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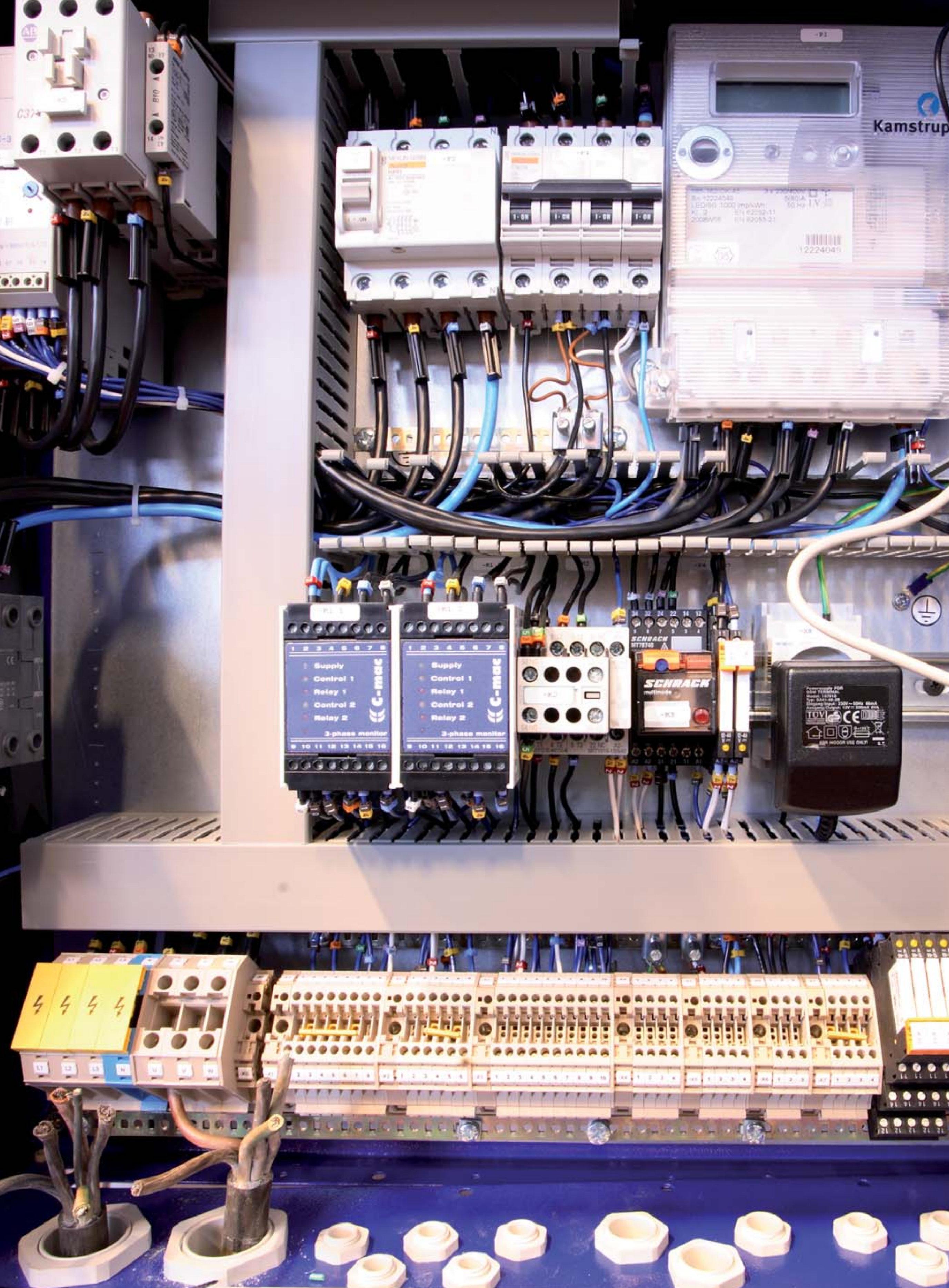
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Towards a new grid infrastructure: Denmark as a full-scale laboratory

Jacob Østergaard

A windy morning in January 2025, Denmark's nearly 5000 wind turbines are running at full speed and generate 6000 MW – enough to cover the electricity demand of your house and the rest of Denmark. Together with 1000 others, your house is a member of a virtual power plant in your region. This system automatically trades the electricity you need on the spot market, where the wind power and generation from other CO_2-neutral sources are sold.

This morning, the market price is relatively low due to the extensive wind power generation, so the electric car in your garage has decided to fully charge its battery, even though it knows that you will only commute the usual 40 km today. Despite the weather forecast, the weather is changing. At 07:00 the wind speed starts to slow, and after 30 minutes wind power generation has dropped to 4000 MW. The reduction in expected generation is reflected in a real-time price signal the system operator broadcasts to all end-users and virtual power plants in the system. The signal indicates that reducing demand to ensure the balance will provide economic benefits. Your electric car, which is now 90% charged, decides to stop charging, and the difference between the real-time price signal and the previously traded spot-market price results in you earning (saving) €3.

At 07:30, you open the refrigerator and are about make your brown-bag lunch. In a flash, as you hardly notice, the buzzing of your electric pantry stops before you close the door. Your refrigerator has just made a small but valuable contribution to preventing a large electricity blackout. A sudden failure in a large transformer station outside the city has resulted in tripping of a 400-MW offshore wind farm. The fault is very severe, because 5 minutes earlier an important transmission cable incidentally was taken out of operation. Back in 2009 this would definitely have led to a major blackout, which would have taken many hours to restore manually and tremendously affected the entire society. But here in 2025, your refrigerator and other intelligent appliances together with some online biomass-fired thermal power plants quickly re-establish the power balance. The sudden lack of generation results in a rapid drop in the frequency of the system, and the electronic controller of your refrigerator detects this. In a split second, the controller decides to disconnect from the grid. So do thousands of other appliances. The drop in frequency is stopped, but the frequency is still low.

To re-establish normal frequency and restart your refrigerator, the system operator adjusts the real-time price signal to activate more responsive demand or generation. Your car in the garage, which has advanced built-in vehicle-to-grid functionality, now starts selling power to the grid by discharging its battery. You have pre-programmed the car, so unless you plan for a long-distance drive, the car is allowed to discharge its battery to 75% if this will save you money. The real-time price is twice the spot-market price now, so you earn another €3. The extra generation in the system brings the frequency back to the normal 50 Hz, and your power system–friendly appliance automatically returns to normal operation after 5 minutes.

The tripping of the large wind farm has resulted in unintentional power flows in the grid, and a sneaking voltage collapse is threatening the system. A new early-warning system based on phasor measurement units has been installed that can automatically detect the approaching voltage collapse. Further, this system evaluates potential actions to avoid the collapse and warns the system operator or, if time is limited, directly activates the most optimal action. This specific morning, the phasor measurement unit–based system decides to isolate three local subgrids in islanding mode, relieving the pressure on the system. Local controls in the three subgrids take over and ensure uninterrupted operation without any customers noticing (Fig. 12.1).

Intelligent energy solutions

This story could be a simplified picture of the future electric power system in 2025, which is designed and operated to accommodate large shares of renewable energy. New intelligent energy solutions based on information and communication technology and automation will have been introduced. The system will differ substantially from the present grid, which is far more passive and has limited capability to absorb intermittent generation.

The described future paradigm shift of the power system is needed to achieve the political goals for renewable energy. In 2007, the Government of Denmark adopted an ambitious energy policy requiring that renewable energy comprise at least 30% of demand in 2025 and that fossil fuel use be reduced by 15%. This is expected to require that wind energy comprise half of electricity generation in 2025. The political objective is 100% independence of fossil fuels in the long term.

Climate change is not solely on the political agenda in Denmark. The European Union (EU) has agreed on binding targets for reducing CO_2 emissions. Nevertheless, Denmark has chosen to be in the forefront. The 20% share of wind power in Denmark's electric power system and the United Nations Climate Change Conference in 2009 in Copenhagen are visible results of this.

There is consensus in the international energy community that the electrical grid needs to be transformed into an intelligent user-interactive energy infrastructure. The EU has established a European technology platform for the electricity system of the future, called SmartGrids, gathering leading European industry and academia within electric energy. The vision is to enable the future smart grid: an electricity network that can intelligently integrate the actions of all users connected to it – generators, consumers and those that do both – to

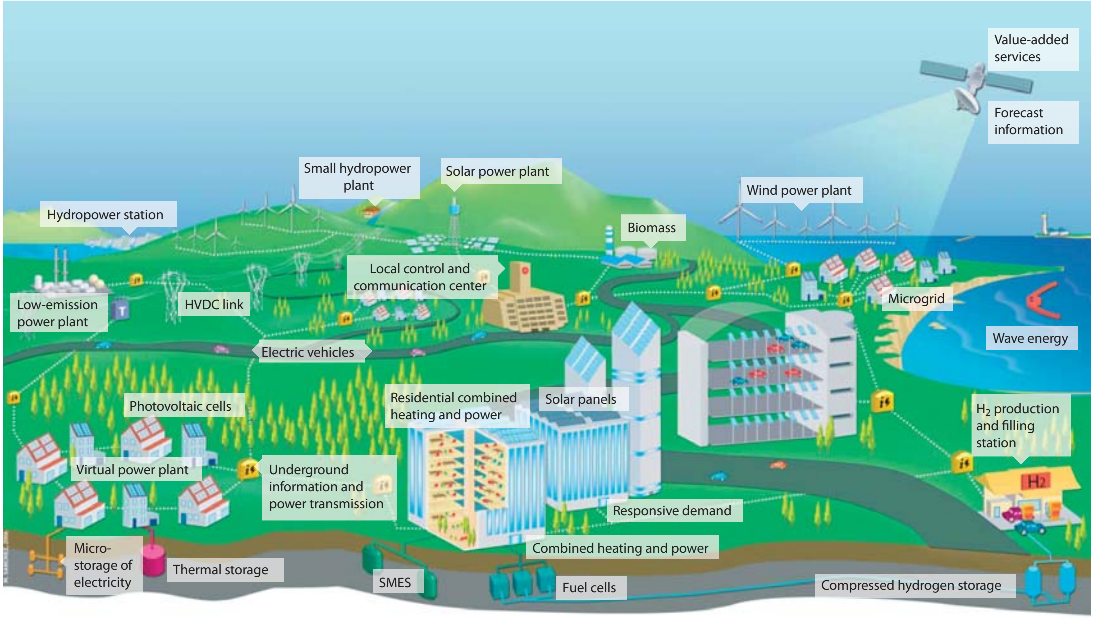


Fig. 12.1. The smart electrical energy system in 2025: wind power and other renewable energy sources cover 50% of the average electricity demand, and intelligent energy technologies based on information and communication technology assist in maintaining the power balance and stability. HVDC: high-voltage direct current. SMES: superconducting magnetic energy storage.

efficiently deliver sustainable, economical and secure electricity supplies (Fig. 12.2).

Denmark's electrical transmission system operator, Energinet.dk, and DTU have taken steps to bring Denmark into a global leading position within intelligent power systems. In October 2004, Eltra (now Energinet.dk) and DTU agreed to establish the Centre for Electric Technology at the DTU Department of Electrical Engineering. Since then, the Centre has been developed into a vital research group with about 40 researchers and a large portfolio of research that is highly relevant for an environmentally sound future. In 2008, the partnerships of the Centre for Electric Technology were extended to include DONG Energy Generation and Siemens Wind Power.

The Centre for Electric Technology aims at developing a more intelligent, flexible and automated electric infrastructure to handle the future expansion of renewable energy on a liberalized energy market maintaining a very high reliability of supply. The Centre has developed a research plan and has decided to focus the research within intelligent electric power systems, with the three focus areas:

- system integration and grid connection of distributed generation and renewable energy sources;
- new network and control architectures; and
- increased flexibility through end-use demand response and integration with other energy systems.

Some of this ongoing research is introduced here.

Intelligent appliances can improve system stability

In interconnected electricity systems, electricity demand and generation must be balanced in real time. An imbalance is directly reflected in the frequency, which deviates from its normal value of 50 Hz (in Europe). After faults and during changes in generation or demand, the balance must quickly be re-established by activating reserves, typically large thermal power plants that are prepared to change

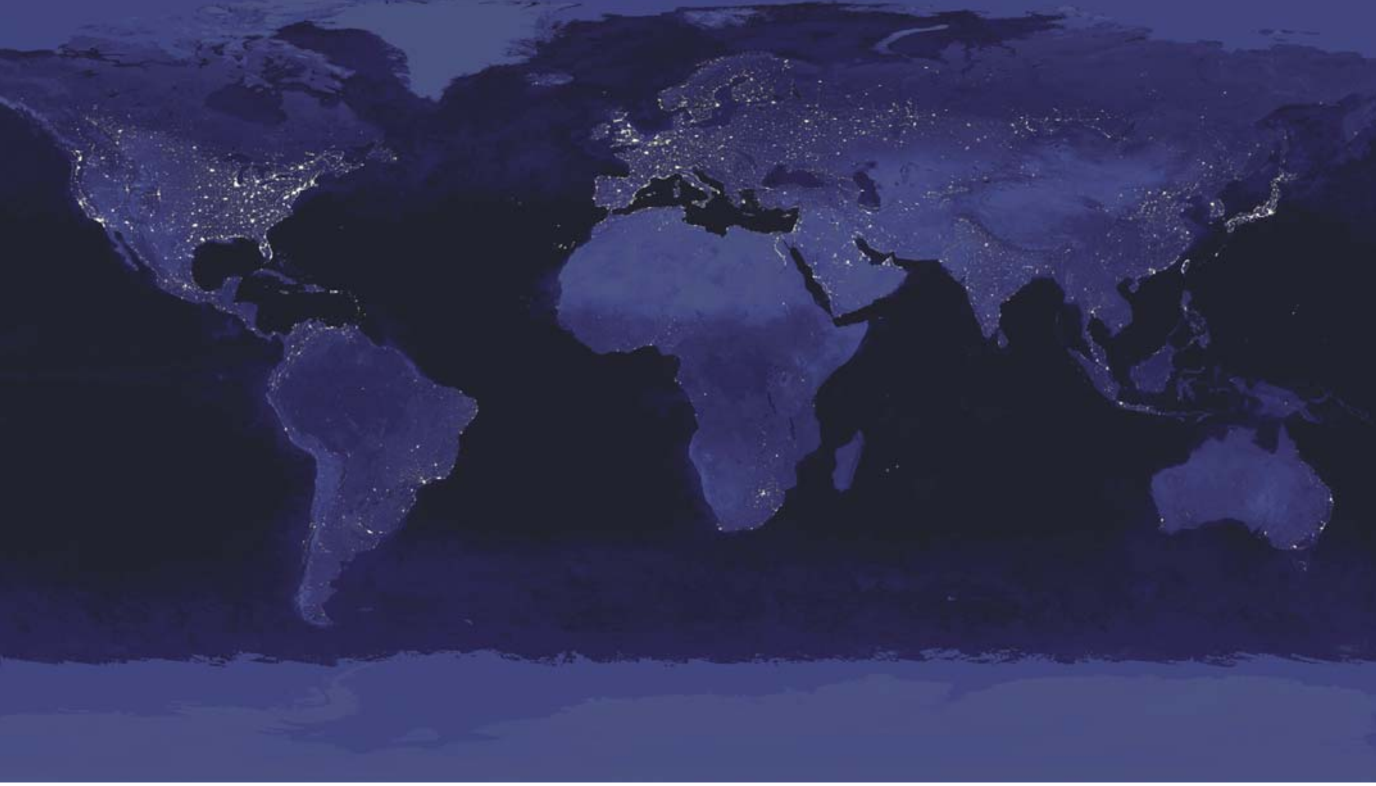


Fig. 12.2. Global electricity consumption is steadily increasing; here is artificial light seen from space in 2000

their generation. In the Nordic power system, Nordel, the frequency-controlled disturbance reserve must be 1000 MW and must be activated linearly between 49.9 and 49.5 Hz. This reserve is distributed to the different countries according to the size of the dimensioning fault: for example, eastern Denmark must have 100 MW. These reserves are costly (up to €100,000 per MW per year). Further, this type of frequency-activated reserve maintains the normal continuous frequency control. The potential and economy of loads compatible with demand for frequency-controlled reserve have been investigated, several types of control logic for demand for frequency-controlled reserve have been developed, power system impact has been analyzed, potential business models have been designed and an implementation strategy has been suggested. The results show that the demand for frequency-controlled reserve technology is promising from several perspectives.

Technically, demand for frequency-controlled reserve can be used to provide reserves and enhance the control of power system frequency while fulfilling power system requirements such as linear activation according to frequency deviation. Environmentally, the demand for frequency-controlled reserve technology is pollution free, in contrast to traditional generation reserves. The cost of such reserves can be low and an attractive business model exists for both society and the involved parties. Given that fluctuating renewable energy is continually being increased in power systems, frequency control will become critical in the future. The demand for frequency-controlled reserve is a novel technology that can facilitate such trends by providing high-quality service at low cost and with zero pollution. If implemented, unique advantages in market competition can be gained to realize the business potential for manufacturers in Denmark. The Centre for Electric Technology has started experimental research involving testing and demonstrating 200 appliances with demand for frequency-controlled reserve together with Vestfrost A/S, Danfoss A/S, Electronic Housekeeper ApS and Ea Energianalyse A/S (Fig. 12.3). Denmark's Energy Technology Development and Demonstration Programme (EUDP) is funding the project.

Early-warning systems and system awareness tools

A phasor measurement unit is a device that provides synchronized measurements of real-time phasors of voltage and current and measures the frequency. A time signal from GPS (Global Positioning System) satellites synchronizes the individual phasor measurement units. Synchronizing the sampling process of the voltage and current, which may be hundreds of kilometers apart, enables measured phasors from different locations in the power system to be put on the same phasor diagram. This could not be done in the past without very expensive atomic clocks.

The accuracy of phasor measurement units is defined in terms of total vector error, which should be within 1%. This implies a phase error within ±0.01 rad (±0.57°) or a maximum time error of ±26 μs. This high accuracy of the phasor measurement units elevates the standards of power system monitoring, control and protection to a new level.

Researchers and engineers at the DTU Centre for Electric Technology have developed phasor measurement units by combining scientific competencies within electric power engineering, signal processing and computer science. Phasor measurment units have been manufactured and together with Energinet.dk installed in seven locations in Denmark's 132–400 kV transmission systems.

Phasor measurement units most affect power systems operation through applications that use their unique capabilities to provide synchronized measurements at dispersed locations in the grid. Such applications require phasor measurement

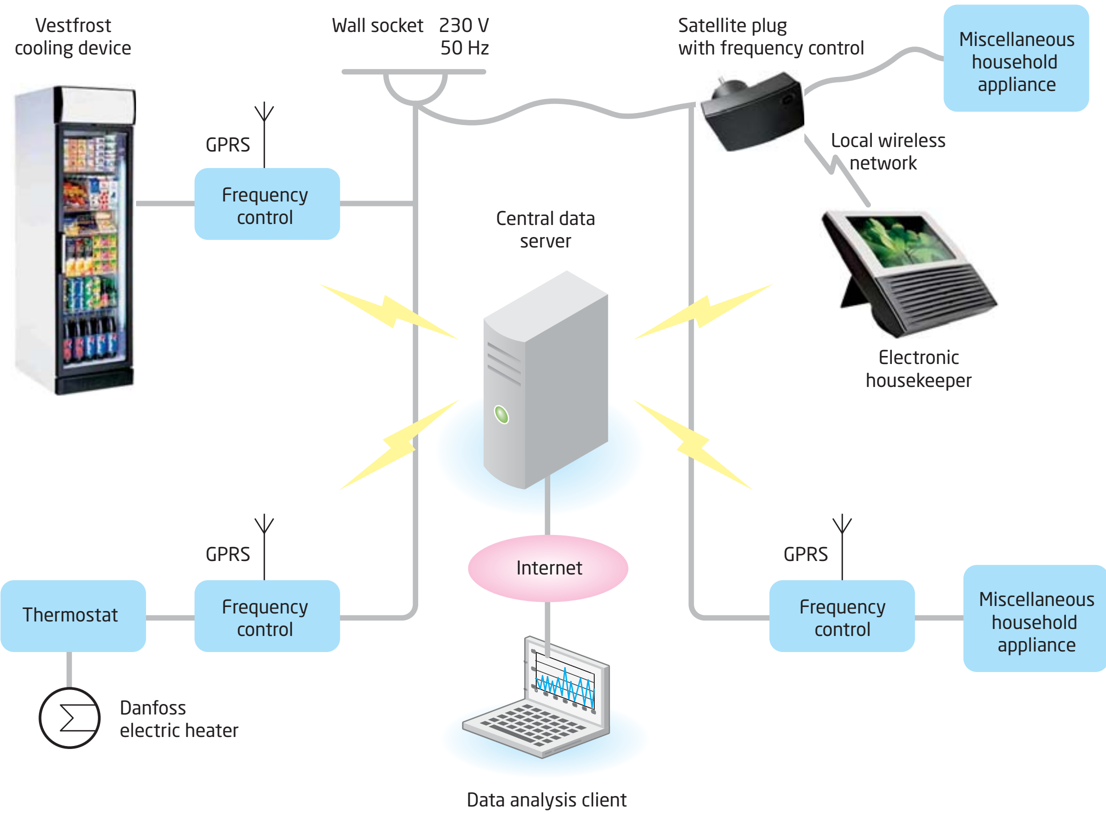


Fig. 12.3 Set-up for demonstrating 200 intelligent appliances supplying a frequency controlled reserve. GPRS: general packet radio service

unit data to be collected at a control center where the data can be analyzed. For research purposes, a server at DTU collects the data from Denmark's phasor measurement units (Fig. 12.4)

In electric power systems in which the proportion of renewable generation has increased significantly, the existing grid is not always designed to cope with the new transmission requirements. In these cases, phasor measurement unit applications can provide intelligent cost-effective monitoring and control solutions that reduce the need for new transmission lines. Ongoing research is taking place at the DTU Centre for Electric Technology in collaboration with major partners regarding online assessment of the power system stability, system awareness tools and blackout prevention systems. This research involves fundamental theory development, algorithm development, advanced simulation, processing of large quantities of data, developing software and experimental verification.

Electric vehicles can help integrate wind power into the grid

An electric vehicle results in less than half the CO_2 emission of a conventional car with an internal combustion engine. Intelligent charging of the car based on the availability of wind power can further reduce or eliminate transport emissions. Electric vehicles also have the potential to play a major role in the economical and reliable operation of the grid with high penetration of renewable energy and they will be an important measure for balancing Denmark's energy system (Fig. 12.5). Analysis by Energinet.dk shows that introducing electric vehicles together with heat pumps can account for about 40% of Denmark's obligations under the EU's 2020 targets regarding: 1) renewable energy penetration, 2) CO_2 emission in sectors not subject to quotas, 3) the share of renewable energy in transport and 4) energy efficiency.

An electric vehicle will be a storage device for

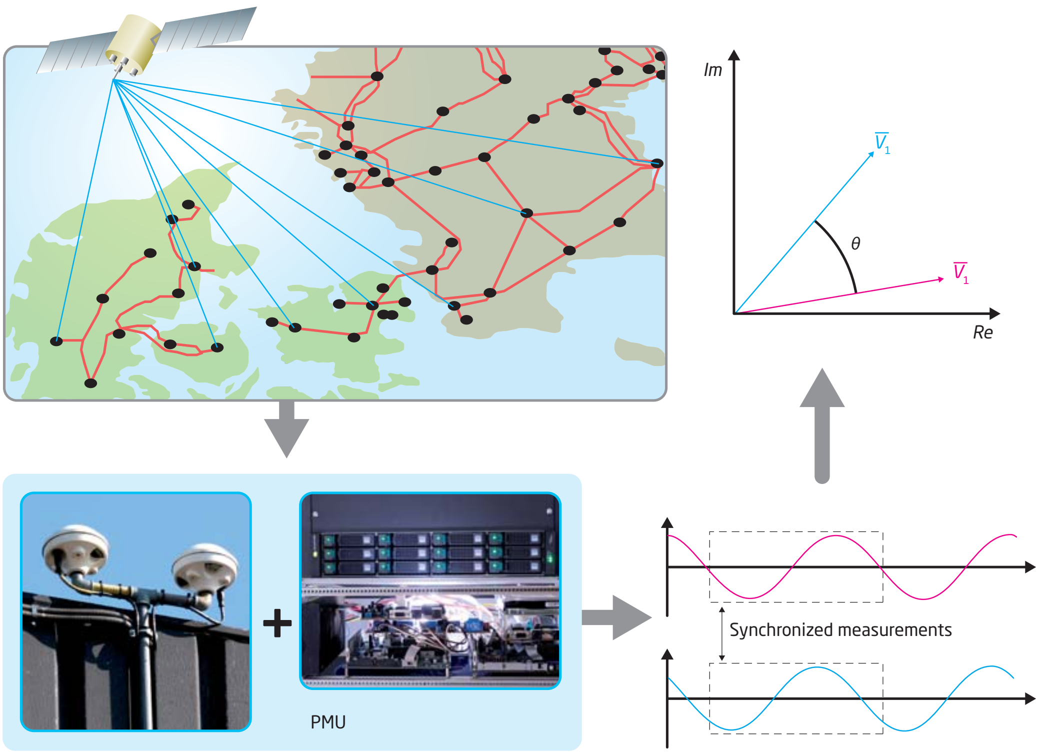


Fig. 12.4. A novel measurement system based on phasor measurement units (PMU) providing measurements in the power system using GPS signals for time synchronization. Differences in the phase angle of the measured 50 Hz voltage signals at various measuring points (illustrated with two measurements – a red one and a blue one) can be determined by the very accurate time stamping and used for advanced supervision, protection and control applications.

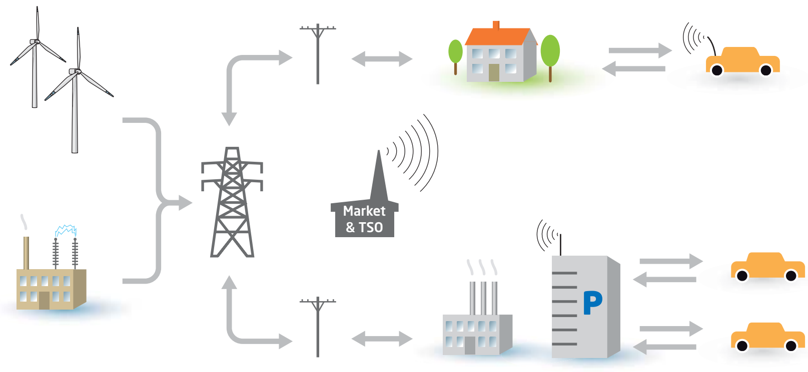


Fig. 12.5. Electric vehicles with vehicle-to-grid functionality can dynamically communicate with and exchange power with the electric power system and thereby ensure real-time balancing of the fluctuating wind power. TSO: transmission system operator.

smoothing electric power fluctuation from renewable resources, especially wind power, and provide valuable system services for reliable grid operation. With the proper technology, the cars can run on wind power and enable an increased share of renewable energy for supplying conventional electricity demand and thereby provide an overall economical, reliable and sustainable energy system.

Denmark does not have a car industry, and Denmark's background for developing electric vehicles themselves is limited. Nevertheless, Danish companies and research institutions have very strong knowledge and competencies regarding designing, developing and operating power systems with high penetration of distributed generation. Further, Danish industry is involved in technologies critical to the widespread use of electric vehicles such as information and communication technology and control systems for charging and discharging batteries. This forms an ideal base for developing systems and integration solutions for electric vehicles (Fig. 12.6).

Denmark's competencies can be used to develop optimal system solutions for integrating electric vehicles with the electrical system, including network issues, market solutions and optimal interaction between different energy technologies. Further, Denmark's electric power system provides an excellent platform for demonstrating developed solutions, thereby providing the commercial basis for exporting Denmark's technology. Further, the advantage of being a first mover constitutes a business advantage and enhances the opportunity for strongly influencing future standards for system integration of electric vehicles to achieve optimal utilization of the electric vehicles in the power system.

In spring 2009, the Edison project was started. The project is the world's largest electric vehicle project, focusing on intelligent integration of electric vehicles with a power system based on renewable energy. The consortium partners in the project are the Danish Energy Association, DONG Energy, DTU Department of Electrical Engineering, DTU Department of Transport, DTU Department of Informatics and Mathematical Modelling, EURISCO ApS, IBM, Risø DTU National Laboratory for Sustainable Energy, Siemens and Østkraft (Bornholm's distribution system operator).

Fig. 12.6. Students and employees from the DTU Centre for Electric Technology examine the Tesla Roadster (pure electric, 0–100 km/h in 4 s, 250 hp, >200 km/h, 360 km per charge). Today electric cars can be compared with conventional cars based on internal combustion engines.

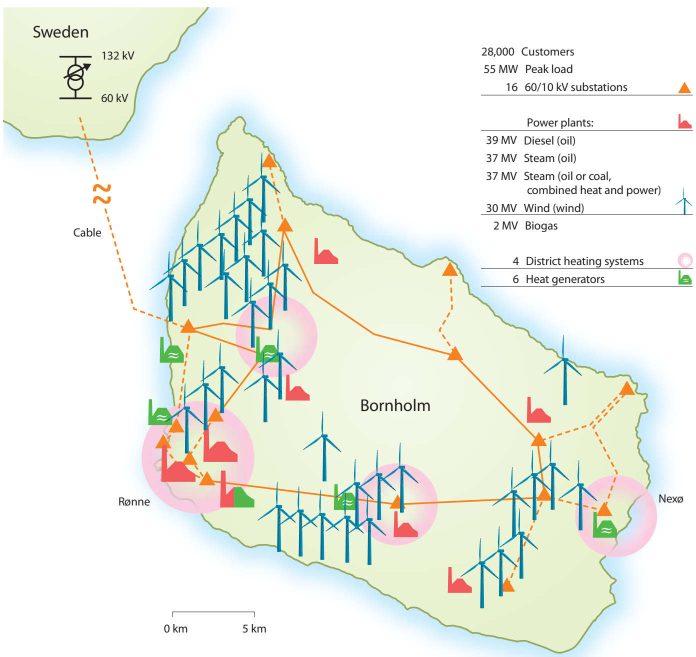
Bornholm as a full-scale laboratory for intelligent energy

From an international perspective, Denmark's electric energy system is unique, with 20% penetration of wind energy, and during selected hours, wind power alone exceeds the demand. Further, Denmark's faces steps no country has taken: developing a system that can manage wind power and distributed energy resources of the planned future proportions. Denmark is probably facing some of the greatest technology developments in its power system so far, in particular because the system changes are expected to involve major implementation of modern information and communication technology that has not been used in the power sector before.

Denmark's unique power system provides very good opportunities for developing, testing and demonstrating new innovative solutions. Combining advanced experimental facilities at the universities with a full-scale true test-bed can provide a quantum leap for developing future low-carbon electric energy systems, thereby strengthening the energy sector in Denmark in general and potentially putting Denmark in the forefront of the global market for intelligent energy solutions.

The ongoing research at the DTU Centre for Electric Technology benefits from Denmark's unique electrical system. Research is being carried out in collaboration with Østkraft, Bornholm's distribution system operator. Bornholm corresponds to about 1% of Denmark in land area, load and population. The island has a representative distribution grid with 30% wind power penetration, more than 27,000 customers and a peak load of 55 MW. The system can be isolated from the interconnected Nordic grid, and a power system with truly high wind power penetration can be studied. This makes Bornholm the perfect case for research, development and demonstration of new technology.

When the Bornholm grid is electrically isolated from the larger grid, frequency stability can become problematic, and today most larger wind turbines have to be shut down, even during such well-planned operations. The current research focuses on some of the problems seen in Bornholm related to high wind power penetration and includes developing islanding capability, using phasor measurement units, demonstrating electric vehicles, developing coordinated frequency control by wind turbines and experimenting with demand as frequency-controlled reserve. The ambition is to carry out research, development and testing within about 5–8 years leading to full-scale demonstration of the future intelligent electric energy systems of 2025 described previously.



Conclusion

A huge research task is ahead in the coming years. The future intelligent user-interactive electricity system has to be developed to efficiently deliver sustainable, economical and secure energy and fulfill the political ambitions regarding CO_2 emission. New technologies have to be introduced and new

Fig. 12.7. Bornholm's power system, with more than 30% wind power penetration and unique potential for isolated operation in island mode, makes it a terrific full-scale laboratory for future intelligent power systems.

system architectures need to be developed. A new architecture will be based on subgrids with increased integrated control of the distribution and transmission systems and active network functions at the distribution level, enabling participation in the electricity market and delivery of services from distributed demand, generation and storage resources. Developing coherent and consistent control architectures will be the prerequisite for releasing the potential of many of the resources in the distribution networks and for an overall economically optimal system design.

Denmark has the opportunity to be a global front-runner in this development. Several new technologies and solutions for the future intelligent grid are already on their way based on the ongoing research. Denmark's unique grid with a high share of wind power constitutes a unique full-scale laboratory facilitating the future technology development – it provides a unique opportunity for Denmark to show the way and provide the global solutions for the long-term goal of 100% independence from fossil fuels.

The author

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More to explore

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