Harnessing Flexibility from Hot and Cold

Heat Storage and Hybrid Systems Can Play a Major Role

AS HAS BEEN OFTEN REPORTED, ELECTRICITY SYSTEMS with high levels of variable wind and solar power generation would benefit from demand flexibility. What is not as often mentioned is that electrification of the transport and heat sectors could exacerbate the need for flexibility, if they are implemented as inflexible loads. This demand could also be made more flexible, but it comes with a cost. The main issue is to identify the cases in which the benefits will outweigh those costs, a matter that will naturally depend on the evolution of specific energy systems. In this article, we lay out some generic principles and characteristics related to heat-sector flexibility and demonstrate its possibilities using specific examples. While we generally use the word *heat* here, most of the discussions also apply to *cool*, which, after all, is just another form of temperature difference.

A major potential for flexibility in the heat sector results from the low cost of storing heat, which allows opportunities to shift electricity demand. Another possibility is to utilize hybrid systems in which either electricity or fuel can be used to produce heat depending on price variations between the two options.

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Hybrid systems may take many different forms, from dual heaters in buildings all the way to large district heating systems with combined heat-and-power (CHP) plants, fuel boilers, and electric heaters.

The Flexibility Potential of Heating and Cooling

Together, heating and cooling represent a huge part of energy consumption. However, the heat system is often not considered as a single system, but rather—due to the historic emphasis on energy supply—as subsystems of different supply sources (e.g., gas, coal, and electricity). Therefore, size and flexibility potential are often overlooked. According to 2014 Eurostat figures, in the European Union (EU) around 30% of primary energy is used to produce heat, 30% is used in the transport sector, and 40% is used for electricity, including electricity to heat (see Figure 1).

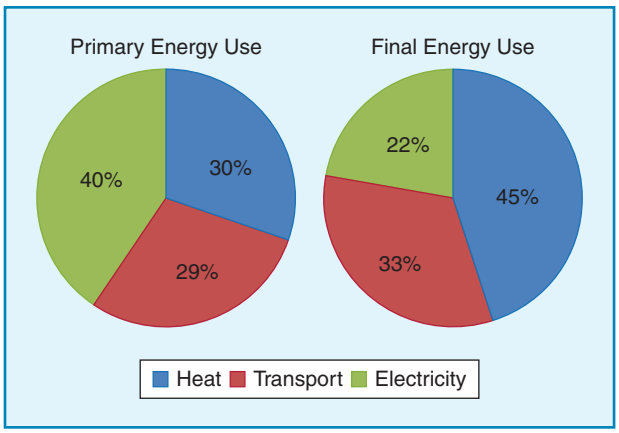

figure 1. The primary and final energy use in the EU for 2014 (based on Eurostat figures) divided into three main categories of energy end use.

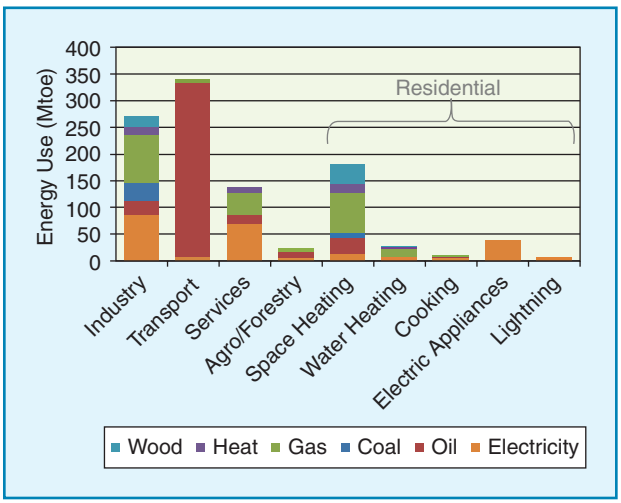

figure 2. The final EU-28 energy use for 2014 (based on Eurostat figures). The residential sector is split into components using 2008 data (ODYSSEE). Losses in transformation and transfer are not included. "Heat" as energy use refers to the heat being a conversion by-product from, e.g., a CHP plant or an industrial process.

The share of electricity in primary energy consumption is higher than in final energy consumption because a large proportion of energy is wasted in electricity generation processes using the Carnot cycle (Figure 1). The opposite is true for heat, because nearly 100% of the energy in fuel is converted to useful heat. The large share of heat in the final energy use translates to a large potential for power system flexibility. For example, the value of surplus wind or solar power is zero, but if that electricity can be used to replace heating fuels, the value rises to the price of the fuel. The value is affected by the conversion efficiency—the value gets higher if heat pumps are used instead of less-efficient direct-resistance heaters. However, there are investment costs that need to be factored in as well.

Heat is consumed in most end-use sectors, except transport, but its use is very diverse. In residential and commercial buildings, heat is used for space and water heating. In the industrial sector, heat additionally provides process heat. In terms of flexibility, some demands are more amenable to being controlled than others. Figure 2 divides final energy use (heat, in particular) among the EU's 28 member states (EU-28) into several categories. Most heat in the EU is generated from natural gas, while coal, oil and biomass make up much of the rest.

In Europe, cooling demand is considerably lower than heating demand. However, it is growing quickly with increasing space-cooling requirements and also due to the heavy urban development in warmer climates and new uses needed in emerging services and industries, such as cooling large data centers.

The heating/cooling usage types and demand profiles will largely impact the flexibility potential, We use the following categories to describe the major parts of the heat/cooling system:

- ✔ local heating and cooling of buildings
- ✔ district heating and cooling
- ✔ heat for industry.

Local Heating and Cooling

Final energy use in residential buildings is dominated by space and water heating demand—roughly 80% in Europe and 60% in the United States. Worldwide, most residential homes and commercial establishments produce heat locally within the building using a variety of different heating/cooling technologies and are not connected to district heating networks. Heating technologies can be mainly differentiated by their fuel (wood, natural gas, biogas, and electricity) and conversion process (combustion in a boiler or burner, liquid evaporation for heat pumps, and Joule's law in resistance heaters). Cooling is generally based on electricity.

The heating/cooling appliance couples the building to the energy supply system. Because solid and gaseous fuels can be stored easily over weeks, if not seasons, these supply

Electric storage heaters make use of the solid materials around the resistance heater as a heat store and may utilize a fan to release the heat in a more controlled manner.

systems inherently have considerable flexibility, and planning boils down to managing supply and storage infrastructure, as with most commodities. On the other hand, electricity-fueled heaters/coolers require the power system to balance supply and demand instantaneously, changing the dispatch in the short run and impacting the generation portfolio in the long run.

Electric heating, if deployed in an uncoordinated manner, requires additional power-system flexibility to meet daily, seasonal, and annual variations. For example, in France most residential heating is based on electric heating and causes considerable temperature sensitivity in the power demand (2,300 MW/°C); this represents a major driver for extreme peak loads and security of supply.

However, a controllable electric heating/cooling can draw on the potential flexibility of heating (thermal inertia) to facilitate renewables integration and manage peak loads. For example, some demand-side management programs are being carried out in France as ad hoc measures to improve flexibility. In another example from Germany, it was realized that electric overnight storage heaters can be a valuable source of flexibility, so an earlier decision to remove them was reversed in 2013. The use of information and communications technologies in electric heaters could, therefore, provide the option to shift demand loads according to power system conditions, while also meeting the building occupants' comfort requirements. These examples illustrate the strong interaction between residential electric heating and the power sector, but they also raise the question on how such integration of electric heating should be managed to provide flexibility in the most cost-effective and nonintrusive manner.

Electric heating systems are mostly based on resistance heaters (including electric storage heaters) and on the more efficient heat pumps. Heat pumps make use of the natural temperature difference between the outdoors and indoors during a condensation/evaporation cycle. The heat cycle only requires electricity to run the compressor and other auxiliary equipment, thereby producing two to four units of heat for each unit of electricity consumed in air-source heat pumps (although the gain tapers off in colder temperatures). The efficiency can be even higher for ground-source heat pumps, reaching performance coefficients of four to five. This minimizes generation requirements and peak load but will not allow as much flexibility to utilize excess renewable electricity.

Local cooling is usually provided by heat pumps (either with air conditioning systems that only cool or by reversible heat pumps that can also heat). When the heat pump is used in cooling mode, it is called a chiller. The energy efficiency ratio is typically lower, ranging 1.5–2.5 units of cooling for one unit of electricity. In regions with high cooling loads, the coordinated cooling of buildings results in the dominant peak electricity demand.

In many cases where a heat pump is installed, it is complemented by use of an electrical resistance heater or a gas boiler. The combination with a gas boiler (the so-called "hybrid" heat pump) shows vast flexibility potential. Its smart integration into the electric system could enable the power system to access the flexibility of the gas system by switching from the heat pump to the gas boiler whenever the electricity system is under stress (this could represent an extended period of several days). Hybrid fuel boiler/resistance heater systems could provide the option of using excess renewables by switching from fuels (often gas) to electricity.

Thermal storage in buildings can enable the optimization of electricity consumption and charging based on electricity market prices while still providing thermal comfort to the user. If the resistance heater is integrated with high-thermal-capacity materials, then the heaters are referred to as *storage heaters*. Electric storage heaters make use of the solid materials around the resistance heater as a heat store and may utilize a fan to release the heat in a more controlled manner. Using resistance coils or hydronic systems in underfloor heating enables some energy to be stored in the thermal capacity of the floor as well. Other technologies for thermal storage include water storage tanks and solid materials. In particular, in hydronic systems, a water tank can be added relatively easily, although there is a cost related to the space use in addition to the cost of the storage device.

Energy can also be stored with a cold storage. Temperature differences are smaller than in heating though; consequently, cold storages would need more volume for the same energy content. However, it is possible to take advantage of the latent heat of freezing/melting, which corresponds to approximately 80 °C of the temperature difference in water. Available commercial chillers use ice storage; these can achieve more operating hours, and, consequently, the chiller can be downsized while also decreasing electricity use during daily peaks compared to traditional air conditioning. Conceivably, these chillers could also offer flexibility for higher shares of wind and solar power, although there would probably be a different optimum in the sizing of the components.

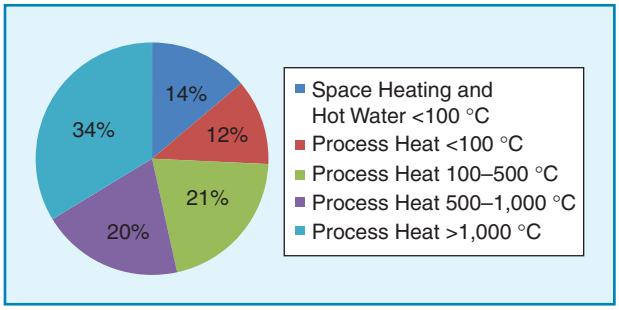

figure 3. The use of different grades of heat in EU-28 industries (based on Naegler et al., 2015).

District Heating and Cooling

District heating pipes carry hot water from centralized heat plants to buildings with heat exchangers. After heat has been transferred to the building's heating system, cooled water flows back to the plants through an adjacent pipe. District heating is mainly used in more densely populated areas in northern latitudes (although it is not widespread in North America).

In addition to economizing with large fuel boilers, district heating offers the possibility to use CHP plants. In some countries (e.g., Germany and Denmark), even small district heating systems often have CHP units, while in others (e.g., Russia and Finland) CHP units are found mainly in bigger systems that can accommodate larger, more economic plants. When used alongside CHP plants, fuel boilers cover heating peaks and back up the CHP units. Combining CHP plants and fuel boilers enables sensitivity to power prices. Some CHP units can also change the ratio between heat and electricity production, which increases their flexibility.

The flexibility of a district heating system can be further increased with heat storages (accumulators) that offer a very low-cost form of energy storage at district heating scale (thousands of cubic meters in insulated steel tanks or caverns). When power prices are sporadically very low [e.g., high levels of wind or solar photovoltaic (PV)] and there are no regulatory hurdles, it can become feasible to install heat pumps and electric resistance heaters in district heating systems. Electric heaters offer a low-cost solution to utilize cheap power, while heat pumps give considerably more heat per unit of electricity for a higher investment cost.

It is costly and inconvenient to install district heating pipelines into existing cities. However, new neighborhoods are a potential target for small-scale networks. In comparison to building-level heating, they decrease the relative cost of heat generation units with a limited investment in heat pipelines. But, more importantly, from a flexibility viewpoint, they offer considerable economies of scale for heat storage, the specific cost of which decreases nearly logarithmically with increasing size.

District cooling is much less common than district heating. The challenge has been that economies of scale are more difficult to achieve in cooling units than in heating units. However, because most people live in climates where cooling is an aspiration, district cooling may have a more important role in the future. District cooling can provide better access to more efficient ambient heat sinks (e.g., sea water) than heat pumps located in buildings. This would also help to keep the cities themselves cooler because waste heat is transferred away from the city. Cooled fluid, typically water, could also be stored in accumulators to gain more flexibility toward the power system.

Heat Use in Industries

Figure 3 shows six grades of industrial heat use, dominated by process heat, which makes up roughly 85% of the total energy demand for industrial heat in Europe. The remaining 15% is due to space heating. Heat pumps can serve low-temperature loads, while CHP units can serve somewhat higher-temperature levels and still be able to produce electricity. A large fraction of industrial heat loads, currently dominated by natural gas burners, requires higher temperatures. However, electric heating technologies such as resistance heating, electric arc heating, induction heating, and dielectric (radio-frequency) heating can provide temperature levels above 500 °C and so can replace, e.g., natural gas burners. These alternatives can achieve a high range of temperatures and offer accurate temperature control. They could provide system flexibility if combined with a heat storage or used in a hybrid configuration with fuel burners. The costs of energy, equipment, and grid connection have so far limited the use of electric heating as compared to combustion.

Also, the type of electric heating capable of replacing or supplementing an industrial gas burner strongly depends on the process. Quite a few industrial processes also use the fuel as a raw material. For example, steel production in blast furnaces requires coke not only as an energy carrier but also as a reducing agent that takes part in the chemical reaction in the blast furnace. Thus, the electrification potential of industrial process heat has to be analyzed carefully for each type of process and will strongly differ across countries.

Characteristics of Heat Demands and Thermal Storages

Heat Consumption Profiles

Heat demand profiles are determined by the weather, building characteristics related to thermal losses, occupant behavior, and occupant expectations about indoor temperature. Consequently, typical daily demand profiles can be quite diverse across countries (Figure 4).

In Finland, buildings are typically well insulated, and thermal losses are relatively small even though outside temperatures can get very cold. In district heating systems, heat is stored in the pipelines and also in the building envelopes, resulting in a daily profile with little variation—mainly

driven by longer-term ambient temperature variations. Inside temperatures are kept nearly constant, even when occupants are not present. By contrast, houses in Ireland leak more, and the small share of buildings that rely on electric radiators use them mainly when occupants need the extra heat—for example, in the morning and evening during weekdays. When occupants are not present or they are sleeping, inside temperatures are often allowed to drop. Despite the weather being more moderate in Ireland than in Finland, the average Irish living room is probably colder than its Finish counterpart due to different occupant expectations.

Annual profiles can also be quite different, although they follow more closely the inverse of the ambient temperature. Figure 5 shows that systems where the heat source also provides hot domestic water have some load during the summer. In China, district heating systems can be shut down outside the heating period.

While not shown in Figure 5, cooling could complement the annual space heating profiles. In some climates where heating and cooling needs are comparable, similar flexibility from cooling could complement flexibility from heating. Wherever there are interconnected power grids spanning across warm and cold climate zones, part of the variations, depending on the relative strength of the interconnections, can be smoothed at this continental scale. In either case, heating and cooling could provide a rather stable source of potential flexibility for the power sector. Furthermore, in hot and sunny countries, cooling loads and PV generation may complement one another well.

Industrial heat demand at the country level does not exhibit strong seasonality and could, therefore, provide year-round flexibility (e.g., the industrial heat demand from Finland shown in Figure 5). Also, daily profiles, especially in heavy industries, are typically relatively flat. In individual industrial sites, the profiles can have more variation—for example, lower demand for products can cut work shifts.

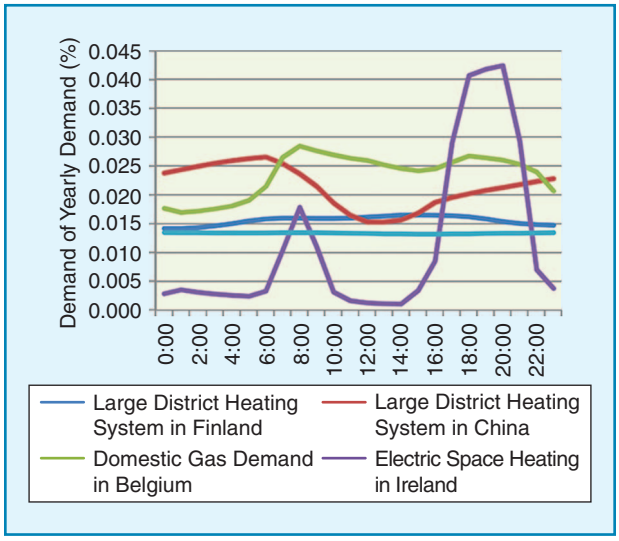

figure 4. Hourly heat profiles from a winter weekday.

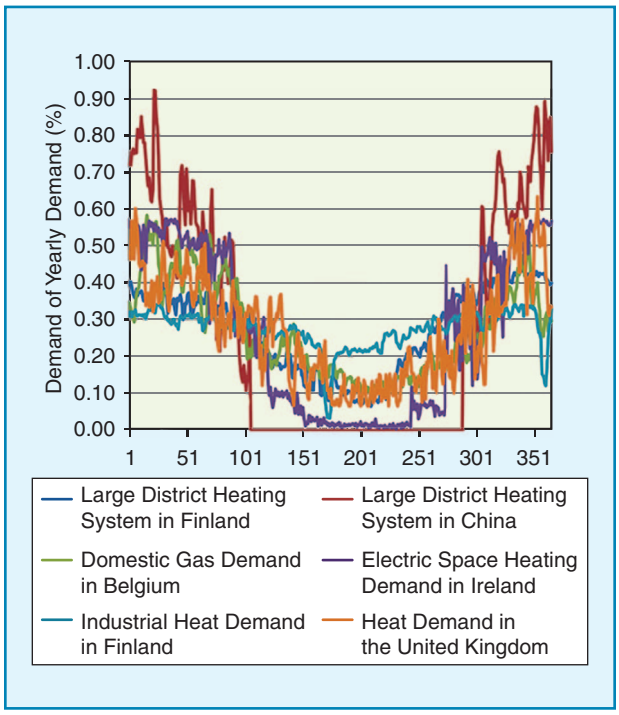

figure 5. The average daily heat demands over a year.

Time Constants and Thermal Storages

It is technically possible to store heat from one season to another, but this has proved economically challenging. Storing heat becomes more viable when considering time spans of several days (or shorter). The storage time constants depend on the storage size or on end-user comfort or needs, which might be affected by the operation of the heating device. Here is an approximate list of time constants for different heat uses:

- ✔ domestic refrigerator/freezer: 15 min–1 hour
- ✔ supermarket refrigeration systems: 15 min–3 hours
- ✔ thermal mass of buildings: 2–12 hours
- ✔ buildings with local hot water storage: 2–24 hours
- ✔ district heating pipelines: 1–5 hours
- ✔ district heating storages: hours to several days.

For economic reasons, water is commonly used as a medium, even though other viable heat storage materials exist. A cubic meter of water changing 55–95 °C offers about 58 kWh of thermal energy storage. In a not-so-well insulated house on a cold day, this would last about half a day. It can become quite impractical to install much larger hot-water tanks inside residential buildings because they require considerable space and would likely not fit through door frames. Most existing water tanks are much smaller. Consequently, for the most part, hot-water tanks offer flexibility constrained by a limited time constant—although the flexibility can still be valuable for the power system when aggregated over millions of houses.

The cost of storing thermal energy in water tanks decreases rapidly with larger tank size (Figure 6). Longer time constants and, consequently, more flexibility could be achieved if the hot-water tank were oversized. Sharing the tank between several buildings would, in turn, decrease the specific costs. District heating systems already often utilize large tanks to make their operation more flexible.

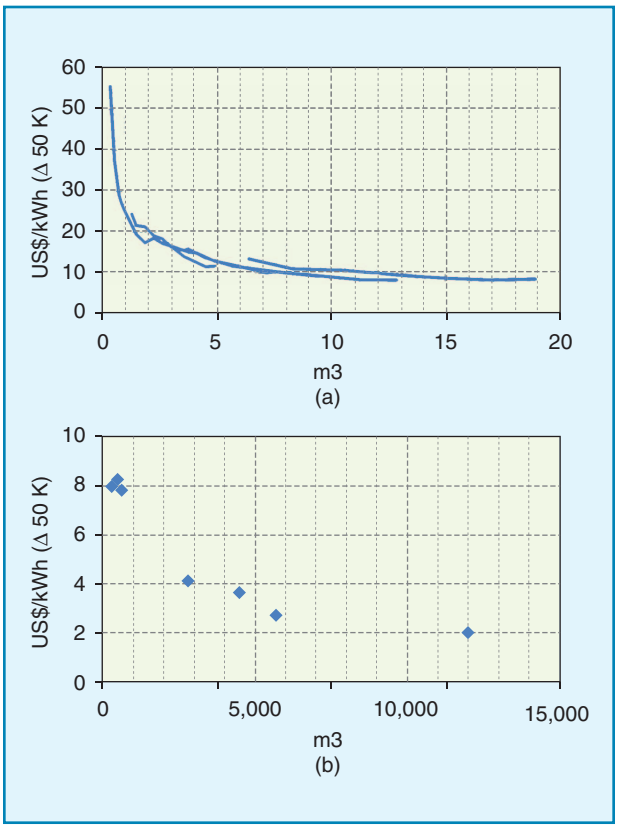

figure 6. The cost of hot water tanks per unit of storable heat in relation to the storage tank size. (Small tank sizes are based on market data; large tank sizes are from the European Commission Joint Research Centre's 2012 report.)

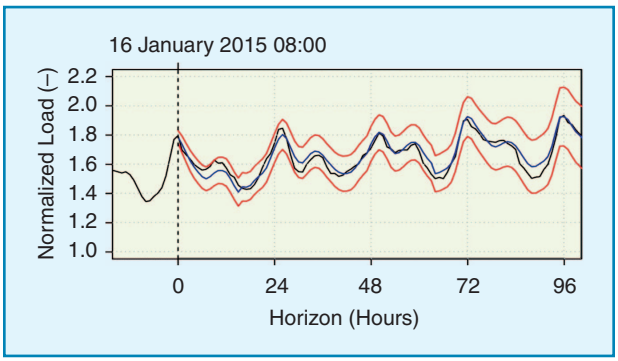

figure 7. The quality of heat forecasts 0–96 hours ahead for the Sønderborg district heating system in Denmark (the blue line). The 5% and 95% percentiles are shown in red, and the actual load as it was observed later is shown in black. The plot is generated using the adaptive heat-load forecasting system PRESS (www.enfor.dk/products/press.aspx).

Thermal electricity end uses such as water heating, space heating/cooling, and refrigerator/freezers are a suitable source for flexibility due to their discretionary nature, inherent thermal inertia, and large volumes. Large thermal inertia means that these loads can be switched off for a while without affecting consumer comfort. Furthermore, because the flexible loads consist of a number of appliances dispersed across the system, reliability can be statistically greater compared to an individual conventional power plant.

The building envelope itself also provides thermal inertia depending on the insulation level and thermal mass of the building. In a well-insulated house, electric load can be shifted (2–12 hours depending on building), while consumer comfort is still met. Preheating or precooling increases flexibility but typically also increases energy usage (depending on the insulation level). Thermal storage and building preheating enable considerable demand-shifting potential at a comparably low cost.

Forecasting

Thermal-load forecasting is often used in district heating systems and for estimating electric heating loads. The uncertainty of heat-load forecasts is important when trying to optimize heating or cooling. Forecasting failures can lead to unwarranted costs or uncomfortable inside temperatures. For example, when a heat-load forecast error persists in one direction for muliple hours, heat storage may become emptied or filled, after which it is not useful any more. When uncertainty is not considered, optimizing the use of heat storage is too easy, and model results or control strategies are too optimistic. Figure 7 demonstrates the quality of heat forecasts 0–96 hours ahead for the Sønderborg district heating system in Denmark.

If heating and cooling loads are to be controlled in a manner that provides flexibility to the power system, accurate forecasts will be important. Good forecasts will need to include climatic variables, building characteristics, and often predictions about user behavior. Building characteristics can be considered either through direct modeling or past behavior. Occupancy behavior varies from family to family: some families have a very systematic and easily predicted load pattern, whereas others seem to have a very random and less predictive load profile.

Similar to electric loads, it has been shown that the aggregation of individual loads can decrease relative forecast errors and smooth out rapid variations. However, when heating/cooling takes place in individual buildings, the control algorithm cannot aggregate. On the other hand, when several buildings are connected to a district heating system, the forecasts for control can be aggregated and relative forecast errors decrease. This is different from just forecasting loads without control, where aggregation can take place in all cases.

In district heating systems, heat is stored in the pipelines and also in the building envelopes, resulting in a daily profile with little variation—mainly driven by ambient temperature variations.

Harnessing Heat Flexibility

Flexibility from heating and cooling can be used in several ways in a power system. Moving loads from electricity net load peaks to net valleys can smooth variations. When the heating devices have suitable controllability, they can also be valuable sources of reserves that mitigate forecast errors and faults. Because heat is such a diverse and heterogeneous load, a selection of system studies and applications is presented in the following to highlight how heat flexibility can potentially be harnessed.

Integrated Energy System Studies

Electricity System Benefits of Heat-Pump Deployment in Belgium

Belgium is a densely populated country with significant plans for variable-power generation. Cost-effective integration will be a challenge; consequently, there is strong interest in finding workable sources of flexibility. In one study, the deployment of 1-GW electricity from flexible heat pumps managed to reduce curtailment of variable generation and avoided 100 GWh of gas-fired generation. However, it was identified that performing demand response with the heat pumps increased the building's heat demand by 1–10%. This increase in electricity use poses a challenge in terms of compensating consumers for participating in demand response, especially since residential consumers are typically exposed to prices higher than wholesale market prices. Another case study shows that the contribution to the peak demand in winter due to electrical space heating can be significantly reduced, by 2 GW on a total of 16.5 GW.

Integration of Heat and Electricity Sectors in the United Kingdom

In the United Kingdom, over 80% of households use natural gas for space and water heating, and this consumes more than 1.5 times more energy than U.K. electricity consumption. Peak heating requirements in winter are more than five to six times higher than electricity peaks. While the electrification of heat could, in principle, provide flexibility to the power sector, the danger is that if electric heating is uncontrollable, it will magnify power system variability and peak demand. Additionally, the parallel deployment of wind and solar power, in combination with relatively inflexible nuclear generation, could exacerbate flexibility demand. Studies suggest that, in an inflexible U.K. electricity system having 30 GW of variable renewables in combination with inflexible nuclear generation, more than 25% of wind energy may need to be curtailed if no additional measures are taken.

In this context, a well-designed integration of heat and electricity systems can lead to a more cost-effective transition toward a low-carbon energy system (see Figure 8). When heat is supplied by heat pumps via district heating systems or through a controllable electric heating device at customer premises, analysis demonstrates significant benefits accrued from three sources:

1) There will be less need for heat production capacity when heat storages that use electricity cut peaks.
2) Curtailment of renewable generation is reduced when heat storages can utilize excess generation.
3) With reduced curtailments, less renewable generation capacity is needed to meet emission reduction targets.

Heat Versus Other Flexibility Sources in the North European Context

The value of flexibility from the heat sector is influenced by the cost-effectiveness and availability of flexibility from other sources. In a Northern European study, a combined generation-planning/operational model was used to evaluate the benefits of adding heat pumps, electric heat boilers, and heat storages to a district heating system in a future where there would be much greater variable generation in the system. The results demonstrated that, while new transmission lines probably have the best cost-benefit ratio, heat-sector flexibility comes as a close second, far ahead of electricity

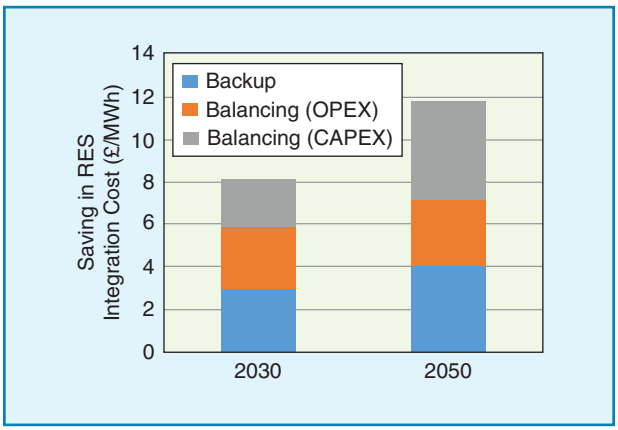

figure 8. The reduction in integration costs of renewable generation (electricity sector only) enabled by the integrated operation of heat and electricity sectors.

The parallel deployment of wind and solar power, in combination with relatively inflexible nuclear generation, could exacerbate flexibility demand.

storages or peak shaving-demand response. Buildings with local heating and the transport sector were not included in the study.

Heat Loads in Primary-Frequency Reserves

When a power system is running mainly with nonsynchronous generation, one option in providing upward primary-frequency reserve is to curtail wind or solar power plants to get the necessary headroom for reserve operation. However, flexible heating and cooling loads can also provide a fast response, typically in the order of 100–400 ms, when using local frequency detection. Consequently, some generation curtailments could be avoided, and system-wide fuel use could be decreased.

In one case study, system-wide operating cost savings ranged €8.5–500 per heating appliance, depending on various factors (fuel costs, wind penetration, etc.), for Great Britain's power system. The cost savings from the activation of flexible heating loads improve with increasing shares of wind power and with increases in reserve requirements. In addition to direct economic benefits, using flexible loads in primary reserve reduces the number of conventional plant startups, enables higher levels of wind penetration, and improves frequency stability.

When implementing heating- or cooling-based reserves, one needs to consider the load pickup that takes place after the load has been curtailed for reserve provision. The magnitude of the pickup varies with the thermal inertia characteristics of the heating/cooling load, the duration of the response, and the control mechanism. For example, activation of 60 MW of primary reserve from a domestic cold load (refrigerator/freezer) for 90 s (5-min recovery duration) requires the addition of 20 MW (35% of activated flexible load) to subsequent reserve categories to allow for the load pickup.

Residential Heat–Electricity Integration Using Hybrid Heaters in Ireland

Hybrid heating systems, such as a combination of a heat pump and a gas boiler, enable shifting between the two different sources of heat. If equipped with smart controls, it is possible to shift in real time, depending on electricity market conditions.

An investment study of the Irish 2030 system, with 40% electricity from wind power, found that the large-scale deployment of such systems can provide electricity system benefits. An optimization model was used to find the least-cost heater capacities and operation schedule. If a gas boiler is combined with a resistance heater, those hybrids will operate primarily on gas but will shift to electricity whenever low-price electricity is available. When compared to a gas boiler alone, the results showed annual system-wide savings of €18–65 per household, depending on the gas price. If a gas boiler is combined with a heat pump, they will operate mainly on electricity and shift to gas during periods of low wind-power supply or high demand. Then, the annual savings were €46–159 per household. The flexibility from hybrid heaters enabled the lowest-cost energy system.

Benefits of Electric Boilers in Reducing Wind-Power Curtailment in Northern China

In the northern provinces of China, 20~40% of wind energy was curtailed in 2015 due to inflexible operation of coal-fired CHP plants. In winter, these plants must operate at nearly full capacity to meet the demand for building heat (delivered as hot water through district heating systems) and must produce electricity at the same time. Combined with a high output from wind power plants, this often causes an oversupply of electricity, and wind power plants need to be curtailed. A series of numerical studies tested the use of thermal storage and/or heat pumps to increase the flexibility of the system. The results demonstrated a significant reduction in wind-power curtailments. On the other hand, air-source heat pumps suffer from low efficiency in the cold winter conditions of Northern China and may not be an economic choice.

Some Real-World Experience and Applications

Denmark is one of the leading countries in the integration of large amounts of wind power. In 2015, 42% of its electricity was generated by wind turbines. Apart from its large interconnectors to neighboring countries, the integration of wind power was enabled by its district heating networks. These networks can store excess wind power generation through a combination of electric heaters and heat storages. Meanwhile CHP plants can be operated when there is not enough low-price electricity available.

In residential buildings, smart thermostats can give functionality beyond temperature and time-of-use control. Communication with the Internet or an aggregator enables the utilization of power prices and weather forecasts. Meanwhile, occupant-modeling intelligence can consider the actual needs of the occupants in the control scheme. For example, the model predictive control (MPC) algorithm can make use of the additional information to better utilize lower power prices and improve energy efficiency. From a power system perspective, this appears as

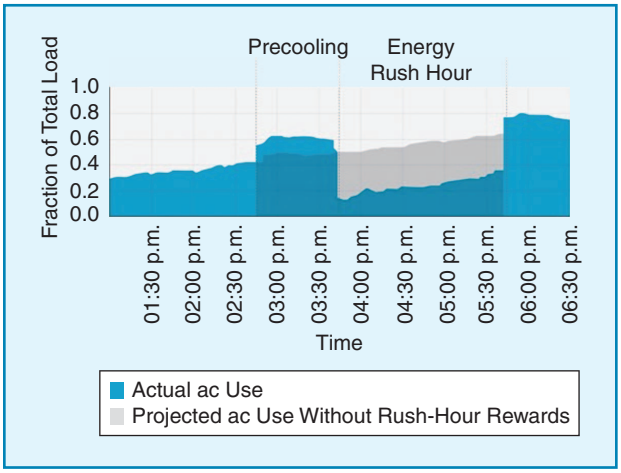

figure 9. Employing heat flexibility in residential buildings to avoid electricity demand when the electricity grid faces high loads. (Source: nest.com.)

increased flexibility. MPC is applied by companies such as BuildingIQ or QCoefficient when they exploit chiller efficiency variations due to ambient temperature to achieve energy savings without overly affecting occupant comfort. An example of smart-thermostat-based control is shown in Figure 9, where the smart thermostat Nest performed large-scale peak shaving by precooling American residential buildings.

In 2011, China initiated a series of pilot projects that substitute electric boilers to for coal-fuelled CHP boilers in the Jilin province. The electric boilers often use surplus wind generation as their energy source. From 2015, the project has expanded to all the northern provinces such as Hebei, Liaoning, Inner Mongolia, and Xinjiang. The electric boilers are equipped with water tanks capable of providing 10~15 hours of storage.

Conclusions

Heating and cooling offer considerable flexibility potential for power systems. Much of this could become cost-effective as the share of variable and uncertain generation increases. Simultaneously, electrification of heating offers a possibility for heat sector decarbonization. However, the picture is not entirely rosy. Seasonality in space-heating needs makes it a less attractive source of flexibility. On the other hand, flexibility from heating could be partially complemented by flexibility from cooling or from more stable loads in the industrial sector. At the same time, the industrial sector is very diverse and will require elaborate research to understand the true flexibility potential in heat-consuming industrial processes.

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For Further Reading

D. Patteeuw, K. Bruninx, A. Arteconi, E. Delarue, W. D'haeseleer, and L Helsen, "Integrated modeling of active demand response with electric heating systems coupled to thermal energy storage systems," *Appl. Energy*, vol. 151, pp. 306–319, Aug. 2015.

S. Heinen, D. Burke, and M. O'Malley, "Electricity, gas, heat integration via residential hybrid heating technologies: An investment model assessment," *Energy*, vol. 109, pp. 906–919, Aug. 2016.

K. MacLean R. Sansom, T. Watson, and R. Gross, "Comparing the impacts and costs of transitions in heat infrastructure," Centre for Energy Policy and Technology, Imperial College, London, U.K., Apr. 2016.

J. Kiviluoma, "Managing wind power variability and uncertainty through increased power system flexibility," Ph.D. dissertation, Aalto Univ., Dept. Applied Physics, VTT Sci 35, Espoo, Finland, 2013, p. 77.

T. Naegler, S. Simon, M. Klein, and H. C. Gils, "Quantification of the European industrial heat demand by branch and temperature level," *Int. J. Energy Res.*, vol. 39, pp. 2019–2030, Oct. 2015.

N. Zhang, X. Lu, C. P. Nielsen, M. B. McElroy, X. Chen, Y. Deng, and C. Kang. "Reducing curtailment of wind electricity in China by employing electric boilers for heat and pumped hydro for energy storage," *Appl. Energy*, vol. 184, pp. 987–994, Dec. 2016.

P. Bacher, H. Madsen, H. A. Nielsen, and B. Perers, "Short-term heat load forecasting for single family houses," *Energy Buildings*, vol. 65, pp. 101–112, Oct. 2013.

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