HOW IS DENMARK INTEGRATING AND BALANCING RENEWABLE ENERGY TODAY?

Educational Article January 2015
by Eric Martinot

Article link: http://www.martinot.info/renewables2050/how-is-denmark-integrating-and-balancing-renewable-energy-today

The capacity of renewable energy in Denmark in 2013 was about 5 GW, which was about equal to the peak power demand of Denmark's power grid. Most of this 5 GW is onshore wind, with a smaller share of offshore wind, and a small amount of solar PV (0.5 GW). In 2013, wind power provided an average 33% share of Denmark's total power demand. In January 2014, wind supplied an average 62% of total power demand. On one day, January 19, 2014, wind generated an amount of electricity equal to 105% of the power demand for that day.

How is Denmark managing to integrate and balance such large shares of renewable energy? This question must be considered in the context of the "prevailing wisdom" of 15-20 years ago among virtually all electric power companies and power engineers. This "prevailing wisdom" was that going above 5-10% shares of "variable" renewables like wind and solar would spell doom for the reliability of the power grid, and the lights would go out. (And perhaps we might manage 15% according to the thinking of the day.)

Most experts today would point to Denmark's strong integration with the neighboring grids of Europe, including the well developed Nordic Pool market, as a primary factor in allowing Denmark to integrate and balance such high shares and keep the lights on. Denmark can freely buy and sell power from its neighbors to balance its renewables. But the Danish story is much more significant than that, and also includes many other innovations that have played a crucial role in Denmark's current situation, and will play a large role in its future as it plans to achieve a 100% share of renewable energy in the long term.

One of the main innovations in Denmark is the integration of heat supply with electricity balancing. Half of all electricity in Denmark is produced by small combined heat-and-power (CHP) plants. These plants feed into district heat-supply networks that include large water tanks for thermal energy storage. This whole system was designed starting in the 1980s with flexibility in mind, and heat plants have been built to allow varying the proportion of heat and electricity, and for storing heat to allow changing the output of the CHP plants without affecting heat supply and indoor comfort. This means that CHP plants can vary their electricity output in response to changes in wind output, and thus provide balancing. Many of these CHP plants are fueled by biomass, which thus provides a long-term pathway for balancing variable renewables like wind and solar with a non-variable but still-renewable resource like biomass.

Another innovation is for the "hourly ramping" and "daily cycling" of coal power plants, that is, varying their output over a wide range during the day and on a daily basis, and even shutting them down. In most of the world, coal power plants are designed to run at constant output, and electric utilities typically claim that ramping and cycling reduces efficiency, increases costs, lowers equipment lifetime, and is generally ill-advised or even impossible. However, in a number of countries, including Germany and Denmark, such ramping and cycling has long been considered normal practice. Again, Denmark anticipated the need for flexibility of the power system much earlier than most, even decades ago.

Over the past twenty years, Denmark has made further modifications to existing coal plants to increase their flexibility still further (as has Germany). These modifications, in both control software and equipment, have allowed increased load gradients (ramping rates), reduced minimum stable outputs, made startup (from zero output) quicker, and added software to improve response times. Through these measures, hard coal plants in Denmark can now ramp at rates up to 3-4% of rated output per minute, which is higher than in Germany and unprecedented among coal plants around the world. (For comparison, recently commissioned CCGT gas turbine plants in Denmark can also ramp at about 3% of rated output per minute.) And coal plants in Denmark can cycle down to the minimum level of 10-20% of rated output, compared to a 45-55% level in Germany and typically 60-70% levels elsewhere. (Again for comparison, recently commissioned CCGT gas plants in Denmark can cycle down to 50% levels.)

A third innovation is the incorporation of advanced day-ahead weather forecasting into the operation of power system control and dispatch. Such day-ahead weather forecasting has become common and highly sophisticated in regions with high shares of renewables, such as California, Germany, and Spain. Such weather forecasting can be credited as a major contribution to our ability to integrate and balance high shares of renewables, because it makes variable renewables highly <u>predictable</u> for power system control and dispatch on a day-ahead basis, which is how most power markets around the world now operate.

But Denmark has taken the day-ahead weather forecasting innovation one step further. During the day, in real time, the Danish power system control center constantly compares the actual output of renewables against the prediction made the day before. The error of actual vs. predicted is then used to forecast the output of renewable in the <u>coming hours</u> ahead of real time. This leads to a situation that one senior manager of the Danish power grid said “virtually eliminates errors” in the predictability of renewable output, and thus one which ensures efficient and reliable power system operation.

A fourth innovation concerns the practice of transmission planning. Denmark’s electricity system operator, Energinet, proactively plans new transmission capacity anticipating future interconnection of wind farms, based on project development plans and actual consented projects. Thus transmission strengthening occurs in parallel with new generation, not afterwards. And Energinet has a comprehensive plan for upgrading the entire transmission grid in the future, consistent with the increasing shares of renewable energy.

The fifth and final piece of the picture for integrating and balancing renewables is the operation of the electricity market itself. Denmark’s electricity market is part of the common EU framework, so that this aspect is true of any EU country. Denmark also benefits from its participation in the Nordic Pool market with Sweden, Norway, and Finland. The flexibility of electricity output from both CHP and coal plants in Denmark allows them to profit from selling into both normal wholesale (day-ahead) markets, and also the “ancillary” markets (also called balancing markets) that are designed to provide balancing power for fluctuations in system demand compared to system generation. Such ancillary/balancing markets are a normal feature of most power markets around the world to provide second-by-second, minute-by-minute, and hour-by-hour balancing of electricity supply and demand, even in the absence of renewable energy.

In Denmark, there are four ancillary/balancing markets. There are two forms of "manual balancing" for time frames of 15 minutes to 1 hour, in which balancing power providers are called upon when needed, and two forms of "automatic balancing," for both sub-15-minute and sub-30-second time frames. In both cases, power generators can choose the day before how much of their power capacity to sell into the normal day-ahead wholesale market, and how much to hold back in reserve to sell into the real-time ancillary/balancing market.

In three out of four of these markets, balancing power providers are also paid a capacity payment, based on the standing reserve capacity they make available, just for agreeing to participate in the next day's ancillary/balancing market, even if they don't actually provide any actual electricity generation (kWh). They also receive an energy payment for any kWh of power they actually provide to the balancing market, based on different tariff regimes.

In Denmark, all power plants, including coal, gas, and biomass, can and do sell into the ancillary/balancing markets. (At current market prices for gas, small, gas-based CHP plants have a difficult time competing with coal power in the normal wholesale market, so these small gas-based CHP plants most often make money by selling into the more lucrative ancillary/balancing markets.)

An extreme example of the market mechanism in action for balancing was that one day in January 2014 when wind power generation was the equivalent of 105% of Denmark's power needs for the day. On that day, electricity prices in Denmark spiked down to zero, creating a large incentive for all other power plants to turn off for the day, and for power to be exported to neighboring countries to realize a higher-than-zero selling price. (Of course, the effect was also to lower market prices in neighboring countries, which is seen as either good or bad, depending on whether one is a producer or a consumer in those other countries.)

(Note: Zero or negative prices are not a common occurrence in Denmark, so don't much affect revenue, but if they happen more frequently, as they do in Germany, this can seriously affect the profitability of coal plant owners, as has been happening with large utilities in Germany. So power plant retirements in Denmark might be expected in response, except where plants are mandated to remain running by the regulatory authority, or if "capacity payments" are paid to plants to remain running but not generating power.)

Denmark's power control and market operations (by Energinet), have also evolved an advanced system for balance management and grid reliability. The power control center every 5 minutes makes an updated forecast of the coming period, and also requires all generators (greater than 10 MW) to submit updates of their output every 5 minutes. This allows the power control and market operation to quickly respond to changes in renewable output. And the ISO has greatly improved its daily "N-1" reliability calculations, to make sure the lights stay on in the event of unexpected events or outages, even with variable renewables, in cooperation with neighboring countries and EU-wide under the EU "ENTSO-E" reliability framework.

Finally, in additional to the normal free-market ancillary/balancing markets, Denmark also orders some power plants into "must run" obligations, in which they are kept online and available, but produce as little energy as possible, so they are ready to provide balancing power when needed. This obligation is similar to the "Resource Adequacy Must-Run" obligations on generators in California, obligations that are created distinctly by both the power system operator itself (ISO), and the regulatory authority for power generators (CPUC). (See also the German case, where Germany requires at least 7 GW of capacity to always be available in the ancillary/balancing market if needed.)

In the long-term, electricity system operators and regulators must also ensure that enough capacity and flexibility remains in the system as power plants are retired and new plants are built. In Germany, regulators currently require some plants to remain in operation even if their owners want to retire them, and these plants are compensated through "capacity payments." The same is true in California, where there is an extensive regulatory framework in place, the Long-Term Procurement Planning (LTPP) process, which ensures that enough flexible capacity will be built in the future, on 10-year planning time scales.

It is also worth noting that Denmark experiences very little wind power "curtailment." "Curtailment" is the default option for dealing with wind power variability, in which wind power generation is shut off for periods of time to balance the grid. Curtailment results in economic losses, as the power that could be generated from the wind at that time is essentially wasted, with no economic benefit to anyone from it. Spain makes extensive use of curtailment, partly because it has so much wind power, and partly because its grid is essentially isolated from the rest of Europe (other than Portugal) and thus it can't sell excess wind power to its neighbors. California predicts higher levels of curtailment in the future unless improvements are made in the flexibility of its power system. In Denmark, wind turbines are curtailed at most a few hours per year.

Most people think of energy storage when it comes to integrating and balancing renewable energy on power grids. But the truth is, electricity storage is still very expensive, and is not yet necessary for balancing even high shares of 20-40%. Germany had plans to develop a whole network of pumped-hydro electricity storage facilities, but has reconsidered and abandoned those plans, and now many in Germany believe it can reach up to 40% shares of renewables or higher with no additional energy storage. And Denmark has no plans for electricity storage, partly because it has such well-developed heat (thermal) storage, which is much cheaper and equally effective for balancing variable renewables on the power grid. (However, long-term, Denmark is considering other ideas for energy storage, such as generating synthetic natural gas or hydrogen from excess electricity generation, and storing the natural gas and/or hydrogen (at least in small percentages) within the country's extensive natural gas storage capacities.)

In many countries, small-scale batteries at the building-level are being integrated with solar PV to enable households to consume their own solar generation without having to sell it into the grid. Such "self-consumption" can yield higher profits, depending on the electricity market and policy framework, if the avoided retail price of buying electricity is higher than the offered price for selling solar into the grid, such as from a feed-in tariff. In many countries where solar is becoming a high share of total generation, such building-scale storage will ultimately reduce the variability of solar power generation as seen at the system level, and can even contribute to overall system stability if smart inverters are used. But in Denmark, solar power is the not the primary source of renewables, and such distributed batteries have yet to make inroads.

Finally, an emerging innovation for integrating and balancing renewables is so-called "demand response." This is the process of varying the level of electricity demand in real-time, using smart-grid technologies and pre-designed operating regimes for what end-use equipment can be turned off, when, and for how long. These operating regimes are specified in contracts with electricity consumers, and allow for reducing demand, or "time-shifting" demand, without infringing on the needed energy services of those consumers. So-called "demand-response aggregators" may simultaneously control the demand of hundreds or even thousands of consumers, under specific contractual and technical parameters. These aggregators can thus vary large amounts of demand in response to signals from the power system operator for balancing power. In this way, demand response functions exactly the same as a balancing power plant, except instead of generating more power, demand response reduces consumption to provide balancing. In Denmark, there is a large potential for demand response, but Denmark has yet to made use of this potential. (In the future, some see a large potential for demand response integrated with the charging of future electric vehicle fleets.)

Denmark's experience may not be entirely relevant to much larger, less interconnected countries, for a number of reasons, including: (a) strong interconnection with neighboring countries; (b) much higher share of wind power relative to solar power; (c) use of CHP plants and heat storage to balance renewables; and (d) advanced market structures coupled with the Nordic Pool. Nevertheless, the several innovations noted in this article can be applied and adapted to virtually any power system in the world. These innovations represent a clear signal, an "existence proof" in the words of former U.S. Secretary of Energy Steven Chu, that high shares of renewable energy can be integrated and balanced on power systems while "keeping the lights on."