Energy Comes Together in Denmark

THE TRANSITION OF THE DANISH ENERGY system to a system based only on renewable energy in 2050 carries many challenges. For Denmark to become independent of fossil energy sources, wind power and biomass are expected to become the main sources of energy. Onshore and offshore wind farms are expected to provide the majority of electricity, and biomass and electricity are expected to become the major sources of heating. On the way toward the 100% renewable goal in 2050, the Danish government has proposed a 2035 midterm goal to cover the energy consumption for power and heat with renewables.

Today, Danish electricity consumption makes up approximately 20% of total national energy consumption; this figure is expected to increase in the coming decades to between 40% and 70%, depending on how much of the transport and heat sector's energy consumption is transferred to electricity. Wind power's share of total power consumption is expected to be approximately 50% by 2020. The entire energy system is thus facing a fundamental transition. The power system is expected to play a key role in future energy supply. Denmark' goal of being independent of fossil energy sources imposes great demands on all energy subsystems—power, gas, heat, and transport—and therefore should be managed in a holistic manner.

The first half of this article describes a future Danish energy system with a large share of fluctuating renewable energy sources. The interactions among the different energy subsystems will be described. Such interactions become necessary to provide the needed flexibility to handle the fluctuating energy production. Supplementing the broad overview given in the first half of the article, the second half will present evidence from hands-on experiences with enabling flexible electricity consumption in Denmark.

Energy Management and Complexity

A simplified diagram showing the energy flows and some of the most important subsystems and technologies in the future Danish energy system is given in Figure 1.

The total energy system consists of multiple technologies and includes energy production, distribution, conversion, and consumption (EPDCC), as shown in Figure 1. EPDCC networks and models are tightly interconnected. In other words, energy networks are—and will be more and more—large-scale, valuable, complex, and interconnected systems requiring complex decision making in all phases. Energy management is among the biggest challenges of this complex system, and the difficulties will only increase in the coming years. This complexity calls for advanced

The Key to a Future Fossil-Free Danish Power System

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methods of modeling, optimization, forecasting, and control. As indicated by the red dashed line in Figure 1, however, a successful implementation for both scenario analysis and online decision making calls for simplified or operational system models that can describe the entire energy management system.

The modeling of such complex systems will require advanced techniques for model building, sophisticated computational methods, and high-power computing facilities. It is important to consider the operation of the system on a number of time scales, from close to real time (to ensure an instantaneous power balance) to seasonal and annual analyses, as the dynamics of both generation and consumption operate on a variety of time scales.

Tools based on mathematical modeling and optimization techniques have a long history in supporting planning and operational decisions. Current challenges, however, call for a new generation of systems or a major revision of some of the most promising existing systems. This is due to the increasing complexity and scope of the EPDCC network. Systems that were considered independent from each other, like the national electrical and gas networks, must in the future be considered as a single, integrated system—a system that also includes an increasing number of distributed and partly unpredictable renewable sources and smart grids. This is extremely challenging because the models will necessarily be huge and at the same time must consider many complex elements, like the stochasticity of energy demand and of wind and solar power.

Besides models and optimization, future energy systems call for advanced techniques for online forecasting and advanced (e.g., hierarchical) control. These techniques also call for intelligent IT solutions, which must be an integrated and important backbone of the future EPDCC network. Simulation tools, for instance, must be able to simulate these integrated intelligent systems; otherwise, decisions about the potential integration of system elements, including renewables, cannot be made.

The extreme complexity of the task calls for a highly interdisciplinary research activity related to all aspects of energy system integration, with experts in all disciplines closely collaborating in establishing mathematical models for forecasting, control, and optimization approaches that exactly reflect the reality of the future EPDCC networks.

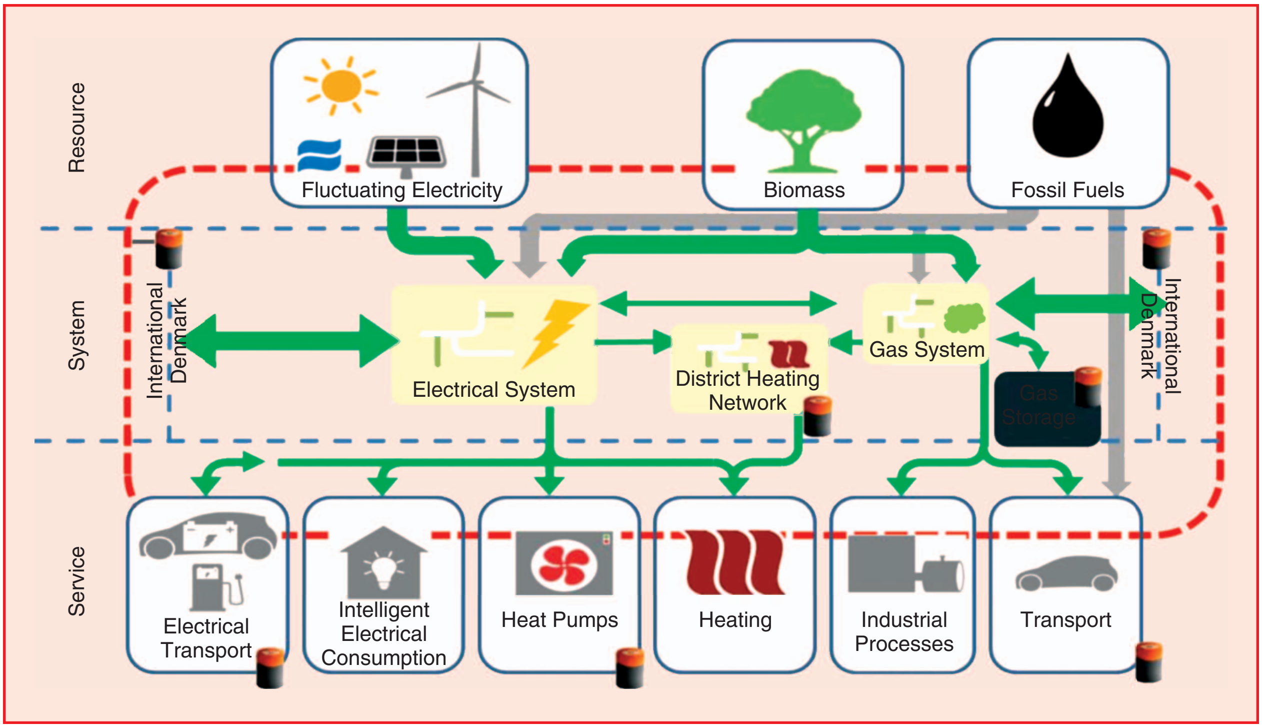

figure 1. Overview of a future Danish energy system. The orange-and-grey cylinders indicate technologies and subsystems with storage capabilities.

On the other hand, these models must be solvable within the time limits set by the operational requirements.

Interaction Among Subsystems: Flexibility Is the Key

The transition of the energy system into a system based on fluctuating energy sources presumes that the system allows energy movement in both time and space and between systems, so as to continuously meet consumer energy demand and to increase the market value of the renewable energy sources. There is a need for an energy system that can ensure competitive prices in energy services, even though the prices of energy resources vary. A precondition for a cost-effective transition is that energy consumption begin to respond to energy prices.

To meet the challenges related to flexibility, markets in which energy is traded must be developed. A precondition for well-functioning markets is that infrastructure is sufficiently developed to support them and that market design is in place. In the short term, the needed flexibility in the energy system and the security of supply must be ensured by supporting market development and through the expansion of international interconnections for electricity and gas.

Along with the increase in the share of fluctuating energy production, the socioeconomic benefit of integrating the heat, gas, power, and transport systems is increased. In the long term, an efficient use of larger amounts of wind power will require extensive energy storage, and in this connection, district heating, gas, and transport systems offer a number of interesting opportunities. There is also a need to produce fuels for energy services that cannot be efficiently supplied using electricity, such as heavy transport and a number of industrial processes. For these purposes, biomass resources become essential. Over the long term, so does generating power with gas in combination with wind power production.

Denmark already has an extensive combined heat and power (CHP) system, a nationwide natural gas system, and experience in handling high proportions of wind power. The flexibility of the future must be built on these strengths and by adding new solutions for even closer and more efficient interactions among the heat, gas, power, and transport sectors.

The Power System

As mentioned, the power system will be challenged in the future due to the integration of large amounts of variable generation such as wind power. In the power system, optimal utilization of domestic flexibility both in demand and production combined with strong infrastructure and international electricity markets are absolute preconditions for maintaining the security of supply and achieving the best value from the renewable energy production.

The primary challenge of the Danish power system is that the share of wind energy in 2020 will be 50% of the traditional electricity consumption on an annual basis and in the long term even more. In the future, wind power production will exceed consumption in many hours and to a much greater extent than today, and there will also be periods when wind power cannot meet demand. There must, however, be a balance between production and consumption in the transmission system. Today, CHP plants and international interconnectors are able to ensure this balance for the most part.

To maintain security of supply and to increase the value of the wind power, increased demand response and smart interactions among the gas, heating, and transport systems must help to provide new services for storage and balancing of electricity in the future. The potential for shifting consumption is expected to increase along the increase in electricity consumption through the development of a range of technologies. Some of the possibilities for flexibility and storage of electricity in the heat, gas, and transport sectors are shown in Figure 2. The figure shows estimates of the total annual need for storage in the Danish energy system and the estimated storage potentials (measured in energy content) for various technologies in 2050. In the electricity system, flexibility and storage are needed over a time frame from seconds to months. Utilization time frames in the electricity system vary by technology: some technologies can be used for flexibility and storage within seconds to hours, while other technologies are more suited for long-term storage during periods lasting weeks or months. The estimated storage demand is for a normalized year, and therefore an increased storage capacity may be needed in extremely dry or extremely wet years or years with unusual variations in annual wind power, heating demand, and so on. The costs shown in the figure are estimated annual costs for storage capacity (operation and maintenance), based on Danish Energy Agency forecast technology data from 2012 for energy plants.

The Heating System

The current Danish heating system consists of a number of district heating systems (covering approximately 60% of the heat supply) and areas heated by natural gas. In the more sparsely populated areas, heating is supplied by individual heating plants such as oil burners, burners fired with wood pellets, and so on.

District heating in the form of hot water is relatively cheap to store. It can utilize energy loss in connection with conversion processes, and it can facilitate flexibility by generating heat from different plants connected to the grid, e.g., from CHP plants for power generation at periods of high power prices and from heat pumps producing heat from electricity at periods of low power prices or by using surplus heat from industrial processes, biofuel production, power-to gas-technologies (electrolysis), or similar processes. A well-developed district heating system is therefore important to ensure high energy efficiency and flexibility.

By virtue of its expansion of CHP and integration of large amounts of wind energy, Denmark is already at an advanced stage with regard to integrated heating and power system

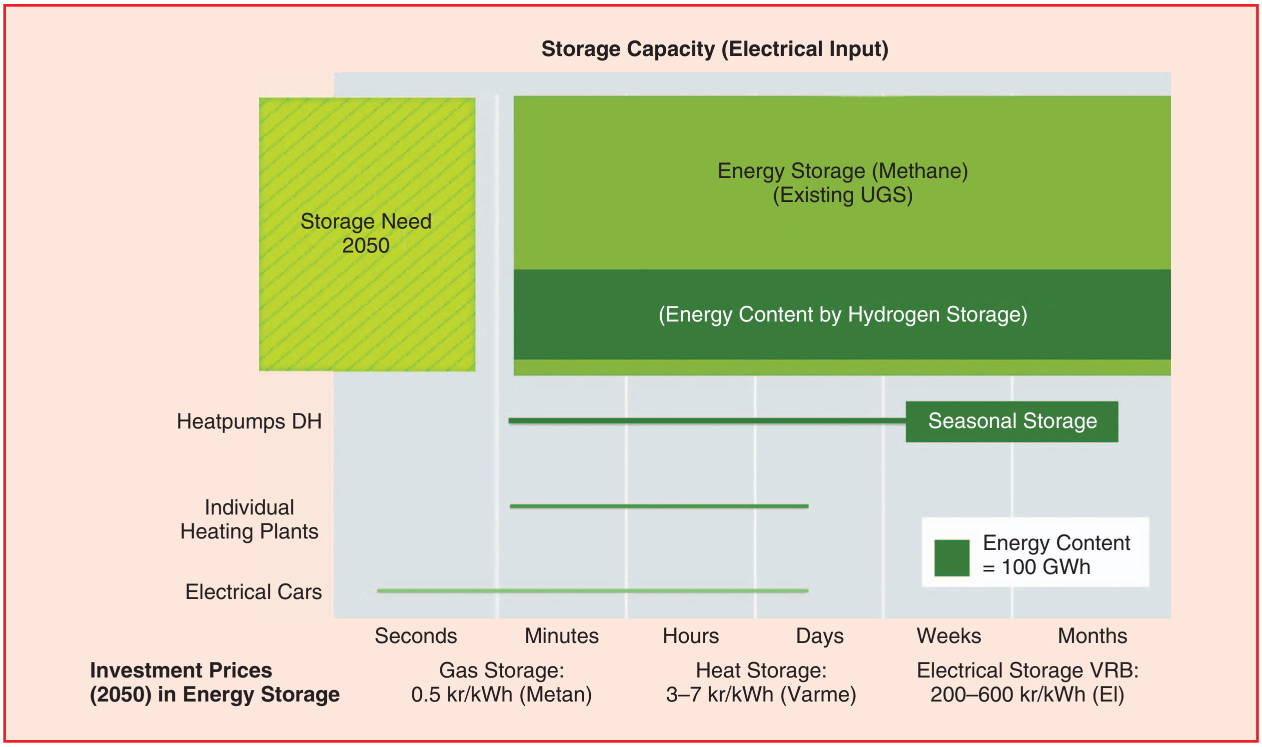

figure 2. Estimates of the total annual need for storage in the Danish energy system and the estimated storage potentials (measured in energy content) for various technologies in 2050. (USG = underground gas storage in salt caverns and in aquifers.)

solutions. There is still considerable potential for increasing synergies between the two systems, particularly by means of heat pumps, expansion of heat storage, and remote cooling. One solution that has been demonstrated is the use of electric boilers, which function like large immersion heaters to heat water for district heating. Wind power can thus be used for heating when the power price is low; at the same time, the electric boilers take part in balancing consumption and production in the power system. The electric boilers have few operation hours due to cost effectiveness and are best suited for use as peak load units in the district heating systems. But as more excess wind is available, these systems will reduce the amount of fossil fuel needed for heating.

Besides electric boilers, large central electric heat pumps can be used in the district heating systems. Heat pumps are most effective when used over long operation periods, and the technology is more expensive than electric boilers. But in return, heat pumps are more energy-efficient, as they can produce three to four times more heat per kilowatt-hour of electricity used. To date, we have had only limited experiences with central heat pumps in district heating systems worldwide. Analyses show that district heating can deliver valuable flexibility to the power system if CHP capacity can be maintained and heat pumps can be established at the same time.

Remote cooling, where cold water is distributed in a closed pipe system in the same way as district heating, also holds possibilities for storage in storage tanks, either when the power price is low or in case of surplus heat in connection with electricity generation. The energy consumption for remote cooling is approximately half that of traditional cooling.

In areas outside the collective heat supply, it is (in general) cost-effective to convert oil burners and electric heating to utilize individual heat pumps, which supports the integration of wind power. Finally, in the longer term, new types of energy conversion, including biomass for fuel and electrolysis for fuel can provide surplus heat, which can then be utilized for district heating.

The Gas System

The Danish gas system, which today is primarily used for natural gas, could be used to transport other "renewable" gases, such as methane obtained from biomass, and the system can store large amounts of energy for longer periods by using the two existing gas storage facilities. Its storage capacity is 1 billion normal m3 methane, corresponding to 11 TWh or 25% of the total current annual gas consumption. The role of the gas system is therefore, considered of great importance in Denmark in relation to ensuring cost-effective seasonal storage and flexibility in the future energy system.

The various possibilities for interaction between the gas system and the other energy subsystems in Denmark are shown in Figure 3. Unlike the storage technologies in the district heating sector, the conversion of electricity to gas

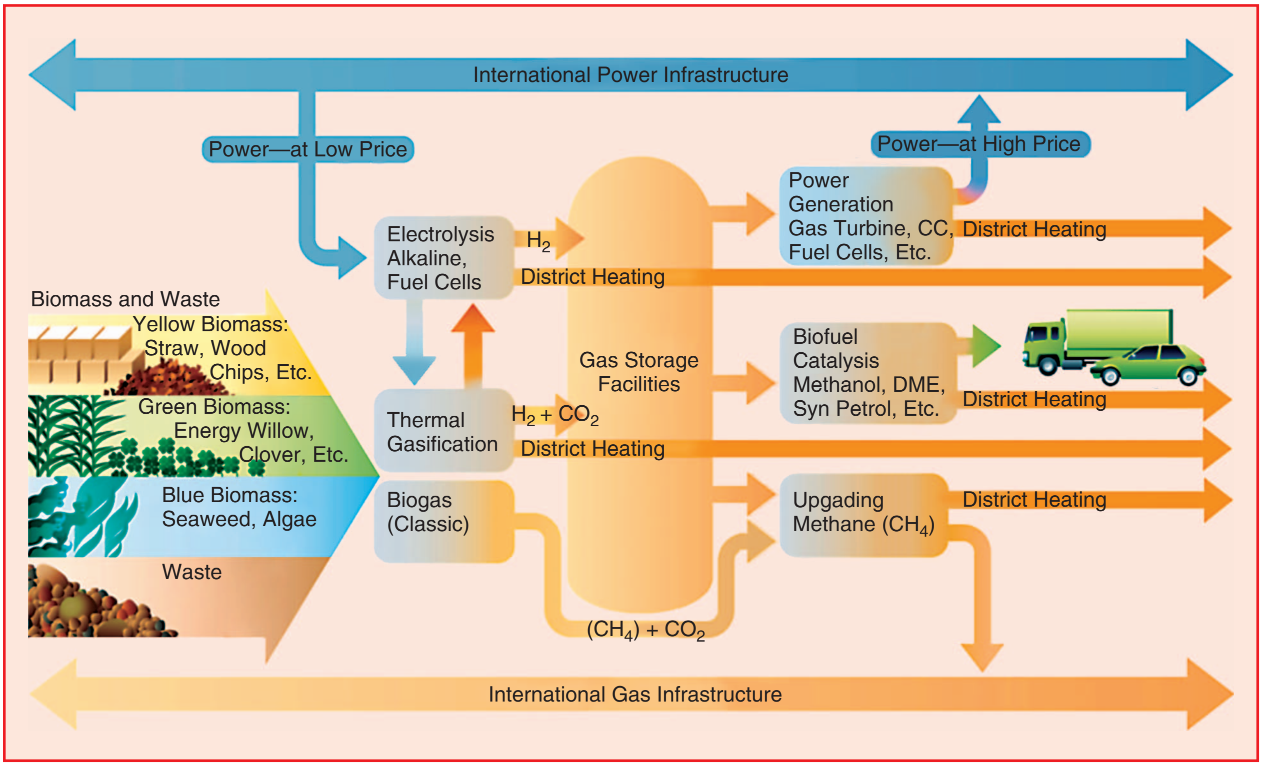

figure 3. Possible interactions between the gas system and the other energy subsystems in Denmark.

can store energy over several seasons, e.g., from summer for use in the winter months, and the gas can be converted back to electricity on days in which the wind is insufficient to satisfy demand.

In the short and medium term, the natural gas system is considered an important bridge builder toward an energy system based on greater proportions of renewable energy. In the longer term, gas from renewable energy is considered an important element of the future energy system because gas can be produced flexibly from biomass and waste and even from electricity, based on renewable energy. Relatively large quantities of energy can be placed in gas storage facilities, and gas can be used directly for transport, in industrial processes, and to produce electricity in peak load situations. Gas can also be converted into liquid fuels. Natural and renewable gas can serve as buffers in periods in which production of renewable energy from wind and hydroelectric power is low, i.e., in "dry years" and "light wind years."

The Transport System

The transport sector constitutes a special challenge for the future energy supply in Denmark. According to projections, this sector is expected to grow considerably in the coming decades. When one examines potential uses for large amounts of wind power, electrification of parts of the transportation sector can provide additional electric consumption. This will provide the best energy efficiency, and a long-term efficient socioeconomic cost is expected. Today, however, there is a lot of uncertainty about the expected prevalence of electric vehicles, and there is also a need for fuels in the transport segment that cannot be supplied by electric power. The current use of biogas and natural gas as fuels in the transport sector is already one of the best socioeconomic initiatives undertaken for replacing oil in the Danish transport sector.

In the long term, the transport sector is expected to develop in the direction of replacing oil with fuels produced from renewable energy sources such as wind, biofuels, and gas produced from electricity. A number of fuels are being considered as possible alternatives to oil, including methane, methanol, hydrogen, and synthetic gasoline.

Demand Response Management and Smart Metering

Advances in energy-metering technologies facilitate the recording of energy consumption data at much higher temporal resolutions, allowing insight into the behavior of consumers, providing valuable information on consumption patterns, and paving the way for the real-time pricing of electricity. The collection and distillation of this information into a useful form is a computational challenge, particularly when considering that much of this computation may need to occur in real time. New research has shown that frequent recording of the energy consumption data for heating or cooling can be used to characterize the energy performance of a building and hence to identify the "low-hanging fruit" in terms of possibilities for energy savings as well as to identify the time constants for the thermal dynamics of a structure.

Information from frequent meter readings is also useful for demand response management solutions. New research has demonstrated how electricity consumption for heating buildings can be controlled through variable pricing, thereby activating its latent flexibility. A recent paper by Halvgaard, Poulsen, Madsen, and Jørgensen has shown how the thermal capacity of buildings can be used to shift the energy consumption in buildings with heat pumps to periods with low electricity prices. Using such methods, the heating system of a house becomes a flexible power consumer in the smart grid. The approach includes forecasts of both weather variables and the electricity price. Compared with traditional operation of heat pumps with constant electricity prices, the optimized operating strategy that was used saves 25–35% of the electricity cost, and at the aggregation level the method demonstrates a framework for shifting power consumption according to fluctuating wind power production. A simple case study demonstrating these principles is presented in the next section.

The implementation of such variable pricing will, however, require an overhaul of the existing national taxation and regulation structure, as indicated in Figure 4. Changes to the tariff structure should not be limited to the end user. In fact, it may be desirable to develop entirely new market

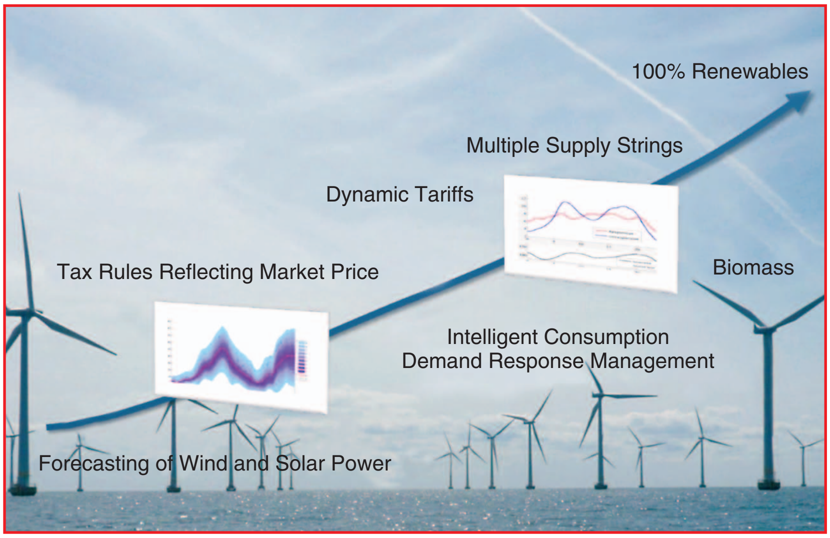

figure 4. Possible measures to activate and utilize flexibility in electricity demand.

> There is a need for an energy system that can ensure competitive prices in energy services, even though the prices of energy resources vary.

structures to suit a paradigm in which uncertain renewable generation sources make up a very high proportion of the generation portfolio and the behavior of demand can be forecast and hence manipulated for the provision of a range of system services.

The transition to renewable energy and power sources will result in a dependence on stochastic resources, including both generation and consumption. Efficient management of such systems will require expertise in stochastic optimization and modeling, statistics, and computing. Forecasting will play an equally pivotal role for all stakeholders in the energy system and markets. An important example related to demand response management is a requirement for forecasting models describing the dynamic relation between price and consumption. One such example is described in the following section.

Controlling Electricity Consumption Through Forecasting

As a consequence of the expected future increase in photovoltaics, electric vehicles, and heat pumps located on the lower-voltage grid in the Danish system, distribution grid operators and the parties responsible for maintaining balance are looking into new procedures for peak shaving and for moving consumption in time and space. Accessing the potential flexibility of the residential segment calls for rather simple approaches, however.

New methods for controlling Danish electricity consumption using price signals have recently been suggested. In the FlexPower and iPower projects, such price-based methods for controlling electricity consumption by forecasting its response to prices are or will soon be simulated and tested. These are sometimes called "indirect control" approaches, since power consumption is controlled indirectly by a price signal rather than directly by turning appliances on and off. In the United States, the concept of "transactive energy" has been suggested as a similar practice.

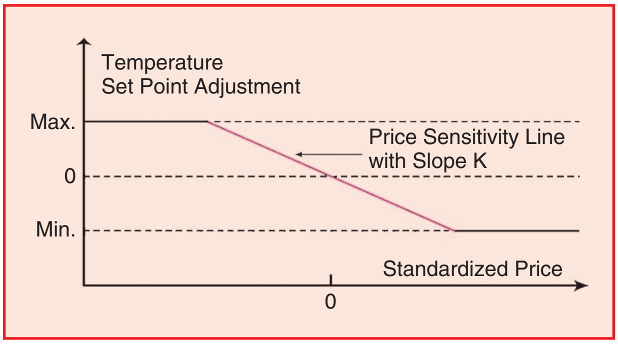

figure 5. Temperature set point as a function of price.

Let us briefly describe one methodology that contains a forecast of the potentially aggregated response. Based on the forecast, real-time prices are determined by means of an optimization or control theoretical approach in such a way that actual power consumption aims to track a desired reference. In the future, this reference would be the total renewable energy production. This methodology thus turns things around: for a classical power system, energy production is controlled so as to keep up with demand, whereas in the new approach consumption is controlled so that it balances the actual production. For a more detailed description, see the paper by Corradi, Ochsenfeld, et al. listed in the "For Further Reading" section.

In what follows, these techniques for a forecast-based control of power consumption are outlined using a real-life case study. The purpose is to obtain a better synchronization between fluctuating energy generation and heat consumption for a particular group of houses.

Based on data from a real-life experiment using 27 houses (located on the Olympic Peninsula) equipped with price-responsive appliances, a model for forecasting household price response was established. This enabled the construction and implementation of a price generator (controller) at a forecast-control portal, with the purpose of tracking a certain consumption target (e.g., one keyed to fluctuating energy production).

The electric heating and cooling system (along with clothes dryers and water boilers) were controlled by price. For the heating system, the flexibility was activated by lowering or augmenting the temperature thermostat (set points) in accordance with the electricity price from the forecasting-control portal while remaining within predetermined comfort-related limits. Slow variations in prices were filtered out; the resulting standardized price is centered around zero, as illustrated in Figure 5.

Additional flexibility was introduced by changing the maximum and minimum set points and the price sensitivities according to certain predefined occupancy modes ("home mode," "work mode," and "night mode"). Obviously, when one is not at home a larger range is possible—say, from 17 °C to 26 °C—but when one *is* home less flexibility is desirable.

To be able to forecast the price response of the aggregation of households, a model describing the dependency on outdoor air temperature, solar radiation, wind speed, To forecast the price response of the aggregation of households, a model describing the dependency on outdoor air temperature, solar radiation, wind speed, time of day, and the price was established.

time of day, and, finally, the price was established. For the Olympic Peninsula, the data sensitivity of the price signal is illustrated by the step response function shown in Figure 6. Assuming a positive step change in price takes place at hour 0, we notice that consumption drops almost immediately, but after a few hours consumption is back where it started. This forecast model is used to establish a control system for finding the optimal price signal, with the purpose of obtaining a given consumption pattern. The control system developed is sketched in Figure 7.

Now this forecast-based control portal can be set to use a time-varying price signal to control (to some extent) power consumption. For the actual case this is illustrated in Figure 8, which shows consumption with and without a price response.

The main advantage of the illustrated indirect price-based control of the aggregated power consumption using a forecast-control portal is that the setup is rather simple. Another plus is that predictions such as weather forecasts can easily be integrated in the portal and thus taken into account for advanced model predictive control. The indirect portal solution is simple; the signal—i.e., the price—is just a one-way signal that can be broadcast, and the meters should be able to accumulate not only the energy consumption (in energy units) but also the accumulated cost.

The potential to extend this methodology to other household appliances and add the possibility of substitutions among energy sources indicates that this approach contains many key elements for implementing future intelligent energy solutions.

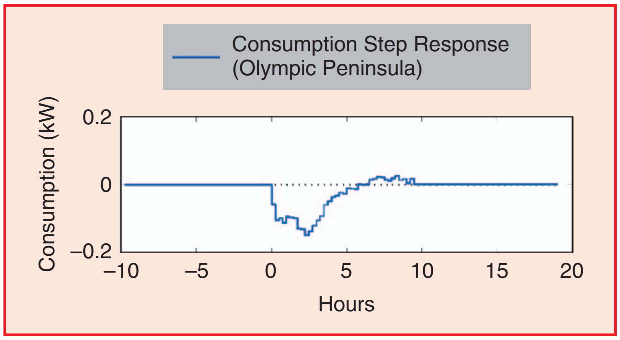

figure 6. Consumption response when the electricity price increases at hour 0.

Mobilizing Local Flexible Loads and Generators for Balancing and Ancillary Services

DONG Energy, a leading energy group in northern Europe, is actively working to demonstrate how flexible loads and distributed generation assets can be aggregated from the distribution layer into a virtual power plant and used in the existing power and ancillary services markets. The aggregated portfolio acts like a conventional power plant and can offer traditional power services to the TSO and balancing markets. This concept is called PowerHub; a mixed PowerHub commercial portfolio consisting of different generation and load assets is already in operation in Denmark (see Figure 9). The generation assets can be wind power, hydropower, or industrial or decentralized CHP plants, e.g., greenhouses. Flexible loads are often found at industrial consumers and include cold storage, wastewater plants, pumping stations, and water supply facilities; but they are also present with fleets of electric vehicles (EVs) and control units for HVAC systems in buildings. PowerHub was developed as part of a large EU project called Twenties (the largest Seventh Framework Programme for Research, or FP7, energy project so far) that is addressing the challenges of integrating large-scale wind power into the European system.

PowerHub has demonstrated the ability to aggregate flexibility across a portfolio of assets and combine and control the response of the units so that primary- or secondary-frequency services can be traded and delivered to the TSO. Moreover, the platform can aggregate the larger energy volumes—e.g., from controllable load and generation—and trade these as balancing services in the regulating markets.

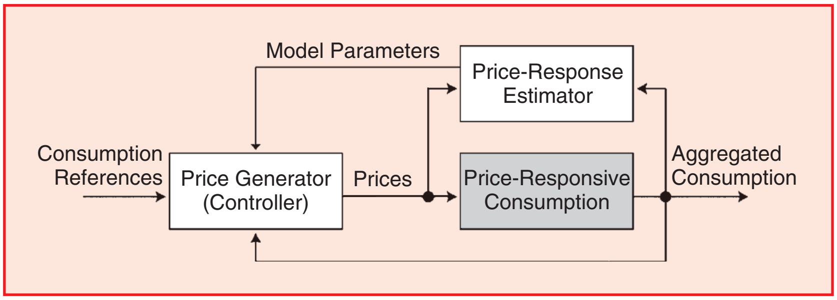

figure 7. Sketch of the control system used to control electricity consumption using price signals.

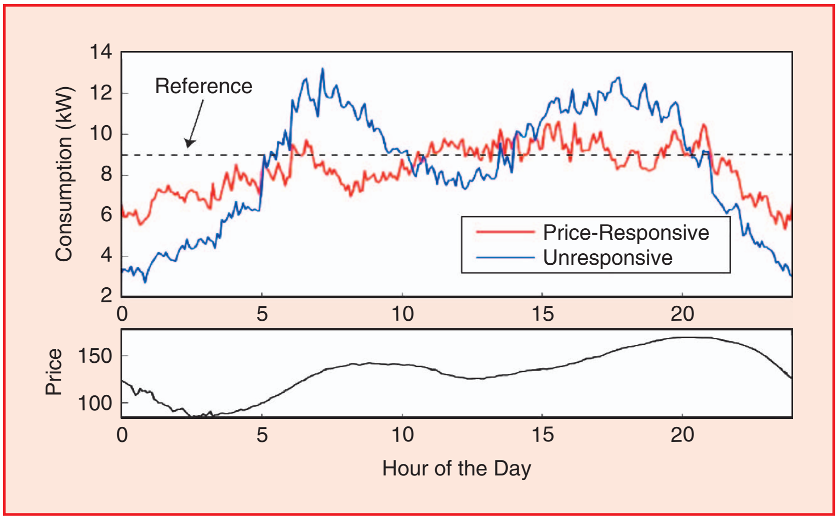

figure 8. (a) Price-responsive and price-unresponsive electricity consumption and (b) the associated electricity price over the course of the day.

Other services, such as reactive power support and provision of virtual inertia, have also been demonstrated by PowerHub. The main challenge in building a virtual power plant is not software but rather running the right business processes toward the markets and getting the asset owners to share their flexibility. Customers are not always aware of what flexibility they have, and they are very concerned about ensuring that their primary production purposes and internal business processes are never compromised. The core component within PowerHub is its ability to handle mixed assets and optimize contracts across the different marketplaces that are trading flexibility. Moreover, PowerHub is seen as a key differentiator within DONG Energy's front-end activities with respect to energy savings and energy advice.

As a real demonstration case, DONG Energy's PowerHub controls some flexible water pumps at the Furesoe Water Company (totaling 150 KW). The water company provides access to five waterworks operating on fresh groundwater with aeration and sand filtration. Serving 35,000 customers and using 1.7 million m³ of drinking water, the company has

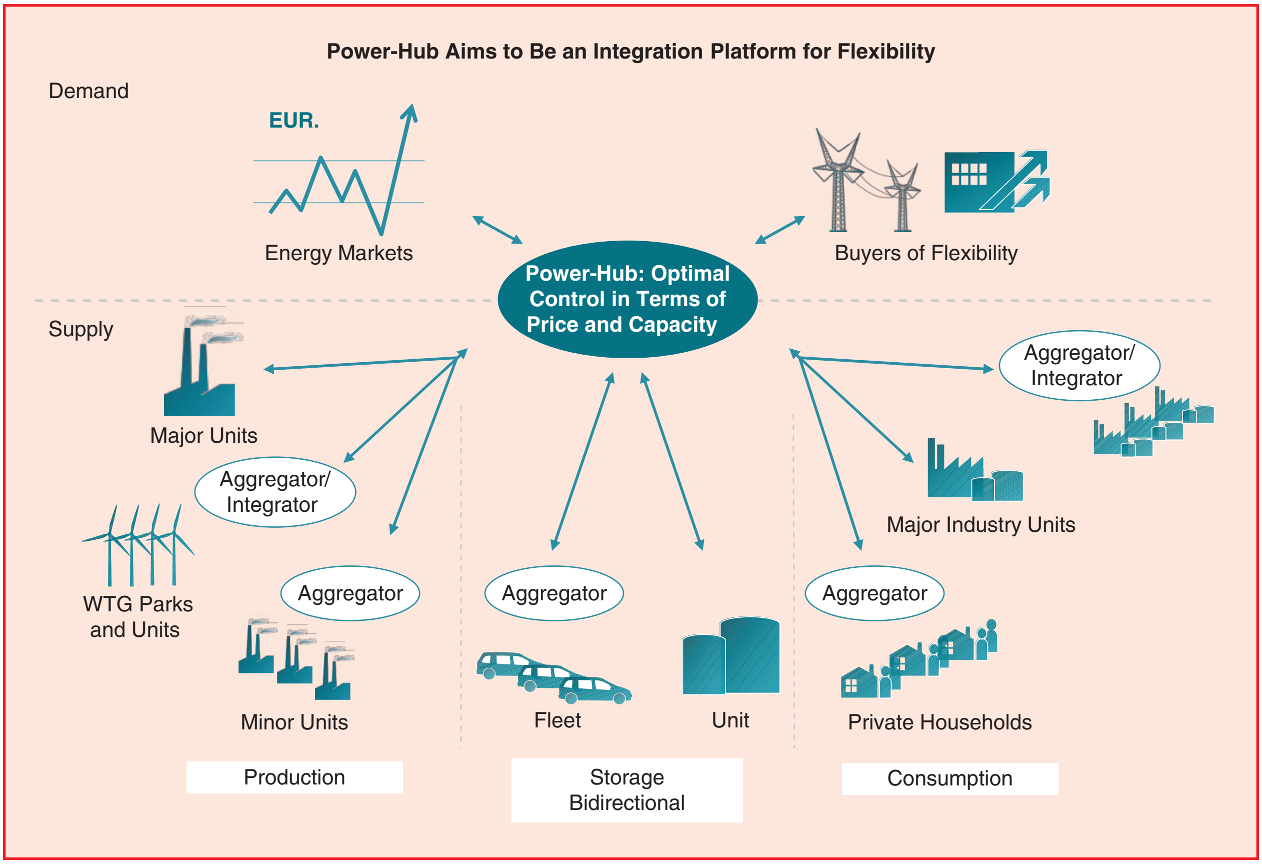

figure 9. Overview of the functionality of PowerHub as it collects and aggregates the power consumption, power production, and flexibility from different demand and supply resources and offers the aggregated demand, production, and flexibility to the various power markets.

> For Denmark to become independent of fossil energy sources, wind power and biomass are expected to become the main sources of energy.

an annual electricity consumption of 1,075,000 kWh. The water company is facing rising energy costs and high pressure to produce energy savings and improve its environmental profile. PowerHub defines the tolerance span of the pumps without interfering with primary production and actively controls and optimizes the unit's consumption. Through this optimization, PowerHub can create real value: it produces significant electricity cost savings by shifting the use of power to times when electricity prices are low, and it provides access to additional income by delivering ancillary services such as frequency support to the TSO by increasing or decreasing loads. This second value pool is currently only available by participation through an aggregator such as PowerHub, as the Furesoe assets are too small to bid into the markets by themselves. In addition, PowerHub can control and optimize the consumption mix to target a carbon-neutral profile, e.g., by consuming when wind or solar generation is abundant. The commercialization of these services is still in its early stages, but proof of value and concept has been given. One of Furesoe's concerns was whether energy use in its water management systems would increase due to changed operational patterns. If that were the case, the customer would not have been able to share its assets' flexibility with the energy system. But PowerHub has documented that water pump energy use is only shifted in time and that, at worst, the total use of energy is kept constant.

The work done in the Twenties project has shown that flexibility is available from industrial customers but that aggregating flexibility from residential segments is still not feasible in the Danish market. In the future, however, when additional power demand enters the residential segments via heat pumps and electric vehicles, there will be a relevant amount of flexible volume to mobilize. Moreover, the intelligent integration of these units into the management of distribution grids will be necessary in the future and can create a new value pool for PowerHub. Distribution grid operators will be challenged in the future with new loads that are doubling and tripling individual household peak consumptions and must consider either putting in new cables or starting to buy peak-shaving services from local flexible loads or generators. The Danish research platform iPower is currently looking at how to create a marketplace for trading flexibility services to DSOs. Solutions are being developed and demonstrated that react to real-time prices and tariffs and also offer aggregation and control through aggregators, where reserves can be procured for later activations and settlements.

Conclusions

Denmark has already established its role as a pioneer in the race to achieve true sustainability by putting in place highly ambitious goals for a renewable power system and eventually an entirely renewable energy system. These goals are highly challenging, and without intensive research the challenges may prove insurmountable. Denmark is ideally equipped with infrastructure and supply systems to facilitate a demonstration of research results in this area. A multidisciplinary approach should mirror the envisaged integration of the individual sectors of transport, heating, and power and ensure that a truly sustainable future is attainable in the best and most efficient manner, taking all constraints and interactions into consideration.

For Further Reading

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O. Corradi, H. Ochsenfeld, H. Madsen, and P. Pinson, "Controlling electricity consumption by forecasting its response to varying prices," *IEEE Trans. Power Syst.*, vol. 28, pp. 421–429, Feb. 2013.

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