Industrial Heat Pumps

Experiences, Potential and Global Environmental Benefits

Annex 21

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Foreword

Mitigating pollutant emissions associated with fossil fuel combustion is becoming an important worldwide priority. The importance of this activity derives from the contribution of fuel combustion to acid rain (e.g., SO_x, NO_x) and from the possibility that fossil fuel combustion may contribute to global warming (e.g., CO_2, CH_4).

Because it is one of the largest consumers of fossil fuels, the industrial sector represents a logical area of focus for reducing fuel consumption and combustion-based emissions. A cost-effective strategy to reduce fuel consumption in this sector is to recover process waste heat, thereby reducing primary energy requirements.

Industrial heat pumps are recognized as a possible option for waste heat utilization; however, their use to date has been far below their true technical and economic potential. This low rate of use partly results from the lack of information on and industrial experience with heat pump technology; it also results from the misperceptions of the technology based on many early, poorly designed installations.

This report provides industrial companies with additional information on heat pump technology to facilitate wider use. A major emphasis is placed on the need to properly integrate heat pumps within the overall process and to provide the tools to aid in heat pump evaluations.

We believe that this report provides valuable information on industrial heat pump technology and its potential application within industrial processes worldwide. The analyses conducted clearly show the energy savings and environmental benefits that can be achieved with industrial heat pumps. The magnitude of these benefits highlights the importance of continued efforts aimed at the wider-scale deployment of heat pumps in industry and at continued technology development, which would expand their range of application for the industrial sector.

U.S. Department of Energy
Washington, DC
RCG/Hagler Bailly, Inc.
Arlington, VA, April 1995

IEA Heat Pump Centre

The IEA Heat Pump Centre is the focal point for the heat pump related activities of the International Energy Agency (IEA).

International Energy Agency

The IEA was established in 1974 within the framework of the Organisation for Economic Cooperation and Development (OECD) to implement an International Energy Programme. A basic aim of the IEA is to foster cooperation among its 24 participating countries to increase energy security through energy conservation, utilization of alternative energy sources, and research and development on energy technologies.

IEA Heat Pump Programme

Set up by the IEA in 1978, the IEA Heat Pump Programme carries out a strategy to accelerate the development of heat pumps, and to stimulate their use in all applications where they can reduce energy consumption for the benefit of the environment. Under this programme, participants fro different countries collaborate in specific heat pump projects known as Annexes.

IEA Heat Pump Centre

A central role within the programme is played by the IEA Heat Pump Centre (HPC), itself an Annex. Using the network of its National Teams, along with links with other organizations, the HPC works towards the aims of the programme by providing a worldwide information exchange service. The functions of the HPC include:

- Collecting, analysing and disseminating heat pump related technical, market, regulatory, and environmental information.

- Fostering international cooperation in research and development.

- Facilitating contacts and information exchange among heat pump policy makers in governments and utilities, and those involved in research, development, design, manufacture, regulation, marketing, and application of heat pumps.

The HPC publishes the quarterly journal *'IEA Heat Pump Centre Newsletter'*, organizes *workshops*, provides an *enquiry service*, and conducts *analysis studies* on selected heat pump topics.

For further information about the HPC and its products, and for enquiries on heat pump issues in general, contact the HPC at the following address:

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The authors would like to thank the staff of the IEA HPC for their valuable help in organizing the expert working meetings around which the execution of Annex 21 was based and for their assistance in production of this report.

Thanks are also due to the National Teams for providing guidance to structure the Annex, guiding the development of the Annex's outputs, for providing detailed topical studies on the use of industrial heat pumps in their respective countries, and for comments on the content of the report.

Chalmers Industriteknik Energiteknisk Analys,
RCG/Hagler Bailly, Inc.

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Executive Summary

Industrial heat pumps (IHPs) can provide a number of process-related benefits, including:

- reduced energy consumption for process heating;
- increased capacity of existing process heating systems;
- improved plant-wide environmental performance;
- expanded production capacity through debottlenecking;
- improved product quality.

Despite these potential benefits, the number of IHPs installed to date is relatively low compared to the number of existing technically and economically viable opportunities. IHPs have been implemented on a wide scale in only a few industrial processes, such as lumber drying and some food, chemical, and pulp and paper industry evaporation and distillation processes.

Several reasons have been identified that have contributed to the level of IHP use thus far:

- lack of knowledge on the potential processing benefits of IHPs;
- lack of experience or familiarity with IHP technology;
- lack of combined process and heat pump technology experience or knowledge.

The last factor is particularly important because some early IHP installations were poorly designed and have created some negative perceptions about the technology and its potential use and benefits. In addition, combined process and heat pump knowledge is necessary to identify potential IHP opportunities that are properly integrated within a process and that take into account other potential energy conservation opportunities, such as heat exchanger network optimization.

To illustrate the potential energy saving and environmental benefits of IHPs, and provide industry with more information on how to properly identify potential IHP opportunities, eight countries jointly sponsored and undertook Annex 21 work. The specific objectives of the Annex were to:

- increase awareness of the energy savings potential associated with heat pumping;
- expand the information base available to help identify IHP applications;
- illustrate current and potential future IHP applications;
- estimate the potential global environmental benefits of IHPs.

Annex 21 was conducted in two parts: a cost-shared effort and a task-shared effort.

Cost-Shared Program

The cost-shared work focused on developing a computer program to assist industry in screening, at least on a preliminary basis, the technical and economic suitability of IHPs to various industrial process applications. The IHP screening program developed for Annex 21 is based on the general theories of pinch technology. Therefore, it aims to identify IHP opportunities that are consistent with fully optimized plant heat exchange systems to provide the most economic IHP designs and the lowest possible plant-wide energy consumption.

The screening program contains data on more than 100 industrial processes in five main industries: food, chemicals, petroleum refining, pulp and paper, and textiles. These data can be used directly, or modified by the user as needed, to assess site-specific IHP opportunities.

The computer program also contains data on more than 50 types of IHPs, divided into five main categories:

- closed-cycle compression;
- mechanical vapor recompression;
- thermal vapor recompression;
- absorption heat pump, type I;
- heat transformer or absorption heat pump, type II.

The two most important characteristics for a heat pump type from a process integration point of view are the range of pinch temperature levels in which it can operate and the q value (defined as the ratio between the heat sink and heat source energy amounts). Economic factors (e.g., energy prices, investment costs) also influence the proper choice of IHP type.

While the appropriate choice of IHP type will be site-specific, the following general parameters for application of the different IHPs types will apply:

- Closed-cycle compression IHPs cannot, with available working fluids, operate at condensing temperatures above approximately 120-130°C; thus, the pinch temperature must be lower than 120°C. To be economic, the COP must typically be higher than at least 3, which limits the temperature difference between the condenser and evaporator, and implies that heat must be extracted and delivered close to the pinch, with q values of about 1.2 to 1.5.

- Mechanical vapor recompression or MVR heat pumps can operate at relatively low condensing temperatures, 60-80°C, if the temperature lift is extremely low. For a common MVR application (process steam production at 120°C or above), the heat source temperature must normally be higher than approximately 80°C for economic and construction-related reasons. Thus, in such cases the pinch temperature should be higher than about 90-110°C for this type of heat pump. The temperature lift for the compressor involved should normally be relatively modest, which also means that heat should be extracted and delivered close to the pinch. COPs are normally quite high compared to other IHP types, normally between 5 and 20, with q values between 1.1 and 1.3.

- Absorption heat pumps (Type I) can deliver heat up to approximately 100°C with current working fluids, which implies that the pinch temperature must be lower than about 80°C. The heat pump is driven by primary heat and yields a constant COP of approximately 1.6 with a q value of about 2.7.

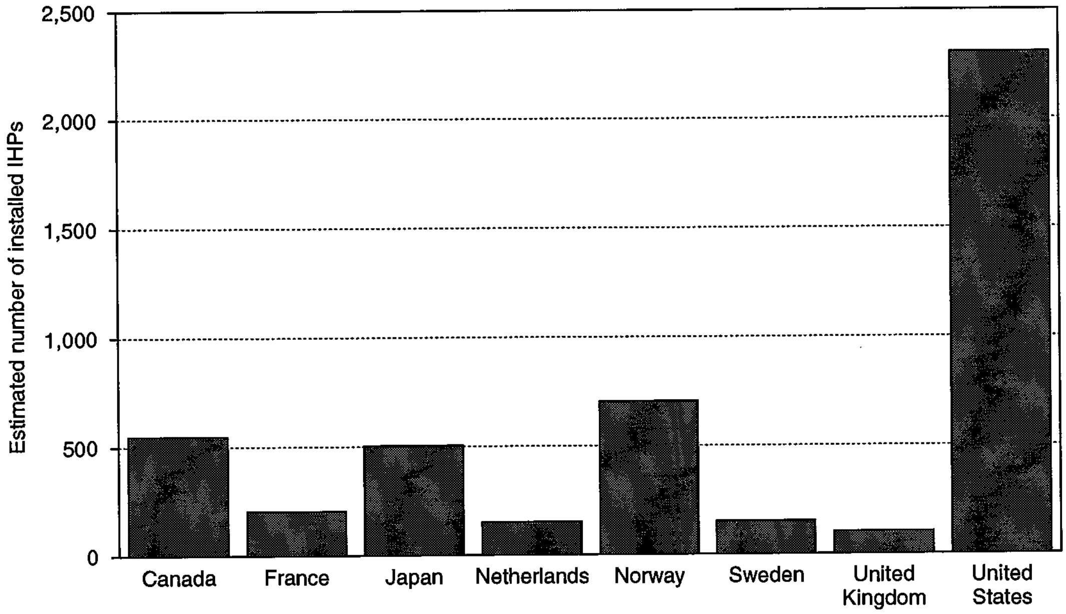
- Heat transformer IHPs can operate at up to 150°C with a maximum temperature lift of about 50°C. The pinch temperature should therefore be between 60 and 130°C. This type of heat pump operates with waste heat and not primary energy, such as electricity, and is generally capable of upgrading one-half of a waste heat source to a higher temperature. Heat sinks, which are half the size of the heat source, are therefore ideal (q = 0.5).

Task-Shared Program

In the task-shared work for Annex 21, each of the participating countries conducted an IHP market assessment to highlight the current experience with IHPs and to estimate the potential energy savings and environmental benefits associated with wide-scale IHP implementation. The participating countries report that more than 4,600 IHPs are now in use (Figure 1). The primary applications for these systems are:

- Food processes, including dairies, corn milling, sugar refining, breweries, liquor production, and fish processing.
- Chemical processes, such as ethanol, ethylene, and fertilizer plants.
- Lumber drying.
- Pulp and paper processes, focusing on evaporation operations.
- Petrochemical and refining processes, such as product separation and distillation.

Figure 1 IHP Experience in the Annex Countries



In Japan and Sweden, IHPs are also widely used for district heating employing heat recovered from industrial processes.

To date, the majority of the installed IHPs have been either MVR or closed-cycle compression heat pumps. TVR IHPs or steam ejectors are most commonly found in food and pulp and paper operations. Comparatively few absorption heat pumps (either type I or type II) have been installed.

Potential Benefits in the Annex Countries

The country-specific IHP market assessments that were conducted under Annex 21 show that wide-scale IHP implementation can provide large energy savings and environmental benefits. These studies showed that, across the different countries, IHPs have the potential to:

- Reduce total industrial process heat energy consumption by an average of 2-4%.

- Reduce process heat energy consumption for individual processes up to 66%, depending on the industry and process.

Supporting research for the market assessments indicates that IHPs can provide additional benefits, including increased process steam capacity, process debottlenecking, and improved product quality.

In total, the seven country-specific assessments analyzed more than 35 different industrial processes (see Figure 2). The use of IHPs looks to be quite promising in processes involving distillation and evaporation with potential energy savings estimated to be quite large for beet/cane sugar, cheese, corn syrup/starch, milk, liquor, ethanol, chlorine/caustic, and pulp production.

The market studies conducted for Annex 21 found that, on a combined basis for the seven countries and for a range of IHP size scenarios, IHPs could provide the following levels of net emissions reductions by 2010:

- SO_x - 45-96 thousand tonnes/year;
- NO_x - 36-77 thousand tonnes/year;
- CO - 13-27 thousand tonnes/year;
- CH_4 - 0.7-1.5 thousand tonnes/year;
- Particulates - 2.1-4.3 thousand tonnes/year;
- CO_2 - 21-42 million tonnes/year(*).

(*) 5.6-11.6 million tonnes/year carbon equivalent (MMTCE).

In conducting Annex 21, the participants recognized that the use of IHPs would reduce emissions associated with fossil fuel burning and would provide net emissions reductions when the increased electricity used by IHPs was taken into account. At the same time, however, the use of closed-cycle IHPs, which use refrigerants for heat transfer, could contribute some emissions of gases with global warming potential.

Based on refrigerant- and technology-specific charges for diesel- and electric-driven closed-cycle IHPs, the combined market studies estimated that IHPs could potentially increase

Figure 2 Estimated Energy Savings by Process

Industrial Process	Countries Analyzed	Estimated Total Energy Savings — % Savings by Process: < 5	5-10	11-15	16-20	21-25	26-30	> 30
Aqua culture/ fish farming	NOR			■	■	■	■	
Aromatics: BTX	CD, US	■						
Beet/cane sugar refining	CD, JPN, UK, US	■	■	■	■			
Biomass drying	SWED	■						
Building ceramics	NETH	■						
Cheese production	CD, NOR	■	■	■	■	■	■	■
Chlorine/caustic soda	CD, JPN, UK, US		■	■	■	■	■	■
Corn syrup/starch production	NETH, US		■	■	■	■	■	■
Dairies	CD, NETH, NOR	■	■	■	■	■	■	■
District heating	SWED	■	■					
Ethanol distillation	SWED, US		■	■	■	■	■	■
Ethylene	JPN, NETH, US	■						
Fish products	NOR				■	■	■	■
Food industry (general)	SWED	■						
Iron and steel-blast furnace	CD	■						
Liquor distilling	CD, JPN, UK	■	■	■	■	■	■	■
Lumber/wood drying	CD, NOR	■						
Malt beverage brewing	UK, US	■	■					
Meat products	NOR	■	■					
Naphtha desulphurization	JPN	■						
Naphtha splitter	JPN	■						
Paper/paperboard production	CD, NETH, SWED, UK, US	■						
Petroleum refining	CD, US	■	■					
Phosphoric fertilizer/acid	US	■	■					
Polyvinyl chloride	JPN	■						
Potato processing	US	■						
Poultry processing	CD	■						
Pulp production	CD, JPN, SWED, US	■	■	■	■	■		
Surfolane	JPN	■						
Synthetic rubber (polybutadiene)	US		■					
Textile finishing	CD, JPN, NETH, US	■	■	■				
Urea	NETH, US	■						
Vegetable processing	US	■						
Viscose rayon	US	■						
Wastewater concentration	SWED	■						

refrigerant emissions by some 83-190 tonnes/year. While not insignificant, these increases are not nearly large enough to offset the substantial environmental benefits that can be achieved with IHPs, either for closed-cycle IHPs or overall.

The IHP assessments also clearly show that the applicability of IHPs and their potential benefits are very country- and site-specific. Local energy prices, the energy mix for process heating, and the energy mix for electricity generation, all play a role in determining whether IHPs "make sense" technically and economically for a specific industrial site and what the associated environmental benefits will be at both the plant and national levels.

The potential environmental benefits of IHPs are closely related to the type of process heating energy that the IHP might displace. The largest average benefits, especially for SO_x, NO_x, and CO_2, were estimated in countries and processes where IHPs would be displacing (i.e., saving) process heat that is heavily based on coal or oil. Lower average benefits are to be expected in processes where IHPs would be displacing mostly natural gas-based process heating.

Net IHP environmental benefits, resulting from the emissions reductions associated with process heating energy savings less those from IHP energy consumption, are also a function of the energy mix used for electricity generation. This is because electricity is the main energy source used to drive MVR and most closed-cycle IHPs. The most favorable conditions are those where electricity is derived primarily from non-fossil energy sources. Potential environmental benefits from IHPs, would, therefore, be greatest in countries using a high proportion of hydroelectric, renewable, and nuclear energy for electricity. This includes Norway, Sweden, Canada, and Japan. The Netherlands, the UK, and the United States rely more heavily on fossil fuels for electricity and would, therefore, see lower overall benefits for IHPs that consume electricity.

Potential Global IHP Benefits

The results of the Annex market studies were used to derive an estimate of the potential global environmental benefits of IHPs. This was done by using key findings in terms of projected average IHP market penetration rates, IHP energy savings and IHP energy, combined with data on industrial energy consumption in 95 additional countries worldwide.

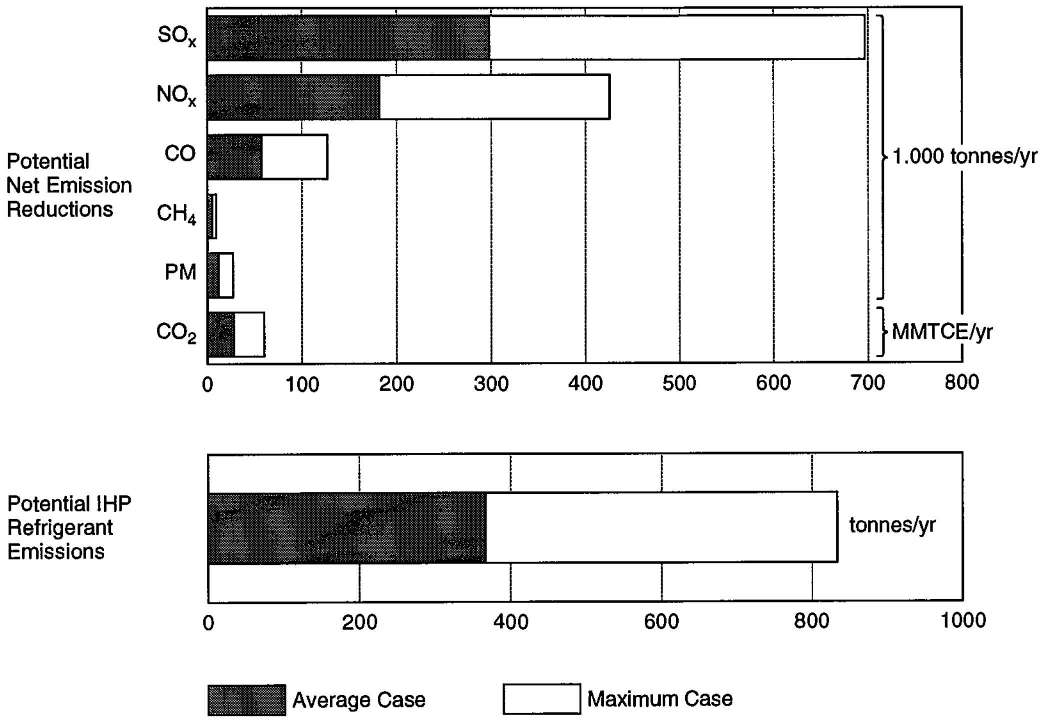
Combining the estimated potential benefits for these countries with those from the Annex results, it was estimated that IHPs could provide the following levels of global net emissions reductions by 2010:

- SO_x - 295-695 thousand tonnes/year;
- NO_x - 180-425 thousand tonnes/year;
- CO - 55-125 thousand tonnes/year;
- CH_4 - 3-6 thousand tonnes/year;
- Particulates - 10-24 thousand tonnes/year;
- CO_2 - 92-215 million tonnes/year(*).

(*) 25-58 million tonnes/year carbon equivalent (MMTCE).

This level of reductions is about five to seven times more than the total projected for the Annex countries. Such emission reductions would be equivalent to eliminating some

Figure 3 Potential 2010 Global IHP Environmental Behaviors



50-150 GW of electric generating capacity, or about 2-5% of the current world total. The potential increase in IHP refrigerant emissions was estimated at some 365-835 tonnes/year. These aggregate results are shown in Figure 3.

The analyses conducted for Annex 21 clearly show that the wider use of IHPs could lead to substantial energy savings and hence strong environmental benefits. As industrial end-users investigate the potential applicability of IHPs to their sites, and as policy makers assess the merits of supporting wider IHP deployment, it is important to stress several key Annex findings and to highlight important assumptions on which the investigations were based:

- The estimates of potential IHP energy and environmental benefits were derived using average industrial process conditions, but aimed to take into account competition from other technologies (e.g., cogeneration) and realistic market factors, such as risk aversion to new technologies and economic hurdle rates for equipment investments.

  In this manner, the Annex results aimed to show a conservative estimate of potential benefits, reflecting potential applications of IHPs that are both technically and economically viable.

- The estimates reflect the incremental benefits that might be achieved by using new IHPs, beyond those now installed in the countries and processes analyzed. These benefits, in terms of process-specific reductions in process heating energy consumption, varied from less than 1% to more than 40% across the different countries and processes.

- The environmental benefits of IHPs could in practice be larger than the values estimated because emission "credits" were not given for the reductions in waste fuel energy consumption, which can account for as much as 20-50% of the energy mix for process heating in many countries.

- The analyses across countries used varying assumptions and the number and mix of industrial processes was different in each country. Therefore, the overall Annex results are most appropriately viewed in terms of the aggregate potential benefits of IHPs across the countries in Annex 21 and globally as well.

The efforts in Annex 21 aimed to assess the applicability of IHPs to industrial processes in five major industries: chemicals, petrochemicals/petroleum refining, pulp and paper, food, and textiles. The country-specific assessments showed that IHPs are widely applicable in such industries and can offer large energy savings and environmental benefits.

Across the Annex countries, industrial processes that look to offer significant IHP potential include pulp, paper and paperboard production, dairies, sugar refining, starch/corn syrup evaporation, textile drying and finishing, and chemical/petrochemical separation processes. The Annex participants strongly see IHPs as a technology which has been under utilized to date and one which can contribute to improved process operations in the future.

The Annex results make clear, however, that IHP evaluations need to be conducted on a site-specific basis to properly determine IHP configurations, sizing and the potential investment cost. The IHP screening program for Annex 21 was developed expressly to aid industrial companies and firms that work with these industries (e.g., engineering firms, utilities) in determining the extent to which IHPs could be applied to their operations. The market assessment studies conducted under Annex 21 and the results of this report aim to highlight the potential benefits of IHPs with the hope that more industrial end-users will consider implementing heat pumps in the future.

1. Introduction

1.1 Background

Industrial heat pumps (IHPs) offer the potential to conserve energy, improve plant productivity, and expand process capacity at lower costs than other methods of process heating (e.g., boilers, fired heaters). They can also reduce pollution (air and water) by decreasing the combustion of fuels. In particular, IHPs can recover waste heat to produce low-pressure steam or, more interestingly, to upgrade low-pressure steam to high-pressure steam. In doing so, industrial heat pumps can reduce the amount of energy that is consumed in industrial boilers, furnaces or heat engines. The result can be a reduction in sulfur and nitrogen oxides emissions, which cause acid rain, and a reduction in emissions of greenhouse gases (e.g., CO_2, CH_4, N_2O) that may contribute to global warming.

To investigate the potential applications of industrial heat pumping and to evaluate the potential market development of IHPs and their possible associated energy savings and emissions reductions, the United States proposed Annex 21 under the International Energy Agency (IEA) Implementing Agreement on Heat Pumping Technologies (IAHP). Seven other countries joined the United States in supporting Annex 21: Canada, France, Japan, the Netherlands, Norway, Sweden, and the United Kingdom.

1.2 Annex Objectives and Scope

Drawing from the original U.S. proposal and from the combined inputs from experts and National Team representatives at two Annex start-up meetings, it was agreed that Annex 21 would have four objectives:

- Heighten industry's awareness of the large energy savings potential associated with industrial heat pumping.
- Broaden the information base available to industry to help further development and deployment of IHPs.
- Estimate the market potential for various types of IHPs and illustrate the opportunities for their use.
- Estimate the potential global environmental benefits of IHPs resulting from energy savings and emissions reductions.

Annex 21 was conducted in two parts: one involving a cost-shared effort and one a task-shared contribution. In the cost-shared effort, the Annex participants engaged three contractors to perform specific tasks to support the Annex:

- Chalmers Industriteknik Energiteknisk Analys (CIT-ETA) of Sweden, to develop a computer program to screen industrial processes for their suitability to heat pumps and to determine, on a preliminary basis, potential IHP configurations and economics.

- RCG/Hagler Bailly, Inc. of the United States, to develop an overall work program for the Annex, to develop a methodology for assessing IHP market potential, and to provide Annex management support.

- IEA Heat Pump Centre of the Netherlands, to provide logistical, technical, and administrative support to the Annex.

The participants in Annex 21 recognized that the situation for industrial heat pumping is unique in each country; therefore, a common work program was necessary to ensure that the combined benefits of IHPs could be determined while still allowing each country to consider its own position with regard to heat pump technology, energy prices, industrial processes, and environmental regulations.

To this end, the National Team from each of the eight participating countries was asked to contribute a task-shared effort under Annex 21. This effort involved providing the contractors with information on the current state of IHP technology in their respective country and conducting a country-specific market study on IHP potential. These market studies were conducted using the methodologies and tools developed by the Annex contractors under the guidance of the National Team representatives participating in Annex 21.

In conducting the various IHP assessments, the National Teams performed three tasks:

- Task 1 - Project IHP Market Potential;
- Task 2 - Estimate Energy Savings;
- Task 3 - Estimate Greenhouse Gas Emissions Reductions.

As a result of the cost- and task-shared efforts, the Annex produced three products that can be used by the various National Teams to facilitate the development of IHPs within their country:

- This technical summary report, which outlines IHP technologies and potential industrial applications and which summarizes the country-specific IHP market studies to highlight the potential energy and environmental benefits of IHPs.

- A summary report on the global environmental benefits of IHPs.

- A computer program to assist with the identification and evaluation of IHP applications.

1.3 Report Structure

The remainder of this report is structured as follows:

Chapter 2 discusses IHP technology, including a review of the different types of heat pumps and their principles of operation.

Chapter 3 reviews pinch technology theory and discusses appropriate methods for integrating IHPs into industrial processes. This chapter also reviews in brief the IHP screening program developed for Annex 21.

Chapter 4 summarizes current IHP experience in the countries that conducted Annex 21, including a discussion of the major industries that have used IHPs and the types of IHPs that have been installed.

Chapter 5 describes in detail the results of the country-specific IHP market assessments. This chapter summarizes the results of each country-specific study, provides an overall summary for the Annex countries, and outlines potential global IHP energy and environmental benefits.

Appendix A outlines the IHP screening program in more detail, including a step-by-step review of the major features of the program and instruction on its use to assess IHP potential.

Appendix B reviews the overall methodology developed to conduct the IHP market assessments.

Appendix C presents the data and assumptions used for the country-specific IHP market assessments.

Appendix D provides a glossary of the main acronyms and terms used, together with definitions.

The appendices are followed by a list of references and a list of the National Team contacts for Annex 21.

2. Different Types of Industrial Heat Pumps

2.1 Introduction

A heat pump can be described, in general, as a machine in which heat is lifted from a low-temperature level (heat source) to a higher (heat sink) temperature levels with the help of some type of primary energy. The coefficient of performance (COP) can, in general, independent of the primary energy type, be defined as:

$$COP = \frac{\text{Heat transferred to the heat sink}}{\text{Primary energy used}}$$

A large number of heat pump cycles are in use or have been proposed for industrial purposes. The most important ones are:

- Closed-cycles:
  - Compression cycle;
  - Absorption cycle;

- Open-cycles:
  - Steam or gas compression cycle (mechanical vapor recompression, MVR);
  - Ejector heat pump (thermal vapor recompression, TVR).

The cycles included in this listing are discussed below. The chapter is divided into four parts:

- Closed Compression Cycles, which reviews electric- or engine-driven IHPs, the most common type of closed-cycle system.

- Mechanical Vapor Recompression or MVR industrial heat pumps, the standard nomenclature for steam or gas compression cycles.

- Thermal Vapor Recompression or TVR heat pumps, the common reference for ejector heat pumps.

- Absorption Cycles, which includes both waste- and prime-heat driven cycles.

Apart from the cycles mentioned above, other cycles such as the Joule, Stirling and Peltier cycles are also being considered for potential heat pump use. Most likely, these will not be of any importance in industrial applications in the foreseeable future.

2.2 Closed Compression Cycles

2.2.1 Operating Principles

The principle for the most simple closed-cycle heat pump is shown in Figure 2.1. The COP can be expressed as:

$$COP = \frac{Q_c}{W} = \frac{Q_E + W}{W}$$

The corresponding ideal cycle working between the sink temperature T_1 and the source temperature T_2 is the Carnot Cycle. The COP for this cycle is:

$$COP_c = \frac{T_1}{T_1 - T_2}$$

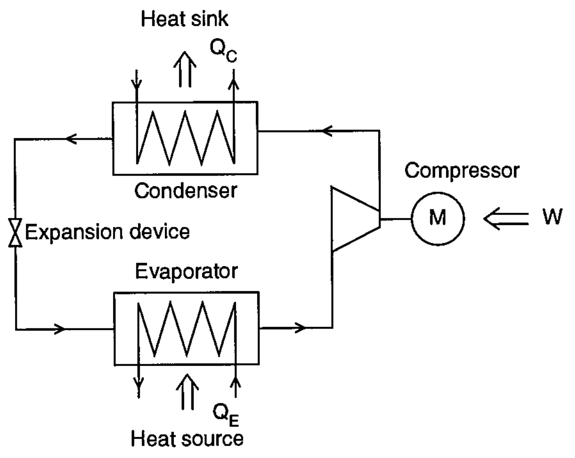
The COP for the real cycle is often expressed as

$$COP = \eta_c \cdot COP_c$$

where η_c is called the Carnot efficiency. This efficiency can often be regarded as constant with varying values of T_1 and T_2, if these variations are reasonable. This means that the equations above can be used for drawing fundamental conclusions about the way in which a variation of the evaporating and condensing temperatures will affect the heat transfer coefficient. With such calculations, it can easily be proved that the COP will increase with about 4% per degree K increase in the evaporation temperature and that the COP will decrease about 1.5% per degree K increase in the condensing temperature.

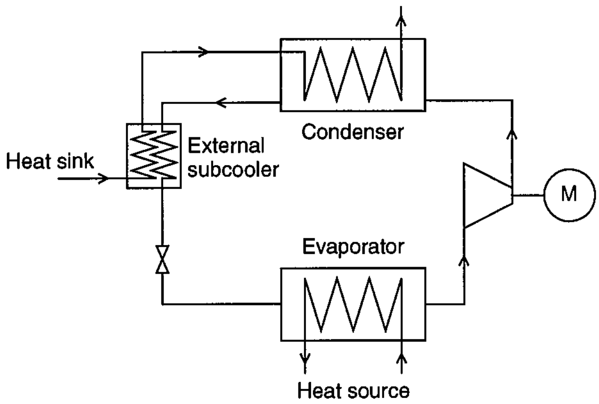
In a given design, the capacity, of course, also varies (i.e., the size of Q_c) with the evaporating and condensing temperatures. Such values for real designs vary with the type of compressor, but are generally about a 3% increase per degree K increase in the evaporating temperature and 1% per degree K of the condensing temperature.

Figure 2.1 Simple closed compression cycle



In industrial heat pumps, subcooling of the condensate after the condenser is often used (Figure 2.2). If the heat sink is a stream with sensible heat and thus is undergoing a change of temperature under heating, it can be used for subcooling of the condensate in the way shown in the figure. This means that the heat delivered by the condenser increases without any increase in the compressor work, i.e., both the COP and the capacity increase. Because the extra investment cost of a subcooler is very often marginal, such a design is, in most cases, economic, at least when the heat sink is in liquid form. Typical improvements of the COP and the capacity are approximately 1% per degree K of subcooling.

Figure 2.2 Simple closed compression cycle with subcooler



Theoretically, the condition before the compressor can be dry, saturated vapor. In reality, the condition before the compressor must, in most cases, be superheated (5-10K) in order to eliminate the risk of having small drops of liquid entering the compressor.

Compared to the Carnot cycle, the main thermodynamic losses for the compression cycle can be found at the isenthalpic expansion and at the compression. These losses can be decreased by using multistage cycles. Some possibilities for improvements over the one-stage cycle are presented below.

Figure 2.3 shows a two-stage cycle with an economizer. The vapor part of the working fluid after the first expansion valve is compressed in a second compressor without passing the evaporator. Thus, the temperature lift and the need for compression for this part will decrease, and the COP and the capacity can increase.

Figure 2.4 shows a design with a so-called flash intercooler, in which the vapor part with a small temperature lift is increased compared to the economizer cycle by using the superheating of the vapor (which comes from the first compressor) to evaporate some of the working fluid in the intercooler. Theoretically, this cycle gives better performance than the economizer cycle, but the disadvantages are pressure drop in the flash intercooler and a risk of the entrainment of drops to the high-pressure compressor.

Figure 2.5 depicts a cascade cycle. This cycle has two main advantages. The pressure ratio for each compressor is small (gives increased isentropic efficiencies) and different working fluids can be used in the two circuits. Its disadvantages are the introduction of an extra temperature difference in the intercooler, greater complexity, and extra control problems.

Figure 2.3 Simple closed compression cycle with economizer

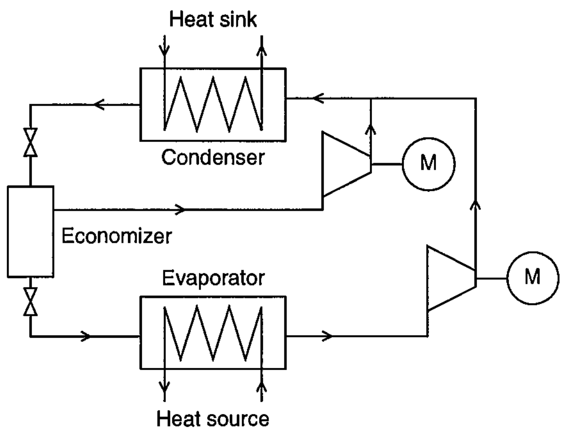


Figure 2.4 Closed compression cycle with flash intercooler

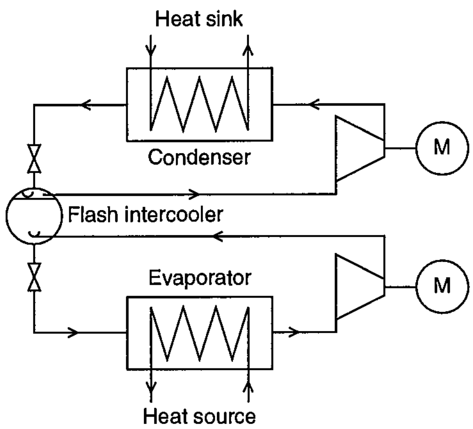
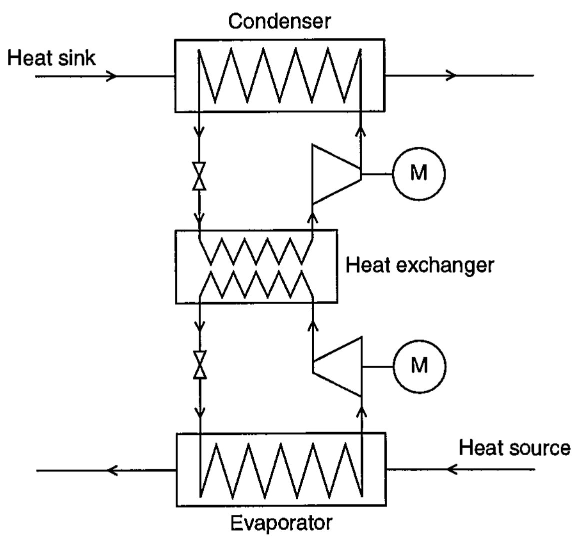
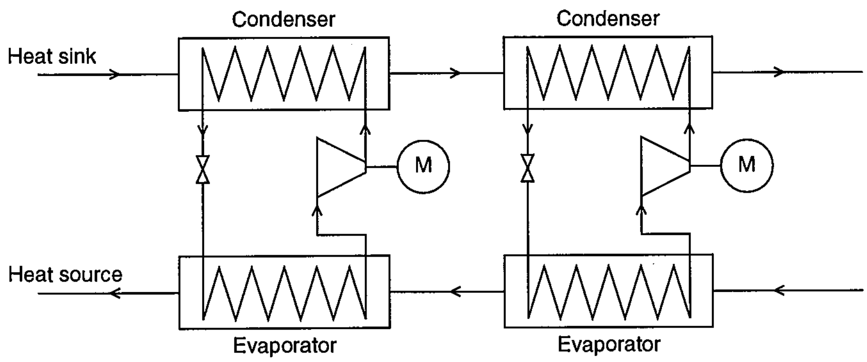


Figure 2.5 Closed compression cycle cascade



Because the temperature decrease of the heat source and the temperature increase of the heat sink sometimes can be large, the possibilities of using two or more heat pumps connected in a series should be taken into consideration (Figure 2.6). This configuration allows a smaller pressure ratio for each compressor to be obtained and, thus, a higher COP.

Figure 2.6 Closed compression cycles in series



The economizer cycle is often used in medium and large systems (i.e., in most industrial applications). The other cycles are used only in very special situations.

2.2.2 Closed Cycle System Components

2.2.2.1 Compressors

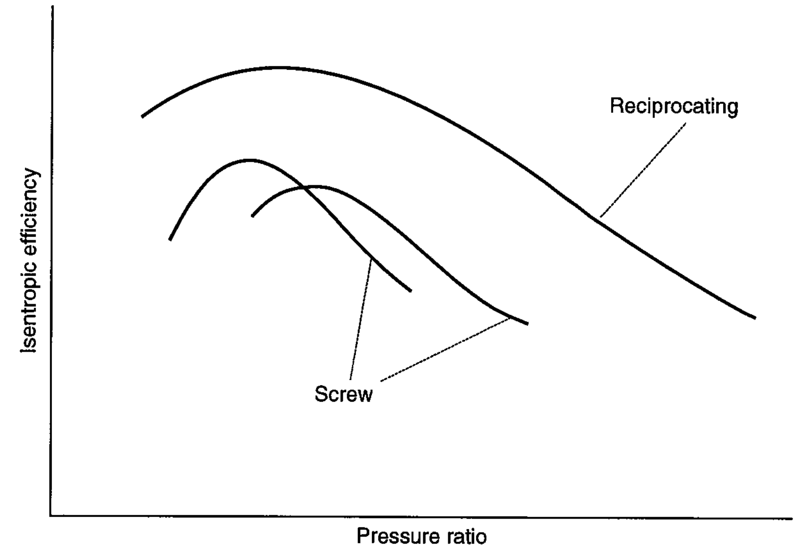
The three traditional types of compressors used in heat pump applications are the reciprocating, the (twin) screw, and the centrifugal compressor. Reciprocating compressors are used in small and medium size systems up to approximately 500 kW heat output, screw compressors are used in medium size systems up to approximately 4 MW heat output, and the centrifugal compressor is used in large systems, above approximately 2MW heat output.

Reciprocating and screw compressors are normally oil lubricated, which means that the lubricant always must be transported with the working fluid under the whole cycle through the condenser, the evaporator and so on. Centrifugal compressors normally work without lubricant. Furthermore, the working fluid in screw compressors is mixed with large amounts of oil for sealing and cooling inside the compressor.

Figure 2.7 shows the variation of isentropic efficiency with pressure ratio for reciprocating and screw compressors. As shown in the figure, the screw compressor efficiency has a maximum value at a certain, rather low, pressure ratio. Larger reciprocating compressors normally have a somewhat higher efficiency than screw compressors, as is also shown.

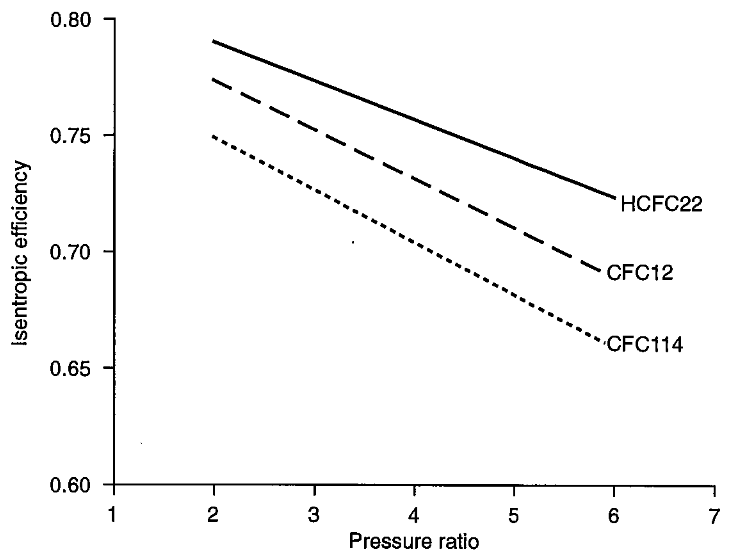
The capacity of a reciprocating compressor decreases with the evaporating temperature and the pressure ratio as a result of the effect of the specific volume of the gas in the compressor and the relative size of the dead volume. In the screw compressor, the effect of the evaporating temperature is approximately the same as for reciprocating compressors. The decrease of capacity with increasing pressure ratio is, in this case, caused by an increasing rate of internal leakage of the working fluid from the outlet to the inlet.

Figure 2.7 Variation of isentropic efficiency versus pressure ratio for reciprocating and screw compressors



The screw compressor is traditionally produced with a permanent built-in volume ratio which is defined as the ratio between the suction and the discharge volumes. Such a compressor has a maximum isentropic efficiency which depends on pressure ratio (Figure 2.7). The choice of built-in volume ratio must be made with regards to what levels of pressure ratio the compressor will be working. Today, compressors are produced with adjustable volume ratios so that a maximum isentropic efficiency can be chosen for each particular operating situation. The variation of isentropic efficiency with pressure ratio for such a compressor is shown in Figure 2.8, which also depicts the influence of different working fluids on the isentropic efficiency.

Figure 2.8 Variation of isentropic efficiency versus pressure ratio for screw compressors with adjustable volume ratios



An important aspect for compressor heat pumps is the possibilities available for capacity control. These are:

- For both types of compressors:
  - on-off control;
  - speed control;

- For reciprocating compressors:
  - cylinder unloading;

- For screw compressors:
  - slide valve control.

The principal effect on COP with different methods of control for both types of compressors is shown in Figures 2.9 and 2.10. It can be noted that a speed control only gives a very small decrease, or even an increase, in COP. The unload of cylinders and, especially, slide valve control give a significantly larger negative effect on COP. On-off-control, however, normally gives an even larger negative effect.

An extra side suction port can easily be installed in a screw compressor. Therefore, an economizer can be used with one single compressor. The extra investment cost for the economizer is thus small. Because the capacity increases simultaneously, the specific investment cost will normally decrease somewhat. Almost all heat pumps with screw compressors use this cycle. A screw compressor with an economizer normally has a higher COP than an economizer with reciprocating compressors. This advantage does, however, disappear at part loads under approximately 70%, since at these load levels the slide valve then makes economizer use impossible.

The centrifugal compressor is used, as mentioned earlier, in larger plants. The volume flow in such compressors can become very large, while the pressure ratio is limited to approximately 4 for normally used working fluids. Therefore, there is generally a need for two wheels, which makes the designing of two-stage cycles with this type of compressor easy. In practice, an economizer cycle is used in almost all centrifugal compressor-based plants.

Figure 2.11 shows a typical performance map for a one-step centrifugal compressor with a so-called inlet guide vanes control. The maximum isentropic efficiency is approximately 82%. The capacity control can normally be done with only small thermodynamic losses using inlet guide vanes, diffuser, speed variation or a combination.

2.2.2.2 Compressor Drive

The compressor can be driven by electric motors, which are most frequently used, or by diesel/Otto engines run on gas, diesel oil or similar fuels. Steam or gas turbines can be used in special cases.

The efficiency for electric motors varies between approximately 70% and 97%, depending on the size. In most industrial applications, it should be possible to operate with efficiencies of 90% or higher. These levels are also valid at part load, down to at least one-half the nominal load.

Figure 2.9 COP versus load for reciprocating compressors at two different levels of evaporating/condensing temperatures, with working fluid CFC12, maximum speed 1,200 rpm

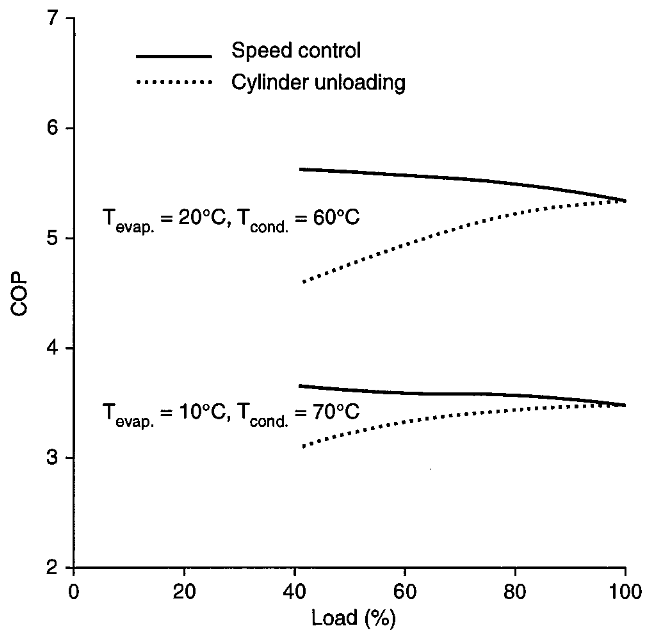


Figure 2.10 COP versus load for screw compressors at two different levels of evaporating/condensing temperatures, with working fluid CFC12, maximum speed 3,000 rpm

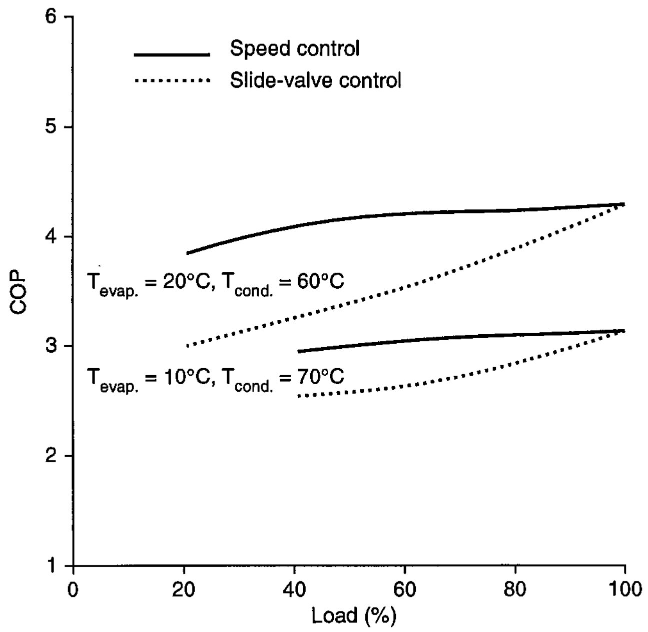
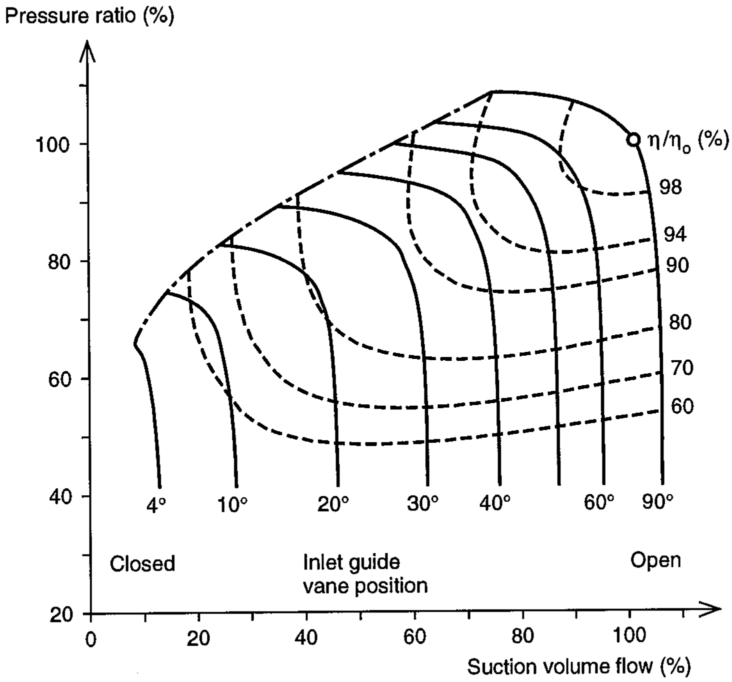


Figure 2.11 Typical performance map for a turbo compressor of radial type (according to Sulzer)



When using diesel/Otto engines, the waste heat from the engine is used to obtain acceptable economics. An example scheme is shown in Figure 2.12. Heat is available in the exhaust gases, cooling water, oil cooler, and turbocharger aftercooler. The relative importance of these heat sources is shown in Table 2.1. As seen in the table, the temperature level of the heat available in the turbocharger aftercooler and the oil cooler is typically too low to recover for industrial process requirements. The waste heat temperature from the cooling water is higher, but is less than 100°C and cannot be used for steam production. This type of engine is therefore most suited to hot water production.

In the example in Table 2.1, the engine efficiency was shown as 40%. With modern, powerful engines it is possible to reach approximately 45%. The total COP-value for such a plant is defined and can be calculated according to:

$$COP = (Q_{hp} + Q_{cooler} + Q_{WHB}) / Q_{fuel}$$

$$COP = \eta_e \cdot COP_{hp} + (\eta_{tot} - \eta_e)$$

where

Q_{hp} = heat from the heat pump condenser
Q_{cooler} = heat from the cooling water
Q_{WHB} = heat from the waste heat boiler
Q_{fuel} = energy supplied by the fuel
COP_{hp} = COP for the heat pump itself (= Q_{hp} / W_{shaft})
W_{shaft} = shaft power
η_e = engine efficiency (= W_{shaft} / Q_{fuel})
η_{tot} = total efficiency of engine (= $(W_{shaft} + Q_{cooler} + Q_{WHB}) / Q_{fuel}$).

Figure 2.12 Example scheme for a diesel/gas-driven heat pump

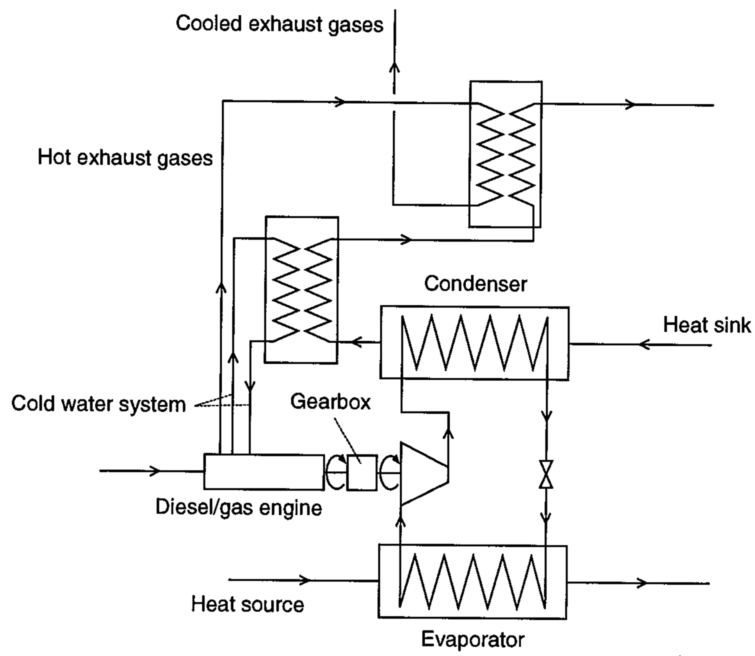


Table 2.1 Heat balance for medium-speed diesel engine

		Typical temperature
Mechanical work	40.1%	
Cooling water	14.0%	<≈ 110°C
Exhaust gases	33.0%	> 140°C (with gaseous fuel, down to 40°C)
Turbocharger aftercooler	10.4%	≈ 45°C
Oilcooler	2.5%	≈ 45°C

2.2.2.3 Heat Exchangers and Expansion Valves

There are a great number of types and design principles for evaporators and condensers, a detailed discussion of which is beyond the scope of this report. The economically optimal smallest temperature difference in such heat exchangers varies with design and application, but typical values are 4-8 K in the evaporator and 2-6 K in the condenser when the heat sink and heat source are liquids. If they are in gas phase, these values can be higher. The evaporator is normally designed for a pressure drop equivalent to approximately 2 K in evaporating temperature [1]. In the condenser, the pressure drop is typically equivalent to 1-2 K. Different types of evaporators and condensers are described in [1] and [2], respectively.

There are different types of expansion valves, for instance, thermostatic, pressostatic and electronically controlled valves. The electronically controlled valves are generally used in industrial plants. They give a more reliable operation than the others and also give a guarantee that the superheating after the evaporator is kept "at the right level". For reciprocating and turbo compressors, it is very important that the vapor from the evaporator does not contain any drops of liquid, since problems with erosion and implosion then can occur with a compressor breakdown as a consequence. Therefore, superheating before the compressor is always used, typically about 10 K. Superheating is also normally used with screw compressors, although it is not that crucial. In principle, such compressors can work with some moisture (i.e., liquid droplets) in the vapor.

2.2.2.4 Working Fluids

As working fluids in closed-cycle compression heat pumps, the chlorofluorocarbon (CFC) and hydrochlorofluorocarbon (HCFC) fluids shown in Table 2.2 have traditionally been used.

Table 2.2 Traditional working fluids

Fluid	Condensing temperature range, °C
CFC 114	75-120
CFC 12	55-80
HCFC 22	40-60

The CFC working fluids are now being, or will soon be, phased out. The next step will be to phase out HCFCs, leaving hydrofluorocarbon (HFC) or other working fluids as the primary alternatives for use with IHPs.

The alternatives to CFC12 are mainly HFC134a and, in applications where flammable fluids can be used, isobutane or propane/butane. The main alternatives to HCFC22 are HFC407C and propane. As a CFC114 replacement, HCFC123 and propane/butane mixtures have been discussed. No HFC alternative has been found in this temperature range.

The general experience to date with the CFC12 alternatives, although still limited, is that the COP and capacity depend slightly on the fluid and the equipment, but are close to the values for CFC12. The same applies to the HCFC22 alternative, HFC407C. For the other HCFC22 alternatives, the experience is very limited. For the CFC114 replacements, the possibilities to achieve higher COPs (at least 10%) than CFC114 are good but, in some cases (e.g., HCFC123), occur at a considerably lower capacity. The fluids that actually will be used in this temperature range are, however, still very uncertain.

Based on the discussion above, for COP and capacity characteristics for heat pumps in different temperature ranges, existing data for CFC114, CFC12 and HCFC22 have been inserted in the Annex 21 computer program. As mentioned, this can be somewhat erroneous for CFC114. However, the user can specify his/her own preferred characteristics.

2.2.3 Performance of Different Types of Closed Cycle Heat Pumps

The Carnot efficiency for a heat pump with CFC12 as the working fluid with different types of compressors can be seen in Table 2.3. The lower efficiency level is typical for small plants and the higher efficiency level is typical for large plants. Some examples of the variation of COP and capacity are shown in Figures 2.13 and 2.14. Examples of the influence of different cycles on COP are shown in Table 2.4. This table clearly shows that COP can be affected considerably by the choice of cycle.

Table 2.3 Carnot efficiency (η_c) for different types of compressors with CFC12

Compressor	Size (kW$_{electricity}$)	η_c
Reciprocating	< 500	0.45-0.53
Screw (with economizer)	100-4,000	0.5-0.58
Turbo (with economizer)	> 2,000	0.62-0.69

Table 2.4 COP with and without subcooling for different types of heat pump cycles with screw compressor and CFC114 at sink temperature 85/55 °C and source temperature 15/5 °C

Cycle	Without sub-cooling		Max sub-cooling	
	COP	COP$_{relative}$	COP	COP$_{relative}$
One-stage	1.52	1.00	1.92	1.00
Economizer	1.98	1.30	2.20	1.15
Flash intercooler	2.45	1.61	2.76	1.44
Cascade	2.46	1.62	2.74	1.43
Two one-stage in series	1.86	1.22	2.12	1.10
Two one-stage, each with economizer	2.41	1.59	2.58	1.34
Two one-stage, each with flash intercooler	2.84	1.87	3.00	1.56

Figure 2.13 COP versus evaporating temperature with condensing temperature as parameter for large screw compressors, with working fluid CFC12

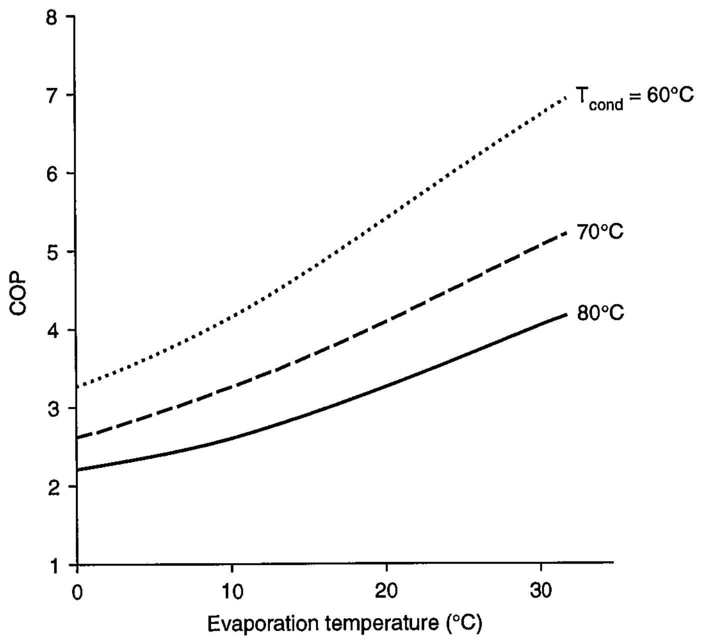
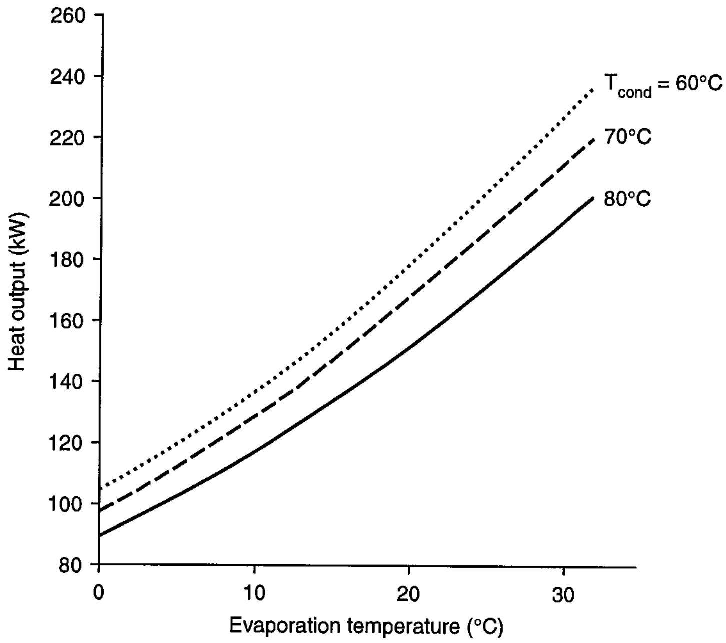


Figure 2.14 Relative heating capacity versus evaporating temperature with the condensing temperature as parameter for large screw compressors, with working fluid CFC12



For CFC114, the Carnot efficiency is lower than that of competing fluids because of its thermodynamic characteristics and the corresponding lower isentropic compression efficiency (Figure 2.8).

2.3 Mechanical Vapor Recompression (MVR)

2.3.1 Operating Principles

Vapor compression is a technique to increase pressure and temperature on gaseous waste heat and thereby reuse it. It is often referred to as mechanical vapor recompression or MVR heat pumping.

There are several types of systems for vapor compression. The most common type of MVR system (Figure 2.15) is where the process steam is compressed directly. After the compression, the steam is condensed in a heat exchanger in order to fulfill a heat demand. This is a semi-open system, but it is often called a direct system.

The second type of semi-open MVR system is shown in Figure 2.16. Here, the configuration is reversed compared to the previous type. This system has an evaporator, but lacks a condenser. This unusual type of MVR system can be used to vaporize a process flow needed in vapor form at a higher temperature compared to the level that can be accomplished with the available heat source. The heat source can be contaminated vapors or some other fluid.

Figure 2.15 Semi-open MVR system of type 1

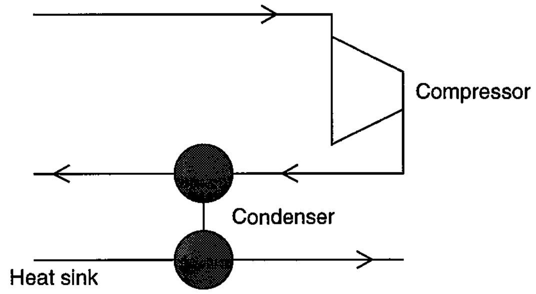


Figure 2.16 Semi-open MVR system of type 2 [3]

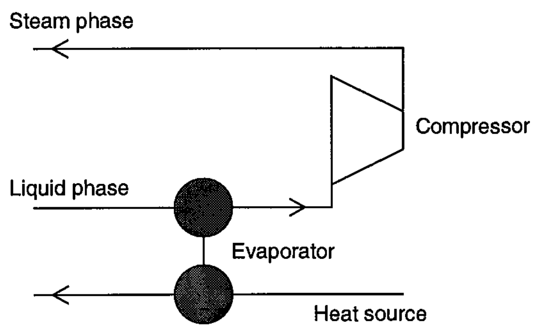
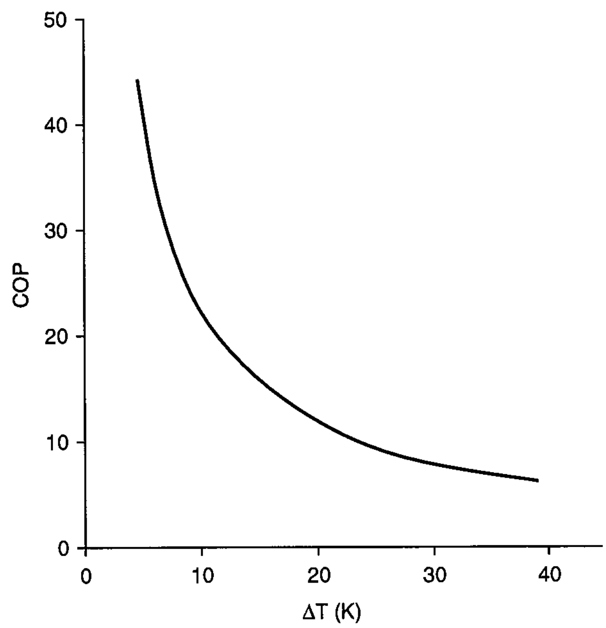


Figure 2.17 COP versus temperature lift for a MVR system [4]



Completely closed cycles with water as the working fluid seldom exist.

For an MVR system where the compressor has an isentropic efficiency of 65% and otherwise negligible losses, Heaton [4] shows COP as a function of the temperature lift (Figure 2.17). From this it can be concluded that the MVR system gives very high COPs, but the graph also shows that the COP is very dependent on the magnitude of the temperature lift. A decrease of this temperature lift requires, at unchanged external conditions, larger heat exchanger surfaces and more effective heat exchangers. In general, this means higher investment costs. A careful analysis of the balance between operation costs and investment costs is important in each design.

Comparisons between direct (semi-open) MVR systems and indirect CCC systems have shown that:

- Direct systems are preferred from the thermodynamic and economic points of view.
- An indirect system in an industrial process is more flexible than a direct system, but more capital intensive. Indirect systems can be used in processes with contaminated fluids, and can more easily be combined with some types of processes (e.g., batch-type processes). The indirect procedure also means that the compressor is more protected from disruptions in operations.
- The disadvantages of the MVR technique at low temperatures of the heat source are large vapor volumes and the risk of air leakage. Therefore, this technique is seldom used at heat source temperatures below approximately 80°C, if the object is to produce low-pressure steam. Lower values often occur, however, if the temperature lift is small (less than approximately 20 K).

2.3.2 MVR System Components and Capacity

2.3.2.1 Introduction

For MVR systems, the choice of compressor is by far the most important design issue. For this reason, compressors in MVR applications are discussed in detail below. They are usually divided into two different main groups, aerodynamic or turbo compressors and volumetric or positive displacement compressors (Figure 2.18).

The different types of compressors that are suitable for vapor compression, their flow regime, possible pressure ratios, and levels of isentropic efficiency at vapor compression are summarized in Table 2.5. Aspects of the compressor, that are of particular significance for vapor compression are discussed below.

Turbo compressors are used mainly for high or medium-high flows. Steam, with its relatively low molecular weight, is not an ideal working fluid for turbo compressors. Low molecular weights of the working fluid give a small possible pressure ratio and cause relatively large losses in a turbo compressor [7]. From this point of view, volumetric compressors are better suited for steam compression. On the other hand, the volume flow is often rather large which, of course, is a disadvantage compared to turbo compressors.

Figure 2.18 Classification of mechanical compressors [5]

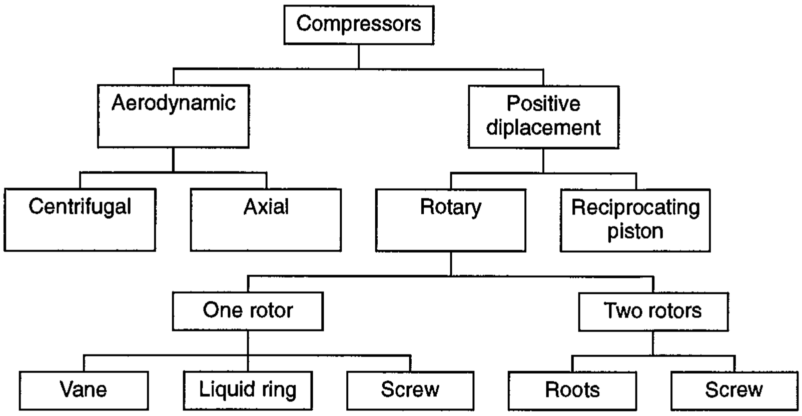


Table 2.5 Flow regimes, possible pressure ratios, and common levels for the isentropic efficiency for different types of compressors at vapor compression [6,10,12]

Category	Volumetric flow rate [m^3/h]	Pressure ratio per stage	Isentropic efficiency
Turbo compressors			
Axial	200,000-500,000	1.2-1.8	80%
Radial	2,500-200,000	1.8-2.5	70-80%
Volumetric compressors			
Twin-screw	500-25,000	2-6	60-80%
Roots	100-15,000	($\Delta P \approx 1$ bar)	40-65%
Liquid ring	< 8,000	1.4-1.5	20-50%
Reciprocating	< 2,000	4-6	50-67%

Volumetric compressors (also called positive displacement machines) can be used for very small flows to medium flows. These compressors were originally developed for air compression. The main difference when using vapor compression is that the compressors must work with the absence of oil. Moving parts must thus work without direct contact with each other or with lubrication of the working fluid (i.e., the steam). Volumetric compressors are less sensitive to fouling in the system than turbo compressors. This is because the volume flow through a volumetric compressor is not affected by changes in pressure ratio over the compressor. In turbo compressors, fouling can cause instable operation.

2.3.2.2 Turbo Compressors

Axial compressors:
Axial compressors are very compact, i.e., they have very high capacity in a small body. Their efficiency is also higher compared to volumetric compressors and is also usually higher compared to radial compressors. The high efficiency of axial compressors is attributable, in part, to their very low level of internal leakage.

Capacity control is not easily accomplished in axial compressors. They also are very sensitive to liquid drops, which can lead to blade erosion and failure. Compared to centrifugal compressors, axial compressors are expensive, which is an important reason for their limited use in vapor compression.

Centrifugal compressors:
The centrifugal compressor is the most common type of compressor in MVR installations. The pressure increase, which can be accomplished per step in a centrifugal compressor, is directly proportional to the square of the peripheral speed of the impeller. According to Tuzson [8], with titanium blades and special design, peripheral speeds over 600 m/s can be attained and, thus, pressure ratios over 3 per compressor step of vapor compression. The peripheral speed does usually not exceed 450 m/s, and the pressure ratio is restricted to approximately 2 per step for compressors of standard material.

Large pressure lifts also mean high superheating temperatures when the vapor is compressed. The working fluid is cooled to prolong the life of the compressor and to decrease the compression work load. The cooling can be done either through liquid injection or indirectly through heat exchange of the vapor between the stages in a multistage installation. Centrifugal compressors capacity can be controlled, while maintaining high efficiency, with inlet guide vanes, with adjustable diffuser vanes, or with variable speed. These methods of control are also used to avoid unstable operation. Centrifugal compressors are usually equipped with a liquid separator in the suction line because liquid drops cause erosion, leading to lower efficiencies and possible blade failure.

Efficiencies for turbo compressors - steam compression:
Very few experimental data about efficiencies for turbo compressors are found in the literature. A reason for this is that these compressors usually are specially designed.

Brun [9] cites research stating that the maximum pressure ratio for vapor compression is 1.8 per step and that the isentropic efficiency is estimated to be 0.80 for a typical one-step centrifugal compressor.

Banquet et al. [10] have published results from tests in connection with the development of a new two-step centrifugal compressor for vapor compression. This compressor is designed for high speeds (50,000 rpm) and relatively small volume flows (up to 3500 m^3 per hour). There are very few compressors for this field of capacity. The compressors work with a pressure ratio between 1.8 and 2.2 per step. The results showed that the new compressor functioned well, and the isentropic efficiency for both steps was approximately 0.58.

2.3.2.3 Screw Compressors

Screw compressors are common in refrigeration and heat pump installations for the compression of halogenated hydrocarbons and ammonia. In these applications, the compressors are usually oil injected. However, oil-free compressors must be used for vapor compression. Cooling in the compressor can then be accomplished by the injection of water or by water-cooling of the compressor jacket. Sealing and lubricating can be done either with the help of injected water, which creates a liquid film, or by covering the rotors with a special coating, which can give a satisfactory internal sealing [11]. The injection of water can be done through the inlet port or through the economizer.

Specially designed screw compressors are an expensive alternative for vapor compression. However, if it is possible to utilize mass produced compressors adjusted to vapor compression these would be an interesting alternative. Atlas Copco's screw compressors, which originally were designed for air compression, have been tested by Electricité de France and Institut Cerac [11]. These tests show promising results for vapor compression. Screw compressors have quite recently been put to use for this application. A few installations are now in operation and are working satisfactorily.

Efficiencies for screw compressors for steam compression:
There are relatively few published data that show how the efficiencies of screw compressors for steam compression vary with important parameters, such as pressure ratio and pressure levels. From tests performed at Electricité de France, Degueurce et al. [11] have published data. The tests have been done with an oil-free twin screw compressor, originally designed for air compression.

A general conclusion from the French study is that screw compressors are good for steam compression and that the two working fluids (despite the fact that the thermodynamic characteristics of steam are different from the corresponding ones for air) give similar efficiencies for the same level of inlet pressure (Table 2.5).

2.3.2.4 Mono Screw Compressors

Degueurce et al. [12] describe tests with mono screw compressors without oil injection for vapor compression, which have been performed by Electricité de France. The results showed that mono screws can be used for vapor compression, and that these give higher isentropic efficiencies than roots blowers and ring compressors. For sealing and lubrication of the compressor, water injection is used. The tests also showed that it was difficult to seal the compressor.

2.3.2.5 Reciprocating Compressors

Reciprocating compressors are seldom used for vapor compression, mainly because oil-free reciprocating compressors are very expensive. They are also very sensitive to liquid in the compressor.

2.3.2.6 Roots Blowers

The roots blower is a robust and inexpensive compressor. The pressure difference is limited to approximately 1 bar per compressor step in order not to make the leakages too large.

The isentropic efficiency for roots blowers is lower than other types of compressors for vapors, usually between 45% and 55%. According to Hodgett, roots blowers in two steps for vapor compression are now being developed [13]. The price will be around one-half that of conventional turbo compressors, and an isentropic efficiency of 55-65% is hoped for.

2.3.2.7 Ring Compressors

Ring compressors are very seldom used in MVR applications. Their simple design makes them relatively inexpensive. They can also work with very contaminated vapor. This type of compressor has three disadvantages: it has low capacity, it only handles pressure ratios up to approximately 1.5, and its isentropic efficiency is low (20-50%).

2.4 Thermal Vapor Recompression (TVR)

Heat pumping can be accomplished with the help of an ejector and a high-pressure vapor according to the principle shown in Figure 2.19. In some applications, two or three ejectors can be coupled in series (Figure 2.20). Unlike the mechanical vapor compressor, this type of heat pump is driven by heat (i.e., steam) instead of electricity. It is also called an ejector heat pump.

Figure 2.19 Principle for TVR

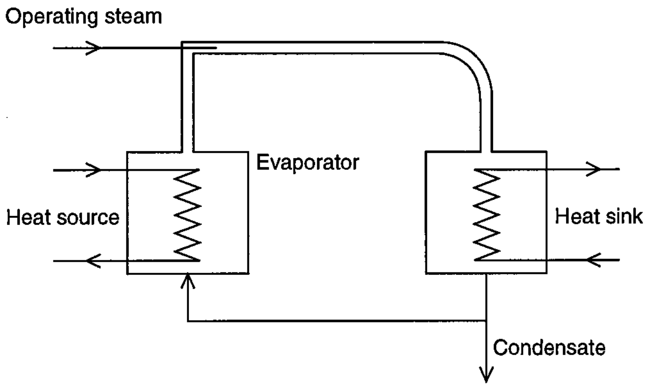
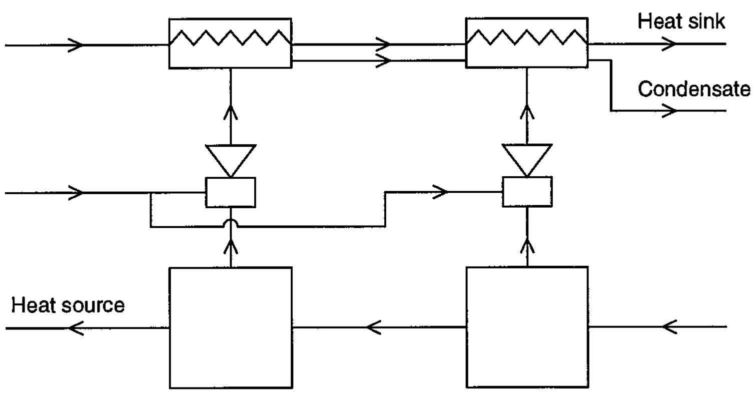


Figure 2.20 Series coupling of TVRs

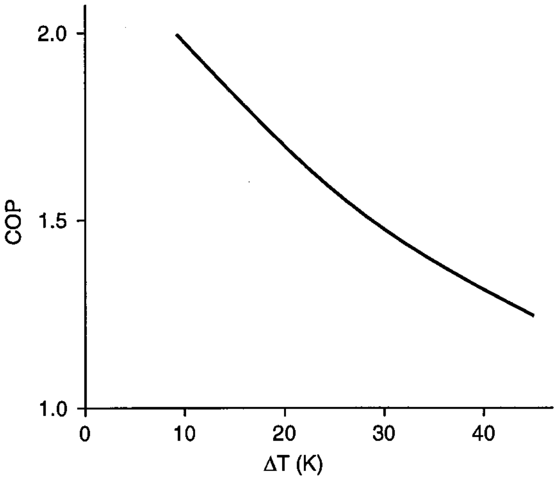


A heat pump like this is simple to design and does not contain any moving parts. On the other hand, it demands motive steam of a relatively high pressure, mostly 7-15 bar. It can be designed for heat loads in all sizes applicable for industry. Common applications of TVR systems are in distillation and evaporation with temperature lifts of 10 K to 20 K.

Important advantages of this cycle are its simple design, low capital cost, and corresponding low maintenance costs. On the other hand, the noise level from such an installation can be rather high.

The coefficient of performance is defined as the ratio of heat output in the condenser to heat input from the motive steam. Using data supplied by a producer (Entropy in France), the values of the COP under different circumstances have been calculated for an installation with two ejectors. Figure 2.21 shows approximated COP values versus the temperature lift, defined as the temperature difference between outgoing heat sink and outgoing heat source. The pressure of the motive steam has been set to 10 bar, but the results are relatively indifferent to the vapor pressure as long as it is between approximately 7 bar and 15 bar. The values in the figure are valid independently of the absolute temperature level of the heat sink, as long as this is clearly below 100°C.

Figure 2.21 COP versus temperature lift for TVR



As can be seen in the figure, the COP can be as high as 2, but is normally around 1.2-1.5. It should be noted that the boiler efficiency for the production of motive steam is not included. Thus, the COP at low temperature lifts is of the same magnitude as for the absorption heat pump, but the ejector heat pump has much lower capital costs.

TVRs permit some capacity control by throttling the motive steam or by using a variable-area motive nozzle. A broad range of capacities is best achieved by using multiple ejectors and turning individual ejectors on and off to match the changing load.

2.5 Absorption Cycles

2.5.1 Operating Principle

An absorption heat pump cycle makes use of the fact that the boiling temperature for a mixture is higher than the corresponding temperature for a pure component at the same pressure. Therefore, the working fluid in an absorption cycle must be a mixture, often a binary mixture consisting of a volatile component and an absorbent (non-volatile) component.

The fundamental absorption one-stage heat pump cycle has two possible configurations (Figures 2.22 and 2.23). An outline for the cycles is shown in a pressure-temperature (P-T) diagram (Figure 2.24), in which the different pressure and temperature levels can be observed.

Figure 2.22 Absorption heat pump cycle, type I

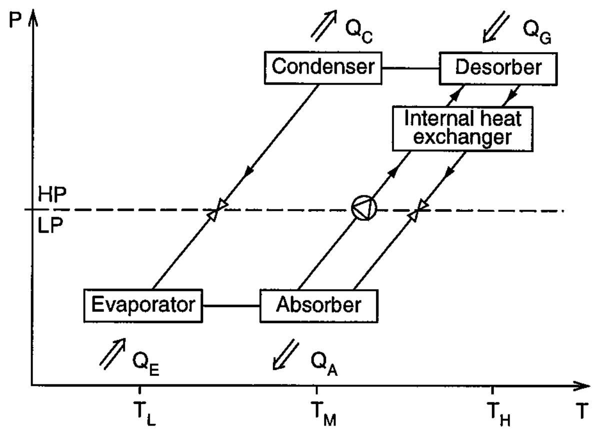
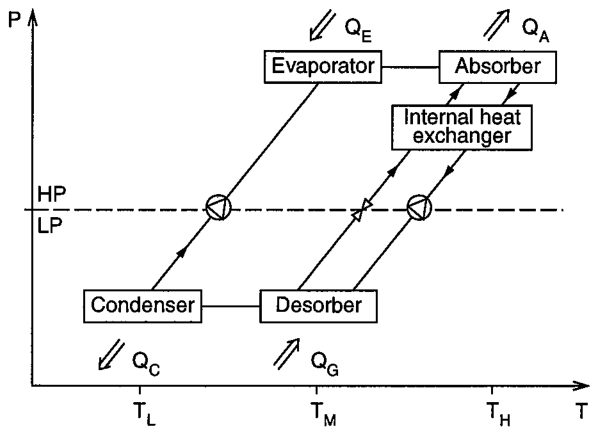


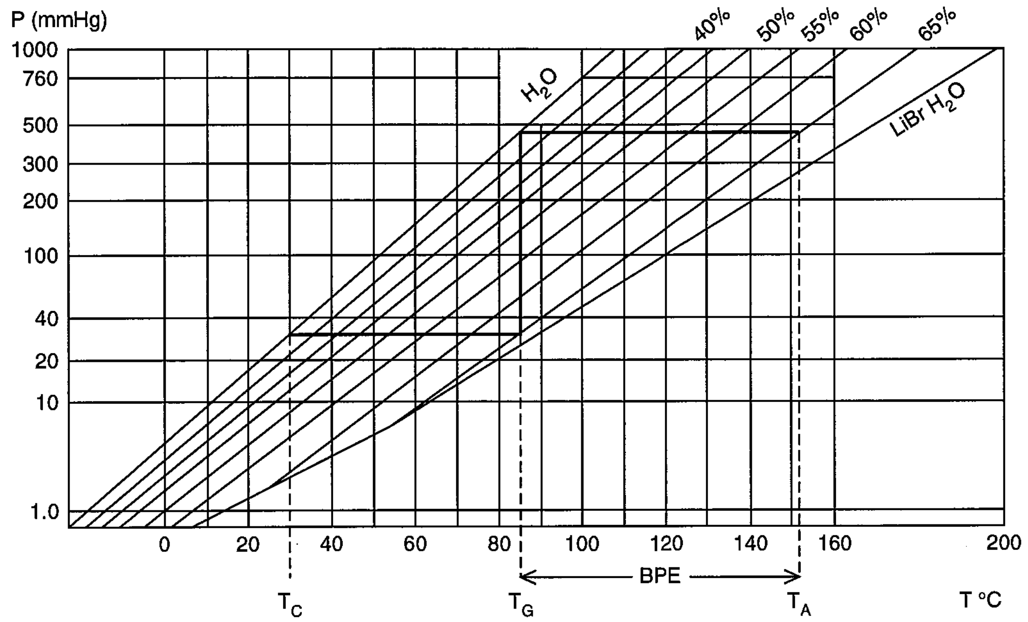
Figure 2.23 Absorption heat pump cycle, type II



The first cycle is generally called an absorption heat pump (AHP, type I) and the other is called a heat transformer (HT) (or AHP, type II). The difference between the cycles, as seen in the figures, is that the pressure levels are reversed. This means that the different heat flows are found at different temperature levels, which indicate the different purposes of the two cycles. In the absorption heat pump, the heat is lifted from a low temperature level (T_L) to a medium level (T_M). This is possible by supplying heat at a high temperature level (T_H). In the heat transformer, the heat is supplied at a medium level (T_M). One part of this heat is transformed to a high level (T_H) and the other is delivered at a low level (T_L). Therefore, the heat transformer is useful for recycling or recovering industrial waste heat in situations where there is an excess of waste heat at a medium temperature level; allowing the plant to run on excess heat alone with no need for a supply of primary energy. To give an understanding of how these cycles work, the absorption heat pump is described below in more detail.

The weaker (regarding the absorbent) solution arrives in the desorber and is heated by supplied primary energy. Here, some of the volatile working fluid is evaporated creating a strong solution. The vapor generated is then condensed in the condenser at a lower temperature, which is a result of the elevation of the boiling temperature in the desorber. The condensate

Figure 2.24 Düring diagram with indicated heat transformer cycle (BPE = Boiling point elevation)



is fed to the evaporator via an expansion valve and is evaporated at low pressure and low temperature. The vapor formed is then absorbed in the strong solution which has been pumped from the desorber to the absorber. The cycle is then closed by pumping the weak solution back to the desorber. The internal heat exchanger between the strong and the weak solutions (Figure 2.23) is necessary in order to reach an acceptable COP.

The two most commonly used working fluids in absorption heat pump cycles are NH_3/H_2 and $LiBr/H_2O$; the latter is the more frequently used in industrial applications. A new working fluid, Alkitrate™, specifically developed by Energy Concepts (Annapolis, MD) with support from the U.S. Department of Energy for high-temperature applications (e.g., 200°C) is also available.

2.5.2 Capacity

When discussing capacity for absorption heat pump cycles, there are three parameters of interest: COP, possible temperature lift, and maximum possible temperature of delivered heat. These are defined as:

AHP: $$COP = \frac{\textit{Useful heat at } T_M}{\textit{Heat supplied at } T_H} = \frac{Q_C + Q_A}{Q_G} \qquad T_{lift} = T_M - T_L$$

HT: $$COP = \frac{\textit{Useful heat at } T_H}{\textit{Heat supplied at } T_M} = \frac{Q_A}{Q_E + Q_G} \qquad T_{lift} = T_H - T_M$$

The maximum temperature lift for a heat pump with $LiBr/H_2O$ is 45-50 K, while it is 5-10 K higher for the heat transformer. The limiting factor is the risk of crystallization. For the same reason the maximum possible temperature of delivered heat in the absorption heat pump (T_M) is approximately 100°C. The corresponding temperature for the heat transformer (T_H) is approximately 150°C.

Typical values of the coefficient of performance for an absorption heat pump with this working pair are 1.6-1.7. This figure does not include the combustion of oil, gas, etc. when supplying primary energy. With reasonable boiler efficiencies, the resulting coefficient of performance is 1.3-1.4. Corresponding figures for the heat transformer are typically 0.45 to 0.49, which means that almost 50% of the waste heat can be brought back to the process at a higher and useful temperature level, without needing to supply any primary energy.

Capacity under different circumstances is often studied in a so-called Dühring diagram which allows the examination of possible temperature lifts (Figure 2.24).

According to Berntsson, the following relations for heat transformers can be formed:

$$T_{absorber} - T_{heat\ source} \leq 0.8 \cdot (T_{heat\ source} - T_{condenser})$$

or

$$T_H - T_M \leq 0.8 \cdot (T_M - T_L)$$

which means that possible temperature lifts are strongly dependent on the temperature of the heat source, i.e., the waste heat [14].

3. Integration of Heat Pumps in Industrial Processes

3.1 Introduction

One of the main objectives of Annex 21 was to develop a computer program to assist potential users in assessing the opportunities to integrate industrial heat pumps into different types of industrial processes. The program is also designed to determine the economics of heat pumps, at least on a preliminary basis. The Annex participants agreed that the computer program would be developed based on pinch technology concepts. This chapter discusses the general principles for the process integration of heat pumps. The main approach used for the computer program and a detailed description of the program are also presented. Additional information on the IHP screening program is provided in Appendix A.

3.2 General Considerations and Principles

3.2.1 Introduction

Compared with residential heat pumps used for household heating, industrial heat pumps have, in many cases, the following advantages [15]:

- High COPs (coefficient of performance) resulting from small temperature lifts and/or high temperature levels.
- Long annual operation time.
- Relatively low investment cost, based on small intervals between the heat sink and heat source.
- Heat source production and heat sink demand occur simultaneously.

Despite these advantages, relatively few heat pumps are now used in industry worldwide compared to the number of technically and economically feasible opportunities. To date, IHPs have been applied on a large scale in only some special applications (e.g., lumber drying, petrochemical distillation, evaporation), even though their economic returns (e.g., payback period) have been shown to be quite attractive in many other industrial processes. Factors explaining this situation include:

- A lack of suitable hardware in some types of applications.
- A lack of experimental and demonstration plants in different types of industries.
- A lack of the combined knowledge of process technology and heat pump technology in industry, consulting companies, and utilities, among others.

Another important reason is the lack of knowledge in industry on how to properly identify or find good, economic IHP applications with the aid of process integration principles. Most heat pumps installed in industry are used with individual unit operations, such as drying and evaporation, and are therefore not process integrated. Systematic searches for appropriate heat sources and heat sinks throughout industrial plants have often revealed that the potential for different types of industrial heat pumps is considerably higher than previously anticipated.

3.2.2 Principles of Process Integration with Pinch Technology

Integrating a heat pump properly within an industrial process requires a good knowledge of the process. In this respect, pinch technology is a very powerful tool in process analysis [16].

In a pinch technology analysis, the process streams are characterized by their start and final temperatures and by their heat flow rate (i.e., the mass flow multiplied by the heat capacity). Streams requiring cooling are called hot streams, whatever their absolute temperatures are, and streams requiring heating are called cold streams.

One of the most important features of pinch technology is that it is possible to identify a temperature (the pinch) in a process that divides the stream system into two separate parts. In the part above the pinch, there is a net heat deficit, and heat must be added to the system by a hot utility. If a cold utility is applied above the pinch, it follows that the demand for the hot utility will increase by the same amount. Thus, valuable heat is just off-set by the amount of cooling added. On the other hand, in the part below the pinch, there is an excess of heat that must be removed from the system by a cold utility. Any heat added below the pinch must also be removed. Hence, in a well designed process, no cold utility should be used above the pinch and no hot utility below the pinch.

Composite curves are useful tools in pinch technology. These consist of two curves representing the composite hot and cold streams. The curves are constructed by adding the heat content of all hot and cold streams, respectively, in each temperature interval. The accumulated heat content can then be plotted on a temperature/heat content diagram (Figure 3.1). It is possible to exchange heat from the hot streams to the cold streams where the two curves overlap horizontally, and the vertical distance between the curves represents the temperature difference in the heat exchange. Where the two curves do not overlap, external heating or cooling by plant utilities is necessary.

Another often used tool is the Grand Composite Curve (GCC). As shown in Section 3.2.4, it can be used to assess different heat pump opportunities. It is constructed as the net heat needed ((heat needed in all hot streams) - (heat available in all cold streams)) in each temperature interval. The temperatures of the streams are adjusted based on the minimum temperature difference (ΔT_{min}) needed for the heat exchange process. One-half of the ΔT_{min} is subtracted from the hot streams and one-half is added to the cold streams.

An example of a GCC is shown in Figure 3.2. At the pinch temperature the net heat needed is zero. Above the pinch the distance between the y-axis and the curve represents the net heat needed at each temperature level, and the distance at the highest temperature corresponds to the hot utility to the system. Below the pinch the horizontal distance represents the net heat available at each temperature level.

Figure 3.1 Composite curves

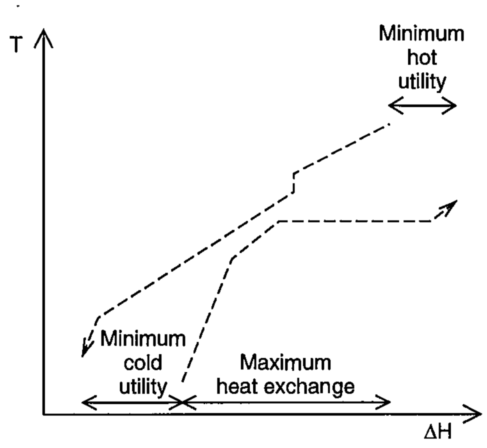
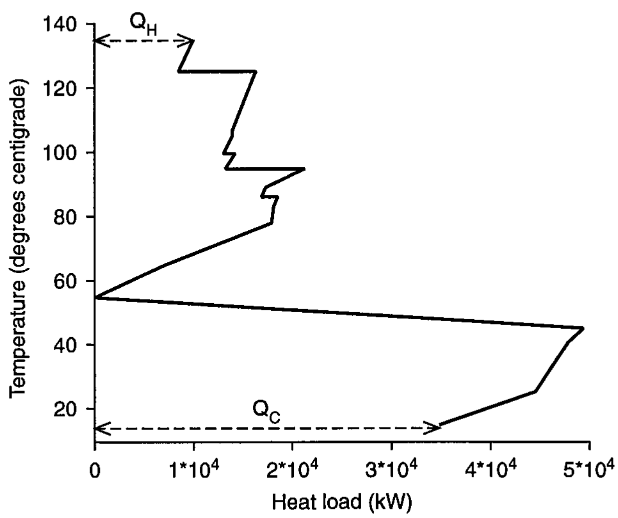


Figure 3.2 A typical example of a Grand Composite Curve

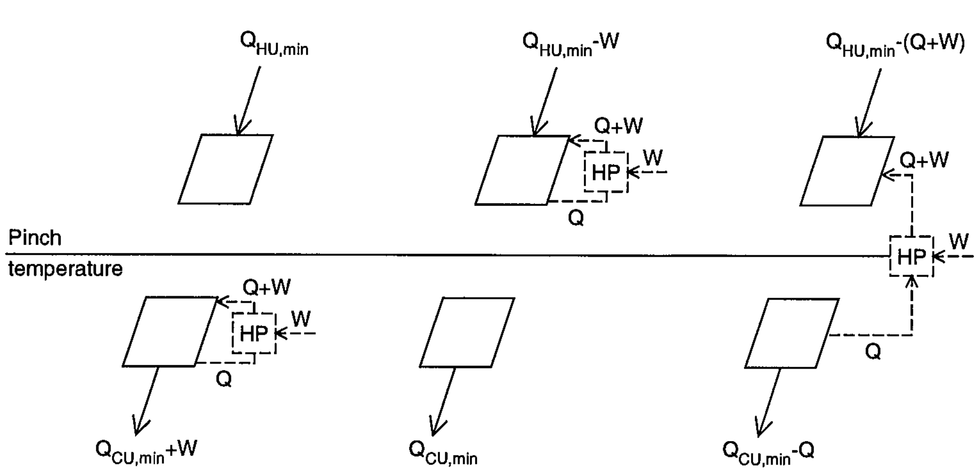


3.2.3 Process Integration of Heat Pumps

Figure 3.3 shows three ways of integrating a heat pump. A heat pump must be integrated in such a way that the heat source is situated where there is an excess of heat (i.e., below the pinch), and the heat sink where there is a need for heat above the pinch. In fact, the existence of a pinch makes a heat pump always thermodynamically feasible, because a certain amount of cooling below the pinch and heating above the pinch would remain even after the most intelligent heat exchanging arrangement.

In practice, technical and economic constraints limit the actual potential for heat pumping, and the pinch temperature in a process is a crucial parameter when assessing heat pump opportunities.

Figure 3.3 Placement relative to the pinch of a heat pump



The consequences of integrating a heat pump into a process can be analyzed with the aid of the composite curves (Figure 3.4). When taking heat to the heat pump below the pinch, the heat available for process heat exchanging decreases. This also means that the vertical distance between the curves decreases below the starting temperature of the heat source stream(s). This decrease in driving force means that the area needed for process heat exchanging in many cases becomes larger, and possibly that more heat exchanger units must be added. The influence on the heat exchanger network obviously increases the closer the heat source temperature is to the pinch.

At each temperature level the theoretically highest amount of heat that can be used as a heat source corresponds either to the horizontal distance between the composite curves at that temperature (in reality a certain ΔT_{min} must be accounted for) or, if a new pinch is created at a lower temperature, the heat amount creating this new pinch. If one extracts more heat, say Q_{add}, it means that the composite curves must be moved from each other, and hence that the hot utility increases by the same amount (i.e., Q_{add}). Therefore, this case means a need for a larger heat pump without any additional heat saving, and consequently is not practical. This same point also holds for the situation above the pinch.

By process integrating the heat pump instead of using it from the cold utility temperature to the hot utility one, the heat pump will, in most cases, by necessity become smaller. On the other hand, this configuration may be economic as a result of the smaller temperature lift and hence higher COP.

The approach to finding the most appropriate heat pump installation in a given plant depends on whether it is a grassroots or a retrofit design problem. In a grassroots design, the most important parameters can be optimized; in a retrofit situation, the practical constraints make it necessary to take another approach. These aspects are discussed below. First, however, some important characteristics of heat pumps in a process integration context are discussed.

Figure 3.4 Two example composite curves with and without installed heat pump

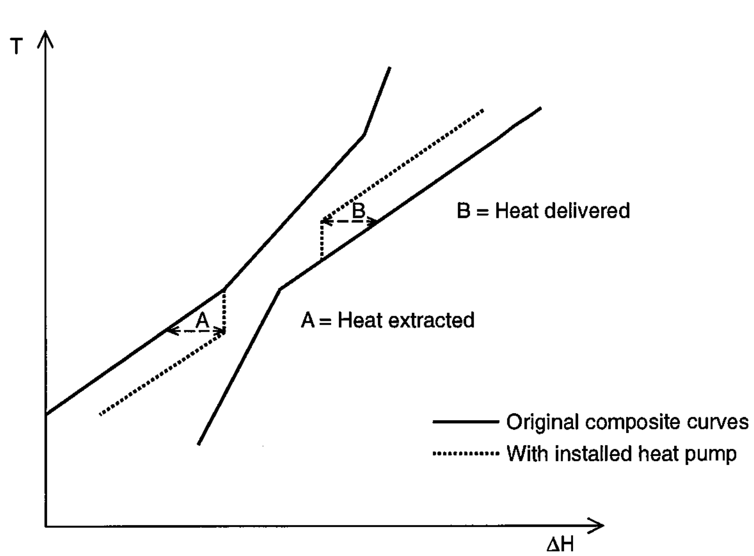


Figure 3.4a

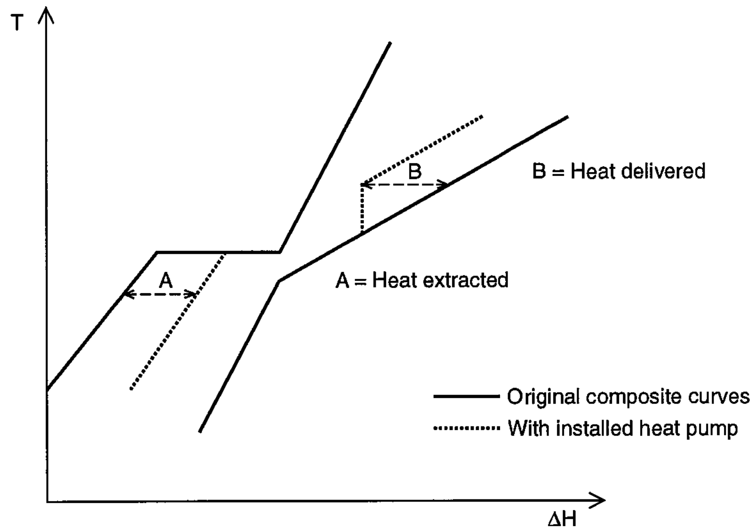


Figure 3.4b

3.2.4 Some Characteristics of Different Heat Pump Types

As has been shown, it is important for a process integration study to include detailed characteristics of both the heat pump and the industrial process. Some technical characteristics and constraints for the most often discussed types of heat pumps for industrial application are presented in this section.

The two most important characteristics of a heat pump type from a process integration point of view are the range of pinch temperature levels in which it can operate and the "q value". The q value is the relation between the heat sink and heat source energy amounts and is defined as follows:

Heat sink = Heat source + Drive Energy

COP = Heat sink / Drive Energy (1)

$$q = \frac{\text{Heat sink}}{\text{Heat source}} = \frac{\text{COP}}{\text{COP-1}}$$

Economic factors (e.g., energy prices, investment costs) will also influence the proper choice of IHP.

3.2.4.1 Closed Compression Cycle

The electrically driven closed-cycle compression heat pump cannot, with the working fluids used today, operate at condensing temperatures above approximately 120-130°C. Thus, the pinch temperature must be lower than 120°C. Furthermore, to be economic, the COP must probably be higher than 3, which limits the temperature difference between the condenser and evaporator. This also implies that the composite curves must allow the heat to be extracted and delivered not too far from the pinch temperature, with q values of about 1.2 to 1.5 (i.e., COPs of 6 or 3) [17].

3.2.4.2 Mechanical Vapor Recompression

The mechanical vapor recompression (MVR) heat pump can operate at relatively low condensing temperatures, 60-80°C, if the temperature lift is extremely low. For the probably most common case in process industries – production of process steam at 120°C or above – the heat source temperature must normally be higher than approximately 80°C for economic and construction-related reasons. Thus, in such cases the pinch temperature should be higher than, say, 90-110°C for this type of heat pump. The temperature lift for the compressor involved should normally be relatively modest, which implies that the composite curves must allow heat to be extracted and delivered not too far from the pinch. COPs are normally quite high compared to other IHP types (generally between 5 and 20), with q values between 1.1 and 1.3 [14].

3.2.4.3 Heat Transformer

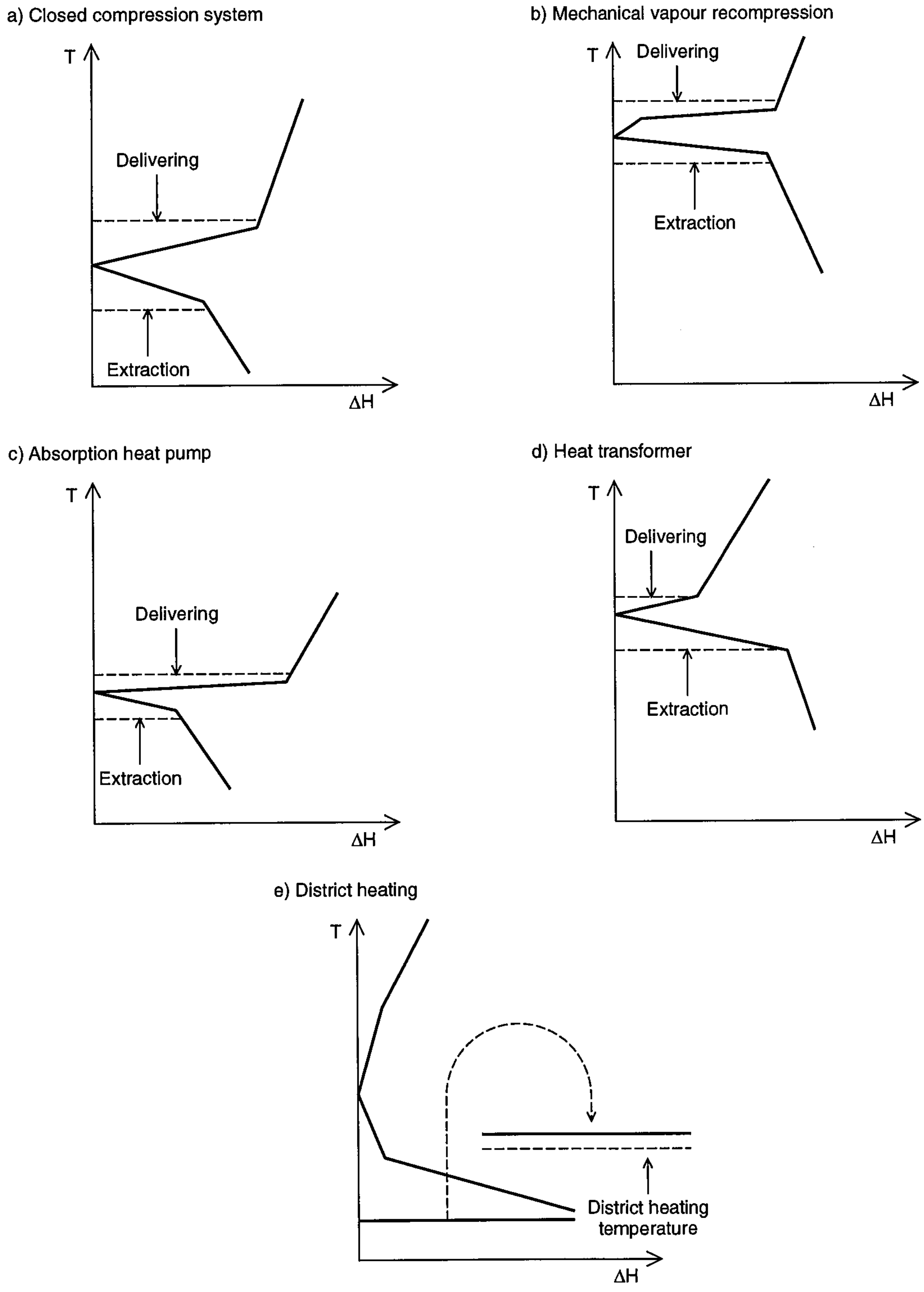
The heat transformer can operate up to 150°C with a maximum temperature lift of about 50°C and a lower limit on the heat source temperature of 55-60°C. The pinch temperature should therefore be between 60 and 130°C to fit the heat transformer. This type of heat pump operates without electricity and is capable of upgrading half of a heat source to a higher temperature. Heat sinks, which are half the size of the heat source, are therefore ideal (q = 0.5) [18].

3.2.4.4 Absorption Cycle

The absorption heat pump (type I) can deliver heat up to 100°C with the working fluids used today, which implies that the pinch temperature must be lower than, say, 80°C to fit this type. The heat pump is driven by primary heat and with a constant COP of approximately 1.6 the q value is about 2.7 [17].

The suitability of a heat pump in a given industrial process varies with the energy characteristics of the process. A Grand Composite Curve can be used to assess suitable types of heat pumps for a given industrial process. Figure 3.5 shows "ideal" forms of these curves for different types of heat pumps.

Figure 3.5 "Ideal" Grand Composite Curves for different types of heat pumps



3.2.5 Important Parameters

Within a given industrial process, there is normally a range of technically possible IHP sizes as well as sink and source temperatures. In such cases, a high COP should be possible to achieve since the sink and source temperatures can be chosen close to the pinch. This means, however, that the IHP size (i.e., heat output) often in small (Figure 3.4). The case when the possible IHP size is large represents, on the other hand, a very beneficial situation.

Another important aspect is the changes that must be made in the heat exchanger network (HEN) when the hot utility (Q_H) is decreased. A decrease in Q_H can be achieved by increased heat recovery (both enlargements of existing heat exchangers and totally new heat exchanger in an existing plant), by the use of a heat pump, or by a combination of these two techniques. In the first case, the global ΔT_{min} (ΔT at the pinch, see A.7) between the composite curves (Figure 3.4) is reduced, whereas in the second, it remains constant.

Also in this case, there is in many instances (depending on the actual location of heaters and coolers) a need for improvement of the HEN, generally both in terms of more area and more heat exchangers (at least in a retrofitting situation). This is because a heat pump reduces the driving forces for heat exchanging at temperatures above the sink, and below the source, temperature (Figure 3.4). Hence, to achieve the desired reduction in Q_H (i.e., equalling the heat pump output), this reduction in driving forces must be compensated for by improved heat exchanging. The investment costs for such modifications vary with the position of the heat pump and the total number of streams (i.e., with the original number of heat exchanger units).
As Figure 3.4 shows, the additional heat exchanger area needed increases with the size of the heat pump, with decreasing sink temperature, and with increasing source temperature. The number of additional heat exchangers needed for this area is a function of the number of streams influenced by the heat pump's introduction and the temperature levels involved, and also by the total number of streams and heat exchangers in the existing system.

The influence of a heat pump's introduction on the HEN must be taken into account when investigating the economic opportunities for heat pumps in a given industrial process.

Improved heat recovery and heat pumping are often viewed as competing energy conservation technologies in industry. However, they should be seen as two possibilities, which combined can be a better solution than either option alone. This means that an improvement of the HEN (i.e., a certain reduction in the global ΔT_{min}) before a heat pump is introduced can, in many cases, be the most optimal solution. Therefore, the global ΔT_{min} should be seen as one of the main design variables when integrating a heat pump.

The most important parameters to take into account are:

- Investment costs for additional heat recovery.
- COP for the heat pump.
- Investment costs for the heat pump and for necessary changes in the HEN (area and additional units) [19].

The main design variables then are:

- global ΔT_{min};
- type heat pump;
- size of the heat pump;
- sink temperature;
- source temperature.

The most appropriate choice of these variables in a given industry will depend on the economic criteria used for the evaluation: payback period (PBP), annual profit (at a given annuity factor, see A.7), maximum allowed investment cost, or any combination of these.

In a grassroots design, when all the parameters discussed above (including the whole heat exchanger network) can be designed freely, all of the main design variables can be optimized in detail [19,20].

However, heat pump integration more commonly involves a retrofit into an existing plant, where the HEN already exists. This causes numerous practical constraints, making it virtually impossible to implement the results of a theoretical optimization. In this case, another procedure must be used. An alternative methodology developed by Wallin and Berntsson [21] is presented below.

3.2.6 Methodology for Assessing Heat Pump Opportunities in Retrofitting Situations

Because of the great number of technical and practical constraints (e.g., physical space, distance between unit operations, desired process flexibility) in an existing industrial plant, the basic principle of Wallin and Berntsson's methodology is to produce a "map" of all economically feasible opportunities for heat pump integration and then compare these results with the actual constraints. In this way, opportunities that are both practically possible and economically feasible can be identified. Also, a number of related values for all the main design parameters for a given type of heat pump can be obtained. The methodology, in which all these parameters are included, is presented below.

A scanning procedure is performed in which all thermodynamically possible heat pump installations are assessed economically. For a given global ΔT_{min}, T_{sink} and T_{source}, the payback period (PBP) for the range of thermodynamically possible sizes for a given heat pump type is calculated. This procedure is repeated for a number of different T_{sink} values until the entire range for this parameter has been scanned. The same is done for T_{source} and, finally, the whole procedure is repeated for a number of decreasing global ΔT_{min} values. For each point, the investment cost of the heat pump and the heat exchanger network (total area and number of units needed for decreasing the global ΔT_{min} and compensating for the temperature driving forces when the heat pump is introduced) as well as the heat pump COP are calculated. The PBP can then be calculated as:

$$PBP = \frac{\text{investment cost}}{\Delta \text{ operating cost}} \qquad (2)$$

The calculation procedure for the heat exchanger area and the number of units needed is complex and is based on "traditional" pinch technology and methods developed by Wallin and Berntsson [21]. A detailed discussion of these methods is beyond the scope of this report.

For a given PBP, there can be several different IHP designs. To choose the most economic alternative, other economic evaluation criteria such as annual profit or maximum allowed investment cost can be used. For a given PBP, the annual profit can be calculated according to:

$$\text{Annual profit} = \left[\frac{1}{\text{PBP}} - a \right] \cdot \text{Investment cost} \qquad (3)$$

where *a* is the annuity factor (defined in A.7).

The most important part of the methodology is the approach for evaluating all the PBP calculations. This is presented in the next section.

3.2.7 Evaluation of Different Heat Pump Integration Opportunities

The evaluation is done in three steps:

- Identification of the most economic global ΔT_{min} value.
- For this ΔT_{min}, identification of the most feasible combinations of size, T_{sink} and T_{source}.
- By comparison with actual practical constraints, identification of one or a few design parameter combinations on which the real design calculations should be based.

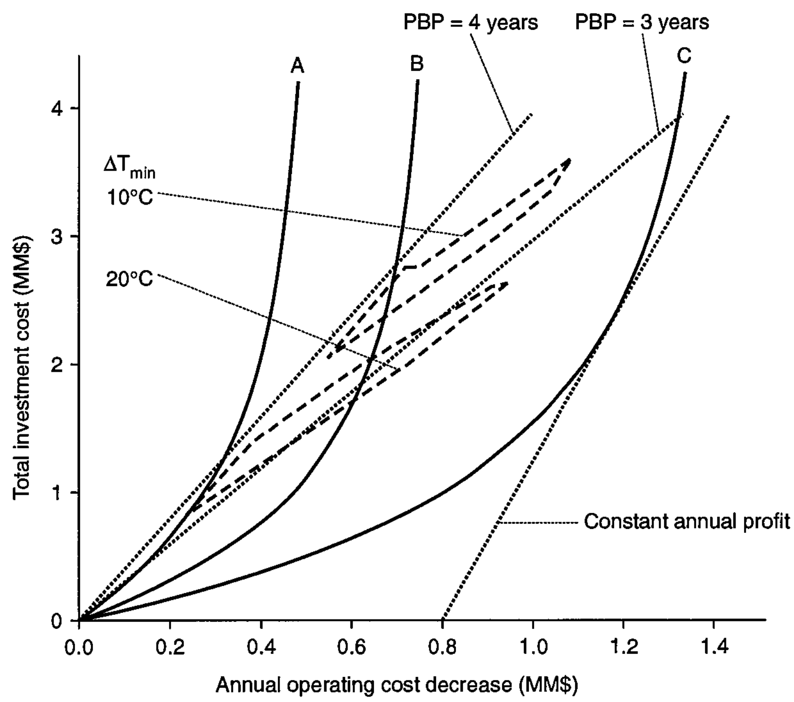
The most economic global ΔT_{min} value(s) is identified by plotting all the scanning procedure results on a diagram, with the total investment cost (nominator in the PBP expression) on the y-axis and the gross annual profit (denominator in the PBP expression) on the x-axis. A constant PBP value can then be shown as a straight line from the origin and a line for a given annual profit as a straight line with the annuity factor as a derivative, and the interception with the x-axis giving the value of the annual profit.

Figure 3.6 shows an example of such a diagram. The different heat pump opportunities are shown for two levels of global ΔT_{min} (10°C and 20°C). These lines thus represent the combined result of heat pumping and heat exchanging compared to the original network. (The global ΔT_{min} must of course be equal to or smaller than in the original network). For comparison, the opportunities for heat exchanging only (i.e., with no heat pump at all in the system) are also shown.

For the purpose of illustration, three different curves of this kind are included in Figure 3.6 (in reality, only one curve can exist). If the heat exchanging opportunities are as in case C in the figure, pure heat exchanging would always be more economic than a combination of heat exchanging and heat pumping.

For the A case, where the costs for pure heat exchanging quickly reach infinity, a combination of heat exchanging and heat pumping should normally be considered with no, or only a small, decrease in the global ΔT_{min}. Finally, in the B case, pure heat exchanging is more

Figure 3.6 Economic heat pumping and heat exchanging opportunities



advantageous for a small decrease in operating costs, but for larger savings a combination of heat exchanging and heat pumping should lead to the most economic design.

In the figure, the global ΔT_{min}, giving the lowest PBP or the highest annual profit with a maximally allowed investment cost (or any other subcriterion), can be identified easily. Sometimes, the areas for different ΔT_{min} are superimposed on each other. In such cases, a detailed evaluation must be done for a few selected ΔT_{min} values.
A number of important conclusions can be drawn from the type of diagram shown in Figure 3.6:

- Overall economic heat pump opportunities when the competing technique of improved heat exchanging is taken into account.

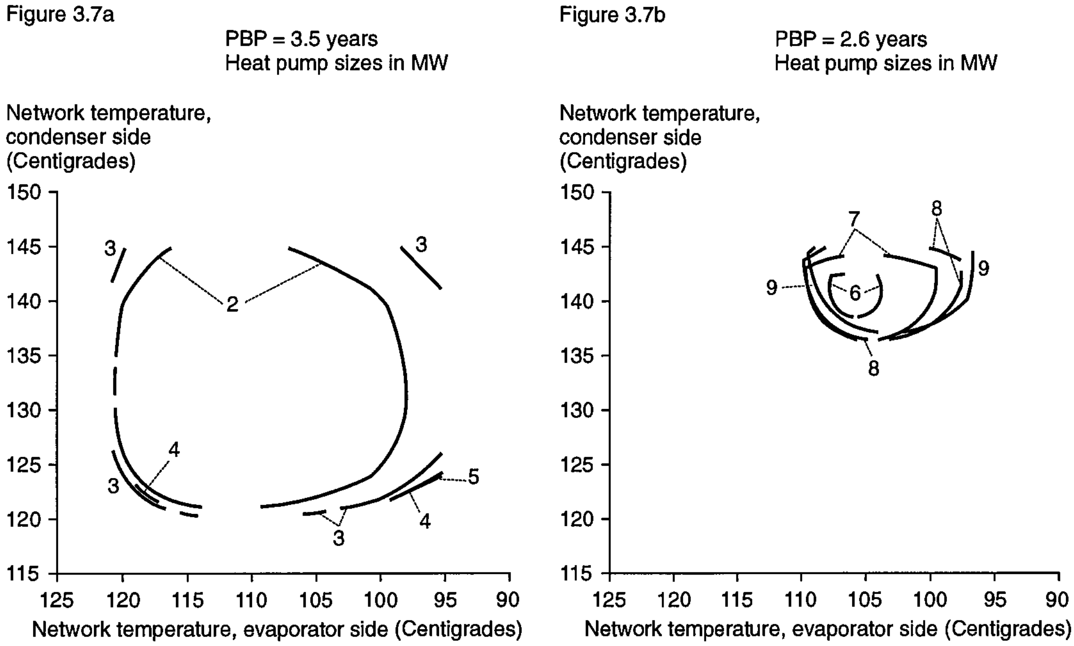
- Possible range of PBPs for energy conservation with heat pumps.

- Most economic value(s) of the global ΔT_{min}.

Figure 3.6 does not address the most economic combinations of IHP size, T_{sink} and T_{source} at a given ΔT_{min}. This must be evaluated separately in the following way.

When a ΔT_{min} value has been chosen, calculation results at this value can be presented in diagrams with T_{sink} versus T_{source} on the y-axis and x-axis, respectively, with the IHP size as a parameter at a constant value of the PBP. Diagrams should be produced for different values of PBP. Two examples of such diagrams are presented in Figure 3.7. They are the results of calculations for a set of conditions for the MVR type of heat pump. Details on the conditions

Figure 3.7 Network temperature for heat pump integration, condenser side versus evaporator side with the size as a parameter for two payback periods



chosen can be found in Wallin and Berntsson [22]. The results for two PBP values, 3.5 and 2.6 years, are shown.

As can be seen in the 3.5 year case, several combinations of IHP size, T_{sink} and T_{source} give the same PBP. The values at the upper right of the diagram have relatively high operating costs (i.e., small savings) and a low investment cost (e.g., high temperature lift, giving a low COP and a small influence on the heat exchanger network), whereas those at the lower left have low operating costs (i.e., large savings) and a high investment cost (e.g., low temperature lift, high influence on the heat exchanger network). This means that the combinations at the lower left have a higher annual profit, as the result of a higher investment cost at a fixed PBP (see Equation 3), whereas the ones at the upper right end influence a smaller number of heat exchanger units and should therefore create fewer problems with installation, flexibility and control.

Moving to a lower PBP means that larger IHP sizes appear in the diagram and at high temperature lifts only. There are two reasons for this. First, the temperature lifts needed in this example, which produce little or no influence on the HEN, still give reasonable COPs and, hence, a low PBP. Second, these low PBPs are impossible to achieve for the smaller sizes because of their higher specific investment cost.

Under the conditions in the example, a higher temperature lift gives opportunities both for decreasing the PBP and for increasing the IHP size. These results are also common under other conditions. Hence, in many cases, a relatively high temperature lift is advantageous, determined by the trade off between increasing operating costs and decreasing specific installation costs at higher temperature lifts.

The consequences for the PBP of a change in temperature lift for a given heat pump size depend on the situation. An increase in temperature lift means:

- An increase in PBP if the total annual heat pump cost is determined mainly by the operating costs.

- A decrease in PBP if the total cost is determined mainly by the investment costs.

The example above addressed only one type of heat pump. Different types of IHPs have different operating characteristics and operating and investment costs, which will result in different integration possibilities. One extreme example would be the heat transformer (absorption heat pump, type II), which has practically no operating cost. However, the principles and the methodological approach discussed in connection with the diagrams can be used for all types of heat pumps. The method should be an excellent tool for making comparisons between different heat pump types.

With the aid of the PBP calculations in the scanning procedure, it is also possible to draw more detailed conclusions about the most economic heat pump designs, when criteria such as annual profit and/or maximum investment cost are used [22].

The following general conclusions can be drawn from the type of diagram shown in Figure 3.7:

- There are often many combinations of IHP size and sink and source temperatures that result in the same PBP.

- The most economic sets of combinations can be identified in the diagrams presented.

- With these diagrams any heat pump installation can be economically evaluated and can be compared with practical constraints at the temperature levels identified.

- Normally, as large a heat pump as possible at a specified demand for PBP should be chosen, due to its high annual profit.

- For a heat pump of a given size the same PBP can, in many cases, be achieved at both a high temperature lift (e.g., low HEN investment costs, high operating costs) and a low lift (e.g., high HEN investments costs, low annual operating costs). The high temperature lift case generally has fewer practical problems (flexibility and control aspects, changes in the HEN), but a somewhat lower annual profit.

3.3 Approach in the Annex 21 Work

As the discussion above indicates, the potential for heat pumping in an existing industry depends to a great extent on the design of the heat exchanger network and the potential for saving energy by improved heat exchanging. Wallin and Berntsson's approach allows the most economic heat pump to be identified in terms of type, size and temperature levels [22]. It also outlines the associated costs for heat exchanger network modifications when the heat pump is introduced.

However, their approach is relatively complicated and is based on a detailed knowledge of the actual heat exchanger network in a specific plant. It was thus not suited for the Annex 21 work, where a more general approach for identifying reasonable opportunities for heat pumping in different types of industry was needed. The Annex 21 approach is described below.

3.3.1 Competition Between Heat Pumping and Improved Heat Exchanging

A heat pump's introduction into an industry would likely be done as part of a larger retrofitting project, where improvements in the heat exchanger network are also carried out. A study of the heat pumping potential in a given type of industry should thus be done at a relatively low global ΔT_{min}, reflecting a reasonable degree of improved heat exchanging. The value to choose depends on a number of technical, economic and site-specific conditions.

For the Annex 21 screening program and market assessments, it was necessary to choose a reasonable ΔT_{min} value. This was done with the aid of the $Q_{H,min}/\Delta T_{min}$ diagrams that were included in the computer program.

In these diagrams, the technically possible energy savings for different processes, as a function of global ΔT_{min}, were outlined. If the slope of the curve is such that an additional saving below a certain ΔT_{min} value is low, then this ΔT_{min} value could be chosen as a reasonable "after-retrofit" value. If the curve did not give any guidance about a reasonable value, a level between 10 K and 15 K was determined as reasonable. These are typical values from real projects, although large variations can occur under different conditions. No direct connection between reasonable after-retrofit global ΔT_{min} and type of industry has been found. In the program, the user can choose his/her ΔT_{min} value for each process to be analyzed. A default value, based on the discussion above, is also included in the process data.

3.3.2 HEN Change and Other Costs when Introducing a Heat Pump

The investment costs for an industrial heat pump can be divided into three main parts:

- the heat pump itself;
- building/enclosure and piping to and from the process plant;
- necessary HEN changes.

The two first costs can be assigned reasonable general values by using information from manufacturers, installers and real heat pump installations, although the piping costs can vary considerably among plants. The third cost item, however, is always very site-specific.

As discussed in Section 3.1, the necessary HEN changes in the form of enlargements of existing heat exchangers and/or the introduction of new ones can, in many cases, be substantial. Therefore, this cost can contribute considerably to the total investment cost and, in many cases even make it impossible economically to introduce a heat pump.

Generally speaking, the closer in size the sink and/or source is to the theoretically maximum size at given temperature levels, the more HEN changes are necessary. The degree of these changes, however, is also dependent on the actual layout of the HEN (the location geographically and in terms of heater and cooler temperatures). Because it is impossible to make an accurate, general estimate of this portion of the investment cost, this is one of the main uncertainties in the Annex 21 computer program. The approach to the calculation of the surrounding costs is presented in Section 3.3.3.

3.3.3 Identification of Heat Pump Possibilities

The screening procedure described in Section 3.2.6 was simplified for the Annex 21 computer program. This procedure is only performed for one ΔT_{min}, although it can be repeated for other user-specified values. Furthermore, only two possible sizes are assessed:

- The theoretically largest heat pump size at each temperature lift derived for further economic evaluation. This was done on the assumption that the main objective is to save energy, even though there could be IHP configurations that are more economically feasible (e.g., shorter PBP).

- A heat pump that is one-half the size of the largest heat pump identified. This was done based on the assumption that this smaller heat pump size might reflect a more realistic situation in industry, and at a minimum would provide a range of energy savings and IHP economic conditions for the potential user to evaluate.

The installation cost of the heat pump (including piping, etc.) is estimated using values derived from existing heat pumps sites with that data included in the program. The cost for the additional heat exchangers and necessary changes in the HEN are estimated from "traditional" pinch technology considerations. The number of heat exchangers above the sink temperature can be calculated from the number of process streams present above the sink temperature. The number of additional heat exchangers, due to the heat pump installation, is then estimated from the heat pump size and minimum hot utility. At the source size, the corresponding estimation is carried out. The procedure is described in detail in Appendix A, Section A.4.

3.4 Computer Program

The main purpose of the Annex 21 IHP screening program is to serve as a tool to allow for preliminary screening of the technical and economic potential of heat pumps in various industrial processes, based on proper integration into the process. To fulfill this main purpose, a number of functions have been built into the program. These functions also make it possible to use the program as:

- a database for process data;
- a database for heat pump performance data;
- a calculation tool to establish heat pump performance.

The program structure and its possible uses are described below. A detailed description of the program is found in Appendix A.

The program consists of three main parts:

- performance;
- processes;
- integration.

3.4.1 Computer Program: Performance

Performance data are available for seven different IHP types:

- electrical motor-driven closed cycle compression (ECC);
- diesel motor-driven closed cycle compression (DCC);
- mechanical vapor recompression (MVR);
- mechanical hydrocarbon vapor recompression (HMVR);
- thermal vapor recompression (TVR);
- absorption heat pump (absorption heat pump, type I) (AHP);
- heat transformer (absorption heat pump, type II) (HT).

The first four types are further subdivided based on compressor type, refrigerant type, and auxiliaries (i.e., with or without economizer). The TVR, AHP and HT types are not further subdivided. This makes it possible to study variations within each type. The total number of IHPs is 52. The user can modify the performance of each IHP by specifying a factor by which the COP is multiplied. In this way, development trends or custom designed IHPs can be studied.

The performance of an IHP can be studied by either plotting the performance or by specifying the conditions in which the IHP is supposed to operate.

The performance of all IHP types, except the AHP and the HT, is based on internal (condensing and evaporation) temperatures. In the case of the AHP and the HT, performance is based on external (sink and source) temperatures. The reason for this is that internal temperatures are not easily defined for AHP and HT.

Plot performance:
By selecting an IHP, the parameters that can be plotted are shown. These vary depending on the type selected. The range of the x-axis and the interval between the parameters can be specified, as well as the range of the y-axis to be shown on the plot.

Calculations:
In this mode, the operating conditions of the IHP should be specified. The program then calculates the performance of the heat pump that delivers the specified heat sink.

Based on the size of the heat source or the operating limitations of the selected heat pump, the entire sink cannot always be satisfied. In these cases, the program will find the largest possible heat pump, taking into account the technical limitations. The operating conditions to be specified are: sink and source temperatures, sink and source sizes, and temperature differences between the IHP and sink/source.

The economics (payback period and net annual profit) of the IHP can also be determined in this mode. The operating cost is calculated from the IHP performance data and user-specified energy costs. The IHP's installed capital cost is estimated by the program based on IHP type, heat output and operating conditions. The estimated installation cost can be modified by specifying a correction factor.

3.4.2 Computer Program: Processes

Over 100 industrial processes are characterized in the Annex 21 program process database. The process data are divided into two groups: full and simple data (see below). The processes initially included in the database are called "predefined" and those that are added by the user are called "user-defined".

Predefined processes cannot be changed by the user, but user-defined processes can. Hence, a predefined process can first be saved in the data base as a user-defined process and then modified to suit the user, for example, changing the absolute size of the process (resizing the process).

The processes included can be listed and information on each can be displayed. The Composite Curves (CC) and the Grand Composite Curve (GCC) can be plotted using a specified global temperature difference or individual stream temperature differences. Furthermore, the minimum heat demand can be plotted versus the global temperature difference.

Full process data:
The data in this group are stored according to pinch technology convention. In pinch technology, each process stream is identified and characterized with start and target temperatures and the heat needed to change the temperature from the start to the target one. The streams are also assigned an individual temperature difference (see A.7) and a heat transfer coefficient.

The data base also includes the current heat and cooling demands of the site where the data were extracted and a global temperature difference (see below). The interval pinch temperature (see A.7) included has been calculated using the preset global temperature difference in the data base. Furthermore, a short description of the process and the source of information are listed.

The global temperature difference specified in the data base reflects a level to which process integration by heat exchanging has been assumed to be economic, and thus will generally take place before heat pumping is considered. The value has been preset by examining the heat demand versus global temperature difference, see Section 3.3.1.

Simple process data:
This group includes data from processes for which full pinch technology data is not available or from processes which only, in principal, consist of a sink and a source. In this group, the data include only a heat sink and source specification that is heat sink and source temperatures and sink and source sizes. It is possible to have multiple sinks and sources.

Other data included are the same as in the full process data group. However, the current heating and cooling demand have no meaning, and the global temperature difference is set to zero degrees.

3.4.3 Computer Program: Integration

In this mode, a preliminary screening of technical and economic opportunities for heat pump installation in a process is performed. The screening is based on the performance of the various IHPs and the processes included in the data base. The program uses the principles described in Sections 3.2 and 3.3 when determining the possibilities to install a heat pump.

Heat should be extracted from hot streams below the pinch temperature and delivered to cold streams above the pinch temperature. The amount of heat that can be delivered and extracted is determined by the shape of the Composite Curves.

Each screening procedure is performed on one process, using one IHP. Each IHP must thus be tested for each process. The number of IHPs tested can, however, be restricted if the level of the pinch temperature and the possible operating temperatures of the various IHPs are known. The global temperature difference of the process determines the relative position of the Composite Curves and, therefore, the necessary heat demand. Hence, it is important to specify a reasonable temperature difference.

For heat transfer to take place, there must be a temperature difference between the heat delivered by the heat pump and that of the heat sink. The same applies on the source side, where there must be a temperature difference between the heat pump's extraction temperature and the heat source. These driving forces for the heat transfer represent the temperature difference between the heat pump and the process streams and thus include distribution systems.

Heat should be delivered to the cold streams of the process between the cold stream pinch temperature and the highest temperature of the cold streams. The program tests six temperature levels inside this interval in the Composite Curves for heat delivery. Temperature limits of the IHP can restrict the interval to be tested.

Heat should be extracted from the hot streams of the process between the hot stream pinch temperature and the lowest temperature of the hot streams. The program tests this interval in the Composite Curves for heat extractions. Temperature limits of the IHP can restrict the interval.

The program tests all combinations of delivering and extraction temperatures, and determines the largest possible heat pump (i.e., greatest amount of energy saved/delivered by the IHP) for each combination. Operational limitations of the heat pump are always taken into account. The theoretically largest possible IHP installations at each temperature lift (the difference between delivering and extraction temperatures) can then be plotted. It should be noticed that two installations, with nearly the same size and temperature lift, do not necessarily need to have nearly the same absolute temperatures.

From specified energy costs and estimated installation costs, the program also calculates the payback period of each of the identified installations. The PBPs are also plotted versus the temperature lift. Based on these two plots, the most advantageous installation should be selected by specifying a temperature lift. Detailed results for this installation are then presented. Short PBPs and large IHP installations are preferred, but it is often necessary to compromise between these criteria.

In practice it is generally not possible to install the largest heat pump identified using the screening procedure. A more realistic size could be half of the maximum one. The results for this size are simultaneously presented in the screening procedure.

The installation cost has two parts: the IHP itself, including piping etc., and additional heat exchangers needed as a result of heat pump installation. The IHP cost is estimated from the data included in the performance part of the program. This cost can only be approximate because it is strongly dependent on site conditions. The number of heat exchangers required above the pinch temperature is estimated based on the number of streams above the sink temperature and the size of the IHP in relation to the heat demand. Below the pinch, a corresponding estimate is made. A minimum of three additional heat exchangers, both above and below the pinch, are assumed. If the estimated cost is not satisfactory, it is possible to enter an adjustment factor by which the total cost is multiplied. If a process of the simple type is evaluated, no additional heat exchangers are assumed. This procedure is described in detail in Appendix A, Section A.4.

4. Experience with IHPs

This chapter reviews the current experience with industrial heat pumps (IHPs) in the eight countries that conducted Annex 21. It outlines the reported level of IHP use in each country, the application of IHPs in industries, and the experience to date for different IHP types.

4.1 Introduction

The information presented in this chapter was taken from four main sources:

- A Questionnaire for Heat Pump Users in industry, which was prepared for this Annex and was used to solicit input from the participating countries on IHP use in their countries.

- Two IHP reviews from the IEA Heat Pump Centre [23,24].

- A state-of-the-art review published by Berntsson [25].

- Reports and additional information received from the participating countries.

The direct responses to the questionnaire developed for Annex 21 were limited. However, most of the Annex countries supplemented their responses with reports and information, originally created for other projects, documenting additional IHP experience to date in their countries. This additional material contained information about specific installations, providing COP, sink and source temperatures, investments costs, and other data. This detailed information makes it possible to perform a more thorough analysis than if only reviews from other sources were available. The combined information from the questionnaire responses and from the supplement information is called the "Experience Results" in this chapter.

In the discussion on IHP experience, the following abbreviations are used for the different heat pump types:

- closed-cycle compression - CCC;
- mechanical vapor recompression - MVR;
- thermal vapor recompression - TVR;
- absorption heat pump, type I - AHP;
- heat transformer or absorption heat pump, type II - HT.

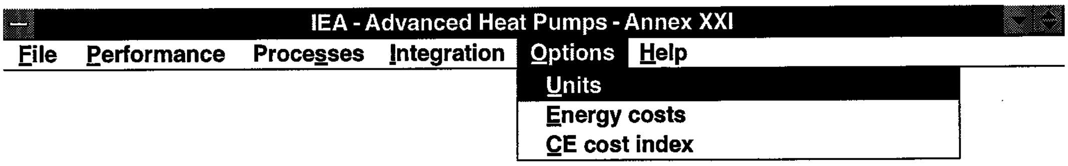
Investment costs are given in 1992 U.S. dollars. Cost data for installations prior to 1992 have been updated using cost indexes from the Chemical Engineering Plant Cost Index.

4.2 The Use of IHPs in the Participating Countries

Industrial heat pump use has increased considerably during the 1980s. Figure 4.1, derived from a recent IEA report and a recent U.S. DOE study, shows the distribution across the countries participating in this Annex of more than 4,600 industrial heat pumps now installed [23,28].

A.5 Options

The "**Options**" menu feature enables the program user to specify the appropriate units for data calculations in the program, allows energy costs to be defined, and allows cost indexes to be updated.



Options

Units

Specification of the units to be used. The selected units are used within the whole program and stored in the "a21.ini" file. The units selected will be default units after starting up.

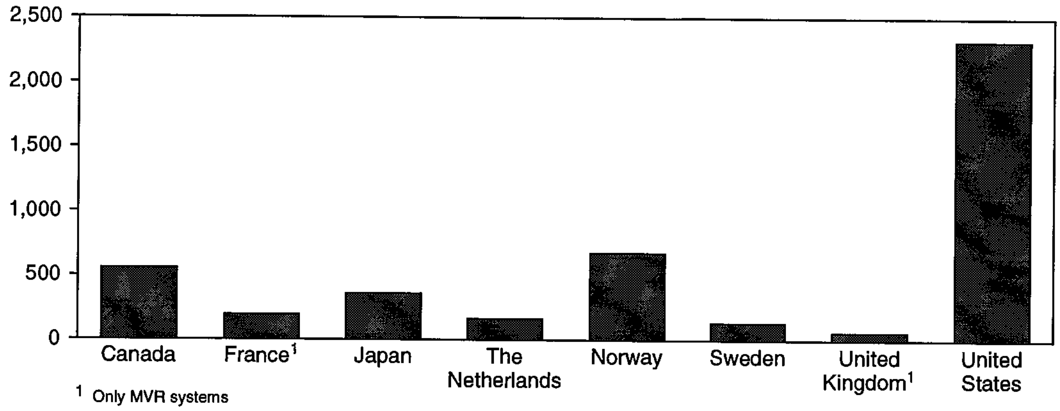
Energy costs

Specification of default energy costs. These values are the default values shown in the economic input fields. The specified values are stored in the "a21.ini" file and will be default values after starting up.

CE cost index

All costs included in the program are valid for 1992. To calculate to the current situation the present Chemical Engineering Plant Cost Index must be set. Installation costs are recalculated to the present cost level. The present index is stored in the "a21.ini" file and will be the default value after starting up.

Figure 4.1 Number of industrial heat pump installations in the participating countries [23,28]



The most common IHP types are the CCC and MVR systems (Table 4.1 and Figure 4.2). In Figure 4.2, three charts are shown. The left chart is based on Table 4.1, while the other two are based on IEA data, updated with DOE data [23,28]. The share of CCC systems is much higher in the middle chart, since this data includes many small, CCC systems (generally less than 100-200 kW heat output) used for lumber drying. In the rightmost chart, which excludes these lumber drying IHPs, the proportion of different IHP types resembles the breakdown found in the Experience Results (shown in the leftmost chart). The Experience Results, therefore, look to be fairly representative of the IHPs in use with the exception of lumber dryers.

Although the Experience Results contain about the same number of MVR and CCC installations, the total installed heating capacity for the MVR systems is more than 15 times that of the CCC systems (Table 4.1). The average and median sizes for MVR systems in the Experience Results vary considerably, as the result of a few very large MVR systems (more than 100 MW heat output).

Table 4.1 Number of installations and heating capacity for the IHPs reported in the Experience Results

HP type	No of reported installations specifying the Heating Capacity	Total installed Heating Capacity [MW]	Average size [MW]	Median size [MW]
CCC	54	48	0.9	0.6
MVR	53	794	15.0	7.0
TVR	3	7	2.3	2.6
AHP	1	2		
HT	3	8	2.7	3.4

Figure 4.2 IHP installations divided according to heat pump type as reported in the Experience Results and references [23] and [28]

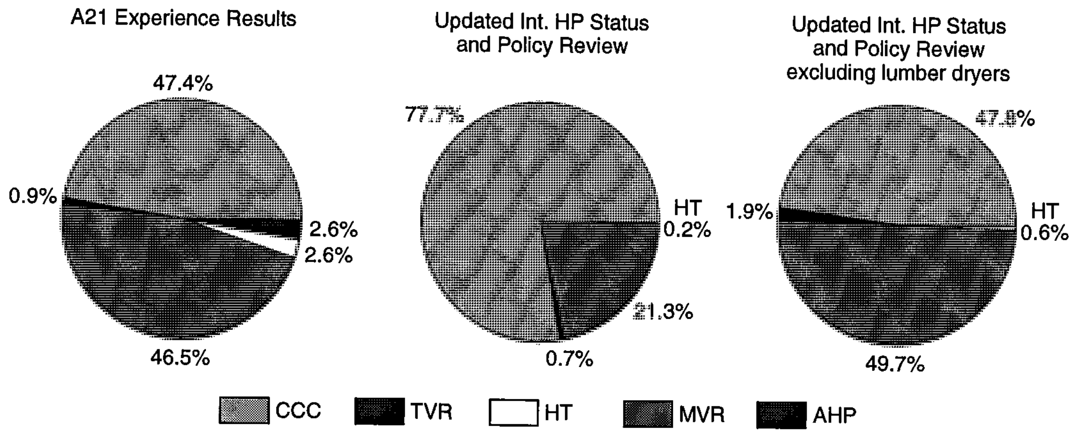


Table 4.2 summarizes typical data for the installations from the Experience Results. Most Experience Results do not include all the information under the headings in Table 4.2. For example, specific investment costs could be based on installations within a more narrow range of heat output than shown under the heading heat output. The data in Table 4.2 are based on at least three reported installations. If a certain heat pump type in a specific country has less than three experience results, no typical data for this heat pump were given in Table 4.2.

4.2.1 Canada

The number of IHPs installed in Canada is estimated at between 370 and 540. The majority of these are used with lumber drying kilns [23]. Because of low gas and high electricity prices, the incentive to install a heat pump is generally based on product quality and/or environment concerns, rather than economics [24].

Of the reported installations in the Experience Results, the majority are closed-cycle compression systems used for waste heat recovery in the food industry sector. The rest are MVR systems, mainly installed in evaporation plants in the chemical industry.

4.2.2 France

About 200 IHPs are installed in France [23]. This figure includes only MVR systems, whose main applications are in evaporation in the food and chemical industries The number of installed CCC systems is uncertain, but is probably low [25]. Electricité de France has conducted successful experiments with refrigerant CFC142b as a replacement for CFC12 and CFC114 in some applications: timber drying, chocolate production and district heating. It seems possible to achieve a condensing temperature of 90°C with the double screw compressor [25].

About 65% of the installations in the Experience Results are MVR systems, which are used for evaporation and drying. The rest are CCC systems used for drying.

Table 4.2 Typical data for IHPs in the Experience Results

Country	Cycle	Sink temperature [°C] Mean	Min	Max	Temperature lift [°C] Mean	Min	Max	COP Mean	Min	Max
Canada	CCC	52	17	76	29	10	50	4.6	2.4	9.7
	MVR	101	60	133	13	8	20	19	11	30
France	CCC	72	58	88	36	26	47	4.6	3	6.2
	MVR	115	75	108	24	6	60	14	3	33
Japan	CCC	64	40	107	32	25	38	3	1.8	3.6
	MVR	111	75	130	25	10	31	8.8	5.4	22
Norway	CCC	50	10	70	25	12	50	5	3	7
Sweden	CCC	64	45	88	50	23	77	3.1	1.7	4.2
UK	CCC	66	60	80	39	15	53	4.7	4	5.4
	MVR	102	69	120	16	4	35	27	7	50
	TVR	127	126	127	12	11	13	1.5	1.4	1.6
US	CCC	60	43	71	40	21	67	3.7	2.6	5.8

Country	Cycle	Specific investment [$/kW] Mean	Min	Max	Heat output [MW] Mean	Min	Max
Canada	CCC	580	200	1210	0.6	0.03	2.6
	MVR	225	90	350	25	5	125
France	CCC	na	na	na	0.8	0.1	2.5
	MVR	130	70	220	18	0.9	57
Japan	CCC	na	na	na	0.3	0.01	0.8
	MVR	540	290	1280	4	2	6.5
Norway	CCC	400	150	750	0.2	0.02	0.7
Sweden	CCC	310	100	650	1.5	0.4	9
UK	CCC	410	110	1110	1	0.9	1.1
	MVR	140	55	330	12	0.7	35
	TVR	na	na	na	2.3	1	3.2
US	CCC	365	140	790	0.5	0.03	1.8

4.2.3 Japan

Japan has between 350 and 500 installed IHPs [23,24]. In contrast to the other countries, a significant portion are absorption heat pumps of both type I (8%) and type II (3%). The most common type of IHP in Japan, however, is also the MVR system (about 70% of the IHPs).

The installations in the Experience Results are also mainly MVR systems (65%), used mostly for distillation and wort boiling. The installations used in distillation have a considerably higher specific investment cost (a mean value of $745/kW) than the systems used in wort boiling (a mean value of $310/kW).

Only a few CCC systems are reported and of these only one has a heat output of more than 50 kW. This is a gas engine-driven system used in a drying system. Its heat output is 0.85 MW and its specific investment cost was $775/kW.

Three absorption systems are reported, one absorption heat pump and two heat transformers. The AHP is installed in a pulp and paper plant, while the HTs are installed in chemical plants.

4.2.4 The Netherlands

The IEA HPC reports some 150 IHPs in the Netherlands (Figure 4.1) [23]. About 65 of these are CCC systems, of which 50 are used in the agricultural industry. There are about 20 MVR and 60 TVR systems in place in various Dutch industries. In general, the closed-cycle systems are small (except one heat transformer), while the open-cycle systems are relatively large (up to 1 MW_e). Next year, a 6.3 MW_e MVR will be installed in a chemical industry distillation process.

In the HPC's overview [24], 17 MVR systems are reported in the chemical and food industries. Their main application is evaporation.

In addition, two HTs are installed in The Netherlands [24]. The first had major corrosion problems, which have been overcome in the second installation.

There are not enough installations reported for any type of IHP in the Experience Results to be able to give typical information on size, investment cost, etc. Data for the Netherlands has thus not been included in Table 4.2.

4.2.5 Norway

Norway has nearly 700 IHP installations, more than 95% of which are electrically driven CCCs [24]. Their main use is in the food industry (fish farming, fish industry, dairies and meat products). Another important application is lumber drying. The total installed heating capacity for CCC systems was about 80 MW in 1992, but a recent investigation indicates the total capacity for CCC systems is now about 170 MW [25,41]. The sink temperature is normally low and the normal refrigerant is CFC22. Ammonia is thus a possible alternative working fluid and lately has been used in some new installations [25]. Ammonia is now being used up to 4 MPa, which corresponds to a condensing temperature of about 75°C [24].

Some 20 MVR systems are installed in Norway [23,25]. They are applied for evaporation.

There are not enough installations reported for any type of IHP in the Experience Results to be able to give typical information on size, investment cost, etc. Data for Norway are thus not included in Table 4.2.

4.2.6 Sweden

Nearly 150 IHPs above 200 kW heat output are installed in Sweden [23]; the vast majority are CCC systems. The systems are generally not used in unit operations (i.e., heat recovery from a process and heat delivery to the same process, for instance, a dryer). Instead, their normal application is waste heat recovery to produce hot water, and they are found in many different types of industries. The total installed heating capacity of these systems is about 60 MW.

In addition, some 20-30 large systems are installed using industrial waste heat to produce district heat. The total heating capacity for these systems is approximately 200 MW (the total installed capacity of all district heating heat pumps in Sweden, including those not using industrial waste heat, is about 1,500 MW of heat output). Of the systems included in the Experience Results, 85% are CCC systems, which represent 40% of the reported heating capacity. The general experience reported is that the systems work as expected and that their availability is good.

MVR systems are generally used in unit operations, i.e., in evaporation plants in the food, chemical and pulping industries. About 20 systems are installed in Sweden, with a total heating capacity of about 160MW.

About 15% of the reported systems in the Experience Results are MVR systems, but the installed heating capacity represents 60% of the reported systems.

4.2.7 United Kingdom

Some 60 IHPs are installed in the United Kingdom [23]. This figure includes only MVR systems.

There may be as many as 40 large CCC systems (above 100 kW heat output) in the United Kingdom [23], but this figure is very uncertain. In the Experience Results, seven CCC systems are reported with a typical size of 1MW heat output. These systems are all in the food industry, and are mostly used in drying operations. In contrast to the other countries where IHPs generally employ the more standard electric motor, a large portion of the IHPs in use in the United Kingdom employ gas engine or back-pressure turbine drives.

The MVR systems in the Experience Results account for 60% of the reported systems in the United Kingdom. They are found mainly in the food industry and are largely used in evaporation operations. The total heating capacity for the reported MVR systems is 160 MW, which represents nearly 95% of the total reported heating capacity.

The United Kingdom is the only country with information on TVR systems contained in the Experience Results. All of the three systems reported are installed in whisky distilleries (pot stills).

4.2.8 United States

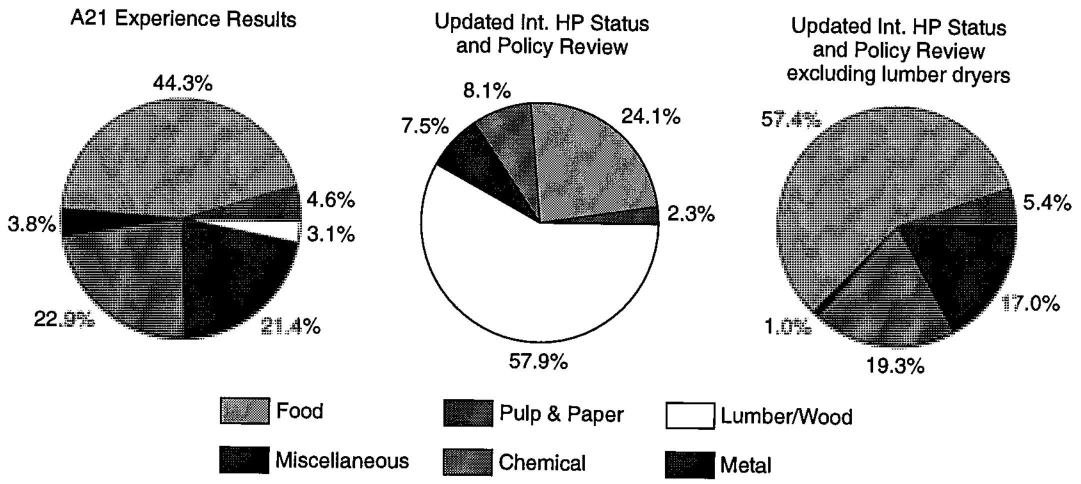
Of the Annex countries, the United States has the largest industrial sector and the most IHP experience to date. Studies conducted for the U.S. Department of Energy and the Electric Power Research Institute estimate that about 2,300 IHPs are now in use, with about 2,000 of these used for lumber drying [26,27,28]. Aside from this application, most IHPs are now found in dairy, corn milling, liquor, pulp and paper, and various chemical plants. The predominant use of the IHPs is for heat recovery from distillation or evaporation operations.

Outside of closed-cycle systems for lumber drying, the predominant type of IHP in use is the MVR type of IHP, with such systems commonly found in pulp and paper, food (e.g., diaries, corn milling, liquor), refining, and chemical industry applications. Some TVR systems are also in use in these industries. The Experience Results show that CCC have seen limited use to date in the United States, with the main application for these systems low-temperature waste heat recovery and all are electric motor driven.

4.3 The Use of IHPs in Various Industrial Sectors

Figure 4.3 shows the total number of IHPs distributed according to various industrial sectors. As in Figure 4.2, three charts are provided to compare various sources. From the figure, it can be seen that the Experience Results are fairly representative of the overall distribution of IHPs by industry, when compared to the other sources, except for lumber dryers. These results (in the leftmost chart) provided the basis for the analysis of IHP use by industrial sector.

Figure 4.3 IHP installations divided according to industry sectors as reported in the Experience Results and references [23,28]



Some 44% of the installations are contained in the food industry, and are mostly used in evaporation operations. About one-third of the IHPs are distributed across chemical, lumber/wood, metals, and pulp and paper applications. The remainder are found in other or miscellaneous industries, including textile, petroleum refining, and related applications such as sewage treatment.

CCC and MVR IHP systems dominate all industrial sectors, as shown in Figure 4.4. The installed heating capacity for MVR systems, however, is much larger than for any other IHP type; see Figure 4.5.

The four reported heat transformers (HT) are found in the chemical industry (two in Japan and one in the Netherlands) and the steel industry (one in the Netherlands), the three thermal vapor recompression (TVR) systems are found in the food and drink industry (United Kingdom), and the reported absorption heat pump (AHP, type I) is found in the pulp and paper industry (Japan).

Figure 4.4 Number of installed IHP systems as reported in the Experience Results by industry sector

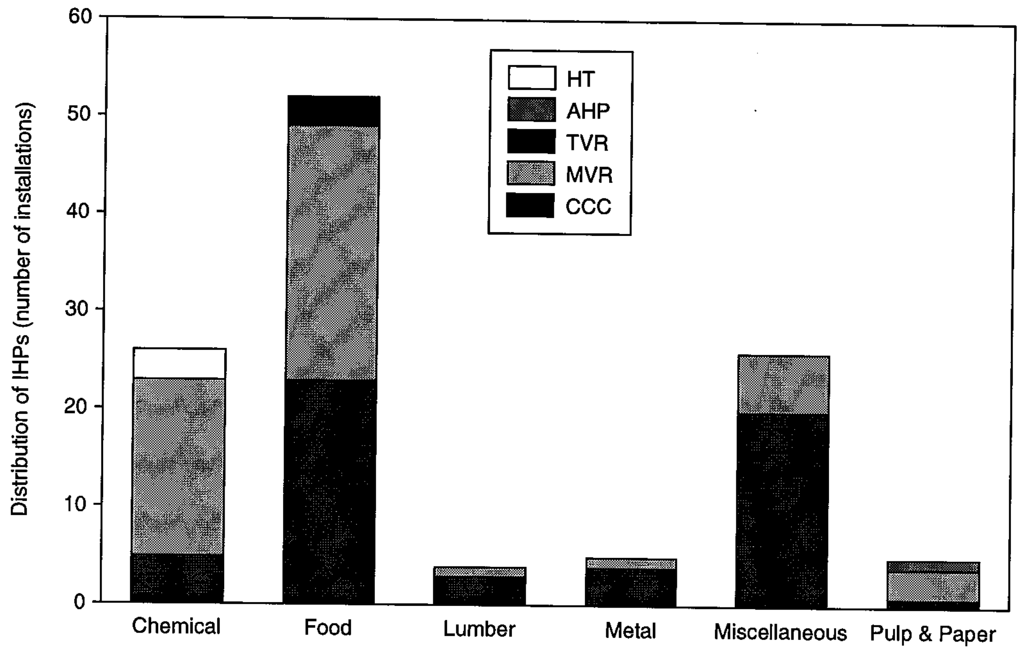
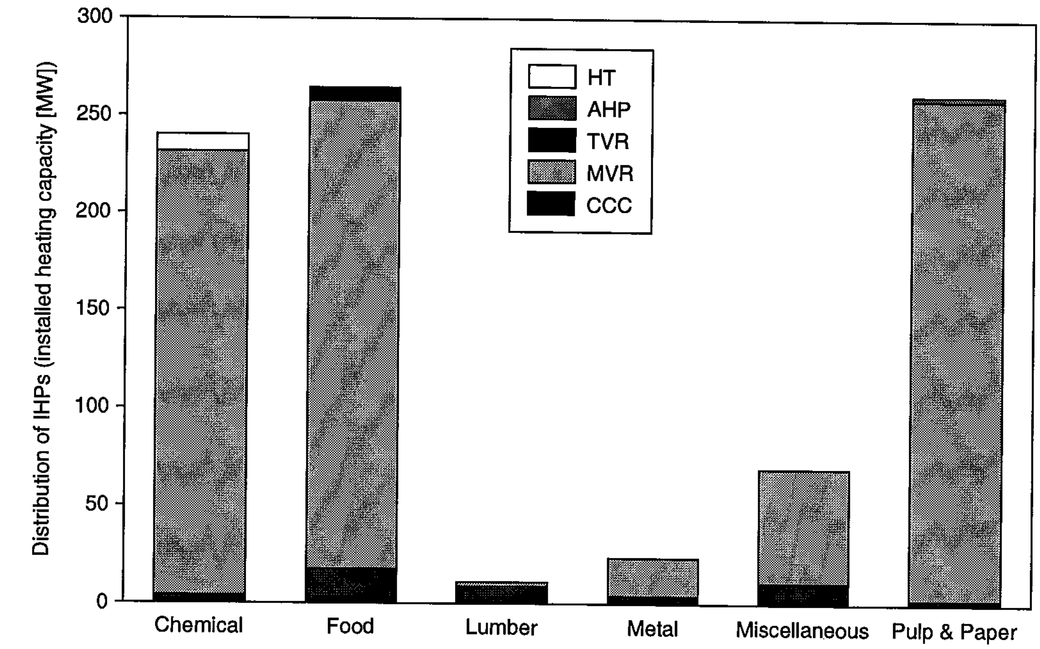


Figure 4.5 Total heating capacity for the IHP systems reported in the Experience Results by industry sector



4.3.1 Chemical Industry

Almost 30 installations were reported for the chemical industry, with a total heating capacity of approximately 240 MW. This corresponds to 23% of the reported installations and 28% of the reported heating capacity. MVR systems are the most common IHP type in this industry (Figure 4.4). Most of the MVR IHPs are installed in evaporation plants (47% of the installations) and they account for a majority of the installed heating capacity (78%). About 30% of the installations are used for waste heat recovery (18% of the installed heating capacity), and the rest are used in distillation columns.

A typical installation (median of reported installations) has a temperature lift of 25°C, a sink temperature of 106°C, and a heating capacity of 3.8 MW. Figure 4.6 summarizes the range of temperature lifts, sink temperatures, and heating capacities reported for the chemical industry.

Figure 4.6 Relative frequency of temperature lift, sink temperature, and heating capacity in the chemical industry reported in the Experience Results

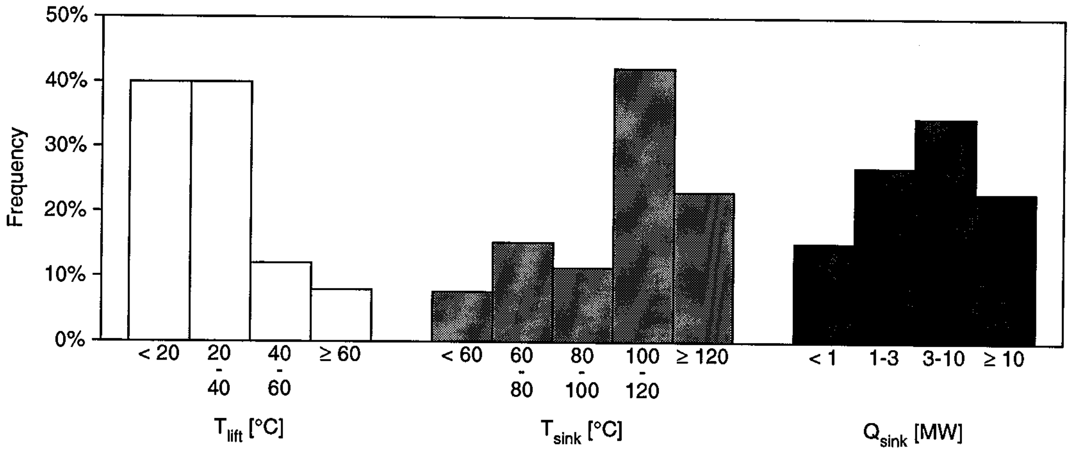
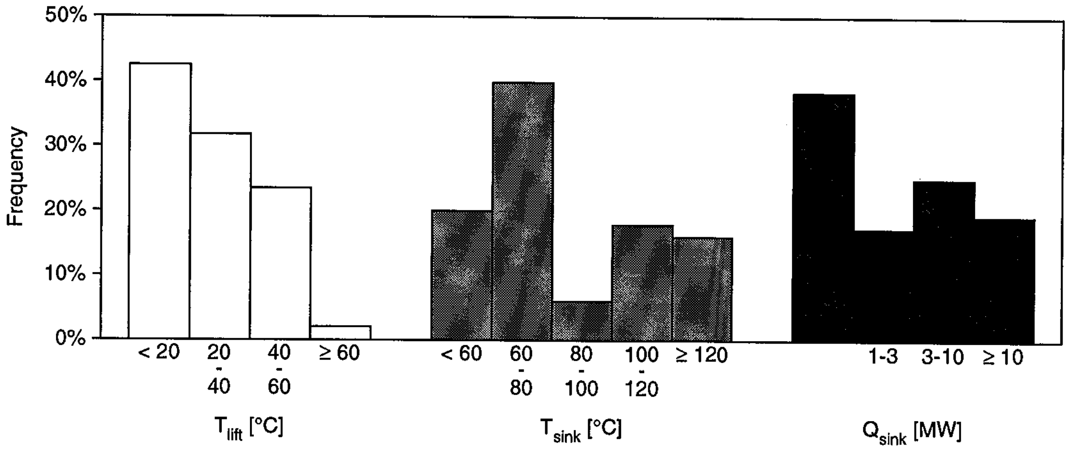


Figure 4.7 Relative frequency of temperature lift, sink temperature, and heating capacity in the food industry reported in the Experience Results



4.3.2 Food Industry

The food and beverage industry has more than 50 IHP installations in the Experience Results, with a total heating capacity of around 260 MW. This corresponds to 44% of all the reported installations and 30% of the reported heating capacity.

The number of CCC and MVR installations are about the same, but the installed heating capacity is dominated by MVR systems (230 MW). The main applications are evaporation, wort boiling, distillation, drying and waste heat recovery. A typical installation (median of reported installations) has a temperature lift of 26°C, a sink temperature of 71°C, and a heating capacity of 2.0 MW. Figure 4.7 summarizes the reported temperature lifts, sink temperatures, and heating capacities for the IHPs found in the food sector.

4.3.3 Metal Industry

Five installations were reported for metal industry processes, with a total heating capacity of about 20 MW. This corresponds to 4% of the reported installations and 3% of the reported heating capacity. CCC systems are the most common IHP type in this industry, although the installed heating capacity in MVR systems is much higher. A typical installation (median of reported installations) has a temperature lift of 60°C, a sink temperature of 80°C, and a heating capacity of 1.2 MW.

4.3.4 Pulp and Paper Industry

Five installations were reported for the pulp and paper industry, with a total heating capacity of about 260 MW. This corresponds to 30% of the reported heating capacity, but only 5% of the reported installations. MVR systems dominates this industry, both in number and installed capacity. The major application is evaporation. A typical installation (median of reported installations) has a temperature lift of 11°C, a sink temperature of 80°C, and a heating capacity of 22 MW.

4.3.5 Lumber/Wood Industry

This industry sector is poorly covered in the Experience Results. Only four installations were reported, representing around 5% of the total installations. Two of the IHPs are used with continuous dehumidifiers, while the other two are installed in batch units. The IHPs in the continuous systems are large units (1.4 MW and 9 MW heat output) and one is a MVR system.

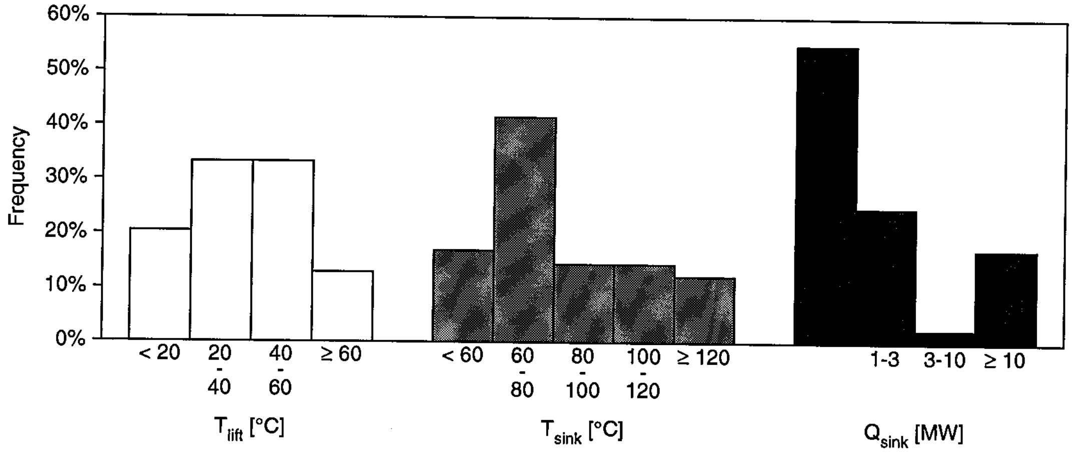
The Experience Results, however, do not reflect the true situation for the participating countries (see Figure 4.2). In the United States and Canada, for example, more than 2,000 CCC IHPs are now installed for lumber/wood dehumidification [23,28]. Most of these IHPs are used with batch operations and the IHPs are typically small (i.e., less than 100-200 kW heat output).

4.3.6 Miscellaneous Industries

This sector comprises all other industrial processes not included in the five industries listed above. The most prominent applications of IHPs in this sector include textiles, petroleum refining, and sewage treatment plants. A total of 26 systems were included in the Experience Results, with a combined heating capacity of about 70 MW. This corresponds to 21% of the total reported IHP systems, but only to 8% of the total installed heating capacity. Most of these systems are apparently quite small as the median heating capacity is about 0.6 MW.

IHP applications are mostly either drying or general heat recovery. The majority of the installed systems are CCC heat pumps, but again, the installed heating capacity for MVR systems is larger. Figure 4.8 shows the different temperature lifts, sink temperatures and heating capacities reported in the Experience Results for this sector, together with data for the metal and pulp and paper industries.

Figure 4.8 Relative frequency of temperature lift, sink temperature, and heating capacity in all other industries reported in the Experience Results



4.4 Experience with Different Types of IHPs

4.4.1 Closed-Cycle Compression

Figure 4.9 shows the sink temperatures of the CCC systems reported in the Experience Results. The figure shows that the great majority of the closed-cycle heat pumps in use today work with condensing temperatures below 80°C, i.e., in the temperature range where CFC12, or even CFC22 and ammonia, could be used. Accordingly, it is not possible to report any general experiences from high-temperature systems (> 90°C).

The general experiences for low-temperature systems seem to be comparable to very large residential heat pumps (i.e., they are working surprisingly well considering the fact that the technique is relatively new and complex) [25]. Their availability is high and, on the whole, they have provided the COPs expected. Figure 4.10 shows the COPs of the reported installations versus the temperature lifts and the sink temperatures, and also indicates the COP trend. Because Figure 4.10 includes several types of working fluids and compressors, the values cannot be strictly compared with each other.

Figure 4.11 outlines the reported specific installation cost (recalculated to the cost level of 1992) versus the heat output. Although there is a large range of costs, the indicated trend shows a cost decrease in larger units.

Figure 4.9 Sink temperatures of the CCC systems reported in the Experience Results

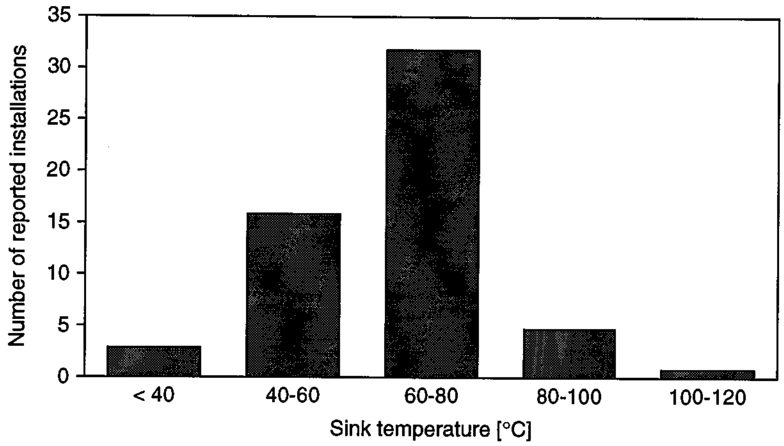


Figure 4.10 COP vs. temperature lift for the CCC systems reported in the Experience Results, with sink temperatures as a parameter

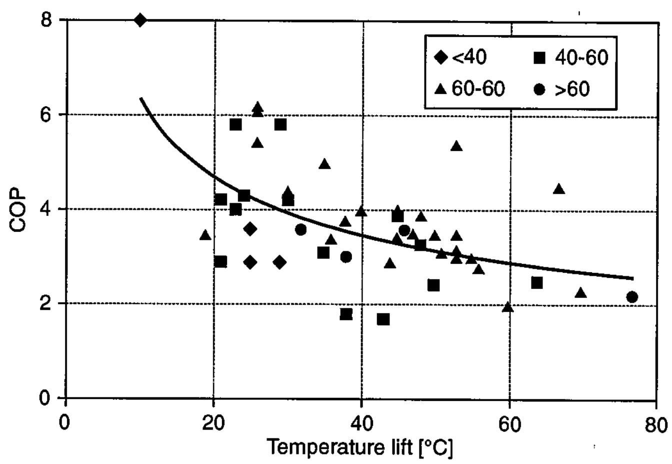
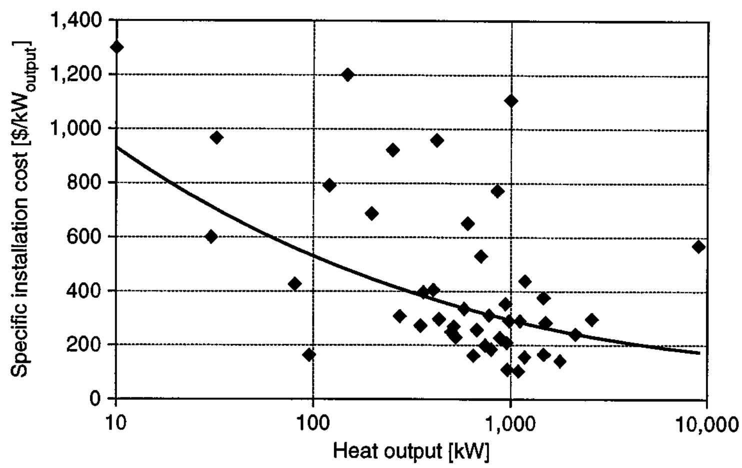


Figure 4.11 Specific installation cost vs. heat output for the CCC systems reported in the Experience Results



The PBP depends on many factors, such as installation costs, energy prices and system performance, and these are difficult to evaluate. The average value for the reported closed-cycle installations is 3.5 years.

The main problems found are [25]:

- Compressor breakdown.
- Leakage of the working fluid, which in some early plants had been as high as 30% annually, but with redesigns is now more likely to be a maximum of 5% yearly.
- Problems with operating and control equipment and, accordingly, the interaction with the other parts of the energy system.
- Incorrectly designed heat pumps (mostly too large).

The number of potential applications for CCC systems is quite large [25]. Many of the systems are utilized for different drying purposes. Process integrated systems (e.g., in the chemical and food industry) also appear to be rather common. However, these are rarely used for steam production, which is somewhat surprising because steam is a very common heat distribution medium in the industry. There should be a large technical potential for closed-cycle compression heat pumps for high-temperature purposes (i.e., steam production of 2-5 bar). There are at least three important reasons why this potential has not yet been reached:

- If the temperature lift is moderate, MVR or TVR IHPs are, in many cases, both technically and economically advantageous.
- Until now, the hardware available was inadequate for high-temperature applications. The CFC114 system is not able to work above 120°C or 130°C and, furthermore, it is more expensive and has a lower COP than the corresponding CFC12 system. A two-stage solution is also expensive and may have difficulties in competing economically.
- The compression/absorption cycle may be an interesting alternative, but is not yet commercially developed.

The ability of the heat pump technique to achieve considerable spin-off effects (e.g., to increase plant production levels by removing bottlenecks or reducing the cold utility need) has been demonstrated in different plants. On the other hand, the positive environmental consequences (e.g., the reduction of CO_2, NO_x, and other emissions) have not been as widely recognized [25].

Today, diesel/gas driven heat pumps are used only in a few special applications, especially in greenhouses in the Netherlands. Also in Germany, a few experimental plants have been built, but the general experiences from these have been rather disappointing. One important aspect is their comparatively high NO_x emissions, which can be up to six times higher than a conventional burner, calculated at the same heat production rate [29]. Furthermore, several technical problems have been reported, including torque transmission problems between the motor and the compressor, vibrations, problems with the service life of the motor, and operating and control problems.

4.4.2 Steam Compression

This section focuses on the experience reported with MVR IHPs, but also briefly discusses the situation for TVR-type IHPs.

4.4.2.1 MVR

The MVR technique has primarily been used to replace multiple-effect evaporation systems in the food and pulp and paper industries. Of the existing MVR plants, 80% are used to replace or complete multiple-effect systems in evaporation plants [30]. Today, however, there is a tendency towards more advanced MVR systems. Examples of MVR systems now introduced in industry are those integrated in several process steps and those for energy recovery in batch manufacturing processes.

Lately, an increasing number of MVR IHPs have been installed as a solution, not only for saving energy but also for chemical and product recycling and waste cleaning. In the future, both environmental considerations and energy conservation will probably be important reasons for investing in MVRs. In a survey by the International Union for Electro-Heat (U.I.E.), France and the United States were reported to have more than one-half of the installed capacity of MVR systems [31].

Figure 4.12 shows that MVR installations have a sink temperature in the range between 80°C and 140°C, which is in accordance with the applications described above. Figure 4.13 shows the COPs of the reported installations versus the associated temperature lift, along with a calculated trend line. As can be seen from this figure, the COP is highly correlated to the temperature lift. There is also a tendency toward higher COPs for large systems.

According to Costa and Missirian, approximately 80% of the existing MVR systems in industry are connected to evaporation processes [30]. In comparison with the conventional method for evaporation energy recovery (multi-stage evaporators), the MVR systems give very large energy savings. The specific investment cost for MVR evaporators decreases considerably with increasing plant size, which is not the case with conventional evaporation techniques [25]. A common inducement to invest in MVR heat pumps is the need for increased

Figure 4.12 Sink temperatures of the MVR systems reported in the Experience Results

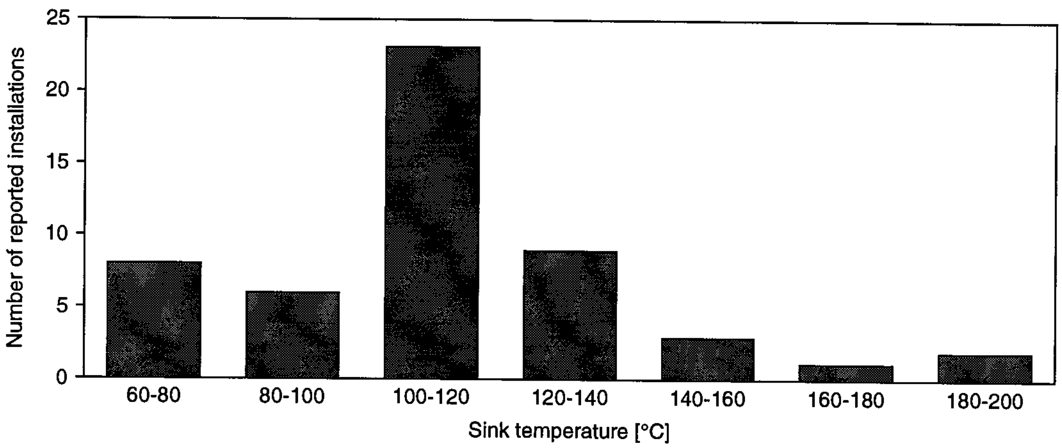
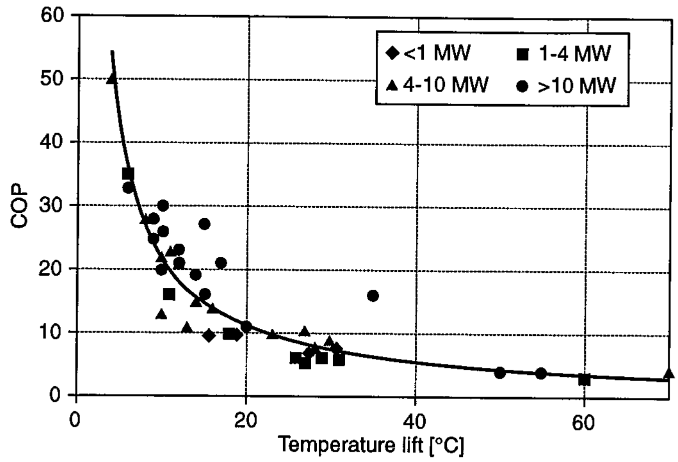


Figure 4.13 COP vs. temperature lift for the MVR systems reported in the Experience Results, with sink temperatures as a parameter



evaporation capacity. In addition, an MVR plant generally means considerable energy recovery, together with reduced maintenance costs and lower costs for cooling water in comparison to conventional evaporation methods.

Many of the existing MVR systems are used in connection with evaporation processes in the dairy sector. This has become a well established technique that has been technically and economically verified in numerous installations. In plants with MVR systems, the number of evaporation effects can be reduced to two or three, compared with five or six in most plants without MVR systems. As the pressure ratios are relatively low (often lower than 1.3), centrifugal compressors or high-speed fans are most often used. From a general point of view, these IHP systems have a very good availability. The reported PBP typically varies from 1.4 to 5 years [25].

In the sugar industry, many MVR systems are used in connection with evaporation and with drying processes. In spite of their low levels of annual operating hours, these systems have shown good economic results.

The introduction of the MVR technique has been more recent and somewhat slower in the pulp and paper industry than in other sectors, but the installed systems are quite large. The average heat output for the installations reported in the Experience Results is 85 MW.

MVR IHPs have mostly been used for evaporation of pulp process liquors and for upgrading steam from thermomechanical pulp (TMP) manufacturing. Experience has shown that these systems work well. In the future, the use of pollution or emission fees or taxes on fossil fuels (e.g., carbon dioxide taxes) would probably increase the use of biomass fuels and thus increase biofuel prices. Such increases would likely stimulate interest in MVR heat pumping in this sector.

Few MVR systems are used in connection with distillation processes (only seven installations were reported in the Experience Results), most likely the result of high temperature levels, large temperature differences, and the use of working fluids other than water in these processes.

These factors make the application of MVR heat pumps more complicated. The average specific investment cost (base 1992) for the reported installations is about $600/kW heat output, compared to about $190/kW for the other MVR systems.

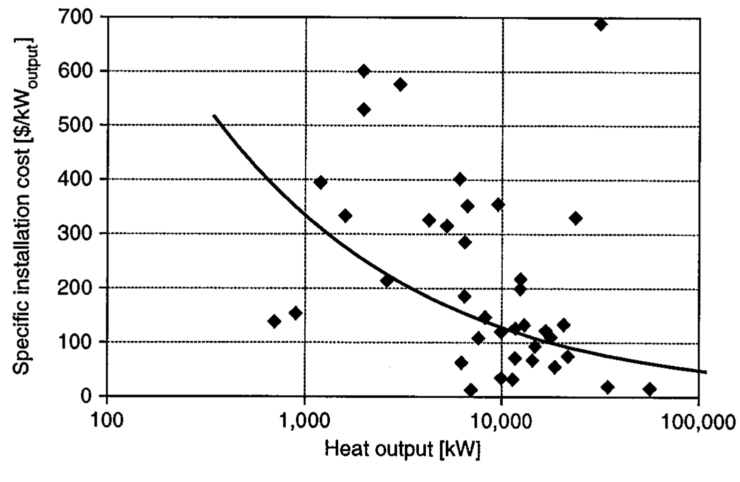
Drying consumes very large quantities of energy. The introduction of MVR IHPs in drying processes can provide substantial energy savings. In direct dryers, air was earlier used as a heating fluid, but by changing to superheated steam, it has been possible to use the MVR technique. There are also many successful examples of using MVR IHPs with indirect drying processes.

In the chemical sector, it has been shown that it is possible to achieve large energy savings and other environmental improvements by using MVR heat pumps. This type of project will probably be of great importance in the future.

The experiences from the whisky industry have shown that MVR systems can be used in connection with sensitive manufacturing processes without influencing the quality of the product.

Figure 4.14 depicts the specific installation costs of the plants reported in the Experience Results versus their heat output, along with the overall trend line. The specific investment cost varies considerably, which is partly attributable to what costs are included in the reported value. As stated previously, the results show a large decrease in IHP costs, on a $/kW heat output basis, as the size of the IHP increases.

Figure 4.14 Specific installation cost vs. heat output for the MVR systems reported in the Experience Results



The average PBP for the reported MVR systems is three years. As was the case for the CCC systems, no trends can be identified.

As a summary, Munch Berntsson [32] reports that the vast majority of the existing MVR plants in industry are working well. The plants are saving large quantities of energy, they have short payback periods, they are extremely reliable and, in many cases, they can lower maintenance costs considerably. For energy saving techniques used in connection with industrial processes, high reliability is of very great importance. Selecting the right type of compressor (assuming the current requirements) in order to avoid operation disturbances is emphasized as a very important aspect of overall IHP design in this and other reports.

Until now, most of the MVR plants have been installed in unit operations such as evaporation and drying. If process integration becomes more widely considered in different process industries, including the possible application of heat pumps, the potential for this technique should increase.

4.4.2.2 TVR

It is difficult to draw specific conclusions about the numbers, sizes, and costs of TVR installations. This is partly because TVR heat pumps, or steam ejectors, are often regarded as conventional pieces of equipment in evaporation plants and are thus not thought of as heat pumps. Such IHPs appear to be used extensively in the food industry sector, where there is a need for small temperature increases at a temperature level of approximately 60°C. This technique is also apparently widely used in the pulp and paper industry.

Three TVR installations were reported in the Experience Results, all in whisky distilleries. The average sink temperature was about 125°C, while the average temperature lift was about 10°C. The typical investment cost was about $100/kW.

4.4.3 Absorption Systems

This section focuses on the Experience Results reported for absorption heat pump systems, including both prime heat-driven (AHP, type I) and waste heat-driven (AHP, type II) systems.

4.4.3.1 AHP

Absorption heat pumps have not been as widely used as compression systems, either for industrial or residential applications. Large plants in sizes suitable for industry (for example, over approximately 500 kW) are mainly used in Sweden and Japan [25]. Besides eight units in incineration plants, Sweden has two industrial applications.

According to information from the Heat Pump Technology Center of Japan, there are 22 absorption heat pumps working in Japan [33]. The sizes range from less than 100 kW up to 3.5 MW heat. They are installed in the paper, textile, food and chemical industries.

The Experience Results include one AHP. The heat pump was installed in a pulping plant in Japan and recovers heat from the bleaching process to feed water heating. The units' heat output is about 2 MW, its temperature lift about 40°C, and the sink temperature is about 80°C. Prime energy to the generator is low-pressure steam (3.7 bar).

The specific investment cost for the heat pump (base 1992) was about $60/kW heat output and the total investment cost was approximately $120/kW. The reported annual maintenance costs correspond to 1.2% of the total investment cost.

4.4.3.2 HT

As of 1989, there were 15 heat transformers (absorption heat pump, type II) in operation in Japan, Germany and the Netherlands [34]. Operating data for these IHPs is summarized in Table 4.3.

The size of installed HT heat pumps ranges between 0.5 MW and 7 MW, with most between 1 MW and 3.5 MW. The heat source is, in all cases but one, steam between 80°C and 100°C, and the heat sink is steam between 115°C and 150°C. The COP varies between 0.47 and 0.49. In a few cases, corrosion problems have been reported, for example, in Delfzijl and Dörnten. Otherwise, the plants have functioned extremely well. Part-load behavior and other control aspects have been very satisfactory.

Two replies in the Experience Results relate to heat transformers installed in Japan. One HT functions as a waste heat-driven absorption chiller during the summer. No investment costs were reported for these HT systems but, as a rough estimate, they should be about twice the investment cost for an AHP with the same heat output. According to Munch Berntsson, et al., the specific investment cost for heat transformers (base 1989) is in the $400-700/kW range, with an annual maintenance cost between 0.5% and 1.5% of the total investment cost [34].

Table 4.3 Data on existing heat transformer plants (December 1989) (continued on next pages)

	Chiba, Japan	Kagoshima, Japan	Niigata, Japan
Type of plant	Butadiene	Ethylalcohol	–
Manufacturer	Sanyo	Sanyo	Sanyo
Start of operation	Dec 1981	Jan 1984	Feb 1984
Heat source	Waste steam	Alcohol, vapour	Dist. top vapour
Input, kW	5,000	1,950	3,450
Inlet °C	98	80	80
Outlet °C	88	80	80
To process	Low press. steam	Low press. steam	Low press. steam
Output kW	2,350	930	1,670
Inlet °C	127 (water)	119 (water)	111 (water)
Outlet °C	133 (water)	124 (water)	116 (water)
Cooling water	–	–	Ground water
Inlet °C	26	20	15
Outlet °C	32	30	20
COP	0.47	0.48	0.48
Relative temp. lift	0.659	0.637	0.474

Table 4.3 Data on existing heat transformer plants (December 1989) (continued)

	Tokuyama, Japan	Korea	Shimonoseki, Japan
Type of plant	Rubber	–	Chemical
Manufacturer	Sanyo	Sanyo	Hitachi Zosen
Start of operation	June 1985	May 1983	July 1982
Heat source	Dist. top vapour	Dist. top vapour	Dist. top vapour
Input, kW	2,220	4,890	3,450
Inlet °C	125, 122	98	83
Outlet °C	91, 79	88	83
To process	Low press. steam	Low press. steam	Low press. steam
Output kW	1,090	2,350	1,660
Inlet °C	134 (water)	127 (water)	100 (water)
Outlet °C	139 (water)	132 (water)	111 (steam)
Cooling water	Sea water	Cooling tower	Cooling tower
Inlet °C	27	31	28
Outlet °C	30	–	32
COP	0.49	0.48	0.48
Relative temp. lift	–	0.629	0.459

	Tokai, Japan	Sin-Nanyo, Japan	Amaki, Japan
Type of plant	Butadiene	Rubber	–
Manufacturer	Hitachi Zosen	Hitachi Zosen	Hitachi Zosen
Start of operation	May 1983	September 1984	December 1984
Heat source	Dist. top vapour	Dist. top vapour	Hot water supply
Input, kW	3,950	6,980	720
Inlet °C	80.5	100	95
Outlet °C	80.5	100	85
To process	Low press. steam	Low press. steam	Hot water
Output kW	1,880	3,330	350
Inlet °C	100 (water)	90 (water)	95 (water)
Outlet °C	112 (steam)	143 (steam)	120 (water)
Cooling water	Cooling tower	Cooling tower	Cooling tower
Inlet °C	32	31	32
Outlet °C	36	37	37
COP	0.48	0.48	0.49
Relative temp. lift	0.606	0.544	0.619

Table 4.3 Data on existing heat transformer plants (December 1989) (continued)

	Fuji, Japan	Delfzijl[1,2], The Netherlands	Dörnten, FRG
Type of plant	–	Ethyle amines	Animal carcass
Manufacturer	Hitachi Zosen	Hitachi Zosen	GEA
Start of operation	May 1985	September 1984	1984
Heat source	Dist. top water	Dist. top vapour	Waste vapour
Input, kW	5,800	13,740	–
Inlet °C	–	–	–
Outlet °C	95	103.3	100
To process	Low press. steam	Low press. steam	Low press. steam
Output kW	2706	6,780	1,000
Inlet °C	25 (water)	130.8 (water)	–
Outlet °C	131 (steam)	144.9 (steam)	145
Cooling water	Cooling tower	Cooling tower	–
Inlet °C	32	10.7	–
Outlet °C	37	36.3	–
COP	0.47	0.49	–
Relative temp. lift	0.507	0.482	–

	Stuttgart[1], FRG	Yugoslavia	Wesseling[1], FRG
Type of plant	Brewery	Animal carcass	Chemical industry
Manufacturer	GEA	GEA	GEA
Start of operation	1986	1986	
Heat source	Waste vapour	Waste vapour	Waste vapour
Input, kW	–	–	–
Inlet °C	–	–	97
Outlet °C	100	100	94.5
To process	Low press. steam	Low press. steam	Low press. steam
Output kW	1,400	1,100	2,000
Inlet °C	–	–	–
Outlet °C	136	144	133
Cooling water	–	–	–
Inlet °C	–	–	–
Outlet °C	–	–	–
COP	–	–	–
Relative temp. lift	–	–	–

1 No longer in operation
2 Dismantled for process modification

5. Potential Energy and Environmental Benefits of IHPs

This chapter presents the results of the Annex 21 market assessments of the potential energy and environmental benefits of industrial heat pumps. The overall methodology used in the market assessments is reviewed first. This discussion is followed by a summary of the findings for each country participating in Annex 21. Chapter 5 concludes with a summary of the overall findings across the participating countries.

5.1 Annex 21 Market Assessment Methodology

A uniform approach was developed to provide consistency among the analyses performed by the countries that formed Annex 21. Each country followed this methodology in assessing the market potential and energy and environmental benefits of IHPs. The methodology is summarized here; detailed descriptions of the methodology and the key country-specific assumptions are provided in Appendices B and C, respectively.

The market potential of IHPs was determined at the individual process level using data derived from the IHP screening program (discussed in Section 3 and Appendix A) and based on a uniform set of process-specific inputs determined by each National Team. Overall, a four-step process was followed to assess IHP market potential:

- develop macro-level data;
- derive IHP data;
- determine process-specific data;
- combine data to assess market potential.

The first step was to develop national, macro-level data on energy prices, energy- and technology-specific emission factors, and the electricity generating mix for 1995, 2000, and 2005. Energy prices were used to assess relative IHP economics at different points in time, while the emission factors were used to estimate the environmental benefits of IHPs. The electric generating mix determined the emission factors for electricity. These factors were corrected for power plant heat rates to more accurately reflect net national benefits, taking into account the fuel required to produce electricity consumed by IHPs.

In this first step, each country also estimated three market penetration factors used in the analysis:

- Market penetration level - the fraction (%) of all end-users that would implement IHPs as a function of different payback levels.

- Risk aversion level - the fraction (%) of all end-users that would not use IHPs at any payback level.

- Diffusion rate - the rate (measured in %/year) at which the market will approach maximum penetration or full utilization.

The second step was to use the IHP screening program to generate data on the technical and economic fit of IHPs in different processes; each country was free to select the specific industrial processes to be analyzed. The individual country studies could be conducted based on the data in the IHP screening program, which covered more than 140 industrial processes, by inputing specific data on processes not found in the program, or by some combination.

Each country then used the IHP screening program to identify those IHPs technically capable of being implemented in the processes that it had selected, and to derive energy and economic data on the suitable IHPs. More than 50 IHPs could be analyzed using the screening program. The energy and economic data covered the amount of energy delivered (i.e., saved) by the IHP, the amount of energy consumed by the IHP, and the IHP's estimated annual profit and payback.

IHP technical fit and economics were determined at three points in time (1995, 2000, and 2005) and under two scenarios: "maximum" size, where the largest (greatest possible savings) possible IHPs were determined as a function of temperature lift; and the "average" size, estimated at one-half the maximum size for each temperature lift. Each country was free to select the best IHP temperature lift/energy savings combination from the technically feasible options. For example, in the U.S. study, the IHPs chosen were those with the minimum payback under the maximum scenario, not the maximum possible savings, which often has an inverse relation to payback.

The third step was to develop process-specific data for each of the processes analyzed, including:

- Estimated number of plants (year-end 1993) and the number already using IHPs.

- Estimated industry growth (%/year from 1994-2010).

- Current process heat demand.

- Projected amount (in %) of process heat supplied by cogeneration systems, waste-heat boilers and incinerators.

- Process heat energy mix.

In the fourth step, the macro, IHP, and process-specific data were combined to project future process heat demand, estimate IHP market penetration, analyze potential IHP energy savings and consumption, and to estimate the net emission reductions possible based on the level of net energy savings.

To ensure consistency among the analyses performed by each country, the market assessment procedure was automated using a spreadsheet program developed for Annex 21. The program included two key assumptions:

- The analysis of IHPs in one process was limited to no more than five different types of IHPs, based on the assumption that no more than this number would be likely to "compete" for the same application.

- The relative potential market shares of different technically feasible IHPs were determined based on a proportional analysis of their overall economics. This was done on the assumption that the IHP with the best overall economics would not always be chosen (a zero-one type of analysis), and users might opt for different IHPs based on fuel preferences, ease of installation, or other factors.

5.2 Country-Specific Findings

In the following discussions, the results of each country's market assessment study are summarized. The findings for each country outline:

- The industrial processes analyzed and their relative share of total industrial process heating demand.

- The estimated energy savings, the projected number of IHPs, and the estimated potential energy and environmental benefits.

The key assumptions and estimates used in each country's analysis are reviewed in Appendix C. This review covers process-specific industry data and data on energy prices, emission factors, and market penetration rates.

The estimates of energy and environmental benefits are presented both for the individual processes analyzed and at the national level. The national-level estimates were derived in one of two ways. Where data was available on IHP potential in processes other than those analyzed for Annex 21, these data were combined with the data for the individual processes analyzed to derive a national-level estimate.

If no such data was provided, the national-level IHP benefits were estimated based on the projected IHP benefits in those processes analyzed in detail. First, a ratio was derived comparing the total projected industrial energy consumption against the total projected energy consumption in those processes analyzed in detail. Projected IHP benefits were scaled using this ratio and a market penetration factor. In most instances, this factor was one-half or less, on the assumption that the processes analyzed in detail represented many of the most promising IHP opportunities; therefore, IHP potential in other processes would be much lower.

The country findings are presented alphabetically for the countries that conducted detailed assessments as a part of Annex 21:

- Canada;
- Japan;
- Netherlands;
- Norway;
- Sweden;
- United Kingdom;
- United States.

Each country summary highlights those industrial processes identified with especially promising IHP opportunities.

For additional information on IHP use in the respective countries that participated in Annex 21, readers are referred to the National Team organizations that represented each country in conducting Annex 21. Additional information can also be found in the country reports submitted for the Annex (see Reference section).

It is important to stress that the results presented in the following sections are intended to provide an indication of the types and relative magnitudes of the energy and environmental benefits that might be achieved through the wider use of IHPs. Each country IHP market assessment was performed using data to represent average conditions for key factors, including plant size and energy prices.

The applicability of IHPs is very site-specific and readers should be aware that IHPs may indeed be practical for their site, even though the general findings herein report less than optimal potential for IHPs in certain industries, based on the assumed average conditions. Thus, a key objective of Annex 21 was to provide industrial end-users with a tool to screen site-specific IHP potential. The IHP screening program, described in Section 3 and Appendix A, is the result of the Annex's efforts in this regard.

5.2.1 Canada

The overall objective for the Canadian market study [35, 36], as with the other National Team assessments, was to assess the potential energy savings and environmental benefits that might be achieved through greater utilization of IHPs in major industrial processes in Canada.

The Canadian study sought to investigate IHP potential in industries already using IHPs to some extent, such as lumber drying, food processing, pulp and paper production, chemical production, and brewing. It also aimed to investigate IHP potential in processes where IHP use has been limited or non-existent to date. In the Canadian market assessment, IHP potential was examined in 14 industrial processes:

- iron and steel blast furnaces;
- poultry processing;
- sugar refining;
- liquor distilling;
- pulp production;
- specialty paper production;
- petroleum refining;
- chlorine/soda production;
- benzene-toluene-xylene (BTX) production;
- textile bleaching/finishing;
- lumber drying;
- milk production;
- cheese production;
- newsprint production.

These 14 processes have a combined total process heat consumption of just over 839,000 terajoules (TJ)/year, and are estimated to account for about 35% of the total Canadian industrial process heating load.

The processes examined contain more than 1,900 individual plants, with about 17% (just over 320) now using IHPs. More than 90% of the IHPs in use, however, are found in one industry: lumber drying, where an estimated 295 IHPs are installed. In terms of current IHP penetration, liquor distilling shows the highest level of IHP use, with about one-third of all plants now using IHPs. The next-highest levels are found in lumber drying (27%), cheese production (6%), and poultry processing (5%).

A detailed screening was conducted to assess the technically feasible IHP options in the 14 processes evaluated in Canada and also to identify the most economic IHP options for each process. The primary types of IHPs evaluated were closed-cycle, electrically-driven IHPs and mechanical vapor recompression (MVR) IHPs. In addition, the potential of diesel-driven and absorption-based IHPs was evaluated in a number of the processes.

Across the 14 processes analyzed, the cumulative market penetration of IHPs under the maximum scenario was estimated to be 9% by 2010, with 225 units projected to be installed. Of the total, electric closed-cycle systems were estimated to account for 70% of the potential installations, followed by MVRs at 19% (Table 5.1). Projected penetration under the average-size IHP scenario was estimated to be about 8%, or some 195 units. Potential market penetration was estimated at over 25% for four industrial processes: chlorine/soda production, newsprint production, pulp production, and specialty paper production.

For the 14 industrial processes combined, and under the two different IHP size scenarios, IHPs are estimated to have the potential to reduce industrial process heat energy consumption by about 5,500-14,600 TJ/year by 2010 (Table 5.2). Five processes were estimated to account for some 88% of the total savings:

- chlorine/soda production (63%);
- petroleum refining (7%);
- iron and steel blast furnaces (7%);
- specialty paper production (6%);
- pulp production (5%).

Depending on the process, the potential level of energy savings per process ranged between less than 1% to 16%, with the highest levels estimated in chlorine/soda production, cheese production, poultry production, and liquor distilling.
Under the two IHP size scenarios, the Canadian assessment estimated that by 2010 IHP use in the 14 processes could provide the following levels of emissions reductions:

- SO_x - 0.6-2.3 thousand tonnes/year;
- NO_x - 0.4-1.4 thousand tonnes/year;
- CO - 73-297 tonnes/year;
- CH_4 - 8-21 tonnes/year;
- Particulates - 16-58 tonnes/year;
- CO_2 - 327-929 thousand tonnes/year(*).

(*) 0.1-0.3 million tonnes/year carbon equivalent (MMTCE).

In the case of Canada, IHPs would be reducing natural gas-based process heating energy consumption in many processes. Therefore, while they would reduce plant- and national-level emissions of all fossil-fuel based pollutants, the primary benefit would be reduced CO_2

emissions, followed by lesser reductions in SO_x and NO_x emissions. The potential overall reductions in CO, CH_4, and particulate emissions would be modest.

The greatest environmental benefits from IHP use can be found in processes that rely most heavily on oil and coal for process heating. Prominent examples include pulp and paper processes (e.g., pulp, specialty paper, newsprint), iron and steel, and petroleum refining (Table 5.2).

From the Canadian IHP assessment, the following overall conclusions can be drawn:

- Promising IHP applications include the lumber, food, pulp and paper, chemicals, and metals industries. Sewage treatment has also been identified as a good potential application of heat pumps.

- Waste heat sources to which IHPs can be applied include heat recovery from evaporation and refrigeration processes, heat recovery from boiler pre-heat makeup water, and from condensed steam.

- IHPs can offer several important non-economic benefits, including an effective increase in the capacity of existing steam plants, better plant-wide environment or building conditioning control, and improved product quality.

- IHP economics are highly sensitive to the annual utilization rate, and correct system sizing is important to ensure trouble-free operation.

To provide an overall estimate of the potential IHP environmental benefits in Canada, the results from the 14 processes studied in detail were used to derive an estimate of potential national energy and environmental benefits. For Canada as a whole, IHPs are estimated to have the potential to provide net national energy savings of about 15,600-41,400 TJ/year (Table 5.2). At this level of savings, IHPs could provide environmental benefits about 3 times the level projected in the 14 processes analyzed in detail (Table 5.2).

The potential benefits from IHPs could be larger in Canada than the figures estimated here. The supporting research conducted for the Canadian study [35, 36] and another recent study [37] found that since 1989 about 20 to 30 new IHPs have been installed in Canada each year, a rate 30-100% higher than the projected level of installations. This suggests that end-users may in fact be willing to accept slightly longer paybacks than the average conditions used for the Canadian study.

Table 5.1 Canada - Projected Maximum IHP Market Penetration

Process Name	Can. SIC #	Est. # Plants (Year End 1993)	Projected Annual Growth (%) (1994-2010)	Cumulative # of IHPs Projected by 2010 - Under Maximum Scenario							Projected 2010 Maximum IHP Market Penetration (%)
				Closed-Cycle Electric	Closed-Cycle Diesel	MVR	TVR	Type 2 Absorption (Waste-Heat Driven)	Type 1 Absorption (Prime-Heat Driven)	TOTAL	
Iron and Steel-Blast Furnace	291	23	1.8			3		—		3	10
Poultry Processing	1012	119	2.8	9	2				2	13	7
Sugar Refining	1081	8	2.8	—		—		—		0	0
Liquor Distilling	1121	24	-0.5	1	—	2		1		4	18
Pulp Production	2711	39	1.0	3	—	14				17	37
Specialty Paper Production	2719	28	3.7	7	4				2	13	25
Petroleum Refining	3611	33	1.8			2	1		1	4	9
Chlorine/Soda Production	3711	16	2.3	7	4					11	47
BTX Production	1992	9	2.3			—				0	0
Textile Bleaching/Finishing	2512	192	2.8	12	3				4	19	6
Lumber Drying	2512	1087	0.8	79						79	6
Milk Production	1041	179	2.8	18						18	6
Cheese Production	1049	108	2.8	2		21				23	13
Newsprint Production	2712	42	1.6	21						21	38
TOTAL		1,907	1.8%	159	13	42	1	1	9	225	9%

— Denotes IHPs evaluated, but none projected.

Table 5.2 Canada - Projected IHP Energy and Environmental Benefits *(continued on next page)*

Process Name	Can. SIC #	Estimated 1993 Process Heat Demand (1,000 GJ/yr)	Projected 2010 Process Heat Demand (1,000 GJ/yr)	Projected 2010 Net Energy Savings (1,000 GJ/year)		
				Average Case	Maximum Case	% of Total
Iron and Steel-Blast Furnace	291	230,578	312,270	0	1,043	0% - 0.3%
Poultry Processing	1012	960	1,535	48	56	3% - 4%
Sugar Refining	1081	4,133	6,609	0	0	0% - 0%
Liquor Distilling	1121	6,087	2,545	0	150	0% - 6%
Pulp Production	2711	180,600	213,885	334	759	0.2% - 0.4%
Specialty Paper Production	2719	38,720	71,808	144	883	0.2% - 1%
Petroleum Refining	3611	253,700	343,584	482	967	0.1% - 0.3%
Chlorine/Soda Production	3711	37,829	55,681	3,750	9,154	7% - 16%
BTX Production	1992	3,593	5,289	0	0	0% - 0%
Textile Bleaching/Finishing	2512	511	817	13	26	2% - 3%
Lumber Drying	2512	16,655	26,633	254	509	1.0% - 2%
Milk Production	1041	2,501	3,999	27	54	0.7% - 1%
Cheese Production	1049	3,339	5,339	183	470	3% - 9%
Newsprint Production	2712	59,850	95,708	268	533	0.3% - 0.6%
TOTAL 14 PROCESSES		839,056	1,145,702	5,504	14,605	0.5% - 1.3%
TOTAL CANADA POTENTIAL		2,398,400	3,248,100	15,604	41,406	0.5% - 1.3%

Table 5.2 Canada - Projected IHP Energy and Environmental Benefits (continued)

Process Name	Projected 2010 Net Emissions Reductions (tonnes/year)					
	SO_x	NO_x	CO_2	CO	CH_4	Particulates
Iron and Steel-Blast Furnace	0 - 707	0 - 310	0 - 106,587	0 - 110	0 - 1	0 - 16
Poultry Processing	6 - 7	3 - 4	2,918 - 3,423	0 - 0.1	0.1 - 0.1	0.1 - 0.1
Sugar Refining	0 - 0	0 - 0	0 - 0	0 - 0	0 - 0	0 - 0
Liquor Distilling	0 - (8)	0 - 7	0 - 8,286	0 - 0.8	0 - 0.2	0 - 0
Pulp Production	120 - 265	37 - 83	23,944 - 54,179	5 - 11	0.4 - 1	2 - 5
Specialty Paper Production	88 - 526	21 - 123	11,682 - 71,091	3 - 14	0.2 - 1	2 - 10
Petroleum Refining	92 - 186	44 - 88	19,158 - 38,510	14 - 29	0.2 - 0.5	2 - 5
Chlorine/Soda Production	146 - 386	269 - 667	224,160 - 548,757	59 - 148	6 - 14	8 - 19
BTX Production	0 - 0	0 - 0	0 - 0	0 - 0	0 - 0	0 - 0
Textile Bleaching/Finishing	4 - 8	2 - 4	985 - 1,832	0.8 - 1	0 - 0	0.1 - 0.2
Lumber Drying	(79) - (158)	(8) - (16)	10,778 - 21,549	(8) - (17)	0.5 - 1	(2) - (4)
Milk Production	(5) - (11)	(1) - (2)	1,211 - 2,422	(1) - (2)	0.1 - 0.1	0 - 0
Cheese Production	27 - 71	14 - 37	11,529 - 29,860	2 - 5	0.3 - 0.7	0.6 - 2
Newsprint Production	162 - 325	31 - 61	21,111 - 42,222	(2) - (3)	0 - 1	3 - 5
TOTAL 14 PROCESSES	561 - 2,304	412 - 1,366	327,476 - 928,718	73 - 297	8 - 21	16 - 58
TOTAL CANADA POTENTIAL	1,591 - 6,532	1,168 - 3,873	928,463 - 2,633,050	206 - 843	22 - 58	44 - 164
Average Reductions per IHP	7	4	2,991	1	0.1	0.2

5.2.2 Japan

Several hundred IHPs are now in use in Japan, with the predominant applications being chemicals (e.g., glycerin, alcohol), food processing (e.g., brewing, gelatin), pulp and paper, and textile dyeing. The Japanese IHP market assessment for Annex 21 [33] sought to assess the potential energy and environmental benefits that might be realized through use of IHPs in industrial processes where IHP market penetration has been more limited to date. Consistent with the overall Annex, the focus was on potential opportunities in food, chemical, petroleum, paper, and textile processes.

The Japanese IHP market study analyzed future IHP potential in 11 industrial processes:

- caustic soda;
- ethylene;
- polyvinyl chloride;
- naphtha splitter;
- naphtha desulfurization;
- surfolane;
- cane sugar;
- beet sugar;
- liquor/spirits;
- kraft pulp;
- textile dyeing.

The 11 industrial processes investigated were estimated to have a combined process heat demand of over 1.4 million TJ/year, which represents some 38% of Japan's current estimated total industrial process heating load.

While as many as 500 IHPs may now be use in Japan, only about 1% (8 units) of the industrial plants in the processes studied are now using IHPs. A key element of the Japanese assessment was thus aimed at determining the potential benefits of increased IHP use in these processes. The potential for strong environmental benefits resulting from IHP use was seen as quite promising in these processes, as the primary fuel now used for process heating is oil.

In the Japanese IHP study, a variety of IHP options were analyzed for their potential applicability in the 11 processes selected for analysis. MVR IHPs were examined across the processes. Absorption IHPs (type I and type II), TVRs, and closed-cycle IHPs (both electric- and diesel engine-drive) were evaluated for between three and six processes each.

For the 11 processes analyzed, the potential market penetration of IHPs under the maximum scenario was estimated to be over 40% by 2010, based on a projected total of 348 IHPs. MVR heat pumps were estimated to account for 80% of the projected installations. The remaining 20% were composed of closed-cycle systems (7%), split between diesel and electrically-driven units, prime-heat (type I) absorption (6%), waste-heat absorption (type II) (3%), and TVRs (3%) (Table 5.3). Total IHP penetration under the average-size IHP scenario was projected at about 35%.

Potential market penetration was estimated at over 35% in all but two of the industrial processes: naphtha desulfurization and surfolane. It should be noted, however, that while potential penetration was estimated to fairly high in most processes, the IHP configurations for many processes were at the same time estimated to be rather modest in terms of their size (e.g., energy savings/heat delivered). In particular, the petroleum refining/petrochemical processes examined (e.g., ethylene, naphtha splitter/desulfurization), showed IHPs typically providing less than 1% total energy savings.

While IHP potential will vary for any one particular industrial site and must be evaluated accordingly, this is consistent with other Japanese analyses [33, 38], which have found that IHP opportunities in petrochemical processes may be somewhat limited. This situation reportedly results from a long payback period, which is associated with large temperature differences and low energy savings.

Across the 11 processes analyzed and at the two different IHP size scenarios, the data derived in the Japanese IHP assessment showed that IHPs could reduce industrial process heat energy consumption by 30,000-63,840 TJ/year by 2010 (Table 5.4). Five processes were estimated to account for more than 90% of the total:

- kraft pulp (70%);
- textile dyeing (15%);
- ethylene (4%);
- naphtha splitter (4%);
- caustic soda (2%).

The potential level of energy savings for the individual processes ranged between less than 1% to more than 40%. The highest levels of potential energy savings (e.g., over 10%) were estimated in liquor distilling, caustic soda production, cane sugar refining, and kraft pulp production. Moderate levels of energy savings (e.g., 2-6%) were estimated for textile dyeing, polyvinyl chloride production, and beet sugar refining. As mentioned previously, the lowest levels of savings were estimated for the petrochemical processes examined.

For the IHP size scenarios evaluated, the Japanese IHP market assessment for Annex 21 projected that by 2010, the energy savings resulting from IHP use in the 11 processes could translate into the following levels of emissions reductions:

- SO_x - 6.9-14.7 thousand tonnes/year;
- NO_x - 3.5-7.5 thousand tonnes/year;
- CO - 0.7-1.6 thousand tonnes/year;
- CH_4 - 64-131 tonnes/year;
- Particulates - 267-565 tonnes/year;
- CO_2 - 1.7-3.6 million tonnes/year(*).

(*) 0.5-1.0 million tonnes/year carbon equivalent (MMTCE).

For the Japanese processes evaluated, IHPs would generally be displacing oil-based process heating energy consumption; therefore, they have the potential to provide quite significant environmental benefits at both the plant and national levels. The displacement of oil-based heating, along with an electric generating mix which is more than 50% non-fossil-fuel based, means that IHPs can provide significant reductions of all pollutants, but in particular CO_2, SO_x, and NO_x. In fact, this mix translates to the largest average reduction per IHP across the countries participating in Annex 21.

From the analysis in the Japanese IHP market study, the main findings regarding IHP potential include the following:

- IHPs appear to offer strong energy savings potential in caustic soda, pulp and paper, and liquor distilling applications. Processes such as cane sugar refining, textile processing, and polyvinyl chloride production were also shown to be reasonably attractive applications.

- The potential energy savings from IHPs are quite site-specific; however, in most of the processes evaluated, IHPs can be installed to yield paybacks of between 1 and 3 years.

Using the results from the 11 processes examined in detail, an overall estimate of the total potential IHP environmental benefits in Japan was derived. Overall, IHPs were estimated to have the potential to provide energy savings of about 73,700-156,900 TJ/year, or about a 2-3% reduction in total projected process heating energy demand (Table 5.4). This level of savings would increase the potential IHP environmental benefits to some two to three times the level projected for the base 11 processes (Table 5.4). Data provided by the Heat Pump Technology Center of Japan [33] suggest that such benefits would represent a 2-5% reduction from current levels of industrial emissions of the various pollutants.

Table 5.3 Japan - Projected Maximum IHP Market Penetration

Process Name	Est. # Plants (Year End 1993)	Projected Annual Growth (%) (1994-2010)	Cumulative # of IHPs Projected by 2010 - Under Maximum Scenario							Projected 2010 Maximum IHP Market Penetration (%)
			Closed-Cycle Electric	Closed-Cycle Diesel	MVR	TVR	Type 2 Absorption (Waste-Heat Driven)	Type 1 Absorption (Prime-Heat Driven)	TOTAL	
Caustic Soda	45	1	9		6	5	—	5	25	47
Ethylene	14	1		4	2	1		2	9	54
Polyvinyl Chloride	24	1	2	2	4	2		3	13	46
Naphtha Splitter	30	2		4	6	4	5	2	21	50
Naphtha Desulphurization	30	2			—		6		6	14
Surfolane	20	2			1				1	4
Cane Sugar	22	0		2	6				8	36
Beet Sugar	8	0.1	—	1	1		1		3	37
Liquor/Spirits	113	1			55		8		63	47
Kraft Pulp	25	0			11		1		12	48
Textile Dyeing	429	0			187				187	44
TOTAL	760	0.5%	11	13	279	12	21	12	348	42%

— Denotes IHPs evaluated, but none projected.

Table 5.4 Japan - Projected IHP Energy and Environmental Benefits *(continued on next page)*

Process Name	Estimated 1993 Process Heat Demand (1,000 GJ/yr)	Projected 2010 Process Heat Demand (1,000 GJ/yr)	Projected 2010 Net Energy Savings (1,000 GJ/year)		
			Average Case	Maximum Case	% of Total
Caustic Soda	3,300	3,908	708	1,417	18% - 36%
Ethylene	153,000	181,199	1,194	2,391	0.7% - 1%
Polyvinyl Chloride	10,800	12,790	218	484	2% - 4%
Naphtha Splitter	75,000	105,018	1,152	2,268	1% - 2%
Naphtha Desulphurization	120,000	168,029	23	138	0.0% - 0.1%
Surfolane	650,000	910,157	6	9	0.0% - 0.0%
Cane Sugar	5,148	5,148	349	870	7% - 17%
Beet Sugar	17,585	17,886	307	797	2% - 4%
Liquor/Spirits	1,651	1,955	458	915	23% - 47%
Kraft Pulp	302,820	320,820	21,376	44,798	7% - 14%
Textile Dyeing	104,018	104,018	4,205	9,755	4% - 9%
TOTAL 11 PROCESSES	1,443,322	1,830,928	29,996	63,840	2% - 3%
TOTAL JAPAN POTENTIAL	3,800,000	4,500,357	73,730	156,917	2% - 3%

Table 5.4 Japan - Projected IHP Energy and Environmental Benefits (continued)

Process Name	Projected 2010 Net Emissions Reductions (tonnes/year)					
	SO_x	NO_x	CO_2	CO	CH_4	Particulates
Caustic Soda	250 - 500	128 - 257	66,851 - 133,701	20 - 39	3 - 5	11 - 23
Ethylene	426 - 852	221 - 443	104,824 - 209,649	25 - 49	4 - 7	11 - 21
Polyvinyl Chloride	77 - 173	40 - 89	20,375 - 45,772	6 - 13	1 - 2	3 - 8
Naphtha Splitter	367 - 722	190 - 376	98,760 - 191,051	29 - 53	4 - 7	16 - 28
Naphtha Desulphurization	7 - 42	4 - 22	1,891 - 11,346	0.6 - 3	0.1 - 0.4	0.3 - 2
Surfolane	4 - 5	2 - 3	1,044 - 1,377	0.3 - 0.4	0.0 - 0.1	0.2 - 0.3
Cane Sugar	10 - 25	5 - 14	2,892 - 7,167	0.5 - 1	0.1 - 0.2	0.4 - 0.9
Beet Sugar	99 - 240	50 - 123	25,601 - 63,256	5 - 12	1 - 2	4 - 10
Liquor/Spirits	111 - 223	64 - 127	35,721 - 71,465	8 - 16	1 - 3	6 - 11
Kraft Pulp	4,298 - 8,943	2,171 - 4,523	1,011,730 - 2,110,308	593 - 1,230	36 - 74	152 - 316
Textile Dyeing	1,269 - 2,945	644 - 1,493	344,754 - 799,771	71 - 166	13 - 31	63 - 145
TOTAL 11 PROCESSES	6,918 - 14,670	3,519 - 7,470	1,714,443 - 3,644,863	758 - 1,583	64 - 131	267 - 565
TOTAL JAPAN POTENTIAL	17,004 - 36,058	8,650 - 18,361	4,214,041 - 8,958,945	1,864 - 3,890	156 - 323	656 - 1,389
Average Reductions per IHP	32	17	8,059	4	0.3	1

5.2.3 Netherlands

As many as 150 heat pumps may now be in use in the Netherlands; however, fewer than 100 are used in industrial process applications [39, 40]. The most wide-scale applications to date include food processing, petrochemicals, paper, and textiles. IHPs are also now in use in non-process applications such as greenhouse heating and heating/drying in the agricultural sector.

The Dutch IHP market assessment [39, 40] aimed to assess potential IHP benefits in major industrial processes, but also focused on processes where heat pumps are not now widely used. The Dutch Annex 21 study investigated IHP potential in seven industrial process applications:

- textile plants;
- dairy production;
- paper production;
- building ceramics production;
- urea production;
- ethylene production;
- starch evaporation.

The seven processes investigated have a combined process heat demand of nearly 85,200 TJ/year, about 17% of the total for industrial use in the Netherlands.

About 27% of the plants contained in the seven Dutch industrial processes analyzed are now using IHPs; however, more than 90% are found in dairy production [39, 40]. A contributing factor to the low level of IHP in the other processes could be the Netherlands' relatively high electricity prices. Projected electricity-to-fuel price ratios range from 3.5 for natural gas to 8.5 for coal, among the highest for the Annex countries.

In the Dutch IHP study, each of the five primary types of IHPs were evaluated, but only one or two IHP types were evaluated for each process. Closed-cycle, gas-engine-driven IHPs were the main type of IHP evaluated across the seven industrial processes.

The potential IHP market penetration under the maximum size scenario was projected at 12% or 36 units by 2010 (Table 5.5). Gas-engine, closed-cycle and thermal vapor recompression (TVR) IHPs were estimated to account for 53% and 28% of the total potential installations, respectively. The comparatively low level of IHP penetration, and the low level of penetration for electrically-driven IHPs is closely related to the relatively high price of electricity in the Netherlands.

For the seven Dutch industrial processes examined, IHPs are projected to have the potential to reduce process heat energy consumption by some 1,700-3,800 TJ/year by 2010, which is close to 4% of the total process heat energy demand in these processes (Table 5.6).

Across the individual processes, the potential level of energy savings ranged between less than 1% to more than 40%, with the highest levels estimated for starch evaporation and textile processing.

In the Dutch study, it was estimated that IHPs would, in most cases, be off-setting natural gas-based process heating energy consumption; therefore, the primary plant- and national-level environmental benefits would be reduced CO_2 and NO_x emissions. For the two IHP size scenarios examined, the Dutch study projected the following levels of emissions reductions by 2010 across the seven processes:

- SO_x - (30)-(62) tonnes/year;
- NO_x - 112-248 tonnes/year;
- CO - 30-67 tonnes/year;
- CH_4 - 3-6 tonnes/year;
- Particulates - 2-5 tonnes/year;
- CO_2 - 88-194 thousand tonnes/year(*).

(*) 0.02-0.05 million tonnes/year carbon equivalent (MMTCE).

While IHP electricity consumption is not projected to be large in the Netherlands, any increase would be substantially based on fossil fuels, increasingly from coal. Particulate, CH_4, and CO emission reductions are thus projected to be quite modest, while SO_x emissions are projected to increase marginally (Table 5.6).

The Dutch study for Annex 21 yielded the following overall findings:

- To date, MVR and TVR IHPs have been the most widely used type of IHP system in Dutch industry. TVR IHPs (or steam ejectors) have been mostly widely used in the dairy industry.

- Less than 5% of the technical potential for IHPs has been exploited. In particular, good opportunities exist in petrochemical, chemical, and food and drink processes.

- Evaporation and drying processes are two of the most promising potential applications of IHPs. Such opportunities can be found in the dairy, sugar/starch, paper, and chemical industries.

Consistent with the other country-specific IHP assessments, the results from the processes analyzed were used to derive an overall estimate of the potential IHP energy and environmental benefits in the Netherlands.

Overall, IHPs were estimated to have a net national energy savings potential of 10,300-22,600 TJ/year, or 2-4% of total industrial process heat demand (Table 5.6). This level of savings would translate into environmental benefits of five to six times the level projected for the seven processes analyzed in detail (Table 5.6).

The Dutch study for Annex 21 underscores the issue that the applicability and economics of IHPs, and the potential associated energy and environmental benefits, are very site-specific. The assessment projected a relatively low level of potential IHP penetration, based on the assumed market factors and the average process conditions evaluated, which in many cases yielded IHP paybacks of more than five years.

Thus, depending on the specific investment criteria of individual industrial sites, current and future IHP economics, and prevailing energy prices, the potential benefits from IHPs at either the plant or national level in the Netherlands could increase quite dramatically. The Dutch study for Annex 21 [39, 40], for example, found that the technical potential for IHPs in the Netherlands could exceed 450 installations with a combined heat supply/energy saving level of more than 2,200 MW.

The Annex 21 results, for net national savings, projected a level of IHP penetration and energy savings equal to about 720 MW, or about one-third of the technical potential level. Improved IHP economics, changing energy prices, or the willingness of end-users to accept slightly longer financial returns (which might be reduced through outside financial support) could greatly increase the overall level of IHP use and the associated energy and environmental benefits.

Table 5.5 Netherlands - Projected Maximum IHP Market Penetration

Process Name	Est. # Plants (Year End 1993)	Projected Annual Growth (%) (1994-2010)	Cumulative # of IHPs Projected by 2010 - Under Maximum Scenario							Projected 2010 Maximum IHP Market Penetration (%)
			Closed-Cycle Electric	Closed-Cycle Diesel	MVR	TVR	Type 2 Absorption (Waste-Heat Driven)	Type 1 Absorption (Prime-Heat Driven)	TOTAL	
Textile Plant	41	1		11					11	23
Dairy Production	91	1				10		1	11	10
Paper Production	32	1		2			—		2	5
Building Ceramics	72	1		5					5	6
Urea Plant	3	1			1				1	28
Ethylene	3	1		—			1		1	28
Starch Evaporation	8	1			5				5	53
TOTAL	250	1.0%	0	18	6	10	1	1	36	12%

— Denotes IHPs evaluated, but none projected.

Table 5.6 Netherlands - Projected IHP Energy and Environmental Benefits (continued on next page)

Process Name	Estimated 1993 Process Heat Demand (1,000 GJ/yr)	Projected 2010 Process Heat Demand (1,000 GJ/yr)	Projected 2010 Net Energy Savings (1,000 GJ/year)		
			Average Case	Maximum Case	% of Total
Textile Plant	5,285	6,259	344	894	5% - 14%
Dairy Production	10,752	12,734	79	293	1% - 2%
Paper Production	19,300	22,857	25	49	0% - 0%
Building Ceramics	7,440	8,811	22	43	0% - 0%
Urea Plant	2,300	2,724	29	64	1% - 2%
Ethylene	35,400	41,924	59	119	0% - 0%
Starch Evaporation	4,700	5,566	1,157	2,307	21% - 41%
TOTAL 7 PROCESSES	85,177	100,875	1,715	3,769	2% - 4%
TOTAL NETHERLANDS POTENTIAL	512,638	607,158	10,300	22,600	2% - 4%

Table 5.6 Netherlands - Projected IHP Energy and Environmental Benefits (continued)

Process Name	Projected 2010 Net Emissions Reductions (tonnes/year)					
	SO_x	NO_x	CO_2	CO	CH_4	Particulates
Textile Plant	2 - 5	26 - 68	19,768 - 51,388	6 - 17	1 - 1	1 - 2
Dairy Production	0 - 0.1	6 - 22	4,501 - 16,683	2 - 5	0.1 - 1	0.1 - 1
Paper Production	0 - 0	2 - 4	1,402 - 2,791	1 - 1	0 - 0.1	0 - 0.1
Building Ceramics	1 - 2	2 - 4	1,324 - 2,618	0 - 1	0 - 0.1	0.1 - 0.2
Urea Plant	(2) - (3)	2 - 4	1,644 - 3,447	0.6 - 1	0 - 0.1	0 - 0
Ethylene	19 - 39	10 - 20	5,217 - 10,435	1 - 2	0.2 - 0.4	1 - 2
Starch Evaporation	(50) - (105)	64 - 126	54,206 - 106,723	20 - 40	1.6 - 3.0	0.3 - 0.4
TOTAL 7 PROCESSES	(30) - (62)	112 - 248	88,062 - 194,085	30 - 67	3 - 6	2 - 5
TOTAL NETHERLANDS POTENTIAL	(181) - (372)	673 - 1,492	530,047 - 1,168,201	181 - 403	15 - 33	13 - 28
Average Reductions per IHP	(1)	6	4,551	2	0.1	0.1

5.2.4 Norway

The Norwegian market study [41] for Annex 21 sought to analyze the potential benefits from IHPs in major industrial processes in Norway, including those where IHPs are now already in some use or those thought to offer strong IHP potential. The main focus was on fish farming, dairy, timber/wood, and meat plants. A total of six industrial processes were analyzed in detail:

- aqua culture/fish farming process water heating;
- fish drying (stockfish/klipfish);
- dairy refrigeration heat recovery;
- dairy (cream/cheese) evaporation;
- timber/wood product drying;
- meat product refrigeration heat recovery.

The six processes analyzed have total process heat consumption of about 9,855 TJ/year, about 18% of the total for Norway.

These processes already show a high level of IHP use, with an estimated 543 IHPs installed, some 31% of the total number of plants. The favorable conditions for IHPs result from low electricity prices and relatively high oil prices.

In the Norwegian assessment, the principal type of IHP evaluated was the closed-cycle, electrically-driven IHP. This type of IHP was evaluated in all six processes. In the two dairy processes evaluated, MVR IHPs were also evaluated.

For the six processes analyzed, the cumulative market penetration of IHPs under the maximum scenario was estimated to be 27% by 2010, with a total of 594 units projected to be installed. The vast majority of the IHPs were projected to be closed-cycle systems, with MVRs accounting for only about 1% of the total (Table 5.7). Market penetration under the average-size IHP scenario was estimated to be about 20%, or about 500 units.

Across the six processes, and at the two projected penetration levels, IHPs are estimated to have the potential to reduce industrial process heat energy consumption by 745-1,525 TJ/year by 2010, or about 6-13% of the projected amount of total process heat energy demand (Table 5.8).

Two processes were estimated to account for some two-thirds of the total projected net energy savings:

- aqua culture/fish farming (50%);
- dairies cream/cheese evaporation TMP pulp (16%).

The potential level of energy savings ranged between 1% and 65% for the six industries, with the highest levels estimated in dairies, fish products, and aqua culture.

In the case of Norway, IHPs would typically be reducing oil-based process heating energy consumption and thus can provide large plant- and national-level environmental benefits. This is particularly true because IHP energy consumption, which is all electricity in Norway, is based on hydroelectric power and is emission-free.

Under the two scenarios analyzed, by 2010 IHP use in the six processes could provide the following levels of emissions reductions:

- SO_x - 0.3-0.6 thousand tonnes/year;
- NO_x - 0.2-0.3 thousand tonnes/year;
- CO - 0.2-0.3 thousand tonnes/year;
- CH_4 - 5-10 tonnes/year;
- Particulates - 29-60 tonnes/year;
- CO_2 - 94-193 thousand tonnes/year(*).

(*) 0.03-0.05 million tonnes/year carbon equivalent (MMTCE).

Positive environmental benefits can be derived from IHP use in five of the six processes analyzed (Table 5.8). In dairy evaporation, electricity use for process heat is being reduced, but based on Norway's electricity generation mix, there are no net environmental benefits in this process.

From the detailed analyses of the six processes examined in Annex 21 and the supporting information for these analyses [41], the following conclusions can be drawn:

- The primary IHP applications in Norway to date include drying and dehumidification in timber, leather, and fish processing. MVR IHPs have also been used extensively in dairy and wood processing.

- IHPs are seen as a means to reduce energy and improve product quality; however, additional education on IHPs benefits is needed.

- Potential impediments to the wider use of IHPs include a perception that they may be more expensive and less reliable than conventional heating systems, uncertainty about the use of refrigerants in closed-cycle systems, and relatively low industrial electricity and oil prices.

- The costs to install IHPs are related to overall size, but would generally be as follows: $135-400/kW (based on 7.5 NOK/USD) for units over 500 kW; $135-800/kW for units between 25 kW and 500 kW; and between $660/kW and $1130/kW for units between 5 kW and 25 kW.

To provide an overall picture of the potential environmental benefits of IHPs in Norway, the results from the six processes analyzed were used in combination with data from the Norwegian Annex report [41] to assess total potential national energy and environmental benefits.

For Norway as a whole, IHPs are estimated to have the potential to provide net national energy savings of about 3,950-8,100 TJ/year, or some 13% of total industrial process heat demand (Table 5.8). Given the already high level of IHP use in Norway, this represents a significant potential level of incremental energy savings.

For the entire Norwegian industrial sector, IHPs could provide environmental benefits that are some five to six times the level projected in the processes analyzed in detail (Table 5.8). Such potential emissions reduction benefits from IHPs would represent a reduction of about

10% from current SO_x emission levels, 14% from CO_2 levels, and nearly 20% from current NO_x levels. Reductions of CO, CH_4, and particulate emissions would be on the order of less than 1% to 5%.

It is important to note that the potential benefits from IHPs could be much larger in Norway. The research conducted for the Norwegian study [41] found that the technical potential for IHPs could be two to four times as large as the potential estimated in the Annex 21 analysis.

Table 5.7 Norway - Projected Maximum IHP Market Penetration

Process Name	Est. # Plants (Year End 1993)	Projected Annual Growth (%) (1994-2010)	Cumulative # of IHPs Projected by 2010 - Under Maximum Scenario						Projected 2010 Maximum IHP Market Penetration (%)
			Closed-Cycle Electric	MVR	TVR	Type 2 Absorption (Waste-Heat Driven)	Type 1 Absorption (Prime-Heat Driven)	TOTAL	
Aqua culture/fish farming (heating process water)	500	1	283					283	48
Fish products (drying stockfish/klipfish)	90	5	98					98	48
Dairies (refrigeration heat recovery)	105	1	17	3				20	16
Dairies (cream/cheese evaporation)	28	3	11	2				13	28
Timber/wood products (product drying)	760	1	80					80	9
Meat products (refrigeration heat recovery)	270	1	100					100	31
TOTAL	1,753	1%	589	5	0	0	0	594	27%

Table 5.8 Norway - Projected IHP Energy and Environmental Benefits (continued on next page)

Process Name	Estimated 1993 Process Heat Demand (1,000 GJ/yr)	Projected 2010 Process Heat Demand (1,000 GJ/yr)	Projected 2010 Net Energy Savings (1,000 GJ/year)		
			Average Case	Maximum Case	% of Total
Aqua culture/fish farming (heating process water)	2,160	2,558	365	767	14% - 30%
Fish products (drying stockfish/klipfish)	243	557	89	177	16% - 32%
Dairies (refrigeration heat recovery)	569	674	22	43	3% - 6%
Dairies (cream/cheese evaporation)	223	368	120	239	33% - 65%
Timber/wood products (product drying)	5,040	5,969	80	159	1% - 3%
Meat products (refrigeration heat recovery)	1,620	1,918	70	139	4% - 7%
TOTAL 6 PROCESSES	9,855	12,044	744	1,524	6% - 13%
TOTAL NORWAY POTENTIAL	54,000	63,952	3,952	8,095	6% - 13%

Table 5.8 Norway - Projected IHP Energy and Environmental Benefits (continued)

Process Name	Projected 2010 Net Emissions Reductions (tonnes/year)					
	SO_x	NO_x	CO_2	CO	CH_4	Particulates
Aqua culture/fish farming (heating process water)	192 - 403	97 - 203	51,729 - 108,689	11 - 23	2 - 4	10 - 20
Fish products (drying stockfish/klipfish)	46 - 91	23 - 46	12,301 - 24,602	3 - 5	1 - 1	2 - 5
Dairies (refrigeration heat recovery)	18 - 36	9 - 18	4,800 - 9,599	1 - 2	0 - 0	1 - 2
Dairies (cream/cheese evaporation)	0 - 0	0 - 0	0 - 0	0 - 0	0 - 0	0 - 0
Timber/wood products (product drying)	12 - 24	19 - 37	13,979 - 27,959	139 - 278	2 - 4	14 - 29
Meat products (refrigeration heat recovery)	42 - 83	21 - 42	11,231 - 22,462	2 - 5	1 - 1	2 - 4
TOTAL 6 PROCESSES	310 - 637	169 - 346	94,040 - 193,311	156 - 313	5 - 10	29 - 60
TOTAL NORWAY POTENTIAL	1,644 - 3,383	897 - 1,837	499,343 - 1,026,462	830 - 1,660	27 - 53	155 - 319
Average Reductions per IHP	3	2	967	1.6	0.05	0.3

5.2.5 Sweden

The Swedish market study [42, 43] for Annex 21 investigated the potential energy and environmental benefits of IHPs in key Swedish industrial processes. IHPs are now widely used in many applications, including pulp and paper, food processing, chemicals, and metals. Many heat pumps are also used to recover industrial waste heat for use in district heating. Heat pumps that recover heat from natural sources for use in district heating are also quite common in Sweden.

The focus of the Swedish assessment was thus to assess the incremental benefits achievable through wider IHP use. Six processes were analyzed in detail:

- food industry central heating;
- pulp and paper black liquor vapor recovery;
- wastewater concentration;
- biomass drying;
- ethanol distillation;
- district heating.

While not directly an industrial process, district heating was included in the assessment because of its importance in Sweden. The assessment was, however, limited to district heating applications involving heat recovery from industrial processes and excluded applications involving natural heat sources (e.g., ambient air, ground water, sea/lake water).

The six processes analyzed have a total process heat consumption of about 47,000 TJ/year, about 10% of the Swedish total.

As mentioned, IHPs are now widely used in Sweden. As an example, across the six processes examined, IHPs are now installed in some 37% of the plants, numbering 92 overall. This high rate of use is attributable, at least in part, to the country's favorable electric-to-fuel price ratio.

The main type of IHP evaluated in the Swedish study was MVR IHPs, assessed in four of the six processes. Absorption IHPs, both prime- and waste-heat driven, and closed-cycle electric IHPs were selectively examined across the six processes.

The projected cumulative market penetration of IHPs across the six processes and under the maximum IHP scenario was estimated to be 12% by 2010, representing a total of 71 units. Nearly 60% of the IHPs were projected to be MVR systems and about 30% were estimated to be prime-heat-driven (Type 1) absorption units (Table 5.9). Market penetration under the average-size IHP scenario was estimated to be about 10%, or about 60 units.

For the two IHP size scenarios and projected penetration levels, IHPs are estimated to have the potential to reduce industrial process heat energy consumption by about 1,400-2,000 TJ/year by 2010, about 1% of the projected amount of total process heat energy demand (Table 5.10). It should be noted, however, that this overall level of savings is a function of relatively low IHP energy savings projected in pulp and paper, wastewater concentration, and biomass drying processes. In the first two processes, cogeneration is estimated to supply at least 80% of the process heating demand, leaving limited opportunities for IHPs. In the other processes examined, IHPs were found to have the potential to provide energy savings ranging between 2% and 33%.

Three processes were estimated to account for nearly two-thirds of the total projected energy savings:

- district heating (29%);
- ethanol distillation (19%);
- biomass drying (18%).

For the six processes analyzed in the Swedish study, a typical IHP would be reducing oil-, coal-, or waste-fuel-based process heating energy, with a corresponding increase in electricity consumption. With electricity having low (but increasing) emission factors, IHPs in Sweden offer a good potential to provide plant- and national-level environmental benefits.

The Swedish study estimated that, for the two IHP size scenarios, IHP use in the six processes could provide the following levels of emissions reductions by 2010:

- SO_x - 0.3-0.6 thousand tonnes/year;
- NO_x - 0.2-0.4 thousand tonnes/year;
- CO - 0.1-0.2 thousand tonnes/year;
- CH_4 - 6-11 tonnes/year;
- Particulates - 29-53 tonnes/year;
- CO_2 - 180-319 thousand tonnes/year(*).

(*) 0.05-0.09 million tonnes/year carbon equivalent (MMTCE).

The Swedish assessment found that IHPs can provide positive net environmental benefits in each of the six processes examined (Table 5.10). The sole exception is SO_x emissions in biomass drying, where IHPs would be reducing the consumption of a waste fuel with a negligible emission factor for SO_x.

From the overall Swedish assessment for Annex 21, the main findings regarding potential IHP use are as follows:

- Until recently, the high costs of fossil fuels (including large taxes on imports), combined with low electricity prices, have created very favorable conditions for IHPs. With lower taxes, fossil fuel prices have been reduced somewhat; therefore, the conditions for IHPs are somewhat less favorable.

- The potential energy and environmental benefits from IHPs are very site- and process-specific. Analyses have shown that potential energy savings can vary widely within industries; therefore, IHPs must be carefully evaluated for each site.

  As an example, potential energy savings in pulp and paper processes could range from 1% to 27%, depending on the specific application. Similarly, savings could vary from 2%-20% in chemicals, from 2-7% in food processing, between 12% and 30% in textile processing, and could be up to 40% in refining processes.

Using the findings for the six industrial processes analyzed in detail along with data from the Swedish Annex reports [42, 43], an overall estimate of the total potential national IHP energy and environmental benefits was derived. At levels of energy savings comparable to the processes analyzed in detail, but discounting the pulp and paper and wastewater processes (because of the level of cogeneration use), IHPs were estimated to have the potential to provide net national energy savings of some 13,600-18,800 TJ/year, or about 2-3% of total industrial process heat demand (Table 5.10). As in the case of Norway, with Sweden also already having high levels of IHP use, these figures represent a substantial level of potential incremental energy savings.

At this level of savings, IHPs could provide environmental benefits that are 9-10 times the level projected in the processes analyzed in detail (Table 5.10). Like the other country assessments, it should be noted that the potential benefits from IHPs could in practice be much greater than the figures shown. In particular for the case of Sweden, several processes rely heavily on waste fuels for process heating (e.g., pulp and paper, ethanol distillation, district heating) and no environmental credits were given for the associated energy reductions in these fuels.

Table 5.9 Sweden - Projected Maximum IHP Market Penetration

Process Name	Est. # Plants (Year-End 1993)	Projected Annual Growth (%) (1994-2010)	Cumulative # of IHPs Projected by 2010 - Under Maximum Scenario						Projected 2010 Maximum IHP Market Penetration (%)
			Closed-Cycle Electric	MVR	TVR	Type 2 Absorption (Waste-Heat Driven)	Type 1 Absorption (Prime-Heat Driven)	TOTAL	
Food industry (central heating)	130	1	6				6	12	8
Pulp & paper (black liquor vapor recovery)	4	5		2		1		3	33
Wastewater concentration	5	13		18				18	45
Biomass drying	30	14		18				18	6
Ethanol distillation	4	5		4				4	44
District heating (from industrial waste heat sources)	75	2	1				15	16	15
TOTAL	248	5%	7	42	0	1	21	71	12%

Table 5.10 Sweden - Projected IHP Energy and Environmental Benefits *(continued on next page)*

Process Name	Estimated 1993 Process Heat Demand (1,000 GJ/yr)	Projected 2010 Process Heat Demand (1,000 GJ/yr)	Projected 2010 Net Energy Savings (1,000 GJ/year)		
			Average Case	Maximum Case	% of Total
Food industry (central heating)	7,200	10,283	216	267	2% - 3%
Pulp & paper (black liquor vapor recovery)	25,000	57,300	126	167	0% - 0%
Wastewater concentration	4,000	31,944	115	231	0% - 1%
Biomass drying	3,000	27,829	183	360	1% - 1%
Ethanol distillation	500	1,146	329	377	29% - 33%
District heating (from industrial waste heat sources)	7,200	10,082	413	575	4% - 6%
TOTAL 6 PROCESSES	46,900	138,584	1,383	1,976	1% - 1%
TOTAL SWEDEN POTENTIAL	475,000	665,115	13,566	18,820	2% - 3%

Table 5.10 Sweden - Projected IHP Energy and Environmental Benefits (continued)

Process Name	Projected 2010 Net Emissions Reductions (tonnes/year)					
	SO_x	NO_x	CO_2	CO	CH_4	Particulates
Food industry (central heating)	94 - 145	47 - 72	23,947 - 36,248	7 - 11	1 - 1	4 - 6
Pulp & paper (black liquor vapor recovery)	18 - 24	9 - 12	5,092 - 6,759	1 - 2	0.2 - 0.3	1 - 1
Wastewater concentration	16 - 32	9 - 17	4,634 - 9,267	1 - 2	0.2 - 0.4	1 - 2
Biomass drying	(30) - (59)	25 - 51	82,999 - 165,858	63 - 126	3 - 6	15 - 31
Ethanol distillation	79 - 90	38 - 44	19,384 - 22,236	4 - 5	0.7 - 1	4 - 4
District heating (from industrial waste heat sources)	162 - 371	93 - 185	43,542 - 78,542	30 - 62	1 - 2	4 - 9
TOTAL 6 PROCESSES	339 - 603	221 - 381	179,598 - 318,910	106 - 208	6 - 11	29 - 53
TOTAL SWEDEN POTENTIAL	3,325 - 5,743	2,168 - 3,628	1,761,508 - 3,037,124	1,040 - 1,981	58 - 101	284 - 505
Average Reductions per IHP	7	4	3,720	2	0.1	1

5.2.6 United Kingdom

The level of IHP use in the United Kingdom has been fairly limited, with only an estimated 100 IHPs now in use. The types of systems installed to date are split fairly evenly between MVR and closed-cycle IHPs. The predominant industrial applications of IHPs to date include food drying and evaporation operations.

The UK IHP study for Annex 21 [44] aimed to analyze the potential benefits that might be derived from wider IHP use in selected industrial processes that have seen limited IHP market penetration thus far. Consistent with the other country-specific analyses, the UK study focused on potential IHP opportunities from among processes in five major industries: food, chemicals, petroleum, paper, and textiles.

The UK assessment examined IHP potential in six major industrial processes:

- paper and paperboard production;
- chlorine/caustic soda production;
- beet sugar refining;
- malt whiskey distillation;
- liquor/spirits distillation;
- brewing.

The industrial processes analyzed currently have a combined process heat demand of nearly 88,000 TJ/year. These six process account for about 5% of the total industrial process heating load in the UK.

Even though nearly 100 IHPs are now used in the UK, the overall rate of IHP penetration to date is low, and only three units (representing only 1% of the plants) are installed in the six processes studied. A contributing factor to this low penetration may be that electricity-to-fuel price ratios in the United Kingdom are among the highest for the countries in Annex 21, particularly for natural gas and distillate oil. A major focus of the UK study was thus to assess the potential energy and environmental benefits of increased IHP use in these processes.

Across the six processes, the primary type of IHPs whose market potential was examined were MVR and TVR IHPs. To date, these types of IHP systems have been the most widely utilized types of IHPs in the UK.

For the six processes analyzed in detail, IHPs were projected to have a market penetration level, under the maximum IHP size scenario, of some 25% by 2010, translating into a total of 91 units. TVR, prime-heat absorption (Type 1), and MVR IHP systems were estimated to account for 43%, 24%, and 20% of the total installations, respectively (Table 5.11). IHP penetration under the average-size IHP scenario was estimated at about 15%.

At the process level, and based on the assumed average process conditions, IHP market penetration ranged between 15% and 50%, with the highest rates found in beet sugar refining and chlorine/caustic soda production. The lowest rates were found in paper and paperboard production and whiskey distilling.

Across the six processes analyzed and under the two different IHP size scenarios, the UK assessment estimated that IHPs could reduce industrial process heat energy consumption by about 1,850-4,975 TJ/year by 2010, or 2-5% of the projected process heating load for these processes (Table 5.12). Three processes were estimated to account for more than 70% of the total projected energy savings:

- beet sugar refining (26%);
- chlorine/caustic production (26%);
- paper and paperboard production (19%).

The potential level of energy savings for the individual processes ranged between less than 1% to 17%. The highest levels were estimated for the chlorine/caustic soda, beet sugar, liquor distilling, and brewing processes. Moderate levels of energy savings were projected for the paper/paperboard and whiskey distilling processes.

The UK study estimated that, by 2010, the potential IHP energy savings in the six processes analyzed could result in the following levels of emissions reductions:

- SO_x - 0.3-0.7 thousand tonnes/year;
- NO_x - 0.2-0.6 thousand tonnes/year;
- CO - 53-122 tonnes/year;
- CH_4 - 4-11 tonnes/year;
- Particulates - 13-28 tonnes/year;
- CO_2 - 139-340 thousand tonnes/year(*).

(*) 0.04-0.09 million tonnes/year carbon equivalent (MMTCE).

For the UK, the industrial process heating energy saved or displaced by IHPs would mostly be natural gas-based; therefore, the environmental benefits of IHPs on a per-plant basis are somewhat modest, particularly for SO_x and particulates. The largest potential benefits, at both the plant and national levels, would be reduced CO_2 emissions.

From the supporting analysis for the UK IHP market assessment, the main findings regarding IHP potential include the following:

- The projected market penetration of IHPs is somewhat below that of the other countries, in part because of relatively higher electric-to-fuel price ratios.

- IHPs are estimated to have energy savings potential as high as 17%, with typical values between 4% and 9% for the processes examined.

- The potential environmental benefits of IHPs are moderate for those processes where IHPs would be reducing natural-gas based process heating; however, the potential benefits are quite good for processes that rely more heavily on oil-based heating.

- The possibility for IHPs to increase emissions through increased electricity consumption, is modest, as the fuel mix for electricity generation is projected to move sharply to natural gas, renewable energy, and nuclear-based generation.

The findings for the six processes were also used to derive an overall estimate of the total potential IHP energy and environmental benefits in the UK. Overall, IHPs were estimated to have the potential to provide energy savings of about 20,700-55,600 TJ/year, or about 1-3% of total process heating energy demand (Table 5.12). This level of savings would increase the potential IHP environmental benefits more than ten times the level projected for the six base processes (Table 5.12).

Table 5.11 United Kingdom - Projected Maximum IHP Market Penetration

Process Name	Est. # Plants (Year End 1993)	Projected Annual Growth (%) (1994-2010)	Cumulative # of IHPs Projected by 2010 - Under Maximum Scenario: Closed-Cycle Electric	Closed-Cycle Diesel	MVR	TVR	Type 2 Absorption (Waste-Heat Driven)	Type 1 Absorption (Prime-Heat Driven)	TOTAL	Projected 2010 Maximum IHP Market Penetration (%)
Paper and Board	120	1		12				22	34	24
Chlorine/Caustic	9	0			4	—			4	44
Beet Sugar	10	0			3	2			5	50
Malt Whiskey Distillery	87	1				15			15	15
Liquor/Spirits Distillery	10	1			3	2			5	42
Brewery	97	-1			8	20			28	34
TOTAL	333	0.4%	0	12	18	39	0	22	91	25%

— Denotes IHPs evaluated, but none projected.

Table 5.12 United Kingdom - Projected IHP Energy and Environmental Benefits *(continued on next page)*

Process Name	Estimated 1993 Process Heat Demand (1,000 GJ/yr)	Projected 2010 Process Heat Demand (1,000 GJ/yr)	Projected 2010 Net Energy Savings (1,000 GJ/year)		
			Average Case	Maximum Case	% of Total
Paper and Board	52,000	61,584	223	962	0% - 2%
Chlorine/Caustic	7,520	7,520	346	1,308	5% - 17%
Beet Sugar	10,140	10,140	758	1,317	7% - 13%
Malt Whiskey Distillery	4,802	5,687	14	221	0% - 4%
Liquor/Spirits Distillery	5,560	6,585	279	592	4% - 9%
Brewery	7,896	6,656	231	576	3% - 9%
TOTAL 6 PROCESSES	87,918	98,172	1,851	4,976	2% - 5%
TOTAL UK POTENTIAL	1,771,475	2,097,966	20,708	55,654	1% - 3%

Table 5.12 United Kingdom - Projected IHP Energy and Environmental Benefits (continued)

Process Name	Projected 2010 Net Emissions Reductions (tonnes/year)					
	SO_x	NO_x	CO_2	CO	CH_4	Particulates
Paper and Board	8 - 31	20 - 87	13,293 - 57,084	4 - 15	0.4 - 2	0 - (1)
Chlorine/Caustic	8 - 29	17 - 64	13,121 - 49,313	4 - 15	1 - 3	1 - 4
Beet Sugar	218 - 379	132 - 230	68,719 - 119,413	32 - 56	2 - 3	8 - 14
Malt Whiskey Distillery	3 - 53	2 - 32	1,110 - 18,007	0.4 - 6	0 - 1	0.1 - 2
Liquor/Spirits Distillery	60 - 124	44 - 91	26,306 - 54,270	7 - 14	1 - 1.4	3 - 6
Brewery	29 - 74	27 - 68	16,252 - 41,505	6 - 16	1 - 1	1 - 3
TOTAL 6 PROCESSES	326 - 690	242 - 572	138,801 - 339,592	53 - 122	4 - 11	13 - 28
TOTAL UK POTENTIAL	3,646 - 7,718	2,707 - 6,398	1,552,510 - 3,798,388	597 - 1,365	48 - 121	147 - 310
Average Reductions per IHP	7	6	3,369	1	0.1	0.3

5.2.7 United States

Within Annex 21, the objective of the U.S. market study [26] was to build on prior IHP assessments sponsored by the U.S. Department of Energy (DOE) and the Electric Power Research Institute (EPRI), including:

- a study by DOE on the market potential for chemical IHPs [45];
- a study by DOE on industrial process heat demand and IHP potential [46];
- a technical manual on IHPs developed by EPRI [27];
- more than 20 process integration studies sponsored by DOE and EPRI [47].

For the U.S. study, the processes contained in the Annex 21 IHP screening program were reviewed to identify those with the largest annual process heat demand. From the processes available in the screening program, 29 were identified with annual process heat demand in excess of 10 trillion Btu/year:

Pulp and Paper (6)
- Integrated bleach kraft pulp and paper
- Integrated unbleached kraft linerboard
- Bleached kraft pulp
- Sulphite pulp
- Thermomechanical pulp (TMP)
- Unbleached kraft pulp

Chemicals/Petrochemicals (9)
- Aromatics - benzene-toluene-xylene (BTX) unit
- Chlorine/caustic soda
- Ethylene
- Phosphatic fertilizer/phosphoric acid
- Polyethylene
- Soaps/detergents
- Synthetic rubber - polybutadiene
- Urea
- Viscose rayon

Textiles (1)
- Cotton - bleaching/finishing

Petroleum Refining (3)
- Crude unit
- Deisobutanizer/naphtha fractionation
- Hydrocracking

Food (10)
- Beet sugar refining
- Cane sugar refining
- Corn milling/starch production
- Corn milling/corn syrup
- Dairy-creamery/fluid milk
- Dairy- cheese production
- Grain alcohol/liquor production
- Malt beverage brewing
- Potato processing
- Vegetable processing (sauces, juices, soups)

These 29 processes were screened for the technical and economic feasibility of various IHP options using the IHP screening program. IHPs were found to be infeasible in one process (refining/hydrocracking) because of temperature lift restrictions, while two processes (fluid milk, soap/detergents) were found to have very poor economics (e.g., paybacks much greater than 10 years for all IHP types). Two processes were known to use IHPs (cheese) or had been closely examined in other studies (polyethylene).

These five processes were eliminated from the analysis and the remaining 24 were studied in detail. The 24 processes analyzed have a total process heat demand of 1,406 trillion Btu/year, about 20% of the U.S. total.

To conduct the U.S. market assessment, the technically feasible IHPs in each process were identified from the five types of IHPs contained in the IHP screening program: electric closed-cycle, MVR, thermal vapor recompression (TVR), Type 1 absorption (prime-heat driven), and Type 2 absorption (waste heat driven). For most processes, the potential of at least three types of IHPs was evaluated; mostly electric closed-cycle, MVR, and absorption IHPs.

For the U.S. study, IHPs were selected to optimize economics by choosing the temperature lift with the lowest payback from the options in the "maximum" case. An alternative would have been to select the IHP with the greatest possible savings; however, larger savings typically require a larger and more expensive IHP, generally with a longer payback period.

Across the 24 processes analyzed, the cumulative potential market penetration of IHPs under the "maximum" IHP size scenario was estimated to be 33% by 2010, with a total of 652 units. Of the total, about 45% of the IHPs were projected to be MVRs, while 35% were estimated to be TVR-type units (Table 5.13). Market penetration under the "average" IHP size scenario was estimated to be about 25%, or approximately 530 units.

Within the 24 processes and at the two projected penetration levels, IHPs were estimated to have the potential to reduce industrial process heat energy consumption by 45,000-101,000 TJ/year by 2010, about 42-96 trillion Btu/year. At the same time, IHPs would induce about 2,500-5,700 TJ/year of increased electricity demand, approximately 700-1,500 million kWh.

With IHP electricity consumption adjusted to reflect power plant energy consumption (about 3 times higher), the U.S. study estimated that IHPs could provide net national energy savings of about 37,000-84,000 TJ/year (about 35-80 trillion Btu/year) in the 24 processes analyzed (Table 5.14). This level of energy savings represents a 2-6% reduction in total process heat demand for the 24 U.S. processes.

Of the total projected net energy savings for the 24 processes, 8 processes were estimated to account for some 68% of the total savings:

- Corn milling/starch (21%);
- TMP pulp (8%);
- Unbleached kraft linerboard (8%);
- Beet sugar refining (8%);
- Bleached kraft pulp (7%);
- Bleached kraft pulp and paper (6%);
- High fructose corn syrup (5%);
- Synthetic rubber (5%).

For the processes examined, the potential use of IHPs can be viewed as a means of reducing industrial fossil fuel consumption (used to generate process heat), with the tradeoff being an increase in electricity consumption to drive the IHPs.

The net potential energy savings from increased IHP use can provide both plant- and national-level environmental benefits. At the plant level, with electricity taken as "emission-free", IHPs can lead directly to reduced SO_x, NO_x, CO_2, CO, methane, and particulate emissions. However, at the national level, with the emissions impact of electricity generation taken into account, the primary potential national benefit of IHPs is reduced CO_2 emissions.

In the U.S. processes that rely heavily on natural gas for process heat and steam, such as food or chemicals, IHPs could actually cause small net increases in some emissions (mostly SO_x) at the national level; however, across the processes analyzed, IHPs were found to provide net reductions of all pollutants examined.

Under the two scenarios analyzed, the U.S. study for Annex 21 found that by 2010, for the 24 processes analyzed, IHPs could provide the following levels of emissions reductions:

- SO_x - 5.2-12.1 thousand tonnes/year;
- NO_x - 4.0-9.2 thousand tonnes/year;
- CO - 1.4-3.1 thousand tonnes/year;
- CH_4 - 58-135 tonnes/year;
- Particulates - 170-390 tonnes/year;
- CO_2 - 2.0-4.8 million tonnes/year(*).

(*) 0.5-1.3 million tonnes/year carbon equivalent (MMTCE).

Among the 24 U.S. processes analyzed, the eight that are estimated to account for the largest portion of the total net energy savings are projected to account for some 60-80% of the total environmental benefits, depending on the particular type of pollutant (Table 5.14).

From the detailed analyses of the 24 processes examined in Annex 21, the following conclusions can be drawn:

- IHPs can provide the greatest environmental benefits to industrial processes that rely heavily on coal for process heat, with examples including corn milling and beet sugar refining.

- MVR and TVR IHPs were found to be the most economic, with paybacks ranging from one to three years achievable in many of the processes analyzed.

- IHPs can represent sizable investments in some instances, over $1 million for example; however, in many of the processes examined the estimated installation costs ranged from $200,000-$500,000, a much more manageable investment for many potential end-users.

It should also be noted that the potential U.S. environmental benefits of IHPs could be substantially greater than the figures cited above. For the U.S. study, the estimates of emissions reductions from IHPs do not include any emission "credits" for waste fuel reductions, which can be 50-70% of the total process heat energy used in some paper, refining, and chemical processes.

To provide an overall picture of the potential environmental benefits of IHPs in the United States, the results from the 24 processes analyzed in Annex 21 were used in combination with two prior U.S. studies [45, 46] and one concurrent U.S. study [28], all sponsored by the U.S. DOE, to assess the total potential U.S. national energy and environmental benefits of IHPs.

From the three related DOE studies, data from 17 industrial processes not covered in Annex 21 were analyzed in a format similar to Annex 21 to assess additional U.S. IHP opportunities and the potential associated energy savings and emissions reductions. These 17 processes were:

- Acetic anhydride;
- Acid recovery;
- Acrylic fiber;
- Ammonia;
- Butyl rubber;
- Cheese;
- Fuel ethanol;
- Lumber drying;
- Milk powder;
- Nitric acid;
- Nylon;
- Pharmaceuticals;
- Polyester fiber;
- Polyethylene;
- Polystyrene;
- Rice production;
- Soda ash.

In these 17 processes, the potential IHP net energy savings were estimated at 27,000-53,000 TJ/year (25-50 trillion Btu/year) by 2010. This represents about a 4-8% reduction in process heat demand in these processes. Of the 17 processes, five were estimated to account for about 90% of the total savings: polyethylene (68%), lumber drying (10%), cheese (5%), polystyrene (4%), and butyl rubber (4%).

The combined analyses of these 17 processes, plus the results from the 24 processes analyzed in detail in Annex 21, were used to estimate potential IHP benefits for the remainder of the U.S. industrial sector.

Across the U.S. industrial sector, IHPs are estimated to have total potential net fuel energy savings of 284,000-581,000 TJ/year, or 270-550 trillion Btu/year, by 2010. Induced electricity demand from IHPs was estimated to reach some 106,000-214,000 TJ/year (100-200 trillion Btu/year) by 2010 or about 9,800-19,700 million kWh.[1] At a net national level, therefore, IHPs were estimated to have the potential to provide net national energy savings of 179,000-367,000 TJ/year, or about 170-350 trillion Btu/year by 2010. This represents some 2-5% of total U.S. industrial process heat demand (Table 5.14).

For the U.S. industrial sector, and based on the estimated energy savings by process and by type of energy source, IHPs are projected to have the following potential environmental benefits:

	Potential Reductions	
	1,000 tonnes/year	1,000 tons/year
SO_x	17.6-36.7	19.3-40.5
NO_x	20.0-41.4	22.1-45.6
CO	8.0-16.5	8.9-18.2
CH_4	0.4-0.8	0.4-0.9
Particulates	0.8-1.6	0.9-1.8
CO_2	10,908-22,482(*)	12,025-24,782

(*) 3.0-6.1 million tonnes/year carbon equivalent (MMTCE).

1 Based on a heat rate of 10,244 Btu/kWh, estimated from the projected 2010 fuel mix for U.S. electricity generation.

These levels of environmental benefits translate to roughly a 1-2% reduction in current U.S. industrial emissions of each pollutant. Because of the increase in electricity consumption from IHPs and the United States' reliance on coal-based electricity generation, the smallest percentage reductions are estimated for particulates, CH_4, CO, and SO_x. The largest potential reductions are for NO_x and CO_2.

To achieve such environmental benefits would require IHPs to penetrate upwards of one-quarter to one-third of the industrial market, compared to a current level of less than 5% in most U.S. industrial processes. Despite the low overall level of current use, increased IHP market penetration is conceivable, given that in those industries where the operational benefits of IHPs have been demonstrated, some 10-20% of the plants now use IHPs. Prominent examples include evaporation- and distillation-based processes in the paper, chemicals, refining, and food industries.

Table 5.13 United States - Projected Maximum IHP Market Penetration

Process Name	U.S. SIC #	Est. # Plants (Year End 1993)	Projected Annual Growth (%) (1994-2010)	Cumulative # of IHPs Projected by 2010 - Under Maximum Scenario						Projected 2010 Maximum IHP Market Penetration (%)
				Closed-Cycle Electric	MVR	TVR	Type 2 Absorption (Waste-Heat Driven)	Type 1 Absorption (Prime-Heat Driven)	TOTAL	
Integ.blch.kraft pulp/paper	2621	65	2.5	4	27	24	—		55	56
Pet.refining-crude unit	2911	184	1		26	6	2		34	16
Integ. unb.kraft linerboard	2631	40	2.5	—	19	12	1		32	53
Ethylene	2869	32	1.5	2	10	6	1	—	19	46
Bleached kraft pulp	2611	16	3	1	7	7	—		15	57
Corn milling/starch	2046	60	2	1	20	20	—	1	42	50
Unbleach. kraft pulp	2611	14	3	3	5	4	—		12	52
Beet sugar refining	2063	42	2		11	15			26	44
Veget.proc.(sauc./jui./soup)	2033	400	2	35		2		11	48	9
Urea	2873	38	1		14	8	2		24	53
Aromatics: BTX	2865	25	1.5		21				21	65
Cane sugar refining	2062	25	2		13	5			18	51
Chlorine/caustic soda	2812	30	1		19	—	—		19	53
High fructose corn syrup	2046	20	2		8	7	—		15	54
Phos.fert/phos.acid	2874	75	1		23	1		17	41	46
Sulphite pulp	2611	15	3	—	4	3		—	7	28
TMP pulp	2611	20	3		11	7	—		18	54
Syn. rubber (polybutad.)	2822	35	2.5	2	18	10	—		30	56
Malt beverage brewing	2082	134	-0.5	2	2	28	1	1	34	28
Viscose rayon	2823	7	2	—	2	2		—	4	41
Grain alcohol	2085	70	-0.5	2	14	15	—		31	48
Pet.refining-deisobutanizer	2911	100	1	16	26	21		6	69	58
Potato processing	2096	60	2	2		23		1	26	31
Textile-bleaching/finishing	2261	50	1	11				1	12	20
TOTAL		1,557	1.5%	81	300	226	7	38	652	33%

— Denotes IHPs evaluated, but none projected.

Table 5.14 United States - Projected IHP Energy and Environmental Benefits (continued on next page)

Process Name	U.S. SIC #	Estimated 1993 Process Heat Demand (1,000 GJ/yr)	Projected 2010 Process Heat Demand (1,000 GJ/yr)	Projected 2010 Net Energy Savings (1,000 GJ/year)		
				Average Case	Maximum Case	% of Total
Integ.blch.kraft pulp/paper	2621	325,995	296,202	2,022	5,387	1% - 2%
Pet.refining-crude unit	2911	210,947	241,466	421	1,611	0% - 1%
Integ. unb.kraft linerboard	2631	158,250	143,787	2,981	7,119	2% - 5%
Ethylene	2869	105,503	118,560	1,817	4,375	2% - 4%
Bleached kraft pulp	2611	82,290	81,218	3,498	6,210	4% - 8%
Corn milling/starch	2046	73,843	77,294	7,872	17,781	10% - 23%
Unbleach. kraft pulp	2611	47,475	46,856	1,940	3,534	4% - 8%
Beet sugar refining	2063	42,725	44,722	2,780	6,745	6% - 15%
Veget.proc.(sauc./jui./soup)	2033	42,201	44,173	207	426	0% - 1%
Urea	2873	41,395	42,599	738	1,635	2% - 4%
Aromatics: BTX	2865	38,771	42,834	581	1,653	1% - 4%
Cane sugar refining	2062	35,075	36,714	569	1,465	2% - 4%
Chlorine/caustic soda	2812	33,945	34,482	1,288	2,900	4% - 8%
High fructose corn syrup	2046	31,656	33,136	1,896	4,402	6% - 13%
Phos.fert/phos.acid	2874	31,630	32,131	442	1,966	1% - 6%
Sulphite pulp	2611	29,540	29,155	28	196	0% - 1%
TMP pulp	2611	29,485	28,114	3,426	6,879	12% - 24%
Syn. rubber (polybutad.)	2822	26,364	34,409	1,806	3,507	5% - 10%
Malt beverage brewing	2082	21,245	14,584	231	856	2% - 6%
Viscose rayon	2823	17,955	21,565	260	520	1% - 2%
Grain alcohol	2085	15,035	10,321	700	1,481	7% - 14%
Pet.refining-deisobutanizer	2911	21,140	24,198	1,102	2,496	5% - 10%
Potato processing	2096	10,710	13,085	119	431	1% - 3%
Textile-bleaching/finishing	2261	10,560	8,574	339	680	4% - 8%
TOTAL 24 PROCESSES		1,483,735	1,500,179	37,060	84,254	2% - 6%
TOTAL U.S. POTENTIAL		7,408,843	8,160,214	178,682	367,497	2% - 5%

Table 5.14 United States - Projected IHP Energy and Environmental Benefits (continued)

Process Name	Projected 2010 Net Emissions Reductions (tonnes/year)					
	SO_x	NO_x	CO_2	CO	CH_4	Particulates
Integ.blch.kraft pulp/paper	178 - 448	144 - 376	74,937 - 195,417	50 - 135	3 - 7	7 - 18
Pet.refining-crude unit	10 - 35	15 - 58	10,324 - 39,059	4 - 14	0 - 1	1 - 3
Integ. unb.kraft linerboard	183 - 450	156 - 376	86,504 - 209,134	48 - 115	3 - 6	7 - 17
Ethylene	6 - 31	73 - 181	49,818 - 122,424	26 - 63	2 - 4	2 - 5
Bleached kraft pulp	107 - 201	107 - 194	60,068 - 109,118	34 - 61	3 - 5	6 - 12
Corn milling/starch	2,653 - 5,986	1,620 - 3,653	775,426 - 1,748,760	540 - 1,214	18 - 40	71 - 160
Unbleach. kraft pulp	79 - 142	67 - 121	37,436 - 67,772	19 - 34	1 - 3	4 - 7
Beet sugar refining	1,110 - 2,698	627 - 1,526	293,197 - 712,891	200 - 488	7 - 16	30 - 72
Veget.proc.(sauc./jui./soup)	(2) - (19)	15 - 29	11,757 - 23,596	4 - 9	0 - 1	0 - 1
Urea	(48) - (80)	44 - 102	38,116 - 85,618	15 - 32	1 - 3	0 - 1
Aromatics: BTX	(89) - (202)	(14) - (23)	(3,420) - (741)	5 - 13	1 - 2	(1) - (2)
Cane sugar refining	(41) - (45)	48 - 130	33,078 - 86,336	26 - 61	2 - 5	2 - 5
Chlorine/caustic soda	(298) - (661)	36 - 84	50,566 - 114,533	43 - 97	3 - 7	(5) - (11)
High fructose corn syrup	633 - 1,468	384 - 890	184,474 - 427,273	126 - 291	4 - 10	17 - 39
Phos.fert/phos.acid	21 - 60	47 - 208	29,133 - 129,713	18 - 84	1 - 5	2 - 6
Sulphite pulp	1 - 10	1 - 8	603 - 4,293	0 - 2	0 - 0	0 - 0
TMP pulp	180 - 366	133 - 270	74,604 - 150,941	33 - 67	2 - 5	8 - 16
Syn. rubber (polybutad.)	293 - 573	218 - 424	110,591 - 214,971	78 - 150	3 - 5	8 - 16
Malt beverage brewing	53 - 197	37 - 136	19,349 - 71,467	11 - 41	0 - 2	2 - 6
Viscose rayon	121 - 243	64 - 129	29,151 - 58,403	20 - 40	1 - 1	3 - 6
Grain alcohol	88 - 175	86 - 182	49,165 - 104,330	27 - 60	1 - 3	4 - 7
Pet.refining-deisobutanizer	(42) - (81)	17 - 43	15,461 - 37,321	9 - 21	1 - 2	1 - 2
Potato processing	16 - 54	14 - 50	8,043 - 29,116	4 - 15	0 - 1	1 - 2
Textile-bleaching/finishing	21 - 46	36 - 73	22,266 - 44,602	13 - 25	1 - 1	1 - 3
TOTAL 24 PROCESSES	5,233 - 12,095	3,975 - 9,220	2,060,647 - 4,786,347	1,353 - 3,132	58 - 135	171 - 391
TOTAL U.S. POTENTIAL	17,546 - 36,722	20,057 - 41,385	10,908,481 - 22,482,015	8,033 - 16,492	389 - 798	772 - 1,593
Average Reductions per IHP	15	11	5,798	4	0.2	0.5

5.3 Overall Benefits

Two of the primary objectives of Annex 21 were to increase awareness of the potential industrial applications of IHPs and their associated benefits, and to assess the potential global environmental benefits of IHPs.

Towards the first objective, Annex 21 developed an IHP screening program that can be used to determine, on a preliminary basis, the feasibility of heat pumping in different industrial processes. In addition, the country-specific market assessments aimed to highlight IHP potential in various processes. To meet the second objective, the results of the country-specific assessments were used to derive an assessment of potential global IHP benefits. The following sections summarize the overall findings from Annex 21.

5.3.1 Summary of Potential Benefits in the Annex 21 Countries

The seven country-specific IHP market assessments that were conducted as a part of Annex 21 clearly demonstrated that IHPs have the potential to offer strong energy savings and environmental benefits. These studies showed that, across the different countries, IHPs have the potential to:

- lower total industrial process heat energy consumption by an average of 2-5%;
- reduce process heat energy consumption up to 66%, depending on the industry and process.

The supporting studies for Annex 21 also showed that IHPs can provide non-economic benefits, including increased process steam capacity, process debottlenecking, and improved product quality.

Collectively, the seven assessments analyzed more than 35 different industrial processes (see Figure 5.1). Processes where IHPs were estimated to the potential to yield large energy savings, and therefore large environmental benefits, included beet/cane sugar, cheese, corn syrup and starch, dairies, liquor, ethanol, chlorine/caustic soda, and pulp production. In these and other processes involving distillation and evaporation, the potential for IHPs looks to be quite promising.

The market studies conducted for Annex 21 found that, on a combined basis and under the two IHP size scenarios examined, IHPs could provide the following levels of net emissions reductions by 2010:

- SO_x - 45-96 thousand tonnes/year;
- NO_x - 36-77 thousand tonnes/year;
- CO - 12-27 thousand tonnes/year;
- CH_4 - 0.7-1.5 thousand tonnes/year;
- Particulates - 2.1-4.3 thousand tonnes/year;
- CO_2 - 21-42 million tonnes/year(*).

(*) 5.6-11.6 million tonnes/year carbon equivalent (MMTCE).

These aggregate results are shown in Table 5.15.

Figure 5.1 Estimated Energy Savings by Process

Industrial Process	Countries Analyzed	Estimated Total Energy Savings % Savings by Process < 5	5-10	11-15	16-20	21-25	26-30	> 30
Aqua culture/ fish farming	NOR			■	■	■	■	
Aromatics: BTX	CD, US	■						
Beet/cane sugar refining	CD, JPN, UK, US	■	■	■	■			
Biomass drying	SWED	■						
Building ceramics	NETH	■						
Cheese production	CD, NOR	■	■	■	■	■	■	■
Chlorine/caustic soda	CD, JPN, UK, US		■	■	■	■	■	■
Corn syrup/starch production	NETH, US		■	■	■	■	■	■
Dairies	CD, NETH, NOR	■	■	■	■	■	■	■
District heating	SWED	■	■					
Ethanol distillation	SWED, US		■	■	■	■	■	■
Ethylene	JPN, NETH, US	■						
Fish products	NOR				■	■	■	■
Food industry (general)	SWED	■						
Iron and steel-blast furnace	CD	■						
Liquor distilling	CD, JPN, UK	■	■	■	■	■	■	■
Lumber/wood drying	CD, NOR	■						
Malt beverage brewing	UK, US	■	■					
Meat products	NOR	■	■					
Naphtha desulphurization	JPN	■						
Naphtha splitter	JPN	■						
Paper/paperboard production	CD, NETH, SWED, UK, US	■						
Petroleum refining	CD, US	■	■					
Phosphoric fertilizer/acid	US	■	■					
Polyvinyl chloride	JPN	■						
Potato processing	US	■						
Poultry processing	CD	■						
Pulp production	CD, JPN, SWED, US	■	■	■	■	■		
Surfolane	JPN	■						
Synthetic rubber (polybutadiene)	US		■					
Textile finishing	CD, JPN, NETH, US	■	■	■				
Urea	NETH, US	■						
Vegetable processing	US	■						
Viscose rayon	US	■						
Wastewater concentration	SWED	■						

Table 5.15 Overall IHP Energy and Environmental Benefits

Country	Projected 2010 Net IHP Energy Savings	Projected 2010 Net Emissions Reductions						Projected 2010 IHP Refrigerant Emissions
	% of Total Process Heating Consumption	Tonnes/Year					MMTCE/Year	Tonnes/Year
		SO_x	NO_x	CO	CH_4	Particulates	CO_2	
Canada	0.5% - 1%	1,591 - 6,532	1,168 - 3,873	206 - 843	22 - 58	44 - 164	0.3 - 0.7	34 - 89
Japan	2% - 3%	17,004 - 36,058	8,650 - 18,361	1,864 - 3,890	156 - 323	656 - 1,389	1.2 - 2.4	7 - 15
Netherlands	2% - 4%	(181) - (372)	673 - 1,492	181 - 403	15 - 33	13 - 28	0.1 - 0.3	5 - 10
Norway	6% - 12%	1,644 - 3,383	897 - 1,837	830 - 1,660	27 - 53	155 - 319	0.1 - 0.3	8 - 17
Sweden	2% - 3%	3,325 - 5,743	2,168 - 3,628	1,040 - 1,981	58 - 101	284 - 505	0.5 - 0.8	4 - 6
United Kingdom	1% - 3%	3,646 - 7,718	2,707 - 6,398	597 - 1,365	48 - 121	147 - 310	0.4 - 1.0	2 - 5
United States	2% - 5%	17,546 - 36,722	20,057 - 41,385	8,033 - 16,492	389 - 798	772 - 1,593	3.0 - 6.1	23 - 48
Total 7 Countries	2% - 4%	44,575 - 95,784	36,320 - 76,974	12,751 - 26,634	715 - 1,487	2,071 - 4,308	5.6 - 11.6	83 - 190

In conducting Annex 21, the participants recognized that the use of IHPs would reduce emissions associated with fossil fuel burning and would provide net emissions reductions when the increased electricity used by IHPs was taken into account. At the same time, however, they acknowledged that the use of closed-cycle IHPs, which use refrigerants for heat transfer, could contribute some emissions of gases with global warming potential.

To assess these potential emissions, the level of closed-cycle IHP use was analyzed in each of the country-specific IHP assessments. Even though current refrigerants (e.g., CFC12, CFC22, CFC114) will be phased out, data on the typical refrigerant charge for current closed-cycle IHPs was used along with the estimated number and size of closed-cycle systems to generate an estimate of potential refrigerant emissions.

Based on refrigerant- and technology-specific charges for diesel- and electric-driven, closed-cycle IHPs (varying between 370-800 kg/MW) and an estimated leakage rate of 10% per year, the combined market studies estimated that IHPs could potentially increase refrigerant emissions by some 83-190 tonnes/year. While not insignificant, these increases are not nearly large enough to offset the substantial environmental benefits that can be achieved with IHPs.

While the country-specific IHP assessments clearly showed the large potential energy and environmental benefits that might accrue through wider IHP implementation, they also highlighted that the applicability of IHPs and their potential benefits are very country- and site-specific. Local energy prices, the energy mix for process heating, and the energy mix for electricity generation play a role in determining whether IHPs "make sense" technically and economically for a specific industrial site and what will be the associated environmental benefits, both at the plant and national levels.

Because the conditions are so varied in the countries that conducted Annex 21, the projected benefits of IHPs for each country were calculated per IHP (Table 5.16) to more readily compare the factors that can influence the level and types of benefits that might be achieved with IHPs. Key assessment parameters were also summarized across the seven countries (Table 5.17).

Table 5.16 Average IHP Environmental Benefits

	Average Projected 2010 Net Emissions Reductions per IHP					
	Tonnes/Year					TCE/Year
Country	SO_x	NO_x	CO	CH_4	Particulates	CO_2
Canada	7	4	1	0.1	0.2	816
Japan	32	17	4	0.3	1	2,198
Netherlands	(1)	6	2	0.1	0.1	1,241
Norway	3	2	2	0.1	0.3	264
Sweden	7	4	2	0.1	1	1,014
United Kingdom	7	6	1	0.1	0.3	919
United States	15	11	4	0.2	0.5	1,581

Table 5.17 Comparison of Key Parameters for the IHP Market Assessments

Assessment Parameters	Canada	Japan	Netherlands	Norway	Sweden	United Kingdom	United States
Projected 2010 Electric-Fuel Price Ratios							
Natural Gas	2.3	2.5	3.5	—	2.6	4.2	2.4
Oil	1.5-2.5	2.6	4.7	0.6	2.2-3.6	2.7-4.5	2.1-3.0
Coal	2.2	11.5	8.5	—	5.0	6.0	7.1
Projected 2010 Electric Generating Mix (%)							
Gas Boilers	2.2	18	20	0	0	0	8.1
Gas Turbines	0.8	0	25	0	25	61.4	6.5
Coal Boilers	17.9	15	50	0	5	3.6	52.9
Oil Boilers	1.6	10	0	0	2	0.3	4.1
Oil Turbines	0.2	0	0	0	3	0	0.5
Nuclear	16.5	43	5	0	0	24.0	18.0
Hydro/Renewables	60.6	14	0	100	65	10.7	9.9
Projected Average 2010 Industrial Process Heating Energy Mix (%)							
Natural Gas	31	4	58	0	3	72	35
Coal	31	10	0	0	9	5	14
Oil	17	68	42	57	38	19	8
Other	21	18	0	43	50	4	43
Relative Country Sizes (*)	48	70	4	1	9	33	137

(*) Based on ratio of total current industrial process heating demand.

As shown in Table 5.16, the estimated potential average benefits per IHP are comparable across the countries; however, there are noticeable differences. The total projected environmental benefits, and also the average benefits per IHP, are a function of the projected level of market penetration. This in turn is closely tied to the overall electricity-to-fuel (E-F) price ratio, especially for electrically-driven, closed-cycle and MVR IHPs. Comparatively low market penetration levels were projected for the Netherlands and Sweden, which have relatively high estimated E-F price ratios.

It is important to caution that IHP applicability must be considered on a site-specific basis, since fuel price ratios will vary for different situations (both across the Annex countries and for plants are regions within each country). Also, while high E-F ratios may disfavor electrically-driven IHPs, local conditions may at the same time be quite favorable for waste-heat or prime-heat driven IHPs, such as TVRs (steam ejectors) or absorption heat pumps; diesel engine-driven IHPs might also be applicable.

While typical IHP benefits are closely related to market penetration, they are more closely tied to the type of process heating energy that the IHP might displace. For example, the largest average benefits, especially for SO_x, NO_x, and CO_2, were estimated in countries and processes where IHPs would be displacing (i.e., saving) process heat that is heavily based on coal or oil, such as in Japan and the United States. Table 5.17 is not correlated at the process level, but does show the estimated overall fuel mix for process heating, which provides a relative indication of those countries that rely on coal and oil for process heat.

Lower average benefits are to be expected in processes where IHPs would be displacing mostly natural gas-based process heating. This is the case in the Netherlands and the UK.

While potential IHP environmental benefits are a direct function of the energy mix for process heating being displaced, overall IHP benefits are also a function of the energy mix used for electricity generation. The most favored conditions are those where electricity is derived primarily from non-fossil energy sources.

Potential environmental benefits from IHPs, especially electrically-driven types of IHPs, would thus be greatest in countries using a high proportion of hydroelectric, renewable, and nuclear energy for electricity. This includes Norway, Sweden, Canada, and Japan. The Netherlands, the UK, and the United States rely more heavily on fossil fuels for electricity and would, therefore, see lower overall benefits for IHPs that consume electricity.

5.3.2 Summary of Potential Global Benefits

An important objective of Annex 21 was to assess the potential global environmental benefits of IHPs. To do so, the results from the seven detailed country-specific IHP market studies were used in combination with information on industrial energy consumption in other countries.

To derive this projection, several estimates and assumptions were required:

- First, total industrial energy consumption was estimated for countries that did not participate in Annex 21. Using two OECD sources [48, 49] and a European Commission report [50], total current industrial energy consumption in 95 countries was estimated at about

72 exajoules (EJ)/year. Combined with the seven countries that participated in Annex 21, current industrial energy consumption was estimated at some 108 EJ/year.

- The same sources were also used to estimate the current energy mix for industrial energy consumption in the 95 additional countries; that mix was assumed to be equal to the energy mix for process heating.

- Next, the detailed results from the Annex 21 country studies were used to derive the following assumptions:

  - Process heating energy demand was estimated to be an average of 40% of total industrial energy consumption.
  - Process heating energy demand was estimated to increase an average of 2%/year.
  - IHP energy savings, exclusive of IHP electricity consumption, were estimated at 2.5-6%, the range used to account for the two IHP size scenarios.
  - IHP electricity consumption was estimated at 8% of total IHP energy savings or energy delivered.

These estimates and assumptions were used to estimate the potential 2010 energy savings of IHPs in the 95 countries and to determine the environmental benefits associated with such potential savings. Environmental benefits were determined using the following emission factors:

	Emission Factors (g/GJ heat or electricity delivered)			
	Gas	Coal	Oil	Electricity
SO_x	0.3	592	326	230
NO_x	75	301	164	105
CO_2	57000	130000	88000	53945
CO	19	100	18	9
CH_4	1.6	2.6	3.5	1.1
PM	1.5	14.6	16.2	7.1

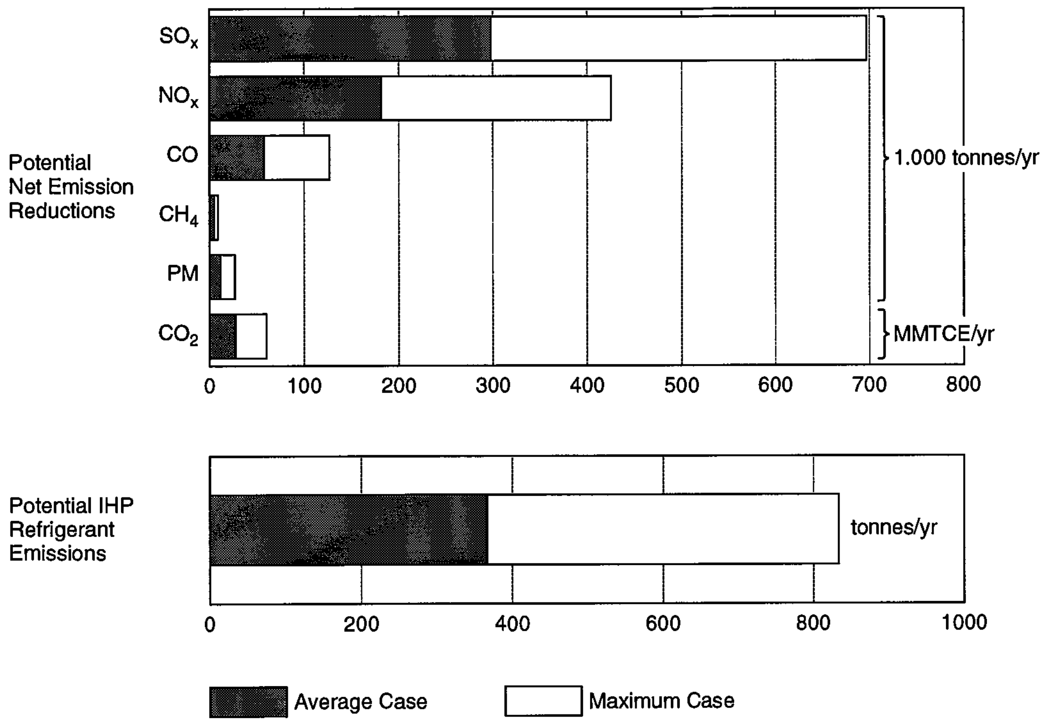
The emission factors for electricity were derived using the following estimated worldwide energy mix for electricity generation: natural gas thermal 6.5%, natural gas turbines 11%, oil thermal 7%, oil turbines 5.5%, coal boilers 36%, and all other energy sources 34%.

Combining the estimated potential benefits for the 95 countries with those from the Annex 21 results, it was estimated that IHPs could provide the following levels of global net emissions reductions by 2010 (Figure 5.2):

- SO_x - 295-695 thousand tonnes/year;
- NO_x - 180-425 thousand tonnes/year;
- CO - 55-125 thousand tonnes/year;
- CH_4 - 3-6 thousand tonnes/year;
- Particulates - 10-24 thousand tonnes/year;
- CO_2 - 92-215 million tonnes/year(*).

(*) 25-58 million tonnes/year carbon equivalent (MMTCE).

Figure 5.2 Potential 2010 Global IHP Environmental Behaviors



Such emission reductions would be equivalent to eliminating some 50-150 GW of electric generating capacity, or about 2-5% of the current world total. The potential increase in IHP refrigerant emissions was estimated at some 365-835 tonnes/year (Figure 5.2).

5.3.3 Overall Conclusions

The country-specific analyses conducted for Annex 21 and the estimates of the potential global environmental benefits of IHPs clearly show that wider IHP use could lead to substantial energy savings and hence strong environmental benefits.

As industrial end-users investigate the potential applicability of IHPs to their sites and as policy makers assess the merits of supporting wider IHP deployment, it is important to conclude this summary report on Annex 21 by stressing several key findings from the Annex and to highlight a few of the important assumptions on which the investigations were based:

- The estimates of potential IHP energy and environmental benefits were derived using average industrial process conditions, but aimed to take into account competition from other technologies (e.g., cogeneration) and realistic market factors, such as risk aversion to new technologies and economic hurdle rates for equipment investments.

  In this manner, the Annex results aimed to show a conservative estimate of potential benefits, reflecting potential applications of IHPs that are both technically and economically viable.

- The estimates reflect the incremental benefits that might be achieved by using new IHPs, beyond those now installed in the countries and processes analyzed. The benefits in terms of process-specific reductions in process heating energy consumption varied from less than 1% to more than 40% across the different countries and processes.

- The environmental benefits of IHPs could in practice be higher than the values estimated because emission "credits" were not given for the reduced energy consumption of waste fuels, which can account for as much as 20-50% of the energy mix for process heating in many countries.

- The analyses across countries used varying assumptions and the number and mix of industrial processes was different in each country. Therefore, the overall Annex results are most appropriately viewed in terms of the aggregate potential benefits of IHPs across the counties in Annex 21 and globally as well.

The efforts in Annex 21 aimed to assess the applicability of IHPs to industrial processes in five major industries: chemicals, petrochemicals/petroleum refining, pulp and paper, food, and textiles. The country-specific assessments showed that IHPs are widely applicable in such industries and can offer large energy savings and environmental benefits.
Across the Annex countries, industrial processes that look to offer significant IHP potential include pulp, paper and paperboard production, dairies, sugar refining, starch evaporation, textile drying and finishing, and chemical/petrochemical separation processes. The Annex participants strongly see IHPs as a technology which has been under utilized to date and one which can contribute to improved process operations in the future.

The Annex results make clear, however, that IHP evaluations need to be conducted on a site-specific basis to properly determine IHP configurations, sizing and the potential investment cost. The IHP screening program for Annex 21 was developed expressly to aid industrial companies and firms that work with these industries (e.g., engineering firms, utilities) in determining the extent to which IHPs could be applied to their operations. The market assessment studies conducted under Annex 21 and the results of this report aim to highlight the potential benefits of IHPs with the hope that more industrial end-users will consider implementing heat pumps in the future.

Appendix A
IHP Screening Program

This appendix presents a detailed description of the screening program developed for Annex 21. Each of the menu choices contained in the program is described and the step-by-step procedures to use the various options are explained.

The program is divided into six main menu choices that reflect the purposes of the program. These are:

- File;
- Performance;
- Processes;
- Integration;
- Options;
- Help.

On the screen these appear as:

These six choices are reviewed in sections A.1-A.6.

In section A.7, definitions of various abbreviations are provided, along with descriptions of the various terminology used in the computer program. This section also outlines heat pump information and reviews various calculation algorithms used in the program.

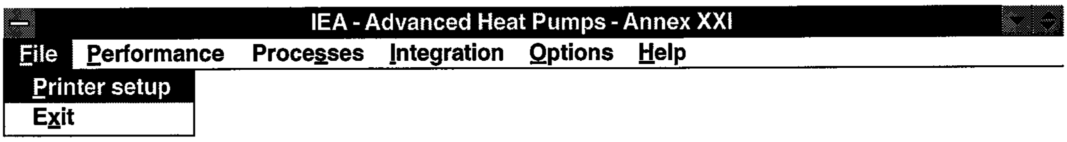
Section A.8 provides a step-by-step example of how the screening program can be used to assess IHP use in an industrial process. This example reviews the program's use for industrial processes contained in the program's data base and discusses how process data can be created for processes not contained in the program or for which the data do not match a user's site-specific conditions.

The purposes and main structure of the IHP screening program are outlined in Section 3.2 of the report, and thus are not included in this appendix.

Menu choices and selections are marked in "**Bold**".

A.1 File

This section describes the "**File**" menu option.



File

Print

This prints the current screen.

Printer setup

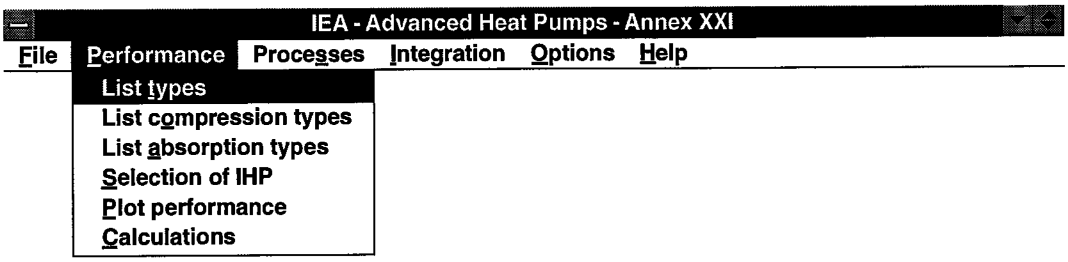
Selection and setup of printers: ordinary Windows setup.

Exit

This stops the program's execution.

A.2 Performance

This section describes the options available under the "**Performance**" menu of the IHP Screening Program. This menu mainly focuses on various features to describe different IHP types and to determine IHP performance under various operating conditions.



Performance

This includes information on the available IHPs.

List types

This lists the IHP types for which information is available. From the list, an IHP can be selected for information.

List compression types

This lists information on compression driven IHPs.

List absorption types

This lists information on absorption IHPs.

Selection of IHP

From specified operating conditions, the program determines the types of IHPs that can operate at these conditions.

The conditions to be specified are:

- heat sink size;
- heat sink target temperature;
- heat source entrance temperature;
- heat source minimum temperature.

An IHP is deemed feasible for the specified conditions if it can satisfy the whole heat sink at the specified temperature and can utilize a heat source in the heat source temperature interval. Temperature and size limitations are considered.

Plot performance

This plots the performance of a selected IHP.

- Start by selecting an IHP.

- If an MVR heat pump using hydrocarbons as the working fluid is selected, it is necessary to specify fluid properties and operating restrictions. First the number of components in the fluid must be specified and then the fluid data on each component (see Section A.7, Definitions). The restriction can be specified by selecting "**Restrictions**" from the menu.

- By selecting "**COP correction**" a custom IHP can be created. The COP of the pure heat pump cycle (not including the motor) will be multiplied by the factor specified.

- Select, from the lists shown, the y-axis, the x-axis, and the parameter. Depending on available information on the selected IHP, various parameters can be plotted.

- If either the AHP or the HT is selected, the third temperature level that is not plotted should be specified.

- By selecting "**Specify detailed IHP conditions**" (check the box) and pressing "**OK**", it is possible to specify detailed data for some of the IHPs.

ECC and DCC:	subcooling in the condenser
	superheating in the evaporator
	size (heat output from the IHP)
MVR and HMVR:	size (heat output from the IHP)

- In those cases, when the variation of capacity (heat output), compression power or fuel consumption are plotted, a reference state (capacity and temperatures) to which the variations are related must be defined.

- Minimum and maximum values on the x-axis can be set.

- The minimum value on the parameter and the interval between each plotted parameter line can be set. Six parameter lines are plotted if IHP limitations do not restrict the numbers.

- By pressing "**OK**" the calculation starts. The calculated minimum and maximum values of the y-axis are shown. It is possible to alter these values. The graph will then only be plotted in the specified interval.

- By pressing "**OK**" the graph will be plotted.

- Save the graph by using the "**File**" menu:

  - "**Print**": This prints the graph on the printer.

  - "**Save as metafile** (WMF)": The graph is saved as a Windows Metafile under the specified file name.

- "**Save as bitmap (BMP)**": The graph is saved as Windows Bitmap under the specified file name.

- "**Clipboard (metafile)**": The graph is copied to the clipboard in metafile format.

- "**Clipboard (bitmap)**": The graph is copied to the clipboard in bitmap format.

Calculations

For given conditions, the program calculates the performance and economics of the selected IHP.

- Start by selecting an IHP. (For MVRs compressing hydrocarbons, see **Plot Performance**.)

- By selecting "**IHP modifications**" and then "**COP correction**", a custom IHP can be created. The COP of the pure heat pump cycle (not including the motor) will be multiplied by the factor specified.

- Specify operating conditions for the IHP:

  - heat sink size;
  - heat sink entrance temperature;
  - heat sink target temperature;
  - heat source size;
  - heat source entrance temperature;
  - heat source minimum temperature.

- Note that the size of the sink and source must reflect the specified temperatures (e.g., if the heat sink target temperature is changed to a higher value, the size of the sink will not increase; only its temperature level will change).

- By selecting "**Specify additional input data**" (check the box) and pressing "**OK**", it is possible to specify additional data:

  ECC, DCC, TVR, MVR, HMVR:
  Temperature difference between heat sink target and condenser temperature.
  Temperature difference between heat source minimum and evaporator temperature.
  ECC and DCC:
  Subcooling in the condenser.
  Superheating in the evaporator.
  TVR:
  Motive steam temperature.
  AHP:
  Prime energy minimum temperature.
  HT:
  Maximum cooling temperature.

- By pressing "**OK**" the program calculates the largest possible IHP at the conditions given. Normally either the sink or the source size will limit the IHP size, but there are situations when temperature conditions are the limiting factor. In these cases, the whole sink is not satisfactory; nor is the whole source utilized. Technical results and the limiting factor are displayed.

- By changing the input data the results are deleted and new results can be calculated.

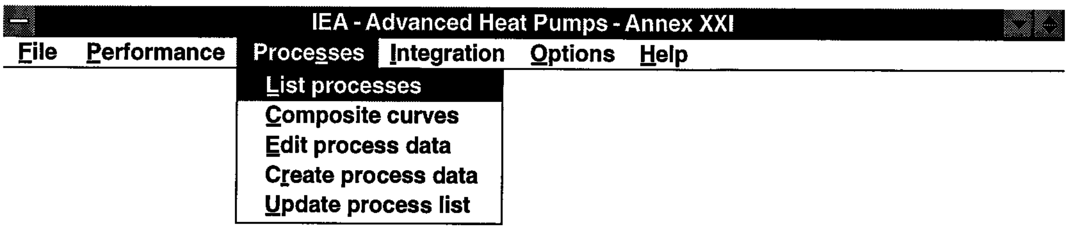
- By pressing "**Economics**" the program estimates the total installation cost of the calculated IHP. If the estimated installation cost is not satisfactory, it is possible to alter a factor by which the cost is multiplied in the next step. Furthermore, a number of economic input data must be specified in order to calculate the economics:

  - Energy costs. These are the: value of saved energy, cost of drive energy, cost of heat source, and cost of cooling. Depending on IHP type the appropriate ones are displayed.
  - Maintenance cost.
  - Annual operation time.
  - Annuity factor.

- By pressing "OK" the payback period and the annual profit of the IHP are determined for the given economic data. By changing the economic input data the results are deleted and new ones can be determined by pressing "OK".

A.3 Processes

This section outlines the information available under the "**Processes**" menu option. This option can be used to access process information on more than 100 industrial processes developed for Annex 21 or can be used to create a user-defined process.



Processes

This includes information on available processes in the data base and possibilities to change and add process data to the base.

List processes

This list the available processes in the data base, both user-defined and predefined. The pinch temperatures listed are based on the global temperature difference included in the process data base.

By selecting a process and pressing "**OK**", information on the process and the source literature is shown.

Composite curves

This calculates and plots the Grand Composite Curve (GCC) and the Composite Curves (CC) for the selected process.

- Select a process and press "**OK**".
- Select whether global temperature difference or individual minimum stream temperature difference contributions from each process stream should be used (see Definitions). The default global temperature difference displayed is the one included in the process data base. If individual stream differences are to be used, be sure to check that these are included in the process data (use the "**Edit process data**" menu). If no stream temperature differences are specified in the process data, 0 K will be used.
- By pressing "**OK**" the GCC and CC are determined. The pinch temperature, minimum heat and cooling demand, and the GCC are displayed.
- Pressing "**GCC/CC**" switches between displaying GCC and CC.
- Pressing "**GCC+CC**" shows both graphs.

- Selecting "**Zoom GCC + CC**" from the menu zooms the graphs:
  - Selecting "**Zoom**" and then the "**GCC**" or "**CC**" displays only one of the graphs.
  - Selecting "**Modify**" makes it possible to add a grid or change the scale of the axes. Scales are changed by giving minimum and maximum values of the axes and then pressing "**OK**".
  - Selecting "**Unzoom**" from the "**Zoom**" menu once again displays both graphs.
  - Output of graphs is possible when only one graph is shown. Select "**File**":
    - "**Print**": Prints the graph on the printer.
    - "**Save as metafile (WMF)**": The graph is saved as a Windows Metafile under the specified file name.
    - "**Save as bitmap (BMP)**": The graph is saved as a Windows Bitmap under the specified file name.
    - "**Clipboard (metafile)**": The graph is copied to the clipboard in metafile format.
    - "**Clipboard (bitmap)**": The graph is copied to the clipboard in bitmap format.

- By selecting "**Heat demand**" the minimum hot utility is calculated and plotted for various global temperature differences from 0 K to 50 K. These calculations may take some time. Modification and output of the graph are done in a way similar to the GCC and CC graphs.

Edit process data

Editing, saving and replacing of processes. Predefined processes cannot be edited.

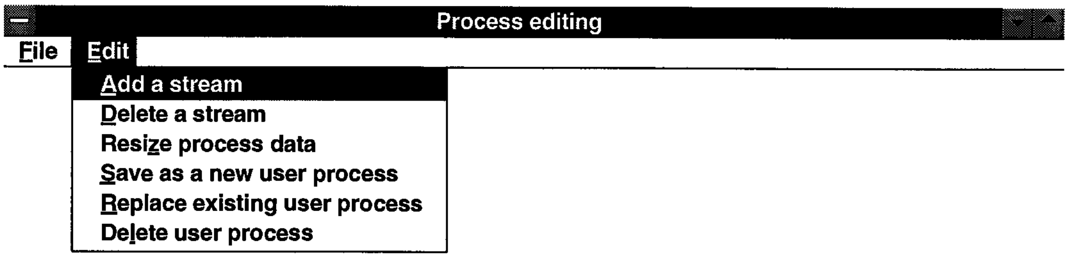
Editing of user-defined processes:

- Select a process and press "**OK**".

- Select the cell to be edited and press "**OK**".

- The cell content is displayed in an edit area where changes can be made. Editing is ended by pressing "**OK**". By pressing "**Cancel**" the changes are ignored.

- The "**Edit**" menu gives other possibilities:



- "**Add a stream**" adds a new row for stream data input. Inputs are given by selecting the cells, one by one, and editing them.
  "**Delete a stream**" deletes the current selected stream data row.
- "**Resize process data**" resizes all size dependent data by multiplying by the factor specified in the input field. These data are: stream heat load, current heating and cooling demand.

- "**Save as new user process**" saves the current process (including changes) as a new user-defined process.
- "**Replace existing user process**" replaces the existing (old) process data with current (new) process data.
- "**Delete user process**" deletes the current process from the list.

Predefined processes can be saved as a user-defined process and then edited.

- Select a predefined process and press "**OK**".

- Select "**Save as new user process**" in the "**Edit**" menu. In this way a user-defined process is created, which can be edited.

Create process data

This creates a new user-defined process.

- Select "**Create process data**".

- Edit each cell as described above.

- Save the new data by selecting "**Save as new user process**".

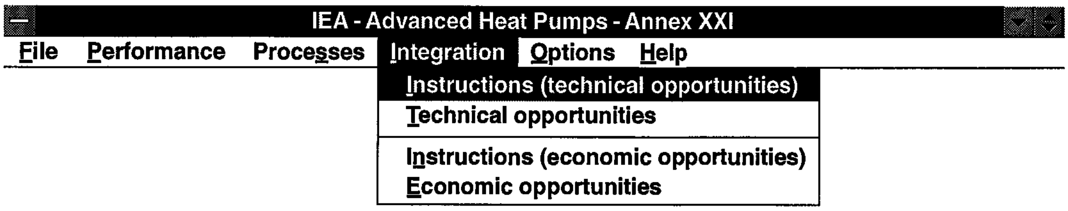
- When creating new data, you may save some time by first saving a predefined process as a user-defined one and then editing it (see above).

Update process list

Updates the process list to include the new user-defined processes created.

A.4 Integration

This menu option is used to determine whether various IHPs are technically and economically feasible in a process.



Integration

This determines technical and economic opportunities to integrate an IHP in a process.

Technical opportunities

This determines the technical possibilities to integrate an IHP in a process. The theoretically largest possible IHPs at various combinations of the heat sink and source temperatures are determined.

- Select a process and press "**OK**".

- Select an IHP and press "**OK**". (For MVRs compressing hydrocarbons, see "**Plot Performance**").

- By selecting "**COP correction**" a custom IHP can be created. The COP of the pure heat pump cycle (not including the motor) will be multiplied by the factor specified.

- Depending on selected IHP, detailed input data are shown and can be altered. Temperature differences between the internal heat pump temperatures and the heat sink and source can also be altered. As is clear from the definitions, the differences include the distribution system. For absorption types these differences should only reflect the distribution system. For open IHPs these differences do not apply (see definitions of IHPs). The data to be specified are:

  ECC, DCC, TVR, MVR, HMVR:
  Temperature difference between heat sink streams and condenser temperature.
  Temperature difference between heat source streams and evaporator temperature.

  ECC and DCC:
  Subcooling in the condenser.
  Superheating in the evaporator.

TVR:
Motive steam temperature.

AHP and HT:
Temperature difference in distribution system from heat pump outlet to sink streams.
Temperature difference in distribution system from heat pump outlet to source streams.

AHP:
Prime energy minimum temperature.

HT:
Maximum cooling temperature.

- The global temperature difference in the process is shown and can be altered. This parameter is very important for the opportunities, and great attention should be paid to setting it. Press "**OK**" to continue after input.

  - By selecting "**Heat demand**" from the menu the minimum hot utility is calculated for various global temperature differences from 0K to 50K and plotted (see above).

  - By selecting "**Composite curve**" from the menu the GCC and CC are plotted (see "**Zoom GCC + CC**" above).

- The program suggests six IHP delivering temperatures to be tested. These temperatures are determined from the sink demand (cold stream pinch temperature and highest cold stream temperature) and the operating temperatures of the selected IHP. The temperatures can be altered and excluded. To exclude a temperature, press the check box. Press "**OK**" to continue.

- A graph is constructed (this may take some time) which shows the theoretically largest possible heat pump at the specified delivering temperatures versus the extraction temperature. Simultaneously the GCC is displayed. The tested extraction temperatures are in the interval between the hot stream pinch temperature and the lowest temperature of the hot streams. The theoretical maximum amounts of heat that can be delivered and extracted are determined by the CC. Operating limitations of the IHP are taken into account during the construction of the graph.

  - By selecting "**Zoom IHP graph**" from the menu the graph showing the largest possible IHP is zoomed. Modifications can then be made on the graph and its output is possible by using the "**File**" menu in a similar way as described above (see "**Zoom GCC + CC**").

Economic opportunities

Economic opportunities

File COP correction Heat demand Composite curves Zoom graphs Result report

This determines the economic possibilities to integrate an IHP in a process. The first steps correspond to the ones in "**Technical opportunities**". However, the delivering temperatures to be tested cannot be changed by the user.

- Select a process and press "**OK**".

- Select an IHP and press "**OK**". (For MVRs compressing hydrocarbons see "**Plot Performance**").

- By selecting "**COP correction**" a custom IHP can be created. The COP of the pure heat pump cycle (not including the motor) will be multiplied by the factor specified.

- Depending on the selected IHP detailed input data are shown and can be altered. Temperature differences between the internal heat pump temperatures and the heat sink and source can also be altered. As is clear from the definitions, the differences include the distribution system. For absorption types these differences should only reflect the distribution system. For open IHPs these differences do not apply (see definitions of IHPs). The data to be specified are:

  ECC, DCC, TVR, MVR, HMVR:
  Temperature difference between heat sink streams and condenser temperature.
  Temperature difference between heat source streams and evaporator temperature.

  ECC and DCC:
  Subcooling in the condenser.
  Superheating in the evaporator.

  TVR:
  Motive steam temperature.

  AHP and HT:
  Temperature difference in distribution system from heat pump outlet to sink streams.
  Temperature difference in distribution system from heat pump outlet to source streams.

  AHP:
  Prime energy minimum temperature.

  HT:
  Maximum cooling temperature.

- The global temperature difference in the process is shown and can be altered. This parameter is very important for the opportunities, and great attention should be paid to setting it. Press "**OK**" to continue after input.

- By selecting **"Heat demand"** from the menu the minimum hot utility is calculated for various global temperature differences from 0 K to 50 K and plotted (see above).

- By selecting **"Composite curve"** from the menu the GCC and CC are plotted (see **"Zoom GCC + CC"** above).

- The hot and cold stream pinch temperatures are shown, as well as brief information on economic integration. Press **"OK"** to continue.

- If the selected IHP, due to temperature restrictions, cannot operate at any combination of possible sink and source temperatures, a message is displayed. Another IHP with suitable operating temperatures should then be selected.

- Economic input data are displayed and should be changed to the desired values.

  - Energy costs. These are the value of saved energy, cost of drive energy, cost of heat source and cost of cooling. Depending on IHP type the appropriate ones are displayed.
  - Maintenance cost.
  - Annual operation time.
  - Annuity factor.

  If the estimated installation cost is not satisfactory, it is possible to alter a factor by which the cost is multiplied in the next steps.

  Additional heat exchangers needed in the process due to the IHP integration are estimated from the numbers of streams above the sink temperature and the size of the IHP in relation to the heat demand. Below the pinch a corresponding estimation is made. The cost of the heat exchangers are calculated by the shown equation (= const. * $size^{0.6}$ (size = heat transferred)). The constant in the equation can be altered. (See Definitions for detailed information.)

- The program determines the theoretically largest IHP at all combinations of delivering and extraction temperatures. The delivering and extraction temperatures tested are described in **"Technical opportunities"**. The largest possible IHP installation at each temperature lift (difference between delivering and extraction temperatures) can then be plotted. The corresponding payback periods (PBP) are also plotted. Simultaneously the same calculations are performed for an IHP, which is half of the largest possible size. This smaller size is supposed to be a more realistic estimation of the economic opportunities than the theoretically largest possible IHP.
  The same technical limitations as used and described in **"Technical opportunities"** are used.

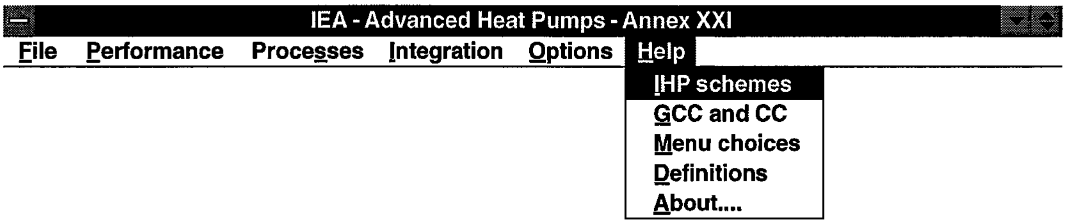
- Modification and output of the graphs are possible by selecting **"Zoom graphs"**. This is done in a way similar to what was done for the GCC and CC graphs, see **"Zoom GCC + CC"**.

- The temperature lift to be evaluated in depth is specified in a data input area. The lift should be selected from the PBP and IHP size graph. A short PBP and a large IHP are preferred. The default value is within the possible lift interval, but is not in any way optimized. Press "**OK**" to continue after temperature lift specification.

- The economic results for the temperature lift specified will then be shown. Detailed and annual results are shown by selecting the "**Result report**" from the menu. These are the results, which should be put into the market study. By selecting "**Save to file**" the results are saved in a file.

A.6 Help

The "**Help**" menu option provides users with additional information about selected program features.



Help

IHP schemes

This displays figures on all available IHP schemes. Click a scheme or select it from the list in the submenu "**Zoom schemes**". The selected scheme will then be displayed on the screen.

GCC and CC

This shows definitions in the curves.

Menu choices

This starts the Microsoft Windows word processor "Write" and displays a description of the menu choices and step-by-step instructions. If "Write" is not installed in the system, it is recommended to load the file "menu_chs.wri" into another editor where the information can be read.

Definitions

This starts the Microsoft Windows word processor "Write" and displays the definitions used in the program. If "Write" is not installed in the system, it is recommended to load the file "def_exp.wri" into another editor where the information can be read.

About

This displays program information.

A.7 Definitions, Nomenclature, IHP Types

This section provides additional information on the various terms and definitions used in the screening program, on computer program nomenclature, IHP types and different data calculations.

Definitions

General

Additional heat exchangers

Integration of an IHP normally requires additional heat exchangers in the original heat exchanger network and to distribute the heat to the sink and from the source. The numbers of heat exchangers are strongly dependent on the actual layout of the plant and on the size of the IHP. The estimation of the numbers required above the pinch is based on the numbers of streams above the sink temperature and the size of the IHP in relation to the minimum heat demand. Below the pinch it is based on the numbers of streams below the source temperature and the extracted heat amount in relation to the minimum cooling demand. A minimum of three additional heat exchangers, both above and below, are assumed. No additional heat exchangers are assumed for processes of the "simple" type.

Above the pinch, the calculation procedure is described in the following.
The number of heat exchangers necessary is generally given by:

$no_{heat\ exchanger} = no_{streams} - 1$

The number of additional heat exchangers above the integration temperature can, therefore, be estimated by this equation. The number of streams is determined by the number of hot and cold streams present in the interval where the composite curves overlap at temperatures above the integration temperature. Cold streams are also heated directly by hot utility, and these streams do not need any new heat exchangers due to the integration. Thus, these streams are subtracted from the ones previously determined.
The number of additional heat exchangers is then given by multiplying the number determined above by the ratio of heat delivered from the heat pump divided by the minimum hot utility. The fact that, in practice, normally 30% more heat exchangers than given by the equation are necessary, is handled by multiplying by the factor 1.3. Not less than three heat exchangers are, however, accepted.
The size of each additional heat exchanger is estimated to be equal to the average size of the ones already installed. The number of these is estimated from the equation above.

Annual profit (AP)

Annual saving minus annual capital cost.
$AP = S - a * I$

Annual saving (S)

Annual difference in energy costs before and after IHP installation plus IHP maintenance cost.

$$S = t * (Q_{hp} * e_{replaced} - Q_{drive} * e_{drive} - Q_{source} * e_{source}) - Q_{hp} * e_{maint}$$

where

Q_{hp} = IHP size, i.e. heat from IHP (kW)
Q_{drive} = Drive energy to the IHP. Electricity or heat depending on type. For HT: heat source (kW)
Q_{source} = Heat source to IHP. For HT: cooling load (kW)
$e_{replaced}$ = Value (cost) of saved (replaced) energy by the IHP ($/kWh)
e_{drive} = Cost of drive energy. HT: cost of heat source ($/kWh)
e_{source} = Cost of heat source. HT: cost of cooling ($/kWh)
e_{maint} = Annual maintenance cost per kW from IHP ($/kW year)
t = Annual operation time (hours/year)

Annuity factor (*a*)

The annuity factor is determined from interest rate (i) and lifetime (n):

$$a = \frac{i}{1 - (1+i)^{-n}}$$

Installation cost times the annuity factor gives the annual capital cost.

CC

Composite Curves

Cold streams pinch temperature

Pinch temperature of cold streams. If a global temperature difference is used, it is half of this difference lower than the pinch temperature.

GCC

Grand Composite Curve

Global temperature difference

Temperature difference between the hot and cold composite curves at the pinch in the CC. The global ΔT reflects the heat demand of the process, i.e., at a certain heat demand it describes the location of the hot and cold composite curves. Hence, it is not a specification of the temperature differences in individual heat exchangers.

Heat output (Q_{hp})

Useful heat output from the heat pump.

Heat sink

Stream or streams to which the heat pump delivers heat, i.e. streams requiring heat.

Heat sink entrance temperature

Temperature of heat sink entering the heat pump.

Heat sink outlet temperature

Temperature of heat sink leaving the heat pump.

Heat sink size

Heat necessary to heat the heat sink from the entrance to the target temperature.

Heat sink target temperature
Desired temperature of heat sink leaving the heat pump.

Heat source
Stream or streams from which the heat pump extracts heat.

Heat source entrance temperature
Temperature of heat source entering the heat pump.

Heat source minimum temperature
Lowest acceptable temperature of heat source leaving the heat pump.

Heat source outlet temperature
Temperature of heat source leaving the heat pump.

Heat source size
Heat extracted from the heat source when it is cooled from entrance to minimum temperature.

Hot streams pinch temperature
Pinch temperature of hot streams. If a global temperature difference is used, it is half of this difference higher than the pinch temperature.

IHP
Industrial Heat Pump.

Individual stream temperature difference
Temperature difference referring to each individual stream. The total minimum difference in a heat exchanger is the sum of the individual stream temperature difference of the hot and cold streams.

Installation cost (I)
Total cost of heat pump installation (= the sum of the heat pump device cost and costs associated with the installation).

Interval pinch temperature
See pinch temperature.

PBP
Simple pay back period (= I / S)

Pinch temperature
A temperature that divides the process streams into two systems. More strictly it is called the interval pinch temperature. The pinch temperatures of the hot streams are determined by adding the individual stream temperature differences of these streams to the interval pinch temperature. In a similar way, the pinch temperatures of the cold streams are determined by subtracting the individual stream temperature differences of these stream from the interval pinch temperature.

The stream system at temperatures above the pinch has a deficit of heat which must be satisfied by external heat. The stream system at temperatures below the pinch has an excess of heat which must be cooled away.

Saved energy
Heat that is replaced by heat from the heat pump.

Computer Program Nomenclature

The available IHPs are numbered from 1.

Minimum plot value
Lowest value on the axis in the graph.

Maximum plot value
Highest value on the axis in the graph.

Minimum parameter
Lowest value of the parameter in the graph.

Interval
Interval between each parameter line in the graph.

Processes
Industrial process for which stream data are available.

Predefined process
Process which are shipped with the program.

User-defined process
Process which are created by the user.

Predefined processes are numbered from 501.

Predefined processes cannot be altered by the user.

User-defined processes are numbered from 1.

User-defined processes can be created, edited and deleted by the user.

Process information can either be "Full" or "Simple":
"Full" means that the data consist of complete process stream data, suitable for pinch analysis.
"Simple" means that the data are simplified, e.g., the total heat demand is given as one load at a temperature.

Interval pinch temperature:
The interval pinch temperatures indicated in the process list refer to the global temperature difference in the process data. This can change considerably when the global temperature difference is changed.

Current heating

Heat demand of the process as reported by the National Teams.

Current cooling

Cooling demand of the process as reported by the National Teams.

Absolute size not specified

If the absolute size is not given in the source literature, this is marked in the process list. The size in the process data has, in these cases, been set in a way that the current heat demand is equal to 1,000 kW.

Global temperature difference

The global temperature difference value in the process data reflects a level to which heat recovery by heat exchanging is assumed to be reasonable. This value has been set by examining the plot of the heat demand versus the global temperature difference. The values have been included due to the requests from the National Teams.

Individual stream temperature difference

This is the temperature difference specified for each process stream. Be sure to check if these are given in the process data list before the GCC and CC are determined. If no data are given, 0 K is used for the difference.

Maximum IHP size

This expression is used in the integration part. It refers to the theoretically largest IHP that can be installed at given delivering and extraction temperatures. The size of the source and sink are determined from the CC. It is assumed that heat is extracted from hot streams below the hot stream pinch and delivered to cold streams above the cold stream pinch. Depending on the relative size of sink and source and the IHP performance, the largest possible IHP can be determined. Temperature limitations of the IHP are taken into account.

Maximum IHP size vs. extraction temperature with delivering temperature as a parameter

This graph shows the maximum IHP size (and half of it) versus possible extraction temperatures (below the hot pinch stream temperature). The parameter is the specified IHP delivering temperatures (above the cold stream pinch temperature).

Maximum IHP size vs. IHP temperature lift

This graph is derived from the previous one by first sorting all possible IHPs in successively increasing temperature lift order and then plotting the largest IHP at each temperature lift.

Heat Pump Types

Compression IHP type

IHP driven by a compression device. The TVR IHP is also included in this group.

ECC	Electrical motor-driven closed-cycle compression
DCC	Diesel motor-driven closed-cycle compression
MVR	Mechanical vapor recompression (water)
HMVR	Mechanical vapor recompression (hydrocarbons)
TVR	Thermal vapor recompression

Absorption IHP type

Heat-driven heat pumps. This group includes the AHP and the HT.

AHP Absorption IHP (or prime-heat driven AHP, type I)

HT Heat transformer (or waste heat driven AHP, type II)

Performance data on the compression types are based on internal temperatures of the working fluid (condensing and evaporating). A temperature difference between the sink and source is therefore necessary to make the heat transfer possible:

The temperature difference between the heat sink and condenser refers to the difference between the IHP working fluid and the sink stream(s).

The temperature difference between the heat source and evaporator refers to the difference between the IHP working fluid and the source stream(s).

Performance data on the absorption types are based on external temperatures (temperatures of sink and source leaving the IHP). Thus, no temperature difference between the IHP and sink/source should be specified. In the integration part of the computer program, temperature differences in the distribution system should, however, be specified. The reason for this perhaps confusing difference between the types is that performance data for the absorption type have been available only for external temperatures.

Delivering temperature

Compression type: internal condensation temperature.

Absorption type: external temperature, i.e., outlet temperature from IHP.

Extraction temperature

Compression type: internal evaporation temperature.

Absorption type: external temperature, i.e., outlet temperature from IHP.

HMVR

The user can select the fluid to be compressed in an MVR system. Pure substances, binary and tertiary mixtures can be handled. Fluid properties of the mixture are estimated from the properties of the individual components. Component data can be found in standard handbooks, e.g., *The Properties of Gases and Liquids* by Reid, Prausnitz and Sherwood. The equation of state used is the most suitable one for hydrocarbons, but other components (not inert gases) can be used, although the results will be less accurate. To be able to calculate the fluid data, the properties below must be specified for each component.

Ideal heat capacity

The ideal heat capacity of the components, i.e., heat capacity gas phase at a low pressure.

Critical T and P

Critical temperature and pressure of the components.

Pitzer acentric factor

The Pitzer acentric factor of the components.

Value (cost) of saved heat sink
Value of the heat that the heat pump replaces.

Value (cost) of heat source
Cost of the heat to the heat pump (if any).

Value (cost) of cooling
Cost of cooling, applies to heat transformers.

Value (cost) of prime heat
Cost of motive steam to TVRs and drive energy to absorption heat pumps.

Value (cost) of electricity
Cost of electricity.

Value cost of diesel fuel
Cost of diesel fuel to diesel-driven closed-cycle compression heat pumps.

A.8 Using the Program to Assess IHP Opportunities

This section provides step-by-step instructions to illustrate how the IHP screening program can be used to determine IHP applicability and preliminary economics in one industrial process. *Data referring to examples is shown in italics.*

IHP Fit in Pre-Defined Processes

To determine IHP applicability or "fit" in processes contained in the screening program's master list of processes (see List processes), these steps should be followed:

Step 1: Process Identification and Re-Sizing

1. List the predefined processes with "**List processes**" in the "**Processes**" menu.

2. *Process No. 549* includes stream data for a paper mill (in this case a UK specialty papers process). Select the process and read the information to confirm that the process is the one desired. The heating demand is smaller (in this case no absolute size of the plant was given in the source literature) than the typical in country XX; hence, the process must be resized.

3. Select "**Edit process data**" in the "**Processes**" menu and select *No. 549* from the list.

4. From the "**Edit**" menu select "**Save as new user process**" and "**Quit**". Select "**Update process**" list in the "**Processes**" menu to update the list.

5. The next step is to resize the new user-defined process. Select "**Edit process data**" in the "**Processes**" menu and select the new process from the list.

6. Select "**Resize process data**" from the "**Edit**" menu and specify the resize factor in the displayed input area. Press "**OK**" when ready. In the example the resize factor is: *20.0 (=20,000/1,000).*

7. Select "**Replace existing user process**" from "**Edit**" menu to save the changes. Update the process list by selecting "**Update process list**" in the "**Processes**" menu.

8. It is also possible to alter the name of the process (or any other information), which might make it easier to identify the process later. Select the cell to be changed and edit it. Press "**OK**" when ready. Carry out the changes before step 7.

Step 2: Determine Integration Possibilities

After the process is identified and re-sized, the integration possibilities for different IHP types, up to five different heat pumps in this example, can next be determined.

1. Selection of heat pumps to be tested.

   Select "**Composite curves**" from the "**Processes**" menu and select the user-defined process created in Step 1 from the list. The heat demand versus the global temperature difference can be seen by selecting "**Heat demand**". The predefined global temperature difference is set from considerations of this graph. In the example the pinch temperature is around 40°C, which indicates that not all of the heat pumps can operate at these conditions. (The heat pump should extract heat below the pinch temperature and deliver it above this temperature.) Above the pinch the amount of heat that can be delivered (=distance from the y-axis to the line) increases as the temperature gets higher. At 90°C the possible heat amount that can be delivered increases rapidly. Below the pinch the available amount of heat increases continuously. Based primarily on the location of the pinch and the shape of the Grand Composite Curve (GCC), it is clear that three types of IHPs ought to be tested in the example, i.e., closed cycle compression - electrical driven, closed cycle compression - diesel motor driven, and absorption heat pump, type I. The types not included cannot operate at the temperatures identified from the GCC.

The cheapest closed cycle compression heat pumps are the ones using CFC22, but there is a temperature limit of about 60°C. Thus, CFC12 and CFC114 must also be tested. The size indicates that screw compressors are the most suitable in this example.

The IHPs to be tested in this example are therefore:

No. 5: Closed cycle compression, CFC22, Electrical driven
No. 7: Closed cycle compression, CFC12, Electrical driven
No. 9: Closed cycle compression, CFC114, Electrical driven
No. 34: Closed cycle compression, CFC22, Diesel motor driven
No. 36: Closed cycle compression, CFC12, Diesel motor driven
No. 38: Closed cycle compression, CFC114, Diesel motor driven
No. 29: Absorption heat pump, type 1

2. Select "**Economic opportunities**" from "**Integration**" menu and select the user-defined process created in Step 1 from the list.

3. From the heat pump list select the first IHP to be evaluated. In the example this is IHP No. 5.

4. The pre-defined global temperature difference is shown as well as the temperature differences between delivering/extraction temperatures to the sink/source. The influence of the global temperature difference can be shown by selecting "**Heat demand**". The pre-defined difference has been set from considerations of this graph. The global temperature difference should be specified to a value that reflects the degree of integration when a major retrofitting of the process is carried out. Thus, it should not reflect the current heating demand. If the data shown are not suitable they can be altered. Press "**OK**" to accept after editing.

5. Brief information is displayed. Press "**OK**" to continue.

6. Energy prices and other economic data should now be specified.

   NOTE: It is important to correctly set up the program to the appropriate units. This is done under the "**Options -- Units**" menu.

- Enter the energy prices (for 1995 in this example).

- Give annual operation time.

- Annuity factor (used to determine the annual profit).

- The cost of the additional heat exchangers is calculated as:
  Heat exchanger cost = constant (e.g., 1,500 $/kW) * $size_{0.6}$
  The constant can be specified to any value. The number of heat exchangers necessary to distribute and collect the heat, as well as necessary due to changes in the process, are presented in the result.

- Annual maintenance cost.

- If the installation costs estimated by the program do not agree with the experience of the user, it is possible to adjust them by using an installation cost multiplier. Thus, a factor of less than 1 decreases the installation cost, while a factor larger than 1 increases the cost. After editing press "**OK**".

At this point, the following data will have been specified for the process:

Process to be evaluated:	*Paper mill*
Typical *paper mill* heating demand in *country XX*:	*20,000 kW*
Energy cost 1995:	
Value of saved (replaced) heat:	*0.00657 $/MJ*
Cost of prime heat (e.g., steam)	*0.0066 $/MJ*
Cost to collect heat source:	*0.00062 $/MJ*
Cost of cooling	*0.00062 $/MJ*
Cost of Diesel fuel:	*0.00584 $/MJ*
Cost of electricity:	*0.01 $/MJ*
Heat exchanger cost:	1500 * $size^{0.6}$ (in $/kW)
Maintenance cost:	IHP dependent (in $/kW)
Installation cost correction factor:	*1*

Note: Data are for illustration only.

7. A graph showing the theoretical maximum IHP size and half of this size versus the temperature lift is shown to the right. All possible temperature lifts have been tested to construct this graph. To the left, the corresponding payback periods for the IHPs are shown.

   The IHP installation to be evaluated should be the largest possible with the shortest possible payback period. The temperature lift to be evaluated in more detail must be specified in the input area. The default temperature lift that is shown is only chosen to be within the possible temperature lift range; i.e., it is not in any way optimized. In this example a temperature lift of *32 °C* seems good. Type this value and press "**OK**".

8. Brief results are shown to the right. By pressing "*Cancel*" a new temperature lift can be tested. In the example *34 °C* is satisfactory since the heat pump size is as large as it can be. Compare the size graph with the size shown in the brief result table. By selecting a larger

value (*38°C*) the payback period increases, but the size does not. A smaller value (*30°C*) decreases the size and increases the payback period.

9. Select "**Result report**" from the menu. The annual results (which were used as input to the market assessment spreadsheet calculations) are presented. By selecting "**Print**" from the "**File**" menu, the screen is printed. By selecting "**Save to file**" from the "**File**" menu, the results are saved into a file.

10. If the user wants to assess IHP economics at different (e.g., future) energy prices, return to Step 6 and specify the economic data assumed for the new year (e.g., 2000) and go through Steps 6 to 9. Be sure to specify an accurate temperature lift.

11. The next heat pump type should now be evaluated. Repeat Steps 3 to 10 for the next type, which in the example is IHP *No. 7*. A temperature lift of *52°C* seems in this case to be the best. Higher lifts result in longer payback periods, but the same IHP size. A smaller lift decreases the size and gives longer payback periods.

12. Repeat Steps 3 to 10 for the other heat pumps selected in Step 1.

The table below summarizes the key result value for this example from which the five IHPs can be selected.

IHP	Temp-lift (°C)	Max size (kW)	Payback (years)
5	*34*	*2429*	*2.5*
7	*54*	*3725*	*3.1*
9	*76*	*14650*	*9.6*
34	*34*	*3214*	*2.8*
36	*54*	*3900*	*4.1*
38	*68*	*14700*	*7.8*
29	*48*	*11484*	*3.4*

Process Data Not Included in Pre-Defined Processes

If the process of interest is not included in the pre-defined process list the user can create the data. This can either be done by entering new data or by editing a pre-defined process. Both methods are presented below.

The process data created by the user are called user-defined processes and can be handled in the same way as described above in the screening procedure.

The process data can be of two types:

"Full" stream data correspond to stream data suitable for pinch analyses, i.e., all streams in the process are included with their start and target temperatures as well as heat loads.

"Simple" data are used when complete data are not available. The data can be specified as a demand (sink) and available (source) heat. The data are, however, described in a way similar to the complete ("Full") case. The sink and source should be given as a load between two temperatures, see below.

Create "Simple" Process Data

In this example a simple process, which only consists of a heat demand and a heat source, is created.

1. Select "**Create process**" data from the "**Processes**" menu.

2. A grid is now displayed and the subject of each cell is shown. Because the data are not full stream data, it is recommended that the option "**Simplified stream data**" is selected.

3. Select cell by cell and give the appropriate input. For example, select the "**Process name**" cell and type a suitable name: *Test of simple input.* Press "**OK**" when ready.

4. Go down to the stream data area. Select the appropriate cell and type the input. An example is:

   Heat demand: *Supply temperature: 90°C*
   Target temperature: 100°C
   Heat load: 5,000 kW

   Heat source: *Supply temperature: 50°C*
   Target temperature: 40°C
   Heat load: 10,000 kW

5. From the "**Edit**" menu select "**Save as new user process**" and "**Quit**". Select "**Update process list**" in the "**Processes**" menu to update the list.

Create "Full" Process Data by Modifying a Pre-Defined Process

By using this method a user-defined process is created from a pre-defined process. One reason to do this could be that a pre-defined process looks much like the process desired. The steps to be carried out are very similar to the ones presented for pre-defined processes.

In the example, data for a brewery will be created.

1. List the predefined processes with "**List processes**" in the "**Processes**" menu.

2. The list *No. 599* includes stream data for a brewery which closely correspond to the data desired.

3. Select "**Edit process data**" in the "**Processes**" menu and select No. 599 from the list.

4. From the "**Edit**" menu select "**Save as new user process**" and "**Quit**". Select "**Update process list**" in the "**Processes**" menu to update the list.

5. The next step is to edit the data of the new user-defined process. Select "**Edit process data**" in the "**Processes**" menu and select the new process from the list.

6. Select each cell that must be changed and edit it. Press "**OK**" after each cell has been edited.

   Add a new line for stream data input by selecting "**Add a stream**" in the "**Edit**" menu. Specify stream data by selecting the empty cell and type the appropriate data. Press "**OK**" when ready and select next cell.

   A whole stream can be deleted by first positioning the pointer on a steam row and then selecting "**Delete a stream**" from the "**Edit**" menu.

7. Select "**Replace existing user process**" from the "**Edit**" menu to save the changes. Update the process list by selecting "**Update process list**" in the "**Processes**" menu.

Appendix B
Market Assessment Methodology

This appendix describes the methodology used to conduct the country-specific IHP market assessments for Annex 21. It first provides an overview of the market assessment methodology, then describes in detail the specific data required and their use in the assessment.

B.1 Methodology Overview

A key part of Annex 21 was to develop a methodology to enable the market potential of IHPs to be estimated and to calculate the potential energy savings and environmental benefits from IHPs. To provide a systematic procedure that all of the National Teams use to conduct comparable analyses, the methodology developed was transformed into a computer-based spreadsheet program. The program was structured to use as inputs IHP data derived from the IHP Screening Program developed for Annex 21 (see Section 3 and Appendix A) along with country-specific data generated by each National Team.

The IHP market assessments conducted by each country participating in Annex 21 were designed to be conducted at the industrial process level. The objectives and methodology for the assessment in each country were to:

- determine the technical feasibility of different IHPs in a specific process;
- characterize the economics of the technically feasible IHP options;
- estimate the total number of similar plants or processes;
- project the potential market penetration of the feasible IHP options in that industry;
- assess the net potential energy savings and environmental benefits from the IHPs.

This approach was to be replicated for the different processes selected for analysis by each country, using their own selection criteria. The individual market assessment results were then aggregated for each country and for all of the participants in Annex 21 (see Figure B.1).

The market analysis for Annex 21 and the spreadsheet tool developed to aid the analysis were designed to incorporate several key features:

- Provide a structure to analyze IHP market potential over the 1995-2010 time frame.

- Enable the use of country-specific energy prices, energy/prime mover combinations for electricity generation, and emission factors for fuels.

- Provide a means to allow different industrial processes to be selected, but to uniformly analyze these processes using country-specific data on the individual industrial processes (e.g., number of plants, industry growth, process heat energy demand, energy mix).

- Account for process heat supplied by other technologies (e.g., cogeneration, waste heat boilers).

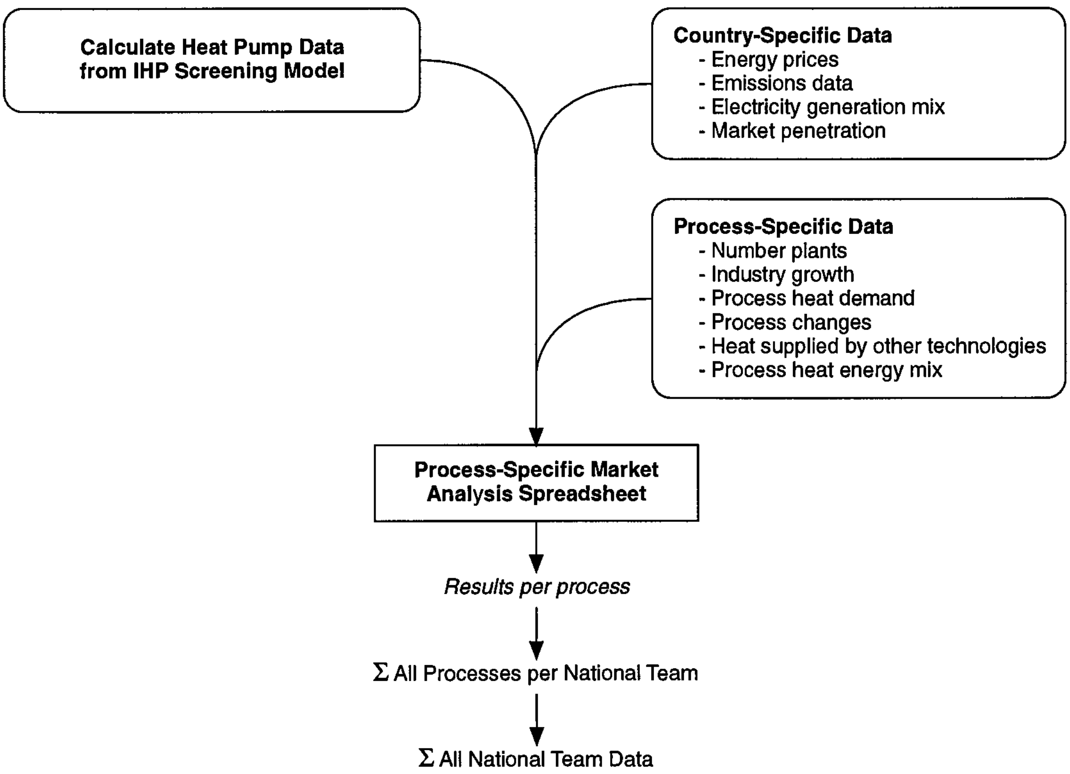
- allow the incorporation of country-specific parameters to calibrate future IHP technology market penetration.

The following sections describe the specific data required to conduct the market assessment. The use of the IHP screening program in conducting the analyses is also reviewed.

- B.2 outlines the macro data needed for the market assessment.
- B.3 discusses the process-specific data needed for the market assessment.
- B.4 describes how the IHP screening model was used to develop the IHP data required for the market assessment.
- B.5 contains a summary of the market assessment spreadsheet program.

For reference purposes, key terms used in the market assessment are defined on the next page.

Figure B.1 Overall Approach to Market Assessment



Market Assessment

– Terms and Definitions –

Annual Profit – The economic value or benefit of a particular IHP as determined from the IHP screening program.

Default Values – Data values (for emission factors and market penetration factors) derived by Hagler Bailly. Can be used by the National Teams in their analyses or can be superseded by inputing Team-specific values.

Diffusion Rate – The rate at which end-users install IHPs, approaching the maximum level of use. Based on practical experience which shows that not all end-users can or will immediately install IHPs (or other technologies) even with promising economics. Percentages are used to model the rate of technology adoption or diffusion.

Drive Energy Consumption – The amount of fuel or electricity consumed by an IHP.

Energy Delivered – The amount of heat supplied by an IHP, assumed equal to the amount of current process heat demand saved by an IHP through the displacement of prime energy requirements.

Market Penetration Level – The fraction (%) of all potential end-users that could be expected to use IHPs for a given payback level. Driven by the assumption that fewer (lower %) end-users will use IHPs as payback level lengthens.

Market Share – The ratio or relative percentage at which an IHP will be installed compared to other IHP options, based on their relative economics. As an example, if four IHPs are deemed feasible with equal annual profits, each will have a market share of 25%. If one IHP is twice as economic, its share would be 40%, each of the other three would have a 20% share.

Potential Process Heat Reductions – Percentages used to reflect that future process heat demand may decrease (or increase) based on continuing efforts in conservation, process modifications (e.g., new materials, new equipment), or conversions from fuel-based to electricity-based processing. For the purposes of the Annex, estimates of these reductions can be accounted for in the IHP screening program by appropriate selection of the global temperature difference being analyzed.

Project Market Penetration – The percentage rate at which an IHP is estimated to enter the market. This percentage combines the market share percentage, the penetration rate based on payback level, the risk aversion factor and the diffusion rate. For example, assume an IHP has an estimated market share of 40% and a payback level of 2.5 years – therefore, it has a projected penetration rate of 60% (see default values). This default risk aversion factor is 33% and, as an example, the diffusion rate in 2000 is 40%.
The projected market penetration would be 6% = 40% x 60% x 67% (1-33%) x 40%.

Risk Aversion Factor – The fraction (%) of all potential end-users that are likely to NOT use IHPs at ANY payback level. This assumes many end-users are averse to using new technologies because of unfamiliarity, disbelief of potential benefits, or fear of modifying their process, among potential factors.

B.2 Macro Data

To conduct the IHP market assessment, each country compiled four sets of macro data. These data remained fixed for each of the individual industrial processes analyzed, unless a country determined that certain data should vary for a specific process. The four macro data items required for the market assessment were:

- energy prices;
- electricity generation mix;
- emissions factors;
- market penetration factors.

These items are reviewed in the following sections.

B.2.1 Energy Prices

The first set of data required for the market assessment was projected energy prices for natural gas, coal, oil and electricity (see Table B.1). Forecast data were required for four time periods: 1995, 2000, 2005 and 2010. The specific requirements for energy price data were:

- data were to be in local currency per gigajoule (GJ), and per kWh for electricity;
- energy price data were to be in 1993 currency units.

The market spreadsheet automatically converted input energy prices to U.S. $ per GJ.

Energy price data were used to determine the cost of heat potentially saved by an IHP and to determine the cost of energy consumed by an IHP. With the exception of electricity, the cost of heat used or saved by an IHP was derived based on a weighted average fuel price according to the estimated process heat energy mix for the processes analyzed (see Process-Specific Data in B.3.5).

B.2.2 Electricity Generation Mix

The second set of macro data for the market assessment was the projected electricity generation mix, divided among natural gas, coal, oil and other energy sources (e.g., nuclear, renewables). To more accurately account for differing emission rates among the various fuels and prime movers, the market assessment was structured so that electricity generation mix projections were divided between eight energy/prime mover combinations (see Table B.1):

- natural gas boilers;
- natural gas turbines;
- coal boilers;
- oil boilers;
- oil turbines;
- nuclear;
- hydroelectric;
- other.

Table B.1 Sample Energy Price and Electricity Generation Data (continued on next page)

ENERGY PRICE DATA									
Local Currency	French Francs								
Currency Conversion Rate	6.32 per U.S. $								
		In local currency (constant 1993 units):				In U.S. Dollars (constant 1993 $):			
		1995	2000	2005	2010	1995	2000	2005	2010
Natural Gas	per GJ	3.52	4.08	4.97	5.26	0.56	0.65	0.79	0.83
Coal	per GJ	1.42	1.54	1.64	1.79	0.22	0.24	0.26	0.28
Oil-residual	per GJ	2.77	3.23	3.75	4.25	0.44	0.51	0.59	0.67
Oil-distillate	per GJ	4.49	5.00	5.56	6.11	0.71	0.79	0.88	0.97
Electricity	per GJ	11.88	12.18	12.56	12.65	1.88	1.93	1.99	2.00
Electricity	per kWh	0.043	0.044	0.045	0.046	0.007	0.007	0.007	0.007
		In local currency (constant 1993 units):				In U.S. Dollars (constant 1993 $):			
Natural Gas	per MMBtu	3.71	4.30	5.24	5.55	0.59	0.68	0.83	0.88
Coal	per MMBtu	1.50	1.62	1.73	1.89	0.24	0.26	0.27	0.30
Oil-residual	per MMBtu	2.92	3.41	3.96	4.48	0.46	0.54	0.63	0.71
Oil-distillate	per MMBtu	4.74	5.28	5.87	6.45	0.75	0.83	0.93	1.02
Electricity	per MMBtu	12.53	12.85	13.25	13.35	1.98	2.03	2.10	2.11
Electricity	per kWh	0.043	0.044	0.045	0.046	0.007	0.007	0.007	0.007

Table B.1 Sample Energy Price and Electricity Generation Data (continued)

AVERAGE GENERATION MIX FOR ELECTRICITY in % (based on kWh produced)				
	1995	2000	2005	2010
Natural Gas:				
Boilers	8.4%	9.4%	8.5%	8.1%
Turbines (simple/combined cycle)	1.8%	3.7%	6.8%	6.5%
Coal: Boilers	54.2%	52.3%	50.8%	52.9%
Oil:				
Boilers	3.3%	4.1%	4.4%	4.1%
Turbines (simple/combined cycle)	0.2%	0.2%	0.5%	0.5%
Nuclear	21.2%	19.8%	18.9%	18.0%
Hydroelectric	10.3%	9.4%	8.8%	8.6%
Other (e.g., solar, wind, geothermal, waste fuels)	0.6%	1.1%	1.3%	1.3%
TOTAL	100.0%	100.0%	100.0%	100.0%

The estimated electricity generation mix was determined as the percent of total electric generation (based on kWh produced) for each energy/prime mover source.

In the market assessment, forecast data were required for four time periods: 1995, 2000, 2005, and 2010. Electricity generating mix data were used to calculate the emission factors for electricity consumption, based on the energy-specific emission factors also developed for the assessment (discussed in the next section).

B.2.3 Emissions Factors

The third set of macro data required for the market assessment was emission factors. In conducting the market assessment, each country was free to specify emission factors for their situation or to use the default values contained in the model.

The default values were developed by Hagler Bailly based on information from the U.S. Environmental Protection Agency and the OECD. Emissions factor data for the U.S. study, and for the default data, were derived from estimates of current U.S. emissions [50], from limits set in the Clean Air Act [51], from two U.S. Environmental Protection Agency (EPA) reports [52,53], and from an IEA/OECD report on greenhouse gas emissions [54]. To provide a consistent basis for the analyses, and to account for differences among the participating countries, the emission factors were specified on a lower heating value (LHV) basis.

The required data were emission factors for SO_x, NO_x, CO_2, CO, CH_4, and particulate matter (PM). Emission factors were specified for natural gas-, coal- and oil-fired industrial boilers as well as for gas-fired utility boilers and turbines, coal-fired boilers and oil-fired turbines and boilers (see Table B.2). Data were required for three time periods: 1995, 2000, and 2005.

Industrial boiler emission data were used to determine the net emission savings from IHPs, based on the projected net IHP energy savings and the estimated process heating energy mix for a specific process (discussed in Section B.3.5). Utility emissions factor data were used to calculate the emissions from electricity consumption, based on the electric generation mix, as specified above.

To not "over credit" the potential emission benefits of IHPs, the default values for emission factors were, to the extent possible, estimated to decrease over time, corresponding to expected changes in regulations or increased compliance of in-place regulations. For the purposes of Annex 21, the emissions factors used represented the LOWER of uncontrolled emission levels or regulated limits. This was also done to not overstate the potential emission reductions possible with IHPs.

Emission factors were also adjusted to reflect emissions per unit of heat or electricity delivered, to account for boiler/furnace efficiencies, and the energy required to generate electricity. These steps were also taken to not over-estimate IHPs benefits and to provide an net national estimate of IHP energy and environmental benefits.

Table B.2 Default Emission Factors for Market Assessment (continued on next page)

EMISSIONS FACTORS (g/GJ)	Industrial Boilers			Utility Boilers			Utility Turbines		
	1995	2000	2005	1995	2000	2005	1995	2000	2005
Natural Gas									
SO_x	0.31	0.31	0.31	0.83	0.79	0.75	17.26	15.62	14.00
NO_x	74.7	74.7	74.7	281.4	267.5	253.8	610.6	295.6	157.0
CO_2	57000	57000	57000	167594	159327	150764	173625	157129	140777
CO	18.9	18.9	18.9	55.3	52.6	49.9	105.3	95.3	42.7
CH_4	1.58	1.58	1.58	0.40	0.38	0.36	19.16	17.34	15.98
PM	1.56	1.56	1.56	4.17	3.97	3.76	23.31	18.90	18.90
Coal									
SO_x	592	592	592	2309	1399	1377	X	X	X
NO_x	301	301	301	888	582	574	X	X	X
CO_2	130000	130000	130000	317098	312066	307282	X	X	X
CO	100	100	100	36	36	35	X	X	X
CH_4	2.64	2.64	2.64	1.73	1.70	1.61	X	X	X
PM	14.60	14.60	14.60	35.54	34.98	34.44	X	X	X
Oil (residual)									
SO_x	433	380	326	1117	947	787	1492	1199	861
NO_x	194	190	164	624	536	397	906	499	160
CO_2	88000	88000	88000	220158	212991	206043	313872	269699	225629
CO	18.3	18.3	18.3	46.0	44.5	43.0	130.1	107.8	38.7
CH_4	3.55	3.55	3.55	2.71	2.62	2.53	23.23	19.96	16.70
PM	16.26	16.26	16.26	41.88	40.52	39.20	59.71	42.72	28.59

Table B.2 Default Emission Factors for Market Assessment (continued)

EMISSIONS FACTORS (g/GJ)	Industrial Diesel Engines 1995	2000	2005	
Oil (distillate)				
SO_x	100.4	100.4	100.4	
NO_x	134	89	45	
CO_2	72917	72917	72917	
CO	223	134	45	
CH_4	3.2	3.2	3.2	
PM	44.58	44.58	44.58	
	1995	2000	2005	2010
Electricity (g/GJ) (*)				
SO_x	489	297	289	299
NO_x	200	137	132	136
CO_2	59518	59979	60269	61620
CO	9	10	9	9
CH_4	0.4	0.5	0.6	0.6
PM	8.0	8.0	8.1	8.3

(*) Sample only, differ based on estimated electricity generation mix.

B.2.4 Market Penetration Rates/Factors

The last set of macro data for the market assessment were estimated market penetration factors for IHPs. In conducting the analyses, each country could use the default values provided or could develop its own estimates for three sets of market penetration factors:

- Market Penetration Level - This represents the expected MAXIMUM level of market penetration for IHPs based on different payback levels. For example, 75% of all companies might install IHPs if the payback was less than 2 years, while only 10% might use IHPs if payback was more than 5 years. Penetration rates were specified for 5 levels of payback: < 2 years (75%); 2-3 years (60%); 3-4 years (50%); 4-5 years (25%); and > 5 years (10%). Note: The numbers in parentheses are the default values provided for the analyses (see Table B.3).

- Risk Aversion Factor - This represents a factor used to limit potential market penetration based on the risk levels found in industry. This value is defined as the estimated fraction of all end-users that would NOT use IHPs at ANY payback level. The default value was estimated at 33%.

- Diffusion Rate - The figures for the diffusion rate were used to estimate the level of IHP market diffusion – the rate at which IHP use would approach the maximum market penetration level. The diffusion rate was determined by specifying values for four time periods: 1995, 2000, 2005, and 2010. The default values used were 10%, 40%, 90% and 95%, which approximate an "S-curve" type diffusion.

The default values for market penetration and risk aversion were Hagler Bailly estimates based on prior U.S. industrial energy technology studies, including IHPs, as well as industrial

Figure B.2 Historical IHP Market Penetration Data

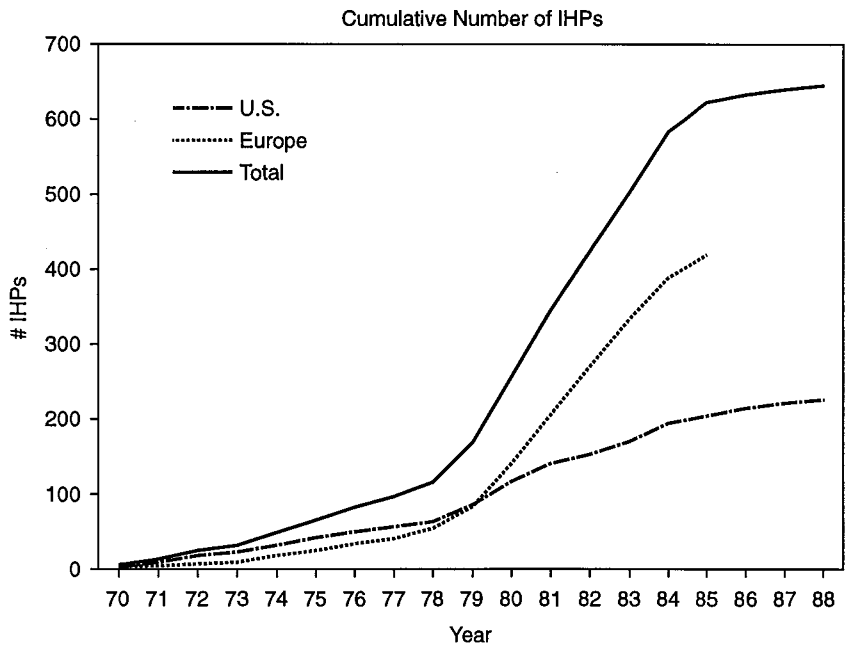


Table B.3 Market Factors Used in IHP Market Assessments

Definition of Terms:

Level of Penetration - % of all end-users that would install IHPs at a given payback level.

Risk Aversion Factor - % of all end-users that would NOT use heat pumps, at ANY payback level.

Diffusion Rate - Rate (based on % each year) at which IHPs are adopted to reach maximum penetration.

Maximum Amount of Market Penetration Based on Profit/Payback Level

Default		National Team Defined	
Payback	Level of Penetration	Payback	Level of Penetration
> 5 years	10%	> 5 years	0%
4-5 years	25%	4-5 years	0%
3-4 years	50%	3-4 years	0%
2-3 years	60%	2-3 years	0%
< 2 years	75%	< 2 years	0%

Risk Aversion Factor

Default	33%	National Team Defined	0%

Diffusion Rate (rate at which use approaches maximum penetration)

	1995	2000	2005	2010
Default ("S-curve" type diffusion from 1994 to 2010)	10.0%	40.0%	90.0%	95.0%
National Team Defined	0%	0%	0%	0%

demand-side management (DSM) technology assessments. The values for the diffusion rate were based on historical IHP data (see Figure B.2). The diffusion rate for IHPs was assumed to be accelerated somewhat, since IHPs are not a new technology.

Of all the data items required for the market assessment, it was expected that the market penetration factors would involve the most judgment or estimation from the National Teams. It was anticipated that the basis for estimating these factors would be in-country IHP experience or assessments of technology adoption for other industrial energy technologies. These data could reflect actual IHP experience to date or the National Teams' estimation of what IHP penetration could be, assuming, for example, more aggressive technology demonstrations and/or information dissemination.

B.3 Process-Specific Data

In general, the macro data described in Section B.2 remained fixed for each of the individual industrial process market analyses. The process-specific data discussed in Section B.3 and the IHP data described in Section B.4 varied for each individual process analyzed.

To conduct the market assessments, each National Team had to specify seven process-specific data items for each industrial process analyzed (see Table B.4):

- estimated number of plants;
- estimated industry growth;
- number of existing plants with IHPs;
- total process heat demand;
- energy mix for process heat;
- projected yearly reductions in total process heat demand;
- projected process heat demand supplied by cogeneration or waste heat boilers/incinerators.

The specific data required for each of these items sections are outlined below.

B.3.1 Number of Plants

The first process-specific data item required for the market assessment was the total number of plants, as of year-end 1993, for the process being analyzed. The figure fixed the baseline number from which the potential market penetration of IHPs was estimated.

B.3.2 Industry Growth Rate

The second item required was the projected growth rate for the industry and/or process being assessed. This figure was to be the average annual growth rate, in %/year, over the 1994-2010 period being studied for Annex 21.

B.3.3 Number of Existing Plants with IHPs

The third data item required was the current number of plants using IHPs. This was needed to ensure that the estimates of market potential and energy savings did not "double count" energy savings from those plants now already using IHPs.

Table B.4 Process-Specific Data Required for the Market Assessment

PROCESS ANALYZED: Chlorine/Caustic Soda			
Estimated Number of Plants/ Year-End 1993	20 number		
Estimated Industry Growth (1994-2010)	1 %/year		
Number of Existing Plants w/Heat Pumps	0 number		
Total Process Heat Demand	45,260 1,000 GJ/year		
	In 1995	In 2000	In 2005
Energy Mix for Process Heat	70 % gas	70 % gas	70 % gas
	20 % coal	20 % coal	20 % coal
	5 % oil	5 % oil	4 % oil
	0 % electricity	0 % electricity	0 % electricity
	5 % other	5 % other	6 % other
Projected Yearly Reductions in Total Process Heat Demand From:			
From Process Modifications	0.2 %/year		
From Electrification	0.5 %/year		
From Conservation	0.2 %/year		
Projected Process Heat Demand Supplied by:	In 1995	In 2000	In 2005
Cogeneration/CHP	33 %	37 %	37 %
Waste Heat Recovery Boilers and Incinerators	3 %	3 %	3 %

B.3.4 Total Process Heat Demand

The next data item required was the estimated current total process heat demand for ALL the plants being analyzed in the relevant process. The estimate of total process heat demand was to be the total heat or energy demand that could potentially be supplied by IHPs, therefore, a fraction of the total energy consumption in a given process. For the market assessment, the total process heat demand was to determined in units of 1,000 GJ/year.

B.3.5 Energy Mix for Process Heat

The fifth set of process data required for the market assessment was the projected energy mix for process heat. For each industrial process analyzed, National Teams were required to estimate the energy mix used to provide process heat for three time periods: 1995, 2000, and 2005. Energy mix data were to be specified as the % of the total process heat demand supplied by natural gas, oil, coal or electricity.

The energy mix data were very important because the projected emissions savings attributable to IHPs were determined based on the total projected energy savings, allocated by the energy mix %s, and then applied to the emissions factors for each type of energy source.

While energy mix was one of the more important data items, it was also one of the more difficult items to determine. The market assessment protocol instructed the Annex 21 participants that potential data sources might include industry or process studies, published reports or statistics, or estimates derived from these types of sources. If process-specific data were not available, the agreed approach was to use data for the next-higher level of industry grouping. Several examples showing the level at which data might be estimated, in increasing order of detail, include:

- chemicals → inorganic chemicals → alkalies/chlorine → chlorine/caustic soda;
- pulp and paper → paper mills → bleached kraft paper;
- food → dairy→ fluid milk.

The estimated process heat energy mix was also used to determine a weighted average energy price for process heat and steam for each industrial process being analyzed. These average prices were used to evaluate IHP economics at average conditions within an industry. An example of how the average price was calculated is shown below:

	% of Process Heat/Steam	1995 Energy Price (1995$/MMBtu)
Natural gas	70	3.71
Coal	20	1.50
Oil	5	2.92
Electricity	0	12.53
Other/Waste Fuel	5	0

Weighted Average Energy Price = $3.04/MMBtu
Process Heat Price (adjusted @90% for furnace efficiency) = $3.38/MMBtu
Steam Price (adjusted @75% for boiler efficiency) = $4.06/MMBtu

These average process-specific energy prices were used to assess IHP economics for a particular process.

B.3.6 Projected Yearly Reductions in Total Process Heat Demand

Based on the discussions at the technical meetings held in conjunction with Annex 21, it was determined that countries would have two options for accounting for potential, future reductions in process heat demand. The first, which was the preferred method, was to select an appropriate global temperature difference (ΔT_{min}) value that was lower than the current process temperature difference level (see discussion in Section B.4). This method would account for future reductions in energy consumption. Temperature selection was to be made by each country based on available information and its experience with IHPs.

The second option was to estimate values for future process heat demand reductions in three areas:

- Process modifications, which would cover new process technologies, new products, or the utilization of different raw materials.
- Electrification, which would account for the impact of electric-based, industrial technologies such as electric furnaces or heaters, electric drives, and conversion to electricity-based processes.
- Conservation, which would include changes resulting from improved process optimization, increased waste heat recovery, and improved process controls, among other potential factors.

Using the second option, % values were to be estimated for each area, representing the projected yearly reductions in process heat demand. In some cases, namely process modifications, changes could result in increased process heat demand.

Both methods were intended to account for process changes that could reduce (or increase) the amount of process heat needed and, therefore, the amount of potential energy that could be supplied (saved) by IHPs.

B.3.7 Projected Process Heat Demand Supplied by Other Technologies

The last process-specific item required for the market assessment was an estimate of the process heat demand that would be supplied by cogeneration and/or waste heat recovery boilers (WHRBs) and incinerators.

Throughout Annex 21, it was stressed that it was important to estimate the heat demand supplied by these technologies. Failure to do so would over-estimate the potential energy and environmental savings of IHPs, by over estimating the future process heat requirements that may be supplied by IHPs.

The specific data required were estimates of the % of total process heat demand supplied by cogeneration or WHRBs/incinerators (combined) for each of three time periods: 1995, 2000, and 2005.

The market assessment proceeded on the basis that steam/heat supplied by these technologies would not be displaceable by IHPs; therefore, IHPs would compete on an economic basis with boilers and fired heaters.

As with several other data items, the ideal situation was to derive a specific estimate for the relevant process being analyzed (e.g., chlorine). The alternatives were to use estimates for an industry sub-group (e.g., inorganic chemicals) or for an entire industry (e.g., chemicals).

B.4 IHP Data for the Market Assessment

Once the macro and process-specific data had been compiled, the next step in the market assessment was to assess IHP fit in each of the processes being analyzed and to extract the necessary IHP data for the market assessment. IHP data were derived from the IHP screening model (see Appendix A) and were input into the market assessment spreadsheet (see Section B.5).

The following discussions outline how the IHP screening program was used, in conjunction with the market assessment spreadsheet, to conduct the market assessments for Annex 21. Section B.4.1 provides an overview of the procedure used to determine the technical potential for IHPs in a specific process. Sections B.4.2 and B.4.3 outline how the IHP screening program was used to adapt processes for analysis, to screen IHP fit, and to generate the input data needed for the market assessment.

B.4.1 Method to Assess Potential for IHP Process Integration

The basic method for assessing IHP potential is based on pinch technology theory.

This theory states that a heat pump should be placed across the pinch temperature and extract heat from below the pinch and deliver it above the pinch. The reason for this is that the pinch temperature divides the process streams into two parts. The part above the pinch temperature has a deficit of heat which must be supplied by an external heat source. The part below the pinch temperature has an excess of heat and thus has to be cooled by an external utility.

The global temperature difference (ΔT_{Global}) determines the minimum temperature difference between the hot and cold streams. The Composite Curves (CC) and the Grand Composite Curve (GCC) can be constructed when a ΔT_{Global} is specified. From the CC and the GCC, the minimum heating and cooling demand can be determined as well as the amount of heat that can be extracted and delivered by a heat pump at various temperatures.

The difference between the current heating demand and the minimum heating demand is the amount of heat that can be saved by better heat exchanging. Since the minimum heating demand is a function of ΔT_{Global} the amount of heat that can be saved also varies with ΔT_{Global}.

In the IHP screening procedure it is assumed that heat exchangers have been installed to such a degree that the heating demand of the process is equal to the minimum heating demand corresponding to the used ΔT_{Global}. Hence, the smaller the ΔT_{Global}, the more heat exchangers have been installed to recover heat. It should be noted that this does not imply that all of the heat exchanging has to be according to the pinch rules. It only means that the heating demand of the process corresponds to the heating demand that is calculated from the ΔT_{Global} used. In fact, in the screening procedure ΔT_{Global} is only used to calculate the CC and GCC, which makes it possible to determine the amount of heat that can be delivered and extracted by a heat pump.

Thus, it can be concluded that ΔT_{Global} should be specified to a value which reflects the degree of integration when a major retrofitting of the process has been carried out. Hence, it should not reflect the current heating demand. A reasonable ΔT_{Global} can be found by examining the graph showing the minimum heating demand versus ΔT_{Global}. From the shape of this curve, it should be possible to select a reasonable value.

B.4.2 Adjusting Process Data for Analysis

For each industrial process selected for analysis by a National Team, the first step in the analysis was to adjust the industrial process data contained in the IHP screening program to fit local industrial process conditions.[1] The process data contained in the IHP screening program were drawn from a variety of sources; therefore, they did not necessarily correspond to the typical plant size(s) found in the countries participating in Annex 21.

The initial step in the IHP fit analysis was, thus, to "resize" the process to fit the local situation. The resizing was done by comparing the current heating demand value contained in the model with the typical or average demand found from the local data. If no value was contained in the model, the resizing was done based on the minimum heating demand shown in the grand composite curve (GCC) for the process and judgments of the specific country situation.

B.4.3 Deriving Process-Specific IHP Data

The next step of the market assessment was to determine the applicability or "fit" of different IHPs in the process selected and to assess their overall economics and performance (e.g., capital cost, operating costs, energy delivered, payback).

For each process, potential IHP fit was assessed for up to five different heat pump types. IHP economics were calculated for three sets of energy prices (i.e., 1995, 2000, 2005).

From the IHP screening program, IHP fit could be analyzed for 52 different types of IHPs (Table B.5). The criteria on which IHP fit were determined were temperature restrictions and the type of drive energy. The basic criterion was that the IHP must be able to operate across the pinch temperature of the process.

When a process and an IHP were tested, the screening program evaluated all temperature and size combinations at which the heat pump can operate. IHP-specific restrictions (temperature limits) and process restrictions (heat demand and available heat) were taken into account. The program then sorted all possible installations in order of increasing temperature lifts and plotted the largest possible IHP at each lift. The corresponding payback periods were also plotted.

1 The IHP screening program has two other options by which industrial processes data can be specified:
1) process data contained in the program can be modified by the user or
2) users can enter data to create a new process. Both methods are outlined in Appendix A.

Table B.5 IHP Types Contained in the Annex 21 IHP Screening Program (continued on next page)

IHP #	Type (drive/cycle,compressor,refrigerant)	Evap. Temp. (°C)	Cond. Temp. (°C)	Max. Size (MW)
1	Elec.C-C/Recip/CFC22	(20)-40	20-60	2.4
2	Elec.C-C/Recip/CFC12	(20)-65	30-80	2.4
3	Elec.C-C/Recip/CFC114	10-96	40-120	2.4
4	Elec.C-C/Screw/CFC22	(20)-40	20-60	8
5	Elec.C-C/Screw w/Econ./CFC22	(20)-40	20-60	8
6	Elec.C-C/Screw/CFC12	(20)-65	30-80	6
7	Elec.C-C/Screw w/Econ./CFC12	(20)-65	30-80	6
8	Elec.C-C/Screw/CFC114	10-96	40-120	3
9	Elec.C-C/Screw w/Econ./CFC114	10-96	40-120	3
10	Elec.C-C/Turbo/CFC22	(20)-40	20-60	30
11	Elec.C-C/Turbo w Econ./CFC22	(20)-40	20-60	30
12	Elec.C-C/Turbo/CFC12	(20)-65	30-80	30
13	Elec.C-C/Turbo w Econ./CFC12	(20)-65	30-80	30
14	Elec.C-C/Turbo/CFC114	10-96	40-120	30
15	Elec.C-C/Turbo w Econ./CFC114	10-96	40-120	30
16	MVR/closed/Turbo	50-145	55-150	200
17	MVR/open-source/Turbo	50-145	55-150	200
18	MVR/open-sink/Turbo	50-145	55-150	200
19	MVR/open/Turbo	50-145	55-150	200
20	MVR/closed/Screw	75-185	80-190	46
21	MVR/open-source/Screw	75-185	80-190	46
22	MVR/open-sink/Screw	75-185	80-190	46
23	MVR/open/Screw	75-185	80-190	46
24	TVR/closed	45-120	60-150	12
25	TVR/open-source	45-120	60-150	12
26	TVR/open-sink	45-120	60-150	12
27	TVR/open	45-120	60-150	12
28	Absorption TII (waste heat)/LiBr-H_2O	—	10-150(*)	20
29	Absorption TI (prime heat)/LiBr-H_2O	—	5-300(*)	20
30	Diesel C-C/Recip/CFC22	(20)-40	20-60	3
31	Diesel C-C/Recip/CFC12	(20)-65	30-80	3
32	Diesel C-C/Recip/CFC114	10-96	40-120	3
33	Diesel C-C/Screw/CFC22	(20)-40	20-60	10
34	Diesel C-C/Screw w Econ./CFC22	(20)-40	20-60	10
35	Diesel C-C/Screw/CFC12	(20)-65	30-80	7
36	Diesel C-C/Screw w Econ./CFC12	(20)-65	30-80	7
37	Diesel C-C/Screw/CFC114	10-96	40-120	4
38	Diesel C-C/Screw w Econ./CFC114	10-96	40-120	4
39	Diesel C-C/Turbo/CFC22	(20)-40	20-60	40
40	Diesel C-C/Turbo w Econ./CFC22	(20)-40	20-60	40
41	Diesel C-C/Turbo/CFC12	(20)-65	30-80	40

Table B.5 IHP Types Contained in the Annex 21 IHP Screening Program (continued)

IHP #	Type (drive/cycle,compressor,refrigerant)	Evap. Temp. (°C)	Cond. Temp. (°C)	Max. Size (MW)
42	Diesel C-C/Turbo w Econ./CFC12	(20)-65	30-80	40
43	Diesel C-C/Turbo/CFC114	10-96	40-120	40
44	Diesel C-C/Turbo w Econ./CFC114	10-96	40-120	40
45	MVR hc/closed/turbo	(**)	(**)	200
46	MVR hc/open-source/turbo	(**)	(**)	200
47	MVR hc/open-sink/turbo	(**)	(**)	200
48	MVR hc/open/turbo	(**)	(**)	200
49	MVR hc/closed/screw	(**)	(**)	46
50	MVR hc/open-source/screw	(**)	(**)	46
51	MVR hc/open-sink/screw	(**)	(**)	46
52	MVR hc/open/screw	(**)	(**)	46

(*) Range of temperature capabilities
(**) Defined based on stream properties.

IHPs that were half of the size of the theoretical maximum size were also shown in the graphs. It was assumed that this size might reflect a more realistic situation because the largest possible IHP would require the maximum investment, a situation not likely to be realized in practice.

From these two graphs a temperature lift was selected to evaluate IHP economics and performance. This was an iterative process to identify the lift yielding the largest IHP (delivering as much prime energy as possible) and having the shortest possible payback period. As these criteria are working in opposite directions, it was up to each National Team to make the decision about the temperature lift conditions selected for evaluation.

To execute the analysis, a three-step process was followed. These steps, with examples of the procedure to implement the analysis, are described below. *Example data are highlighted in italics.*

1. Select IHPs to be Tested

   First, a specific process was selected for analysis. Using the screening program, the heat demand versus the global temperature graph difference was analyzed. The pre-defined global temperature difference was set from considerations of this graph. This graph might show a pinch temperature around 40°C, which indicates that not all of the IHPs can operate at these conditions. (The heat pump should extract heat below the pinch temperature and deliver it above this temperature.)

   Above the pinch, the amount of heat that can be delivered (= distance from the y-axis to the line) increases as the temperature becomes higher. At 90°C the possible heat amount that can be delivered increases rapidly. Below the pinch the available amount of heat increases continuously. The location of the pinch and the shape of the Grand Composite

Curve (GCC) suggest that three types of IHPs should be tested – closed-cycle compression, both electrically-driven and diesel motor driven, and absorption heat pump, type I. The types not included cannot operate at the temperatures identified from the GCC.

The least expensive closed-cycle compression heat pumps are the ones using CFC22, but there is a temperature limit of about 60°C. Thus, CFC12 and CFC114 must also be tested. The size indicates that screw compressors are the most suitable in this example.

The IHP fit analysis might identify numerous feasible options for the processes. For example, the following seven IHPs might be identified:

No. 5: Closed cycle compression, CFC22, electrical driven
No. 7: Closed cycle compression, CFC12, electrical driven
No. 9: Closed cycle compression, CFC114, electrical driven
No. 29: Absorption heat pump, type 1
No. 34: Closed cycle compression, CFC22, diesel motor driven
No. 36: Closed cycle compression, CFC12, diesel motor driven
No. 38: Closed cycle compression, CFC114, diesel motor driven

The market assessment limited IHP evaluation to five types of IHPs; therefore, two IHPs would be eliminated (based on economics) and not included in the market evaluation. The limit of five was arbitrary, but agreed to by the participating countries which felt that, in most cases, fewer that five IHPs would likely be fully evaluated or compete for one potential IHP application at a specific industrial site.

2. Evaluate One IHP

For each IHP identified as potentially feasible in Step 1, the detailed economics were evaluated for the specific process.

The pre-defined global temperature difference was identified using the screening model. The temperature differences between delivering/extraction temperatures to the sink/source were also determined. A new global temperature difference was then entered to reflect the degree of integration when a major retrofitting of the process is carried out. Thus, it should not reflect the current heating demand. Specifying a new temperature difference eliminated the need to estimate future process heat reductions (as discussed in Section B.3.6).

After the global temperature difference was specified, energy prices and other economic and operating data were specified. These data included:

- fuel/energy prices and cost of cooling;
- annual operation time;
- annuity factor, which was used to determine the annual profit;
- cost of additional heat exchangers, calculated as:
  heat exchanger cost = constant x size$^{0.6}$;
- annual maintenance cost.

If the IHP installation cost calculated by the program did not agree with the experience of the user, it was possible to alter the results by entering a factor to scale the installation costs. Entering a factor of less than 1 decreased the installation cost; a factor greater than 1 increased the cost.

Once completed, the following data, as an example, would have been input for one IHP for one year of evaluation:

Process to be evaluated:	*Paper mill*
Typical *paper* mill heating demand:	*20,000 kW*
Re-size ratio:	*0.8*
Energy cost (1995 or 2000 or 2005):	
Value of saved (replaced) heat:	*0.00657 $/MJ*
Cost of prime heat (e.g. steam)	*0.0066 $/MJ*
Cost to collect heat source:	*0.00062 $/MJ*
Cost of cooling	*0.00062 $/MJ*
Cost of diesel fuel:	*0.00584 $/MJ*
Cost of electricity:	*0.01 $/MJ*
Heat exchanger cost:	1500 x $size^{0.6}$ (in $/kW)
Maintenance cost:	IHP dependent (in $/kW)
Installation cost correction factor:	*1*

Once the data were entered, a graph showing the theoretical maximum IHP size (and average or one-half size) versus the temperature lift was plotted. All possible temperature lifts were tested to construct this graph. The corresponding payback periods for the IHP were also determined.

The next step was to determine the largest possible IHP with the shortest possible payback period. The program provided a default temperature lift within the possible temperature lift range. Trial and error iterations were used to identify the most appropriate temperature lift.

Once the appropriate temperature lift was determined, the IHP economics were calculated. The program provided a data summary on the IHP's economics (see sample in Table B.6) and these results were then used in the market assessment spreadsheet.

3. Evaluate IHP Over Time and Evaluate Additional IHPs

To derive the necessary data for the market analysis, IHP economics were evaluated at three points in time – 1995, 2000, and 2005 – using different energy prices. Recall from Section B.3.5 that these prices were derived as a weighted average purchased fuel price, adjusted for boiler efficiency to reflect the cost of delivered energy, and based on the projected energy prices. The average fuel prices developed for each process were based on the estimated energy mix for each process. For one IHP, steps 1 and 2 were executed under three different energy price scenarios.

After the first potential IHP was evaluated, the entire process was repeated for the remaining potential IHPs – up to five total. Through this process, the following types of data were generated:

IHP #	*Temp lift (°C)*	*Max size (kW)*	*Payback (years)*
5	*34*	*2429*	*2.5*
7	*54*	*3725*	*3.1*
9	*76*	*14650*	*9.6*
29	*48*	*11484*	*3.4*
34	*34*	*3214*	*2.8*
36	*54*	*3900*	*4.1*
38	*68*	*14700*	*7.8*

National Teams then selected those IHPs to be evaluated in the market assessment, generally corresponding to the options with the best overall economics.

Table B.6 Example IHP Analysis Results from the IHP Screening Program

Results for Process No. 29 and IHP No. 11	
Economic Assumptions	**Values**
Cost of heat source ($/MJ)	0.00041
Cost of heat saved ($/MJ)	0.0041
Cost of electricity ($/MJ)	0.01188
Annual operation time (hours/year)	6000
Annuity factor (1/year)	0.13
Heat exchanger cost ($/kW):	1500
Annual maintenance cost ($/kW):	5
Optional factor to adjust total installation cost:	1

IHP Analysis Results	Maximum Case	Average Case
Annual heat delivered by the heat pump (MJ)	101,811,000	50,905,500
Annual electricity consumption	10,824,210	5,479,265
Annual value of heat delivered ($)	417,425	208,713
Annual cost of electricity ($)	128,592	65,094
Annual cost of source energy ($)	37,514	18,757
Estimated heat pump installation cost ($)	998,835	582,724
Estimated number of additional heat exchangers	20	9
Estimated cost of additional heat exchangers ($)	463,635	208,804
Estimated annual maintenance cost ($)	23,567	11,784
Payback period (years)	6.4	7.0
Annual profit ($)	37,631	10,179
COP	9.4	9.3
Delivering temperature (°C)	48	48
Extraction temperature (°C)	25	25

Appendix C
Country-Specific Assumptions and Key Data

This appendix outlines the key country-specific assumptions and industrial process data used in the Annex 21 market assessments. For each country, it summarizes the key data and assumptions for:

- energy prices and process-specific industry data;
- emission factors;
- market penetration rates.

The appendix also summarizes the IHP types for which market potential was analyzed in the selected processes.

The key assumptions and data used in the U.S. study are presented first because this study formed the basis for the overall market assessment approach (see Appendix B). In addition, several data items (e.g., emission factors, market factors) derived for the U.S. study were provided as the "default" values in the market assessment program (see Appendix B).

After the U.S. data, country-specific information is presented alphabetically for the other countries that conducted detailed market assessments:

- Canada;
- Japan;
- Netherlands;
- Norway;
- Sweden;
- United Kingdom.

C.1 United States

The U.S. assessment for Annex 21 analyzed IHP market potential in 24 processes. The analysis used as input four sets of key data: energy prices, process-specific industry data, emission factors, and market penetration rates. The data used in each of these areas are outlined in the following sections.

C.1.1 Energy Prices/Process-Specific Data

The base energy prices used for the U.S. study are shown in Table C.1. These figures were derived primarily from a U.S. DOE forecast [51]. IHP economics were evaluated for 1995, 2000, and 2005 scenarios by using a weighted average purchased fuel price, adjusted for boiler efficiency to reflect the cost of delivered energy. The average fuel prices were developed for each process based on the estimated energy mix for each process shown in Table C.1.
For each of the 24 processes analyzed, detailed process data were developed including data on the number of plants, number of plants already with IHPs, projected industry growth,

process heat demand, operating hours, process heat energy mix, and heat demand supplied by other technologies (e.g., cogeneration, waste heat boilers). These data are summarized in Table C.1. The major data sources used to develop the U.S. process-specific data are listed in the reference section.

C.1.2 Emission Factors

The emission factors used in the U.S. study (Table C.2) were also provided as the default values for the market assessment program (see Appendix B). These factors were derived from several sources, including estimates of current U.S. emissions [52], limits set in the U.S. Clean Air Act [53], from U.S. Environmental Protection Agency reports [54, 55], and from an OECD report on greenhouse gas emissions [56].

To not "over credit" the potential environmental benefits of IHPs, the emission factors used in the U.S. study were the lower of regulated limits or uncontrolled emission levels. For some pollutants, fuels, and prime movers (e.g., NO_x from gas turbines, SO_x from coal boilers), emission factors were assumed to decrease over time as regulations become more stringent and older power plants are retired.

To be consistent with the IHP screening program and with the energy convention of the other countries participating in Annex 21, energy calculations and emission factors were derived on a lower heating value (LHV) basis. To provide a more accurate picture of energy savings and emission reductions on a national basis, the emission factors for electricity were adjusted to reflect energy delivered, based on technology- and fuel-specific utility power plant heat rates (Table C.2). Similarly, emission factors for industrial boilers were adjusted based on boiler efficiency to reflect emissions per unit of heat/steam delivered.

The emission factors for electricity were derived based on a weighted average of the projected electricity generating mix in the United States. This mix was derived from DOE [52] and North American Electric Reliability Council reports [57].

A summary of the 1995 and 2010 emission factors used in the U.S. study is shown in Table C.2.

C.1.3 Market Factors

For the U.S. market analysis, the three required market factors were estimated as follows:

- Market penetration rate - the maximum level (%) at which IHPs would be adopted as a function of their economics (i.e., payback level):

Payback Level (years)	Maximum Level of Adoption
< 2	75%
2-3	60%
3-4	50%
4-5	25%
> 5	10%

- Risk aversion rate - the fraction (%) of all industrial end-users that would not use IHPs at any payback rate: estimated at 10%.

- Diffusion rate - the rate (measured in % by year over time) at which market penetration would approach maximum or full market penetration: estimated at 10% by 1995, 40% by 2000, 90% by 2005, and 95% by 2010. These rates were derived based on historical rates of IHP adoption in the United States and Europe, and generally follow an "S-curve" type of market penetration.

These factors were estimated based on prior IHP studies and technology assessments on the rate of adoption of industrial energy technologies, including industrial demand-side management (DSM) measures.

C.1.4 IHPs Assessed by Process

The specific IHPs examined in each different industrial process are shown in Table C.3. The potential applicability of these IHPs to the particular process was determined using the IHP screening program developed for Annex 21 (see Section 3 and Appendix A).

Table C.1 United States - Summary Process Data for Annex 21 (continued on next pages)

Process Name	U.S. SIC #	# of Plants	Typical Operation (Hrs./yr)	Projected Growth (%)	# of Plants w/IHPs	Process Heat Demand: Total 1,000 GJ/yr	Total Trill. Btu/yr	Total Bill. kW/yr	Average Plant 1,000 GJ/yr	Average Plant Trill. Btu/yr	Average Plant Bill. kW/yr	Average Plant MMBtu/hr	Average Plant kW/hr
Integ.blch.kraft pulp/paper	2621	65	8,400	2.5%	12	325,995	309.0	90.6	5,015	4.8	1.4	565.9	165,866
Pet.refining-crude unit	2911	184	8,000	1.0%	20	210,947	200.0	58.6	1,146	1.1	0.3	135.8	39,811
Integ. unb.kraft linerboard	2631	40	8,400	2.5%	8	158,250	150.0	44.0	3,956	3.8	1.1	446.4	130,841
Ethylene	2869	32	8,400	1.5%	2	105,503	100.0	29.3	3,297	3.1	0.9	372.0	109,037
Bleached kraft pulp	2611	16	8,400	3.0%	3	82,290	78.0	22.9	5,143	4.9	1.4	580.4	170,093
Corn milling/starch	2046	60	8,400	2.0%	6	73,843	70.0	20.5	1,231	1.2	0.3	138.9	40,702
Unbleach. kraft pulp	2611	14	8,400	3.0%	2	47,475	45.0	13.2	3,391	3.2	0.9	382.7	112,149
Beet sugar refining	2063	42	4,000	2.0%	2	42,725	40.5	11.9	1,017	1.0	0.3	241.1	70,650
Veget.proc.(sauc./jui./soup)	2033	400	5,000	2.0%	5	42,201	40.0	11.7	106	0.1	0.0	20.0	5,862
Urea	2873	38	8,400	1.0%	1	41,935	39.7	11.6	1,104	1.0	0.3	124.5	36,497
Aromatics: BTX	2865	25	8,400	1.5%	0	38,771	36.7	10.8	1,551	1.5	0.4	175.0	51,289
Cane sugar refining	2062	25	6,000	2.0%	2	35,075	33.2	9.7	1,403	1.3	0.4	221.6	64,960
Chlorine/caustic soda	2812	30	8,400	1.0%	0	33,945	32.2	9.4	1,132	1.1	0.3	127.7	37,421
High fructose corn syrup	2046	20	8,400	2.0%	2	31,656	30.0	8.8	1,583	1.5	0.4	178.6	52,347
Phos.fert/phos.acid	2874	75	8,400	1.0%	0	31,630	30.0	8.8	422	0.4	0.1	47.6	13,947
Sulphite pulp	2611	15	8,400	3.0%	5	29,540	28.0	8.2	1,969	1.9	0.5	222.2	65,130
TMP pulp	2611	20	8,400	3.0%	3	28,485	27.0	7.9	1,424	1.4	0.4	160.7	47,103
Syn. rubber (polybutad.)	2822	35	8,400	2.5%	4	26,364	25.0	7.3	753	0.7	0.2	85.0	24,912
Malt beverage brewing	2082	134	8,400	-0.5%	4	21,245	20.1	5.9	159	0.2	0.0	17.9	5,243
Viscose rayon	2823	7	8,400	2.0%	0	17,955	17.0	5.0	2,565	2.4	0.7	289.4	84,829
Grain alcohol	2085	70	8,400	-0.5%	10	15,035	14.3	4.2	215	0.2	0.1	24.2	7,103
Pet.refining-deisobutanizer	2911	100	8,000	1.0%	10	21,145	20.0	5.9	211	0.2	0.1	25.1	7,343
Potato processing	2096	60	6,000	2.0%	1	10,710	10.2	3.0	179	0.2	0.0	28.2	8,265
Textile-bleaching/finishing	2261	50	6,000	1.0%	2	10,560	10.0	2.9	211	0.2	0.1	33.4	9,779
TOTALS		1,557			104 7%	1,483,281	1,406						
TOTAL INDUSTRIAL SECTOR						7,408,843	7,023						

Table C.1 United States - Summary Process Data for Annex 21 (continued)

Process Name	Estimated 2010 Process Heat/Steam Energy Mix					Process Heat Demand Supply					
						Cogeneration/CHP			Waste Heat Boilers/ Incinerators		
	Natural Gas	Coal/ Coke	Oil/ Pet.Coke	Electricity	Other/ Waste Fuel	1995	2000	2005	1995	2000	2005
Integ.blch.kraft pulp/paper	25%	15%	10%	0%	50%	30%	37%	45%	0%	0%	0%
Pet.refining-crude unit	30%	1%	10%	0%	59%	10%	12%	12%	5%	6%	7%
Integ. unb.kraft linerboard	25%	10%	5%	0%	60%	30%	37%	45%	0%	0%	0%
Ethylene	40%	5%	5%	0%	50%	33%	37%	37%	3%	3%	3%
Bleached kraft pulp	15%	5%	10%	0%	70%	30%	37%	45%	0%	0%	0%
Corn milling/starch	40%	55%	1%	0%	4%	15%	20%	25%	0%	0%	0%
Unbleach. kraft pulp	15%	5%	10%	0%	70%	30%	37%	45%	0%	0%	0%
Beet sugar refining	30%	65%	4%	0%	1%	15%	20%	25%	0%	0%	0%
Veget.proc.(sauc./jui./soup)	90%	0%	7%	0%	3%	15%	20%	25%	0%	0%	0%
Urea	94%	0%	1%	0%	5%	33%	37%	37%	3%	3%	3%
Aromatics: BTX	30%	1%	10%	0%	59%	33%	37%	37%	3%	3%	3%
Cane sugar refining	55%	10%	20%	0%	15%	15%	20%	25%	0%	0%	0%
Chlorine/caustic soda	80%	5%	1%	0%	14%	33%	37%	37%	3%	3%	3%
High fructose corn syrup	40%	55%	1%	0%	4%	15%	20%	25%	0%	0%	0%
Phos.fert/phos.acid	65%	15%	10%	0%	10%	33%	37%	37%	3%	3%	3%
Sulphite pulp	15%	5%	10%	0%	70%	30%	37%	45%	0%	0%	0%
TMP pulp	15%	5%	10%	0%	70%	30%	37%	45%	0%	0%	0%
Syn. rubber (polybutad.)	40%	30%	0%	0%	30%	33%	37%	37%	3%	3%	3%
Malt beverage brewing	55%	35%	7%	0%	3%	15%	20%	25%	0%	0%	0%
Viscose rayon	15%	76%	5%	4%	0%	33%	37%	37%	3%	3%	3%
Grain alcohol	60%	20%	10%	0%	10%	15%	20%	25%	0%	0%	0%
Pet.refining-deisobutanizer	30%	1%	10%	0%	59%	10%	12%	12%	5%	6%	7%
Potato processing	65%	20%	5%	0%	10%	15%	20%	25%	0%	0%	0%
Textile-bleaching/finishing	65%	15%	10%	0%	10%	10%	15%	20%	0%	0%	0%

Table C.1 United States - Summary Process Data for Annex 21 (continued)

Energy Prices (in 1993$)					
		1995	2000	2005	2010
Natural Gas	$/GJ	3.52	4.08	4.97	5.26
Coal	$/GJ	1.42	1.54	1.64	1.79
Oil-Resid.	$/GJ	2.77	3.23	3.75	4.25
Oil-Dist.	$/GJ	4.49	5.00	5.56	6.11
Electricity	$/GJ	11.88	12.18	12.56	12.65
	c/kWh	4.28	4.39	4.52	4.56

Table C.2 United States - Emission Factors for Annex 21

Emission Factors per Unit Heat/Electricity Delivered In grams/gigajoule (g/GJ) - LHV						
Fuel/Pollutant	Industrial Boilers		Utility Boilers		Utility Turbines	
	1995	2010	1995	2010	1995	2010
Natural Gas						
SO_x	0.31	0.31	0.83	0.75	17.26	14.00
NO_x	74.7	74.7	281.4	253.8	610.6	157.0
CO_2	57000	57000	167594	150764	173625	140777
CO	18.9	18.9	55.3	49.9	105.3	42.7
CH_4	1.58	1.58	0.40	0.36	19.16	15.98
PM	1.56	1.56	4.17	3.76	23.31	18.90
Coal						
SO_x	592	592	2309	1377	X	X
NO_x	301	301	888	574	X	X
CO_2	130000	130000	317098	307282	X	X
CO	100	100	36	35	X	X
CH_4	2.64	2.64	1.73	1.61	X	X
PM	14.60	14.60	35.54	34.44	X	X
Oil						
SO_x	433	326	1117	787	1492	861
NO_x	194	164	624	397	906	160
CO_2	88000	88000	220158	206043	313872	225629
CO	18.3	18.3	46.0	43.0	130.1	38.7
CH_4	3.55	3.55	2.71	2.53	23.23	16.70
PM	16.26	16.26	41.88	39.20	59.71	28.59

Utility Power Plants			
Fuel/Prime Mover	1995 Heat Rates Btu/kWh)	1995 Generating Mix (Est. %)	2010 Generating Mix (Est. %)
Gas-Boilers	10720	8.4%	8.1%
Gas-Turbines	13060	1.8%	6.5%
Coal-Boilers	10380	54.2%	52.9%
Oil-Boilers	10340	3.3%	4.1%
Oil-Turbines	14740	0.2%	0.5%
Nuclear	11000	21.2%	18.0%
Hydro/Renewables	10300	10.9%	9.9%
Weighted Average Heat Rate		10,587	10,244

Emission Factors for Electricity (g/GJ - LHV)		
	1995	2010
SO_x	1292	766
NO_x	539	351
CO_2	196963	193490
CO	28	27
CH_4	1.5	2.1
PM	21.5	21.5

Table C.3 United States - IHPs Evaluated by Process for Annex 21

Process Name	U.S. SIC #	IHP Type				
		Electric Closed-Cycle	MVR	TVR	Type 2 Absorption (Waste-Heat Driven)	Type 1 Absorption (Prime-Heat Driven)
Integ.blch.kraft pulp/paper	2621	O	O	O	O	
Pet.refining-crude unit	2911		O	O	O	
Integ. unb.kraft linerboard	2631	O	O	O	O	
Ethylene	2869	O	O	O	O	O
Bleached kraft pulp	2611	O	O	O	O	
Corn milling/starch	2046	O	O	O	O	O
Unbleach. kraft pulp	2611	O	O	O		O
Beet sugar refining	2063		O	O		
Veget.proc.(sauc./jui./soup)	2033	O		O		O
Urea	2873		O	O	O	
Aromatics: BTX	2865		O			
Cane sugar refining	2062		O	O		
Chlorine/caustic soda	2812		O	O	O	
High fructose corn syrup	2046		O	O		
Phos.fert/phos.acid	2874		O	O		O
Sulphite pulp	2611	O	O	O		O
TMP pulp	2611		O	O	O	
Syn. rubber (polybutad.)	2822	O	O	O	O	
Malt beverage brewing	2082	O	O	O	O	O
Viscose rayon	2823	O	O	O		O
Grain alcohol	2085	O	O	O		O
Pet.refining-deisobutanizer	2911	O	O	O		O
Potato processing	2096	O		O		O
Textile-bleaching/finishing	2261	O				O

C.2 Canada

The Canadian IHP market study examined 14 industrial processes. The key data on which the IHP assessment was conducted are summarized in the following sections.

C.2.1 Energy Prices/Process-Specific Industry Data

The energy prices used for the Canadian market study are summarized in Table C.4. The detailed process-specific data, including number of plants, process heat demand, projected industry growth, and process heat energy mix, for each of the 14 industrial processes examined are also shown in Table C.4.

C.2.2 Emission Factors

The emission factors used in the Canadian study were a combination of the default values provided for the market assessment (see Appendix B) and data derived from studies by the Canadian National Energy Board [58] and Energy, Mines and Resources Canada [59]. The base emission factors were derived on a per-unit fuel input basis. In conducting the final analysis of potential IHP environmental benefits, the base emission factors and the factors for electricity emissions were corrected to reflect heat and energy delivered, by taking into account boiler efficiency and the estimated electricity generating mix and estimated heat rates for Canada. The adjusted emission factors used for the Canadian assessment are summarized in Table C.5.

C.2.3 Market Factors

For the Canadian IHP study, the default values (see Appendix B) were used for the three market factors corresponding to market penetration, risk aversion, and diffusion rate.

C.2.4 IHPs Assessed by Process

The IHP types assessed, by process, are outlined in Table C.6. The applicability of these IHPs was determined using the IHP screening program.

Table C.4 Canada - Summary Process Data for Annex 21 (continued on next pages)

Process Name	Can. SIC #	# of Plants	Typical Operation (Hrs./yr)	Projected Growth (%)	# of Plants w/IHPs	Process Heat Demand: Total 1,000 GJ/yr	Total Trill. Btu/yr	Total Bill. kW/yr	Average Plant 1,000 GJ/yr	Average Plant Trill. Btu/yr	Average Plant Bill. kW/yr	Average Plant MMBtu/hr	Average Plant kW/hr
Iron and Steel-Blast Furnace	291	23	8,760	1.8%	0	230,578	218.6	64.1	10,025	9.5	2.8	1,084.8	317,925
Poultry Processing	1012	119	6,000	2.8%	6	960	0.9	0.3	8	0.0	0.0	1.3	374
Sugar Refining	1081	8	6,000	2.8%	0	4,133	3.9	1.1	517	0.5	0.1	81.6	23,920
Liquor Distilling	1121	24	8,000	-0.5%	8	6,087	5.8	1.7	254	0.2	0.1	30.1	8,807
Pulp Production	2711	39	8,000	1.0%	2	180,600	171.2	50.2	4,631	4.4	1.3	548.7	160,806
Specialty Paper Production	2719	28	8,000	3.7%	1	38,720	36.7	10.8	1,383	1.3	0.4	163.8	48,020
Petroleum Refining	3611	33	8,000	1.8%	0	253,700	240.5	70.5	7,688	7.3	2.1	910.9	266,965
Chlorine/Soda Production	3711	16	8,400	2.3%	0	37,829	35.9	10.5	2,364	2.2	0.7	266.8	78,192
BTX Production	1992	9	8,400	2.3%	0	3,593	3.4	1.0	399	0.4	0.1	45.0	13,203
Textile Bleaching/Finishing	2512	192	6,000	2.8%	0	511	0.5	0.1	3	0.0	0.0	0.4	123
Lumber Drying	2512	1087	8,400	0.8%	295	16,655	15.8	4.6	15	0.0	0.0	1.7	507
Milk Production	1041	179	6,000	2.8%	2	2,501	2.4	0.7	14	0.0	0.0	2.2	647
Cheese Production	1049	108	6,000	2.8%	7	3,339	3.2	0.9	31	0.0	0.0	4.9	1,431
Newsprint Production	2712	42	8,000	1.6%	2	59,850	56.7	16.6	1,425	1.4	0.4	168.8	49,484
TOTALS		1,907			323 17%	839,056	795						
TOTAL INDUSTRIAL SECTOR						2,398,400	2,273						

Table C.4 Canada - Summary Process Data for Annex 21 (continued)

	Estimated 2010 Process Heat/Steam Energy Mix					Process Heat Demand Supply					
						Cogeneration/CHP			Waste Heat Boilers/ Incinerators		
Process Name	Natural Gas	Coal/ Coke	Oil/ Pet.Coke	Electricity	Other/ Waste Fuel	1995	2000	2005	1995	2000	2005
Iron and Steel-Blast Furnace	3%	77%	3%	11%	7%	0%	0%	0%	10%	10%	10%
Poultry Processing	82%	0%	18%	0%	0%	15%	20%	25%	0%	0%	0%
Sugar Refining	96%	0%	4%	0%	0%	15%	20%	25%	0%	0%	0%
Liquor Distilling	98%	0%	2%	0%	0%	15%	20%	25%	0%	0%	0%
Pulp Production	56%	9%	35%	0%	0%	30%	37%	45%	50%	43%	35%
Specialty Paper Production	35%	12%	53%	0%	0%	30%	30%	30%	10%	10%	10%
Petroleum Refining	21%	23%	5%	0%	52%	10%	12%	12%	5%	6%	7%
Chlorine/Soda Production	87%	1%	5%	7%	0%	33%	37%	37%	3%	3%	3%
BTX Production	87%	1%	5%	7%	0%	33%	37%	37%	3%	3%	3%
Textile Bleaching/Finishing	55%	0%	8%	37%	0%	10%	15%	20%	0%	0%	0%
Lumber Drying	98%	0%	0%	2%	0%	15%	20%	25%	0%	0%	0%
Milk Production	89%	0%	11%	0%	0%	15%	20%	25%	0%	0%	0%
Cheese Production	77%	4%	19%	0%	0%	15%	20%	25%	0%	0%	0%
Newsprint Production	35%	12%	53%	0%	0%	30%	30%	30%	10%	10%	10%

Table C.4 Canada - Summary Process Data for Annex 21 (continued)

Energy Prices (in 1993$)					
		1995	2000	2005	2010
Natural Gas	$/GJ	2.91	3.63	4.18	4.81
Coal	$/GJ	3.96	4.34	4.61	4.91
Oil-Resid.	$/GJ	2.56	3.89	4.14	4.40
Oil-Dist.	$/GJ	6.44	8.66	6.87	7.04
Electricity	$/GJ	10.33	10.39	10.51	10.96
	c/kWh	3.7	3.7	3.8	3.9
Currency Conversion Rate: 1.32 CD $ / U.S. $					

Table C.5 Canada - Emission Factors for Annex 21 (continued on next page)

Emission Factors per Unit Heat/Electricity Delivered In grams/gigajoule (g/GJ) - LHV								
Fuel/Pollutant	Industrial Boilers		Utility Boilers		Utility Turbines		Industrial Diesel Engines	
	1995	2010	1995	2010	1995	2010	1995	2010
Natural Gas								
SO_x	0.24	0.24	1.16	1.18	26.15	26.53		
NO_x	69.4	69.4	332.6	198.2	1,067.5	297.0		
CO_2	58471	58471	118877	79308	118877	79308		
CO	18	18	87	88	174	72		
CH_4	1.5	1.5	7.5	7.6	29.0	29.4		
PM	1.5	1.5	7.5	7.6	35.3	35.9		
Coal								
SO_x	685	685	5465	3638	X	X		
NO_x	313	313	1899	1767	X	X		
CO_2	107375	107375	796618	757931	X	X		
CO	116	116	885	858	X	X		
CH_4	0.68	0.68	5.15	4.98	X	X		
PM	16.91	16.91	128.80	124.92	X	X		
Oil								
SO_x	853	853	6264	5871	6264	5871	136	136
NO_x	196	165	2739	2892	2739	2892	133.85	44.58
CO_2	87059	87059	517566	508853	517566	508853	70700	70700
CO	16.9	16.9	105.7	104.6	220.8	90.7	350	350
CH_4	0.96	0.96	6.01	5.94	39.56	39.17	12.5	12.5
PM	16.26	16.26	101.41	100.35	101.41	66.84	44.58	44.58

Table C.5 Canada - Emission Factors for Annex 21 (continued)

Utility Power Plants			
Fuel/Prime Mover	1995 Heat Rates Btu/kWh)	1995 Generating Mix (Est. %)	2010 Generating Mix (Est. %)
Gas-Boilers	8215	2.0%	2.2%
Gas-Turbines	8215	0.5%	0.8%
Coal-Boilers	10529	14.9%	17.9%
Oil-Boilers	9244	1.5%	1.6%
Oil-Turbines	9244	0.2%	0.2%
Nuclear	11465	19.5%	16.5%
Hydro/Renewables	3498	61.3%	60.6%
Weighted Average Heat Rate		6,324	6,294

Emission Factors for Electricity (g/GJ - LHV)		
	1995	2010
SO_x	921	757
NO_x	342	375
CO_2	130467	147208
CO	137	158
CH_4	1.2	1.5
PM	21.2	24.5

Table C.6 Canada - IHPs Evaluated by Process for Annex 21

Process Name	Can. SIC #	IHP Type					
		Closed-Cycle		MVR	TVR	Type 2 Absorption (Waste-Heat Driven)	Type 1 Absorption (Prime-Heat Driven)
		Electric	Diesel(*)				
Iron and Steel-Blast Furnace	291			O		O	
Poultry Processing	1012	O	O				O
Sugar Refining	1081	O		O		O	
Liquor Distilling	1121	O	O	O		O	
Pulp Production	2711	O	O	O			
Specialty Paper Production	2719	O	O				O
Petroleum Refining	3611			O	O		O
Chlorine/Soda Production	3711	O	O				
BTX Production	3712			O			
Textile Bleaching/Finishing	1992	O	O				O
Lumber Drying	2512	O					
Milk Production	1041	O					
Cheese Production	1049	O		O			
Newsprint Production	2712	O					

(*) Gas-fired

C.3 Japan

A total of 11 industrial processes were examined in detail to assess IHP market potential. The key data on which this examination was based are summarized below.

C.3.1 Energy Prices/Process-Specific Industry Data

The baseline energy prices on which IHP economics were calculated are shown in Table C.7. This table also contains the process-specific data (e.g., number of plants, heat demand, industry growth) estimated for the 11 processes for which IHP potential was assessed.

C.3.2 Emission Factors

The emission factors used in the Japanese study were the default values provided for the market assessment. The base emission factors, summarized in Table C.8, were derived on a per unit heat/electricity basis. Electricity emission factors were determined based on the projected electric generation mix. With this mix estimated to decrease from about 49% fossil fuel-based to about 43% by 2010, and with emission factors expected to decrease based on more stringent regulations and higher levels of compliance, Japan's emission factors for electricity were also projected to decrease over the time frame of analysis (see Table C.8).

C.3.3 Market Factors

The default values provided in the market assessment program were used in the Japanese IHP study for each of the three market factors: market penetration, risk aversion, and diffusion rate.

C.3.4 IHPs Assessed by Process

The IHP types assessed, by process, are outlined in Table C.9. The applicability of these IHPs was determined using the IHP screening program.

Table C.7 Japan - Summary Process Data for Annex 21 (continued on next pages)

Process Name	# of Plants	Typical Operation (Hrs./yr)	Projected Growth (%)	# of Plants w/IHPs	Process Heat Demand							
					Total			Average Plant				
					1,000 GJ/yr	Trill. Btu/yr	Bill. kW/yr	1,000 GJ/yr	Bill. Btu/yr	Mill. kW/yr	MMBtu/ hr	kWh/ hr
Caustic Soda	45	8,000	1.0%	0	3,300	3.1	0.9	73	70	20	9	2,547
Ethylene	14	8,000	1.0%	2	153,000	145.0	42.5	10,929	10,359	3,036	1,295	379,500
Polyvinyl Chloride	24	8,000	1.0%	0	10,800	10.2	3.0	450	427	125	53	15,626
Naphtha Splitter	30	8,000	2.0%	0	75,000	71.1	20.8	2,500	2,370	695	296	86,814
Naphtha Desulphurization	30	8,000	2.0%	0	120,000	113.7	33.3	4,000	3,791	1,111	474	138,902
Surfolane	20	8,000	2.0%	0	650,000	616.1	180.6	32,500	30,806	9,029	3,851	1,128,579
Cane Sugar	22	2,160	0%	1	5,148	4.9	1.4	234	222	65	103	30,095
Beet Sugar	8	4,000	0.1%	0	17,585	16.7	4.9	2,198	2,084	611	521	152,662
Liquor/Spirits	113	7,300	1.0%	4	1,651	1.6	0.5	15	14	4	2	556
Kraft Pulp	25	7,200	0%	0	302,820	287.0	84.1	12,113	11,481	3,365	1,595	467,359
Textile Dyeing	429	5,000	0%	1	104,018	98.6	28.9	242	230	67	46	13,472
TOTALS 11 PROCESSES		760		8 1%	1,443,322	1,368	401					
TOTAL INDUSTRIAL SECTOR					3,800,000							

Table C.7 Japan - Summary Process Data for Annex 21 (continued)

	Estimated 2010 Process Heat/Steam Energy Mix					Process Heat Demand Supply					
						Cogeneration/CHP			Waste Heat Boilers/ Incinerators		
Process Name	Natural Gas	Coal/ Coke	Oil/ Pet.Coke	Electricity	Other/ Waste Fuel	1995	2000	2005	1995	2000	2005
Caustic Soda	4%	9%	82%	5%	0%	0%	0%	0%	0%	0%	0%
Ethylene	4%	9%	82%	5%	0%	10%	13%	15%	0%	0%	0%
Polyvinyl Chloride	4%	9%	82%	5%	0%	10%	12%	15%	0%	0%	0%
Naphtha Splitter	5%	10%	80%	5%	0%	10%	13%	15%	0%	0%	0%
Naphtha Desulphurization	5%	10%	80%	5%	0%	10%	13%	15%	0%	0%	0%
Surfolane	5%	10%	80%	5%	0%	10%	13%	15%	0%	0%	0%
Cane Sugar	0%	0%	5%	8%	87%	1%	2%	3%	1%	2%	3%
Beet Sugar	0%	0%	86%	12%	0%	1%	2%	2%	2%	4%	4%
Liquor/Spirits	22%	0%	76%	12%	0%	1%	2%	3%	1%	2%	3%
Kraft Pulp	3%	17%	21%	0%	59%	30%	37%	45%	1%	2%	3%
Textile Dyeing	0%	0%	90%	10%	0%	1%	2%	3%	1%	2%	3%

Table C.7 Japan - Summary Process Data for Annex 21 (continued)

Energy Prices (in 1993$)					
		1995	2000	2005	2010
Natural Gas	$/GJ	13.65	16.75	19.85	22.95
Coal	$/GJ	2.99	3.67	4.43	5.03
Oil-Resid.	$/GJ	—	—	—	—
Oil-Dist.	$/GJ	13.00	16.00	19.00	21.96
Electricity	$/GJ	34.00	41.00	50.00	57.81
	c/kWh	12.30	14.70	18.00	20.80
Currency Conversion Rate: 110 Yen / U.S. $					

Table C.8 Japan - Emission Factors for Annex 21 (continued on next page)

Emission Factors per Unit Heat/Electricity Delivered In grams/gigajoule (g/GJ) - LHV								
Fuel/Pollutant	Industrial Boilers		Utility Boilers		Utility Turbines		Industrial Diesel Engines (distillate)	
	1995	2010	1995	2010	1995	2010	1995	2010
Natural Gas								
SO_x	0.31	0.31	0.83	0.75	17.26	14.00		
NO_x	74.7	74.7	281.4	253.8	610.6	157.0		
CO_2	57000	57000	167594	150764	173625	140777		
CO	18.9	18.9	55.3	49.9	105.3	42.7		
CH_4	1.58	1.58	0.40	0.36	19.16	15.98		
PM	1.56	1.56	4.17	3.76	23.31	18.90		
Coal								
SO_x	592	592	2309	1377	X	X		
NO_x	301	301	888	574	X	X		
CO_2	130000	130000	317098	307282	X	X		
CO	100	100	36	35	X	X		
CH_4	2.64	2.64	1.73	1.61	X	X		
PM	14.60	14.60	35.54	34.44	X	X		
Oil								
SO_x	433	326	1117	787	1492	861	100.4	100.4
NO_x	194	164	624	397	906	160	134.0	45.0
CO_2	88000	88000	220158	206043	313872	225629	72917	72917
CO	18.3	18.3	46.0	43.0	130.1	38.7	223.0	45.0
CH_4	3.55	3.55	2.71	2.53	23.23	16.70	3.2	3.2
PM	16.26	16.26	41.88	39.20	59.71	28.59	44.6	44.6

Table C.8 Japan - Emission Factors for Annex 21 (continued)

Utility Power Plants			
Fuel/Prime Mover	1995 Heat Rates Btu/kWh)	1995 Generating Mix (Est. %)	2010 Generating Mix (Est. %)
Gas-Boilers	10720	22.0%	18.0%
Gas-Turbines	13060	0.0%	0.0%
Coal-Boilers	10380	12.0%	15.0%
Oil-Boilers	10340	15.0%	10.0%
Oil-Turbines	14740	0.0%	0.0%
Nuclear	11000	35.0%	43.0%
Hydro/Renewables	10300	16.0%	14.0%
Weighted Average Heat Rate		10,653	10,693

Emission Factors for Electricity (g/GJ - LHV)		
	1995	2010
SO_x	445	185
NO_x	262	171
CO_2	107946	93834
CO	23	19
CH_4	0.7	0.6
PM	11.5	9.8

Table C.9 Japan - IHPs Evaluated by Process for Annex 21

Process Name	IHP Type					
	Closed-Cycle		MVR	TVR	Type 2 Absorption (Waste-Heat Driven)	Type 1 Absorption (Prime-Heat Driven)
	Electric	Diesel				
Caustic Soda	O		O	O		O
Ethylene		O	O	O		O
Polyvinyl Chloride	O	O	O	O		O
Naphtha Splitter		O	O	O	O	O
Naphtha Desulphurization			O		O	
Surfolane			O			
Cane Sugar		O	O			
Beet Sugar	O	O	O		O	
Liquor/Spirits			O		O	
Kraft Pulp			O		O	
Textile Dyeing			O			

C.4 Netherlands

The Dutch market study assessed IHP potential in seven industrial processes. The industrial and market data used to conduct this assessment are outlined in the following sections.

C.4.1 Energy Prices/Process-Specific Industry Data

The base energy prices used in the Dutch assessment are provided in Table C.10. These data show electric-to-fuel (E-F) price ratios ranging from 3.5 for natural gas to 8.5 for coal, among the highest E-F ratios for the countries that participated in Annex 21. The process-specific data derived for the seven industrial processes are also summarized in Table C.10.

C.4.2 Emission Factors

The Dutch IHP assessment used the default emission factors to determine the potential environmental benefits of IHPs. Emission factors for electricity were derived from the projected energy mix for electric generation (see Table C.11). A summary of the emission factors used in the Dutch assessment is provided in Table C.11.

C.4.3 Market Factors

The market factors used in the Dutch IHP study were a combination of factors specified by the Dutch National Team and default values (see Appendix B). The market penetration factors used (representing a maximum level of IHP use as function of IHP payback level) were: payback less than 2 years, 80%; 2-3 years, 60%; 3-4 years, 40%; 4-5 years, 20%; and over 5 years, 10%. These levels are somewhat higher than the default values for paybacks under 2 years and somewhat lower than the default values for payback levels over 3 years.

The Dutch assessment used the default risk aversion rate, but specified its own diffusion rate (the rate at which market penetration would approach maximum penetration), estimated at: 10% by 1995; 40% by 2000; 80% by 2005; and 86% by 2010. The 1995 and 2000 levels were the same as the default values; however, the 2005 and 2010 values were lower, reflecting a slower level of overall market diffusion for IHPs.

C.4.4 IHPs Assessed by Process

The IHP types assessed, by process, are outlined in Table C.12. The applicability of these IHPs was determined using the IHP screening program.

Table C.10 Netherlands - Summary Process Data for Annex 21 (continued on next page)

Process Name	# of Plants	Typical Operation (Hrs./yr)	Projected Growth (%)	# of Plants w/IHPs	Process Heat Demand: Total 1,000 GJ/yr	Total Trill. Btu/yr	Total Bill. kW/yr	Average Plant 1,000 GJ/yr	Average Plant Bill. Btu/yr	Average Plant Mill. kW/yr	Average Plant MMBtu/hr	Average Plant kWh/hr
Textile plant	41	8,000	1.0%	0	5,285	5.0	1.5	129	122	36	15	4,476
Dairy production	91	8,000	1.0%	63	10,752	10.2	3.0	118	112	33	14	4,103
Paper production	32	8,000	1.0%	0	19,300	18.3	5.4	603	572	168	71	20,944
Building ceramics	72	8,000	1.0%	0	7,440	7.1	2.1	103	98	29	12	3,588
Urea plant	3	8,000	1.0%	0	2,300	2.2	0.6	767	727	213	91	26,623
Ethylene	3	8,000	1.0%	0	35,400	33.6	9.8	11,800	11,185	3,278	1,398	409,761
Starch evaporation	8	8,000	1.0%	4	4,700	4.5	1.3	588	557	163	70	20,401
TOTALS 7 PROCESSES	250			67 27%	85,177	81	24					
TOTAL INDUSTRIAL SECTOR				94	512,638							

Table C.10 Netherlands - Summary Process Data for Annex 21 (continued)

	Estimated 2010 Process Heat/Steam Energy Mix					Process Heat Demand Supply					
						Cogeneration/CHP			Waste Heat Boilers/ Incinerators		
Process Name	Natural Gas	Coal/ Coke	Oil/ Pet Coke	Electricity	Other/ Waste Fuel	1995	2000	2005	1995	2000	2005
Textile plant	99%	0%	1%	0%	0%	0.2%	5%	10%	0%	0%	0%
Dairy production	100%	0%	0%	0%	0%	24%	35%	35%	0%	0%	0%
Paper production	100%	0%	0%	0%	0%	62%	70%	70%	0%	0%	0%
Building ceramics	90%	0%	10%	0%	0%	0.2%	5%	10%	0%	0%	0%
Urea plant	100%	0%	0%	0%	0%	10%	20%	30%	0%	0%	0%
Ethylene	0%	0%	100%	0%	0%	10%	20%	30%	0%	0%	0%
Starch evaporation	100%	0%	0%	0%	0%	10%	20%	30%	0%	0%	0%

Energy Prices (in 1993$)					
		1995	2000	2005	2010
Natural Gas	$/GJ	3.78	6.49	6.49	6.49
Coal	$/GJ	2.16	2.70	2.70	2.70
Oil-Resid.	$/GJ	2.70	4.86	4.86	4.86
Oil-Dist.	$/GJ	2.70	4.86	4.86	4.86
Electricity	$/GJ	18.02	22.92	22.92	22.92
	c/kWh	6.5	8.2	8.2	8.2
Currency Conversion Rate: 1.85 Dutch Guilders / U.S. $					

Table C.11 Netherlands - Emission Factors for Annex 21 (continued on next page)

Emission Factors per Unit Heat/Electricity Delivered In grams/gigajoule (g/GJ) - LHV								
Fuel/Pollutant	Industrial Boilers		Utility Boilers		Utility Turbines		Industrial Diesel Engines (distillate)	
	1995	2010	1995	2010	1995	2010	1995	2010
Natural Gas								
SO_x	0.31	0.31	0.83	0.75	17.26	14.00		
NO_x	74.7	74.7	281.4	253.8	610.6	157.0		
CO_2	57000	57000	167594	150764	173625	140777		
CO	18.9	18.9	55.3	49.9	105.3	42.7		
CH_4	1.6	1.6	0.4	0.4	19.2	16.0		
PM	1.6	1.6	4.2	3.8	23.3	18.9		
Coal								
SO_x	592.0	592.0	2309.4	1377.3	X	X		
NO_x	301.1	301.1	888.3	573.5	X	X		
CO_2	130000	130000	317098	307282	X	X		
CO	100.0	100.0	36.4	35.2	X	X		
CH_4	2.6	2.6	1.7	1.6	X	X		
PM	14.60	14.60	35.54	34.44	X	X		
Oil								
SO_x	433.4	326.2	1116.7	786.7	1492.1	861.5	100.4	100.4
NO_x	193.5	164.5	624.2	396.6	906.1	160.3	134.0	45.0
CO_2	88000	88000	220158	206043	313872	225629	72917	72917
CO	18.3	18.3	46.0	43.0	130.1	38.7	223.0	45.0
CH_4	3.55	3.55	2.71	2.53	23.23	16.70	3.2	3.2
PM	16.26	16.26	41.88	39.20	59.71	28.59	44.6	44.6

Table C.11 Netherlands - Emission Factors for Annex 21 (continued)

Utility Power Plants			
Fuel/Prime Mover	1995 Heat Rates Btu/kWh)	1995 Generating Mix (Est. %)	2010 Generating Mix (Est. %)
Gas-Boilers	10720	41.6%	20.0%
Gas-Turbines	13060	13.0%	25.0%
Coal-Boilers	10380	39.3%	50.0%
Oil-Boilers	10340	0.3%	0%
Oil-Turbines	14740	0%	0%
Nuclear	11000	7.8%	5.0%
Hydro/Renewables	10300	0%	0%
Weighted Average Heat Rate		11,126	11,149

Emission Factors for Electricity (g/GJ - LHV)		
	1995	2010
SO_x	867	692
NO_x	530	377
CO_2	211228	218988
CO	50	38
CH_4	3.3	4.9
PM	18.2	22.7

Table C.12 Netherlands - IHPs Evaluated by Process for Annex 21

Process Name	IHP Type					
	Closed-Cycle		MVR	TVR	Type 2 Absorption (Waste-Heat Driven)	Type 1 Absorption (Prime-Heat Driven)
	Electric	Diesel(*)				
Textile Plant		O				
Dairy Production				O		O
Paper Production		O			O	
Building Ceramics		O				
Urea Plant			O			
Ethylene		O			O	
Starch Evaporation			O			

(*) Gas-fired

C.5 Norway

In the Norwegian IHP study, IHP market potential and energy and environmental benefits were examined for six industrial processes. The key data and assumptions for this analysis are outlined below.

C.5.1 Energy Prices/Process-Specific Industry Data

The energy prices used for the Norwegian market study are shown in Table C.13. The detailed process data developed for the six industrial processes are also included in Table C.13.

C.5.2 Emission Factors

The emission factors used in the Norwegian study were the default values provided for the market assessment, with one exception. The predominant fuel for process heating in the timber industry is biomass or biobrensel; therefore, emission factors were also derived for this energy source. Based on electricity derived entirely from hydroelectric power, the emission factors from electricity use were set equal to zero. A summary of the emission factors used in the Norwegian assessment is shown in Table C.14.

C.5.3 Market Factors

For the Norwegian study, the default values (see Appendix B) were used for the three market factors corresponding to market penetration, risk aversion, and diffusion rate.

C.5.4 IHPs Assessed by Process

The IHP types assessed, by process, are outlined in Table C.15. The applicability of these IHPs was determined using the IHP screening program.

Table C.13 Norway - Summary Process Data for Annex 21 (continued on next pages)

Process Name	# of Plants	Typical Operation (Hrs./yr)	Projected Growth (%)	# of Plants w/IHPs	Process Heat Demand							
					Total			Average Plant				
					1,000 GJ/yr	Trill. Btu/yr	Bill. kW/yr	1,000 GJ/yr	Bill. Btu/yr	Mill. kW/yr	MMBtu/hr	kWh/hr
Aqua culture/fish farming (heating process water)	500	6,000	1%	230	2,160	2.0	0.6	4.3	4.1	1.2	0.7	200
Fish products (drying stockfish/klipfish)	90	8,000	5%	60	243	0.2	0.1	2.7	2.6	0.8	0.3	94
Dairies (refrigeration heat recovery)	105	8,000	1%	18	569	0.5	0.2	5.4	5.1	1.5	0.6	188
Dairies (cream/cheese evaporation)	28	8,000	3%	15	223	0.2	0.1	8.0	7.5	2.2	0.9	277
Timber/wood products (product drying)	760	7,000	1%	170	5,040	4.8	1.4	6.6	6.3	1.8	0.9	263
Meat products (refrigeration heat recovery)	270	7,000	1%	50	1,620	1.5	0.5	6.0	5.7	1.7	0.8	238
TOTALS 6 PROCESSES	1,753			543 31%	9,855	9	3					
Other Processes				127	44,145							
TOTAL INDUSTRIAL SECTOR				670	54,000	51	15					

Table C.13 Norway - Summary Process Data for Annex 21 (continued)

	Estimated 2010 Process Heat/Steam Energy Mix					Process Heat Demand Supply					
						Cogeneration/CHP			Waste Heat Boilers/ Incinerators		
Process Name	Natural Gas	Coal/ Coke	Oil/ Pet.Coke	Electricity	Other/ Waste Fuel	1995	2000	2005	1995	2000	2005
Aqua culture/fish farming (heating process water)			100%			0%	0%	0%	0%	0%	0%
Fish products (drying stockfish/klipfish)			100%			0%	0%	0%	0%	0%	0%
Dairies (refrigeration heat recovery)			100%			0%	0%	0%	0%	0%	0%
Dairies (cream/cheese evaporation)				100%		0%	0%	0%	0%	0%	0%
Timber/wood products (product drying)			20%		80% (*)	0%	0%	0%	0%	0%	0%
Meat products (refrigeration heat recovery)			100%			0%	0%	0%	0%	0%	0%

(*) Biomass or biobrensel

Table C.13 Norway - Summary Process Data for Annex 21 (continued)

Energy Prices (in 1993$)					
		1995	2000	2005	2010
Natural Gas	$/GJ	—	—	—	—
Coal	$/GJ	—	—	—	—
Oil-Resid.	$/GJ	—	—	—	—
Oil-Dist.	$/GJ	14.40	15.20	15.60	16.00
Electricity	$/GJ	8.13	8.80	9.20	9.60
	c/kWh	2.93	3.20	3.33	3.47
Currency Conversion Rate: 7.5 NOK / U.S. $					

Table C.14 Norway - Emission Factors for Annex 21 (continued on next page)

Emission Factors per Unit Heat/Electricity Delivered In grams/gigajoule (g/GJ) - LHV						
Fuel/Pollutant	Industrial Boilers		Utility Boilers		Utility Turbines	
	1995	2010	1995	2010	1995	2010
Natural Gas						
SO_x	0.31	0.31	0.83	0.75	17.26	14.00
NO_x	74.7	74.7	281.4	253.8	610.6	157.0
CO_2	57000	57000	167594	150764	173625	140777
CO	18.9	18.9	55.3	49.9	105.3	42.7
CH_4	1.58	1.58	0.40	0.36	19.16	15.98
PM	1.56	1.56	4.17	3.76	23.31	18.90
Coal						
SO_x	592	592	2309	1377	X	X
NO_x	301	301	888	574	X	X
CO_2	130000	130000	317098	307282	X	X
CO	100	100	36	35	X	X
CH_4	2.64	2.64	1.73	1.61	X	X
PM	14.60	14.60	35.54	34.44	X	X
Oil						
SO_x	433	326	1117	787	1492	861
NO_x	194	164	624	397	906	160
CO_2	88000	88000	220158	206043	313872	225629
CO	18.3	18.3	46.0	43.0	130.1	38.7
CH_4	3.55	3.55	2.71	2.53	23.23	16.70
PM	16.26	16.26	41.88	39.20	59.71	28.59

	Industrial Boilers	
	1995	2010
Biomass/Biobrensel(*)		
SO_x	20	20
NO_x	120	120
CO_2	98300	98300
CO	1190	1190
CH_4	15	15
PM	120	120

	Industrial Diesel Engines	
	1995	2010
Oil		
SO_x	100	100
NO_x	134	45
CO_2	72917	72917
CO	223.0	45.0
CH_4	3.20	3.20
PM	44.60	44.60

(*) wood, wood chips, bark, and other wood waste

Table C.14 Norway - Emission Factors for Annex 21 (continued)

Utility Power Plants			
Fuel/Prime Mover	1995 Heat Rates Btu/kWh)	1995 Generating Mix (Est. %)	2010 Generating Mix (Est. %)
Gas-Boilers	10720	0%	0%
Gas-Turbines	13060	0%	0%
Coal-Boilers	10380	0%	0%
Oil-Boilers	10340	0%	0%
Oil-Turbines	14740	0%	0%
Nuclear	11000	0%	0%
Hydro/Renewables	10300	100%	100%
Weighted Average Heat Rate		10,300	10,300

Emission Factors for Electricity (g/GJ - LHV)		
	1995	2010
SO_x	0	0
NO_x	0	0
CO_2	0	0
CO	0	0
CH_4	0	0
PM	0	0

Table C.15 Norway - IHPs Evaluated by Process for Annex 21

Process Name	IHP Type				
	Electric Closed-Cycle	MVR	TVR	Type 2 Absorption (Waste-Heat Driven)	Type 1 Absorption (Prime-Heat Driven)
Aqua culture/fish farming (heating process water)	O				
Fish products (drying stockfish/klipfish)	O				
Dairies (refrigeration heat recovery)	O	O			
Dairies (cream/cheese evaporation)	O	O			
Timber/wood products (product drying)	O				
Meat products (refrigeration heat recovery)	O				

C.6 Sweden

The Swedish study assessed IHP potential in six processes, using the data outlined below.

C.6.1 Energy Prices/Process-Specific Industry Data

The energy prices used for the Swedish assessment are shown in Table C.16. The detailed process data estimated for industrial processes investigated are also summarized in this table.

C.6.2 Emission Factors

To conduct the market study, the default emission factors (see Appendix B) were used in the analysis, with one exception. The biomass drying application relies on waste fuel for process heating; therefore, emission factors were also derived for this waste fuel energy source. As with the other assessments, the emission factors for electricity were derived based on Sweden's estimated electric generation mix. This mix is projected to move from mostly hydroelectric and nuclear power at present to include a higher proportion of fossil-fuel based sources. As such, the emission factors for electricity were projected to increase significantly over the period of analysis. The emission factors used in the Swedish study are outlined in Table C.17.

C.6.3 Market Factors

In the Swedish assessment, the default values were used for the three market factors corresponding to market penetration, risk aversion, and diffusion rate.

C.6.4 IHPs Assessed by Process

The IHP types assessed, by process, are outlined in Table C.18. The applicability of these IHPs was determined using the IHP screening program.

Table C.16 Sweden - Summary Process Data for Annex 21 (continued on next page)

Process Name	# of Plants	Typical Operation (Hrs./yr)	Projected Growth (%)	# of Plants w/IHPs	Process Heat Demand							
					Total			Average Plant				
					1,000 GJ/yr	Trill. Btu/yr	Bill. kW/yr	1,000 GJ/yr	Bill. Btu/yr	Mill. kW/yr	MMBtu/ hr	kWh/ hr
Food industry (central heating)	130	8,000	2%	30	7,200	6.8	2.0	55	52	15	7	1,923
Pulp & paper (black liquor vapor recovery)	4	8,000	5%	3	25,100	23.8	7.0	6,275	5,948	1,743	743	217,903
Wastewater concentration	5	8,000	13%	5	4,000	3.8	1.1	800	758	222	95	27,780
Biomass drying	30	8,000	14%	2	3,000	2.8	0.8	100	95	28	12	3,473
Ethanol distillation	4	8,000	5%	4	500	0.5	0.1	125	118	35	15	4,341
District heating (from industrial waste heat sources)	75	8,000	2%	48	7,200	6.8	2.0	96	91	27	11	3,334
TOTALS 6 PROCESSES	248			92 37%	47,000	45	13					
TOTAL INDUSTRIAL SECTOR					475,000	450	132					

Table C.16 Sweden - Summary Process Data for Annex 21 (continued)

	Estimated 2010 Process Heat/Steam Energy Mix					Process Heat Demand Supply					
						Cogeneration/CHP			Waste Heat Boilers/ Incinerators		
Process Name	Natural Gas	Coal/ Coke	Oil/ Pet.Coke	Electricity	Other/ Waste Fuel	1995	2000	2005	1995	2000	2005
Food industry (central heating)	1%	8%	80%	10%	1%	0%	0%	0%	0%	0%	0%
Pulp & paper (black liquor vapor recovery)	4%	1%	40%	5%	50%	60%	80%	80%	0%	0%	0%
Wastewater concentration	4%	1%	40%	5%	50%	60%	80%	80%	0%	0%	0%
Biomass drying	0%	0%	0%	0%	100%	0%	0%	0%	0%	0%	0%
Ethanol distillation	0%	0%	50%	0%	50%	0%	0%	0%	0%	0%	0%
District heating (from industrial waste heat sources)	0%	50%	0%	0%	50%	0%	10%	20%	0%	0%	0%

Energy Prices (in 1993$)					
		1995	2000	2005	2010
Natural Gas	$/GJ	6.25	6.63	6.68	7.25
Coal	$/GJ	3.25	3.38	3.63	3.75
Oil-Resid.	$/GJ	4.38	4.63	4.88	5.13
Oil-Dist.	$/GJ	7.25	7.63	8.00	8.38
Electricity	$/GJ	12.50	13.13	15.28	18.75
	c/kWh	4.5	4.8	5.5	6.8
Currency Conversion Rate: 8 SEK / U.S. $					

Table C.17 Sweden - Emission Factors for Annex 21 (continued on next page)

Emission Factors per Unit Heat/Electricity Delivered In grams/gigajoule (g/GJ) - LHV						
Fuel/Pollutant	Industrial Boilers		Utility Boilers		Utility Turbines	
	1995	2010	1995	2010	1995	2010
Natural Gas						
SO_x	0.31	0.31	0.83	0.75	17.26	14.00
NO_x	74.7	74.7	281.4	253.8	610.6	157.0
CO_2	57000	57000	167594	150764	173625	140777
CO	18.9	18.9	55.3	49.9	105.3	42.7
CH_4	1.58	1.58	0.40	0.36	19.16	15.98
PM	1.56	1.56	4.17	3.76	23.31	18.90
Coal						
SO_x	592	592	2309	1377	X	X
NO_x	301	301	888	574	X	X
CO_2	130000	130000	317098	307282	X	X
CO	100	100	36	35	X	X
CH_4	2.64	2.64	1.73	1.61	X	X
PM	14.60	14.60	35.54	34.44	X	X
Oil						
SO_x	433	326	1117	787	1492	861
NO_x	194	164	624	397	906	160
CO_2	88000	88000	220158	206043	313872	225629
CO	18.3	18.3	46.0	43.0	130.1	38.7
CH_4	3.55	3.55	2.71	2.53	23.23	16.70
PM	16.26	16.26	41.88	39.20	59.71	28.59

	Industrial Boilers	
	1995	2010
Biomass(*)		
SO_x	0	0
NO_x	45	45
CO_2	96000	96000
CO	65	65
CH_4	4	4
PM	17	17

	Industrial Diesel Engines	
	1995	2010
Oil		
SO_x	100	100
NO_x	134	45
CO_2	72917	72917
CO	223.0	45.0
CH_4	3.20	3.20
PM	44.60	44.60

(*) agricultural waste/bagasse

Table C.17 Sweden - Emission Factors for Annex 21 (continued)

Utility Power Plants			
Fuel/Prime Mover	1995 Heat Rates Btu/kWh)	1995 Generating Mix (Est. %)	2010 Generating Mix (Est. %)
Gas-Boilers	10720	0%	0%
Gas-Turbines	13060	0%	25%
Coal-Boilers	10380	0%	5%
Oil-Boilers	10340	1%	2%
Oil-Turbines	14740	1%	3%
Nuclear	11000	45%	0%
Hydro/Renewables	10300	53%	65%
Weighted Average Heat Rate		10,660	11,128

Emission Factors for Electricity (g/GJ - LHV)	1995	2010
SO_x	26	114
NO_x	15	81
CO_2	5340	61448
CO	2	14
CH_4	0.3	4.6
PM	1.0	8.1

Table C.18 Sweden - IHPs Evaluated by Process for Annex 21

Food industry (central heating)	O				O
Pulp & paper (black liquor vapor recovery)		O		O	
Wastewater concentration		O			
Biomass drying		O			
Ethanol distillation		O			
District heating (from industrial waste heat sources)	O				O

C.7 United Kingdom

The UK market study analyzed IHP potential in six processes. The industrial and market data on which these processes were analyzed are described below.

C.7.1 Energy Prices/Process-Specific Industry Data

The base energy prices for the UK IHP study, used to assess IHP economics in each of the industrial processes examined, are summarized in Table C.19. These data show that the E-F price ratios are among the highest for the countries in Annex 21, particularly for natural gas (4.2) and distillate oil (4.5). Table C.19 also summarized the process-specific data used to assess IHP potential for each of the individual processes.

C.7.2 Emission Factors

The emission factors used in the UK to assess the potential environmental benefits of IHPs were the default values provided for the market assessment (see Appendix B). The base emission factors, summarized in Table C.20, were derived on a per-unit heat/electricity basis.

Electricity emission factors were determined based on the projected electric generation mix. As the energy mix for electric generation in the UK is projected to move dramatically from coal to natural gas turbine and renewable energy sources, the emission factors for electricity were also projected to decrease significantly over the time frame of analysis (see Table C.20).

C.7.3 Market Factors

The market factors used in the UK assessment were a combination of factors specified by the UK National Team and default values (see Appendix B). The market penetration factors used (representing a maximum level of IHP use as function of IHP payback level) were: payback less than 2 years, 75%; 2-3 years, 60%; 3-4 years, 25%; 4-5 years, 10%; and over 5 years, 3%. These levels were the same as the default values for paybacks of 3 years or less, but were lower (representing lower penetration) for paybacks over 3 years.

The UK assessment used the default risk aversion rate, 33%, but specified its own diffusion rate (the rate at which market penetration would approach maximum penetration), estimated at: 3% by 1995; 20% by 2000; 50% by 2005; and 90% by 2010. These values reflect an overall market diffusion rate that is slower than that implied in the default values.

C.7.4 IHPs Assessed by Process

The IHP types assessed, by process, are outlined in Table C.21. The applicability of these IHPs was determined using the IHP screening program.

Table C.19 United Kingdom - Summary Process Data for Annex 21 *(continued on next page)*

Process Name	# of Plants	Typical Operation (Hrs./yr)	Projected Growth (%)	# of Plants w/IHPs	Process Heat Demand							
					Total			Average Plant				
					1,000 GJ/yr	Trill. Btu/yr	Bill. kW/yr	1,000 GJ/yr	Bill. Btu/yr	Mill. kW/yr	MMBtu/hr	kWh/hr
Paper and Board	120	8,000	1.0%	0	52,000	49.3	14.4	433	411	120	51	15,048
Chlorine/Caustic	9	8,000	0%	0	7,520	7.1	2.1	836	792	232	99	29,015
Beet Sugar	10	8,000	0%	1	10,140	9.6	2.8	1,014	961	282	120	35,212
Malt Whiskey Distillery	87	8,000	1.0%	1	4,802	4.6	1.3	55	52	15	7	1,917
Liquor/Spirits Distillery	10	8,000	1.0%	1	5,560	5.3	1.5	556	527	154	66	19,307
Brewery	95	8,000	-1.0%	0	7,896	7.5	2.2	83	79	23	10	2,886
TOTALS 6 PROCESSES	331			3 1%	87,918	83	24					
TOTAL INDUSTRIAL SECTOR					1,771,475							

Table C.19 United Kingdom - Summary Process Data for Annex 21 (continued)

Process Name	Estimated 2010 Process Heat/Steam Energy Mix					Process Heat Demand Supply					
	Natural Gas	Coal/ Coke	Oil/ Pet.Coke	Electricity	Other/ Waste Fuel	Cogeneration/CHP 1995	Cogeneration/CHP 2000	Cogeneration/CHP 2005	Waste Heat Boilers/ Incinerators 1995	Waste Heat Boilers/ Incinerators 2000	Waste Heat Boilers/ Incinerators 2005
Paper and Board	88%	0%	12%	0%	0%	30%	35%	40%	0%	0%	0%
Chlorine/Caustic	45%	0%	5%	50%	0%	35%	35%	40%	0%	0%	0%
Beet Sugar	38%	27%	35%	0%	0%	40%	40%	40%	0%	0%	0%
Malt Whiskey Distillery	35%	10%	55%	0%	0%	0%	10%	20%	0%	0%	0%
Liquor/Spirits Distillery	55%	0%	45%	0%	0%	8%	20%	30%	0%	0%	0%
Brewery	70%	10%	20%	0%	0%	2%	15%	20%	0%	0%	0%

Energy Prices (in 1993$)		1995	2000	2005	2010
Natural Gas	$/GJ	3.41	4.65	5.89	5.89
Coal	$/GJ	2.39	3.26	4.14	4.14
Oil-Resid.	$/GJ	3.19	4.35	5.51	5.51
Oil-Dist.	$/GJ	5.42	7.39	9.36	9.36
Electricity	$/GJ	14.41	19.66	24.91	24.91
	c/kWh	5.2	7.1	9.0	9.0
Currency Conversion Rate: 0.66845 Pounds Sterling / U.S. $					

Table C.20 United Kingdom - Emission Factors for Annex 21 (continued on next page)

Emission Factors per Unit Heat/Electricity Delivered In grams/gigajoule (g/GJ) - LHV								
Fuel/Pollutant	Industrial Boilers		Utility Boilers		Utility Turbines		Industrial Diesel Engines (distillate)	
	1995	2010	1995	2010	1995	2010	1995	2010
Natural Gas								
SO_x	0.31	0.31	0.83	0.75	17.26	14.00		
NO_x	74.7	74.7	281.4	253.8	610.6	157.0		
CO_2	57000	57000	167594	150764	173625	140777		
CO	18.9	18.9	55.3	49.9	105.3	42.7		
CH_4	1.6	1.6	0.4	0.4	19.2	16.0		
PM	1.6	1.6	4.2	3.8	23.3	18.9		
Coal								
SO_x	592.0	592.0	2309.4	1377.3	X	X		
NO_x	301.1	301.1	888.3	573.5	X	X		
CO_2	130000	130000	317098	307282	X	X		
CO	100.0	100.0	36.4	35.2	X	X		
CH_4	2.6	2.6	1.7	1.6	X	X		
PM	14.60	14.60	35.54	34.44	X	X		
Oil								
SO_x	433.4	326.2	1116.7	786.7	1492.1	861.5	100.4	100.4
NO_x	193.5	164.5	624.2	396.6	906.1	160.3	134.0	45.0
CO_2	88000	88000	220158	206043	313872	225629	72917	72917
CO	18.3	18.3	46.0	43.0	130.1	38.7	223.0	45.0
CH_4	3.55	3.55	2.71	2.53	23.23	16.70	3.2	3.2
PM	16.26	16.26	41.88	39.20	59.71	28.59	44.6	44.6

Table C.20 United Kingdom - Emission Factors for Annex 21 (continued)

Utility Power Plants			
Fuel/Prime Mover	1995 Heat Rates Btu/kWh)	1995 Generating Mix (Est. %)	2010 Generating Mix (Est. %)
Gas-Boilers	10720	0%	0%
Gas-Turbines	13060	18.5%	61.4%
Coal-Boilers	10380	47.5%	3.6%
Oil-Boilers	10340	4.4%	0.3%
Oil-Turbines	14740	0%	0%
Nuclear	11000	27.0%	24.0%
Hydro/Renewables	10300	2.6%	10.7%
Weighted Average Heat Rate		11,039	12,166

Emission Factors for Electricity (g/GJ - LHV)		
	1995	2010
SO_x	435	23
NO_x	202	40
CO_2	58565	38071
CO	12	8
CH_4	1.2	3.1
PM	8.2	4.3

Table C.21 United Kingdom - IHPs Evaluated by Process for Annex 21

Process Name	IHP Type					
	Closed-Cycle					
	Electric	Diesel	MVR	TVR	Type 2 Absorption (Waste-Heat Driven)	Type 1 Absorption (Prime-Heat Driven)
Paper and Board		O				O
Chlorine/Caustic			O	O		
Beet Sugar			O	O		
Malt Whiskey Distillery				O		
Liquor/Spirits Distillery			O	O		
Brewery			O	O		

Appendix D
Acronyms, Units and Definitions

Acronyms	**Definitions**
ΔH	Enthalpy difference
ΔT	Temperature difference
ΔT_{min}	Minimum temperature difference
η_c	Carnot efficiency
a	Annuity factor
AHP	Absorption heat pump, typically prime-heat driven or AHP, type I
CC	Composite curve
CCC	Closed-cycle compression heat pump
CFC	Chlorofluorocarbon (fully halogenated)
CH_4	Methane
CO	Carbon monoxide
CO_2	Carbon dioxide
COP	Coefficient of performance
COP_c	Coefficient of performance at Carnot efficiency
DCC	Diesel-driven closed-cycle compression heat pump
DSM	Demand-side management
E	Engine
ECC	Electric motor-driven closed-cycle compression heat pump
E-F	Electricity-to-fuel price ratio
GCC	Grand composite curve
global ΔT_{min}	Global minimum temperature difference at the process pinch (also ΔT_{Global})
HCFC	Hydrochlorofluorocarbon (partly halogenated)
HEN	Heat exchanger network
HFC	Hydrofluorocarbon (chlorine free)
HMVR	Mechanical hydrocarbon vapor recompression
HP	Heat pump
HPC	(IEA) Heat Pump Centre
HT	Heat transformer (waste-heat driven AHP or AHP, type II)
IAHP	Implementing Agreement on Heat Pumping Technologies
IEA	International Energy Agency
IHP	Industrial heat pump
LHV	Lower heating value
$LiBr/H_2O$	Lithium bromide/water (AHP working fluid pair)
M	Motor
MVR	Mechanical vapor recompression
N_2O	Nitrous oxide
NH_3/H_2	Ammonia/hydrogen (AHP working fluid pair)
NO_x	Nitrogen oxides
PBP	Payback period
PM	Particulate matter
q value	Ratio of heat source and heat sink energy levels, $q = COP/(COP-1)$
Q	Heat input or output levels (of an industrial heat pump)

Q_A	Heat output at the AHP absorber
Q_C	Heat output from the CCC or AHP condenser or the cold utility level
$Q_{CU,min}$	Minimum cold utility of a process (in CC and GCC)
Q_E	Heat input to the CCC or AHP evaporator
Q_G	Heat input at the AHP desorber
Q_H	Hot utility level
$Q_{HU,min}$	Minimum hot utility of a process (in CC and GCC)
SO_x	Sulfur oxides
T_C	Condenser temperature (valid for CCC)
T_E	Evaporator temperature (valid for CCC)
T_H	High-temperature level (valid for AHP)
T_L	Low-temperature level (valid for AHP)
T_M	Medium-temperature level (valid for AHP)
TMP	Thermomechanical pulp
TVR	Thermal vapor recompression
W	Power or work (in reference to energy input to the IHP)
WHRB	Waste heat recovery boiler

Units	**Definitions**
°C	Degree centigrade
EJ	Exajoule (10^{18} Joule)
GJ	Gigajoule (10^{9} Joule)
K	Degree Kelvin
kJ	kilojoule (10^{3} Joule)
kW	Kilowatt
m^3	Cubic meter
m^3/h	Cubic meter per hour (volumetric flow rate)
MJ	Megajoule (10^{6} Joule)
MMBtu	Million British Thermal Units
MMTCE	Million metric tons carbon equivalent
MW	Megawatt
PJ	Petajoule (10^{15} Joule)
rpm	Revolutions per minute
TJ	Terajoule (10^{12} Joule)
tonne	Metric ton

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