2024: an energy storage tale

FAST FORWARD TO 2024, AND LET'S IMAGINE THAT WIND POWER IS MORE COMMON THAN IT IS EVEN TODAY. BUT HOW CAN THE MANAGER OF A LARGE, FICTIONAL, DANISH UTILITY COMPANY MANAGE VARIATIONS IN WIND POWER ONCE AND FOR ALL, USING AN ABANDONED NATURAL GAS STORE? IN THE SECOND OF HIS COLUMNS ON THE ENERGY STORAGE DILEMMA, **BENT SØRENSEN** FOLLOWS THE MANAGER ON HIS ROUNDS.

The CEO of our fictional Danish power utility had fulfilled the command of the government and built offshore wind parks so that the total power from wind matched the total electricity demand. In reality, large surges of surplus power were spread over the year with intervals of several weeks, and, unfortunately, so were lulls. Wind follows the weather patterns of front systems passing over the region, so having the turbines dispersed over the country, occupying offshore sites in the North Sea, the Baltic Sea and the Kattegat Sea, bordered by Sweden, Norway and Denmark, helped to smooth out wind power production. The goal was to make the power availability curve for the whole system rise from above-zero power 70% of the time (for one wind turbine) to 100% of the time. The CEO had just shown the **power duration curve** at a board meeting. It looked like the one in *figure 1*.

The power duration curve is very different from the nearly flat one that characterised coal-fired plants, forbidden in our fictional 2024 scenario. It drops more or less linearly from twice the average to zero. Referring to demand does not change this fact, so the CEO realised that something had to be done. As load mismatch used to be handled by the **Nordic Power Pool** or through bilateral agreements with the neighbouring countries, the CEO picked up his phone and called his Norwegian counterpart. He could have spared the effort. The policy of the Norwegian power utility was unchanged.

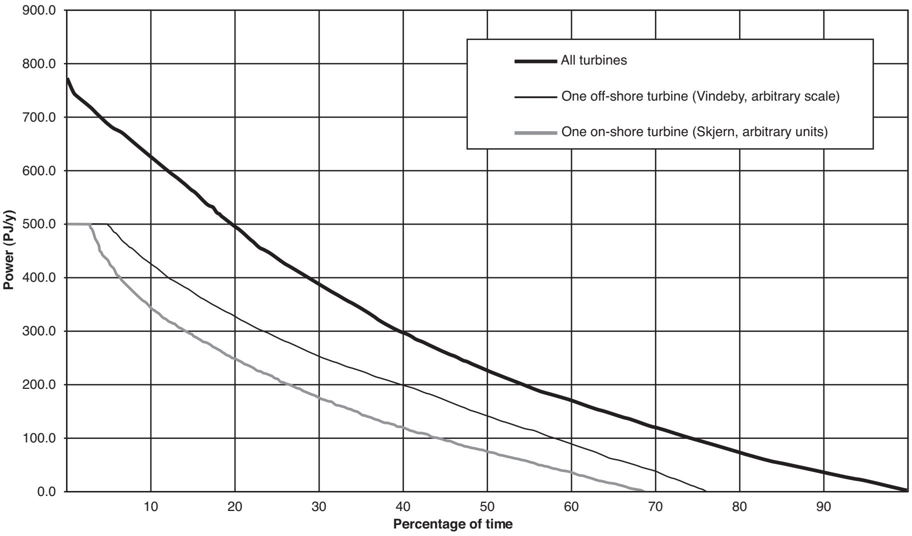

Figure 1: Annual wind power duration curve (percentage of time the wind power production exceeds a given value) for Denmark, for one onshore turbine, for one offshore turbine, and for a system with turbines all across the country. All three curves assume the same total rated turbine power (from Sørensen: Renewable Energy, Elsevier 2004).

Why? When Denmark had a wind power deficit, the price of Norwegian power was 90 cents per kWh and when Denmark wanted to sell, the buying price was zero. In Denmark, the average production price for wind power was 6 cents per kWh, i.e. below the price of fossil power even ignoring the environmental tax. In Norway, the average production price of hydro power was three cents per kWh, and the seasonal water reservoirs upon which the Norwegian system was based hardly noticed the extra fluctuations that would have occurred if Norway covered the Danish wind deficits and imported the surpluses. The Norwegians knew they had a unique power option, a sellers' market, and they enjoyed using market mechanisms to their full extent.

But there was another option to try. He would simply use the natural gas storage system already in place.

Underground storage

Denmark's natural gas storage systems go back to the 1980s, when the first gas pipeline from the North Sea to mainland Denmark was constructed. At that time fear had been expressed that the line might become severed by a Russian submarine or even a trawler. Should this happen, repair might in the worst case take 6 months, according to estimates made at that time. Therefore, the Danish government had

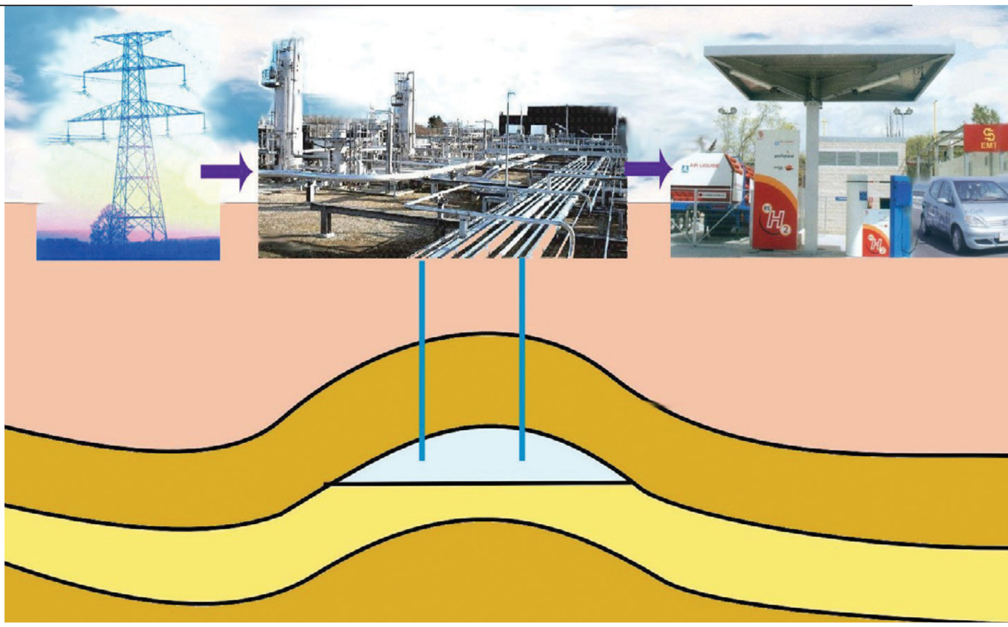

Figure 2: Underground hydrogen store in aquifer, with indication of front-end electrolyser and hydrogen piping to vehicle filling station (from Sørensen: Hydrogen and Fuel Cells, Elsevier, 2005).

decided that an underground store should be built to hold 6 months of natural gas use. This was accomplished by two underground facilities. One was based on a salt intrusion – a dome of salt reaching nearly to the surface.

Compared to other types of stores, a salt dome store is extremely cheap to construct: You drill a vertical hole and flush water through it at low pressure (to minimise energy costs) for, say, two years, thereby creating an underground cavern. When completed, it may be sealed with a tightening gel, or steel canisters may be lowered into the cavity, allowing gas storage at pressures of around 23 MPa at extraction (*see figure 2*). The Danish store at Lille Thorup holds 4.2×10^{8} m^{3} of natural gas.

The second underground store was an aquifer store, taking advantage of an upward bending of an underground aquifer to store gas at the top (*see figure 2*), with the water in the aquifer preventing the gas from flowing away. This facility, at Stenlille, holds 3.5×10^{8} m^{3} of natural gas at an exit pressure of 17 MPa. The glaciation-deposit geology of Denmark with 2-4 km down to solid rock allowed these two low-cost stores to be built. In regions with rock near the surface, more costly drilling is required to make the cavity, but sometimes this cost can be avoided, i.e. if an abandoned mine can be used for gas storage.

The CEO was aware that his company owned only one of the two stores. European Union antitrust laws had forced his company to sell off one of the stores. However, the natural gas store not owned by his company could more than serve the purpose of the Danish requirement. This was because natural gas had become a scarce and expensive resource and, moreover, because the current estimates of maximum repair time in case of pipe rupture was two months rather than six.

So, to solve his wind fluctuation problem without having to deal with the Norwegians, he decided to just use the store belonging to his company (no longer required for supply security). His preferred storage medium would be hydrogen, for a number of reasons. Electricity could be regenerated at times of insufficient wind at roundtrip efficiencies above 50%, especially if the Solid Oxide Fuel Cell (SOFC) fuel cell generators on the market reduced in price, but probably also with the new generation of hydrogen-optimised gas turbines. Surplus wind power would be converted to hydrogen by a reverse-operation fuel cell, either the conventional alkaline type or one of the new concepts. His company would prefer an SOFC, but of course there would be competition from the decentralised Polymer Electrolyte Membrane (PEM) fuel cells being installed by the thousands in homes and buildings as replacements for earlier gas boilers, under the motto: "Be your own power producer".

As often as possible, the hydrogen would be used directly, thereby avoiding the storage cycle losses. This would be possible, because hydrogen hybrid vehicles (hydrogen fuel cell plus batteries, as a replacement for the earlier common-rail diesel engine plus batteries) were reaching a sizeable proportion in the transportation sector.

Problem solved

After all, there was no need to buy and sell power through international transmission lines, as this approach only works if the parties at opposite ends of the line can both see an advantage in the arrangement. But the thoughts of the CEO continued to travel and he was soon considering what would happen if Denmark produced more wind energy than it could use domestically on average. There was plenty of wind available. The previous CEO of his company had already in the late 1990s mapped the offshore wind potential of Denmark and had identified a total potential of more than twice Denmark's total energy consumption (not just electricity consumption). If he continued to expand offshore wind park construction, therefore, not only would his company be supplying energy for the non-electricity sectors in Denmark, but there would be a surplus to export, most likely to Germany, which has much less wind potential than Denmark and where a Denmark-Germany transmission connectivity was already established and ready for reinforcement.

The transmission network could be expanded later to accept the huge wind potential in Sweden and Finland (and Norway if they realised their opportunity), as this potential, as in Denmark, by far exceeded their total domestic energy needs. The Nordic countries could be a major supplier of energy for Germany, in the form of electricity or piped hydrogen or both.

The CEO ordered the conversion of the gas storage facility to a hydrogen store, and asked his staff to prepare the tender for a new round of wind power expansion in the waters around Denmark. This day that started so bleakly had turned into a very productive one, and he had certainly earned the right to relax with his family for the evening.

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Hydrogen & Fuel Cells (Elsevier 2005).