

RECENT AND HISTORICAL ADVANCES IN HEAT PUMP TECHNOLOGY AND MARKET IN SWEDEN

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Abstract: The ground source heat pump has reached a mature level in terms of technology and market penetration in Sweden. Typical figures for the seasonal performance factor has been steadily increasing from 2,5 to 3,5 and the energy coverage factor has been increasing up to 95-98%, thus minimizing the need for peak heating to a minimum in many installations. This does however not mean that the full technical (thermodynamic) potential is realized, rather that the market, i.e. customers and manufacturers, have found a temporal equilibrium relation between cost and performance (reliability, efficiency, design, noise etc). Ongoing development efforts are the elimination of peak electric heating and easy to install distribution systems for direct electric houses. A strive for higher seasonal performance is needed to clearly demonstrate the benefit of heat pumps in the energy system to all stakeholders. Several development efforts are ongoing at universities and manufacturers, often in close cooperation, including more efficient control, variable capacity, and better utilization of bore holes and so on. Other development efforts are increased use of natural refrigerants and charge minimization through new types of heat exchangers. Large scale heating only heat pumps in district heating remain an efficient alternative but new system are not likely due to a strong focus on cogeneration of heat and electricity. On the other hand development of district cooling systems may open up new possibilities.

Key Words: *heat pumps, market, technology, development*

1 INTRODUCTION

The ground source heat pump (GSHP), as we know it today, has been developed in Sweden for well over 30 years. The improvements of components such as heat exchangers, compressors and control systems have been a continuous process as a result of a research and development by heat pump manufacturers in close cooperation with universities and research institutes. The first GSHP with integrated domestic hot water storage was in fact developed as early as 1973 by the company Thermia in Arvika (Thermia 2005). In parallel other types of heat pump systems have been developed over the years such as exhaust air heat pumps for both domestic hot water heating and residential heating and air source heat pumps of various types. One example of more recent product innovation is the IVT495 Twin from IVT in Tranås which combines two heat sources, exhaust air and ground coil (IVT 2007), since the available energy in exhaust air is insufficient for a high energy coverage factor. More recently, variable speed control of compressor and/or circulation pumps has been introduced on the market by several manufacturers e.g. the Fighter 1250 (NIBE 2007) by NIBE. The heat pump shown in figure 1 is a generic representation of the typical GSHP in Sweden today.

The general understanding of how heat pump units should be designed to meet customer demands (economy and reliability) and manufacturer's preferences (profit) has thus grown to a mature level although several issues remain to be clarified. Some of these are further elaborated throughout the paper.

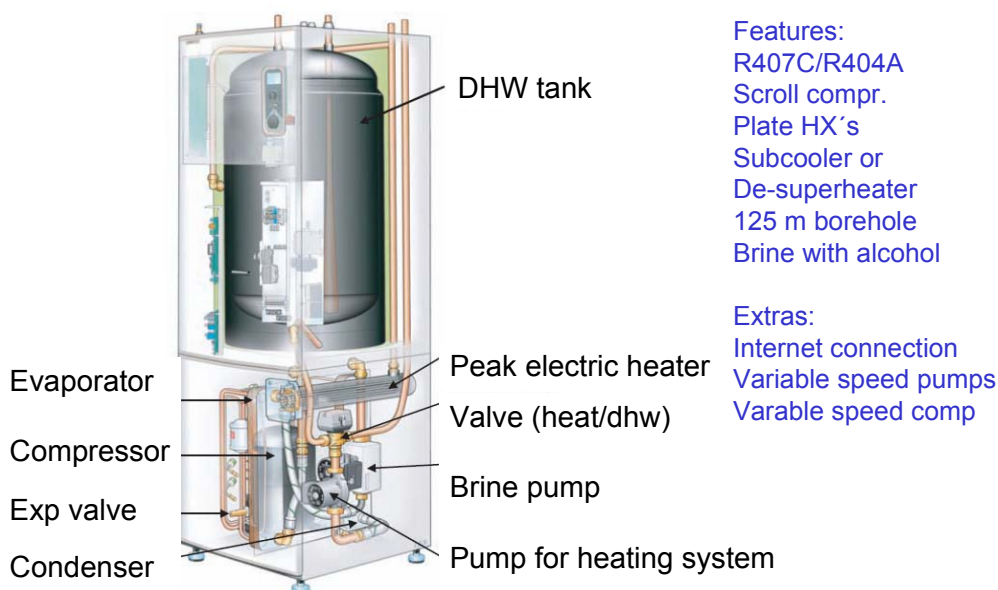


Figure 1: A typical Swedish GSHP (Thermia 2005, slightly modified)

Computerized tools for system dimensioning/sizing including calculation of necessary borehole depth have been developed by the major manufacturers in close cooperation with universities. To avoid misleading information and to guide installers and customers the Swedish Heat Pump Association, SVEP, provided a common calculation tool (algorithm) for heat pump systems with a single borehole (Forsén 2005). The program calculates suitable borehole length and simplifies the choice of heat pump capacity for various types of houses and climate. This tool is based on vast experiences gained from several other efforts and various calculation tools have been developed from the early 80-ties by for example AIB¹, Vattenfall², LTH³, KTH and the various manufacturers themselves. The technical development of the heat pump units has also been driven by technology competitions arranged by the Swedish National Board for Technical Development, NUTEK. New environmental legislation with respect to working fluids has forced the industry to a number of conversions from CFC to HCFC to HFC. Today GSHP heat pumps typically use refrigerants R407C and R404A but also R134a. Only a few manufacturers offers GSHP with propane (NIBE uses it in the exhaust air Fighter P-series).

The research invested in heat pumps is a success story. Today 15 TWh of heat are collected from the nature with heat pumps at a value for the taxpayers of about 1.3- 1.5 G€/year. All the money that the taxpayers have invested through the governmental financed heat pump research over 30 years is repaid in only 4 – 5 days by free heat (Nowacki 2007). Small reversible air/air heat pumps have also found their way into the Swedish market as a complement in houses with direct baseboard electrical heating. Typically they are made in the Far East and use R410A as refrigerant. There is also since 10 years for obvious reasons an interest for alternative environmentally benign working fluids. Propane was introduced several years ago in exhaust air heat pumps for domestic hot water and/or residential heating. An air/water heat pump using CO₂ as refrigerant has recently been introduced on the market (Sanyo 2007). Several new research efforts are put into systems using refrigerants such as ammonia, CO₂ and propane in smaller residential systems and the market penetration of such system is strongly dependant on future environmental constraints for HFC refrigerants (for example the so-called F-gas directive within the European community).

¹ A technical consultancy firm (Allmänna Ingenjörbyrå)

² Swedish State Power Board

³ Lund Technical University

2 SIX PHASES OF EVOLUTION

2.1 1940 – 1960 Recognition of the possibilities

Early pioneers took out some patents and the economical circumstances under which heat pumps could be used were clearly outlined by Prof Matts Bäckström at KTH.

2.2 1975–1985 Early Pioneering ...

The period can be characterized by different ambitious initiatives and R&D efforts. Also numerous field measurements and evaluations were undertaken. A certain success for shallow ground source heat pumps on the market, often with direct expansion coils. This technology was strongly supported by the Swedish State Power Board's (Vattenfall) research program on Solar Energy and Heat Pumps. Generous governmental subsidies and research grants made available through the Swedish Council for Building Research led to a first "HP-boom" in the early 1980's. In 1985 there were roughly 100 large heat pumps in District heating (MW size) and 110 000 small ones in residential houses. Heat pumps also became a "research issue" at the universities mainly KTH and Chalmers. Ground source systems were analyzed at LTH. A major achievement during the time was the ground-source manual (Claesson 1985) which covers all types of system for heating, cooling and storage in three volumes. The mathematical models of this source-book are still used as the basis for modelling of the heat source behavior in ground source heat pump systems. The largest heat pump in the world was built in Stockholm during the period. It has a heat output of 250 MW and has supplied the district heating network of Stockholm with up to 60 % of the total heat demand during some years. As more than two thirds of the output originates from solar heated surface water – Stockholm has some years been heated by more than 40 % of solar energy! Refrigerants were not an issue: Ozone depletion and global warming were unknown whereas refrigerants were well-known and not considered a problem. A typical choice was either R22 or R502 in ground-source applications. One unique thing was that many systems was monitored right from the beginning through extensive test programs thus leading to experience building.

Typical performance figures of single-family, residential units 1975-1985 (Karlsson 2007)

$$\eta_{\text{Carnot}} = 0.4 - 0.5^4,$$

SPF = 2.0 - 2.5 (ground-source), 1.5 - 2.2 (outdoor air) and 2.0 - 2.5 (exhaust-air).

2.3 1986–1995 Market collapse and refrigerant phase out:

The period started with drastically reduced prices on heating oil coupled with a drastic cut of governmental subsidies and an increase in interest rates. This made the market collapse in a short time. It created large problems for the companies, many of whom went bankrupt. Phasing out CFC-refrigerants added to the complexity for manufacturers. This involved phasing out of the traditional refrigerants, first R12 and R502, later R22. Sweden was thus in the forefront of banning CFC and HCFCs, see table 1, and the first in a series of intensive national research programs, Alternative Refrigerants, for research on alternative refrigerants was initiated. R134a was quickly identified as the alternative for R12, R404a and R507 for R502 and at the end of the period R407C for R22 (Johansson 2001). The period also saw the first experiments with so-called natural refrigerants and propane was tried with excellent thermodynamic performance as an alternative to R22.

In the early 1990-ies however a heat pump competition, supported by NUTEK was announced with a very ambitious time frame. Initially the contest was successful, but large

⁴ COP₂ of the heat pump unit divided by the theoretical limit based on evaporation and condensation temperatures

problems arose later for some of the contestants (Fahlen 1995). Even faulty in many respects, the resulting new products reignited the slumbering heat pump market. During this period a relatively large number of air/air heat pumps were also installed. Small series not fully adapted for heat pump operation and larger than intended/expected temperature lifts and frost formation caused malfunction.

The plate type heat exchanger was introduced during this period leading to a drastic reduction of refrigerant charge and smaller temperature differences in although advanced heat exchanger concepts had been tried earlier, for instance by Thermia in the DUO-series (Fernando 2007). The compressors were becoming increasingly more efficient at pressure ratios more suitable for heat pump applications. This period also saw a reduction of the price for drilling due to market competition and rationalization.

Typical performance figures of single-family, residential units 1986 - 1995 (Karlsson 2007)

$\eta_{\text{Carnot}} = 0.45 - 0.55$

SPF = 2.5 - 3.0 (ground-source), 2.0 - 2.5 (outdoor-air), 2.5 - 3.5 (exhaust-air)

Typical performance figures of district heating units 1986 - 1995 (Ibid.)

$\eta_{\text{Carnot}} = 0.60 - 0.65$

SPF = 2.5 - 3.0 (sewage water $\approx 10^\circ\text{C}$, district heating $\approx 80^\circ\text{C}$).

2.4 1996-2000 Exhaust air and slow recovery

The period can be characterized by a certain recovery of the market, especially with small units like exhaust air HPs. The very complicated machines and installations from the early days were simplified and more or less standardized. Normal HVAC firms, electricians, well drillers and plumbers took up heat pump installation as a part of their normal business. Exhaust air HPs were primarily implemented in new built houses as heat recovery for domestic hot water heating in accordance with the then new building code. As the new building code also enforced thicker insulation the heating demand for smaller residential buildings decreased and the heating capacity of the exhaust air HPs covered typically 30 % of the buildings heat demand resulting in a potential of approximately 50 % energy coverage (the remaining capacity was covered by electric heaters in the liquid heat distribution circuit). Henceforth exhaust air HPs more or less became the standard heating solution for small and medium size domestic houses. Still, a few houses were built using the exhaust air HP only for domestic hot water heating, and direct electric heating for space heating through electric radiators (especially in the slightly lower prize segment).

The research programs Climate 21 and subsequently EffSys 1 were initiated with a stronger focus on efficiency and system issues for heat pump and refrigeration systems. Research was mainly carried out by technical universities (mainly Chalmers and KTH) and research institutes (SP) in close cooperation with manufacturers of heat pumps, heat exchangers, control systems, utilities, and consulting engineers. Projects concerned component as well as system aspects, ranging from heat transfer, refrigerant substitution, charge minimization, variable speed compressors and pumps, recharging of boreholes, combined heating and hot water, integrated control systems etc. to the effect on the national electricity grid by the extensive use of heat pumps (in particular the use of electric supplementary heating).

2.5 2001 – 2005 Market take-off and product sophistication

Increasing acceptance of heat pumps. Good market, especially for ground source units in relatively large one family houses. Sales are picking up. Certain governmental support investments aiming for oil reduction and replacement of electrically heated houses. Air/water heat pumps seem to pick up quickly and several new models are appearing on the market due to favourable investment costs and/or less suitable conditions for boreholes. A biased, largely market driven, discussion of the importance of electricity use in heat pump systems

was initiated. The competition on the heating market between suppliers of bio-fuels or district heating was more open.

The design of residential units was now more sophisticated with controls that better adapted the heating water supply temperature to the outdoor air temperature and the minimum downtime between starts, incorporated Legionella protection cycles etc. At the end of the period the first GSHPs with capacity control as standard equipment were announced as stated earlier. Plate heat exchangers with narrower channels and thus improved distribution of refrigerant and more efficient heat transfer surfaces were universally used as condensers and evaporators (Claesson 2006). Also, more efficient pumps were incorporated for circulation of brine and heating water. The scroll compressor became a favourite and R407C was selected as the refrigerant.

Performance continued to increase, not by leaps and bounds but steadily:

Typical performance figures of single-family, residential units 1996-2005 (Karlsson 2007)

$\eta_{\text{Carnot}} = 0.50 - 0.60$,

SPF = 2.5 - 3.5 (ground-source), 2.0 - 3.0 (outdoor-air), 2.5 - 3.5 (exhaust-air)

Typical performance figures of district heating units 1996-2005 (Ibid.)

$\eta_{\text{Carnot}} = 0.65 - 0.70$,

SPF = 2.5 - 3.5 (sewage water $\approx 10^\circ\text{C}$, district heating $\approx 80^\circ\text{C}$),

SPF = 4.0 - 6.0 (combined heating and cooling).

2.6 2006 - A bright future with some surprises

The market value of houses has recently been reported to increase if equipped with an efficient GSHP system thus giving the ground coupled heat pump increased status and a new role. New products with variable speed compressors and/or pumps are gaining market shares. Passive cooling e.g. using the cold from the borehole is becoming more and more popular. Smart and cost effective systems for retrofit of direct electric houses with hydronic heat distribution systems are expected to reach the market if the price of electricity increases. So-called "monovalent" systems with no-peak-electricity will become more common and is likely to be subsidized partly by the electric utility companies. A growing interest for heat pumps in the size 25-40 kW for small multi-family dwellings or offices/industries seems to be a new attractive market for manufacturers and several new models with higher efficiency have recently appeared on the market. Systems are typically installed in parallel to achieve higher capacities. There are now about 100 large ground-source heat pumps for heating and cooling of office buildings with more than 15 boreholes (total borehole depth > 3000 m, heat pump capacity > 200 kW) and about 40 large open-loop systems (groundwater), (Hellström 2007).

3 THE HEAT PUMP MARKET IN SWEDEN

3.1 Primary energy for heating

The total heating market is the first departure point for a market segmentation of heat pumps. However, this statistical information does not immediately reveal the amount of heat delivered from heat pumps. For instance, a relatively large part of the heat delivered through district heating, approximately 6 TWh, is covered by large electrically driven heat pumps utilizing waste heat in sewage water or sea water.

By studying Figure 2 several interesting observations can be made: The use of oil for heating purposes was totally dominant in 1970 with a 75 % share. Since then it has gradually

decreased to approximately 12 % in 2005. During 2006 this value has further decreased but since statistical data is not yet available, an estimate could be 6-7 %.

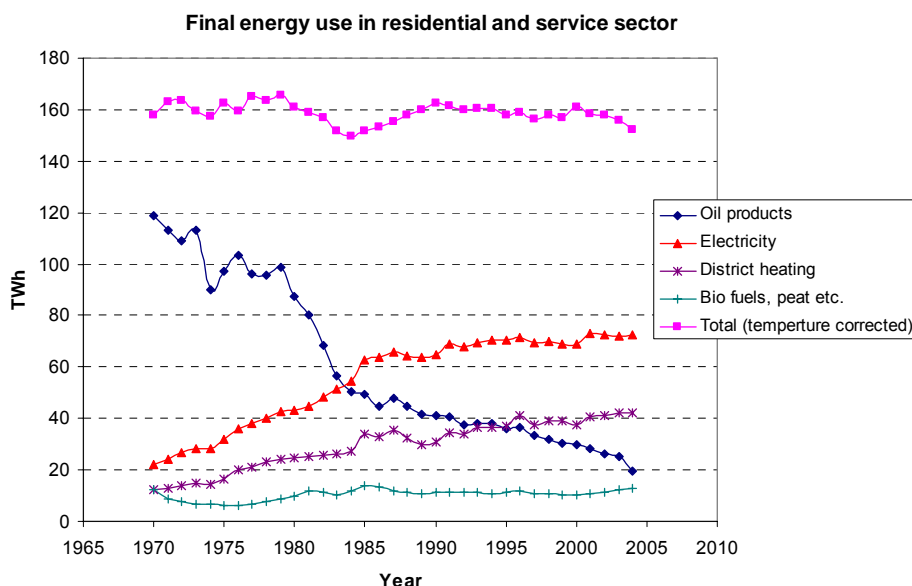


Figure 2: Final energy use in residential and service sector by type (Stem 2005)

The use of electricity for heating was growing rapidly from 1970 to 1990 but this figure is now levelling off. Retrofitting of direct base board heating in houses built during the seventies and early eighties to various combinations of air/air heat pumps/pellet heaters or even retrofit to hydronic heating systems is likely to reverse the trend through the coming years.

The sub-market for heating of residential single-family houses amounts to a total of 40 TWh of which 4.3 TWh has been estimated to be electricity to heat pumps. These heat pumps have been estimated (conservatively) to deliver approximately 8-9 TWh heat, which for obvious reasons does not appear in the statistics. One has to bear in mind that energy use normally is counted as "energy supply". There is no available statistics concerning useful energy or "heat losses" from buildings.

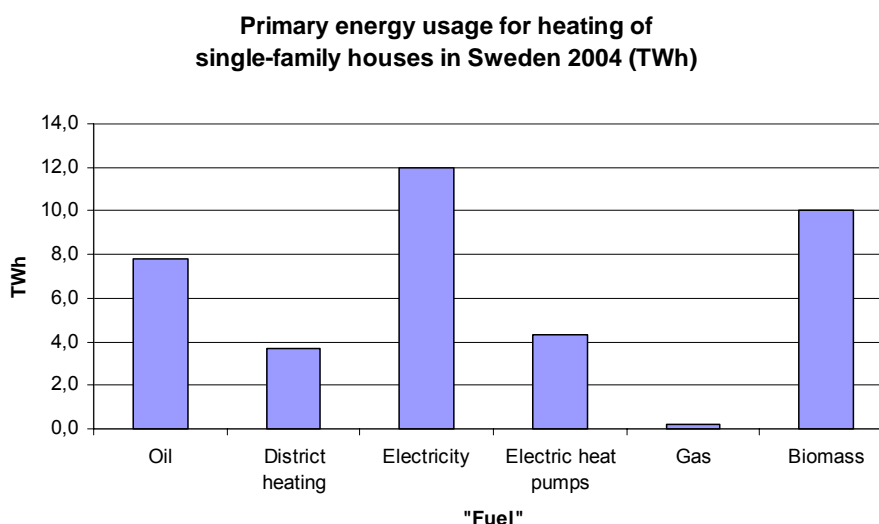


Figure 3: Primary energy usage for heating of single-family houses based on data from Statistics Sweden⁵.

⁵ www.scb.se

If the total heat delivered by domestic heat pumps is broken down by heat pump type, assuming typical efficiencies, the dominance of the GSHP system is evident (Figure 4).

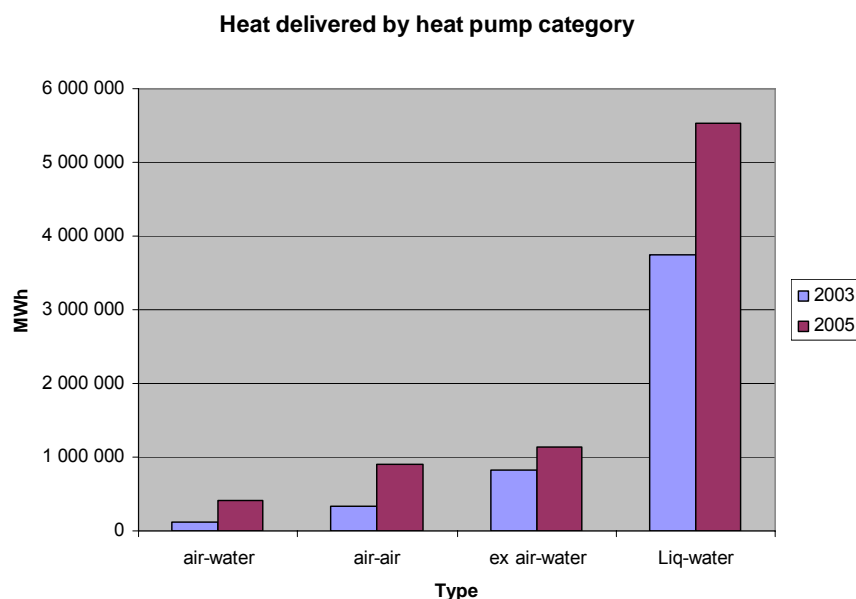


Figure 4: An estimation of heat delivered by heat pumps broken down by category. The diagram is constructed by assuming typical seasonal performance factors and information on heating demand from figure 3 (Forsén 2005)

3.2 Building size and utilisation

An overview of the Swedish domestic heating market is given in Figure 3 and 4. A relatively large portion of the building stock is quite old. For new dwellings there are two counteracting factors (i) Building heating demand per m² is decreasing due to better insulation standards and (ii) The average size of new buildings are increasing

Interestingly enough similar data for multi-family houses do now show the same clear trend in decreasing energy demand per square meter living area. One may wonder why...

Net energy need for single family dwellings

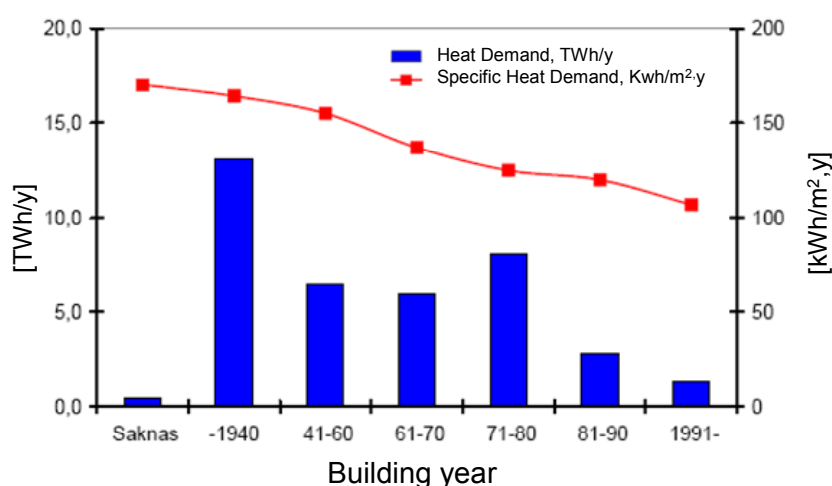


Figure 5: Net annual energy demand for single-family dwellings bundled for 10 years span of erection (left axis). Specific annual heat demand, kWh/m²,year for the periods are also given on the right axis (Dalenbäck 2007)

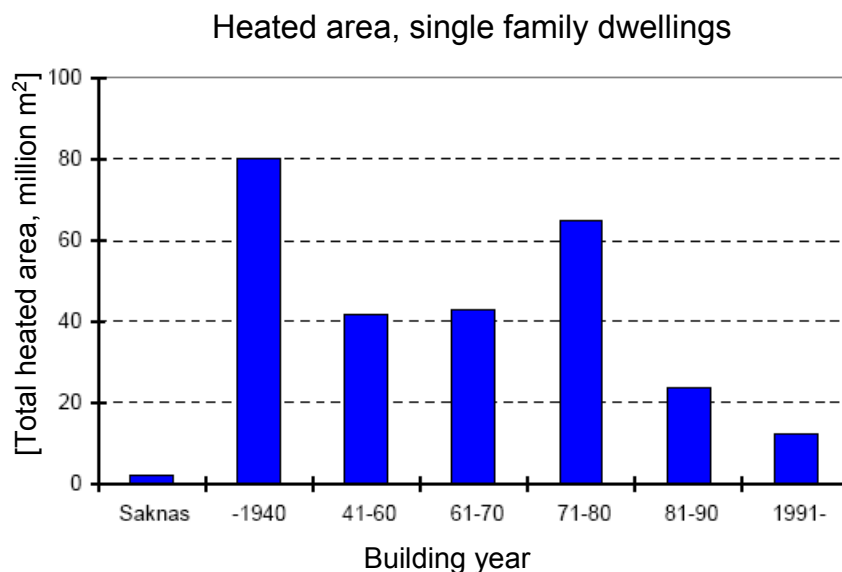


Figure 6: Total heated area single-family dwellings (Ibid.)

3.3 Heat Pump Sales

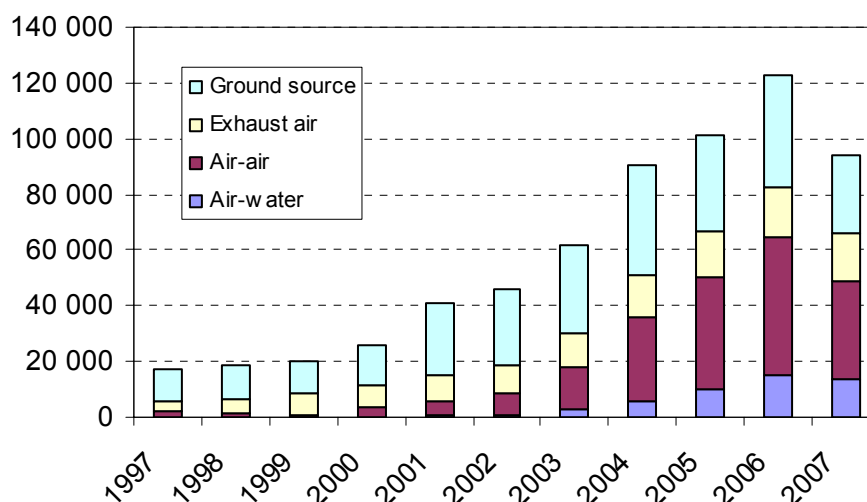


Figure 7: Sales statistics for the period 1997 – 2007. Data is given for air/water (bottom), air/air (second from bottom), exhaust air/water (second from top) and liq/water (top), (Forsén 2008).

4 CURRENT ISSUES AND TRENDS (ENVIRONMENTAL CONCERN, WORKING FLUIDS, LEGISLATION, PEAK ELECTRICITY)

The heat pump working fluid has been one factor to consider for manufacturers and several attempts have been done to enforce new legislation or labelling promoting increased use of so-called natural refrigerants. Today, the standard choice is typically R407C or other HFC-refrigerants such as R404A, R410A or R134a even though a small number of heat pumps with other fluids such as propane or CO₂ exist on the market (Palm, 2007). Active research to facilitate the use of other fluids such as CO₂, ammonia or propane is undertaken at universities and research institutes with governmental support.

Table 1: Refrigerant phase-out in Sweden (Johansson 2001)

ASHRAE Number	Primary Replacement	Type of refrigerant	Stop for import or new installations	Stop for refill	Stop for use	Share of the total refrigerant charge in Sweden 1993
R12, R500, R502	R134a R404A	CFC	1/1 1995	1/1 1998	1/1 2000	32% 6%
R22	R407C	HCFC	1/1 1998	1/1 2002	N/A	50%

5 RESEARCH NEEDS AND ONGOING RESEARCH AND DEVELOPMENT

The research and developments need for heat pump systems can be broken down to heat pump unit issues dealing with the performance of components such as heat exchangers (heat transfer), energy efficient pumps, capacity control, charge minimization, environmentally benign refrigerants etc. Other issues with R&D needs are related to ground coupling of systems (boreholes, collector design, drilling techniques, site-investigation methods, and calculation methods), passive cooling, dual heat sources, techniques for non-electrical supplementary peak energy etc. A complete list is beyond the scope of this brief report.

Ongoing research in Sweden, relevant for the development of more efficient and reliable heat pump systems, is mainly carried out at universities (KTH, Chalmers, LTH and LuTH) and the research institute SP in Borås and IUC in Katrineholm. Work at the universities are dealing with various issues such as heat transfer and heat exchanger issues as well as improved thermodynamic cycles but also system oriented issues such as control strategies or low temperature distribution systems. Work at Luleå and Lund technical universities has mainly been directed to heat exchange with the ground, evaluation of compact heat exchangers for horizontal installations, characterization of boreholes etc (the well known "Thermal Response Test" for example), completion and maintenance of wells for groundwater applications. A great effort has been put into modelling of heat exchange with the ground, thermal interaction between multiple adjacent boreholes, and hybrid GSHP systems involving solar heat by Hellström at LTH, Lund and Nordell at LuTU, Luleå.

The use of natural refrigerants has been encouraged throughout the last 15 years in research programs and small heat pumps using refrigerants such as propane, NH₃ and CO₂ are being tested and evaluated (Palm 2007). A complete list of ongoing or completed research projects is beyond the scope of this report. The interested reader is encouraged to visit the home page or the different organisations listed at the end of the paper.

A recent effort worth to mention is the new national research and development program EFFSYS2. It is a four year program for applied R&D in Refrigeration and Heat Pump Technology operated by the Royal Institute of Technology Sweden. It was formally started July 1, 2006, and will run up to June 30, 2010. The overall budget is 70 million SEK (about 9 million US\$), of which Industrial Partners are to contribute 60% and Swedish Energy Agency 40%.

The program is a continuation of previous programs: "Alternative Refrigerants", "Klimat21" and "EffSys". In total these programs have been running since the start in 1994 until 2004. After an interruption during 2005, the new program, EFFSYS 2 was started, formally July 1st 2006. Generally the experiences of the previous programs have been very positive. The aim of EFFSYS 2 is to contribute to further strengthen the Swedish R&D community and industry in Refrigeration and Heat Pump Technology. A purpose is to maintain and if possible

strengthen the position, nationally as well as internationally. The purpose is to develop more effective systems for refrigeration and heat pumps, reducing the use of electricity and other forms of energy as well as reducing the peak electricity demand. The program focus is on systems, including the building and the energy supply system in general. This does not exclude projects on components, provided that they are important for the system performance.

The vision of the program is to position "heat pumping technologies" as an integral part of an efficient and sustainable energy system of the future. Projects should have practical applications as well as being useful for academic advancements for doctoral students as well as for senior researchers. 16 projects are now ongoing and more information can be found on the program website: www.effsys2.se.

Large development efforts are also undertaken at the different manufacturers and several new initiatives have recently been taken. New R&D laboratories are constructed well integrated with the respective design office in order to develop next generation of efficient GSHP. The reader is encouraged to visit the home page of the various manufacturers to learn more about these activities. Some links are given at the end of the chapter.

Several new EU projects related to heat pump technology have recently been initiated with Swedish participation. One recent example is GROUNDMED a program with a strong focus on ground source heat pumps adopted for the Mediterranean region. Another example is GROUNDREACH involving the Swedish Heat Pump Association. Another activity of interest for heat pump manufacturers is the new working party for reduction of refrigerant charge initiated by the IIR and strongly supported by section E2, Heat Pumps and heat recovery⁶.

Table 2: University and research centra in Sweden active in heat pump research

Name	Contact	Tel	e-mail and web
Chalmers TU	Prof. Per Fahlen	+46 31 7721142	Per.Fahlen@chalmers.se www.chalmers.se
KTH TU	Prof. Per Lundqvist Prof. Björn Palm	+46 8 7906000	per.lundqvist@energy.kth.se bpalm@energy.kth.se www.kth.energy.se
Luleå TU	Prof. Bo Nordell	+46 920 491646	bo.nordell@ltu.se www.ltu.se
Lund TU	Dr. Göran Hellström	+46 46 2229091	goran.hellstrom@matfys.lth.se www.lu.se
SP	Dr. Monica Axell	+46 10 5165519	monica.axell@sp.se www.sp.se
IUC	Dir. Jörgen Rogstam	+46 150 57782 +46 768 581545	jorgen.rogstam@iuc-sek.se www.iuc-sek.se

Table 3: Other heat pump related activities

Name	Contact	Tel	e-mail and web
IEA Heat Pump Centre	Dr. Monica Axell	+46 10 5165519	monica.axell@sp.se www.heatpumpcentre.org
Swedish Heat Pump Association	Dir. Martin Forsén		martin.forsen@svepinfo.se www.svepinfo.se
Swedish Energy Agency	Mr Mattias Törnell	+46 16 5442169	mattias.tornell@energimyndigheten.se www.energimyndigheten.se

⁶ www.iifir.org

6 CONCLUSION AND DISCUSSION

The GSHP has reached a mature status in Sweden; almost 30 % of all single-family houses are now heated with some kind of heat pump system. GSHP is thus today the preferred heating method in single-family houses with a reasonable energy demand. For smaller houses with low energy demand exhaust air heat pumps is the standard solution, but systems utilizing a dual heat source, exhaust air and ground coupling, may become more common thus offering a better energy coverage factor required by the new energy performance directives.

Although large efforts for R&D have been put into HP research many issues remain. A broad competence within academia does exist today and research funding is for the time being relatively stable.

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