Chapter 24

Smart grids, smart loads, and energy storage

Joachim Luther

Joachim Luther was born 1941 in Hanover, Germany. He obtained his PhD in atomic physics at the University of Hanover in 1970. From 1974 – 93 he taught at the University of Oldenburg as Professor of Applied Physics. His main research topics were oceanographic laser remote sensing and the physics of renewable energy sources. In 1992 he became a member of the board of directors of the International Solar Energy Society. From 1993 – 2006 he served as Director of the Fraunhofer Institute for Solar Energy Systems and Professor of Solid-State Physics and Solar Energy at the University of Freiburg. Luther was a member of the German Advisory Council on Global Change, and joined the Expert Commission of the German Government on Science and Innovation in 2007. Since 2008 he has served as Chief Executive Officer at the Solar Energy Research Institute in Singapore (SERIS).

The energy system of the future must be sustainable and must, therefore, be largely based on renewable energy sources. Solar energy will play by far the most important role, but wind energy, biomass, hydro energy, geothermal energy, ocean energy, and others will also contribute to a sustainable energy supply. The use of fossil fuels will remain essential in the next few decades, during which a sustainable energy supply system must be established (WBGU, 2003). However, during this transition period the carbon-dioxide emission rates of fossil fuels must be greatly reduced, for example through technological advances and the large-scale introduction of carbon-capture technologies such as sequestration. In this context it is essential that reliable and cost-effective carbon dioxide sequestration technologies become available quickly.

Due to energy scarcity, the rising cost of energy, and the fact that carbon dioxide emissions must be greatly reduced, efficiency of energy use will become increasingly important. In sustainable energy systems this will lead to buildings characterized by an extremely low demand for external energy input for heating and air-conditioning, and to a highly efficient transport system based largely on electric batteries, biofuels, and novel fuels like hydrogen (generated using electricity from renewable sources) or hydrogen derivatives. Simultaneously, electricity will become by far the most important form of distributed and traded energy. The question this raises is how to implement a reliable electricity supply system that distributes the required energy and that is powered to a large extent by fluctuating energies from solar and wind resources.

The answer has several principal components:

1. distributed energy generation and smart grids;
2. energy meteorology;
3. smart loads;
4. careful use of dispatchable sources for electricity generation; and
5. energy storage systems (both centralized and decentralized).

The balance in electricity supply will be provided by a mix of electricity generating systems powered by fossil fuels, biomass, or hydro energy (point 4 from above). This point will be addressed in combination with the discussion of point 1. In general, it will be essential to merge information technologies, power generation, power distribution, energy storage, and demand-side management in an optimal way.

Distributed energy generation and smart grids

In contrast to fossil-fuel and nuclear systems, renewable energy sources – particularly solar, wind and biomass – are characterized by a relatively low spatial power density (W/m^2). Thus, these technologies will necessarily be large-area technologies (several percent of the global land surface will be required), and they will be applied in a highly distributed manner (to use as far as possible existing anthropogenic structures such as buildings as installation sites and in order to avoid unacceptable environmental effects). The low power density leads, on the one hand, to relatively high initial investment costs (however, the 'fuel' for operation is free); on the other hand, large-area statistical effects even out the characteristic fluctuations of solar and wind energy availability.

The temporal variations in solar and wind energy fluxes have two components: a trend pattern (daily and seasonal), and a random (or stochastic) component. The stochastic component is characterized by a spatial coherence that decays approximately exponentially with increasing distance between the sites. That is, the power fluctuations of two wind turbines situated at the same site are considerably larger than the fluctuations of the lumped power output of two turbines installed much further (e.g., 100 km) apart. The 'decay constant' mentioned above is roughly inversely proportional to the frequency of the power fluctuations. In other words, high-frequency fluctuations (in the range of seconds to minutes) are evened out much more effectively than low-frequency fluctuations (in the range of hours) (Beyer *et al.,* 1993). By means of computer simulation it has been shown that for large-area grids (with spatial dimensions exceeding 1000 km) and distributed generation of wind and solar electricity, the stochastic fluctuations with frequencies higher than 30 minutes are almost completely eliminated (Bubenzer and Luther, 2003).

Thus, if very low-frequency fluctuations are compensated by dispatchable electricity generators connected to the grid (powered, for example, by fossil fuels, hydro power or biomass) a reliable electricity supply can be guaranteed. In order to implement such an electricity supply scheme, two prerequisites have to be met: strong bidirectional grids, and the availability of sufficient and suitable dispatchable power generation capacity. This will, of course, require investments in grids as well as appropriate power plants.

As part of this infrastructure build-up, electricity generation from fossil fuels will also be decentralized to a certain extent. This will have the advantage that the locally generated waste heat from power plants can be used, for example, for district heating, dehumidification of air, and/or cooling of air, thereby increasing the overall efficiency of the energy supply system.

The effectiveness of evening out the stochastic fluctuations depends greatly on the spatial extension of the grid. By using an intercontinental grid (e.g., from western France to eastern Russia) that spans several time zones, even the daily trend component of the solar energy flux can be significantly evened out. Such long distance electricity transport (e.g., by means of high-voltage, direct current links) is technically state of the art. Thus, in particular a large-area network of solar and wind power plants can produce a considerable amount of base power with the same reliability as conventional power plants. The fraction of this base power component compared to the peak power of the whole installation (the capacity credit) depends greatly, of course, on the spatial extension of the network. Naturally, strong bidirectional electricity transport over long distances is essential for this scheme. Today, high-voltage direct-current technology would be the technology of choice. In the future this may be complemented by transmission lines based on high-temperature superconductors.

In distributed power generation schemes, a very large number of power generators will be connected to the distribution grid. Each generator will have its own power electronics unit that serves as the interface with the grid. If these units are designed properly, and if they are connected via information technology links, several additional benefits can be realized in future smart grids: (i) increase of power quality in the grid by means of local suppression of harmonics, local provision of reactive power and local voltage control, and (ii) increase of power supply security (e.g., in the case of natural disasters or terrorism) by forming island grids that guarantee at least a basic electricity supply. In such cases the cold-start capability of grids has to be addressed carefully in the design of the networks.

Energy meteorology

In order to assess and predict the behaviour of smart distributed electricity grids that are largely powered by solar and wind energy, the temporal and spatial behaviour of the solar and wind energy fluxes must be known with high precision. A combination of distributed ground-based measurements and satellite information (most likely special sensor systems will be needed) seems to be the best way to collect the required data. Using elaborated meteorological models and suitable data distribution systems (e.g., the Internet), essential information concerning the meteorological energy fluxes and the status of the grid will be readily available whenever and wherever it is needed.

Statistical information is essential to optimally design (i) the spatial distribution of solar and wind electricity generators, (ii) the optimal fraction of solar- and wind-generated electricity in the grid (taking into account their partly complementary behaviour), (iii) the structure of the grid, and (iv) the information and control system of the entire network. Real-time information on the energy production of the individual electricity generators is essential for operating the smart distributed electricity supply system in an optimal way. This includes control of solar and wind power stations (in the event of electricity surpluses), control of smart loads (see below), control of dispatchable power plants (including distributed fossil fuel-powered combined heat/cold power units), and optimization of the power quality in the grid.

'Energy weather forecasts' for several days will be highly useful in efficiently operating dispatchable power plants and storage systems. All this information will also be essential for the electricity stock markets.

With the help of the information supplied by the required advanced energy meteorology systems, the hardware requirements of smart distributed energy supply systems can be considerably reduced; information in this case would substitute for hardware.

Smart loads

Today's electricity supply systems are designed to ensure that most of the power plants can operate for the longest possible amount of time during a year. Economically this is sensible given the high investments in the power supply system. Since generation and load must match at any point in time, this means that the temporal variations of the lumped load must be smoothened as far as possible. Generally, this is achieved via sophisticated tariff structures such as penalizing peak loads, favouring electric night-time heating, and switching off large loads (e.g., refrigerating units, air-conditioners, etc) by the utility companies.

The same set of tools will also be applied in solar-dominated electricity supply systems. However, in contrast to today's approach, the lumped load pattern will be shaped such that there is a peak around noon times. A prerequisite for this are smart loads; loads that can easily react to external tariff signals (e.g., washing machines, heating units, etc.) and/or loads that can be externally switched off or on by the utility companies. In all these cases the quality of energy services has, of course, to be maintained.

The realization of smart loads generally includes two components: a certain 'technical intelligence' within the load combined with connection to an information network (in this case the issue of data security will have to be addressed carefully), and a certain storage capacity for energy in various forms. Examples of the latter include batteries in electronic devices, the heat capacity of buildings, the heat capacity of cooling units, compressed air, and process heat storage systems (for heat temperatures greater than 100 °C). It is not necessary that all the switching or control of loads will be done automatically (locally or remotely); the consumer who reacts to tariff signals will also create smart loads.

The largest single type of smart load will very likely be electric cars. The car batteries can be charged according to current demand (priority charging), the prevailing electricity tariff (via smart electronics), or remotely controlled by a utility company. If more than 50% of local transport needs is met by battery-powered electric vehicles, this will constitute a smart load representing 10–20% of total energy demand in Western Europe (Langniß *et al.,* 1998).

Energy storage systems

By applying the above-mentioned schemes to large-area electricity grids, a high penetration of the grids with fluctuating energy inputs is feasible without the need for large energy-storage systems. This has been shown both by computer simulations and in practice (e.g., in Denmark and in Northern Germany). A large-area smart electricity supply system in Europe can handle a penetration with fluctuating energy inputs of at least 30 % without applying bulk energy storage (Langniß *et al.,* 1998). A prerequisite for this are, of course, targeted investments in grids, loads and information technology.

A higher penetration of grids with fluctuating energy inputs will require increasingly large energy-storage systems. Today, the main options for high-capacity storage are electrochemical systems and hydro power, although the latter has only a limited capacity on a global scale (WBGU, 2003).

Among the electrochemical storage systems, hydrogen-based systems have in principle an unlimited capacity; using electricity-powered electrolysers, water is split into hydrogen and oxygen (Luque and Hegedus, 2003). These gases are stored and later recombined in a fuel cell to generate electricity. The main disadvantage of this process is its low energy-efficiency. Even in future optimized systems, the overall efficiency will not be much higher than 50 %. Other storage options include advanced batteries (in particular for cars and other smart loads), redox systems (e.g., on the basis of vanadium compounds), supercapacitors, compressed air systems, and superconducting units. In solar thermal-power plants the possibility exists to store thermal energy at a high temperature, enabling an extension of the daily operating time by several hours. All of these technologies provide the basis for an appropriate storage of electricity on different time scales and with different capacities per unit; some are suitable to stabilize the grid on a short time-scale (seconds), while others may be utilized for bulk electricity storage. Some of the technologies mentioned above are not yet available for use in electricity supply systems. Further targeted research and development is needed.

Conclusion

By applying the concepts of smart grids, smart loads and energy storage, grids with a high penetration of fluctuating energy inputs from solar and wind sources can be designed and operated reliably, while at the same time maintaining a high degree of energy security and power quality. The three concepts have to be viewed and optimized as a whole (this is why, from a technical point of view, ‘unbundling’ of power supply systems does not seem to be the best path towards a sustainable energy system).

As a rule of thumb, the larger the spatial extension of such a grid, the smaller the (relative) investment needed to construct and to operate the energy supply system.

Investments in storage systems, in transmission lines, and in smart control technologies have to be seen as three necessary steps that complement each other. Given today's penetration levels, there is presently no urgent technological need for large centralized bulk energy storage systems (e.g., on the basis of hydrogen), provided that proper investment is made in enhancing grid capacity (including smart loads, etc.). Bulk storage capacity will become important once the penetration of fluctuating energy inputs in large-area grids exceeds 20–30%.

The latter statement does not apply to small-area systems such as remote power systems or village and island power supplies. In these cases storage demand will become important much earlier, because of the inability to even out the fluctuations in energy input through statistical effects, and because of the relatively small number of (smart) loads. From this it follows that, if economically and politically feasible, such units should be electrically linked and operated as larger-area smart systems.

The world-wide installation of a sustainable electricity supply system based to a large extent on solar and wind energy sources is not, fundamentally, a technological problem. A basic set of proven energy conversion and distribution technologies already exists and will be further developed. This will lead to a considerable reduction of the cost of energy from renewable sources. Political will, coherence and a suitable global financing scheme are required to transform today's energy supply system towards sustainability.

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