ON THE USE OF SURPLUS ELECTRICITY IN DISTRICT HEATING SYSTEMS

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ABSTRACT

Maintained balance between supply and demand is a fundamental prerequisite for proper operation of electric power grids. For this end, power systems rely on accessibility to various balancing technologies and solutions by which fluctuations in supply and demand can be promptly met. In this paper, balancing approaches in the case of surplus electricity supply, due to long-term, seasonal, or short-term causes, are discussed on the basis mainly of compiled experiences from the Swedish national power grid. In Sweden, a structural long-term electricity surplus was created in the 1980s when several new nuclear plants were commissioned and built. One of four explicit domestic power-to-heat solutions initiated to maximize the utilization of this surplus electricity, as export capacities were limited, was the introduction of large scale electric boilers and compressor heat pumps in district heating systems. In retrospective, this solution not only satisfied the primary objective by providing additional electricity demand to balance the power grid, but represents today – from an energy systems perspective – a contemporary example of increased system flexibility by the attainment of higher integration levels between power and heat sectors. As European power supply will be reshaped to include higher proportions of fluctuating supply technologies (e.g. wind and solar), causing occasional but recurring short-term electricity surpluses, the unique Swedish experiences may provide valuable input in the development of rational responses to future balancing challenges. The main conclusions from this study are that district heating systems can add additional balancing capabilities to power systems, if equipped with electrical heat supply technologies, hereby contributing to higher energy system flexibility. Consequently, district heating systems also have a discrete but key role in the continued integration of renewable intermittent power supply technologies in the future European energy system.

INTRODUCTION/PURPOSE

District heating systems are mostly associated to combined heat and power (CHP), based on heat recovery from thermal power stations. This heat recovery is part of the basic fundamental idea of district heating [1]. This cogeneration of heat and power is based on the normal condition that electricity prices are considerable higher than heat prices. The exergy content in the fuel is then shaved off as electricity and exported to the power system. The remaining low-exergy and anergy parts are then used for heat generation supplying the district heating system. However, when electricity prices are low, the CHP advantage is lost and an opportunity appears for importing electricity to district heating systems for heat generation. This import direction of electricity to district heating systems is the basic theme for this article.

Low electricity prices are the result of some kind of surplus situation in the power system, when ordinary electricity customers cannot absorb the temporary supply surplus. If the power grid have high capacity power transmission cables to other regions, these temporary surpluses can be exported and substitute flexible power supply in these regions. If the export capacity to other regions is limited, the surplus must be absorbed in the region concerned. It can also be accomplished by using storage possibilities within the power systems as hydropower dams, batteries in future electric vehicles, or large compressed air storages.

The electricity surplus can also be absorbed outside the power system by export to heating systems for heat generation, either in individual heating systems or in district heating systems (power-to-heat solutions). The required flexibility in the power system from fast balancing power is then delivered from the heating systems. The obtained heat can then substitute ordinary flexible heat generation and local heat storages can also be used in order to supply the heat for later use. These heat storages can deliver flexibility to the power systems to a lower cost than most storage possibilities within the power system [2]. The competitive advantage for district heating systems compared to individual heating systems is that the absorption of surplus electricity can be implemented to a lower cost from economy-of-size. The electric surpluses can also be absorbed by gas generation technologies within the gas system (power-to-gas solutions). Hence, several competing solutions within the energy system can supply flexibility to the power system.

These electricity surpluses have different time scales from short-term (hours or days) to more long-term (one to many years). One example of short-term electricity surplus is supply peaks in the future power systems with high proportions of fluctuating wind and solar power during windy and sunny days. The future use of surplus electricity in district heating systems has been foreseen and discussed in [3] for Denmark, in [4, 5] for Germany, and in [6] for Russia.

Seasonal electricity surpluses appears in power systems dominated by hydropower plants from the variation from year to year with respect to precipitation received, also called dry and wet years. This annual variation initiated the introduction of Norwegian district heating systems in the 1980s, where requirements for

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sale of firm power[1] due to reliability was set to a minimum limit so that capacity on average was sufficient 27 years out of 30 years, thus creating a surplus of power on the majority of the years during a period of 30 years [7].

A more long-term electricity surplus appeared in early power systems when an initial major hydropower plant was built with a capacity much higher than the current electricity demand. Examples are the electric heating of the city hall in Borås in Sweden from the newly built and initially oversized Haby hydropower station in 1916 [8], the use of electric heating in Bergen, Norway [9], and the use of surplus hydropower electricity in two small district heating systems in Munich [10].

Another more structural long-term electricity surplus was created in Sweden in the 1980s, when many new nuclear power plants were commissioned. The possible supply of nuclear power became higher than the sum of the current electricity demand increase and the substituted thermal power plants using fossil fuels. The surplus could not be exported to other countries, since the current export capacity was too small, so the surplus had to be absorbed within the country. In order to maximize the utilization of the surplus, four activities were initiated: introduction of electric heating resistors in domestic oil boilers, general promotion of electric boilers and heat pumps for substitution of oil boilers in single-family houses, introduction of large electric boilers for industrial heat demands, and finally introduction of large electric boilers and large heat pumps in district heating systems.

The focus in this article is the documentation of the fourth activity above concerning district heating systems. The purpose is to provide experiences for other future power-to-heat solutions associated to district heating systems. First, the development in the Swedish power system is described. Second, the Power-to-heat technologies mainly used in district heating systems (large electric boilers, large heat pumps) are presented. Thirdly, the article aims to discuss general implications regarding the balancing role of district heating systems in highly integrated future energy systems. The added option in such systems, i.e. to use surplus electricity for heating purposes, may prove increasingly valuable as the proportion of intermittent power supply technologies escalate in the power supply mix.

SWEDISH POWER SUPPLY

Hydropower dominated initially according to Fig. 1 giving some national dependence of dry and wet years in the national power balance.

In the late 1940s, a future deficit of hydropower compared to demand was identified. This initiated many municipalities to start up district heating systems as heat sinks for future CHP plants. The first district heating systems was introduced in Karlstad 1948 [11]. Nine more cities started up district heating systems in the 1950s. In general, all early CHP plants used fuel oil as energy source.

Expanding electricity demands initiated also two major oil-fueled condensing power plants (Stenungsund and Karlshamn), also using fuel oil. This gave more space in the power balance for substituting the operation of these power plants with further CHP plants in both industries and district heating systems.

The first major Swedish nuclear power reactor was commissioned in 1972. During the following thirteen years, another eleven nuclear power reactors were commissioned; giving a considerable proportion in the Swedish power generation, see Fig. 1. This fast expansion of nuclear power created a surplus of electric power.

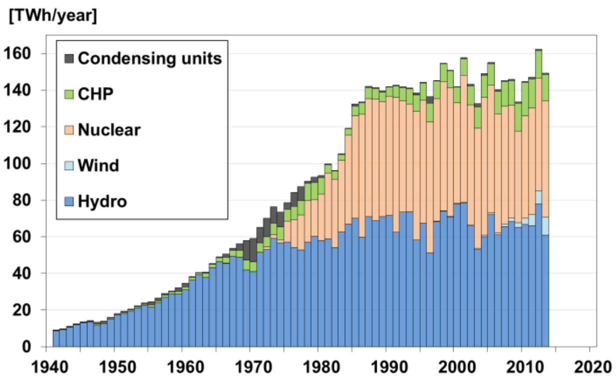

Fig. 1 Power generation in Sweden 1941-2011.

A major part of the temporary power generated, due to the surplus situation, was absorbed within district heating systems. During the period of 1985 to 1995, the relative proportion of temporary electricity supplied into district heating systems was 71 %. Industrial and residential/service sectors were also represented during the time period, but to a lower extent. They represented 27 % and 2 % respectively, see Fig. 2.

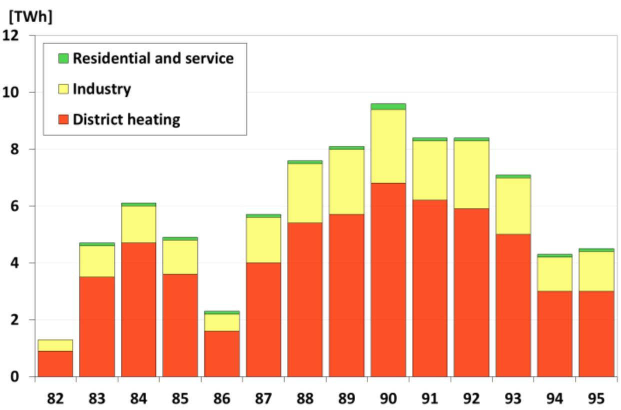

Fig. 2 The use of temporary electricity in the national electricity demand.

STATE OF THE ART: POWER-TO-HEAT IN DISTRICT HEATING SYSTEMS

In coherence with the national energy policy, surplus power was to be used as a replacement for fossil oil use. This goal was partly achieved by promotion of large electric boilers and use of large compression heat

[1] Firm power refers to electric power that is continuously available from the water stream, even in times of lowest flow and lowest head.

pumps for central use mainly in district heating systems.

Since power-to-heat reached its peak in 1990 with a 35 % proportion of heat supplied, see Fig. 3, there has been a steady decline of heat supply proportion from electric boilers into the district heating systems. The decline in proportion of heat supply from heat pumps is partly mitigated by the increase of heat supplied into district heating systems, see Fig. 4, and the expansion of biomass CHP plants. A reason for this development was that demand of electrical power caught up with supply, thus increasing the price; making power-to-heat solutions less viable.

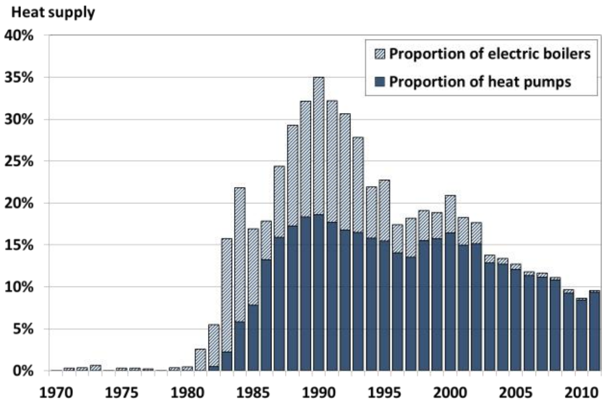

Fig. 3 Annual proportion of heat supplied from electric boilers and heat pumps, into district heating systems 1970-2011.

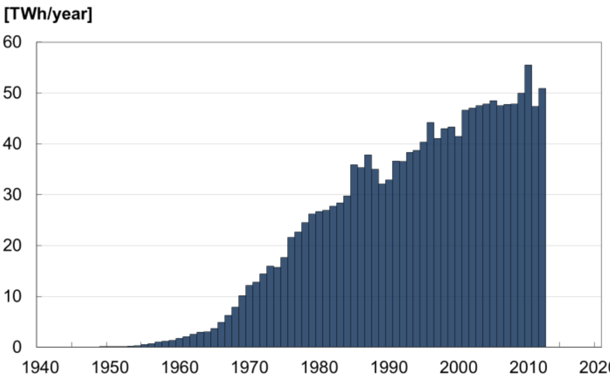

Fig. 4 Annual heat delivered from district heating systems 1949-2012.

Large electric boilers

For large electric boilers such promotion was partly introduced in the form of an energy tax reduction on electric energy. This tax reduction could be obtained during 1984 to 1991 [12]. Prerequisites to be entitled a tax reduction enclosed a special agreement with the electricity supplier about temporary power supply, which at any time could be interrupted due to power system reasons. In addition to be classified as temporary power, capacity of installed units was to exceed 1 MW of heat power, no oil-based power generation had occurred for a consecutive period of five days and there had to be an alternative source of heat for when the electric boiler was out of use [13].

Agreements for temporary power have existed in Sweden since 1950s. At this point in time power-to-heat was however rarely used; the exception was during wet years. It wasn't until the late 1970s and early 1980s that the use of large electric boilers, for temporary power, became a more common feature with the integration of nuclear power in the Swedish power system.

In order to ensure demand of surplus power, the Swedish state owned company Vattenfall promoted large electric boilers in two different ways. Investments could receive a grant of 100 SEK per installed kW, alternatively Vattenfall guaranteed a certain payoff time, and if the payoff time could not be achieved then Vattenfall paid the remaining sum.

Table 1. Electric boilers in industries and district heating systems for temporary power, above 30 MW in operation, December 1986

Owner	**Electric Power [MW]**	**Units**
Akalla Värmeverk	75	2
Drefvikens Energi AB	32	1
Edet AB	30	1
Gislaveds AB	30	1
Karlit AB	40	1
Karskärsverket, Gävle	40	1
Malmö Energiverk AB	105	3
Munksjö AB	32	1
St Kopparb-Bergvik	40	1
Stockholm Energi Värtaverket	150	3
Stockholm Energi Produktion	80	2
Stora Kraft, Kvarnsveden Papper	34	1
Stora Kraft, Skutskärsverken	40	1
Sundbybergs Energiverk	60	1
Sydkraft AB	35	1
UKAB	50	1
Vivstavarvs AB Timrå	50	1
Volvo AB	30	1
Västerås Stads kraftvärmeverk	60	2
Grand Total	**1013**	**26**

In the end of 1986, there was 422 units of electric boilers installed for temporary power equal to 3400 MW [13]. According to Table 1, approximately 6 % of the units corresponded to 30 % of installed capacity. A majority of the capacity was installed during a few years in early 1980s as can be seen in Fig. 3. In the beginning of 1986, Vattenfall withdrew any further promotion of large electric boilers.

Table 2. Heat capacity from heat pumps > 1 MW arranged by install year and heat source, value in MW, total number of facilities 114, total number of units 155 as of 1986 [14]

	Industrial excess heat	Sewage water	Ambient water	Groundwater	Air	Grand Total
1980					3	3
1981	4	3				8
1982	12	60	22			93
1983	31	106	38	3	8	186
1984	121	135	24	1	17	298
1985	28	53	86	20	3	190
1986	5	314	185	40	11	554
Grand Total	**201**	**671**	**355**	**63**	**41**	**1330**

Two statements can be made with this knowledge. First, it is unlikely that any more capacity of electric boilers was built. Second, it is questionable whether or not the rapid development of electric boilers was justified, with the consideration that too much capacity may have been installed.

Large heat pumps

As of 1987, there were 155 units of large heat pumps in use in Sweden[2], corresponding to 1330 MW of heat power. The growth rate was high during 1982 to 1986 as seen in Table 2. Thereafter, expansion decreased dramatically, the reason for this change of pace in expansion was the same as for electric boilers, market saturation. At this point in time a majority of the district heating companies had invested in a large heat pump. The decrease of proportion in heat supply from large heat pumps as seen in Fig. 3 depends partly on larger heat supply from district heating systems in general but a part of the decline is due to heat pumps which are decommissioned due to age. Also newly installed capacity in biomass combined heat and power plants preceded heat pumps in merit order depending on price of electricity.

Heat pumps were profitable on continuous operation and thus they required a continuous power supply whereas electric boilers relied on a recurring surplus. Heat pumps did neither share the tax benefits nor the investment guarantees of electric boilers. In addition it is of importance to note that large heat pumps cannot be operated as intermittently as electric boilers, due to mechanical wear during start-up, and time for start-up which amounts to minutes, while COP is low during start-up.

Potential heat sources for utilization in heat pumps ranged from: ambient water in seas, lakes, rivers, or groundwater, sewage water from sewage treatment plants (treated or untreated), geothermal heat from boreholes, industrial excess heat and solar heat. A prominent part of installed capacity from large heat pumps in Sweden used sewage water as heat source, see Table 2. The temperature level from sewage water is limited at a rather low temperature, though usually higher than temperature levels of ambient water. Performance of heat pumps is dependent on required increase of temperature, thus making a heat source with higher temperature levels more attractive. Even though this, coefficient of performance (COP) seen as an annual average has been kept at around three or above since the early 1980s, see Fig. 5. From an annual average perspective, it also seems that development in heat pump technology has been constant; since the difference in COP is marginal during the time period, see Fig. 5.

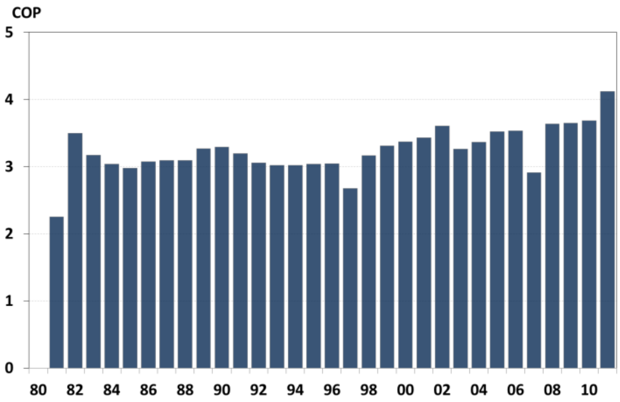

Fig. 5 National annual average COP for heat pumps in district heating systems 1981-2011.

DISCUSSION/OUTLOOK

Power-to-heat solutions can be beneficially implemented in power systems where electricity periodically occurs as a surplus, as is the case in countries with a high proportion of power generation associated with a varying degree of predictability such as hydro-, wind- and solar power. The key to unlocking power-to-heat at a large scale is district heating systems and with it, possibilities to occasionally even out fluctuations on an electric power grid.

In the past surplus power was usually based on seasonal and long-term sources, as was the case in Sweden, Norway and Germany during the early 20th century, where surplus of power lead to power-to-heat solutions in conjunction with hydropower. During the 1980s in Sweden, power-to-heat solutions once again flourished when the nuclear power was introduced. In the future however, a higher proportion of short-term surplus power from fluctuating sources is to be expected. Since surplus electricity once led to the expansion of district heating, as it did in Norway during the 1980s, it seems reasonable that power-to-heat

[2] Not only in district heating systems.

solutions once again should be introduced in already developed district heating systems.

Access to a long term recurring surplus of electrical power is an uncommon phenomenon. There is a need for large quantities of renewable energy sources, usually hydro- or geothermal power as seen from a historical perspective, but in the future, wind and solar power as well. Sweden is one of few countries that on a on and off basis has had documented access to surplus power during a time period of a century, thus there is large amount of experience to be gained from.

A compilation of Swedish historical experience on power-to-heat usage in district heating systems is a fundamental cornerstone to alleviate introduction of such solutions in future energy systems.

As the proportion of power-to-heat peaked in 1990 it is uncertain how much higher the share could have been with access to more surplus power, with regard to already installed capacity. Also to consider is the rapid decline of power-to-heat proportion in district heating systems over the following two decades. The development seems hasty and irrational, perhaps the possibilities of power-to-heat was greatly overestimated in correlation to the measurements taken to ensure their introduction. Thus creating a first come, first served situation, it could be considered that the benefits were too favorable and therefore allowed an excessive amount of capacity to be built.

Investments in energy systems are usually of long term character in nature. In the case of power-to-heat however, with focus on large electric boilers, the payback time were usually around two to three years and due to market saturation, economic life became short, only a few years for early investments and less for investments made at a later stage, while technical life of an electric boiler most likely could reach a few decades at least.

This paper gives a short general overview of large electric boilers and large heat pumps, mostly with regard to district heating systems. Continued work on this paper could include data on individual unit level, ensuring quality and quantity on data and to deliberate what the actual operating experiences has been, what to think of and which pitfalls to avoid.

CONCLUSIONS

The main conclusion of this paper is that power-to-heat solutions used in district heating systems can be a cost efficient way to introduce more flexibility to an energy system and thus allow a larger proportion of renewable power in an energy system. Power-to-heat is however dependent on low-cost electricity it should therefore primarily be used where a recurring electric power surplus occurs.

Further it has been shown that history is about to repeat itself, whereas in the past surplus power was generally supplied from hydro- and nuclear power while in the future new sources of surplus power is more likely to derive from wind- and solar power.

Sweden is historically one of the few countries together with Norway with substantial experience in the field of power-to-heat solutions and given its continued relevance in the energy system as a source of demand for balancing peaks in electric power systems, it is necessary to compile and document the experience for future reference.

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