Grid Integration of Renewables in China: Learning from the Cases of California, Germany, and Denmark

A White Paper for the China Variable-Generation Integration Group (CVIG)

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1. Introduction

California, Germany, and Denmark are three leading examples worldwide of grid integration of variable renewable energy. How are these three jurisdictions managing to integrate and balance large shares of variable renewables today? What market and regulatory mechanisms and frameworks exist to integrate and balance these large shares? And how might this experience be relevant to China? This paper explores these questions and describes the current market and policy frameworks for renewables integration in these three jurisdictions.

These questions 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 15% might be possible as an upper limit.

Such "prevailing wisdom" of the past is clearly wrong, given the levels of renewable energy penetration already seen today in many jurisdictions, while clearly, the "lights are remaining on." California currently gets 20% of its electricity from renewable energy, including wind, solar, geothermal, biomass, and small hydro. Large hydro adds another 7%, bringing California's current share to 27%. By 2020, California's Renewable Portfolio Standard (RPS) policy requires a 33% share of renewables (excluding large hydro, which means around 40% total share of renewables by 2020). By 2020, a big part of California's renewables will be solar power, which has been growing vey rapidly in recent years thanks to a variety of state and federal incentives and rapid cost reductions. The high share of variable renewable power, both solar and wind, poses a challenge for California's power grid. But California's power companies, regulatory authorities, and power grid operator are today addressing this challenge successfully and collectively, and anticipate little difficulty through 2020.

In Germany, renewables now provide close to 30% of Germany's power on an average basis. And on some peak days in 2014, solar and wind alone supplied close to 80% of peak power demand at specific times of the day. In the future, Germany is targeting a 35% average share by 2020 and a 50% average share by 2030. Because of Germany's feed-in tariff law (EEG), renewables have dispatch priority, meaning they are always used first, sometimes leaving very little power demand left to be supplied by coal, nuclear, and natural gas plants. So far, Germany has managed well to integrate large shares of variable renewables and "keep the lights on." (Indeed, Germany has among the lowest power outage rates of any country.)

The recent solar eclipse in Europe in March 2015 further proves the success of grid integration in Germany today. During the eclipse, Germany experienced a ramp-down of about 6 gigawatts (GW) of solar generation capacity in one hour, followed by an increase of about 13 GW in capacity during a 75-minute period at the end of the eclipse. These are huge and unprecedented ramping rates for a power system, equivalent to turning on a dozen coal or nuclear plants in slightly more than an hour. Yet Germany's existing power market design and conventional generation resources handled these huge power swings with no power outages, by using existing mechanisms, described in this paper, including market price swings, imports and exports, and flexible response of hard-coal power plants. (Numbers are preliminary; a forthcoming report by Agora Energiewende will explain this case in detail.)

Denmark is targeting 100% of its electricity from renewables by 2035, arguably the most ambitious target of any country. Today, Denmark is already a leader. In 2013, the capacity of renewable energy was about 5 GW, which was just slightly less than the peak power demand of Denmark's entire power grid (about 6.5 GW). Most of this 5 GW of renewables is onshore wind, with a smaller share of offshore wind, and a small amount of solar PV (about 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 Denmark's power demand for that day.

2. How Is California Integrating and Balancing Renewable Energy Today?

California has many well-developed innovations, mechanisms and frameworks that are intended to ensure reliability of the power system as variable renewables grow in the future, and to "keep the lights on."

The most important of these frameworks is simply California's electricity market. The inherent flexibility of many of California's natural gas power plants, which altogether provide about 60% of California's power, allows these plants to profit from selling into both the normal day-ahead wholesale market, as well as the "ancillary" markets. The "ancillary" markets could also be called "balancing" markets, and are designed to provide balancing power for short-term fluctuations in demand and generation. Such ancillary/balancing markets are a normal feature of most power markets around the world today, and operate 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.

Most of the newer gas turbine power plants built in California have been designed with high levels of flexibility, which enables them to respond quickly to system conditions and profit from selling into the balancing markets. These gas turbines routinely and profitably provide the balancing power necessary to balance variable renewables, through the normal operation of the wholesale and ancillary/balancing markets. (Denmark is another exemplary case for the use of flexible gas turbines. In Denmark, gas turbines of recent vintage are able to quickly ramp output up and down between 50% and 100% of full output, at fast rates up to 3% per minute.)

As part of the electricity market operation, the power grid operator (ISO) has developed two innovative mechanisms for ensuring flexibility and reliability to balance variable renewables. The first of these is more of a mandate, which requires power generators to bid a portion of their most flexible capacity into the market at all times, so that he grid operator can call upon that capacity when needed to balance renewables. Such "must offer" market obligations can be found in many other jurisdictions besides California. For example, 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.

A second mechanism by the ISO is called the "Flexible Ramping Product." This market mechanism has been under development and discussion since 2011 and was expected to become operational in 2015, after further stakeholder meetings and discussions during 2014-2015. The basic goal of the Flexible Ramping Product is to enable the ISO to shift generation in time, from "low-ramp" periods to "high-ramp" periods.

Of particular concern to the ISO is the "high ramp" period in the late afternoons of the future, when solar output declines rapidly as the sun goes down, and total system demand simultaneous increases towards an early-evening peak. This "ramping problem" has been much-discussed in California, and is depicted as the ISO's well-known "Duck Curve." This curve shows that by 2020, up to 12 gigawatts of ramping capacity, equivalent to more than one-third of California's total power capacity, might need to be routinely switched on over a short 3-hour period in the late afternoons, to compensate for the declining solar power output.

With the Flexible Ramping Product, the ISO pays generators to remain "off" during low-ramp periods, so that the generator is then available to turn "on" during high-ramp periods, at the request (dispatch) of the ISO. The payments made to remain off during low-ramp periods, coupled with the payments when the generator is used during high-ramp periods, should be sufficient to compensate the generator for lost revenue while "off." Generators can voluntarily bid flexible capacity into this new market and earn extra revenue compared with selling into the normal wholesale market. The Flexible Ramping Product is designed to allow all types of generators to participate, including wind and solar, and also energy storage.

One key aspect of the Flexible Ramping Product is that it introduces a new scheme for allocating the extra costs of flexibility. The basic principle of this new scheme is this: the market costs of ramping capacity under the Flexible Ramping Product should be paid by those market participants who are creating the need for greater flexibility.

California also has extensive regulatory frameworks in place to ensure system reliability with high shares of variable renewables. The most important of these frameworks is the "Resource Adequacy" (RA) framework, which ensures that adequate balancing capability to integrate renewables will be available at all times. The electric utilities in California (the power generators) must show the regulatory authority, on both a monthly and annual basis, that they have sufficient capacity to meet the needs of the power system.

In 2011, the "Resource Adequacy" framework was strengthened to ensure greater flexibility. The "showing" of adequate generation capacity to the regulatory authority must now also include a subset of "flexible capacity" to provide enough balancing capability for a reliable power system. This is called "Flexible Capacity Need," and is defined by regulation as the capacity needed to "follow" the power system ramping up or down, depending on load and variable generation. The specific amount of "Flexible Capacity Need" is overseen and approved by the regulatory authority, the California Public Utilities Commission (CPUC).

A second regulatory framework in California relates to long-term planning. In the long-term, electricity system operators and regulators must 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.

Under the California LTPP framework, the regulatory authority (CPUC) reviews and authorizes the plans of utilities for procuring or building new capacity over the next ten years. It also authorizes power plant retirements, consistent with the needs of the power system. As part of the LTPP, the CPUC and the ISO conduct modeling studies that show capacity ten years ahead, and analyze whether that capacity provides adequate flexibility to accommodate the projected levels of renewable energy and other resources, to ensure system reliability.

Beyond the electricity market and these important regulatory frameworks, a number of other important innovations for flexibility have occurred in California in recent years.

1. Day-ahead weather forecasting. The incorporation of advanced day-ahead weather forecasting into the operation of power system control and dispatch 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. California has made great improvements in its modeling and forecasting of tomorrow's weather, to be able to predict and dispatch variable solar and wind in the normal day-ahead wholesale market.

2. Distribution system planning and innovation. The distribution system is the part of the grid closest to end-consumers. Historically, distribution utilities have not had to be innovators, as the job of grid expansion and replacement was quite simple. So distribution utilities have not needed an "innovation culture." However, in the future, distribution utilities will need to plan and innovate in a variety of new ways—to manage distributed generation, two-way power flows, demand response, storage, smart inverters, micro-grids, and a host of other trends. Distribution utilities will need to monitor, collect, analyze, and use data in completely new ways, and will need to analytically model their distribution systems to a degree far beyond current practice.

California is now putting itself at the forefront globally of distribution system planning and innovation. And California recognizes this as a clear priority for integrating and balancing variable renewables. Assembly Bill 327, which passed the California Legislature in 2013, requires utilities to submit "Distribution Resource Plans" that recognize, among other things, the need for investment in upgrading the distribution system to integrate cost-effective distributed generation. Assembly Bill 327 and an associated 2014 CPUC regulatory proceeding together represent a new initiative in California to address distribution system planning and innovation. The new regulatory framework should allow distributed renewables to better contribute to overall power system flexibility and reliability, for example through the use of "smart" inverters for solar systems, and "smart" demand-management strategies at the local level.

3. Interconnection standards and cost allocation for distributed generation and storage. California has a sophisticated regulatory framework, called Rule 21, for interconnection and cost allocation of distributed generation. Basically, distributed generation not subject to net metering must pay for the necessary distribution system upgrade costs. But the regulatory framework is evolving to account for distributed energy storage, for "smart" and flexible operation of distributed generation, and for minimizing economic costs. Rule 21 continues to be improved to better support the business case for distributed storage and distributed renewable generation.

4. Energy Imbalance Market. Today, there is a patchwork of 39 grid operators (ISOs) across the Western U.S., with insufficient coordination among most of them. Improving coordination is an opportunity for each ISO to better balance and integrate renewable energy. California and several western states are currently developing a proposal for an "Energy Imbalance Market" (EIM) that would allow surplus renewable generation to flow to neighboring electricity systems more easily, under new market mechanisms for the real-time (short-term) market. Day-ahead dispatch coordination across regions is also being discussed.

5. Power grid reliability calculations and dispatch. California's power control and market operations 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. This rapid updating 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.

3. How Is Germany Integrating and Balancing Renewable Energy Today?

Germany has so far managed to integrate and balance high shares of renewable energy with very modest changes to its power system. Bigger changes will be necessary in the future, certainly, including new market frameworks that are currently under active discussion. But today, Germany has managed quite well to reach close to a 30% share, for seven main reasons, which are discussed below.

The two most important reasons are: (1) the existing strength of its power grids; and (2) flexible operation of coal and nuclear plants (and to a lesser extent gas and pumped hydro). In addition, Germany has managed quite well because of: (3) better design of the balancing (ancillary) power markets, to make them more effective, faster, and open; (4) better system control software and day-ahead weather forecasting; (5) modest technical improvements to local-level distribution systems; (6) exports of power to neighboring countries; and (7) solving the "50.2 hertz" inverter problem.

(1) First, Germany's grids are already very strong, relative to typical grids found in other countries. This "grid strength" means that outages almost never occur, and that the grid has

more capacity than necessary given current demand. From the beginning, when Germany started connecting renewables in the 1990s, this underlying strength has meant that few upgrades have been necessary to accommodate renewables. And this strength continues to serve Germany well, as more and more renewables are connected to the system.

Even with strong grids, Germany has needed to strengthen some transmission lines, although not too many yet. Germany has also needed to plan for further transmission capacity to accommodate higher renewables. In particular, there is a need for additional north-south transmission capacity to manage the regional imbalance of generation and demand. Since 2011, the state regulator BNetzA has been required to conduct annual transmission planning analyses that incorporate projections of where renewables will be developed over the next ten years. An additional three north-south transmission lines are being planned as part of this process. In general, "network planning with future renewables in mind" has represented a major paradigm change in Germany. In conducting this planning, BNetzA has had to conduct future scenarios for renewable energy, and also engage in greater public discussion.

(2) Second, there is a surplus of dispatchable power capacity, counting hard coal, lignite, gas, and nuclear power plants. This means that an excess of flexible hard-coal power capacity is being used very effectively to provide sufficient flexible balancing power to offset (or balance out) the variability of renewables. (Nuclear and lignite are not so flexible, so even though there is surplus, they do not play as big a role in balancing as hard-coal plants do. And gas plants are being under-utilized because low costs of coal and low CO2 prices in Europe have made coal power much cheaper than gas power in Germany.) The surplus of dispatchable power capacity is partly due to reduced power demand in recent years due to general economic conditions, and partly because the huge upsurge in renewables was not anticipated to the degree it actually happened.

(Note that surplus coal power capacity, while it provides cheap balancing power for renewables, could be viewed negatively because it results in lower revenue for coal plant owners, and also results in more coal being used relative to natural gas. As nuclear and lignite plants are retired over the coming decade, the situation will change. Germany's 2014 "green paper" on future electricity market reform addresses this and many other issues.)

And most of the hard-coal power plants in Germany have been originally designed or later modified for flexible output—the ability to "ramp" on an hourly basis to much less than full output, and "cycle" on and off on a daily basis. The lignite power plants in Germany are less flexible, but many of these have been modified in recent years to allow ramping down to 40% of their maximum output, compared to only 60% previously. And many of the combined heat-and-power plants in Germany are not so flexible either, because they must operate above a minimum level necessary to provide heat in cold seasons, in the absence of any thermal storage.

Coal power plants can sell their power into the "ancillary" (also called "balancing") electricity markets in Germany. These markets are designed to provide minute-by-minute and hour-by-hour balancing of the difference between supply and demand. Coal power plants are not selling as much of their power into the normal wholesale markets, because wind and solar receive priority dispatch in those markets—i.e., get purchased first. So coal plants sell into the balancing markets as a modest alternative source of revenue, which creates more robust balancing markets and lower balancing-energy prices. In participating to a greater extend in the balancing markets, coal power operators have also developed better software to ramp their plants faster, and developed operational practices that reduce the stress on equipment from ramping and cycling.

It is not only coal plants that sell power in the balancing markets, but also nuclear, gas, and pumped hydro plants. Nuclear plants in Germany have also been designed to be flexible on a routine basis, to allow ramping their output up and down. (The German experience operating nuclear on a flexible basis is contrary to conventional thinking that nuclear cannot be flexible.) Gas turbine plants can also be flexible, although gas plants have not been able to compete very well with coal in recent years, as the price of gas has made them uncompetitive. Some gas plants are seeing service levels of only hundreds of hours per year, when they need to be used for thousands of hours to be profitable. So some gas-turbine plants are even being retired earlier than planned. Thus for economic rather than technical reasons, most of the balancing today is done with coal and nuclear, and less with gas and pumped hydro.

(3) Third, the balancing and intra-day electricity markets have been modified in ways that provide greater flexibility for renewables. Both of these markets provide additional power on short time frames (minutes and hours) to handle the imbalances between supply and demand that might occur as renewable output varies. The design and features of these markets are complex, but to put it simply, the market rules and designs have improved flexibility, opened the markets to more participants, allowed for faster balancing and ramping responses, and made it easier for demand response (see below) and storage to participate in these markets.

For example, in 2011, the German regulatory authority BNetzA designated that the intra-day market in Germany should be used for trading to handle the imbalances created by wind forecast errors. (The intra-day market existed before this, as part of the European Power Exchange and common EU market framework, but played a less significant role.) To achieve this, the intra-day market auction period was then reduced from 1-hour auctioning to faster 15-minute auctioning to handle faster system "ramping" dynamics.

(4) Fourth, power system operators (ISOs) have greatly improved their power control and dispatch software and analytical tools. One of the impacts of high shares of renewables is that the German network has had to contend with much higher system ramp rates than in the past, for example up to 1800 MW per hour, due to swings in renewable power output. ISOs have been able to successfully modify their software to accommodate higher ramp rates. In addition, day-ahead weather forecasting was greatly improved, which is a important part of integrating and balancing renewables in several countries (see the California and Denmark cases for more on day-ahead weather forecasting). System reliability calculations (so-called "N-1" contingency events) are also greatly evolved from 15 years ago to incorporate the effect of renewables. (And reliability checking also includes Europe-wide power-system security conferences every morning, among system operators across Europe, to coordinate their reliability).

(5) Fifth, modest technical improvements have been made to local-level distribution systems. At the distribution level, power utilities in Germany have had to cope with two-way ("reverse") flows of power from solar generators. This happens when solar generation increases in a local node higher than power demand in that node. In general, power systems were never designed for reverse flows at the distribution level. Some distribution utilities have had to do grid upgrades, including substations, transformers, and power lines. But many distribution grids have not yet required upgrades. Some distribution utilities have installed special tap-changing transformers to manage reverse flows. For many distribution utilities,

reverse flows are one of the main manifestations of high shares of solar, and the main challenge at the distribution level to-date.

Some distribution utilities have done pilot projects of smart-grid technologies. This includes new monitoring and data acquisition systems. In particular, some distribution utilities are starting to monitor voltages on the distribution grid, to better manage reverse flows. (One distribution expert said, “distribution utilities measuring the voltage on the network is akin to landing on the moon; who would have thought it was possible in earlier times?”) But in general, utilities are at the early stages of the planning and innovation that will be required in the future. (See the California case for more on distribution system planning and innovation.)

In the future, a variety of additional measures will be required on distribution grids to handle storage, demand response, smart inverters, two-way flows, “virtual power plants” combining generation with flexible load, integration with heat supply and heat storage, and other developments yet to be encountered on distribution grids. For example, some German distribution utilities are starting to forecast local renewables output to better manage the local grid. Others are considering how to integrate local balancing and peak-shaving with local combined-heat-and-power plants and heat storage. Some utilities are experimenting with smart inverters installed on distributed solar power systems as a new way to regulate distribution system voltage and reactive power. And some utilities are thinking about long-term planning and modeling for their local networks, a practice not seen historically.

(6) Sixth, when wind and solar reach very high levels of generation on peak days, this causes electricity market prices to decline in Germany, even go to zero or negative. This price mechanism has the effect of reducing output from other sources like coal and gas, and also causing those other sources to export their power to neighboring countries instead of trying to sell into the German market. (This also has the effect of reducing power prices in those neighboring countries.) However, the mechanism of importing and exporting power with neighboring countries plays a very modest role in balancing renewables. This is because imports are prohibited from participating in Germany’s balancing markets, and the bidding time frames for exports and imports (i.e., multiple days in advance, not day-ahead or intra-day) are too long to provide balancing functionality. (Note: imports and exports are mostly governed only by market mechanisms. However, sometimes cross-border exchanges become a technical issue, as when phase shifters were installed for transmission connections with Poland to limit flows of power into Poland. This was mostly a network stability issue.)

(7) Finally, One of the most comprehensive changes has been in response to the “50.2 hz inverter problem.” An inverter is the equipment that feeds solar power into the grid, converting the power from DC to AC. The inverter can sense the state of the grid and decide to “cut off” the solar output to the grid if conditions indicate an abnormal state (like an over-frequency of 50.2 hertz). Initially, all inverters on distributed solar PV systems around the country were designed with the same “cut off” frequency. However, with the growing share of power from solar, this meant that if the grid frequency went above 50.2 hz, <u>all</u> the solar could go off-line at once, which became a huge threat to system stability since there was so much solar. So inverter firmware was redesigned and inverters modified to vary the cut-off frequency. (This problem arose in the first place because no one in earlier years could have imagined that solar would become such a large share of total generation in Germany.)

4. How Is Denmark Integrating and Balancing Renewable Energy Today?

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. However, Denmark was beginning to balance high shares of wind power even before the Nordic Pool existed. Thus the "Danish story" is much more significant than just its interconnection with the Nordic Pool. That "story" 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. These innovations are discussed below.

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 combined heat-and-power (CHP) plants, including many small and flexible 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 predictable 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 continues to update weather forecasts in real-time. The control center also constantly compares the actual output of renewables against the prediction made the day before. The error of actual vs. predicted is then used to better forecast the output of renewables in the coming hours 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.

Beyond these four innovations, there 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. 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.

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.)

The case of zero or negative market prices highlights the fact that Denmark employs a market mechanism for reducing generation of both conventional and renewable generators when necessary. (Ordered shutdowns by the TSO are very rare.) Even so, zero or negative prices are not a common occurrence in Denmark, so don't much affect power plant revenue. But if zero or negative prices were to happen more frequently, this can affect plants' profitability, 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 when their output changes. 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.

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.)

5. Relevance of California/Germany/Denmark Experience to China

In most countries around the world, a central challenge of the power sector in the future will be how to integrate higher and higher shares of renewable energy, particularly variable renewables like wind and solar. Electric utility companies face some of the greatest challenges in planning, operations, and investment they have ever faced, as well as paradigm shifts in many of the fundamental tenets that have guided electric power planning, operation, and design for the past several decades. And a range of new market and business models are emerging, opening the power sector to a much broader array of companies, energy traders, and other market participants.

In thinking about the future of China's power sector, how relevant is the experience from California, Germany, and Denmark? This section considers several subject areas, questions, and the author's thoughts on relevance to China. Other experts may offer different opinions, so this section could be considered "food for thought."

Nine subject areas are considered here, with an emphasis on power system *flexibility* for integration and balancing:

(a) Market-based frameworks vs. regulatory or administrative control
(b) Flexibility of conventional generation
(c) Flexibility of demand/load
(d) Flexibility from regional interconnection
(e) Ramping capacity requirements and adequacy
(f) Distribution-level contribution to flexibility and grid services
(g) Integration with heat supply
(h) TSO/ISO operation and dispatch
(i) Least-cost approaches to system-wide "flexibility adequacy"

(a) Market-based frameworks vs. regulatory or administrative control

Questions for China: One of the most central questions for China is: to what extent should market-based frameworks be employed for integration and balancing of renewables, and to what extent should regulatory or administrative control mechanisms be used? This requires an understanding of the prevailing forms of electricity markets around the world, and how they are evolving in response to the need for more flexibility to integrate variable renewables. A variety of sub-topics include: energy-only markets vs. capacity markets; ramping markets; day-ahead vs. real-time vs. ancillary markets; reduction in market intervals (i.e., reduction from 1-hour to 5-minute intervals); inclusion of distributed generation and demand-response into markets; zero and negative market prices; economic curtailment vs. forced curtailment of renewables; and energy futures trading. Or, in lieu of markets, what are the regulatory or administrative alternatives to markets that might also suit the Chinese situation?

Relevance of experience to China: Germany and Denmark rely heavily on market-based frameworks for integration and balancing, and these frameworks appear to be working well. As part of the Nordic Pool market, Denmark can easily balance its variable wind generation using both wholesale and ancillary/balancing Nordic Pool markets. The recent experience in Germany with the March 2015 solar eclipse noted in the introduction is clear evidence that the electricity market by itself is able provide sufficient flexibility and balancing, at least under current conditions. However, Germany currently has a large surplus of generating capacity, and is also giving payments to some coal plants to remain operating due to the need to keep sufficient reserves for low-renewables periods. So Germany is not entirely relying just on the market, even today. And as the capacity surplus dissipates in the future, Germany may have to consider some outside-of-market regulatory measures (see also Germany's 2014 "green paper" on future electricity market design). California's electricity markets also provide strong support for integration and balancing, but California also has many regulatory measures in place, such as a requirement for utility companies to maintain adequate "flexible capacity," and "must-offer" obligations that require generators to bid their flexible capacity into the market. Denmark also has such "must run" obligations for generators, which are a similar form of regulatory intervention in otherwise "free" electricity markets.

(b) Flexibility of conventional generation

Questions for China: What flexibility characteristics of conventional generation (i.e., coal, gas, nuclear) are possible and desirable? What benchmarks exist? How feasible are retrofits to existing plants? What is the special role of combined heat-and-power plants? How can control/dispatch of variable renewables themselves (i.e., wind power) contribute to overall system flexibility and reliability?

Relevance of experience to China: The experience of Germany and Denmark in making their conventional generation plants more flexible is of great relevance to China. Both countries have managed to lower their minimum-output level of hard coal plants (in Denmark's case some down to 10%), and are increasingly using these plants as intermediate ("mid-merit") plants rather than as baseload plants. Of course, the problem emerges of lower revenue from lower full-load hours (lower capacity factors), and how to maintain the commercial viability of coal-plant owners. Here, Germany's current thinking about capacity markets for flexible capacity, vs. energy-only markets, can be relevant. California has many flexible gas plants, and gas provides 60% of California's power, but the California experience to-date, in terms of flexibility of conventional generation, is probably less relevant because of the primary role of coal for power generation in China.

(c) Flexibility of demand/load

Questions for China: What are the options and potentials to achieve flexibility of load, such as dynamic or time-of-use (TOU) rates, demand response (DR), energy efficiency, electric vehicle charging, and distributed electric and thermal energy storage?

Relevance of experience to China: The experience with demand/load flexibility is only emerging slowly in California, Germany, and Denmark (see also Section 6 below on Demand Response). Many studies and analysis, including those by the International Energy Agency, suggest that demand response and other demand-side measures may be the cheapest forms of flexibility, compared to supply-side flexibility or transmission and distribution measures. But there is still relatively little experience in practice with showing how demand-side measures can contribute. Germany has a small amount of demand response being sold into the ancillary/balancing markets. A number of other jurisdictions around the world make extensive use of demand response, such as ERCOT in Texas, and China can learn from these other jurisdictions. Experience with the contribution of dynamic or time-of-use rates to providing flexibility is also just emerging in many jurisdictions, although not so much yet in California, Germany, or Denmark.

(d) Flexibility from regional interconnection

Questions for China: How can strengthened transmission networks and regional trading mechanisms contribute to greater power system flexibility, reduced curtailment of renewables, and more effective utilization of renewables in remote areas of China? How are power systems incorporating greater regional interconnection, trading, and harmonization? What benefits could China gain from larger and more integrated grid balancing areas and authorities? China already has a long history of transmission planning for renewables, particularly in relation to the development plans for several 10-GW-scale wind power "bases" in several regions. And a lot of discussion and analysis has already taken place on how to better integrate wind in China by strengthening transmission interconnection.

Relevance of experience to China: There are many international examples to learn from, including Nord Pool, the development of grid codes among TSOs in Europe, the Europe ENTSO-E joint reliability framework, the Western U.S. Energy Imbalance Market, and long-term transmission planning for renewables in California, Germany, and Germany. The recent experience in Europe, including both Germany and Denmark, with long-term transmission planning and greater market integration and TSO coordination has clear relevance to China. And explorations in the Western United States, including California, on how to create larger and more integrated grid balancing areas, including the "Energy Imbalance Market" across multiple TSOs, are also very relevant.

(e) Ramping capacity requirements and adequacy

Questions for China: What will system ramping levels and rates look like in the future, due to variable wind and solar? How much ramping capacity will China need? What forms will that ramping capacity take? How will future higher levels of solar create steep morning and afternoon ramps, and in which regions of China?

Relevance of experience to China: Germany is already managing to handle very high ramp rates through its market framework, exports and imports, the ancillary/balancing markets, and flexibility of hard-coal generation plants. Germany was able to handle a 14 GW down-ramp in net load over 75 minutes during the solar eclipse in March 2015 through these mechanisms. California is projecting a 13 GW up-ramp in net load over 3 hours during the afternoons by 2020, given the projected penetration of solar PV by then. The California ISO is developing a "Flexible Ramping Product" market to handle greater ramping needs in an economically efficiency manner. However, until China faces much greater penetration of solar power in the coming 10-15 years, it appears that such ramping capacity considerations may not be so important for China in the shorter term.

(f) Distribution-level contribution to flexibility and grid services

Questions for China: How will distribution systems of the future contribute "grid services" such as flexibility and reliability? Sub-topics include: smart inverters, local area balancing with storage and demand flexibility, local energy markets, micro-grids, distributed reliability services, energy dispatch coordination between TSO and DSOs, and emerging re-definitions of the T-D boundary in terms of coordination and market functions.

Relevance of experience to China: California has just started a regulatory proceeding entitled "Distributed Resources Planning" (DRP), that represents the beginning of regulatory and utility action on these distribution-grid level flexibility issues. But this is still the early stages. Denmark already has some relevant experience, while Germany is awaiting a new electricity market law that many hope (or expect) will address some of these distribution-grid level issues.

(g) Integration with heat supply

Questions for China: How can heat supply, and especially thermal storage, contribute to system balancing and flexibility?

Relevance of experience to China: China has many CHP plants that could be made more flexible like those in Denmark, especially with the addition of thermal storage. But China's CHP plants are of a larger scale, and have not been designed for flexibility from the start, like many of Denmark's have. So Denmark's experience with heat supply integration is very relevant, but China may face a more difficult path in utilizing the potential flexibility of CHP, compared to

Denmark. Germany is moving along this path too, but has yet to go far. California has very few CHP plants and there is very little thermal storage to provide flexibility.

(h) TSO/ISO operation and dispatch

Questions for China: In what ways could improvements in system operation and dispatch in China aid the integration and balancing of variable renewables?

Relevance of experience to China: All three jurisdictions, California, Germany, and Denmark have developed advanced operation and dispatch mechanisms that help integrate and balance renewables. This includes day-ahead variable renewable forecasting (based on weather forecasts), shorter market time-frames (i.e., 5 minutes) for more flexible response, and more sophisticated power control and dispatch software.

(i) Least-cost approaches to system-wide "flexibility adequacy"

Questions for China: How much "flexibility" do China's power systems need in the future? What metrics should be used to measure and quantify power system flexibility? What are the cheapest options for flexibility? Considering all of the available supply-side and demand-side resources and their potential contributions to system-wide flexibility, which options are going to be the cheapest, to what extent can they contribute to total flexibility, and how can they being compared in a practical way?

Relevance of experience to China: the International Energy Agency in its pioneering 2014 book, *The Power of Transformation*, has developed models and analysis tools for considering the costs of flexibility across all options, both supply and demand, as well as transmission and distribution. But such comprehensive analysis of flexibility options, costs, and least-cost approaches has yet to be seen in practice anywhere in the world. California, Germany, and Denmark still have far to go in this area, and thus experience relevant to China is lacking.

6. Future Issues

Four future issues, among many others, stand out in considering the future of integration and balancing in California, Germany, and Denmark: Curtailment, demand response, storage, and capacity markets.

(a) Curtailment

Curtailment is a common "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. Some curtailment is "forced curtailment," in which the ISO or DSO orders a wind plant shut off, and some curtailment is "economic curtailment," in which zero or negative market prices cause wind generators to voluntarily reduce their output. And a third emerging form of curtailment is "ramping-market curtailment," in which wind generators would reduce output in response to price premiums offered in a ramping-related market, such as California's new Flexible Ramping Product. In general, it is often not clear whether reported levels of curtailment refer to forced curtailment, economic curtailment, or both, and this can create confusion.

Curtailment levels of wind power in many countries today are just a few percent, including countries with high shares of wind power like Spain and Ireland. Spain makes use of curtailment as a routine strategy 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, like Denmark for example. Portugal itself has no curtailment, as a law prohibits curtailment except in exceptional cases of grid reliability events (which haven't happened so far). Portugal instead uses pumped hydro and exports to balance wind. Many power grids in the U.S. have had wind power curtailment levels of roughly 1-3% in recent years.

Germany and Denmark have curtailment levels well below 1%. In Germany in 2013, only 0.3% of wind turbine output was curtailed. Strict curtailment rules have been instituted for ISOs, which have to curtail wind power output if transmission bottlenecks appear. However, curtailment may become a bigger issue in the future in Germany, particularly depending on progress with transmission upgrades and planning.

In Denmark, aside from occasional market-induced (negative price) curtailment ("economic curtailment"), wind turbines are curtailed by the TSO very rarely ("forced curtailment"), at most a few hours per year.

California today also experiences very little wind power curtailment, but modeling studies conducted by the California ISO show much higher levels of solar curtailment in the future, unless improvements are made in the flexibility of its power system. (Much of the increase in renewable generation in California between now and 2020, in meeting California's 33% RPS goal, will come from solar.)

(b) Demand response

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 California, there is a large potential for demand response. But so far, California has done only a few pilot projects, particularly for large energy consumers (like oil refineries), and for commercial air conditioning, among others. California has yet to make use of its huge demand response potential.

In Germany, there has been some movement towards demand response in Germany, but this is still small relative to the potential for providing flexibility and balancing. Some large power generators are selling this flexible demand into the balancing markets. Some generators are integrating demand response with their coal plants to give them economic flexibility for selling into the balancing market. Some system operators (ISOs) have also been contracting directly with large demand response providers on a pilot basis. However, the regulator does not explicitly include demand response in its planning, or set rules specifically for demand response.

In Denmark, there may be a large potential for demand response, but Denmark has yet to understand and made use of this potential. In the future, some in Denmark see a large potential for demand response integrated with the charging of future electric vehicle fleets.

(c) Storage

Most people think of energy storage first when it comes to integrating and balancing renewable energy on power grids. But many experts, scenarios, and analyses are now showing that power grids can reach high shares of renewables without much energy storage, at least in the range of 20-40% renewables share, because of the many other options for integrating and balancing variable renewables. This includes studies in recent years by the U.S. National Renewable Energy Laboratory, the International Energy Agency, Agora Energiewende, and others.

Energy storage has played almost no role in Germany's integrating and balancing renewables so far. 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. For example, Agora Energiewende studies show storage only being used after 2032, as Germany approaches a 50% share of renewables. And among many German experts interviewed by Eric Martinot during 2014, no one pointed to a company that had plans to invest in storage in Germany. Only a few pilot projects exist. Of course, there is interest in household-level storage in conjunction with the "self-consumption" economic model for distributed solar PV, now that retail electricity tariffs (and thus avoided energy costs from self-generation) are so much higher than the feed-in tariff rate for selling to the grid. During 2009-2013, the German government created a "small residential storage" program that provided incentives for distributed customer-side storage, with the aim of fostering self-consumption of distributed solar. However, this program continues at only a small scale.

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. 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.

California has a well-developed network of pumped hydro energy storage facilities that already provide some electricity storage capacity. And some homes and businesses are starting to integrate small batteries with solar. Overall, California has not yet turned to energy storage as a significant means of balancing renewable energy. However, there is a growing focus on storage, with new regulatory frameworks. So far, California has taken a regulatory approach, rather than a market approach, to storage. (California calls this approach "procurement.") In particular, electric utilities are required by law to collectively add 1.3 GW of storage projects in California by 2020. The first of these projects were just starting in 2014. Small building-level storage projects are also supported through California's Small Generator Incentive Program (SGIP).

(d) Capacity markets

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, some coal and gas plants are required by the regulatory authority to remain operating, even if they generate very little power. These plants have been determined to be necessary for covering regional bottlenecks or seasonal variations (where the plant might only be needed in winter, for example). These plants receive "capacity payments" to cover their costs of operating at zero output. However, a full "capacity market" does not exist in Germany, although many have been debating the merits of one.

In California, there are no capacity markets, and experts interviewed in 2014 don't consider it likely that California will adopt capacity markets. (Other power systems in the United States do use capacity markets.) Rather, in California, there is an extensive regulatory framework in place, called 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. This regulatory mechanism mitigates the need for capacity markets.

7. Conclusion

California is already at 27% renewables, counting large hydro. Germany is close to 30%. Denmark is already beyond a 33% share from wind power alone. All three of these jurisdictions are managing successfully to integrate and balance these large shares today, clearly refuting the "prevailing wisdom" of past decades. Their experience is relevant to China, but in different ways. And the issues they face in the future are also different.

California continues to grapple actively with the issues necessary to ensure the "lights stay on" in the future. These issues include ramping rates, over-generation, grid reliability frameworks and modeling methodologies, conventional plant retirements, capacity payments, rate design and interconnection, energy storage tariffs and interconnection, demand response, and advanced power system modeling methodologies that account for the presence of high shares of variable renewables.

Germany faces similar challenges, and in 2014-2015 was engaged in a stakeholder process based on its 2014 "green paper," and was developing reform of its basic electricity law and market framework through a "white paper," including considering the ideas of capacity markets and some type of additional carbon price, beyond the carbon price mechanism of the EU Emissions Trading System, to help reduce the use of carbon-intensive lignite in power generation.

Denmark's experience could be considered relatively unique 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. However, the several innovations noted for Denmark in this paper can be applied and adapted to virtually any power system in the world. For example, the innovation of cheap thermal storage used for balancing purposes could be adapted to warm climates by adding thermal storage to air conditioning (chillers) instead of heating. And advanced weather forecasting and quicker and more flexible conventional power plants can be applied anywhere.

The experience from California, Germany, and Denmark represents a clear signal, an "existence proof" in the words of former U.S. Secretary of Energy Steven Chu when he recently spoke of international experience on grid integration of renewables, that high shares of renewable energy can be integrated and balanced on power systems while "keeping the lights on." Given the current situations and active trends underway, there seems little doubt that California, Germany, and Denmark will succeed in balancing and integrating even higher shares of renewables in the future. China should manage to do the same, and the logical beginning is the most recent round of electricity sector reform that was underway in 2015.

8. Sources and Acknowledgements

The information for this paper comes primarily from an extensive series of interviews, discussions, and workshops conducted by and attended by the author, Eric Martinot, during 2014 and early 2015. The author lived in Berlin, Germany for three months during 2014 and conducted an extensive set of interviews with over 30 experts, utility staff, policy-makers, and managers of private companies. He also attended a number of conferences and workshops of direct relevance. The author also was resident in San Francisco, California for 3 months during 2014 and early 2015, as a visiting fellow with the California Public Utilities Commission, and conducted extensive research, including interviews with a variety of stakeholders. Finally, the author interviewed staff, and attended several presentations of the Danish TSO, Energinet.dk, during 2014 and early 2015.

A much more extensive set of references and citations is possible, but not provided here. Some basic sources that the author has used in understanding these issues include:

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