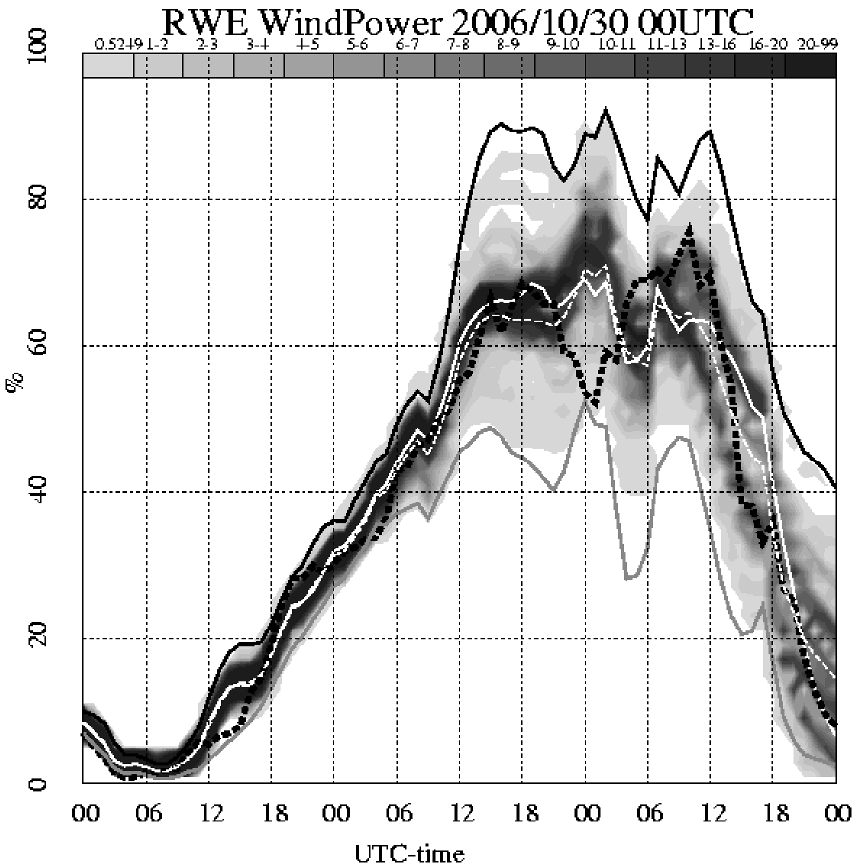
This study was carried out before publication of measurements was enforced by law and the estimated measurements of the wind power generation were not accurate enough to describe the details in the diurnal cycle. It was therefore decided to ignore the diurnal cycle and rather aim at a constant generation instead of the differences between demand and wind power generation, which would be the target to strive for.

Hydro power was used in this study to balance low frequency noise, which would result in a less profitable usage of the hydro power compared to supplying regulation on the minute time scale. The highest profit is gained on balancing the high frequency variations typically generated by large wind farms located in regions with high levels of wind such as offshore wind farms. Such wind farms generate a variable power on the minute time scale at wind speeds on the order of 6 - 12 ms^{-1}, where planetary boundary layer eddies may cause such variation on time scales shorter than 15 minutes. A hydro plant has probably the lowest marginal costs to balance such variability in the generation of wind power and is certainly also preferable from an environmental perspective in comparison to thermal power plants.

This paper has focused on hydro energy, but other storage systems such as pumped air and battery solutions would be applicable with the same approach and will in the future add to the current storage capacity, which is hydro-dominated at present. The idea can also be extrapolated to a combined heat and power (CHP) plant, but discharging of the storage device would then have to take place via local heat consumption. This approach may have a wider application because CHP is geographically correlated with the consumption. The inertia level of CHP is higher than that of hydro energy, but the combined effort of the two sources would add extra balancing capacity, giving the possibility to split the balancing into low and high frequencies. This combined pool can provide more optimized resources for the balancing requirements of intermittent energy sources.

Strictly speaking, there is no particular need to keep a constant generation

Figure 10: Example of a wind power forecast (percent of installed capacity in the RWE balancing zone), generated with WEPROG's MSEPS.
The upper (maximum) and lower (minimum) solid lines represent the range of the forecast. The shaded area indicates the probability of the forecast, with dark shading corresponding to the highest probability. The dashed and solid white lines are two different statistical "best guess" forecasts. The thick black dashed line is the measurement.



from the pool, because the TSO will use the market to achieve enough energy from non-intermittent sources to reach the demand. The goal is rather to create pools of renewable energy, which are able to keep the balance costs lower than what wind power can achieve alone. The optimization targets for this type of operation are however different and more complex than those used here in this study. The actual competition and pricing on the market must then also be accounted for.

The total available electricity generation capacity is effectively higher for strong wind events and the prices of energy are consequently lower during such periods. This means that many generating units will be passive and flexible units therefore have an incentive to participate in balancing pools instead of risking to remain standby without a contract.

There is a need for ensemble predictions to quantify the regulation requirements for wind power under such conditions. One of the benefits from using an ensemble of weather forecasts for this purpose is that this approach gives the possibility to optimize the reservoir usage. The most likely wind power forecast is often skewed relative to the mean of the prediction measured from the maximum and minimum. The optimization should therefore focus on scheduling the power in such a way that the reservoir is kept at a level to be able to capture the predicted uncertainty at all times. This means that there should at all times be enough water to down-regulate or be enough space in the reservoir to up-regulate. The ensemble can also predict the required fraction of the reservoir capacity for wind power. The remaining capacity can then be made available on the market.

An example of the predicted uncertainty is given in Figure 10 of a wind power forecast, generated with WEPROG's MSEPS. The black dashed line represents the measurement and the upper (maximum) and lower (minimum) solid lines indicate the boundaries of the ensemble. The darkest shaded area is the most likely forecast. The obvious selection algorithm for the wind power forecast is to use a maximum probability constraint. This provides a smooth variation in time as shown in Figure 10, but the measurement curve shows spikes above and below the region of maximum probability. These spikes should then be balanced by pumping water into and releasing water from the hydro reservoir. In this way a single reservoir can balance a substantial amount of wind power.

Summary and outlook

The power output of wind farms depends considerably on the natural fluctuations and variability of the wind. To balance power fluctuations, which affect grid stability, direct coupling of wind and pumped hydro storage in a „first-order energy pool" for power production was examined. It has been shown that balancing reserve power with conventional thermal power stations, whose usage as balancing power diminishes the positive effects of wind energy due to fuel consumption and emissions, can be reduced substantially. System performance of the "first-order energy pool" was analyzed for two representative periods (high wind load in the winter, low wind load in the summer). It was shown that by coupling wind with pumped hydro storage the range of power output fluctuations decreased by 42.6 % (high wind load) and by 65.0 % (low wind load). More importantly, the power output can be delivered rather constant to the grid. In addition, the reserve capacity from other power stations, which would have to be purchased daily, is reduced by 78.0 % (high wind load) and 91.9 % (low wind load). Further reductions may be achieved by a larger reservoir storage volume. However, it was shown that further expansion of the system leads to comparably small improvements and in addition, the pumps and turbines were not yet used to their full capacity in the present study. These promising results support further improved optimization with longer forecasting horizons and other renewables in the energy pool.

It was found that the base load for the wind-hydro system is less than for wind alone. This is due to the definition of base load, which is adjusted to the maximum power output of a particular day in order not to leave renewable energy unused, as stipulated by the EEG. However, to achieve the optimized output power of the coupled system with wind alone, for the July-week an average daily reserve capacity of 915 MW is necessary, partly positive (424 MW) and partly negative (491 MW). The latter would be unused renewable energy. Hence, the required reserve, as in this example of 915 MW, should be balanced with the optimization of the coupled wind-hydro system to avoid negative effects due to surplus and deficits.

Coupling of renewables into energy pools, as shown here by coupling wind and hydro power, could help to establish a new understanding of the balance requirements, generated by wind power, and to support trading of available renewable energy capacities instead of reserve capacity from fossil fuels. In this way, several smaller power plants could complement each other, which would support the structure of a decentralized utility system. One relevant study in the context of structural changes was published by Krämer[17]. This study aimed to optimize the costs for electricity generation in Germany under the assumption of high penetration of wind power (about 44 GW in 2020, amounting to approximately a quarter of the total electricity supply) and to give priority to wind power under the German Renewable Energy Sources Act. This study suggests that there exist possibilities that high penetration of wind power under cost optimized aspects and with the objective to reduce CO_2 emissions by 40 % by 2020 could increase the replacement of base load power plants such as brown coal plants through a more flexible system

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[17] See Krämer (2003).

based on wind and gas. However, this approach would certainly require substantial changes in the energy systems and requires a change in paradigm; whether or not this change in paradigm is practical requires certainly further long-term studies. Nevertheless, in many countries a significant number of conventional (fossil and nuclear fueled) power plants are to be replaced because of their age, thus opening the general opportunity for such a paradigm shift.[18] Coupling renewables into a hybrid system or "energy pool", as shown here with the wind and hydro power coupling example to smooth and at the same time increase deliverable power output, may aid in further increasing wind power penetration and thereby economic profit by reducing grid issues due to the fluctuating nature of wind power. This approach may prove beneficial in terms of competitiveness in a liberalized energy market without financial incentives, in addition to reducing CO_2 emissions.

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[18] See IEA (2005).