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Review of Large-Scale Heat Pumps and Potential of their Introduction to Natural Gas Markets

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Abstract **– Heat pumps are gaining popularity all over the world. A lot of attention is paid to household and commercial use markets, as well as diverse small and medium scale industrial applications. On the other hand, large-scale customized heat pumps are still more an exception in energy industry than a common practice. This paper looks into existing large-scale heat pump installations in order to gain understanding of their integration acceptance. The investigation shows that a vast majority of large-scale heat pumps use electricity as input driving energy.**

In many areas of the world, electric energy is comparatively expensive and therefore heat pumps are not utilized to a great extent. However, by changing the input driving energy source, large-scale heat pump systems may find acceptance in new markets. In this paper, large-scale heat pump systems which use the mechanical energy output from a natural gas fired gas turbine as input driving energy source are investigated. The output heating energy from the heat pump is used to satisfy the heating energy requirement for a city using district heating. A simplified feasibility study shows that a large reduction in primary energy consumption can be achieved with such a system compared to production of heating energy by combustion of natural gas in a boiler.

Keywords **– Electricity, gas turbine, heat pump, natural gas.**

1. INTRODUCTION

Heat pump technology is a well-known technique for ensuring efficient heating and cooling. Heat pumps are widely spread all over the world while particular popularity has been gained in such countries as Sweden, USA, Japan, Germany, Austria, Denmark, and other. Each specific region and each specific country possess diverse prerequisites that stimulate and continue to drive forward extensive heat pump technology introduction. Legislation, energy tariffs, subsidies, energy availability, and existing infrastructure are just a few of several preconditions to be mentioned that have direct or indirect influence on heat pump technology development and corresponding integration.

Heat pumps vary in many aspects; capacity-wise (from several kW up to tens of MW), technology-wise (compression or sorption), and primary energy usage-wise (electricity, vapor, gas, heat). However, most of the attention is paid to heat pumps for residential applications as it implies mass production, standard products use and an easier integration process.

Even though there are large-scale (industrial) heat pumps on the market, information of such installations is often quite scarce. The main advantages of large-scale heat pump systems as compared to small-scale units are lower specific investment cost, better system performance, operational flexibility, higher reliability and availability resulting in shorter pay-back time and better overall economy [1]. However, due to the needs of system customization, needs of technical expertise to design a suitable system for each specific application, especially for high-temperature systems, it has traditionally been hard to introduce large-scale heat pump systems.

Large heat pumps’ heating energy production in Sweden constituted 6.2 TWh in year 2005, while their mean seasonal performance factor, SPF, (defined as the ratio of delivered heating energy to supplied input driving energy) was around 3.5 [2]. Considering the latest trends when biofuel prices decrease and electricity prices increase, there is a probability that electrically driven large heat pumps will be phased out and will be replaced by biofuel fired or waste incineration boilers for heating energy production [3], [4]. On the other hand, future changes in Swedish legislation, the necessity of fuel diversification and flexibility, and the possibility of combined production of heating and cooling energy using heat pumps might keep the heat pumps in operation [5], [6].

Facilities based on large-scale heat pumps (over 5 MW heating capacity) have been erected in different parts of the world, but have not become widely spread due to a number of aspects. Driving factors for large-scale heat pumps integration into communal or industrial infrastructure are the ratio between heating energy tariff and primary energy cost [3], [5], substantial low-energy or waste-energy heat sources availability, feasibility of combined heating and cooling energy generation, temperature requirements and limitations, specific investment cost, to mention just a few.

In this paper, a review of large-scale vapor compression heat pump systems in Sweden and Norway as well as in a few other countries in the world is presented. Focus is set on the input driving energy source, as well as the heat source of the heat pump. In this study, absorption heat pumps are omitted as they are characterized by low coefficient of performance (if compared to vapor compression heat pumps), restricted achievable temperature lift as well as considerable limitations in operational flexibility, including part-load modes [7]. In addition, absorption equipment investment cost is proportional to its installed capacity while in many other cases (i.e. considering other technologies) an opposite situation is observed which is of substantial importance for large-scale applications.

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TABLE 1

LARGE-SCALE (OVER 5 MW HEATING CAPACITIES) COMPRESSOR DRIVEN HEAT PUMP FACILITIES IN SWEDEN

Location	Operator	Installed heating capacity	Primary energy	Facility features
[5] Stockholm (Ropsten 1,2,3)^{DH}	Fortum Värme	250 MW	Electricity	- Commissioned: 1984…1986, and later - Sea water as a heat source
[6] Lund^{DH}	Lunds Energi	27.9 MW (winter)	Electricity	- Commissioned: 1984, 2003 - Combined heating and cooling energy generation - Geothermal energy utilization (winter)
[8] Solna (Solnaverket)^{DH}	Norrenergi	100 MW	Electricity	- Commissioned: 1985 - Sewage as a heat source - Combined heating and cooling energy generation
[9] Göteborg (Rya Värmepumpverk)^{DH}	Göteborg Energi	150 MW	Electricity	- Commissioned: from 1985 - Sewage as a heat source - Heating/cooling
[5] Stockholm (Hammarbyverket)^{DH}	Fortum Värme	225 MW	Electricity	- Commissioned: 1986, 1991, 1997 - Sewage as a heat source - Combined heating and cooling energy generation
[5] Stockholms län (Vilundaverket)^{DH}	Fortum Värme	24 MW	Electricity	- Sea water as a heat source - Combined heating and cooling energy generation
[10] Sollentuna^{IND}	Jästbolaget, Sollentuna Energi	6 MW	Electricity	- Commissioned: 1992 - Heat sources: waste heat from a fermentation process and ground waters
[11] Västerås^{DH}	MälarEnergi	27 MW	Electricity	- Commissioned: 1992 - Sewage as a heat source - Combined heating and cooling energy generation
[12] Helsingborg (Västhamnsverket)^{DH}	Öresunds-kraft	29 MW	Electricity	- Sewage as a heat source - Combined heating and cooling energy generation
[13] Umeå (Dåvaverket)^{DH}	Umeå Energi	11.4 MW	Electricity	- Commissioned: 2000 - Flue gases as a heat source
[5] Stockholm (Nimrod)^{DH}	Fortum Värme	36 MW (winter)	Electricity	- Commissioned: 2000…2001 - Combined heating and cooling energy generation (winter) - Heat pump/chiller mode
[14] Umeå^{DH}	Umeå Energi	13.7 MW	Electricity	- Commissioned: 2001 - Heat source: waste heat from a flue gas cleaning process of a power plant
[10] Stockholms län (Akalla – Kista)^{DH}	Fortum Värme	26.2 MW (winter)	Electricity	- Commissioned: 2001…2003 - Combined heating and cooling energy generation - Heat pump/chiller mode
[6] Malmö (Sysav)^{DH}	Sysav	19 MW	Electricity	- Commissioned: 2003 - Flue gases as a heat source
[5] Stockholm (Värtan, KVV6)^{DH}	Fortum Värme	50 MW	Electricity	- Commissioned: 2010 - Flue gases as a heat source
[5] Stockholms län (Brista)^{DH}	Fortum Värme	7.2 MW	Electricity	- Commissioned: year 2013 - Flue gases as a heat source

Finally, attention is also paid to an alternative primary energy source in the markets where electricity is far too expensive to be utilized as an input driving energy source. Instead of supplying electric energy, focus is turned to usage of mechanical energy as shaft work directly produced by a gas turbine. A simplified feasibility study is carried out to investigate this possible system configuration from a primary energy point of view.

2. EXISTING LARGE-SCALE COMPRESSION HEAT PUMPS OVERVIEW

Scandinavia is an outstanding region from large-scale heat pumps prevalence point of view and Sweden is at the forefront. There are a number of reasons to such a state of affairs: scarcity of energy related natural resources, comparable district heating and electricity tariffs, collectivism and certain unity within Swedish society, implying extensive district heating and district cooling systems under continuous development. A major impulse towards energy infrastructure modernization and cardinal structural alterations was gained after the oil crisis in the early 1970s. Electrically driven large-scale heat pumps have managed to occupy a niche, partially due to the fact that a substantial share of the electricity in Sweden is being generated at the facilities with low production self-costs, i.e. hydro power plants and nuclear power plants, which stand for 44% and 26% of total installed electricity production capacity in Sweden respectively [3]. As of year 2011, 45% of the total electricity energy was produced by hydro power and 40% by nuclear power plants.

Since electricity and heating energy prices are comparable, a lot of large-scale heat pumps have been installed in Sweden. Table 1 above represents some of the large-scale compressor driven heat pump facilities, which are presently in operation in Sweden.

In Tables 1-3 more than one year of commissioning means that the facility has been erected in stages. Each facility is also classified according to the sector of integration: DH – district heating (communal sector), IND – industry (industrial sector).

Table 2 complements Table 1 with examples of large-scale compressor driven heat pump facilities which are operated in Norway thus staying within the same geographic region.

Though large-scale compressor driven heat pump facilities are not presented in the world at the same rate as in Scandinavia, some of them are listed in Table 3.

TABLE 2

SOME OF THE LARGE-SCALE COMPRESSOR DRIVEN HEAT PUMP FACILITIES IN NORWAY

Location	Operator	Installed heating capacity	Primary energy	Facility features
[15] Sandvika^{DH}	Fortum fjernvarme	20 MW	Electricity	- Commissioned: 1989, 2008 - Sewage as a heat source/heat sink - Combined heating and cooling energy generation
[6] Sandvika^{DH}	Baerum Fjernvarme	13 MW (winter)	Electricity	- Commissioned: year 1989 - Sewage as a heat source - Combined heating and cooling energy generation
[16] Oslo Airport Gardermoen^{DH}		7.5 MW	Electricity	- Commissioned: year 1998 - Groundwater aquifer - Heating/cooling
[15] Lysaker^{DH}	Fortum fjernvarme	9.2 MW	Electricity	- Commissioned: 1999, 2012 - Sea water as a heat source/heat sink - Combined heating and cooling energy generation
[15] Fornebu, Snarøyveien^{DH}	Fortum fjernvarme	13.7 MW	Electricity	- Commissioned: 2001, 2006 - Sea water as a heat source/heat sink - Combined heating and cooling energy generation
[6] Fornebu^{DH}	Baerum Fjernvarme	5.4 MW (winter)	Electricity	- Commissioned: year 2002 - Fjord water as a heat source (winter) - Heat pump/chiller mode
[15] Fornebu, Martin Linges vei^{DH}	Fortum fjernvarme	16 MW	Electricity	- Sea water as a heat source/heat sink - Combined heating and cooling energy generation
[17] “Skoyen Vest”, Oslo^{DH}	Viken Fjernvarme	27.6 MW	Electricity	- Commissioned: 2005, 2007 - Untreated sewage as a heat source
[16] University Hospital in Akershus^{DH}		8 MW	Electricity	- Commissioned: 2008-2009 - Bedrock thermal storage - Combined heating and cooling energy generation
Drammen, Norway^{DH}	Drammen Fjernvarme	14.3 MW	Electricity	- Commissioned: year 2011 - Fjord water as a heat source

TABLE 3

SOME OF THE LARGE-SCALE COMPRESSOR DRIVEN HEAT PUMP FACILITIES IN THE WORLD

Location	Operator	Installed heating capacity	Primary energy	Facility features
[14] Swiss Federal Institute of Technology in Lausanne, Switzerland^{DH}		7.8 MW	Electricity	- Commissioned: 1986 - Water from Lake Geneva as a heat source - Closed loop heat pump system

[18] Pernis, The Netherlands^{IND}		50.2 MW	Electricity	- Commissioned: 1995 - Heat pump system integration into an industrial distillation process
[6] Helsinki, Finland^{DH}	Helsinki Energy	84 MW (winter)	Electricity	- Commissioned: 2006 - Sewage as a heat source (winter) - Combined heating and cooling energy generation (summer)
[14] Postal sorting office of Muelligen/ Schlieren of the Swiss Mail, Switzerland^{DH}		5.5 MW	Electricity	- Commissioned: 2006 - Treated sewage as a heat source/heat sink - Heating/cooling
[10] Olympic village, Beijing, China^{DH}		20 MW	Electricity	- Commissioned: year 2007 - Sewage as a heat source (winter) - Sewage as a heat sink (summer) - Heat pump/chiller mode
[10] Dalian, China^{DH}	Dalian Municipal Government	25 MW (winter)	Electricity	- Commissioned: year 2007 (first 25 MW) - Sewage as a heat source (winter) - Sewage as a heat sink (summer) - Heat pump/chiller mode

3. CURRENT STATUS ANALYSIS

As is clearly shown in Tables 1-3, all of the large-scale heat pumps presented use electricity as input driving energy. Operation in heating mode during heating season will lead to a substantial increase of electricity consumption. Consequently, this will cause a need for additional electricity generation capacities as well as the entire corresponding infrastructure, which will be idling during non-heating season. On the other hand, the mentioned disadvantages can be well compensated for by the following aspects: availability of electricity with low self-cost, substitution of more expensive or inefficient heat generation facilities, possibilities for simultaneous heating and cooling energy generation (implying consolidation possibilities of district heating and district cooling networks, or collating of corresponding energy loops within industrial processes), among others. Thus, every single case is unique and requires an individual approach.

Heat pump technology reliability has been proven by decades of successful operation, while some common problems are often observed. Most of the facilities suffer from insufficient maintenance which normally leads to enhanced electric energy consumption in one way or another. Operating personnel continuous qualification improvement is also of crucial importance.

Another aspect to be considered is heat pump operation at suboptimal (i.e. off-design) conditions which is a common practice and is hard to be avoided. Heat pump equipment is normally designed for some specific operational temperature range thus aiming at the best efficiency at certain temperature lifts. But changes in market conditions might cause competition alteration between various thermal energy production facilities as, for example, shifting heat pumps into another operational temperature area. Operation at off-design profile causes degradation in heat pumps efficiency, which, on the other hand, might be compensated by benefits from a smaller temperature lift, which is not always the case.

Modification in legislation is one more factor which is hard to anticipate. Landfill tax introduction in Sweden and its consecutive increase during the years, as well as landfill ban on sorted combustible waste in 2002 and landfill ban on organic waste in 2005 has led to extensive introduction of waste incineration power plants [4]. The power plants are fueled with cheap waste, operating on a year-round basis and covering heating base load. All these aspects shorten heat pumps operation duration, which is substantially sensible for new non-depreciated facilities. Certain complexities arise for production units which are run in a mode of simultaneous heating and cooling energy generation during the summer period.

A current trend is also conversion from HCFC to HFC refrigerants as the working media in heat pumps, which is specifically applicable to equipment commissioned in the 1980s. For example, conversion from R22 to R134a can cause heating capacity drop by 35% - which has to be substituted by alternative heating production facilities within the corresponding energy infrastructure [19]. On the other hand, there are technical solutions available to avoid such a drop in heating energy output. By using refrigerants mixtures (as one of the solutions) one can receive an improvement in heating capacity by 17% compared to pure R134a, while COP will drop by up to 14% [19]. The latest Regulation (EU) № 517/2014 sets even higher requirements on HFC refrigerants (from global warming potential (GWP) perspective) thus creating prerequisites for additional challenges for existing heat pumps.

4. INTRODUCING HEAT PUMPS ON NEW MARKETS

If interest instead is turned to countries in Western and Eastern Europe, CIS states, and other regions, natural gas is often an available type of fuel. Considering that electricity in these countries often is generated using natural gas as a primary energy source, electrically driven heat pumps seem to be a questionable alternative for heating energy production both from a primary energy, as well as from an economical perspective [20]. Therefore, natural gas driven heat pumps become an option. In this case, heating energy generation from heat pumps should be compared with natural gas boilers which are one the most common methods of heating energy production. Usage of natural gas as the primary energy source guarantees operation within exactly the same heating energy tariff/primary energy cost ratio as natural gas boilers will do.

Vapor compression heat pumps with internal combustion gas engines as accessory drive are rather widely used and are extensively reported [21].

In addition, when implying large-scale applications (for example, with around 20 MW heating capacity per heat pump unit) vapor compression heat pumps utilizing gas turbines as a direct accessory drive can be used as an alternative. For such a system configuration, a gas turbine can out-perform an internal combustion gas engine both technically and economically [22].

From a thermodynamic point of view, there are several other cycles (e.g. reciprocating engines) that will have better performance, i.e. produce more mechanical work, compared to a gas turbine. However, when the heat in the flue gases is of use and waste energy of the cycle is considered, the gas turbine has the advantage of producing heating energy at a higher temperature level and with higher magnitudes compared to other cycles. This leads to a better overall energy usage of the fuel as more heat can be recuperated. Flue gases recuperation will not only provide higher heat flux but will also allow possible higher temperatures of the heating energy compared to a heat pump functioning on its own.

Attempts to look into gas turbine driven heat pumps have already been reported decades ago. Prototypes for domestic applications development have been reported in 1979 [23]. A similar concept for commercial use was presented in 1989 [24]. As far as large-scale applications are concerned, there is very scarce information available.

5. EXISTING APPLICATIONS – NATURAL GAS FIRED GAS TURBINES FOR MECHANICAL DRIVE

Various types of drives for chillers, including large-scale ones based on centrifugal compressors, have been considered. For example, there are cooling facilities where gas turbines are applied for driving refrigeration compressors in a rather unique tandem configuration [25]. Additionally, the market can already offer a steam turbine driven chiller as a standard solution.

Keeping in mind that chillers and heat pumps are based almost on the same technique, experience gained in the chiller industry will be valuable for heat pump applications as well.

When looking into gas turbine applications from an experience gaining perspective, diverse fields of industry can become a valuable source of information. It is a common configuration to drive compressors and pumps using gas turbines [26].

Oil and gas industry is one of the ``experts`` with regard to utilizing components and systems mechanically driven by gas turbines [26]. This is true for the whole field of this industry, which embrace upstream applications (i.e. oil and gas industry production facilities of various types), midstream applications (which are mainly related to transportation of gas and oil) and downstream applications (which include diverse process plants).

However, there are no limits to modernization and efficiency enhancement. There are examples of natural gas compression stations where waste heat recovery system integration allows utilizing flue-gas energy from gas turbines (which are driving natural gas compressors) for the purpose of steam production, which, in its turn, becomes a primary energy for a steam turbine driven compressor for the same initial application [27].

6. FEASIBILITY STUDY

The following simplified comparison clearly indicates the feasibility of gas turbine driven heat pumps when compared to conventional natural gas boilers from a primary energy consumption point of view.

The heating energy output from a natural gas boiler can be found from:

$$Q_{boiler} = \eta_{boiler} \cdot PE_{boiler} \tag{1}$$

In equation (1):

Q_{boiler} – nominal installed heating capacity of a natural gas boiler,

PE_{boiler} – primary energy capacity (consumed by a natural gas boiler),

η_{boiler} – performance efficiency of a natural gas boiler (assumed to be 0.93).

The above assumption means that a natural gas boiler effectively utilizes 93% of the consumed primary energy.

A heating energy system based on a gas turbine driven heat pump should be viewed as an energy chain of three major components: gas turbine, heat pump, and heat recovery heat exchanger:

$$Q_{HPsystem} = Q_{HE} + Q_{HP} \tag{2}$$

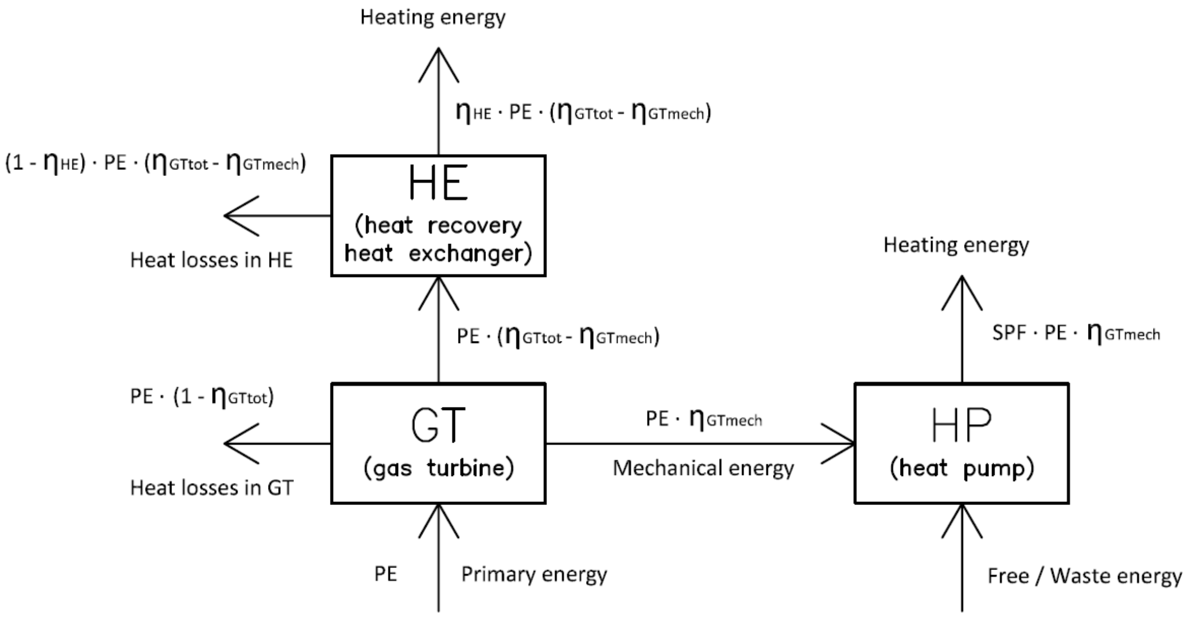

Fig. 1. Energy flows distribution over a gas turbine driven heat pump system.

In equation (2):

$Q_{HPsystem}$ – nominal installed heating capacity of a heat pump system,

Q_{HE} – nominal installed heating capacity of a heat recovery heat exchanger,

Q_{HP} – nominal installed heating capacity of a heat pump.

Fig. 1 describes energy flows distribution that might be expected over gas turbine driven heat pump system.

The heating energy output from a heat pump system directly driven by a gas turbine can be found from, see Fig. 1:

$$\begin{aligned} Q_{HPsystem} &= (SPF \cdot \eta_{GTmech} + \\ &+ (\eta_{GTtot} - \eta_{GTmech}) \cdot \eta_{HE}) \cdot PE = \\ &= (3.1 \cdot 0.32 + (0.85 - 0.32) \cdot 0.8) \cdot PE = \\ &= 1.41 \cdot PE \end{aligned} \qquad (3)$$

In equation (3):

PE – primary energy capacity (consumed by a heat pump system),

SPF – seasonal performance factor of a heat pump (assumed to be 3.1) [2], [22],

η_{GTmech} – efficiency of a gas turbine, mechanical drive (assumed to be 0.32) [22], [28],

η_{GTtot} – total efficiency of a gas turbine at full load operation (assumed to be 0.85) [22], [29],

η_{HE} – thermal efficiency of a heat recovery heat exchanger (assumed to be 0.8) [30].

This means that a heat pump system generates 41 % more heating energy than total primary energy been consumed.

Assuming that $Q_{boiler} = Q_{HPsystem}$ one can compare primary energy consumption of both systems and present it in the form of primary energy ratio (PER):

$$PER = \frac{PE_{boiler}}{PE} = \frac{\dfrac{Q_{boiler}}{0.93}}{\dfrac{Q_{HPsystem}}{1.41}} = \frac{1.41}{0.93} = 1.52 \,. \qquad (4)$$

It is shown that the heat pump system consumes 52 % less primary energy compared to the natural gas boiler at the same heating energy output operating at similar conditions – thus also implying 52% lower emissions. It can also be interpreted in a form of 52 % larger heating energy production by the heat pump system compared to a boiler consuming the same amount of primary energy. Clearly, there is a vast potential in utilizing gas turbine driven vapor compression heat pumps in terms of primary energy consumption. This will be further investigated in a future paper.

7. CONCLUSION

According to the present review, most of the currently existing large-scale heat pumps utilize electricity as a primary energy. An interesting possible market for such heat pumps is countries with abundant natural gas resources. Substitution of an electric motor (i.e. electric energy as input energy) to a gas turbine (considering heat pump accessory drive) converts the large-scale heat pump into a large-scale natural gas boiler competitor. Usage of gas turbines for drive applications is a well-known technique, and much experience could be utilized from other research fields. However, complementary research should be performed in order to look into various economic scenarios considering numerous system-based integration alternatives with the system solution in focus. Corresponding macro- and microeconomic conditions and other relevant issues must also be investigated and assessed. The feasibility study showed a vast potential for primary energy savings.

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