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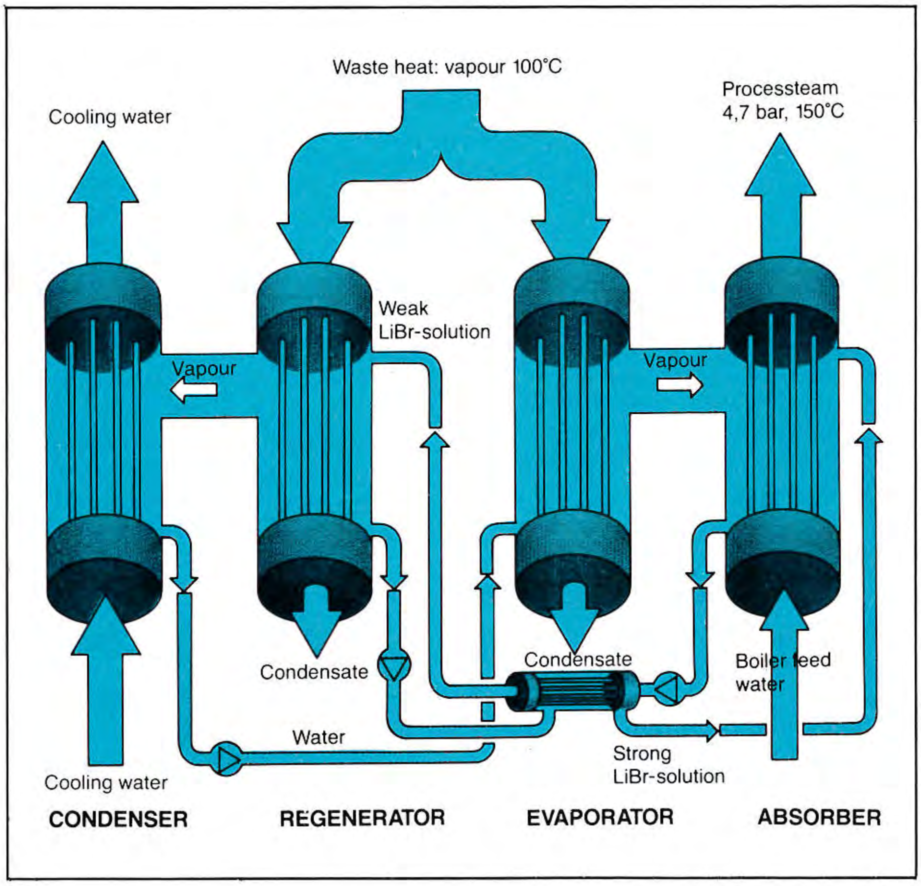

APPLICATION OF HEAT PUMPS IN INDUSTRY

HPC-R-5

IEA Heat Pump Center

Report

on the

APPLICATION OF HEAT PUMPS IN INDUSTRY

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1. INTRODUCTION

This report contains the result of a study regarding the application of heat pumps in industry. It is limited to countries which are members of the Heat Pump Center of the International Energy Agency.

The goals of this study are threefold. First an overview of present applications of heat pumps in industry is given, identifying those sectors and processes in which heat pumps have had some success. Second, a study is made of the economics of heat pumps in which the influence of the major parameters determining their economic success is brought forward. Finally, an overall analysis of the most important industrial sectors is undertaken in order to determine their potential market for heat pumps.

The present study was undertaken in order to identify those sectors and processes which lend themselves for heat pump applications. In this way the study responds to a request for guidance expressed by the IEA Heat Pump Center member countries while investigating the future direction of their heat pump promotion activities. It is hoped that this study provides sufficient information to make the necessary choices.

The preparation of this report heavily relied upon collaboration with the IEA Heat Pump Centre staff and with the National Teams from its member countries. This fruitful collaboration is gratefully acknowledged.

2. PRESENT MARKET SITUATION

2.1 SURVEY

During the fall of 1987 a survey was made of heat pump applications in IEA Heat Pump centre member countries. The survey is based upon a questionnaire (see appendix A) which was sent to the national teams of these countries. The results obtained are listed in tables 2.1 to 2.8.

The tables refer only to those countries which responded to the questionnaire. It can be assumed that very few industrial heat pumps exist in those countries which did not fill in the questionnaire. This is, for example, the case in Belgium in which less than 10 industrial heat pumps are applied.

Table 2.1 Application of heat pumps in industry - Austria.

SECTOR (Nr.)	Installed Capacity MW	Total Number of Installed Heat Pumps				Total Energy Potential GWh			
		a	b	c	d	a	b	c	d
Chemicals, petroleum (1)	66	-	2	-	-	-	528	-	-
Dairy (2)	16,5	-	2	-	-	-	91	-	-
Fabricated metal prod. (7)	1	1	-	-	-	7,2	-	-	-
Fruit, vegetables (21)	15	-	1	-	-	-	75	-	-

a) CCHP : closed cycle compression heat pump.
b) OCHP : open cycle compression heat pump.
c) AHP(1): absorption heat pump type 1.
d) AHP(2): absorption heat pump type 2, heat transformer.

Table 2.2 Application of heat pumps in industry - Sweden.

SECTOR (Nr.)	Installed Capacity	Total Number of Installed Heat Pumps				Total Energy Potential			
	MW					GWh			
		a	b	c	d	a	b	c	d
Chemicals, petroleum (1)	26	11	-	-	-	208	-	-	-
Dairy (2)	18,25	8	-	-	-	105	-	-	-
Pulp and paper (3)	24	6	-	-	-	190	-	-	-
Textiles (4)	40	16	-	-	-	152	-	-	-
Lumber, wood (5)	11,5	7	-	-	-	63,5	-	-	-
Rubber (6)	4,25	4	-	-	-	21,5	-	-	-
Fabricated metal prod. (7)	17,6	16	-	-	-	85,5	-	-	-
Machinery (except electrical) (8)	2,5	1	-	-	-	10	-	-	-
Electrical equipment and supplies (9)	1,75	4	-	-	-	74	-	-	-
Stone, clay, glass (11)	3,5	3	-	-	-	8,75	-	-	-
Fabricated plastic products (14)	5,2	9	-	-	-	26	-	-	-
Meat products (16)	9,8	12	-	-	-	30,9	-	-	-
Grain mill products (17)	0,25	1	-	-	-	0,75	-	-	-
Bakery products (18)	0,25	1	-	-	-	7	-	-	-
Sugar (19)	2	-	-	-	-	6	-	-	-
Beverages (20)	0,25	1	-	-	-	0.75	-	-	-
Fish culture (22)	0,5	2	-	-	-	4	-	-	-
Fish drying (23)	0,33	1	-	-	-	1	-	-	-
Oil and grease (26)	0,25	1	-	-	-	1,5	-	-	-

Table 2.2 Application of heat pumps in industry - Sweden (continued).

SECTOR (Nr.)	Installed Capacity MW	Total Number of Installed Heat Pumps				Total Energy Potential GWh			
		a	b	c	d	a	b	c	d
Ice cream (30)	0,8	2	-	-	-	4	-	-	-
Tobacco (31)	1,4	3	-	-	-	4	-	-	-
Chocolate (34)	0,25	1	-	-	-	0,75	-	-	-

a) CCHP : closed cycle compression heat pump.
b) OCHP : open cycle compression heat pump.
c) AHP(1): absorption heat pump type 1.
d) AHP(2): absorption heat pump type 2, heat transformer.

Table 2.3 Application of heat pumps in industry - Japan.

SECTOR (Nr.)	Installed Capacity	Total Number of Installed Heat Pumps				Total Energy Potential			
	MW					GWh			
		a	b	c	d	a	b	c	d
Chemicals, petroleum (1)	37	4	4	8	8	49,2	49,2	98,5	98,5
Pulp and paper (3)	17,5	-	-	7	-	-	-	140	-
Textiles (4)	12,8	2	-	6	-	12,2	-	36,5	-
Lumber, wood (5)	0,3	2	-	-	-	1,7	-	-	-
Fabricated metal prod. (7)	5,5	3	-	1	-	29,0	-	9,7	-
Machinery (except electircal) (8)	0,6	4	-	-	-	6,8	-	-	-
Electrical equipment and supplies (9)	0,5	-	-	2	-	-	-	2,0	-
Transportation equip. (10)	5,28	8	-	-	-	23,8	-	-	-
Fabricated plastic products (14)	5	1	-	1	-	10,6	-	10,6	-
Brewery (15)	25	2	2	-	-	68,8	68,8	-	-
Meat Products (16)	1,55	5	-	-	-	5,3	-	-	-
Bakery industry (18)	0,75	2	-	1	-	1,9	-	-	0,9
Fruit, vegetables (21)	1,52	8	-	-	-	7,6	-	-	-
Fish culture (22)	0,95	5	-	-	-	7,6	-	-	-
Fish drying (23)	0,38	4	-	-	-	0,44	-	-	-
Seaweed drying (24)	0,13	1	-	-	-	-	-	-	-
Soybean fermentation (25)	0,27	2	-	-	-	-	-	-	-
Oil, grease (26)	0,06	-	-	-	-	-	-	-	-

a) CCHP : closed cycle compression heat pump.
b) OCHP : open cycle compression heat pump.
c) AHP(1): absorption heat pump type 1.
d) AHP(2): absorption heat pump type 2, heat transformer.

Table 2.4 Application of heat pumps in industry - Norway.

SECTOR (Nr.)	Installed Capacity MW	Total Number of Installed Heat Pumps				Total Energy Potential GWh			
		a	b	c	d	a	b	c	d
Dairy (2)	7	7	4	-	-	22	16,5	-	-
Pulp and paper (3)	30	-	4	-	-	-	800	-	-
Lumber, wood (5)	6	200	-	-	-	42	-	-	-
Leather (12)	1,5	50	-	-	-	4,5	-	-	-
Plastics (14)	0,7	10	-	-	-	5,5	-	-	-
Meat products (16)	14	20	-	-	-	48	-	-	-
Bakery products (18)	0,2	5	-	-	-	1	-	-	-
Fish culture (22)	44	220	-	-	-	264	-	-	-
Fish drying (23)	12,5	50	-	-	-	44	-	-	-
Fish processing evaporator (27)	4	-	3	-	-	-	12	-	-
Fish Products	5	20	-	-	-	18	-	-	-

a) CCHP : closed cycle compression heat pump.
b) OCHP : open cycle compression heat pump.
c) AHP(1): absorption heat pump type 1.
d) AHP(2): absorption heat pump type 2, heat transformer.

Table 2.5 Application of heat pumps in industry - The Netherlands.

SECTOR (Nr.)	Installed Capacity MW	Total Number of Installed Heat Pumps				Total Energy Potential GWh			
		a	b	c	d	a	b	c	d
Chemicals, petroleum (1)	14,515	2	7	-	1	8,16	56,76	57,2	-
Dairy (2)	15	1	4	-	-	2,75	79,8	-	-
Lumber, wood (5)	0,13	1	-	1	-	0,4	-	0,33	-
Fabricated metal prod. (7)	0,5	1	-	-	-	3,6	-	-	-
Brewery (15)	5,4	1	1	-	-	18,7	12,1	-	-
Meat products (16)	1,2	1	2	-	-	4,1	-	-	-
Grain mill products (17)	21,7	-	3	-	-	-	65,1	-	-
Oil, grease (26)	3	-	1	-	-	-	16	-	-

a) CCHP : closed cycle compression heat pump.
b) OCHP : open cycle compression heat pump.
c) AHP(1): absorption heat pump type 1.
d) AHP(2): absorption heat pump type 2, heat transformer.

Table 2.6 Application of heat pumps in industry - Finland.

SECTOR (Nr.)	Installed Capacity	Total Number of Installed Heat Pumps				Total Energy Potential			
	MW					GWh			
		a	b	c	d	a	b	c	d
Chemicals, petroleum (1)	20	-	2	-	-	-	-	-	-
Dairy (2)	80	20	15	-	-	-	-	-	-
Pulp and Paper (3)	110	-	4	-	-	-	-	-	-
Lumber, wood (5)	10	580	-	-	-	-	-	-	-
Fabricated metal prod. (7)	2	5	-	-	-	-	-	-	-
Electrical equipment (9)	1	5	-	-	-	-	-	-	-
Sone, clay, glass (11)	4	1	-	-	-	-	-	-	-
Leather (12)	10	1	-	-	-	-	-	-	-
Fabricated plastic products (14)	9	47	-	-	-	-	-	-	-
Meat products (16)	4	10	-	-	-	-	-	-	-
Sugar (19)	19	-	1	-	-	-	-	-	-

a) CCHP : closed cycle compression heat pump.
b) OCHP : open cycle compression heat pump.
c) AHP(1): absorption heat pump type 1.
d) AHP(2): absorption heat pump type 2, heat transformer.

Table 2.7 Application of heat pumps in industry - Canada.

SECTOR (Nr.)	Installed Capacity MW	Total Number of Installed Heat Pumps				Total Energy Potential GWh			
		a	b	c	d	a	b	c	d
Chemicals, petroleum (1)	0,2	2	-	-	-	-	-	-	-
Dairy (2)	0,4	1	-	-	-	-	-	-	-
Pulp and paper (3)	2.4	1	-	-	-	-	-	-	-
Lumber, wood (5)	20	200	-	-	-	-	-	-	-
Bakery industry (18)	0,16	1	-	-	-	-	-	-	-
Fish drying (23)	4	50	-	-	-	-	-	-	-

a) CCHP : closed cycle compression heat pump.
b) OCHP : open cycle compression heat pump.
c) AHP(1): absorption heat pump type 1.
d) AHP(2): absorption heat pump type 2, heat transformer.

Table 2.8 Application of heat pumps in industry - Federal Republic of Germany.

SECTOR (Nr.)	Installed Capacity MW	Total Number of Installed Heat Pumps 1)				Total Energy Potential GWh			
		a	b	c	d	a	b	c	d
Chemicals, petroleum (1)	10,25	1	1	–	1	–	–	–	–
Dairy (2)		1	–	–	–	–	–	–	–
Textiles (4)		1	–	–	–	–	–	–	–
Fabricated metal prod. (7)	2,55	7	–	–	–	–	–	–	–
Electrical equipment (9)	0,12	1	–	–	–	–	–	–	–
Transportation equip. (10)	0,5	2	–	–	–	–	–	–	–
Stone, clay, glass (11)	0,75	1	–	–	–	–	–	–	–
Leather (12)	0,05	1	–	–	–	–	–	–	–
Fabricated plastic products (14)	8,75	7	–	–	–	–	–	–	–
Brewery (15)	7,5	3	1	–	1	–	–	–	–
Meat products (16)	7,25	6	–	–	1	–	–	–	–
Grain mill products (17)	0,25	1	–	–	–	–	–	–	–
Bakery products (18)		1	–	–	–	–	–	–	–
Fruit, vegetables (21)	1,2	1	–	–	–	–	–	–	–
Food - unspecified	2,75	2	–	–	–	–	–	–	–
Unspecified	26,25	7	–	–	–	–	–	–	–

a) CCHP : closed cycle compression heat pump.
b) OCHP : open cycle compression heat pump.
c) AHP(1): absorption heat pump type 1.
d) AHP(2): absorption heat pump type 2, heat transformer.

1) A heat pump plant can consist of more than one heat pump.

Figure 2.1 shows the evolution of heat pumps installed in the different countries over the last 8 years. It should be pointed out that the data regarding Canada and Germany is not adequate enough to draw a time evolution for these countries.

2.2 DISCUSSION AND CONCLUSIONS

The tables clearly indicate that heat pumps applied in industry consist mainly of the compression type. The data suggests that very few open cycle (MVR-mechanical vapour compression) systems are in operation. However, it should be brought to one's attention that it is known that several thousand MVR systems are presently being applied in industry. Thus, in this respect the data from the tables cannot considered to be accurate; the MVR systems were not reported in most questionnaires.

Type 1 absorption heat pumps are applied to a limited extent in Japan and the Netherlands. Also, only a small number of heat transformers are applied in Japan, the Federal Republic of Germany, and the Netherlands.

Heat pumps are applied in large numbers in Finland, Norway, and Canada. In each of these countries, most of the heat pumps used are for wood drying. In Norway, a few hundred heat pumps are applied also in the fish industry (fish culture and drying).

The application of heat pumps in Sweden, Japan, and Germany is distributed over many industrial processes.

With respect to heat pump output, it is found that of all the wood drying heat pumps and almost all of the fish culture heat pumps have thermal outputs of 100 kW or less. Therefore, the thermal output of the majority of industrial heat pumps is rather small. Heat transformers have heat outputs in the MW range and are applied in the chemical industry only.

It can be seen from figure 2.1 that industrial heat pumps were applied before 1980 in Finland and Norway. A very steep increase in heat pump applications took place in the early eighties in the Netherlands, Japan, and Sweden. It is also estimated that in these countries in addition to Canada and the Federal Republic of Germany that heat pump application has stagnated in the last two years.

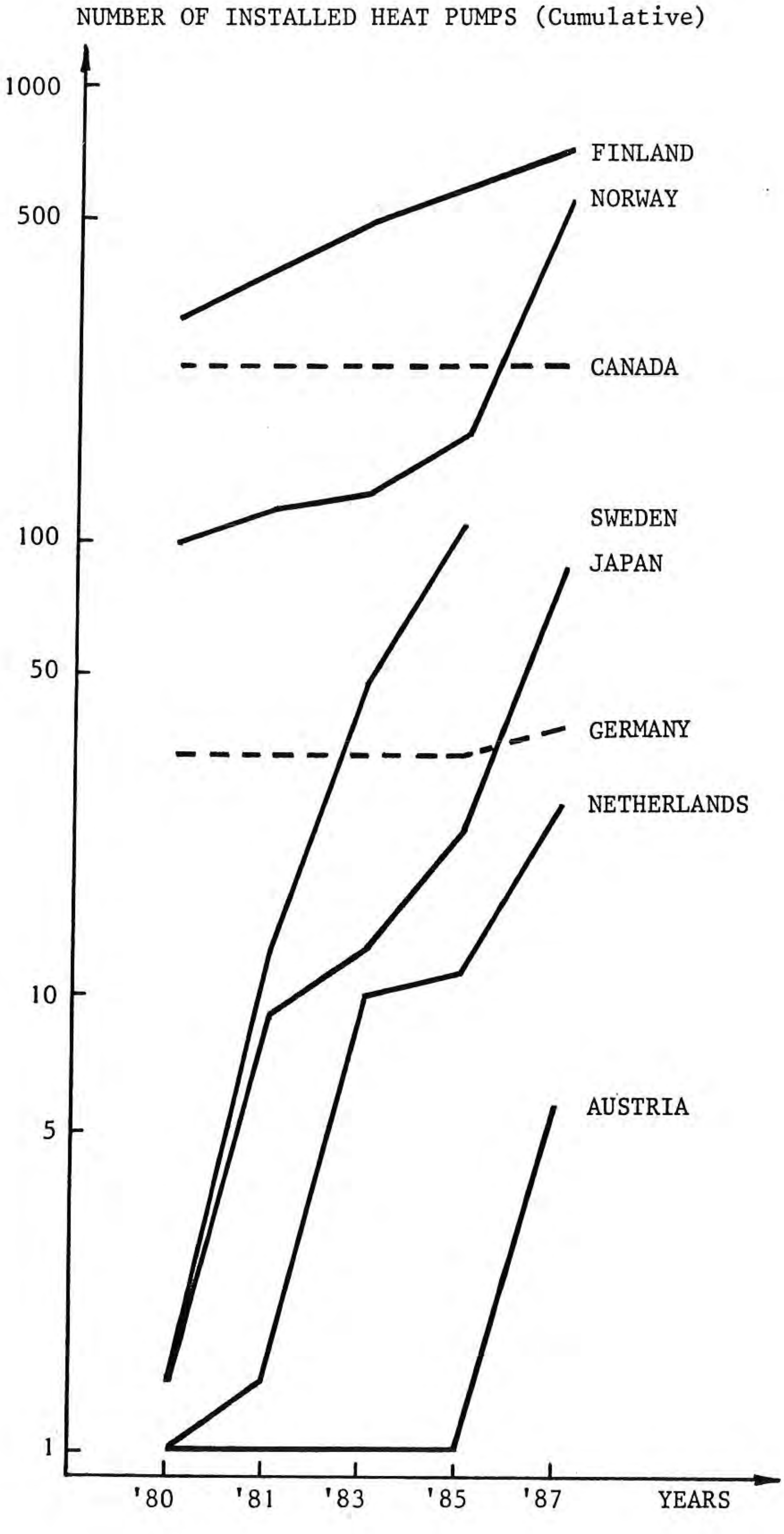

Figure 2.1 Evolution of heat pumps installed.

3. ECONOMICS OF HEAT PUMPS

It is the purpose of this chapter to identify those parameters which influence the economic success of industrial heat pumps. A simple simulation model will be developed for this purpose based on the payback period. This model will then be applied to different countries in order to estimate the potential for heat pumps in their industries. Attention will be given only to vapour compression heat pumps of the closed cycle type. The compression heat pump can be driven either by an electric motor or by a gas engine.

3.1 PERFORMANCE MODELS

The production of heat by a heat pump is characterized by costs. In order for a heat pump to be economical, the cost to produce heat from a heat pump must certainly be less than the cost of heat produced in a conventional manner. The conventional system here is taken to be a gas or fuel boiler. For a heat pump to be justified economically it is often accepted that the savings in fuel costs, to which it gives rise, should equal its investment expenditure over a period of not more than two years: The *payback period* of a heat pump should be *less than two years.*

3.1.1 Electrically Driven Heat Pumps

For an electrically driven heat pump added to an already existing plant the payback can be calculated by means of:

$$PB = \frac{C}{\left[F \frac{Q}{\eta} - E \frac{Q}{COP}\right] h} \tag{3.1}$$

in which:

PB	=	payback period (years)
C	=	heat pump system cost ($)
F	=	fuel cost ($/kWh)
E	=	electricity cost ($/kWh)
η	=	thermal efficiency of the boiler
COP	=	heat pump coefficient of performance
Q	=	heat pump thermal output (kW)
h	=	number of hours of yearly heat pump operation (h/year)

The cost C^* of an electrically driven heat pump can be correlated to its output by means of:

$$C^* = 900\ Q^{0.7} \qquad (3.2)$$

The heat pump system cost C can be substantially larger than C^* due to the installation cost. It will be assumed here that the installation cost is equal to the heat pump cost such that:

$$C = 1800\ Q^{0.7} \qquad (3.3)$$

It should be point out that correlation (3.2) is based upon analysis of the cost of (water-water) heat pumps of several different brands for outputs up to 1 MW and for applications up to 80°C [2]. Insufficient data is available to determine whether this correlation is also applicable at higher outputs and temperatures.

From (3.1) and (3.3) it is found that a payback period of two years is obtained for an electricity cost given by:

$$E = COP\ \left(\frac{F}{\eta} - \frac{1800}{h\ Q^{0.3}}\right) \qquad (3.4)$$

For lower electricity costs, the payback will be smaller.

From here on the efficiency of the boiler (η) will be taken to be equal to 0.85. Expression (3.4) allows one to calculate the maximum price of electricity (for a payback of 2 years). In this expression the number of hours of operation of the heat pump h occurs. It is assumed here that h can be put equal to the number of hours that the industrial process to which the heat pump is attached is in operation. Table 3.1 lists the typical yearly hours of operation in a number of industrial sectors [3].

Table 3.1 Run Time per Industrial Sector

INDUSTRIAL SECTOR	Nr.	RUN TIME (hours/year)
Chemicals, Petroleum	1	8000
Dairy	2	5000 - 6000
Pulp, Paper	3	8000
Textiles	4	3800
Lumber and Wood Products	5	3000 - 8000
Fabricated Rubber Products	6	3000 - 7000
Fabricated Metal Products	7	6000 - 8400
Machinery, Except electrical	8	3000 - 5000
Electrical Equipment & Supplies	9	3000 - 5000
Transportation Equipment	10	3000 - 6000
Stone, Clay, Glass	11	2500
Leather	12	3000
Graphical	13	5000
Fabricated Plastic Products	14	1500 - 7000
Brewery	15	3000 - 8000
Meat Products	16	2800 - 4000
Grain Mill Products	17	3000
Bakery Products	18	2000 - 5500
Sugar	19	3000
Beverages	20	3000
Fruit, Vegetable Products	21	4000 - 6000
Fish Culture	22	8000
Fish Drying	23	3000
Seaweed Drying	24	5000
Soybean Fermentation	25	5000
Oil, Grease	26	3000 - 8000
Fish Processing: Evaporator	27	3000
Non-ferrous metal	28	6000 - 8400
Iron, Steel	29	6000 - 8400
Icecream	30	3000
Tobacco	31	3000
Sweet Products	32	3000
Sawing - Mills	33	6000 - 8000
Chocolate	34	2500 - 6000
Pressed Wood Plate	35	6000 - 8000

The COP of the heat pump depends upon the heat delivery temperature and the temperature lift T achieved by the heat pump. For a water to water heat pump the following correlation is used to calculate the coefficient of performance [4]:

$$COP = 0.5 \frac{273°C + \text{delivery temp.} + 5°C}{\text{temp. lift} + 5°C} \quad (3.5)$$

The delivery temperatures for a number of interesting processes are listed in Table 3.2 [3].

Table 3.2 Delivery Temperature per Industrial Sector (10/13)

Nr.	INDUSTRIAL SECTOR	TEMPERATURE
1	Chemicals, Petroleum:	
	crude	168°C
	BTX	143°C
	ethyleen	85°C
	area	126°C
	electrical refining	67°C
	heating chemicals/solutions	110°C
2	Dairy:	
	washing	60°C
	pasteurization	65°C
	evaporation	50 - 80°C
	sterilization	110°C
	drying	80°C
3	Pulp, Paper:	
	digestor	160°C
	liquor	100°C
	evaporator	60°C
4	Textiles:	
	dye heating	90°C
	drying	70 - 105°C
	processing	100 - 150°C
5	Lumber and Wood Products:	
	log soaking	90°C
	drying	70°C
6	Fabricated Rubber Products	85°C
7	Fabricated Metal Products:	
	metal cleaning and plating	60 - 90°C
	paint drying	80 - 120°C
	space heating	70°C

Nr.	INDUSTRIAL SECTOR	TEMPERATURE
8	Machinery, Except electrical:	
	metal cleaning and plating	60 - 90°C
	paint drying	80 - 120°C
9	Electrical Equipment & Supplies:	
	metal cleaning and plating	60 - 90°C
	paint drying	50 - 120°C
	space heating	75°C
10	Transportation Equipment:	
	metal cleaning and plating	60 - 90°C
	paint drying	80 - 120°C
11	Stone, Clay, Glass	
12	Leather	60°C
13	Graphical	60°C
14	Fabricated Plastic Products	70°C
15	Brewery	60 - 100°C
16	Meat Products:	
	drying	70°C
	washing	60°C
	cooking	100 - 115°C
	scalding	50 - 60°C
17	Grain Mill Products	60 - 100°C
18	Bakery Products:	
	washing	60°C
19	Sugar:	
	washing	120°C
20	Beverages:	
	washing	60°C
	cooking	100 - 115°C
21	Fruit, Vegetable Products	75 - 110°C
22	Fish Culture	20°C
23	Fish Drying	70°C
24	Seaweed Drying	50°C
25	Soybean Fermentation	50°C
26	Oil, Grease	60°C
27	Fish Processing	60°C
28	Non-ferrous metal	70°C
29	Iron, Steel	70°C

3.1.2 Gas or Diesel Engine Driven Heat Pumps

For a heat pump driven by a gas engine the payback period can be calculated by means of:

$$PB = \frac{C}{\left(\frac{1}{\eta} - \frac{1}{PER}\right) Q\, h\, F} \qquad (3.6)$$

in which now

C = heat pump system cost ($)
F = cost of gas or diesel ($/kWh)
η = boiler efficiency (taken to be 0.85)

The primary energy efficiency PER of the heat pump can be calculated from:

$$PER = \eta_m \, COP + (1 - \eta_m) \, \eta_r \tag{3.7}$$

where:

η_m = engine efficiency (taken to be 0,33)
η_r = efficiency of recovery of cooling and flux gas heat (taken to be 0,7)

Based upon an analysis of the cost of gas engine driven heat pump systems the following correlation is used:

$$C = 3600 \, Q^{0.7} \tag{3.8}$$

This means that for the same thermal output an engine driven heat pump system is taken to be twice the cost of an electric heat pump system. From (3.6), (3.8), and the efficiencies mentioned it is found that the cost of natural gas (or diesel oil), which corresponds to a payback of two years, is given by:

$$F = \frac{3600}{\left(1{,}176 - \frac{1}{PER}\right) Q^{0.3} \, h} \tag{3.9}$$

Here again use is made of expression (3.5) to calculate PER from (3.7). Run time and delivery temperatures, as before, can be taken from tables 3.1 and 3.2.

3.2 RESULTS

The models described above were utilized to analyze the economic feasibility of industrial heat pumps in different countries. Only a global analysis was performed based upon the cost of electricity and fuels in these countries. A sectorial analysis will be made later. In this study, two typical values (namely 20°C and 35°C) are chosen for the temperature lift. The run time is assumed to be 4000, 6000, and 8000 hours per year and the delivery temperature is given the value: 60, 80, 100, and 120°C. Furthermore, from the questionnaires which were sent to the National Teams of the IEA-HPC members, it is found that the heat pump capacity can be divided into three groups with each group represented by an average value of 100, 500, and 2500 kW.

Figures 3.1 to 3.6 give the maximum cost of electricity as a function of fuel oil cost for electrically driven heat pumps. These figures are based upon equations (3.4) and (3.5). The average values of electricity and fuel costs are also shown for 1978, 1985, and 1986 in these figures. Each country is represented by a number, and the number for a particular country can be obtained from Table 3.3.

Table 3.3 Enumeration of countries.

NUMBER	COUNTRY
1	Austria
2	Belgium
3	Canada
4	Denmark
5	Finland
6	France
7	Germany
8	Italy
9	Japan
10	Netherlands
11	Norway
12	Sweden
13	Switzerland
14	United Kingdom
15	United States of America

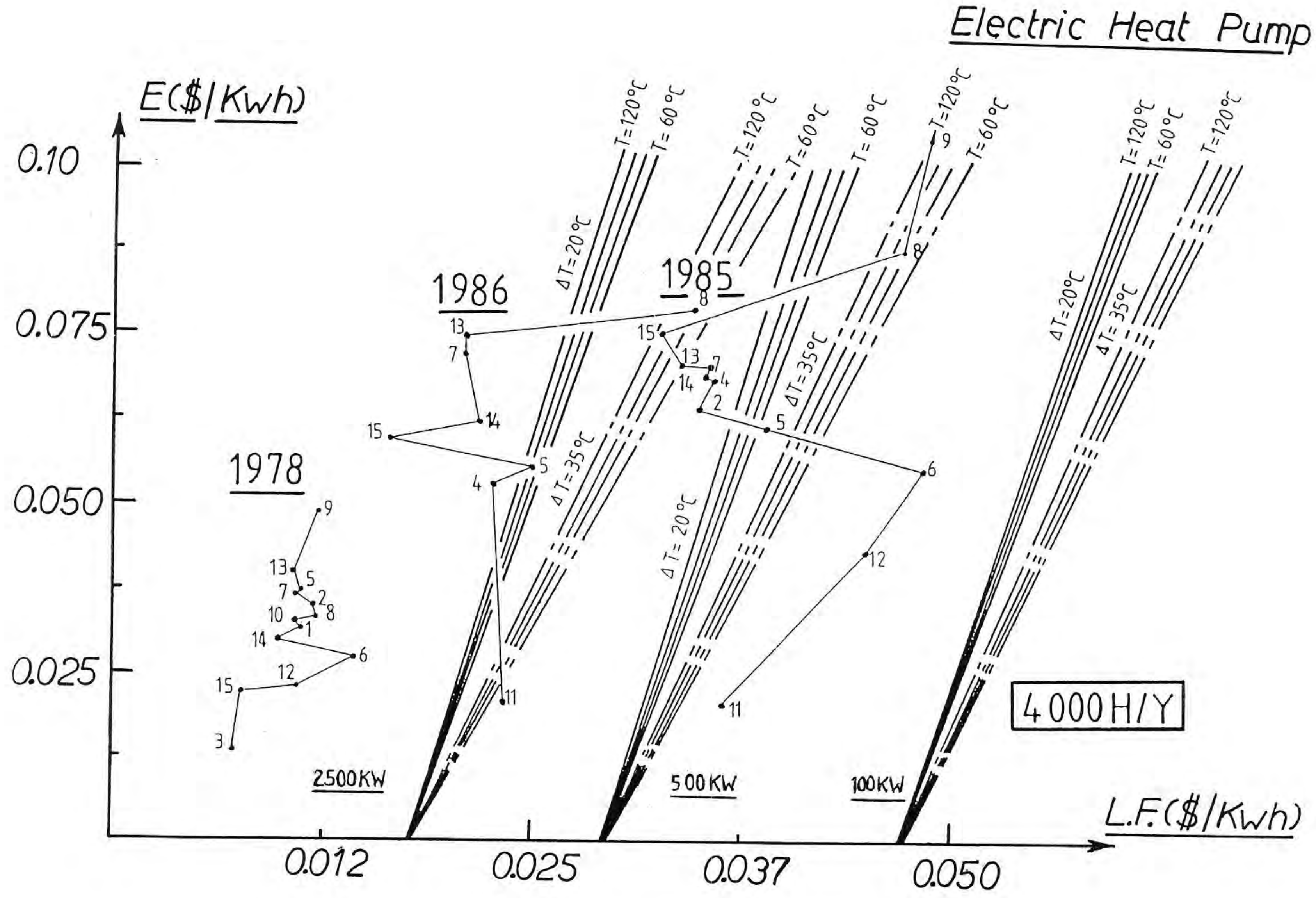

Figure 3.1 Maximum electricity price (E) for a given light fuel price (LF).

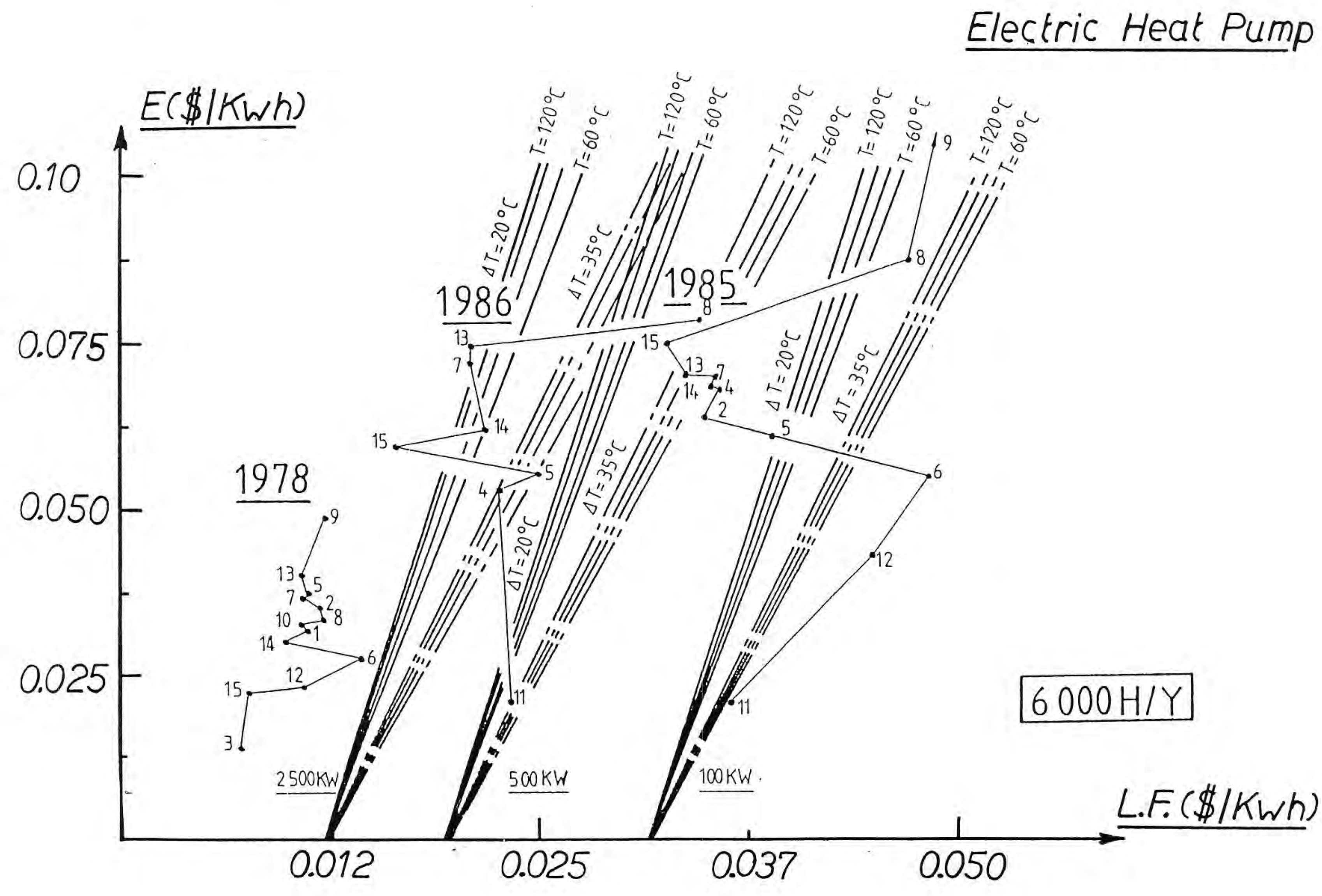

Figure 3.2 Maximum electricity price (E) for a given light fuel price (LF).

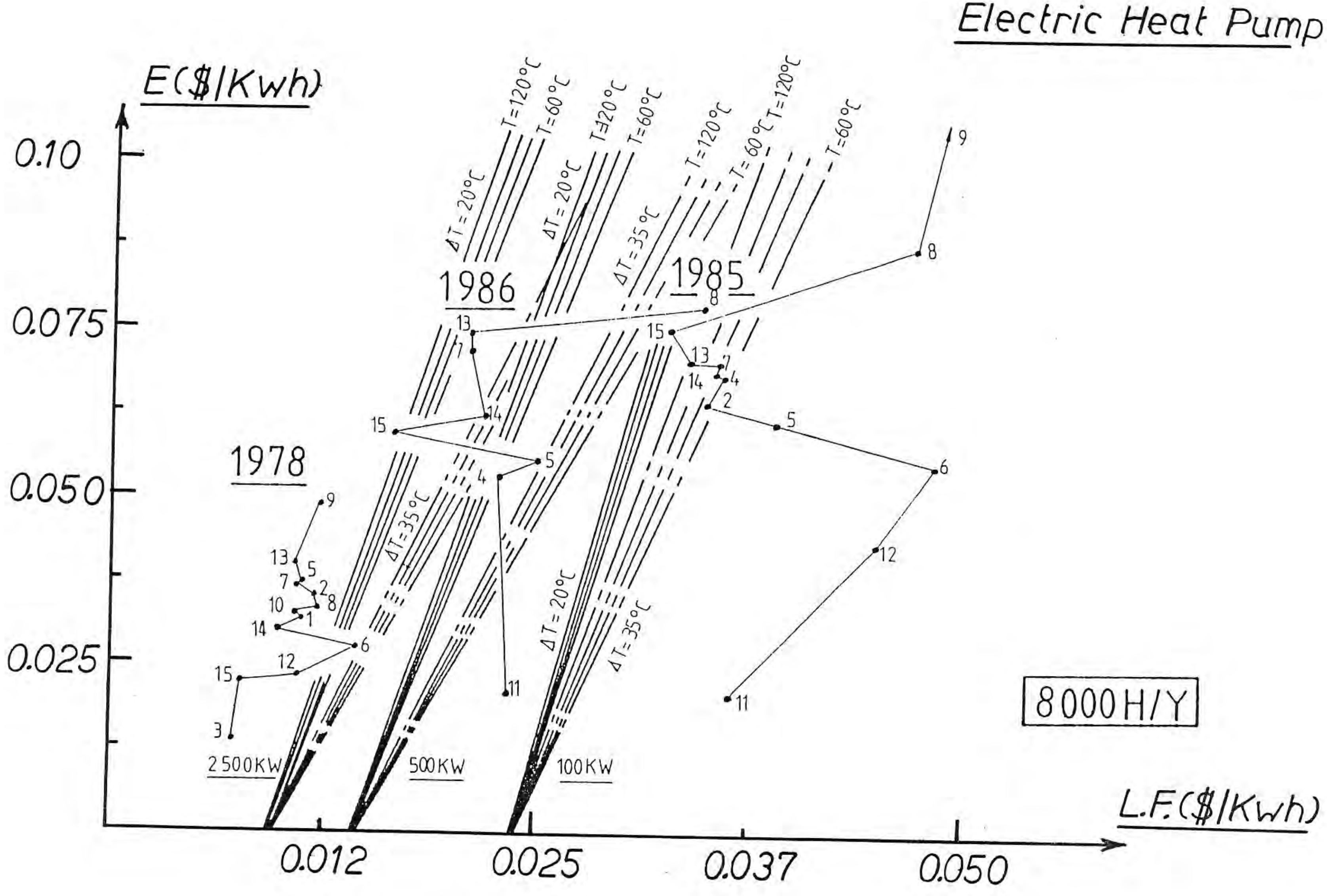

Figure 3.3 Maximum electricity price (E) for a given light fuel price (LF).

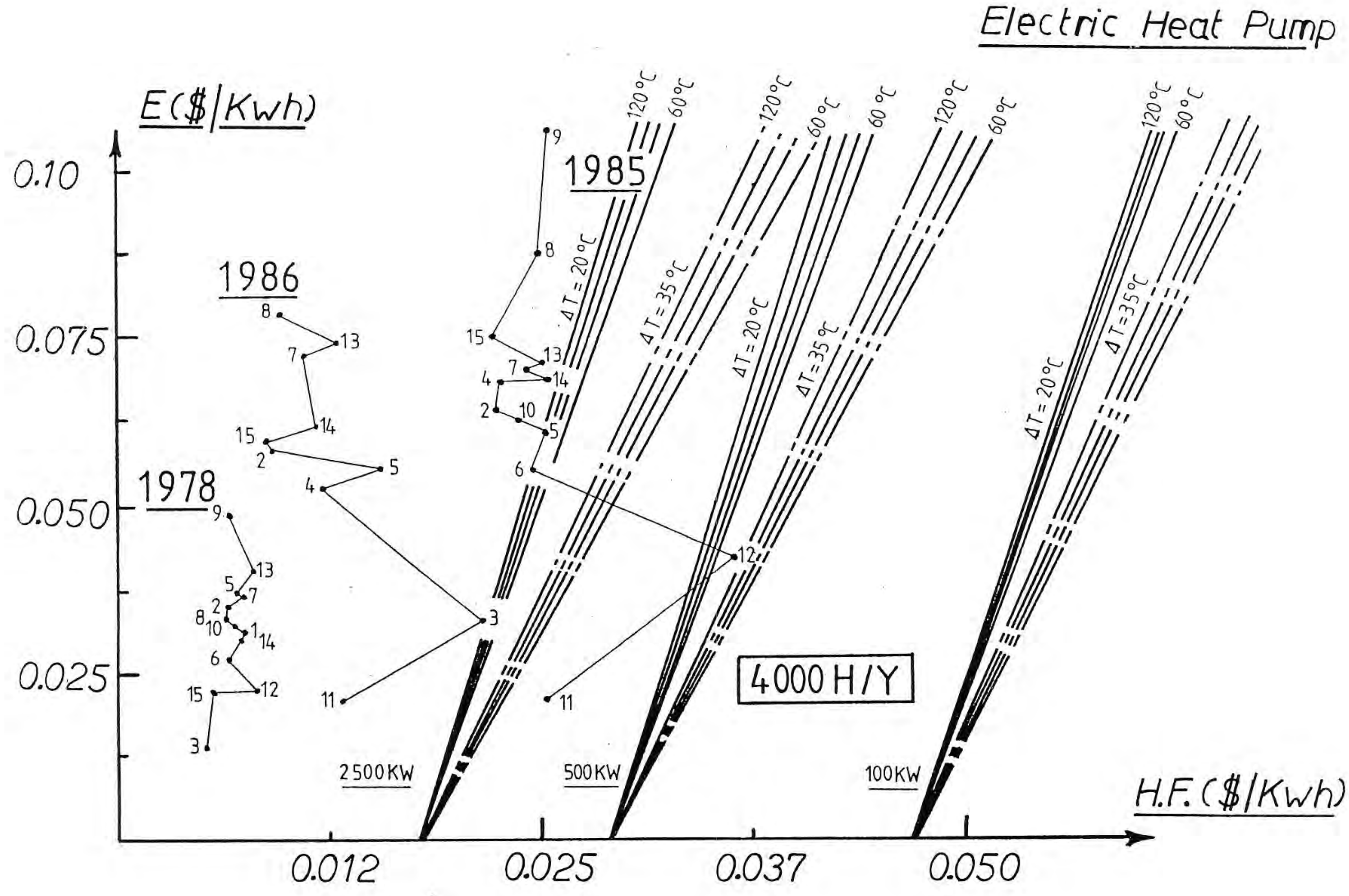

Figure 3.4 Maximum electricity price (E) for a given heavy fuel price (HF).

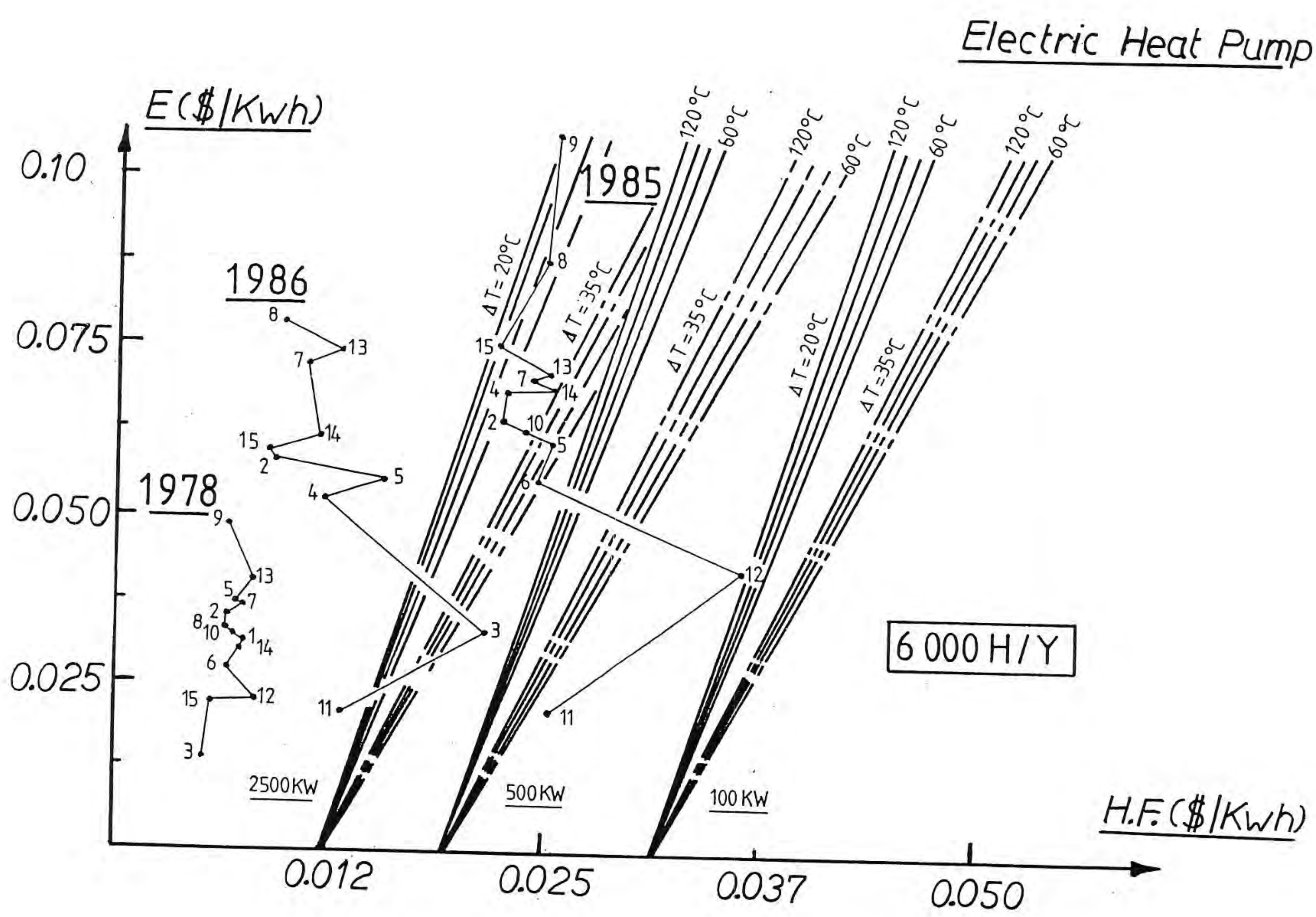

Figure 3.5 Maximum electricity price (E) for a given heavy fuel price (HF).

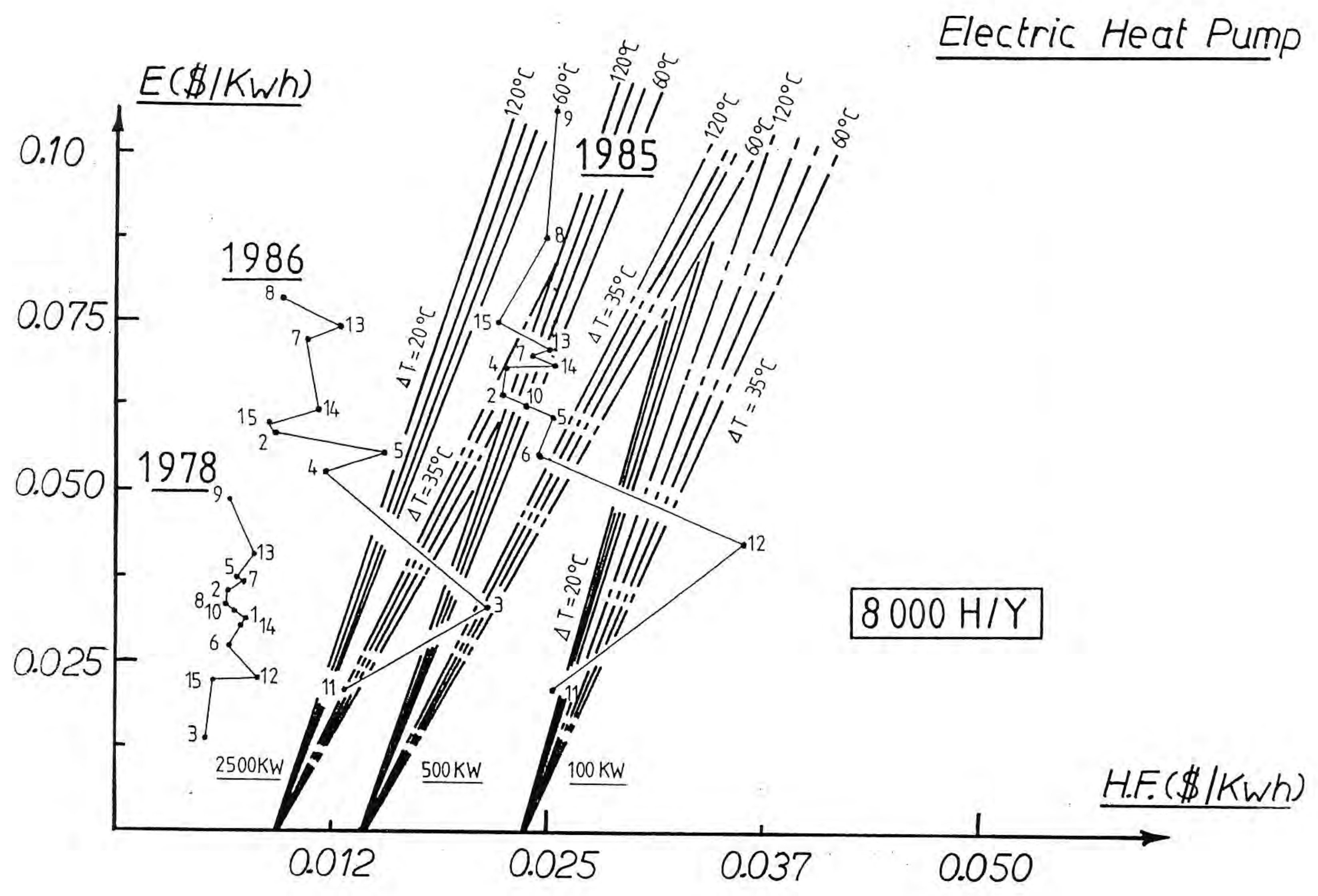

Figure 3.6 Maximum electricity price (E) for a given heavy fuel price (HF).

From these figures it can be deduced whether a heat pump application is economically justifiable. For the heat pump application considered, the electricity cost in the country considered should be smaller than the one derived from the straight lines of the figures (given capacity, output temperature, temperature lift, hours of operation, and fuel cost). As the correlations for the cost of heat pumps obviously relate to 1987 only comparison with the national 1985-86 data for electricity and fuel costs is possible.

Figures 3.1 to 3.6 illustrate the influence the basic design parameters of a heat pump have on the successful application of a heat pump. A high run time, high installed capacity, low temperature lift, and high delivery temperature are the major elements in making a successful application possible. In industrial sectors where run time is about 4000 hours per year, it appears that only Norway, Sweden, and France provide good opportunities for heat pumps with a capacity of 500 kW and higher (based on the energy cost of 1985). A somewhat less potential for application is found in Finland and Japan. In these countries possibilities are limited to capacities of about 500 kW and temperature lifts below 20°C. The other countries form a cluster and do not appear to offer good prospects for successful use of heat pumps. Likewise, when the energy cost changes to the level in 1986 the situation does not look good either. Only Sweden, Norway, and France become marginal in the Megawatt range.

Based on the findings above it is obvious that industrial sectors with a high run time are more profitable in view of energy savings by use of heat pumps. In figure (3.2) sectors with an assumed run time of 6000 hours are presented. From this figure and based on the energy cost of 1985 the same conclusions can be drawn as above for capacities above 100 kW for Sweden, Norway, France, Japan, and Finland. The other countries provide good perspectives for heat pumps with a capacity of 500 kW and a low temperature lift. A decrease in light fuel price in 1986 results in a reduced potential for most countries. Only Sweden, Norway, and France show marginal potential in those cases where the heat pump capacity is higher than 500 kW. An increased run time, up to 8000 hours, results in a better potential for heat pump application. Most industrial sectors provide good opportunities for capacities around 100 kW and higher. One can conclude that for the light fuel costs of

1985, Sweden, Norway, France, and to a somewhat lesser extend Japan and Finland, provide good opportunities for a run time close to 8000 hours. A decrease in fuel price (such as in 1986) results in lowered prospects for a successful heat pump application. Figures 3.4 to 3.6 relate to heavy fuel as conventional heat sources. It can be seen from figure 3.4 that for 1986 price levels and 4000 hours of annual operation, heat pumps cannot be applied economically. Based on figures 3.5 and 3.6, Norway and Canada provide an opportunity for only very large heat pumps in which the processes run at 6000 and 8000 hours. Here again the dramatic influence of the fuel price decrease from 1985 to 1986 is demonstrated. Comparing figures 3.1, 3.2, and 3.3, to figures 3.4, 3.5, and 3.6 it is clearly seen that heat pumps have a higher potential for application when replacing light fuel oil as compared to heavy fuel oil. The least interesting heat pump application consider in this analysis is one in which the temperature lift is 35°C and the delivery temperature is 60°C. The limiting electricity cost for this application (straight lines utmost to the right in figures 3.4, 3.5, and 3.6) are given by:

$E = 0.1\ F - 0.2$ (for 4000 h/year)
$E = 0.1\ F - 0.15$ (for 6000 h/year)
$E = 0.1\ F - 0.1$ (for 8000 h/year)

The expressions above allow one to determine the cost of electricity at which heat pumps become economic irrespective of their size, temperature lift, or output temperature.

For gas engine driven heat pumps, figure 3.7 gives the maximum gas price as a function of the parameters involved. The vertical lines to the left show the actual gas prices in 1984 and 1988 in different countries. It is found that only in a few countries, such as Japan and Switzerland, gas engine driven heat pumps can give rise to economical application of heat pumps.

Finally, Table 3.4 presents in a condensed form the conclusions which can be drawn thus far. In the case of electrically driven heat pumps; Norway, Sweden, France, and to a lesser extent Finland, Japan, Italy, and Denmark are countries where it is possible to achieve successful results concerning energy recovery where heat pumps are used. Only in Japan and Switzerland is the natural gas price high enough to assure realistic heat pump applications when gas motor driven heat pumps are used.

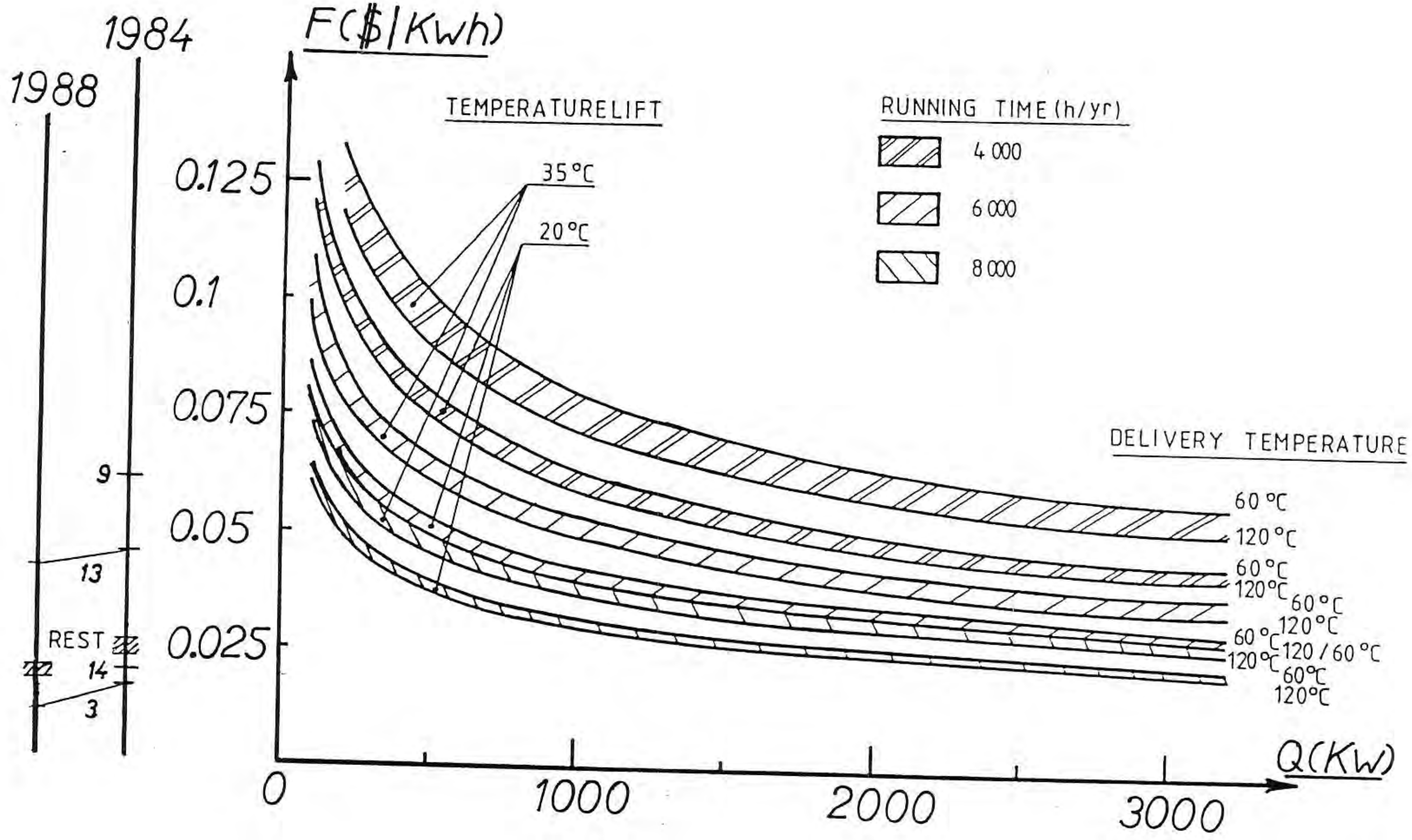

Figure 3.7 Minimum gas price for gas engine driven heat pumps.

Table 3.4 Review of the most promising countries for gas motor and electrically driven heat pumps.

RUN TIME (h/yr)	LIGHT FUEL		HEAVY FUEL		NATURAL GAS	
	1985	1986	1985	1986	1984	1986
4000	Norway Sweden France (Q > 500 kW) Finland Japan (Q > 500 kW and $\Delta T < 20°C$)	Norway Sweden France (MW range)	Norway Sweden (Q > 500 kW)		Japan $\Delta T = 20°C$: Q > 1MW $\Delta T = 35°C$: Q > 2MW Switzerland $\Delta T = 20°C$: Q > 3MW	
6000	Norway Sweden France Finland Japan (Q > 100 kW)	Norway Sweden France (Q > 500 kW)	Norway Sweden (Q > 500 kW) France Finland U.K. Netherlands (MW range)	Canada (Q > 500 kW)	Japan $\Delta T = 20°C$: Q > 300 kW $\Delta T = 35°C$: Q > 600 kW Switzerland $\Delta T = 20°C$: Q > 800 kW $\Delta T = 35°C$: Q > 1 MW	Switzerland $\Delta T = 20°C$: Q > 1,1 MW $\Delta T = 35°C$: Q > 2,5 MW
8000	All Countries (Q > 100 kW)	Norway (Q > 100 kW) Italy (Q > 100 kW and $\Delta T < 20°C$) Denmark Finland (Q > 500 kW and $\Delta T < 20°C$) Germany Switzerland (MW range)	Norway Sweden (Q > 100 kW) Finland France U.K. (Q > 500 kW)	Canada (Q > 500 kW) Norway (MW range)	Japan $\Delta T = 20°C$: Q > 400 kW $\Delta T = 35°C$: Q > 300 kW Switzerland $\Delta T = 20°C$: Q > 400 kW $\Delta T = 35°C$: Q > 700 kW	Switzerland $\Delta T = 20°C$: Q > 400 kW $\Delta T = 35°C$: Q > 800 kW

4. MARKET POTENTIAL FOR INDUSTRIAL HEAT PUMPS

The results obtained from the questionnaires show that the application of heat pumps has been successful in a few industrial sectors and in a few countries. In this present chapter an analysis is made of the potential for heat pumps to be applied in the most promising industrial sectors.

First, the approach taken here will be explained. In principle, a market analysis for industrial heat pumps can be achieved in a very straight forward way. However, in reality it is found that statistical data regarding heat consumption coupled to data on the availability of waste heat (in the same plant) is not available. Such data, however, is absolutely necessary in order to analyze the market for industrial heat pumps. The approach taken here to solve this problem is first described.

The method developed is then applied to 14 different countries which results in a global estimate of the heat pump market in 13 different industrial sectors of these countries.

4.1 METHODOLOGY

The limited character of the statistical data on energy consumption relevant to heat pumps resulted in the methodology which is described in figure 4.1.

The first step consists in the collection of data regarding total energy consumption, (mechanical as well as thermal energy), in the industrial sectors of the country considered. From this the thermal energy consumption in each sector can be derived by comparison with the same industrial sectors in other countries. Of course if the statistical data on heat consumption is available, then step 1 can be deleted. In step 3 the distribution of heat consumption in each sector as a function of temperature levels is determined. Such distributions are known for a number of countries (U.S.A., Japan, Belgium, ...). Known distributions are taken to be valid also in those countries where they have not been determined statistically. From the temperature distributions, the heating needs below 150 (or 200°C) can be derived for each sector (step four). This represents the maximum heat production potential for heat pumps.

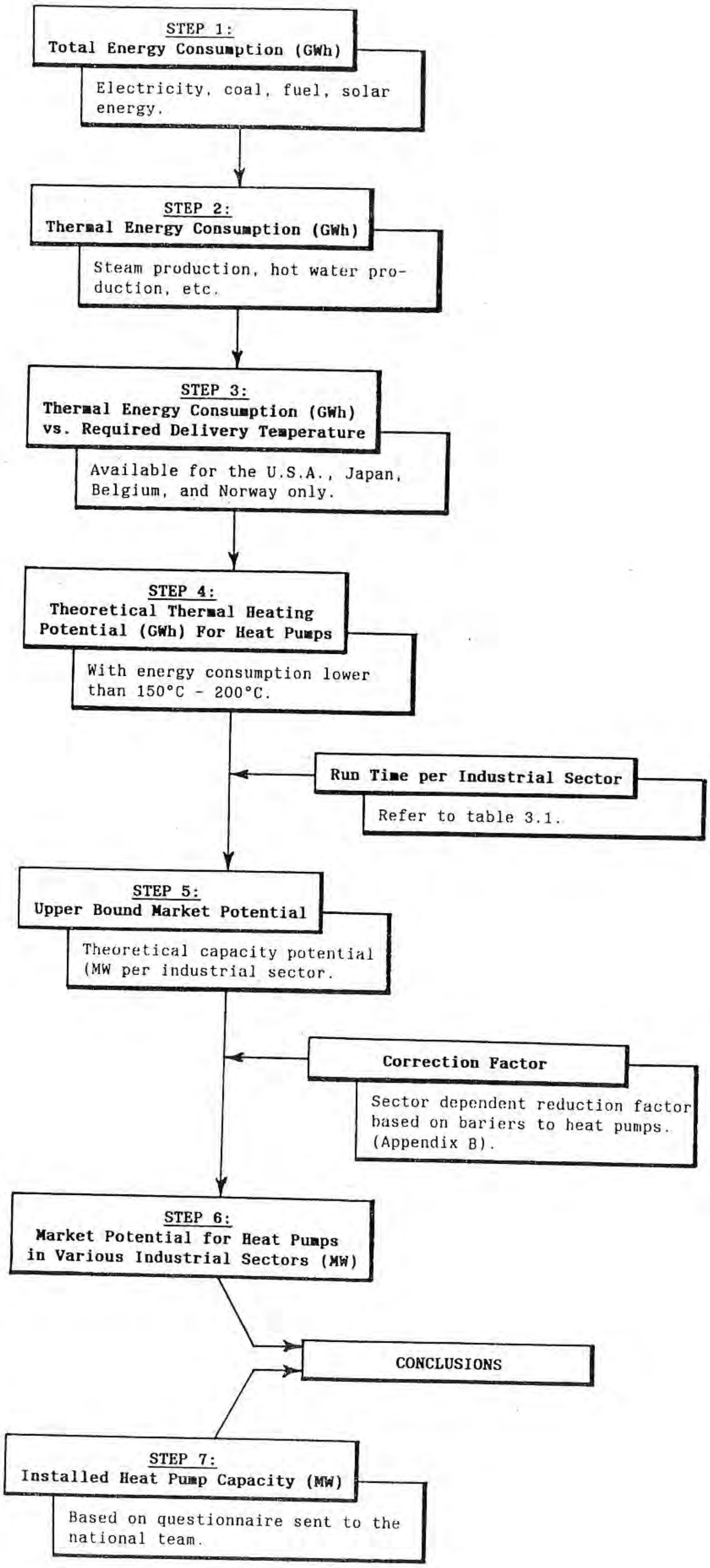

Figure 4.1 Market potential (MW) calculation method for heat pumps.

Data regarding average numbers of hours of yearly operation of processes in the different industrial sectors is then utilized to calculate the maximum heating capacity in the sectors. This constitutes an upper bound for the thermal capacity of all the heat pumps which can be installed (step five).

This market potential must then be compared with the data on installed capacity to determine present market penetration and to identify those sectors to which efforts to promote heat pumps should be directed in particular.

Table 4.1 [2] illustrates the different technical, economic, and institutional barriers to heat pumps one may encounter in relation to a particular industrial sector. When taking these barriers into account, only 10% to 20% of the theoretical heating potential for heat pumps can be reached. This gives a more realistic estimate for the market potential [4]. This correction factor is not precise for all sectors. However, it can be used to correct national figures.

Appendix B contains the percentages for the theoretical thermal energy consumption deliverable by means of heat pumps. These percentages are specified for numerous industrial sectors and vary between 0 and 44% [6]. The correction factors involved are based on detailed technical and economical information for large industrial plants in Sweden.

Reference [14] discusses the importance and benefits of process integration and correct placement of industrial heat pumps. In particular, industrial heat pumps must be placed across pinch temperatures. Inaccurate placement can markedly reduce potential savings. Likewise, it appears that about one-third of all potential applications are likely to be placed incorrectly.

Table 4.1 Barriers to heat pump application.

SECTOR \ BARRIER	TECHNICAL: Lack of Innovative Technology	TECHNICAL: Lack of Proven Technology	TECHNICAL: Lack of Industry R & D Funds	ECONOMIC: Not Cost Competitive	ECONOMIC: Shortage of Total Capital	ECONOMIC: Shortage of Discretionary Capital	INSTITUTIONAL/OTHER: Risk to Performance	INSTITUTIONAL/OTHER: Fuel Price Uncertainties Defer Investments	INSTITUTIONAL/OTHER: Low Asset Turnover	INSTITUTIONAL/OTHER: Low Energy Cost as a Percent of Sales	INSTITUTIONAL/OTHER: Supply Security More Critical Than Price	INSTITUTIONAL/OTHER: Environmental and Safety	INSTITUTIONAL/OTHER: End Market Behavior	INSTITUTIONAL/OTHER: Legal and Regulatory	INSTITUTIONAL/OTHER: Politically Unpopular
ELECTRIC UTILITIES	*	*		*	*	*	*	*				*		*	
INDUSTRIAL															
- Petroleum Refining	*	*				*				*					
- Paper	*	*	*		*	*	*	*	*		*				
- Steel	*	*	*		*	*	*	*	*	*	*				
- Chemicals	*	*				*				*	*				
- Glass	*	*	*		*	*	*	*	*		*				
- Textiles	*	*	*		*	*	*	*	*	*	*				
- Cement	*	*	*	*	*	*	*		*						
- Aluminum		*	*		*	*	*		*	*	*				
- Food Processing	*	*	*		*	*	*	*	*	*	*				
RESIDENTIAL	*	*		*	*	*							*		*
COMMERCIAL	*	*		*	*								*		*
TRANSPORTATION				*	*		*					*		*	*

4.2 MARKET POTENTIAL STUDY

The goal of this section is to calculate the market potential (MW) for heat pumps in various industrial sectors for 5 countries (U.S.A., Japan, Belgium, Netherlands, and Sweden), as well as to compare these values with the installed heat pump capacity (MW) obtained from the questionnaire sent to the national team. Figure 4.1 shows a representation of the calculation method used to determine the market potential (MW) for heat pumps.

4.2.1 The United States of America

Table 4.2 shows the thermal energy consumption (10^5 TJ) versus the required delivery temperature, as well as the theoretical capacity potential, or upper bound market potential, for 8 industrial sectors [1]. The market potential (MW) for heat pumps per industrial sector is derived through the use of the sector reduction factors and run time per sector also shown in table 4.2. It should be mentioned that the correction factors used in table 4.2 were based on the technical and economical barriers for heat pumps in Sweden.

As a total, the U.S. has a market potential of about 18.000 MW. This suggests that 16% of the theoretical thermal energy consumption or 3,27 10^5 TJ of 21,15 10^5 TJ can be provided by means of heat pumps. These figures coincide with the findings in reference [4].

4.2.2 Japan

According to a survey carried out by JRAIA [3] a high potential for industrial heat pumps is found in those sectors producing hot water or steam as illustrated in table 4.3. Table 4.4 shows the thermal energy consumption (GWh) versus the required delivery temperature, as well as the theoretical capacity potential, or upper bound market potential, for 8 industrial sectors. The market potential (MW) for heat pumps per industrial sector is derived through the use of the sector reduction factors and run time per sector as shown in table 4.4. The amounts shown in table 4.4 coincide with the findings in reference [2]. In particular, only 10 to 15% of the national thermal energy consumption is deliverable by means of heat pumps.

As a total Japan has a market potential for heat pumps of about 8800 MW. This suggests a theoretical capacity potential or upper bound market potential of 18%.

Table 4.2 Energy consumption in the U.S. [4]

SECTOR		SECTOR REDUCTION FACTOR	RUN TIME HOURS/YEAR	DELIVERY TEMPERATURE 60-100 °C	%	100-140 °C	%	140-180 °C	%
Food, Tobacco	a	19%	3000 - 5000	1,30	41,3	1,10	34,9	0,75	23,8
	b			7222-12037		6111-10185		4166-6944	
	c			1830		1550		1050	
Textiles	a	32%	3800	0,75	60	0,50	40	-	-
	b			5482		3650		-	
	c			1750		1170		-	
Furniture and Fixtures	a	29%	3000 - 5000	0,6	32,4	0,55	29,7	0,7	37,8
	b			3333-5555		3055-5092		3888-6481	
	c			1290		1180		1500	
Pulp, Paper	a	12%	8000	1,85	24,4	1,7	22,4	4,04	53,2
	b			6423		5902		14027	
	c			770		710		1680	
Chemicals	a	13%	8000	0,9	24,7	1,4	38,4	1,35	37
	b			3125		4861		4687	
	c			375		580		610	
Stone, Clay, Glass	a	12%	2500	0,125	19,4	0,17	26,4	0,35	54,3
	b			1390		1890		3888	
	c			170		230		470	
Fabricated Metal Products	a	3%	6000 - 8400	1,62	100	-	-	-	-
	b			7500-5357		-		-	
	c			190		-		-	
Petroleum	a	13%	8000	-	-	-	-	1,7	100
	b			-		-		5902	
	c			-		-		770	
TOTAL	a			7,15	33,3	5,42	25,3	8,89	41,4
	c			6375		5420		6080	

a) Thermal energy consumption (10^5 TJ) versus required delivery temperature. (Figure 4.1, step 3).
b) Theroretical capacity potential (MW). (Figure 4.1, step 5).
c) Average market potential (MW) for heat pumps. (Figure 4.1, step 6).

Table 4.3 Sectors with a high percentage of boiler heating in Japan [3].

SECTOR	TOTAL ENERGY CONSUMPTION (GWh)	BOILER HEATING	
		GWh	%
Food	66666	41944	63
Pulp, paper	122222	90000	73,7
Chemicals	243055	124722	51,4
Textiles	50000	30000	60
Publishing	17500	17500	100
Oil and coal	138888	34722	25
Rubber	17500	17500	100
Stone, clay, glass	173611	14166	8,3
Transportation equipment	86111	3333	4,25

Table 4.4 Market potential for the sectors with a high percentage of boiler heating in Japan.

SECTOR		SECTOR REDUCTION FACTOR	RUN TIME HOURS/YEAR	DELIVERY TEMPERATURE <100°C	%	100-150°C	%	150-183°C	%	>183°C	%
Food, Tobacco	a			1048		26166		6972		7812	
	b	19%	3000 - 5000	280	2,5	6970	62,3	1860	16,6	2080	18,6
	c			53		1330		350		400	
Textiles	a			121		15089		14791		-	
	b	32%	3800	32	0,4	3970	50,3	3890	49,3	-	0
	c			10		1270		1245		-	
Lumber, Wood	a			190		1628		1156		14534	
	b	4%	3000 - 8000	45	1,1	370	9,3	265	6,6	3330	83
	c			1,75		15		11		135	
Pulp, Paper	a			-		77376		3695		-	
	b	12%	8000	-	0	9670	5,9	460	4,1	-	0
	c			-		1160		55		-	
Chemicals	a			5996		33606		62467		23488	
	b	13%	8000	750	4,8	4200	26,9	7810	50,5	2940	18,8
	c			100		550		1015		380	
Rubber	a			-		4604		9346		3572	
	b	28%	3000 - 7000	-	0	1100	26,3	2230	53,4	850	20,4
	c			-		310		620		239	
Leather	a			-		2777		-		-	
	b	-	3000	-	0	-	100	-		-	0
	c			-		-		-		-	
Stone, Clay, Glass	a			-		12332		2076		-	
	b	12%	2500	-	0	4930	85,6	830	14,4	-	0
	c			-		530		100		-	

a) Thermal energy consumption (GWh) versus required delivery temperature. (Figure 4.1, step 3).
b) Theroretical capacity potential (MW). (Figure 4.1, step 5).
c) Average market potential (MW) for heat pumps. (Figure 4.1, step 6).

4.2.3 Belgium and the Netherlands

Table 4.5 [4] presents the total energy consumption (TJ), as well as the theoretical capacity potential (MW), or upper bound market potential, for 11 Belgian industrial sectors with heating demands of less than 100°C and 150°C respectively. As a total Belgium has a market potential for heat pumps of about 140 MW and 280 MW respectively. Similarly, this suggests that only 10 to 20% of the national thermal energy consumption is deliverable by means of heat pumps [2].

Table 4.6 [5] presents the theoretical energy consumption (GWh) and the theoretical capacity potential (MW), or upper bound market potential, for heat pumps in 13 industrial sectors in the Netherlands.

4.2.4 Sweden

In reference [6] a market potential for alternative energy techniques is presented for Sweden. Table 4.7 shows for 17 sectors total heat demand (or thermal energy consumption (GWh)), the heat demand substitutable by alternative energy techniques (GWh), and the market potential (MW) for heat pumps. For the 17 industrial sectors mentioned in table 4.7, Sweden can replace 12% of the thermal energy consumption through the use of heat pumps. As a total Sweden has a market potential for heat pumps of about 1750 MW.

Referring to figure 4.1 step 4, a method was developed to estimate the potential for alternative energy techniques in the above mentioned industrial sectors. First information concerning the number and capacity of the existing boilers used in industry was collected, and the total energy consumption (GWh) was computed. Secondly, a description of a typical heating plant for each of the 17 industrial sectors was made. A representative plant was chosen for each sector and the following information was collected from this plant: a detailed description of the heat demand (local heating, hot water production, distillation, drying, and evaporation); an estimation of capacity; run time; amount of heat for each purpose; and an estimation for the technical possibilities for alternative techniques. Size data was extrapolated for each sector. From the data collected the thermal energy consumption (GWh) was derived.

Table 4.5 Energy consumption for the Belgian industrial sectors [4].

SECTOR	TOTAL ENERGY CONSUMPTION (TJ)	% FOR INDUSTRIAL PROCESSES	HEATING DEMAND < 100°C (MW)	%	HEATING DEMAND < 150°C (MW)	%
Chemicals	39081	95,6	112	8,6	240	18,5
Iron, Steel	204929	97,9	181	2,4	209	2,7
Non-ferrous Metals	13268	96,7	88	17,8	94	19,0
Fabricated Metals, Metal Constructions	2565	71,5	29	28,6	31	31,0
Transportation equipment	35	21,2	0,4	78,8	0,4	79,3
Food, Beverages, Tobacco	15005	90,5	88	8,9	327	34,2
Textiles	6144	81,2	69	19,0	234	64,0
Rubber	570	81,4	3	10,1	9	33,3
Paper, Pulp	4160	92,5	26	19,7	82	61,4
Stone, Clay, Glass	24422	96,8	120	4,6	168	6,4
Paint Industry	528	51,9	4	48,2	4	48,2

Table 4.6 Energy consumption for the Netherlands industrial sectors [4].

for hps

SECTOR	TOTAL ENERGY CONSUMPTION (TJ)	THEORETICAL ENERGY CONSUMPTION (GWh)	THEORECTICAL CAPACITY POTENTIAL (MW)
Food, Tobacco	47790	10970	469
Dairy	18550	4633	94
Oil, Grease	6750	1741	40
Brewery	5550	1324	22
Textiles	10413	1814	48
Wood, Lumber	3500	891	21
Pulp, Paper	25300	6567	82
Graphical	6450	1611	64
Chemicals	549750	142750	9315
Rubber	8450	1511	37
Stone, Clay, Glass	39150	9845	3426
Iron, Steel	91500	24220	2734
Non-Ferrous Metals	25500	1985	236

Table 4.7 Energy consumption for the Swedish industrial sectors.

SECTOR	RUN TIME (Hour)	TOTAL HEAT DEMAND (GWh)	%	TOTAL SUBSTITUTABLE HEAT DEMAND (GWh)	%	HEAT PUMP MARKET POTENTIAL (MW)	%
Meat Products	2800-4000	529	88	277	52	30	18
Dairy	5000-6000	1167	87	923	79	82	38
Fruit, Vegetable	4000-6000	421	70	343	81	23	25
Oil, Grease	3000-8000	335	80	260	78	10	8
Brewery	3000-8000	359	80	288	80	20	24
Chocolate	2500-6000	206	85	149	72	8	12
Textiles	3800	620	88	494	80	52	32
Saw Mills	6000-8000	4076	78	129	3	3	0,4
Pressed Wood Plate	6000-8000	841	100	47	6	4,5	4
Paper, Pulp	8000	57586	100	6628	12	828	12
Chemicals	8000	6142	85	850	14	98	13
Graphical	5000	533	85	264	50	29	27
Fabricated Plastic	1500-7000	335	70	130	39	46	33
Rubber	3000-7000	519	85	365	70	35	28
Porcelain, Clay	2500	205	80	58	28	10	12
Iron, Steel	6000-8400	15921	90	1440	9	73	3
Workshop Industry	6000	7980	70	3850	48	383	29

An estimation of the market potential for some chosen alternative energy techniques was made. Three market potential scenarios were used (Table 4.8). Scenario one and two have an interchangeable boiler heating distribution system that is different than that of scenario three. Similarly, scenario one and three are based on variable energy prices whereas scenario two is based on constant energy prices. Likewise, it was assumed that the number of heat pump plants were increasing proportional in the industrial sectors. This growth was assumed to be 10 to 15% in the period 1980 to 2010 in all sectors except for the textile, porcelain, and pressed wood plate industries were growth was assumed to be 15%, 0%, and 0% respectively. More detailed information on these scenarios can be found in reference [15].

4.2.5 Norway

Table 4.9 shows the potential for heat pumps in the Norwegian industry based upon energy consumption data, making use of the correction factors from the Swedish Study (Appendix B).

4.2.6 Calculated Market Potential Comparison

In analysing tables 4.2 to 4.9 it is found that the paper and pulp, chemical and petroleum, textile, and food industries are some of the high potential sectors for industrial heat pump application. Table 4.10 reviews the market potential (MW) for these sectors for the U.S., Japan, Sweden, Belgium, the Netherlands, and Norway.

These sectors have a high potential for industrial heat pumps due to their great thermal energy potential and their relatively long run times. The paper and pulp industry is of particular interest due to its demand for drying and evaporation, as well as its run time of 8000 hours (table 3.1).

Other possible sectors for industrial heat pumps may be the iron and steel industries, as well as the dairy industries. Through the use of heat pumps Sweden and the Netherlands can generate 440 GWh and 510 GWh, respectively, in their dairies. Likewise, Sweden has a potential of approximately 415 MW installed heat pump capacity until the year 2010. The iron, steel, and chemical industries also appear to be likely candidates for heat pump application due to their relatively long run times (6000 - 8400 hours), as well as their high theoretical thermal

Table 4.8 Penetration of inudstrial heat pumps in Swedish industrial sectors. Installed capacity (MW).

SECTOR		PERIOD					
		1980/1985	1986/1990	1991/1995	1996/2000	2001/2005	2006/2010
Meat Products	a	3	5	12	11	10	7
	b	4	4	8	28	46	46
	c	3	7	10	15	18	13
Dairy	a	35	53	75	89	99	98
	b	35	52	74	89	100	100
	c	35	51	64	71	72	88
Fruit, Vegetable	a	–	–	20	24	24	24
	b	–	–	20	24	24	24
	c	8	8	13	17	14	14
Oil, Grease	a	–	–	–	–	–	–
	b	–	–	–	–	–	–
	c	1	1	1	1	1	1
Brewery	a	–	–	12	17	20	20
	b	–	–	12	17	20	20
	c	2	3	6	6	8	10
Chocolate	a	–	–	–	–	–	–
	b	–	–	–	–	–	–
	c	4	4	8	13	16	19
Textiles	a	–	5	17	18	17	12
	b	–	5	15	22	35	35
	c	7	13	18	17	11	17
Pressed Wood Plate	a	–	–	3	4	5	5
	b	–	–	3	4	5	5
	c	1	2	2	3	3	4

SECTOR		PERIOD					
		1980/1985	1986/1990	1991/1995	1996/2000	2001/2005	2006/2010
Pulp, Paper	a	199	369	559	702	910	949
	b	199	369	559	702	910	949
	c	270	510	750	900	980	1110
Chemicals	a	11	36	130	160	177	178
	b	11	36	128	158	175	177
	c	43	119	130	130	145	136
Graphical Industry	a	-	-	-	-	-	-
	b	-	-	-	-	-	-
	c	-	5	10	15	15	22
Fabricated Plastic Products	a	7	12	17	20	22	23
	b	7	13	17	20	23	23
	c	9	15	18	19	18	19
Rubber	a	6	12	20	29	37	38
	b	6	12	20	29	37	38
	c	10	17	23	26	27	27
Porcelain, Clay	a	-	-	-	-	-	-
	b	-	-	-	-	-	-
	c	-	-	-	-	-	3
Iron, Steel	a	7	27	59	89	113	113
	b	7	27	59	86	110	113
	c	11	22	33	39	34	54

a) Scenario One: Variable energy prices.
b) Scenario Two: Constant energy prices.
} Interchangeable boiler heating distribution is different than that for (c).

c) Scenario Three: Variable energy prices.

Table 4.9 Market potential for heat pumps in Norway

SECTOR		SECTOR REDUCTION FACTOR	RUN TIME HOURS/YEAR	DELIVERY TEMPERATURE			
				<100°C	%	100-200°C	%
Meat Products	a	18%	2800 - 4000	-	-	-	-
	b			-		-	
	c			-		-	
Fish Products	a	38%	3000 - 4000	-	-	-	-
	b			-		-	
	c			-		-	
Dairy	a	38%	5000 - 6000	-	-	-	-
	b			-		-	
	c			-		-	
Other Food Products	a	16%	4000	-	-	-	-
	b			-		-	
	c			-		-	
Wood Working	a	20%	6000 - 8000	1020	60	215	13
	b			146		31	
	c			29		6	
Pulp, Paper	a	12%	8000	196	2	6762	69
	b			25		845	
	c			3		101	
Other Forestry	a	12%	6000 - 8000	-	-	-	-
	b			-		-	
	c			-		-	
Graphical	a	27%	5000	119	32	-	-
	b			24		-	
	c			6		-	
Chemicals, Petroleum	a	13%	8000	256	4	181	3
	b			32		23	
	c			4		3	

Table 4.9 Market potential for heat pumps in Norway (-continued)

SECTOR		SECTOR REDUCTION FACTOR	RUN TIME HOURS/YEAR	DELIVERY TEMPERATURE			
				<100°C	%	100-200°C	%
Oil, Grease	a			-		-	
	b	10%	3000 - 8000	-	-	-	-
	c			-		-	
Plastic Products	a			-		-	
	b	33%	1500 - 7000	-	-	-	-
	c			-		-	
Rubber Products	a			-		-	
	b	26%	3000 - 7000	-	-	-	-
	c			-		-	
Textiles	a			147		187	
	b	32%	3800	39	27	49	35
	c			12		16	
Iron, Steel	a			25		-	
	b	3%	6000 - 8400	4	1	-	-
	c			0,1		-	
Aluminium	a			75		-	
	b	5%	6000 - 8400	10	1	-	-
	c			0,5		-	
Other Non-Ferrous Products	a			111		532	
	b	5%	6000 - 8400	15	4	74	20
	c			0,77		4	
Workshop Industry	a			1132		315	
	b	29%	6000	189	40	53	11
	c			55		15	

a) Thermal energy consumption (GWh) versus required delivery temperature. (Figure 4.1, step 3).
b) Theroretical capacity potential (MW). (Figure 4.1, step 5).
c) Average market potential (MW) for heat pumps. (Figure 4.1, step 6).

Table 4.10 Market potential (MW) for the most promising sectors of some IEA Heat Pump member countries. (Only heat pumps with temperatures lower than 150°C are considered).

SECTOR \ COUNTRY	USA (MW)	JAPAN (MW)	SWEDEN/2010 (MW)	BELGIUM (MW)	NETHERLANDS (MW)	NORWAY (MW)
Paper, Pulp	1480	1160	828/1110	13	10	102
Chemicals, Petroleum	955	650	98/136	31	375	201
Textiles	2920	1280	52/17	96	16	46
Food	3380	1358	173/144	62	78	271

energy consumption (tables 4.5, 4.6, and 4.7). In particular, a thermal energy consumption for iron and steel of 15920 GWH and a market potential of 401 MW heat pumps over the next 25 years is estimated for Sweden.

4.3 UPPER BOUND MARKET POTENTIAL (MW) FOR INDUSTRIAL HEAT PUMPS

Table 4.11 reviews the oil and gas consumption for the 13 industrial sectors shown in table 4.13 for 14 countries [7]. Only 10 to 20% of the theoretical thermal oil and gas consumption seems deliverable by means of industrial heat pumps. Taking 15% of the oil and gas consumption, table 4.12 shows a rough calculation for the upper bound installed heat pump capacity (MW) for the 13 industrial sectors shown in table 4.13.

Table 4.11 Oil and gas consumption (TJ) per industrial sector in 14 countries.

COUNTRY	SECTOR CODE												
	A	B	C	D	E	F	G	H	I	J	K	L	M
Austria	16328	56521	42705	1256	12979	2093	2930	4605	11304	14653	2093	2512	4605
Belgium	31401	148631	96296	7955	24283	3349	7536	837	23864	7117	-	7117	5024
Canada	65314	490692	378905	32657	28051	2930	837	132302	15072	147794	13816	34750	5024
Denmark	2930	7117	-	-	13397	1674	7954	418	20096	2930	1256	5861	2512
Finland	16328	33913	23027	1674	10048	2093	5442	3349	15072	31819	3768	6698	2093
France	49822	571498	325733	48985	86248	12141	75781	7954	100064	47310	2093	81223	26376
Germany	119323	725991	521675	31401	134815	57777	108856	16747	109275	60289	10885	-	46892
Italy	84573	427053	236972	7117	206827	-	82898	837	56521	41449	-	-	43961
Japan	95459	1085637	879228	21771	65314	-	-	4605	98808	40612	-	166634	110531
Netherlands	15491	471852	265443	3768	26376	5442	18003	418	51079	14653	1675	12979	5442
Norway	1256	55684	49404	4605	5861	1256	2093	2930	10048	3349	1674	18003	418
Sweden	15072	34750	24283	2930	10048	4186	11723	4186	12979	28051	3349	-	3349
Switzerland	0	19678	4605	1256	2512	-	11304	3768	5861	6698	-	2093	4605
U.K.	72013	456779	227761	20515	77874	43542	93784	15072	100064	45217	5442	33494	32238

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Table 4.12 Upper bound market potential (MW) of installed capacity per industrial sector.

COUNTRY	SECTOR CODE												
	A	B	C	D	E	F	G	H	I	J	K	L	M
Austria	98	294	222	8	219	22	32	32	119	77	13	26	57
Belgium	187	774	502	47	33	3	84	6	249	38	-	74	2
Canada	389	2556	1974	195	473	32	10	920	158	770	84	362	62
Denmark	17	38	-	0	227	17	89	3	209	15	8	62	32
Finland	98	177	120	10	170	23	61	23	158	166	23	70	26
France	297	2977	1697	292	1454	127	842	56	1043	247	13	846	328
Germany	710	3782	2717	187	2274	602	1210	116	1139	314	66	-	583
Italy	504	2225	1235	42	3488	-	921	6	589	216	-	-	546
Japan	568	5654	4580	130	1102	-	-	32	1029	212	-	1736	1374
Netherlands	92	2458	1382	23	445	57	200	3	533	77	11	135	68
Norway	8	290	257	27	99	13	23	20	105	17	10	188	5
Sweden	20	181	126	17	170	44	130	29	135	146	20	-	42
Switzerland	-	102	24	8	42	-	126	26	61	35	-	22	57
U.K.	429	2352	1186	122	1313	454	1042	105	1042	236	33	349	401

Table 4.13 Coding of industrial sectors.

INDUSTRIAL SECTOR	SECTOR CODE
Iron and steel	A
Chemical	B
Chemical: Foodstocks	C
Non-ferrous Metals	D
Non-metallic Minerals	E
Transportation Equipment	F
Machinery	G
Mining and Quarrying	H
Food and Tobacco	I
Paper, Pulp, and Printing	J
Lumbar and Wood Products	K
Construction	L
Textile and Leather	M

5. CONCLUSIONS

It can be concluded that the market potential for heat pumps depends very much on the country and the industrial sector considered. Presently, economic conditions are not favorable for heat pumps in most IEA countries. On the average the potential for heat recovery of industrial heat pumps is found to be about 15% of industrial heat consumption.

Based upon the cost of electricity, Norway and Canada offer the best prospects for electrically driven heat pumps. Irrespective of the local cost of electricity, heat pump applications are most suited to low temperature processes of large annual run times such as:

* drying recovery for production of boiler feed water, washing, pasteurization, fish culture, etc. and,
* simultaneous heating and cooling in chemical and other processes.

It is to these processes and industrial sectors that efforts to promote heat pumps should be directed.

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APPENDIX A

Fachinformations-
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IEA heat pump center

FIZ Energie, Physik, Mathematik GmbH · D-7514 Eggenstein-Leopoldshafen 2 FRG

Tel. no. 0 7247 82- 4541
Our ref.
Date

Re: **Industrial Heat Pumps**

Dear

Part of the project "Industrial Heat Pump" is undertaken by the Belgian National Team. For their work they need, among others, basic information about industrial heat pump plants in operation. They have therefore prepared the enclosed questionnaires, which we ask you to return to the Heat Pump Center **latest 7th September 1987.**

Questionnaire 1: collects the number of installed heat pumps in the different types of industries, specified by:
- year of installation
- installed capacity
- type of heat pump

Questionnaire 2: collects more detailed information concerning plants and processes:
- specific industrial processes
- year of installation
- plant address

To simplify the work, please use the enumeration of industries and industrial processes enclosed.

We are looking forward to receiving your information.

Sincerely

IEA HEAT PUMP CENTER

cc: STC-member

Sitz der Gesellschaft
Karlsruhe
Vorsitzender des
Aufsichtsrats:
MinDirig Dr. Hans Dohr
Geschäftsführer:
Dr. Werner Rittberger
Ernst-Otto Schulze
Deutsche Bank,
Karlsruhe
(BLZ 660 700 04)
Konto-Nr. 01637 66
Handelsregister:
Amtsgericht Karlsruhe
HRB 1892

Questionnaire 1																		
Industry or Industrial Process (see enclosed list)	Year of Installation						Installed Capacity (MW)						Type of Heat Pump					
	Before 1980	'80-'81	'82-'83	'84-'85	'85-'86	'87	<0,1	0,1-0,5	0,5-1	1-5	5-10	>10	AHP(1)	AHP(2)	CCHP	OCHP	CHP	INJ

List of abbreviations:

AHP(I) : absorption heat pump type 1
AHP(II): absorption heat pump type 2(heat transformer).
CCHP : closed cycle compression heat pump.
OCHP : open cycle compression heat pump.
CHP : chemical heat pump.
INJ : steam ejector.

Questionnaire 2			
Industry or Industrial Process (see enclosed list)	Year of Installation	Capacity (MW)	Plant Address

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Enclosed List of Industries and Industrial Processes

Industry (products)	Nr.	Process
Chemicals and Petroleum	1	Fuel Alcohol by Fermentation
		Potash
		Salt
		Sugar
		Sulfuric Acid and Sulfates
		Caustic Soda
		Enhanced Oil Well Water Recovery
		Water Desalination
		Waste Water Concentration
		Solvent Recovery for Paints
		Cationic Resin Manufacture
		Heavy Metals Processes
		Ceramics
		Specialty Chemicals
		Phosphoric Acid
		Urea Process
		Ammonuim Nitrate Process
		Others
Dairy	2	Cheese-Whey Powder Process
		Skim Milk Powder Process
		Others
Pulp and Paper	3	Kraft Black Liqour Pulping
		Thermo-mechanical Pulping
		Chemi-thermo-mechanical Pulping
		Magnified Pulping
		Soda Pulping
		Sulfite Pulping
		Others
Textiles	4	Nylon Process
		Polyester Process
		Solvent Recovery from Latex
		Dying
		Finishing
		Caustic Recovery
		Others
Lumber and Wood Products	5	
Fabricated Rubber Products	6	
Fabricated Metal Products	7	
Machinery, Except electrical	8	
Electrical Equipment & Supplies	9	

Industry (products)	Nr.	Process
Transportation Equipment	10	
Stone, Clay, Glass	11	
Leather	12	
Graphical	13	
Fabricated Plastic Products	14	
Brewery	15	
Meat Products	16	
Grain Mill Products	17	
Bakery Products	18	
Sugar	19	
Beverages	20	
Fruit, Vegetable Products	21	
Others		

APPENDIX B

Reduction factors for heat pump application as found to be valid in different sectors in the Swedish industry.

Nr.	Sector	%
1	Chemicals and Petroleum	13
2	Dairy	38
3	Pulp, Paper	12
4	Textile	32
6	Fabricated Rubber Products	28
11	Porcelain, Clay	12
13	Graphical	27
14	Fabricated Plastic Products	33
15	Brewery	24
16	Meat Products	18
18	Bakery Industry	7
21	Fruit, Vegetable	25
26	Oil, Grease	10
29	Iron, Steel	3
33	Sawing - Milling	0.4
34	Chocolate	12
35	Pressed Wood Plate Industry	4
	Cement Industry	44
	Cast Iron	5
	Workshop Industry	29

APPENDIX C

RESEARCH & DEVELOPMENT WORK - INDUSTRIAL HEAT PUMPS

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TABLE OF CONTENTS

I. INTRODUCTION

This report is intended to give an overview of research and development work in the area of industrial heat pumps. A literature search concerning this topic has been made in the past by the IEA Heat Pump Center in which all the work which has been done in the last 20 years is identified. In this report an overview of present ongoing work in the area of industrial heat pumps is given in which attention is limited to more recent publications.

II. COMPRESSION HEAT PUMPS

2.1 WORKING FLUIDS

2.1.1 Pure Fluids

Current research and development effort in the area of compression heat pumps is directed mainly at the development of working fluids which enable the heat pump to reach higher temperature levels and higher COP's. In particular, most of the heat pump research involved is related to new working fluids or mixtures with a special emphasis on non-azeotropic mixtures.

From a thermodynamic point of view many of the known refrigerants can be used in high temperature heat pumps. R11, R12B1, R21, R113, R114, R114a, R114B2, R133a, R216, trifluoroethanol-water mixtures, fluorinol FL50, and fluorinol 85, are acceptable when a restriction of a maximum pressure of 20 bar at condensing temperature of 100°C is considered. For higher temperatures, fluorocarbons of the perfluorotype may be advantageous as well as, of course, water [28].

Today's heat sink temperatures, accomplished through the use of freon R114 and R12, are approximately 110°C and 70°C, respectively. Halogenated hydro-carbons, such as R114, are suitable for operating temperatures up to about 120°C and could allow for the production of low pressure steam. However, a sufficient, high temperature level is needed for the steam generated from these heat pumps to be used as process steam. Heat pumps using halogenated hydro-carbons, such as R114, produce an insufficient, high temperature level such that the steam produced would have to be combined with a steam compressor in order to be useful. The search for new high temperature refrigerants up to 200°C, (such as fluorocarbons, fluoro-alcohols or perfluoro-alcohols), is still continuing [15]. R142b can be used as an alternative refrigerant to R114 due to the fact that R144 needs superheating before compression to avoid slugging and requires large size compressors due to its low density. However, this fluid is only applicable for the production of hot water (95°C – 100°C). Blaise and Dutto [4] found that the stability of R142b in the presence of oil and metals is the same as that of R114. However, the heat production is highly superior to the one of R114 which allows for an important reduction in compressor size. In addition, R142b does not need to be superheated before compression seeing that the isentropic curves remain in the vapor domain during compression. The experimental COP of the tested installation was closed to 65% of the Carnot COP. This means COP = 4.03 for a T_c of 100°C and a temperature lift of 60°C.

R133a is considered as an alternative working fluid to R114 due to the superheating requirement of refrigerant R114 [1]. R133a has a higher density than R114. However, refrigerant R133a is costly and toxicity problems may need to be resolved.

Takeshi Yoshii [31] developed an advanced vapor compression heat pump. The aim was to double the COP and to attain higher output temperatures of 150°C to 300°C. Pure working fluids, as well as mixtures, were a part of the project.

Kubo and Sakuma [18], also from Japan, attempted to increase the utilization temperature of an electrically driven screw compressor heat pump with a condensation temperature of 135°C. Normal pentane was selected as the best fluid, in a study on the different types of freon and hydrocarbon refrigerants which included tests in thermal stability, costs, durability tests (sealed tube test), safety, COP, and pressure required compressor capacity. However, pentane is flammable which limits it's applicability.

During the development and design of an electric heat pump for the generation of process steam (5.4 bar, 11°C superheat) Moreland and Wolfe [21] selected methanol as a working fluid. In their study only 100 of 1000 compounds considered passed the requirements of: $T_c >$ 205°C, and $T_b <$ 105°C. Out of these 100 compounds only four passed eight additional requirements: methanol, thiophene, n-hexane, and Fluorinol 85. Methanol was chosen on the basis of associated equipment cost, assuming that chemical stability and compatibility with materials used in the heat pump are acceptable. Special techniques were used to quantitatively measure the thermal stability of methanol. Minor amounts of dimethylether and water were detected as products of decomposition but were not expected to give problems in the heat pumps. This high temperature heat pump has a pay-back period of 1.3 years and the source exit temperature must be at least 70°C in order to avoid problematic low pressures in the evaporator.

At the Nagasaki Institute of Applied Science in Japan [15], the development of a reciprocating steam heat pump with a turbo supercharger delivering an output of up to 300°C is undertaken. The refrigerant used is H_2O (R718) and the expected value of the COP is 3 with a temperature rise of 150°C [15].

Similarly, in a report from the IEA [14], a project in which a high temperature heat pump (approximately 150°C) is described. Water is also used here as a working fluid, and various operation paramters that influence the performance of the heat pump are investigated.

A comparison of the COP of heat pumps working with water and fluorinated hydrocarbons is made by Tolle [28]. Tolle proposes that moist steam be compressed to avoid high temperatures at the end of compression.

2.1.2 Mixtures

It is known that non-azeotropic fluid mixtures can enhance the COP and/or thermal capacity in compression heat pumps. However, little data is available concerning non-azeotropic mixtures of refrigerants in high temperature heat pumps.

The main parameters that may be influenced by the use of mixtures, in addition to the COP, are; heating capacity, compressor discharge temperature, higher temperature gradients in the heat sink and the heat source, pressure levels in the condenser and evaporator, and heating capacity control [3, 17, 22, 24].

Mixtures capable of increasing both the heating capacity and COP will probably in the future be competitive with the pure working fluids used today [3, 22]. Without decreasing the COP, higher temperature gradients in the heat sink and heat source are allowed. This results in a somewhat reduced cost of the heat exchangers.

It is possible to vary the thermal and mechanical powers by varying the composition of the mixtures. With the same heat pump working at the same temperature conditions (80°C) the thermal output can vary from 1 to 2 with the same value of COP (3.5). Blaise and Dutto found that leakages had no influence on the composition of the non-azeotropic mixtures [4].

Struck [26] examined low-cost screw compressors for refrigerant R12 and R114 and their mixtures. He considered condensing temperatures up to 90°C. Kruse [16] tried to increase the application field of diesel-engine driven heat pumps for condensing temperatures up to 90°C through the use of a screw compressor and the refrigerant mixture R12/R114.

The Commission of the European Community has taken into its four year Non-nuclear Energy Research and Development Programme the development of an industrial heat pump which can produce heat up to 300°C. This includes investigations of fluid mixtures for high temperatures. Up to now no data is available concerning the research and development projects.

In the field of non-azeotropic mixtures the following large projects are being conducted:

1. *Measurements of cycle performance are being carried out in a laboratory test plant.*
   Technical University of Denmark.
2. *A methodical search for more optimal mixtures.*
   Professor Moser, Graz University (Austria).
3. *Insight into the problems related to lubricants in contact with mixtures.*
   Professor Kruse, University of Hanover.
4. *Performance of evaporator heat transfer measurements and collection of PVT-data for mixtures [3].*
   Professors Berntsson and Gron, Chalmers University of Technology.
5. *Expansion valves and heat transfer problems of evaporators.*
   National Bureau of Standards, USA.
6. *Measurement of heat transfer on condensers.*
   Professor Stoecker, University of Illinois, U.S.A..

2.2 COMPRESSORS

Only a few research projects are related to the topic of compressors. Likewise, little information is known about this subject seeing that most of this work is done by compressor manufactures. However, it should be pointed out that in the Super Heat Pump Project in Japan [15] a high speed screw compressor is developed with bi-directional gas flow. This compressor uses R12 as a working fluid and can achieve temperature lifts of 100°C with a COP of 3. In the C.E.C. research program on energy conservation only two projects are undertaken concerning compressors.

III. SORPTION SYSTEMS

3.1 WORKING PAIRS

The choice of solute-solvent working pairs to be used in the heat pump is crucial to its energetic performance, the size of its components, and thus its economic success. For these reasons many extensive studies on suitable working pairs have been made. Thermodynamic as well as thermal properties of solute and solvent and their solution have to be available in order to calculate the performance of the heat pump and the size of the components. Berghmans [2] aimed to develop an industrial heat pump which can recuperate waste heat at temperature levels from 90°C to 120°C and which can pump this heat up over a 30°C temperature increase. The temperature of the driving heat should be in the neighborhood of 200°C. The chosen working pair in this study was TFE/quinoline.

Higher condenser- and absorber temperatures can also be achieved by a two-stage heat pump cycle [11]. Two-stage heat pumps are more complicated to realize and to design. They are definitely more expensive and would be difficult to justify economically. Girsberger [11] investigated the use of different high temperature working pairs in a two-stage absorption heat pump. In the first stage NH_3/H_2O was used. The second stage working pairs were considered in detail. The result was that the best working pair is hexafluorisopropanol in quinoline.

Energy Concepts Company [7] was contracted by the Oak Ridge National Laboratory to develop a working pair capable to work at higher operating temperatures and higher temperature lifts than LiBr. As a result they found a ternary absorption working pair of $LiNO_3$, K NO_3 and $NaNO_3$ in H_2O, stable above 260°C. In those cases where high temperature lifts and high temperature working conditions are required this ternary mixture shows a number of advantages.

For binary systems, the two most used working pairs are $LiBr/H_2O$ and H_2O/NH_3. Both have their limitations, the corrosiveness of $LiBr/H_2O$ in connection with O_2 limits its application to 180°C.

NH_3 is poisonous and generates high pressures even with low temperatures. The high pressure limits the output temperature to 90°C. The conclusion is that for high temperature applications only $H_2O/LiBr$ can be used, but also here there are a lot of disadvantages. Looking for better stability, pressure and corrosion properties, the working

pair H_2O/zeolite is found to be stable up to 180°C [29]. It also gives a large temperature lift high COP, high solubility, high temperature at normal pressure and it is not corrosive [29]. This working pair can only be used in discontinuous absorption heat pumps.
E181/Trifluorethanol is also stable up to 230°C. The disadvantages of this pair are high viscosity and a low heat of evaporation.

With the working pair NaOH/H_2O temperatures above 250°C can be realized by NaOH is very corrosive in this temperature range [23]. This working fluid is under investigation in Japan and is not applicable for temperatures below 80°C due to the low pressures occurring in this temperature range.

3.2 HEAT PUMPS

The following lists some recent investigations that are carried out in Europe and in the U.S.A. [32].

3.2.1 West Germany

a) *University of Essen*

- * Investigation of promising fluid pairs. Special attention is paid to heat and mass transfer problems, compatibility with materials and stability (especially decomposition of the fluid pairs in the generator).
- * Studies on different combinations of heat transformers and absorption heat pumps. The most promising system will be built (100 kW).

b) *University of Munich*

- * Studies on different combinations of heat transformers (low temperature range) and absorption heat pumps (high temperature range) using LiBr/H_2O.
- * A study on a discontinuous heat pump for heating and cooling at the same time, using water/zeolites. A heat input higher than 200°C is possible and a temperature rise of about 100°C is possible in one stage. A heat pump with a 10kW heat storage is tested during two years.

c) *Battelle*

- * Two stage LiBr/H_2O absorption heat pump producing 100 kW of heat at 130°C from waste heat at 105°C [20, 32].

* A two stage AHP was developed after selection between different heating systems. The following gives a review of the technical data:

  working pair: H_2O/LiBr
  desorber temperature: 155°C
  evaporator temperature: 50°C
  useful achieved temperature level: 110 - 115°C
  COP: 1.35
  heating capacity: 10 MW
  investment cost: DM 2 million
  operating hours: 8000 hours/year

The effect of different energy prices on the payback period for different countries was investigated. A payback time of less than 3 years is possible in Germany, [9].

3.2.2 Netherlands

a) *Duintjer*

* Development of a cheap plate fin heat exchanger with improved performance.

3.2.3 Italy and France

a) *CNR (Italy) and CNRS, UTC, CETIAT, and BLM (France).*

* Research on solid gas combinations used in periodical operating AHP up to a temperature level of 250°C (zeolite/water and active coal/methanol).
* Development of suitable heat exchangers and reactors.

3.2.4 Denmark

a) *Technical University of Denmark*

* Investigation on NH_3 (refrigerant) in combination with different metal halides (absorbents).
* Design of a quasi continuous AHP to circumvent the disadvantages of periodic operation of a solid AHP. The prototypes include:

  i) Air/air heat pump for energy recovery in a drying process.

ii) A 2.3 kW two-stage heat transformer which produces heat at 300°C.

3.2.5 France

a) *ING*

* Investigation of NH_3 (refrigerant) in combination with graphite containing metallic salts which may have a better performance than metal halides and NH_3.

b) *Gaz de France and Creusot-Loire*

* Investigations on a 100 kW prototype industrial high temperature absorption heat pump, [6].
* Tests were carried out at evaporating temperatures of 55°C - 65°C and useful temperatures of 120°C - 130°C with a COP between 1.20 and 1.56. This experimental plant is a representative design of the real absorption heat pump which would be installed in a paper mill dryer.

3.2.6 Belgium

a) *Katholieke Universiteit Leuven* [2]

* A single stage absorption heat pump is developed which is able to upgrade industrial waste heat above 120°C. From a literature review trifluorethanol and quinoline is chosen. A computer model is developed incorporating the latest heat transfer augmentation techniques. Based on heat and mass transfer models applied to the different components the results show a reduction of the heat exchanger areas of 30%.
* From the practical side TFE and quinoline have very good properties compared to H_2O/LiBr (high COP and no crystallization problems).

3.2.7 U.S.A.

a) *Oak Ridge National Laboratory*

* An absorption heat pump design has been made for upgrading industrial waste heat from 60°C to 120°C [13]. The first step was the construction of a laboratory scale system. A reduced power prototype was built and

successfully operated to demonstrate the possibility of using relatively low waste heat temperatures to produce industrial process steam. The prototype single-stage system, using H_2O/LiBr as working pair, was successfully operated and demonstrated close agreement with the computer model.

b) *Energy Concept Company*

* The objective of the project carried out was to locate a retrofit site and bring one of the first absorption heat pumps in use for directly recycling distillation reject heat [8]. The process uses overhead vapor condensing heat upgraded by an absorption heat pump which reboils the fractional distillation column. The first step was to find a suitable application for the AHP augmented distillation column prototype. A preliminary design and a cost estimation was prepared. The second step was the assembly of the prototype. Its performance was monitored for 56 months. Afterwards several candidate sites were identified and preliminary designs and cost estimates have been prepared.

3.3 TRANSFORMERS

Most part of the research on heat transformers concerns:

* expanding the operating temperature range (high output temperature and high temperature lift),
* improving the performance (energy efficiency), and
* matching source and sink for total system optimization.

GEA (Germany) has started a development project featuring the development of advanced heat transformers utilizing new working pairs and multistage cycles. The obtained results at GEA are very promising. Further investigations will be made under the E.C.C. Research and Development program and in cooperation with French companies under the EUREKA-project [12].

A research team of Essen University undertook the task of finding new working fluids for absorption plants. Although the research program concerns new working pairs for absorption heat pumps mainly, some of the working fluids are also suitable for use in heat transformers. Under the project some 150 different working fluids were investigated with respect to vapor pressure, density, viscosity, solubility, thermal stability, phase coincidence, enthalpy of mixture and specific thermal capacity. The thermodynamic properties of the working pairs PFPA-DTG and HFIP-NMP make them seem especially suitable for being used in heat transformers.

Another pair suitable for high temperatures is $NAOH/H_2O$. Temperatures of 250°C can be realized. Research on this topic is done by a Japanese university. It is not suitable for temperatures lower than 80°C due to the low pressures [12].

At Chalmers University of Technology in Sweden, research is done on a laboratory-sized regenerator. This regenerator works according to the falling film principle. The advantages with this type are:

* high heat and mass transfer coefficients,
* possibilities to have countercurrent flow in the regenerator which is important if low temperature waste heat is to be used [7, 11, 12].

3.4 CHEMICAL HEAT PUMPS

The development of chemical heat pumps for the medium/high temperature range is in a very early stage. However, present results yield an indication of the anticipated problem areas. Problems, for instance, occur due to differences in reaction rates for the desorption and the absorption steps. Heat and mass transfer problems are likely to be of paramount importance in the development of dissociation reaction systems. Methods to minimize the pressure drop and the concentration gradient inside the solid material have to be studied. Also poor heat transfer properties of solids create considerable difficulties. Other points of importance are: the occurance of side reactions, possible sagging or swelling of the solids, corrosion and costs. References [10, 19, 25] and [27] give a good overview of the research and development work in the field of chemical heat pumps.

Refrigeration systems which use the technique of adsorption and desorption of gases in solids, without chemical reactions taking place, have been studied since the days of Faraday. With respect to application in heat pumps, the couple zeolite-water has been studied most frequently. A zeolite-water couple allows temperature lifts up to

70°C to be attained. This high temperature lift obviously represents an important advantage of this couple which in principle can be used to operate up to a temperature of 300°C. At low temperatures the system pressure may be very low, posing special requirements on the air tightness of the systems in which it is used. Although, it is found that ammonia can replace water in the low temperature range. Active coal as a replacement of zeolite has been investigated extensively. Active coal can be used with methanol up to -10°C and with ammonia up to -30°C. To be complete, one should mention that the combination of active carbon or zeolite with organic refrigerant alcohols have also been investigated, however, without much success.

Adsorption systems are presently commercialized, however, only for solar refrigeration applications. Research and development work is ongoing in the field of heat pumps in Europe, the U.S., and Japan [10, 27]. The main topics of research are still concerned with cycles and fluid pairs, although more and more attention is being given to heat and mass transfer in the absorbers. Special problems occur when refrigerants are used which give low pressures in the evaporator. Hydrostatic pressure differences may then become important when one choses to operate without refrigerant circulation pumps. This in turn requires special evaporator designs.

A considerable amount of research and development work is going on with respect to heat pumps which operate based upon reversible chemical reactions. Most of this work is related to the study of gas-solid reactions. Hydrogen-hydrate, ammonia-chlorinated salts, methanol-salts and water-hydrated salt systems are investigated. Also gas-liquid interactions are studied in which the gas is hydrogen or ammonia. The result of this work is still preliminary in nature. At best reduced scale prototypes of chemical heat pumps are analyzed. However, some of the pairs studied offer very interesting prospects with an operating temperature up to 400°C and one stage temperature lifts of 70°C.

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