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Harnessing Flexibility from Hot and Cold — Source link

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Flexibility from heating and cooling

1. Introduction: Heating/cooling and flexibility

As has been often reported, electricity systems with high levels of variable and uncertain 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 big question is in which cases will the benefits outweigh the costs. This will naturally depend on the evolution of specific energy systems. This article lays out generic principles and characteristics related to heat sector flexibility as well as demonstrates its possibilities with specific examples. While the article often uses the word 'heat', most descriptions also apply to 'cool', which after all is just another form of temperature difference.

A major potential for flexibility in the heat sector is created by the low cost of storing heat. This provides an opportunity to shift electricity demand. Another option is to utilize hybrid systems where either electricity or fuel can be used to produce heat depending on the price variations of either option. This category includes many different options starting from dual heaters in buildings all the way to large district heating systems with combined heat and power plants (CHP), fuel boilers and electric heaters.

2. The flexibility potential of heating and cooling

Heating and cooling is a huge energy consumer. However the heat system is often not considered as a single system, but - due to the historic emphasis of energy supply – as subsystems of different supply sources (e.g. gas, coal, electricity). Therefore the size and flexibility potential are often overlooked. In the EU (2014, Eurostat) around 30% of primary energy is used to produce heat, 30% in transport sector and 40% for electricity (including electricity to heat) (see Figure 1).

The share of electricity in primary energy consumption is higher than in final energy consumption, since a large portion 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 the 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.

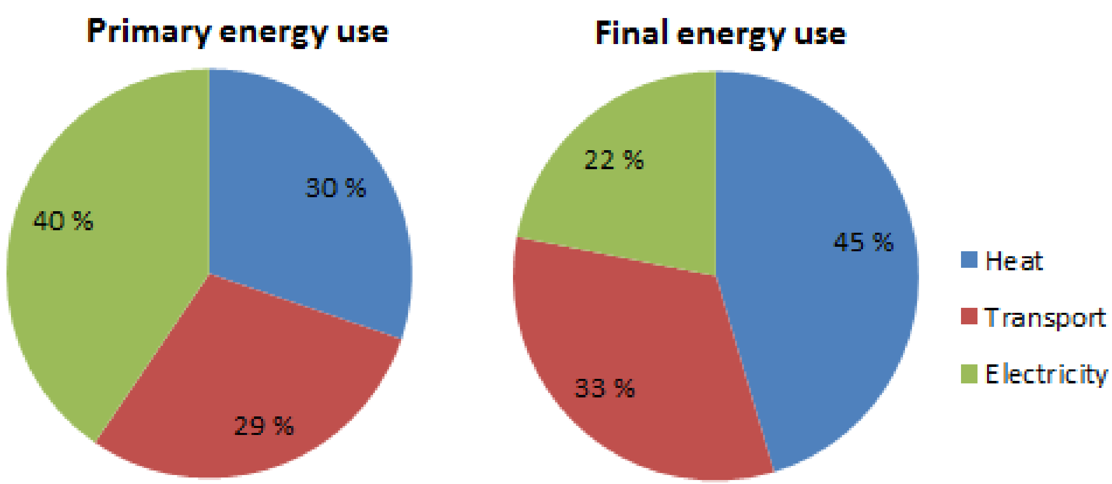

Figure 1*. Primary and final energy use in EU 2014 (Eurostat) divided into three main categories of energy end use.*

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 amiable to being controlled than others. Figure 2 divides EU-28 final energy use, heat in particular, into several categories. Most heat in EU is generated from natural gas while coal, oil and biomass make up most of the rest.

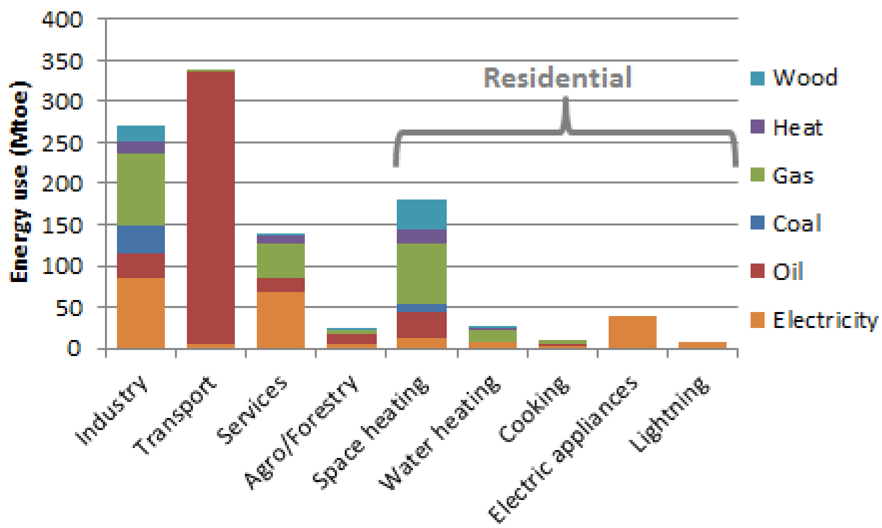

Figure 2. Final energy use in EU 2014 (based on Eurostat). Residential sector split into components using 2008 data (ODYSSEE). Losses in transformation and transfer are not included. 'Heat' as energy use means that the heat is a conversion by-product from e.g. combined heat and power plant or an industrial process.

In Europe, the cooling demand is considerably smaller then heating, but it is growing fast with increasing space cooling demands – also due to the strong urban development in warmer climates and new uses in services and industries, such as cooling of large data centers.

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

- Local heating and cooling of buildings
- District heating and cooling
- Heat for industry

2.1. 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. Most residential and commercial buildings in the world produce heat locally in 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, electricity) and conversion process (combustion in a boiler or burner, liquid evaporation for heat pump 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. Since solid and gaseous fuels can be stored easily over weeks, if not seasons, these supply systems have inherently a lot of flexibility and planning boils down to managing supply and storage infrastructure like for most commodities. On the other hand, electricity-fuelled heaters/coolers require the power system to balance supply and demand instantaneously changing the dispatch in the short run and impacting generation portfolio in the long run.

Electric heating, if deployed in an uncoordinated manner requires additional power system flexibility to meet the daily, seasonal and annual variations. For example in France the majority of residential heating is based on electric heating and causes considerable temperature sensitivity in the power demand (2300 MW/°C). It is 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 the flexibility. In another example from Germany it was realised that electric over-night storage heaters can be a valuable source of flexibility and an earlier decision to remove them was reversed in 2013. The use of Information and Communications Technologies (ICT) in electric heaters could therefore provide the option to shift demand loads according to power system conditions, while also meeting the building occupant's comfort requirements. These examples illustrate the strong interaction of residential electric heating and the power sector, but also raise the question on how such integration of electric heating should be done to provide flexibility in the most cost effective 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 outdoor and indoor in a condensation/evaporation cycle. The heat cycle only requires electricity to run the compressor and other auxiliary equipment, therefore producing 2-4 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 coefficients of performance of 4-5. This minimizes generation requirements and peak load, but will not give as much flexibility to utilize excess renewable electricity. Local cooling is usually provided by heat pumps (either 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 between 1.5 and 2.5 units of cooling for one unit of electricity. In regions with high cooling loads, the coordinated cooling of buildings causes the dominant peak electricity demand.

In many cases where a heat pump is installed, it is complemented with 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, which can include an extended period of several days. Hybrid fuel boiler/resistance heater systems could provide the option to use 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 conditions 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 more controlled manner. Using resistance coils or hydronic systems in underfloor heating enables to store some energy also in the thermal capacity of the floor. 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 storage device cost.

Cool can also be stored. Temperature differences are smaller than in heating and consequently cool 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 temperature difference in water. There are commercial chillers available that use ice storage. They 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 they 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.

2.2. 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 heating system cooled water flows back to the plants on 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 combined heat and power plants (CHP). 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 can be found mainly in larger systems that can accommodate larger, more economic, plants. When used alongside CHP plants, fuel boilers cover heating peaks and backup CHP units. Combination of 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 the 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 photovoltaics) 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 the cheap power while heat pumps give lot 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 neighbourhoods 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 flexibility viewpoint, they offer considerable economies of scale for heat storages whose specific cost 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, since most people live in climates where cooling is an aspiration, district cooling may have a more important role in the future. District cooling can have a 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 since waste heat is transferred away from the city. Cooled fluid, typically water, could also be stored in accumulators in order to gain more flexibility towards the power system.

2.3. Heat use in industries

Figure 3 shows six grades of industrial heat use. It is dominated by the demand for 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 also somewhat higher temperature levels while still being able to produce electricity. A large fraction of industrial heat loads require higher temperatures, which are currently dominated by natural gas burners. However, electric heating technologies such as resistance heating, electric arc heating, induction heating, and dielectric (radio-frequency) heating can provide temperature levels above 500° and are thus principally capable of replacing 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 gas burners. Cost of energy, equipment and grid connection have so far limited the use of electric heating in comparison 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 use the fuel also 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 which takes part in the chemical reaction in the blast furnace. The electrification potential of industrial process heat has therefore to be analysed carefully for each type of process and will strongly differ across countries.

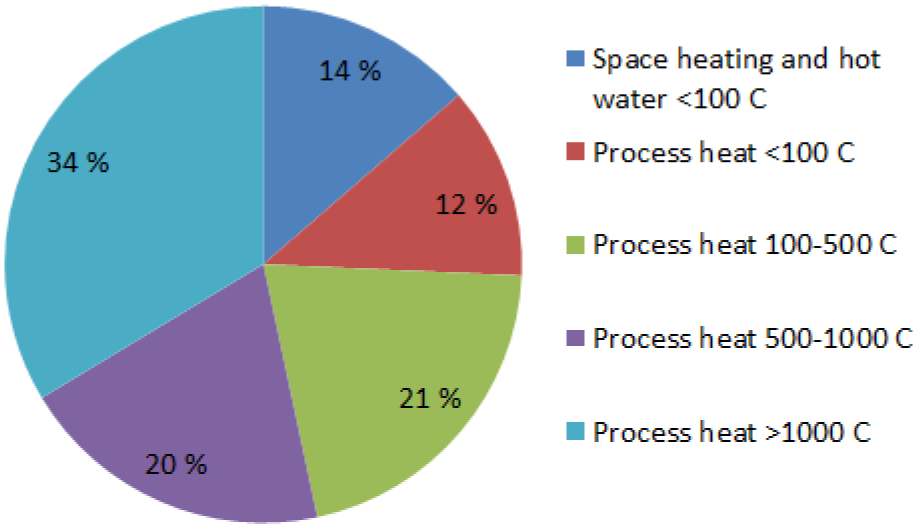

Figure 3. Use of different grades of heat in industries in EU-28 (based on Naegler et al. 2015)

3. Characteristics of heat demands and thermal storages

3.1. Heat consumption profiles

Heat demand profiles are determined by the weather, building characteristics related to thermal losses, occupant behaviour, and occupant expectations about indoor temperature. Consequently the 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 ambient temperature variations. Inside temperatures are kept nearly constant even when occupants are not present. In contrast, in Ireland houses leak more and the small share of buildings that rely on electric radiators use them mainly when occupants need the extra heat - in the mornings and evenings during the weekday. 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 expectations.

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

While not shown in the figure, cooling could complement the annual space heating profiles. In some climates, where heating and cooling needs are similar, cooling can complement heating locally. 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 coincide and complement each other well.

Industrial heat demand at country level does not exhibit strong seasonality and could therefore provide flexibility all year round (e.g. industrial heat demand from Finland 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.

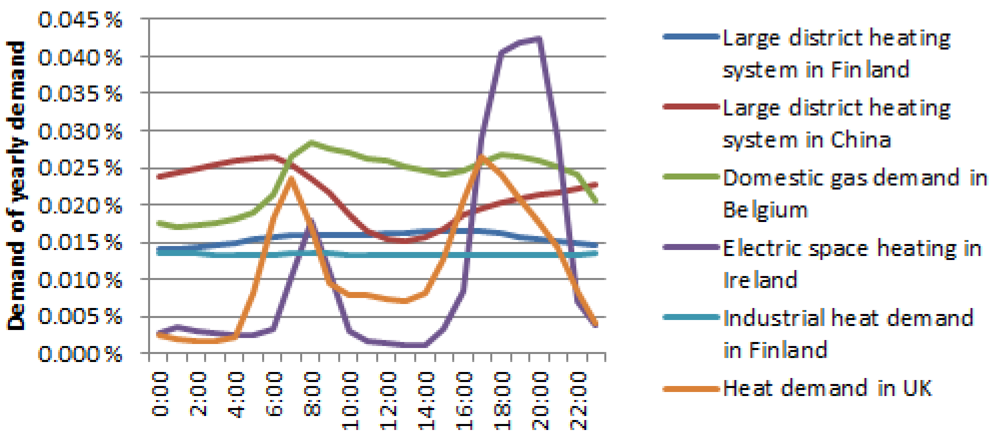

Figure 4. Hourly heat profiles from a winter weekday

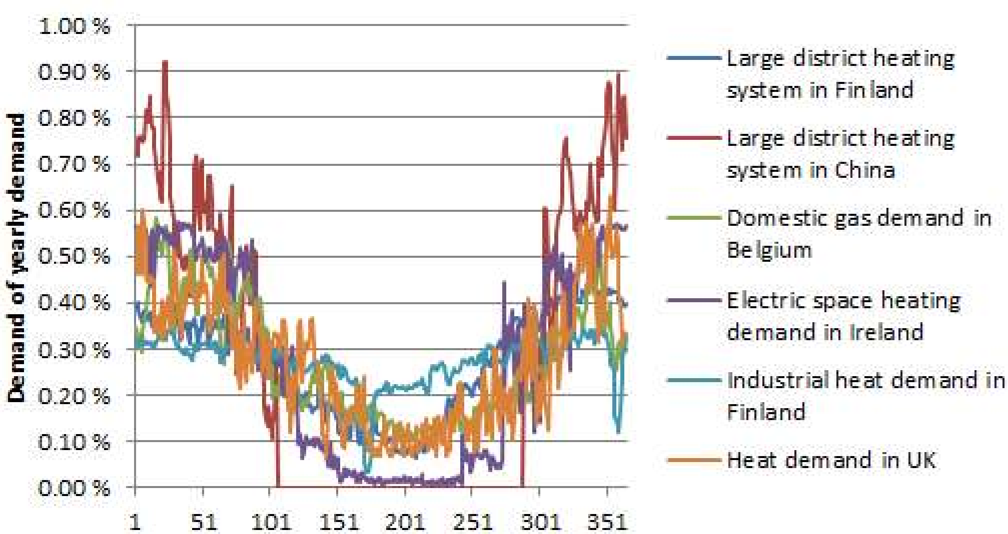

Figure 5. Average daily heat demands over the year

3.2. Time constants and thermal storages

It is technically possible to store heat from one season to another, but it has been 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 the end-user comfort or needs that might be affected by the operation of the heating device. Here is an approximate list of time constants for different heat uses:

- Domestic fridge-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 used commonly as a medium, even though other viable heat storage materials exist. A cubic meter of water changing between 55 and 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 get quite impractical to install much larger hot water tanks inside residential buildings as they would require considerable space and would 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.

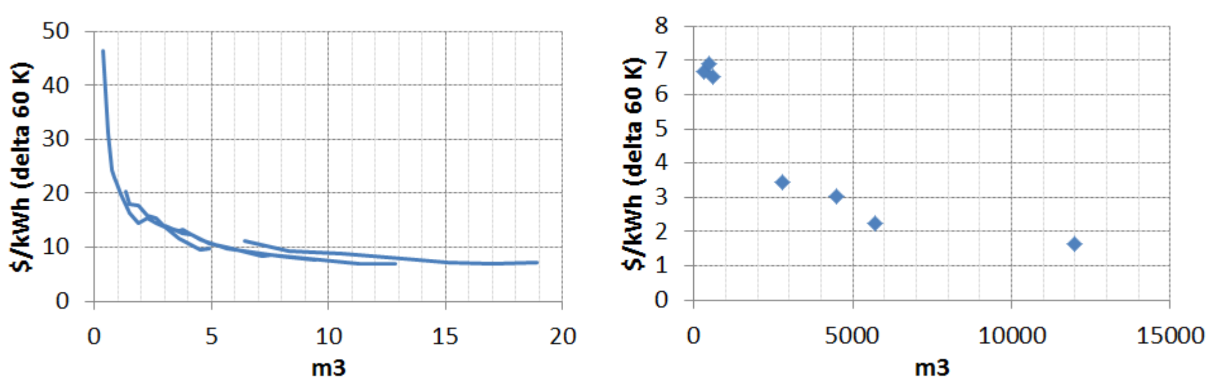

Figure 6. The cost of hot water tanks per unit of storable heat in relation to the storage tank size. Small tanks sizes based on market data and large tank sizes from JRC 2012.

Thermal electricity end-uses such as water heating, space heating/cooling and fridge-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 the consumer comfort. Furthermore, since the flexible loads consist of a number of appliances dispersed across the system, the reliability is statistically greater compared to an individual conventional power plant.

The building envelope itself also provides thermal inertia depending on the insulation level and on the thermall 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. Pre-heating or pre-cooling increases flexibility, but typically increases energy usage (depending on the insulation level). Thermal storage and building pre-heating enables considerable demand shifting potential at a comparably low cost.

3.3. 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 cause unwarranted costs or inside temperatures that cause discomfort. For example, when heat load forecast error persists in one direction for consequent hours, heat storage may get emptied or filled after which it is not useful any more. When uncertainty is not considered, optimizing the use of heat storages is too easy and model results or control strategies are too optimistic. Figure 7 demonstrates the quality of heat forecasts for 1 to 96 hours ahead for the Sønderborg District Heating system in Denmark.

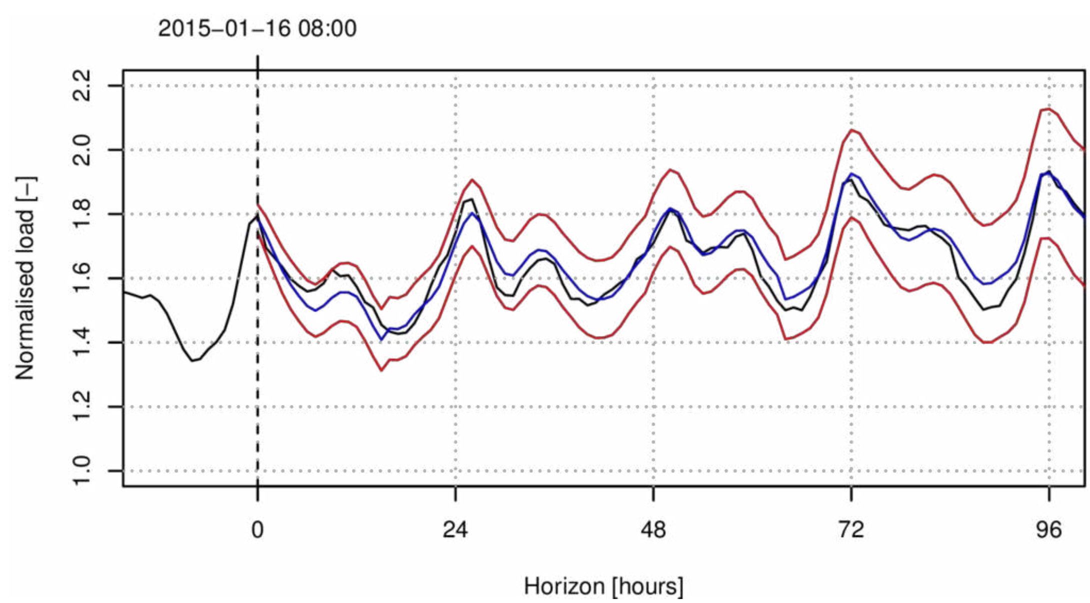

Figure 7. The blue line shows the heat load forecasts 0 to 96 hours ahead for a Danish district heating system. The 5 pct. and 95 pct. percentiles are shown in red, and the actual load as it was observed later is shown in black. The plot is generated using the adaptive heat load forecasting system.

If heating and cooling loads are to be controlled in a manner that gives flexibility to the power system, accurate forecasts will be important. Good forecasts will need climatic variables, building characteristics and often also forecasts about user behaviour. Building characteristics can be considered either through direct modelling or past behaviour. Occupancy behaviour varies from family to family and some families have a very systematic and easy predictable load pattern whereas some other families seem to have a very random and less predictive load profile.

Similar to electric loads, it has been shown that aggregation of individual loads can decrease relative forecast errors and smoothen 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.

4. 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. Since heat is such a diverse heterogeneous load, a selection of system studies and applications are presented below to highlight how the heat flexibility can possibly be harnessed.

4.1. Integrated energy system studies

Electricity system benefits of heat pump deployment in Belgium

Belgium is a densely populated country with big plans for variable power generation. Cost effective integration will be a challenge and consequently there is a strong interest to find workable sources of flexibility. In one study, the deployment of 1 GW_{elec} of 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 to 10%. This increase in electricity use poses a challenge for compensating consumers for participating in demand response, especially since residential consumers are typically exposed to prices higher than wholesale market prices. In another case study, 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 UK

In the UK, over 80% of households use natural gas for space and water heating and they consume more than 1.5 times more energy than the electricity consumption of the UK. Peak heating requirements in winter are more than 5 to 6 times higher than electricity peaks. While electrification of heat could in principle give flexibility to the power sector, the danger is that if electric heating is uncontrollable, it will magnify the 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 UK electricity system, with 30GW 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 towards low carbon energy system. 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: a) There will be less need for heat production capacity when heat storages that use electricity cut peaks. b) Curtailment of renewable generation is reduced when heat storages can utilize excess generation. c) With reduced curtailments, less renewable generation capacity is needed to meet the emission reduction targets.

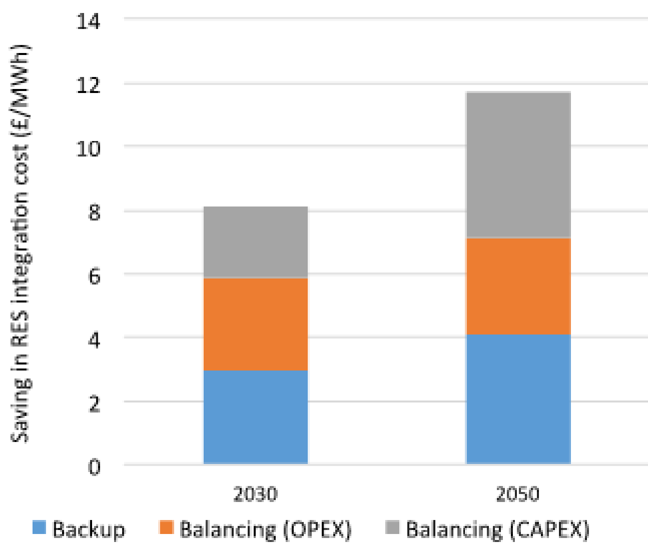

Figure 8. Reduction in integration cost of renewable generation (electricity sector only) enabled by integrated operation of heat and electricity sectors

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 combination of a generation planning model and 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 lot more 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, much before electricity storages or peak shaving demand response. Buildings with local heating or transport sector were not included in the study.

Heat loads in primary frequency reserve

When a power system is running mainly with non-synchronous generation, one option to provide upward primary frequency reserve is to curtail wind or solar power plants in order 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 of the generation curtailments could be avoided and system-wide fuel use could be decreased.

In one case study, system-wide operating cost savings ranged from 8.5£ to 500£ per heating appliance, depending on various factors (fuel costs, wind penetration etc.) for the power system of Great Britain. 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 start-ups, enables higher levels of wind penetration and improves frequency stability.

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

Residential heat-electricity integration of using hybrid heaters in Ireland

Hybrid heating systems, such as a combination of a heat pump and a gas boiler, enables to shift 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 just a gas boiler, 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 least-cost energy system.

Benefit of electric boilers in reducing wind power curtailment in Northern China

In the northern provinces of China, 20%~40% of the wind energy were curtailed in 2015 due to inflexible operation of coal-fired combined heat and power 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.

4.2. 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 neighbouring 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 modelling intelligence can consider the actual needs of the occupants in the control scheme. The algorithm, for example model predictive control (MPC), can take use of the additional information in order to better utilize lower power prices and improve energy efficiency. From power system perspective this appears as increased flexibility. MPCs are applied by companies such as BuildingIQ or QCoefficient when they exploit chiller efficiency variations due to ambient temperature in order to achieve energy savings without overly affecting occupant comfort. An example of smart thermostat based control is in Figure 9, where the smart thermostat Nest performed large-scale peak shaving by pre-cooling American residential buildings.

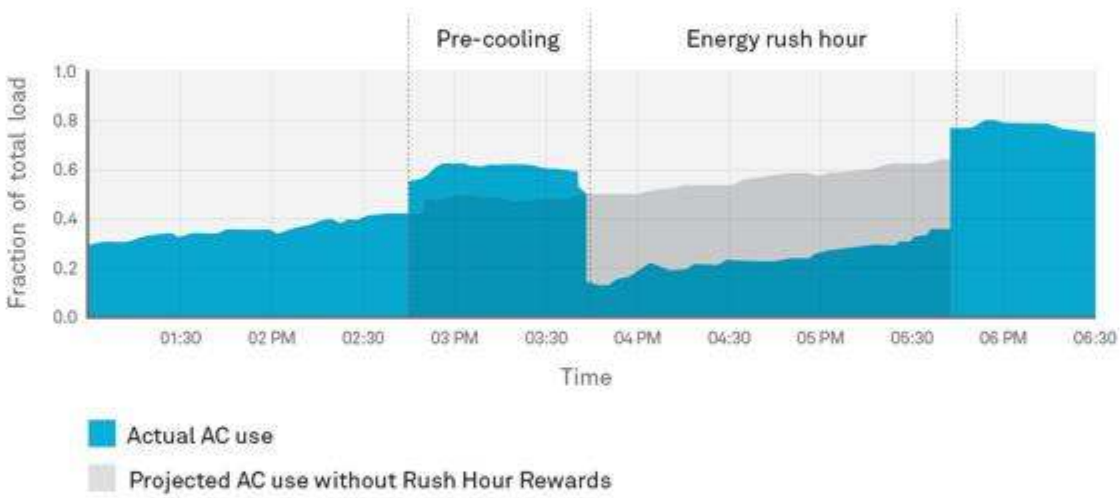

Figure 9. Employing the heat flexibility in residential buildings in order to avoid electricity demand when the electricity grid faces high loads. Source: nest.com

In 2011, China started a series of pilot projects that use electric boilers to substitute coal-fuelled CHP boilers in the Jilin province. The electric boilers will often use surplus wind generation as their energy source. From 2015, the project has expanded to all of 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.

5. Conclusions

Heating and cooling offers a very large flexibility potential for power systems. Much of it could become cost-effective as the share of variable and uncertain generation increases. Simultaneously, electrification of heating offers a possibility for heat sector de-carbonization. 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 the heat consuming industrial processes.

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Chongqing Kang and Ning Zhang are with the Tsinghua University, China.
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