

SUSTAINABLE ELECTRICAL ENERGY SUPPLY WITH WIND, BIOMASS AND PUMPED HYDRO STORAGE – A REALISTIC LONG-TERM STRATEGY OR UTOPIA?

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Abstract: Sustainability of the future energy supply based on renewable resources is a long-term strategic objective [1] in view of limited fossil resources and the avoidance of emissions and toxic waste. Of the various resources, available now or in future, wind is presently considered in Europe to hold most promise for contributing in the next few decades a sizeable part of the electrical energy; generating electricity from wind is state of the art and feeding large amounts of wind power to the electrical grid is believed by many to pose no problems.

Evaluating recent data from one of the four control areas in Germany it is discussed how a sustainable electrical energy supply based on off-shore wind power and pumped storage, called a "wind and water"-model, might look. It turns out that such an energy scheme, while being feasible in principle, would require an immense storage capacity that is impossible to realise, hence thermal generation continues to be needed; the addition of biomass as a regenerative source is not substantially changing the picture.

Keywords : Sustainable energy supply, Fluctuating wind power, Control power, Pumped Storage, Biomass.

Introduction

The acquisition of wind energy is politically encouraged by strong financial incentives in different European countries, where about 24 GW of generating capacity are presently installed, among them 13 GW in Germany alone; assuming an average of 1 500 full-load-hours per annum, this corresponds to 20 TWh/a or about 4 % of generation in Germany, comparable to the electricity produced from hydro sources.

With favourable wind sites in the coastal regions becoming scarce and the rise of public opposition to additional wind farms in the neighbourhood, the interest is now turning to the sea, where the wind is stronger and blowing steadier, and where the off-shore wind farms would be out of sight. Early installations have been built in Denmark and Sweden, close to the shore and in shallow waters of about 10 m depth; off-shore wind projects are also discussed in USA.

Due to the regulations in international waters, dense shipping lines and protected Natural Reserves the German off-shore wind farms would have to be sited more distant from the coast; water depths to 40 m are being considered and building generating equipment on pontoons is also discussed. Large windmills up to 4.5 MW are under development and are being tested on-shore [2, 3]. Should it be technically feasible to install such large equipment at high sea and maintain it through many years at tolerable cost, this could indeed turn into an inexhaustible source of natural energy, offering little cause for ecological controversy. There are hopes that, given adequate public support, 35 GW

off-shore wind farm capacity might be built in the North and Baltic Seas in the coming 20 to 30 years.

Control energy

However, after various legal barriers are overcome and the protected National Shoal zone is crossed with AC- or DC-cables, only part of the problem has been solved when the power is finally coming onshore, because it must now be transmitted with the existing grid and new high voltage lines to the industrial and commercial centres. Since wind power and grid load are not correlated in time, this requires large amounts of balancing power for frequency control and stabilisation [4, 5]:

Supplementary or **positive control power** (which may be thermally generated) is required during periods of low wind. As seen during last summer's heat wave, the calm could last days and weeks; if it extends over the whole control area, the available generating capacity must cover the full grid load. On the other hand, **negative control power** is needed during periods of high wind when the grid cannot absorb the excessive power and energy should be stored and preserved for later intervals with insufficient wind. This is possible with pumped hydro or with compressed air energy storage, CAES, plants [14,15,16]. **Energy storage is a precondition of any sustainable energy policy.**

Some recent records from a large German control area during a week are shown in Figures 1. The wind power collected with priority and at a subsidised rate by thousands of (presently on-shore) turbines depends on

existing meteorological and atmospheric conditions and clearly follows a pattern that is entirely different than the grid load resulting from the economic activities and living habits of millions of consumers in the control area. Altering the load would call for demand-side-management but the easily deferred domestic power consumption (washing, cooking, cooling etc) is only a small part of the total load, while the larger industrial consumption is subject to cost optimisation; deferring is often not possible at all, for instance with linked factory production or railway schedules. During the Californian energy crisis, the Independent System Operator had to resort to unselective "rotating blackouts" to preclude general breakdowns during periods of insufficient supply [6].

The mismatch of wind power and grid load will not improve when extending the acquisition to the sea, as the wind power is already averaged over thousands of distant sites in a large area.

In grids with a sizeable content of hydro generation such as in Norway (99%), hydro plants with storage reservoirs (without or with pumping) could provide the necessary control power, but not in Germany with its minimal hydro generation, where the control power comes mainly from thermal (fossil and nuclear) stations. The efficiency of a fossil plant is reduced at part load so that fuel consumption and emissions per MWh are rising and some of the environmental relief by wind energy is lost, while the cost increases [7, 8].

The wind power usually changes with a limited gradient according to regional aerodynamics, but occasionally it may also decay quite rapidly. This happened in March 2002 during a high wind regime, when many rotors reached in short succession their power limits, often set at a wind velocity of 25 m/s, and the equipment was protectively shut down. This led in the control area to a loss of injected wind power of up to 2 500 MW for several hours, changing the power flow in the European grid and affecting neighbouring areas [9]. Such events cannot be ruled out even with the improved prognostic tools presently under development [10].

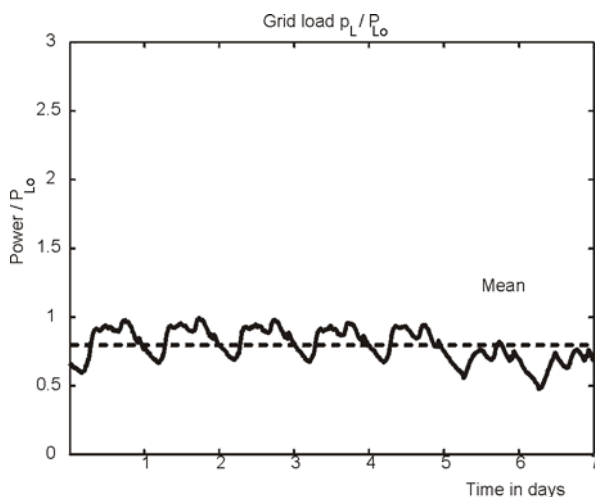


Figure 1a Grid load during the week

When many more GW of uncontrolled off-shore wind power will in future be fed to the electrical grid with its short-term balancing need, large storage facilities on a GWh scale will be required.

Energy storage with pumped hydro plants, "Wind and Water"- model

Pumped hydro power stations employ a long-established method for storing mechanical potential energy by using surplus power for pumping water from a lower level, a reservoir or a river, to a higher level reservoir; when returning the water to the lower level, dispatchable peak- or control- power is generated at an efficiency of up to 80 %. Both modes of operation may be combined in a single hydraulic machine acting as a turbine or a pump. World wide close to 280 pumped hydro storage installations exist with a total power of about 90 GW or ca. 3 % of installed generating capacity, having power ratings up to several GW and storing energy for generating periods of hours to days [11].

Large pumped storage plants in the Alps with hundreds of m head serve for secondary grid control, where short response times of a few minutes are important; other plants are strategically sited in mountainous areas. Recently, after decades of planning and 7 years of construction, a large pumped storage was put in service near Goldisthal in Thuringia (in another control area); for improving the efficiency, two of the four units are operating with adjustable speed.

In principle, a sufficient number of large pumped storage plants could provide dispatchable control power for future off-shore wind farms, but the high voltage grid would have to be enlarged and new lines built for connecting the plants to the shore. Possibly DC links from remote wind farms could be extended with HVDC to the inland hydro power stations. It has been suggested to employ the Scandinavian grid with its large hydro content for storage but this would also call for new long transmission lines, apart from political problems; as the example of Finland shows, the available hydro resources there are insufficient and thermally generated power has to be imported in dry

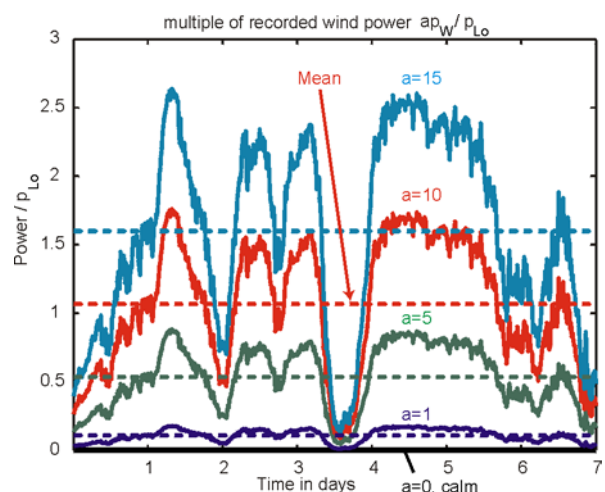


Figure 1b a-fold of recorded wind power scenario

years; another difficulty would be the high cost of subsidised German off-shore power, hindering international trade. Similar problems exist with regard to the proposed creation of a single European control area, trading control power on a larger scale; however, in view of recent black-outs, questions would arise about the wisdom of transmitting additional blocks of non-dispatchable power over ever longer distances.

Pumped storage plants, while employing an existing technology for storing large amounts of energy with acceptable efficiency and converting it to dispatchable control power, require a suitable topography and have a strong environmental impact, not to mention the long construction time and often high cost; they would meet with strong public opposition. Still, as the combination of wind power and pumped storage could in principle be part of a sustainable energy scenario, this "wind and water"-model may serve as an example, using recent data from a large control area in Germany.

Note: As with all prognoses, estimates are needed, where the **wind power** is subject to particularly large statistical changes, extending from occasional storms to totally calm periods. With the **grid load** the situation is less critical, because it may be accurately forecast and major increases are unlikely in a service-orientated society with a diminishing population.

Figure 1a depicts the recorded grid load p_L in the control area during a week in December 2002, having a peak load $P_{L0} = 20$ GW, subsequently used for normalisation, and an energy content of 2.67 TWh. In Figure 1b, the curve marked with the parameter $a = 1$, presents the wind power p_w injected into the same control area during an earlier week with high winds; the recorded peak power was 3.5 GW and the energy 0.36 TWh or about 13 % of the load during the week.

Next it is estimated, by which factor $a > 1$ the wind power would have to be increased, mainly by off-shore production over the next decades, in order to supply today's grid load solely with wind power, assuming a gradual phasing out of existing generating plants.

When comparing the curves in Figures 1a and 1b it appears that enlarging the wind power generation by a factor $a = 10$ to a peak of 35 GW and an energy potential of 3.6 TWh might be adequate; this is in line with projections by the German Environment Ministry (which however includes all the four German control areas); hence $a = 10$ is chosen for the subsequent discussion.

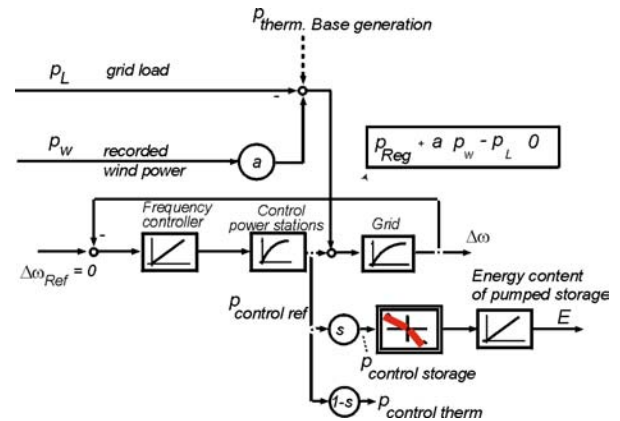
Since the traces of the grid load $p_L(t)$ and the projected wind power $a p_w(t)$ are differing strongly, while the total power fed to the grid must be balanced to maintain the grid frequency, it is assumed that the

necessary control power $p_{\text{control}}(t)$ is produced by pumped storage power plants. (Thermal power is ignored for the time to remain consistent with the sustainable "wind and water"-model). A control scheme is shown in Figure 2, where the varying need for control power $p_{\text{control}}(t)$ is derived from a simulated grid-frequency control loop. In view of the widely differing time scales, considerable simplification of the grid control is possible,

$$p_{\text{control}} + a p_w - p_L \approx 0, \quad \text{resulting in}$$

$$p_{\text{control}} \approx p_L - a p_w.$$

This signal could serve as power reference for all available storage plants.



For $p_{\text{control}} > 0$, supplementary electrical power is

Figure 2 Scheme of grid control with wind power and pumped storage, "wind and water" model

needed for maintaining the grid frequency, when the hydro plants operate in generating mode and the stored energy, corresponding to the water level in the storage reservoirs, is reduced. For $p_{\text{control}} < 0$, pumping is called for and the water levels are rising. Unavoidable power losses may be estimated or could be more accurately accounted for by the non linear function generator in Figure 2, which causes an overall reduction of stored energy during a periodic control power cycle. Figure 3 shows the resulting control power p_{control} for the chosen power scenario, ranging from total calm to a 10-fold increase of today's recorded wind power.

The maximum storage power lies between $p_{\text{control}} = 20$ GW (generating) and $p_{\text{control}} = -21$ GW (pumping); it could be reduced by using the wind rotors for grid control, i.e. throttling them during periods of high wind and cutting down on the pumping operation at the expense of diminishing reserves for later low wind periods.

Finally, the stored energy in the reservoirs during the week is plotted in Figure 4 for the scenarios $a = 0$; 1; 10, ignoring losses and possible power constraints. With $a = 10$, i.e. very large future off-shore generation, an energy surplus would result, but for $a = 1$, corresponding to present wind power generation, and even more for $a = 0$ (no wind at all) and

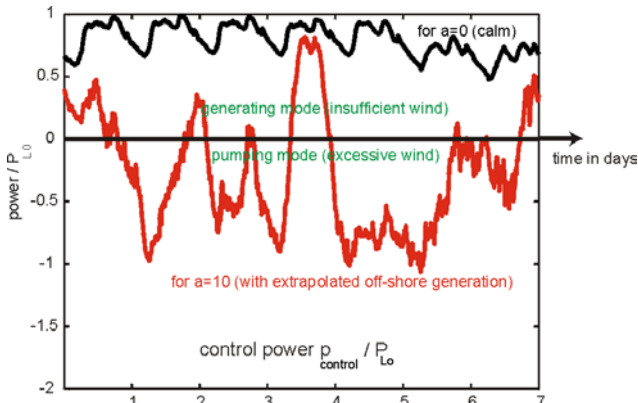


Figure 3 Control power during the week

including power losses, the stored energy would decay by nearly 3 TWh during the week, threatening the reservoirs to run dry and enforcing current rationing.

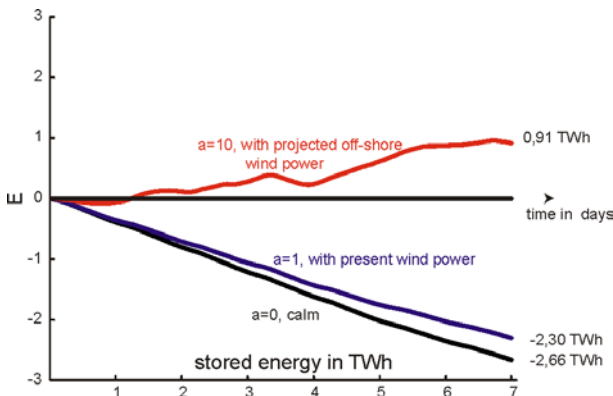


Figure 4 Change of stored energy

This result should be related to the total presently available pumped storage capacity of the control area of only 1.2 GW and 6.5 GWh. For comparison the capacity of the new Goldisthal pumped storage plant is 1.06 GW and 8.5 GWh.

So, implementing the sustainable "wind and water"-model would require, just to be able to maintain supply for one week of calm weather, a 20-fold larger pumped storage power and a 350-fold larger storage capacity than is available in the new Goldisthal plant. This obviously is impossible for topographical reasons and totally out of question, considering environmental effects and cost.

A recent report by the federal agency for renewable energy sources [12] indicates that the total potential of biomass in Germany may be about 220 TWh/a. Since

biomass must be used locally and there are other possible uses, such as the conversion to Biofuel, only a limited amount will be available for producing electricity in the control area discussed. Assuming a 40% share of the total biomass potential for electrical conversion in the control area would allow an additional sustainable base load generation of 10 GW from biomass.

Including this in the power balance of Fig. 2, an extension of wind power by a factor $a = 4$ proves to be adequate but the required pumped storage in the control area would still amount to an 11-fold increase in power and a 115-fold rise in storage capacity of the large new Goldisthal plant. So, one clearly is faced with an unsolvable problem.

Only by abandoning the goal of sustainability and admitting the use of dispatchable resources in coal- or gas-fired plants (including cogeneration) [13] or nuclear energy can the storage problems created by the large wind power indeed be handled.

Another option according in Fig. 2 is to use hydraulic storage for only a part of the needed control power $s p_{\text{control}}$ and assign the rest $(1-s) p_{\text{control}}$, $s < 1$, to gas-fired power stations with compressed air energy storage (CAES), which in contrast to normal gas turbine plants can accommodate both signs of control power; they too consume natural gas, but in reduced quantities [14, 15, 16]. The storage there takes place in large pressurised cavities created by solution mining in underground or undersea salt domes. By mechanically separating the compressor from the combustion turbine, storage is achieved by driving the compressor through an electric converter with fluctuating wind power, while dispatchable generation takes place with the compressed air and the now compressorless turbine. With the example of the 290 MW peaking plant in Huntorf, Germany, successfully operated for over 20 years, CAES plants optimised for balancing fluctuating wind power, are now in the planning phase.

Summary

A future electrical energy supply system based on a "wind and water"-model, where the fluctuations of greatly increased off-shore wind power are balanced by pumped storage hydro stations, appears as a remotely conceivable possibility for a sustainable energy scenario, given today's technology. However, as the extrapolation from recent data of a German control area shows, this would call for a prohibitive enlargement of the existing pumped storage capacity which is not only incompatible with topography but also out of question for ecological and cost reasons, even when including the projected available biomass. Therefore thermal power stations will still be needed in future and the idea of a sustainable electrical energy

supply fed only by wind power and biomass is quite unrealistic.

Assuming that the surely immense potential of uncontrolled off-shore wind power is technically accessible, it would make more sense to use it for the production of secondary fuel, such as hydrogen, that can be stored, transported and distributed [17]; with the



depletion of fossil resources, such fuels will be in world wide demand for fuel-cells in stationary and mobile applications. Developing these enabling technologies in parallel with the primary energy acquisition from off-shore wind power would indeed be a challenging and rewarding long-term strategy, instead of endangering the electrical grid by feeding it with ever rising quantities of fluctuating wind power.



Figure 5 Off-shore wind and pumped storage: Not the road towards a sustainable energy supply

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