Hydrogen as a Means of Controlling and Integrating Wind Power into Electricity Grids – The HyWindBalance Project

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ABSTRACT

The integration of wind energy into electricity grids will pose considerable challenges in the future as the levels of wind electricity production rise, power fluctuations have to be balanced and grids, especially in coastal regions, are overloaded. Ways of controlling and storing wind electricity have to be developed in order to better integrate the wind resource into the supply system and overcome limitations of grid development. Hydrogen storage offers some advantages towards these goals.

The HyWindBalance project, which is described here, looks into the possibilities of using hydrogen production and storage to accumulate wind electricity and a fuel cell system to re-convert the hydrogen to electricity.

With the help of these systems and wind power prediction software, wind energy resources can be integrated into the electricity supply in analogy to conventional generating capacity.

The long-term goal of the project is to facilitate the integration of large offshore wind farms into power grids.

This paper reports on the first phase of research and development activities. It communicates findings from the testing of components in a small-scale research system, reports on simulation results concerning large-scale plants, and discusses economic considerations.

INTRODUCTION

The power produced by wind farms varies due to the natural fluctuations in wind speed. Although the short-term variations (including turbulence) generally obey random patterns, the mid-term and geographical variations in wind speed show some correlation. This results in a levelling out of high frequency (short-term) contributions, when large wind energy systems are considered since these are necessarily distributed over considerable areas [1]. The energy contained in the wind flow is predictable to a high degree. This has given rise to the development of wind energy prediction tools [2].

With increasing contributions of wind energy in the power supply system, as seen in many parts of Europe today, problems are expected concerning:

- The management of wind energy production, in making maximum use of the natural resources;
- The necessary enhancement of grid capacity, creating additional transport lines connecting the up-to-now little developed coastal regions to the centres of electricity demand;
- The additional provision of balancing power, in order to compensate the fluctuations in wind electricity production.

It is generally expected that an increasing need for balancing power will result from the advent of large offshore wind parks in the North Sea. In order to neutralise this effect, it is necessary to adjust the operation of the grid as a whole to the requirements of a modern mix of energy sources. Critics claim that the additional supply of balancing power will induce increased use of fossil fuels in conventional power plants at low capacity factors and thus low efficiencies [3]. Consequently, this would cause additional emissions and fossil fuel consumption, which would contradict the basic idea of environmentally benign energy production from wind.

THE HYWINDBALANCE CONCEPT

The electricity grids will have to adapt to the new challenge of high renewable energy penetration and will not be able to proceed with "business as usual" regarding the integration of fluctuating power generation. A closer analysis reveals that many predictive tools are already available in balancing power generation and demand – weather forecasts have been a standard instrument in grid management for decades, as have knowledge-based approaches to predicting electricity demand and balancing the short term, statistical fluctuations of the electrical load. Therefore, the problem of integrating fluctuating renewable power is reduced to an optimised network management obeying novel constraints.

The HyWindBalance concept addresses this issue by attempting to describe solutions to renewable power management (concentrating on wind energy) by making use of electricity storage via hydrogen. The overall performance of renewable energy supply is increased by the possibility of feeding wind energy into the grid in a scheduled manner ("dispatching").

The concept couples hydrogen production, storage and re-conversion to electricity with an intelligent control unit that incorporates wind as well as load prediction routines and (optionally) price data from the power spot market. Figure 1 shows an overview of the system modules and their interaction. The overall goal is to develop a wind-hydrogen system that, in its function as a "virtual power plant", establishes a number of options for wind energy:

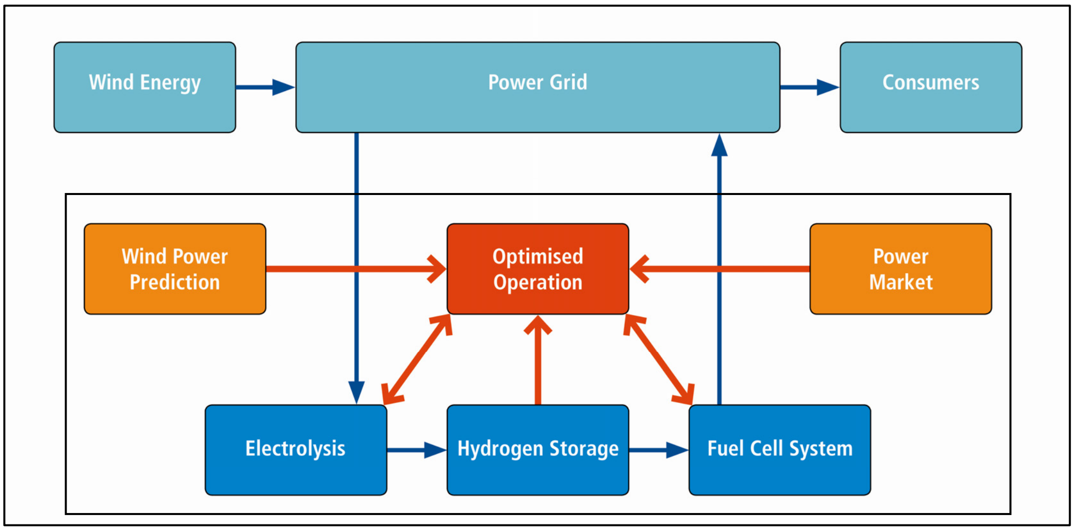

Figure 1: Schematic of the HyWindBalance approach. Blue arrows depict the flow of energy and red arrows the flow of information.

- Scheduled generation, thus making the wind resource "controllable",
- Reduction of the need for balancing power from conventional power plants (secondary balancing power), and
- Active (scheduled) sale of wind electricity as balancing or peak power on the spot market.

In the medium term, it will also be possible to sell hydrogen from excess wind energy to other markets than the electricity sector, for example as fuel for road vehicles.

Companies and organisations with a variety of backgrounds cooperate in HyWindBalance: Scientific bodies, engineering companies and consultancies in the fields of wind energy, hydrogen and information technology, as well as a financial service provider and a utility have teamed up.

The plans for large offshore wind farms off the German coast to be realised over the coming 10 – 20 years catalyse the project. However, the HyWindBalance concept may be adapted to other situations, such as electricity supply on islands with a high share of renewable sources.

It is expected that development and demonstration of commercial systems up to the Gigawatt range will take several steps over maybe a decade. This paper reports on the R&D activities so far.

The objectives of the current phase have been:

- Gaining experience with the operation of a research system,
- Developing operating strategies for different meteorological, technical, and market conditions,
- Building a simulation tool that can map out the behaviour of system components and plant management,
- Assessing the feasibility of this technology at a large scale, and
- Developing a training module for teaching technology and state-of-the-art of fuel cells, energy storage, and balancing power.

The paper focuses on the research system, on results from simulating large units and, briefly, on economic considerations.

THE RESEARCH SYSTEM

The research system was designed und built to investigate hardware performance under realistic operating conditions. It was installed at the “Energy Laboratory” of Oldenburg University, a place that has been used for research and teaching for more than 25 years [4].

The unit consists of:

- An alkaline electrolyser capable of producing 1 Nm^3/h at 30 bar with about 6 kW installed AC power (manufacturer: Accagen),
- A PEM fuel cell with a rated electrical power output of 1.2 kW (manufacturer: Ballard),
- A controllable electronic load (1 kW maximum) for the fuel cell; see Figure 2,
- A hydrogen storage consisting of 2 bundles of 12 cylinders with 50 litres geometrical volume each and 200 bar rated pressure,
- A control unit that governs and monitors the plant,

and the necessary auxiliaries such as treatment of the feed water, nitrogen supply for purging etc.

Only commercially available products (i.e. no prototype equipment) were purchased to obtain insight into the state-of-the-art of hydrogen and fuel cell technology, and to get standard warranties.

The system is not connected to a wind turbine but receives its input power signal from the control unit. The same applies for the signal that drives the electronic load and the fuel cell, respectively. The advantage of this approach is that the same time series of power supply and load can be imposed on the system several times while employing different operating parameters. Such time series can be derived, for example, by scaling measured wind power and load data to the size of the research system.

A compressor for charging the storage vessels to rated level was not installed. Therefore, the maximum storage pressure was 30 bar. This corresponds to a usable hydrogen volume of about 36 Nm^3, equivalent to 1.5 days of operating both the electrolyser (producing hydrogen) and the fuel cell (consuming hydrogen) at full load. This is considered sufficient and does not affect the objectives of the current development step. Forgoing the use of a compressor at this stage reduces the investment and avoids issues encountered with operating current hydrogen compressors in other projects, such as downtime or contamination [5].

A key prerequisite for a wind-hydrogen system that has to meet challenges as outlined in the introduction is the ability to follow rapidly (virtually instantaneously) changes in input power to be converted to hydrogen and in demand for power to be supplied by the fuel cell, respectively. Fuel cell and electrolyser were thus tested with respect to these properties.

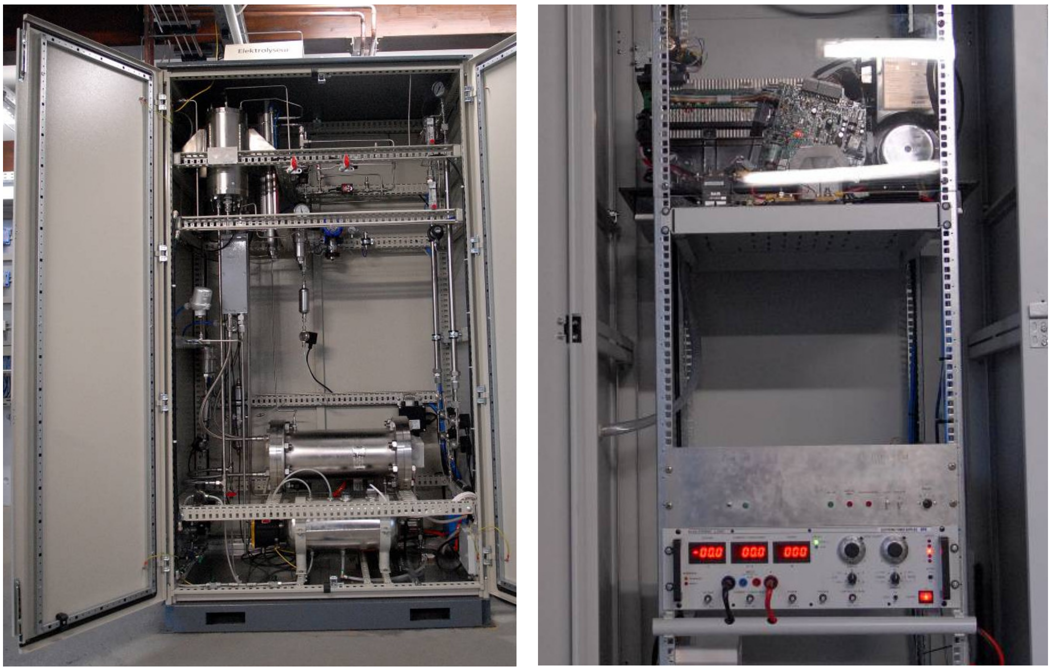

Figure 2: Alkaline electrolyser 1 Nm^3/h (left), PEM fuel cell 1.2 kW (top right) and electronic load (bottom right) in a 19’’ rack.

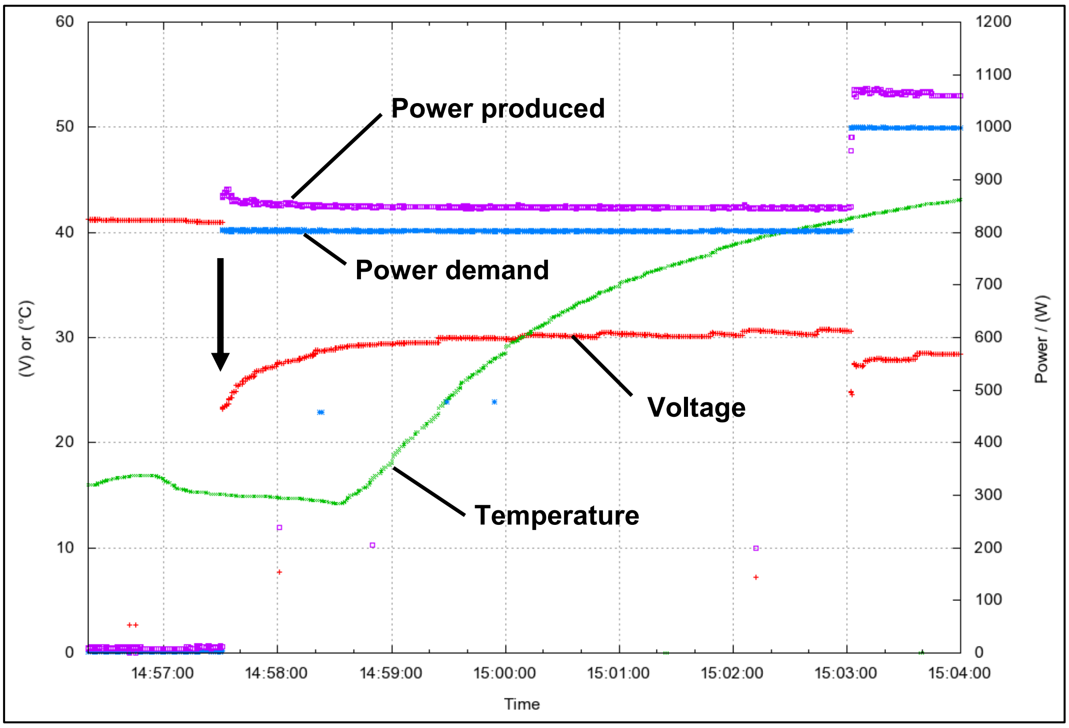

Figure 3: Step function response of the fuel cell to a sudden increase in power demand. At about 14:57:30, power demand changes from 0 W to 800 W (blue dots) and the fuel cell responds accordingly in terms of power (purple dots). Voltage (red dots) displays a sharp drop, indicated by the arrow. This drop is due to the necessary adjustment of the operating point with respect to fuel supply, membrane moisture and operating temperature.

Figure 3 exemplifies the response of the fuel cell to a step increase in power demand by the electronic load at about 14:57:30 when the stack is close ambient temperature. The critical observation is the sharp drop in voltage to about 23 V. At 21 V load shedding would have occurred. It takes more than five minutes until voltage recovers close to the tolerable level of about 33 V. Any event below this minimum value can result in a reduction of cell membrane lifetime. Sharp steps in power demand at low stack temperatures are likely to occur regularly in everyday operation of a wind-hydrogen system, though. Moreover, it is worth noting that even when the stack is at operating temperature (50°C), problematic voltage drops take place following a step in power demand from 0 kW to 1 kW.

The fuel cell follows the power demand with a delay of some 3 seconds (not discernible in Figure 3). Similarly, the electrolyser “lags behind” when responding to step changes in terms of power input. When the control unit demands a higher rate of production, it takes some seconds until power consumption actually increases.

In a storage system like HyWindBalance, the overall efficiency of the power-to-hydrogen-to-power loop is a critical parameter. Typical efficiencies of today’s technology are circa 67% for pressurised alkaline electrolysers (with regard to the net calorific value of hydrogen) and of some 45% for PEM fuel cells. Therefore – excluding auxiliaries – about 30% efficiency can be expected. In the future, more than 40% seem possible. Considering all auxiliaries, the current research system displays an overall efficiency of just about 20%. It must be noted, of course, that optimised system efficiency has not been a focus of attention during this R&D phase.

INVESTIGATION OF LARGE-SCALE SYSTEMS

In order to assess the performance of large systems, a number of case studies have been carried out. Options considered include:

- Providing “green” balancing power,
- Participating in the electricity spot market,
- Peak shaving on the supply and/or on the demand side, and
- Power supply according to a self-defined schedule.

The last option is discussed in the following.

Current feed-in tariffs for renewable power as implemented in several European countries guarantee a fixed remuneration per kilowatt-hour over a defined period, such as 20 years. Introducing a dependency of remuneration on spot market prices could form a first step towards a more market-oriented approach in the future.

Alternatively, there could be a reward when the level of power fed into the grid matches closely with a prediction (24 to 48 hours ahead). Such a scheme is currently in place in Spain on an optional basis: Actual supply of power from wind is benchmarked against a day-ahead forecast.

The wind power forecast employed in HyWindBalance is a so-called physical system and is based on a meteorological description of the atmosphere [2]. Wind speed at hub height is calculated from this model and then used to determine the power output from the power curves of the installed wind turbines. The system can deliver forecasts for single wind farms or for the aggregated output of many wind farms in a region up to five days ahead.

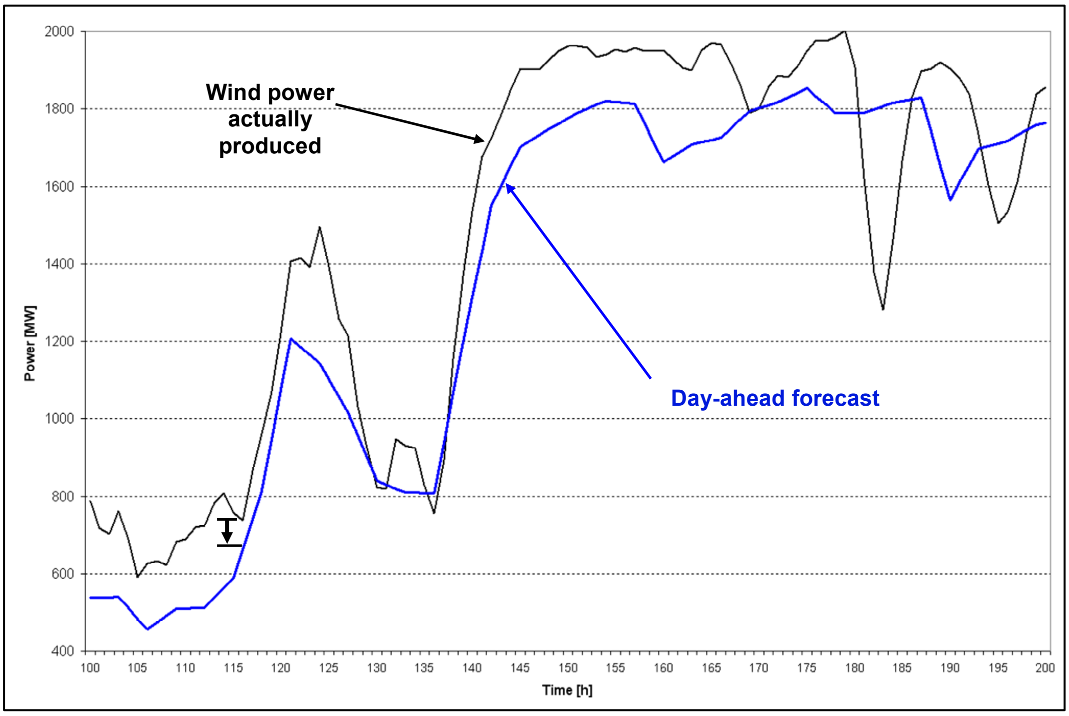

Figure 4: Comparison between a day-ahead forecast of wind power supply (blue line) and the actual power time series (black line) over 100 hours in 2005 for all wind farms in the Northwest of Germany. The prediction line has been reduced by a constant value (57.5 MW) in order to account for the energy required to produce hydrogen.

Figure 4 compares such a day-ahead forecast for all wind farms in the Northwest of Germany (2300 MW installed) with the actual level of wind power produced over a period of 100 hours in 2005. It must be noted that the forecast displayed in Figure 4 is already a modified one compared to what was predicted originally: The hourly figures were reduced by a constant value of 57.5 MW, which is equivalent to 2.5% of the installed wind power. This reduction in predicted power accounts for the energy required to produce hydrogen. The extent of the shift is visualised by the arrow near hour no. 115. It shows that at this point in time the original forecast (unshifted) and the actual production matched closely.

In general, both curves in Figure 4 are similar in shape, although the exact power levels differ to some extent most of the time, even when considering that 57.5 MW have been subtracted from the original forecast. However, from about hour no. 180 onwards, both time series are markedly distinct. The reason was an increase in wind speed to an extent that caused many turbines to shut down for safety reasons. This caused a sharp drop in production and was not anticipated by the prediction.

Figure 5 shows the same situation with a third curve added. It displays how the system "wind farms plus HyWindBalance plant" can improve the performance in terms of matching the prediction. The HyWindBalance unit employed here comprises 230 MW of electrolysis and a fuel cell system of the same rated electrical power, i.e. they can absorb or supply, respectively, 10% of the rated power of the wind farms in the Northwest. During periods when the wind power actually produced is higher than the forecast, hydrogen will be produced and stored. When the actual wind power level falls short of the forecast, hydrogen will be re-converted.

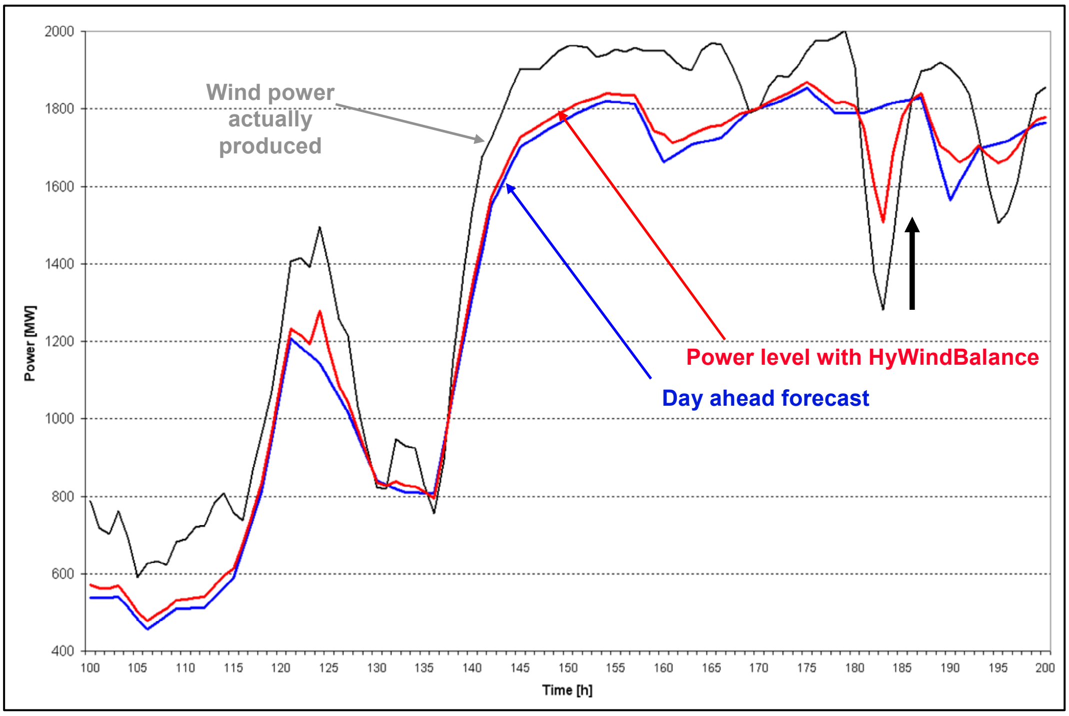

Figure 5: The HyWindBalance plant improves performance by better matching the power fed into the grid (red line) with the forecasted level of power (blue line). It follows from the limited size of the system components that extreme differences between actual wind power production (black line) and forecast cannot be balanced entirely (see hour no. 183, for example).

It can bee seen in Figure 5 that as long as the difference between forecast and actual wind power is smaller than 230 MW the "power level with HyWindBalance" matches the forecast well. In situations with greater deviations, the HyWindBalance plant of course cannot close the gap, as observed near hour no. 185: The sharp power drop is reduced by 230 MW, as depicted by the black arrow. To match the forecast, however, a fuel cell system about twice as large would be required.

Figure 6 shows the distribution of the relative deviations from the day-ahead forecast for the Northwest of Germany between January and October 2005. The dark bars represent the deviations of the power supplied without hydrogen storage from the original (unshifted) forecast. The light bars stand for the case with a HyWindBalance plant in place, as above (i.e. deviations from the shifted forecast with 57.5 MW subtracted). Without hydrogen storage, forecast and actual supply match during about 43% out of 7296 hours. Deviations up to ±35% occur. With HyWindBalance, more than 91% of correspondence can be achieved. The deviations from prediction lie in the range of -25% to +30% of rated power.

Negative deviations from the forecast pose the main challenge because they cannot be counteracted by limiting wind turbine output as positive variations can (even though this is not desirable). Without hydrogen storage, the actual wind power supply falls short of the predicted values during 1978 hours (some 27%). With the HyWindBalance system in place, some 200 hours remain (2.7%).

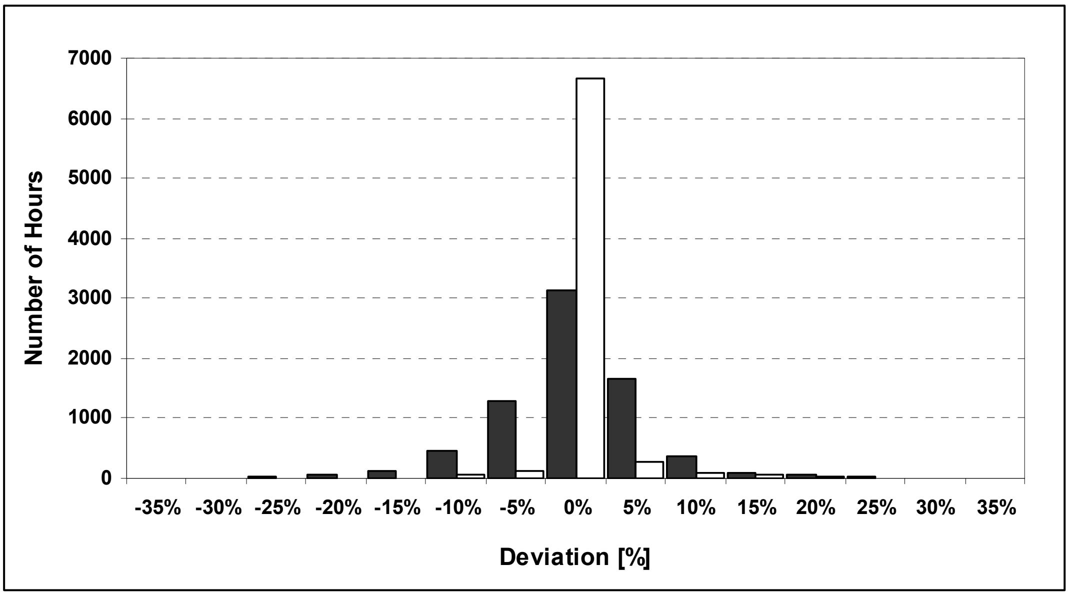

Figure 6: Relative deviations of the actually supplied power from the day-ahead forecast without (dark bars) and with (light bars) a HyWindBalance plant in place over 7296 hours (January – October 2005).

Doubling the size of the fuel cell system to 460 MW could further reduce hours with deviation from prediction to about 20, but it does not appear economically sensible to install additional 230 MW of fuel cell that operate less than 200 hours per year, at least in a grid connected system.

ECONOMIC CONSIDERATIONS

At the time of writing this paper, the economic calculations have not been completed. Nevertheless, it is worth pointing out the relevance of storage size in this respect. Table 1 demonstrates that storage can be a significant cost factor when it has to secure energy supply for fuel cell operation over several days[1]. Therefore, the tradeoffs between possible advantages of a bigger storage in terms of revenue on the one hand and a higher investment on the other hand must be carefully evaluated.

The appropriate storage capacity depends on the main purpose that the system has to serve, such as providing balancing power or following a pre-defined schedule. The simulation discussed in the previous section for simplicity uses an infinite storage in order to establish the technically necessary size (found as the maximum loading). In the next step, storage size is optimised adding financial routines to the model. They provide the basis for balancing technical and economic performance.

In a further step, the way of reducing the wind power forecasts in order to account for the energy needed to produce hydrogen must be improved. At present, constantly 57.5 MW are subtracted, as mentioned. A more flexible and, probably, more economical approach is wanted.

[1] The system studied in Table 1 is rather small compared to units required to interact with large wind farms. It can be assumed, though, that investment increases more or less linearly with the size of the major components, so similar cost breakdowns are expected for larger systems.

Table 1: Breakdown of investment costs for a wind-hydrogen system with an electrolyser of 55 Nm^3/h rated production and a fuel cell that can deliver 200 kW electrical power. Storage capacity is expressed as full-load days of the fuel cell.

	Share in total investment			
	Electrolyser	**Fuel Cell**	**Storage**	**Auxiliaries**
System with a 2-day storage	21%	39%	18%	22%
System with a 5-day storage	16%	31%	35%	18%

CONCLUSIONS AND OUTLOOK

Operation of the research system has shown that the major components still require improvement in their responses to sudden load changes and their efficiency. The tradeoffs between component lifetime and operational requirements have to be established and optimised. Overall system efficiency will have to double compared with the performance of the research system.

Simulations of large systems show that errors in wind power predictions can be substantially corrected by a system like HyWindBalance. It is not easily accomplished, though, in particular due to the economics involved. This holds true even more for islands, which are typically smaller than the region taken into account here (i.e. the Northwest of Germany): The smaller the region, the larger the average error in wind power prediction will be. This in turn will result in different, presumably higher requirements regarding the size of the energy converters, storage capacities and operating strategies.

Converting and storing energy will always be more costly than employing it directly. Nevertheless, technical requirements of grid stability can necessitate the implementation of electricity storage. When storage is installed in order to satisfy boundary conditions such as a high rate of fluctuating renewables in a power grid, then the individual storage options need to be benchmarked in terms of performance, costs, efficiency, technical viability etc.

The utilities are currently analysing and evaluating different energy storage systems. Hydroelectric power plants, for example, offer good solutions to the problem of supplying balancing power. Due to the local topographical conditions, though, it is not possible to install large plants of this type in Northern Germany, near to the main German wind resources. Another possibility to handle the described challenge is to operate compressed air energy storage systems (CAES). The disadvantages of these systems are high costs, low storage densities and the discharge of carbon dioxide.

Underlined by the actual climate discussion, energy storage systems should not be evaluated exclusively with regard to current energy costs. The environmental compatibility equally plays an important role. Hydrogen production and storage offers an important opportunity for handling fluctuating wind power in an efficient and ecological way. Further results of HyWindBalance will determine, whether hydrogen systems can be operated economically in the future.

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