Dependable Energy Supply from Fluctuating Natural Sources
- A Case for Energy Storage

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Summary: Sustainability through the use of regenerative sources is a longterm political goal [1], the reasons are finite fossil resources and avoidance of toxic emissions and waste. Of the natural resources, available now or in future **- Water, Sun, Wind, Biomass, Waves, Tidal and Geothermal, Fusion** - wind energy is presently considered in Europe to offer best promise for contributing in the coming decades a substantial portion of the electrical supply; the generation of electricity from wind is state of the art and feeding even large surges of wind power into the supply grid is believed by many to pose no unsolvable problems.

In the paper it is discussed, whether the present environment-oriented policy in Germany of feeding with priority large quantities of subsidized wind and solar power into the electrical grid offers the promise of reducing in the long run the dependance on fossil and nuclear fuels. To achieve a dependable supply from fluctuationg natural sources large scale energy storage facilities would be needed that are presently not available. Generation of storable and transportable secondary energy carriers such as hydrogen for decoupling the fluctuating supply and demand might be a preferable alternative.

Introduction

The power fed to a transmission or distribution grid must match the electrical load determined by the consumers, otherwise the load flow in a meshed grid and the frequency are varying. Power control is achieved by changing the fuel input to the power station generators. With some natural energy sources there is no storage of fuel, instead the electrical power is generated from the instantaneous supply (wind velocity, water run of the river, solar radiation) that depends on seasonal, meteorological or other conditions and is not controllable. Hence the electrical power fluctuates and is not always available; with insufficient supply, the needs of the load cannot be met, while primary energy is wasted when the supply exceeds the grid demand.

To balance these natural fluctuations, energy storage is necessary**.** Besides pumped hydro storage other principles are also in use but are still under development or are unsuitable for high power applications, some could serve for local storage with pulsating loads, such as city street cars, industrial plants or research installations.

Present state of using regenerative sources in Germany

An overview of available natural energy resources and their use may serve as an indication whether they could eventually lead to a sustainable energy supply without fossil and nuclear fuel and if this might be a realistic strategic goal for a national energy policy. **Primary hydro power** in Germany is contributing about 20 TWh/a or 4 % of the total energy of 520 TWh/a fed to the public grid but hydro resources are nearly exhausted and there is little additional potential. It is different with electricity produced from **wind** which, caused by financial incentives, has experienced an enormous rise in recent years. Out of 36 GW wind power generation equipment in Europe, about 17 GW are presently installed in Germany contributing 20 to 25 TWh/a.

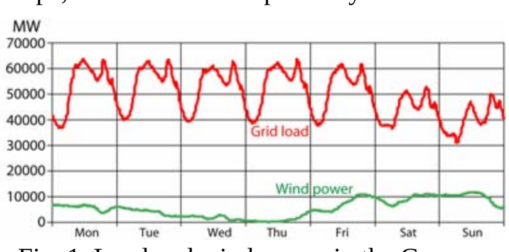


Fig. 1 Load and wind power in the German transmission grid during the week of 15. 3. 2004

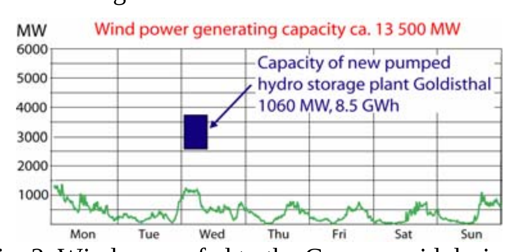


Fig. 2 Wind power fed to the German grid during a calm week of 28. 7. 2003.

Fig. 1 depicts the German grid load with a winter peak of about 80 GW and the wind power infeed during a week in 2003. The power produced by the thousands of windmills depends on meteorological and atmospheric conditions and has an entirely different shape than the electrical load drawn by millions of consumers; while the grid load is accurately predictable from proven load models, wind power is varying statistically and cannot be reliably forecast; it is smoothed by the geographic dispersion of the rotors. During a calm week in the hot summer of 2003, the average wind power amounted to less than 1 GW, supplied by a generating capacity of then 13.5 GW, Fig. 2; clearly, wind power is available when the wind is blowing, not when the power is needed. In stormy weather windmills may have to be shut down for protective reasons [7] resulting in an unexpected loss of possibly several GW, Fig. 3. Hence a dependable supply based on this fluctuating source calls for immense energy storage facilities.

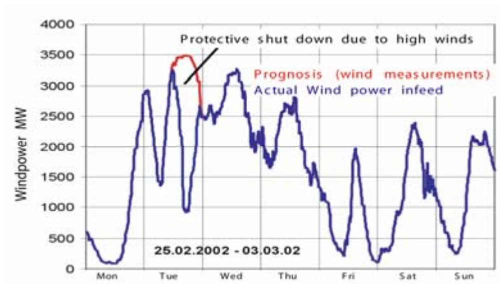


Fig. 3 Loss of 2500 MW by protective shut-down of windfarms in E-On North grid in 2002

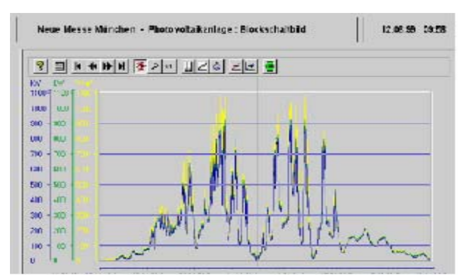
Fig. 4 Enercon 4.5 MW E-112 Prototype variable speed, gearless, individual pitch control, 112 m rotor diameter, IGBT voltage-source-converter, controlled power factor

Since the favourable sites for rotors on the wind-swept coastal plains are becoming scarce and popular opposition to nearby windfarms rises, the interest is now directed towards the sea, where they would be out of sight and the wind is blowing stronger and steadier. First off-shore windfarms were built in Sweden and Denmark, close to shore and in shallower water of about 10 m depth; similar projects exist in the USA.

Due to international coastline regulations and national protected zones, German off-shore windfarms will have to be installed farther from the shore in water depths to 40 m; the use of floating platforms is also discussed**.** Large prototypes of wind rotors up to 5 MW are now being tested on-shore or close to the coast [3, 4], Fig. 4. Indeed, if equipment of this size can be sited on the open sea and reliably maintained over years at acceptable cost, it could promise a substantial contribution to the energy supply, causing less environmental concerns; hopes are that in 20 or 30 years, given adequate public support, up to 30 GW of generating capacity with an energy yield of 85 TWh/a might be constructed in the North and Baltic seas.

Photovoltaic converters, producing electricity directly from solar radiation, are considered by many as an ultimate form of power generation, tapping an inexhaustible energy source, Fig. 5. Of course, in view of the poor conversion efficiency, low solar radiation at a latitude near Newfoundland and the production of solar cells, the costs are high. Still, with lucrative rates of up to 0.5 €/kWh there is a growing market; the PV generating capacity now installed in Germany is 0.35 GW, producing about 0.5 TWh/a. It is at present only a minor portion of the much larger wind power. Because of the dependance on daytime, weather and temporary shadowing by clouds, the electrical power produced varies widely and can exhibit rapid fluctuations so that local energy storage may be desirable.

Fig. 5 Photovoltaic generator Munich 1 MW, 1000 MWh/a



Power delivered at day of eclipse 1999

Producing energy from biomass may be done in a variety of ways, starting with different raw materials (waste wood, energy plants, household and industrial waste, gas from reactors or landfills etc) and the methods of utilization (burning, chemical transformation, fermentation, bacterial decomposition etc). Competing alternatives for energy use exist, such as Bio-Diesel or fuel to be mixed with gasoline; in small co-generation plants heat is produced besides electricity, resulting in a high overall conversion efficiency which makes these processes again eligible of large subsidies. Presently the electrical power from biomass is very small, but rising rapidly. An important advantage of biomass-produced electricity, compared with wind or solar energy is that primary resources may be stored, offering some freedom for power control so that the generation can be scheduled in a daily rhythm. According to a report by the Agency for renewable raw material [8] the total biomass potential in Germany, when converted exclusively to electricity, could some day become 220 TWh/a. Generating electrical **energy from geothermal sources** is another option at an early stage of development but it is unlikely to contribute substantially to our future energy supply. The reasons are costs and the risk of deep drilling. Even in a volcanic area such as the Jura Mountains a prototype drilling operation did not produce sufficiently hot water until a depth of 4100 m was reached, while another attempt was discontinued at 2700 m for technical reasons. At the end of the Continental Deep Drilling operation in Oberpfalz, that was serving geological research, a temperature level of 300 deg C was found at a depth of more than 9000 m. The only geothermal pilot station in Germany produces hot water of 100 deg C from a depth of 2450 m, yielding 210 kW of electricity.

Whether nuclear fusion will some day be considered as a renewable energy is still unclear; besides the uncertainties, the outlook for a commercial fusion reactor has remained unchanged for a long time at about 50 years, and the far more difficult technological problems than with nuclear fission, it cannot be ruled out that todays hostility toward nuclear energy may some day be turned against fusion reactors as well.
This reduces our hopes for a sustainable future energy supply, apart from energy saving, to
Off-shore wind energy, Solar, Biomass and primary Hydro-energy.

As seen in Fig. 1, wind power is totally uncorrelated with the grid load, but this is only part of the problem. When the power from neighbouring off-shore windfarms has been collected with local grids and carried to shore with, depending on distance, AC- or DC-cables it must be carried to distant load centers. Since the relatively weak transmission grids in coastal regions are not suitable for accepting large blocks of fluctuating wind power, new high power AC- or HVDC-links would have to be built connecting the incoming cables with the load centers. This is not an unsolvable problem but it may take years to establish the rights-of-way and obtain legal permission to build the necessary power lines. In fact, the extension of the high voltage grid could turn out as the major obstacle to rapidly develop off-shore wind energy.

Control power

In order to keep an AC transmission- or distribution-grid in a stable equilibrium state, control power Pc is needed to establish a balance between infeed and load, illustrated in Fig.6 by a freqency control scheme. Input quantities are the load power P_L and the mainly thermal scheduled generation P_{SG} that is accurately predicted by load models from past experience and includes also the generation from biomass; wind/solar power P_W is added with a scale factor a >1 still to be determined. The deviations between the actual load, the scheduled generation P_{SG} and the wind power P_W act as disturbances.

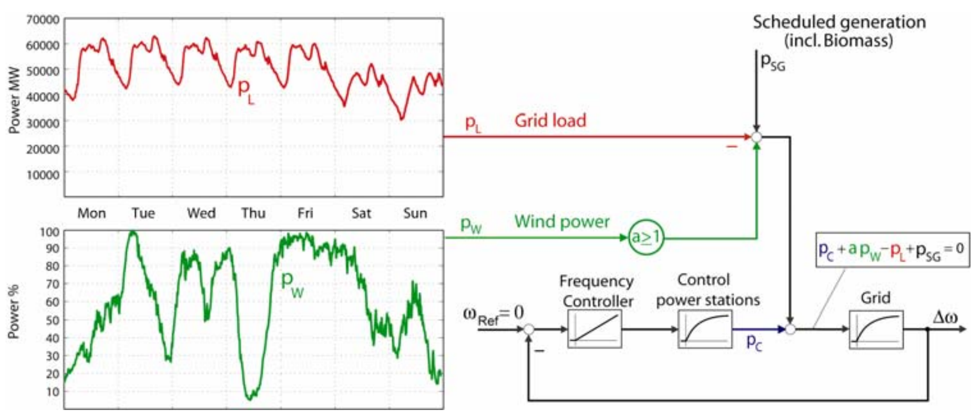


Fig. 6 Frequency control scheme for determining control power

Since wind power cannot be accurately forecast, back-up and control power plants are needed, usually rapidy responding hydro- or combustion-turbine plants; coal or even nuclear plants which normally generate base load or according to schedule, have to be employed as well.
If wind power is below prediction, positive control power is substituted. At total calm, all the scheduled and control power plants must be able to meet the total load; as the experience from 2003 shows, such conditions could last for days and even weeks. If the wind is stronger or the load lower than predicted, the control power becomes negative, $P_C < 0$, and power stations must be throttled or temporarily shut-down because, according to

present German law, **wind energy has priority**. With thermal plants, this has the undesired effect that their efficiency drops and the specific fuel consumption and CO_2 emissions as well as the costs are rising [6].
If control power plants with storage facilities are available, surplus wind energy can be conserved and (subtracting unavoidable losses) fed to the grid later, when power is needed. However pumped hydro or other storage plants presently available are far too small for balancing the fluctuating wind energy, even at todays early state of wind utilization.

In the following it is roughly estimated, whether a sustainable energy supply without fossil and nuclear fuel could be achieved at all [15]: For this the total electrical load energy drawn from the German public grid of about 520 TWh/a is assumed to remain unchanged; subtracting the biomass potential of 220 TWh/a and the primary hydro energy of 20 TWh/a leaves about 280 TWh/a to be supplied by wind power, mainly from future off-shore installations, which corresponds to an a = 14-fold increase of the present on-shore wind power generation. The balancing control power would have to be produced solely by pumped hydro plants, whose storage reservoirs, filled by excess wind power, would supply the grid during calm periods.

Clearly there are major discrepancies: The mean balancing energy needed to feed the grid during just one calm week (as in 2003) is 280 TWh / 52 = 5.4 TWh which amounts to more than 600 times the storage capacity (8.5 GWh) of the new pumped hydro storage plant Goldisthal in Thuringia, Fig. 7.

Fig. 7 Pumped hydro storage plant Goldisthal 1060 MW, 8.5 GWh

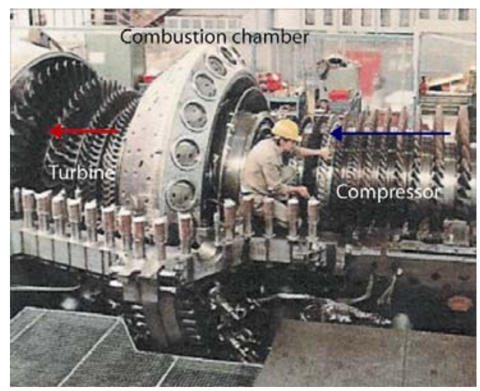


Fig. 8 Gas turbine with annual combustion chamber

Obviously, the lack of a suitable topology, the environmental impact, the necessary power lines and the cost would render this an utopian proposition. Instead, thermal power stations will remain necessary for supplying the balancing power and one can only argue how this could be achieved in an environmentally acceptable way. The presently preferred solution is to expand efficient cogeneration in gas-and-steam power plants, accepting the increased dependencey on imports, risk of supply shortages and cost.

Compressed air energy storage (CAES)

This method of storing energy on a GWh scale still requires fossil fuel [9]. By storing in a large underground cavity the air produced by the compressor of a combustion turbine and feeding it later to the compressorless turbine for driving the generator at full power, wind energy is preserved in the form of compressed air, Fig. 8. Large cavities can be created by solution mining in underground salt domes, aquifer structures or in abandoned and sealed deep mines; suitable geological formations exist in Northern Germany and under the North Sea, serving for seasonal oil- or gas-storage.

The example for all later CAES projects is the 290 MW power station at Huntorf near Oldenburg, Germany, built 20 years ago and used today as a rapidly controllable peaking plant. The turbine and the compressor are mounted on the generator shaft and are disconnectable by clutches; for storing compressed air the generator acts as a motor (as in a pumped hydro plant) while electrical peaking power is produced with natural gas and air coming from the cavern or the compressor. The dates of the Huntorf plant are 2 h of generator operation with 290 MW and 8 h compressor operation at 60 MW, charging two caverns with a combined volume of 0.3 Mio m^3 at a pressure between 40 and 80 bar; a third cavern serves for storing natural gas. A similar plant was later built in Macintosh, AL, USA.

Storage cavities in salt domes are tight at these pressures but in the interest of structural stability the temperature must be limited to about 40 deg C, hence the compressed air needs to be cooled before entering the cavern and heated when fed to the combustion chamber of the turbine, thus involving losses. The total efficiency of the charging and discharching cycle is about 42%.

When further developing the CAES concept to balance fluctuating wind power, the compressor would be permanently separated from the generator shaft and driven at adjustable speed by a load-commutated synchronous motor drive, mainly fed from wind-generated power.

With this scheme, charging and discharging of the storage are independent: Wind energy acquisition depends no longer on the grid load and power can be delivered to the grid even in calm periods, hence the power station is reversible and - as long as there is adequate pressure in the cavern- , capable of "black starts" and rapid control. CAES-storage plants could be sited in suitable on-shore locations or on platforms near off-shore windfarms and salt domes; a gradual expansion strategy with regard to compressor-, turbine generator- and storage-capacity as well as power links to the shore seems feasible. Most of the installation would remain invisible to an observer. EU-sponsored research is under way for "adiabatic CAES" with the aim of storing and recuperating the compression heat and removing the need for natural gas [13, 14].

VDE-Memorandum on future energy

The German Electrotechnical Association (VDE) has recently published a detailed memorandum on the future electrical energy supply, that has been prepared by a panel from industry, utilities and universities [10]. The main conclusions are depicted in Fig. 9:

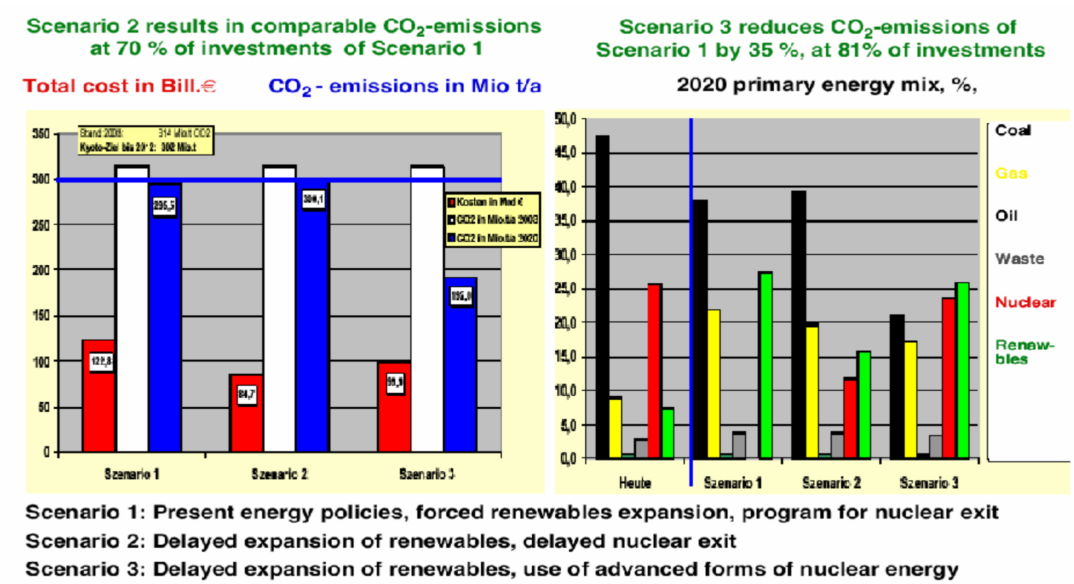


Fig. 9 Results of VDE-Memorandum 2005 on the electrical energy supply in 2020

Assuming a rise of electricity consumption of 0.5 %/a, the memorandum describes three possible options for a future national energy policy until 2020, giving estimates of the expected CO_2-emissions/a and total cost. Continuing with the present government policy **(Scenario 1)** which includes a rapid expansion of renewables and phasing out of nuclear power, the expected emissions per annum will be reduced only marginally compared with 2003 because the urgent reconstruction of obsolete fossil generating plants (40 GW), the substitution for the existing nuclear capacity (20 GW) and the back-up for the expansion of renewables, mainly wind, would necessitate an enormous increase of new fossil generation. It is quite uncertain whether legal hurdles would permit the timely construction of new high power transmission lines for carrying the off-shore generated wind power to the load centers.

In the Memorandum it was found that the Kyoto-defined goal for limiting emissions could be met in an alternative way, when following the **Scenario 2**, where the phasing out of nuclear plants and the expansion of renewables are delayed. With this strategy the 2012 Kyoto-goal regarding emissions could also be met, but at much lower, about 40 Bill €, total costs.

In a third **Scenario 3** it is assumed that nuclear energy will remain in use, as discussed in various countries, and is further developed. The predicted costs would lie between those of Scenarios 1 and 2 while the emissions could be reduced by one third, making room for a possible future tightening of the Kyoto limits. With this strategy one might even hope to bridge the gap until fusion energy becomes available.
These proposals are, of course, highly controversial and need to be discussed at political and technical levels but they show for the first time in well-founded numbers the consequences (with nearly identical emissions in Scenarios 1 and 2), if one wishes to abolish nuclear energy at any cost.

A preliminary first part of the government-sponsored DENA-study [12] that has also been published recently is dealing with questions of feasible wind power expansion until 2015 from technical, environmental and financial points of view, but still omitting details of restructuring the High Voltage transmission grid. The final report may include an assessment of CO_2 sequestration in the foreseeable future and what this could mean in terms of additional fuel consumption and costs.

Secondary energy carriers for storage

While the options discussed so far for storing large quantities of energy are based on todays technologies, there are other long-term possibilities for energy storage and decoupling the fluctuating energy acquisition from varying demand; for instance, converting fluctuating natural resources, off-shore wind and solar, to secondary energy carriers, such as hydrogen, that could be stored, transported, distributed and converted back to electricity with stationary or mobile fuel cells [11]. This would remove an important obstacle to the use of regenerative resources; it would mean a strategic change towards a future-oriented system, instead of continuing on a path that may eventually turn out to be a dead-end. At the same time a solution could be promoted that is better suited to the technological status of an industrial country than just feeding raw electrical wind energy to the grid.

Naturally this approach also involves substantial costs and energy losses but electrolysis is a proven technology and industrial equipment with good efficiency is available that could be developed towards higher power. Considering the widespread optimism towards fuel cells, it should be practical to develop the technologies for conversion, storage and transportation in step with the gradual increase in off-shore wind power expansion. Recently Norsk Hydro installed the model of an autonomous energy supply based on wind and hydrogen on the small Norwegian island of Utsira.

Conclusions

While a sustainable electrical energy supply based only on wind, solar, biomass and pumped hydro may offer at first sight an exciting perspective, a quick look at actual numbers reveals that it would mean a prohibitive increase of storage capacity. Hence the question arises what sense it makes to pursue such a goal at any cost. Thermal power stations, strategically distributed throughout the grid will remain necessary, some of them nuclear und some with storage capability.

If the potential for off-shore wind energy can indeed be tapped in quantity, it should be considered to convert the fluctuating wind energy into secondary fuel that can be stored and transported for producing electricity when and where it is needed. Developing these technologies would be a major challenge for an industrial country instead of feeding growing quantities of raw wind power into the grid, whether it is needed or not, thereby endangering its stability. Authorization and construction of power stations and transmission lines takes many years and if the nuclear plants are closed down before new generating capacity based on reliable primary energy is in place, the country would become dependent on power imports and follow the road of Italy in 2003.

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