INNOVATION PROCESS IN THE ENERGY TRANSFORMATION SECTOR: A CASE STUDY FOR DIESEL DRIVEN HEAT PUMP DEVELOPMENT

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PREFACE

Peter Moeller's case study is the result of cooperation between the Innovation Task Group at IIASA and the Institute of Prognosis and Applied Research in Hannover, Federal Republic of Germany.

Dr. Moeller worked at IIASA for one month and during this time the conceptual framework and the first draft of his study were completed. In developing the relative efficiency approach he comes to an interesting formula for market price calculation, which can also be useful in other technologies.

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Innovation Task Group

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1. Technical Options for Heat Pump Systems

Heat pump systems have four distinguishable technical levels. The technical options for these four levels are shown in Figure 1.

External energy source	air	water	waste energy
Heat pump process	compression	absorption	
Drive	electro motor	combustion motor	heat
Operational process	monovalent	bivalent	

Figure 1. Technical Options for Heat Pump Systems.

In the following chapter, the technical options for the "heat pump process level" [1] and the "drive level" [2] will be analysed.

1.1. The Heat Pump Process

The definition of a "heat pump" applies only to the refrigeration part of a total heat pump system. The "heat pump" consists of

-- the heat exchanger on the cold side; and

-- the temperature raising component on the warm side.

The general pattern of energy flow in a heat pump is shown in

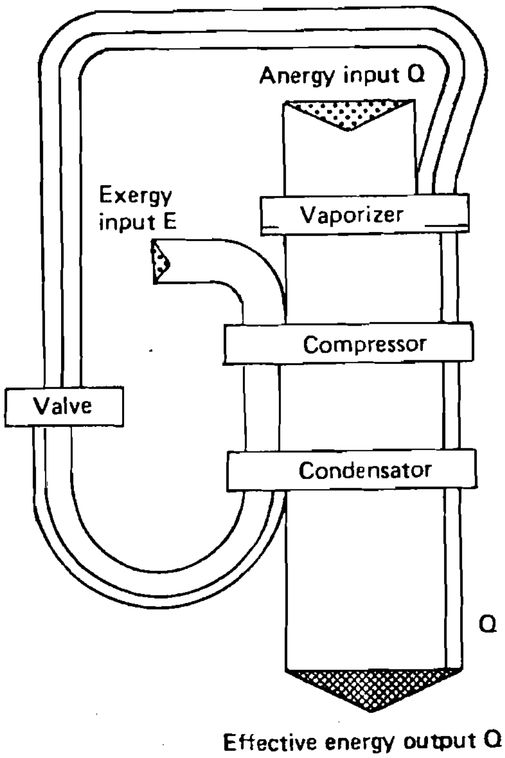


Figure 2. General Flow of Energy of a "Heat Pump".

In order to raise the temperature of the heat-transporting medium, several types of external energy inputs are possible. (See Figure 3.)

external energy input

- mechanical energy (motor)
  - electro motor
  - combustion engine
- heat on a higher temperature level (absorber)

Figure 3. Possibilities for External Energy Input into the Temperature Elevation Component of a Heat Pump.

Heat pumps which have mechanical external energy input are called "compression heat pumps", those with energy input in the form of heat are called "absorption heat pumps". Mechanical energy can be transmitted to the heat pump system by either electric or combustion engines.

1.1.1 Flow of Energy in a Compression Heat Pump

Figure 4 shows the anergy and exergy flow of a compression heat pump. The gross power factor (F) of a heat pump system is equal to the relation of input energy transmitted to the driving unit (E) and the used energy (Q).

$$F = \frac{Q}{E}$$

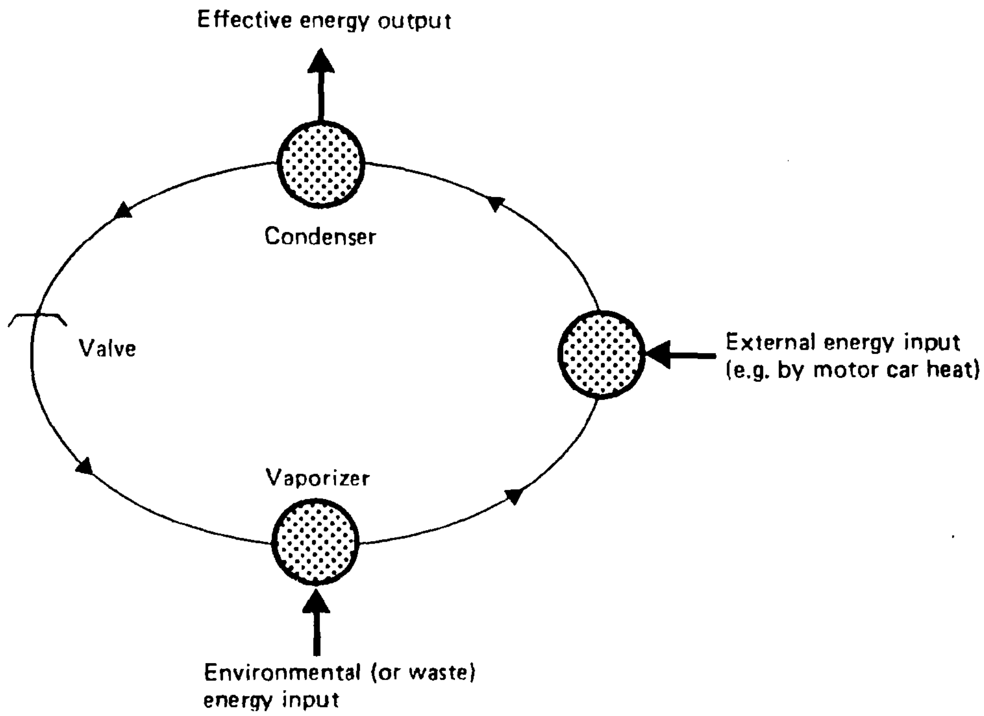


Figure 4. Anergy-Exergy Flow in a Compression Heat Pump System with a Gross Power-Factor of 3.7.

The energy-transporting medium of the compression heat pump is a liquid circulating in the tubes of a closed system (as shown in Figure 2). The pressure of this liquid in the vaporizer is low enough to reduce its evaporation temperature to a level lower than its surroundings. Induced by this temperature difference, heat flows from the surroundings to vaporize the medium. The heat-transporting gas is then drawn in by the compressor and brought to the level of pressure where the liquefying temperature is higher than the object to be heated. In a condensator, this temperature difference transfers heat from the circulating medium to the heated object. Finally, the liquid flows back via a throttel-valve to the vaporizer, where the circuit starts again.

1.1.2. Flow of Energy in an Absorption Heat Pump

The temperature elevation in an absorption heat pump is induced not by the input of mechanical energy, but by the input of heat. The compressor is replaced by a second liquid circuit, in which a pump--the only mechanical part of the system--drives a solution. Figure 5 gives an overview of the absorption heat pump system.

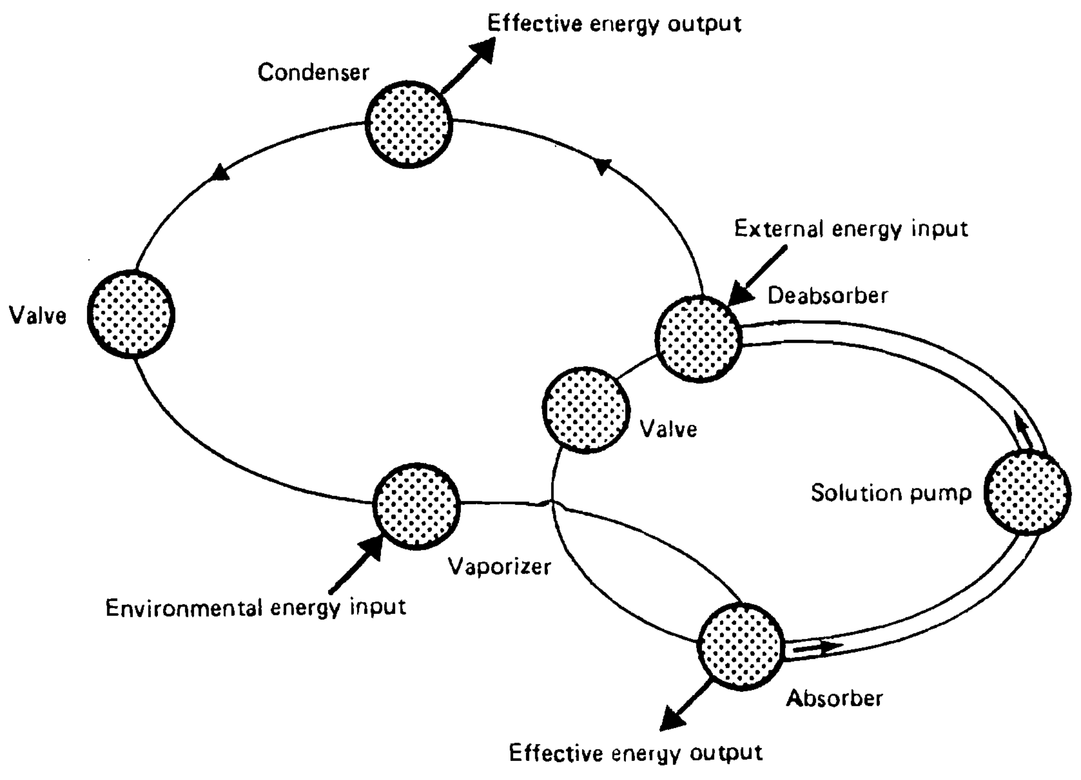


Figure 5. Overview of the Absorption Heat Pump System.

The left circuit of the system as shown in the Figure is identical to that in a compression heat pump. The temperature is raised in the deabsorber, where the dissolved gas from the main circuit is expelled by the input of heat. The gas thus released now follows the same route as in the compression heat pump. As a result of the difference in temperature in the vaporizer, external energy is generated and raises the temperature of the gas to that of the environment. The gas is now dissolved in the solution of the second system. Effective energy at a lower temperature level than in the condenser can be taken from the absorber.

In order to obtain the gross power factor of an absorption heat pump system, it is necessary to control five different energy flows in the system:

1. input of heat to the deabsorber;
2. input of mechanical energy to the solution pump;
3. environmental energy flow to the vaporizer;
4. output of effective heat from the condenser;
5. output of effective heat on a lower temperature level from the absorber.

The gross power factor of larger absorber systems (in breweries, slaughterhouses, etc.) is between 1.5 and 1.7. Absorption heat pumps for the energy supply of smaller houses have not yet been developed. The main advantage of the absorption heat pump over the compression heat pump is its higher operational safety, due to the use of only one mechanical part (the solution pump) in the whole system.

1.2. Two Types of Drives for Compression Heat Pumps

1.2.1. Electromotric Drive

The usual driver of small compression heat pumps is the electro motor. The advantages of this driving system over combustion engines are:

-- simple construction with only rotating parts;
-- high safety in operation;
-- relatively infrequent need for service;

- -- low production costs;
- -- no emittance, no air pollution, and relatively low noise level.

The disadvantage of the electo motoric drive is its relativey low energetic efficiency in relation to the input of primary energy.

Figure 6 gives an overall view of the flow of energy from primary energy via an electric power plant and a compression heat pump with electro motor to the effective energy for room heating, etc. The example shows that, in this system, effective energy amounts to 78% of the primary energy input. A compression heat pump with electro motoric drive has higher energetic efficiency than a normal oil or gas heasted boiler, which generally reaches an efficiency of only 55-75%.

1.2.1. Combustion Engine Driven Heat Pump

Until now combustion engine driven heat pumps have generally been used in larger constructions for the heating of public swimming pools or department stores. [3] Most of these use gas as a source of primary energy. Smaller units for use in single-family-houses are still being developed.

Combustion engines have certain specific disadvantages when compared with electro motors:

- -- the whole construction is more complicated: the engine needs more service and maintenance;
- -- the investment volume per unit of produced mechanical energy is higher;
- -- the noise during operation is higher and flue gas (CO_2, CO, NO_x, SO_2) is emitted;
- -- the energetic rate of efficiency is lower (ratio of input of primary energy to output of mechanical energy).

The main advantage of the combustion engine driven heat pump that it allows the use of fuel oil or natural gas, both of which are secondary energy sources having relatively small losses during the transformation process from primary to secondary energy. Figure 7 shows the total energy flow from secondary to effective energy in a gas supplied heat pump system with a combustion engine.

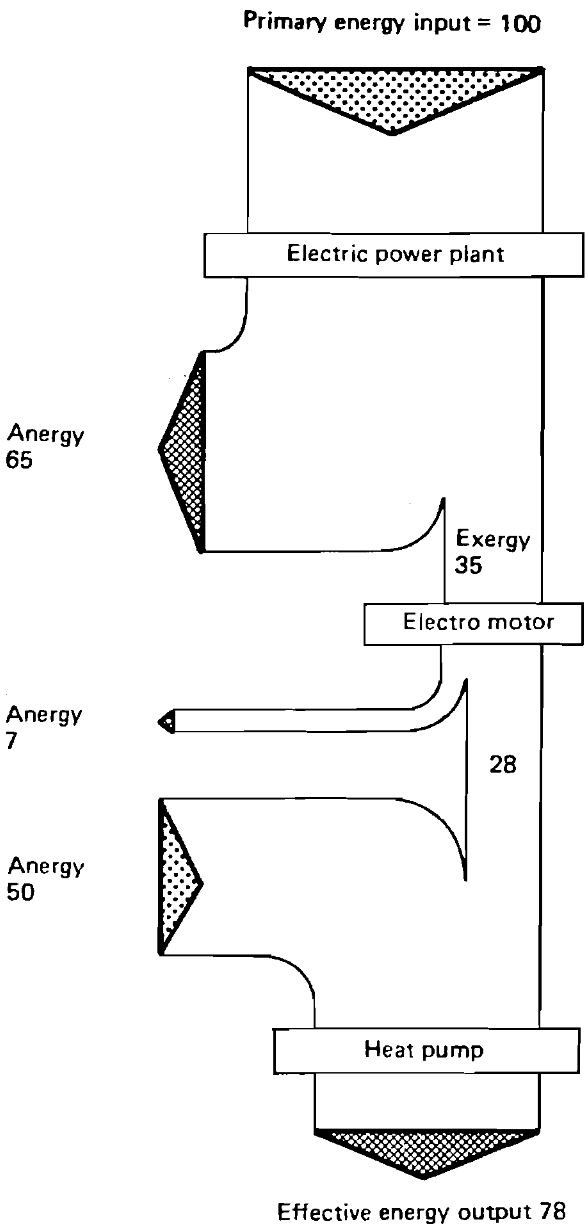


Figure 6. Energetic efficiency diagram of a comparison heat pump.

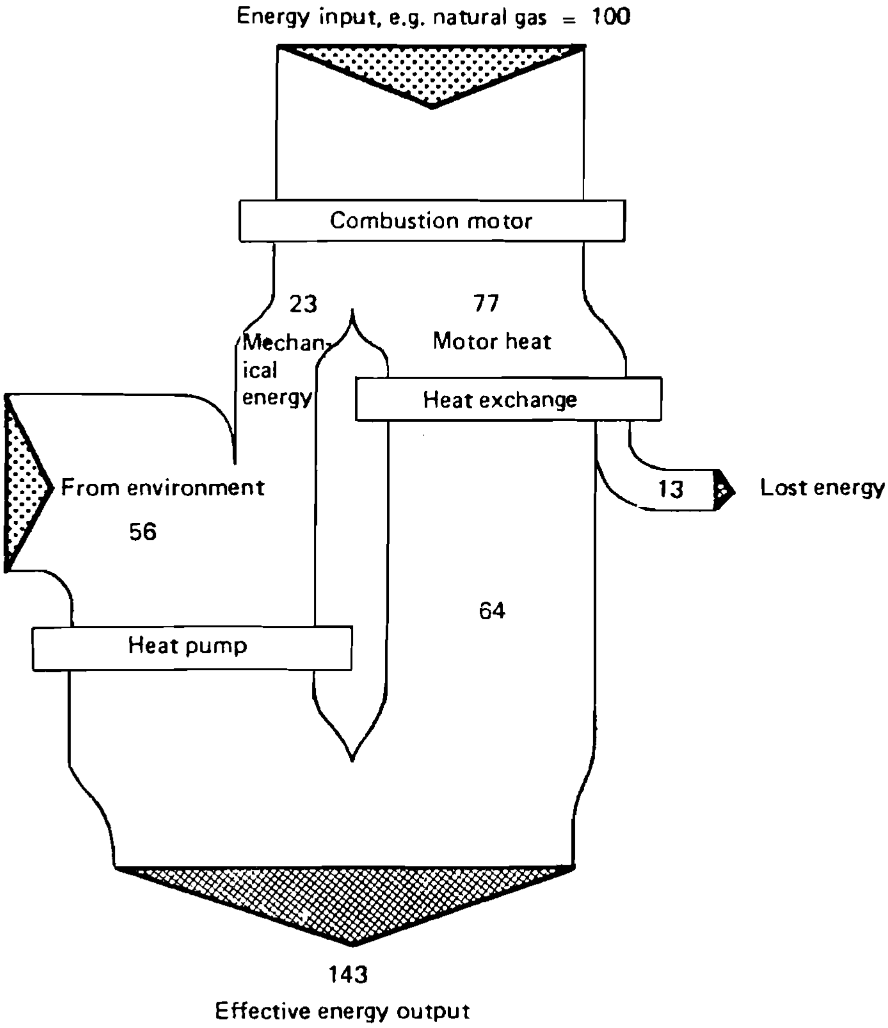


Figure 7. Energy Flow from Secondary to Effective Energy in a Gas Supplied Heat Pump System with Combustion Engine.

The energetic efficiency in relation to the input of primary energy is 80% higher than with the electro motoric drive. Thus the disadvantages mentioned seem to be overshadowed and the linkage of the combustion engine with a heat pump should result in a reasonable system. [4]

In Figure 8 the three circuits of a combustion motor driven heat pump system for room heating are shown:

-- the refrigerator circuit of the heat pump;
-- the cooling water circuit of the combustion motor;
-- the hot water circuit for the room heating.

As seen in Figure 7, 23% of the secondary energy input is converted into mechanical energy which goes to the compressor. 64% of the input energy goes to the room heating circuit via the cooling water and exhaust heat exchangers. Only 13% of the energy input is lost, largely in the form of exhausted flue gas.

Chapter II describes the innovation and development process of a diesel driven heat pump system which use fuel oil as its primary energy input.

2. INNOVATION AND DEVELOPMENT PROCESS OF A DIESEL DRIVEN COMPRESSION HEAT PUMP IN AN AUTOMOBILE CORPORATION

The whole innovation and development phase of a complete combustion motor-driven heat pump system is a long and complex process. It involves several departments and areas of the corporation and has at least three independent time phases. In each phase the total process is reversible. This means that the process can be halted if the decision-making management should be convinced that it is ineffective to proceed with the program.

According to the general innovation cycle theory [5] four different stages may be distinguished. These four steps are shown in Figure 9.

Small electro motor driven compression heat pumps and large combustion motor driven heat pumps have already reached the second stage (II) in the innovation cycle, where their dynamic efficiency is higher than the general efficiency of all presently used heating

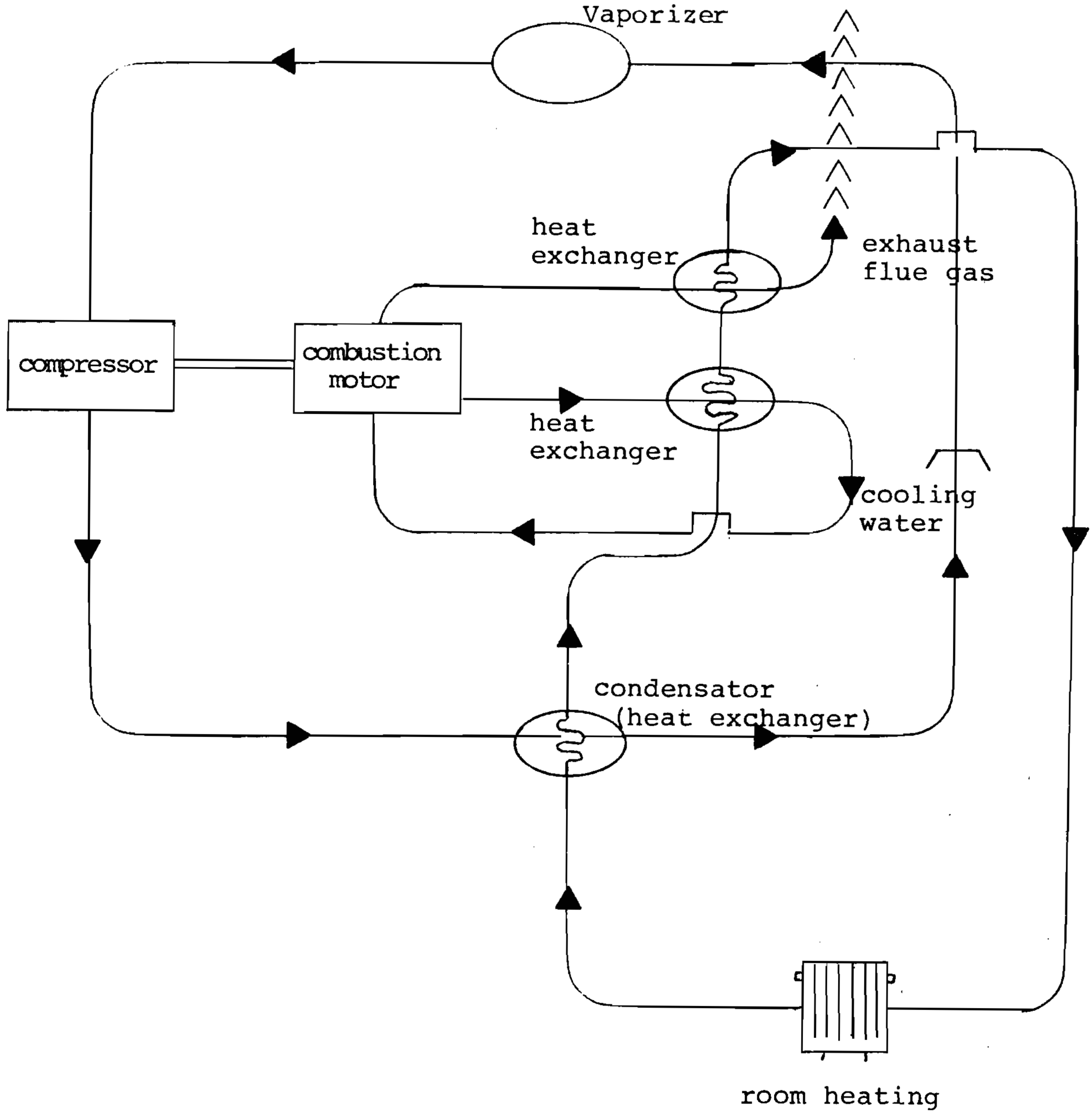


Figure 8. Three Circuits of the Total Combustion Motor Driven Heat Pump System for Room Heating.

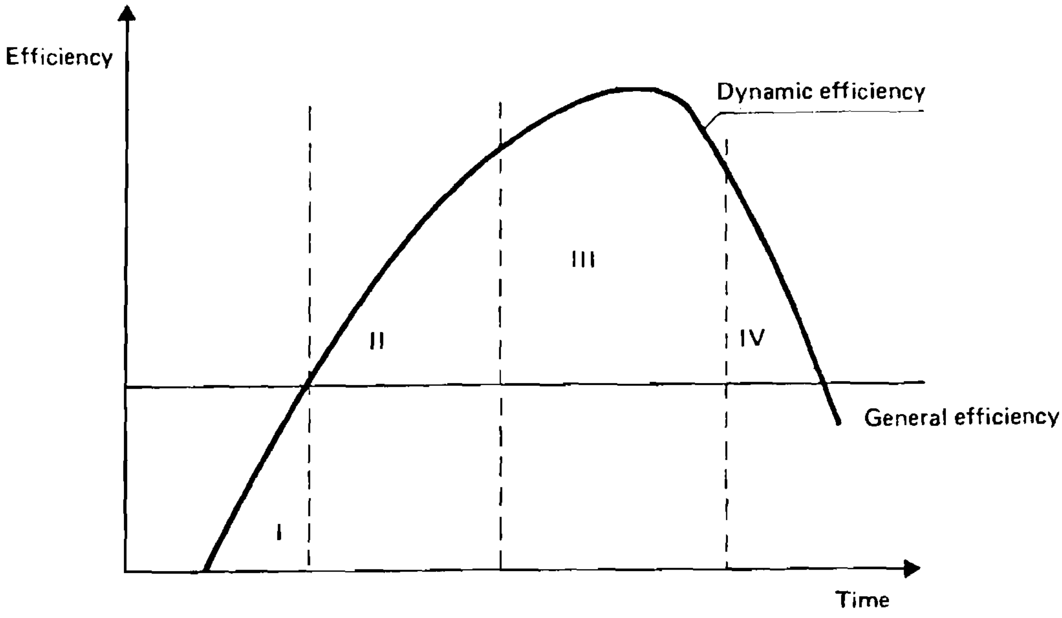


Figure 9. General Innovation Cycle

systems [6]. Smaller combustion motor driven heat pumps are still in the first stage (I). The construction of this type of heat pump is possible by simply coupling existing parts from other systems (i.e., an automobile motor and a refrigerating machine), but the operational safety of such systems is extremely low; and the service and maintenance costs which incur through this safety are extremely high, so that the 'dynamic' efficiency of this type of heat pump is still lower than the general efficiency of generally used heating systems.

The innovation process in a corporation, beginning with the original conception and continuing to the final product is described in the following chapters.

2.1. Invention Phase

In the years following 1973, rising energy prices induced all automobile companies to develop new engines having lower average gasoline consumption. In 1974 the management of VW in Wolfsburg, FRG ordered the company-owned R&D Center to design a small diesel engine for a mid-sized car. The motor was constructed with a 1600 cm^3 spark ignition engine. Production of the new engine began in 1977. During the development of the diesel motor a smaller group of people at the R&D center came up with the idea of combining the new engine with a heat pump.

At this time, several other experiments using combustion motors as combined heat and power generators were being carried out. Fiat in Italy had started the "TOTEM" [7] project in which a normal spark ignition car engine fueled by biogas or natural gas drives an electric generator and transfers heat via a heat exchanger to a domestic heating system. In Heidenheim, FRG [8] the local energy supply company began an experiment in which apartment houses and a public indoor swimming pool were heated with stationary truck engines fueled with natural gas. These engines are also coupled with a generator which coproduces electricity and heat during peak load times.

All of these experiments are based on the coproduction of power and heat, a technique also used in electric power plants. By making use of the mechanical energy of the combustion, the energetic efficiency related to the input of secondary energy was increased to more than 85% in comparison with only 60% for conventionally heated boilers. The combination of gas fueled combustion engines with heat pumps was also known in 1977 [9] but all experimental constructions were for larger units.

The idea of coupling a diesel motor with a heat pump was very new. This combination made it possible to use fuel-oil as secondary energy. The relatively low power level of the diesel engine also made it possible to supply single or double family houses and other small domestic dwelling objects with heat.

Only half of the work which is carried out in the VW R&D centers is done so upon the specific instructions of the management. The remainder is "free research". While much of the results of this work will never be used, such arbitrary research is necessary to develop new products for possible future use by the company.

The diesel driven compression heat pump was the result of this "free research". Figure 10 shows an overview of the decision structure during the "invention phase" of the innovation.

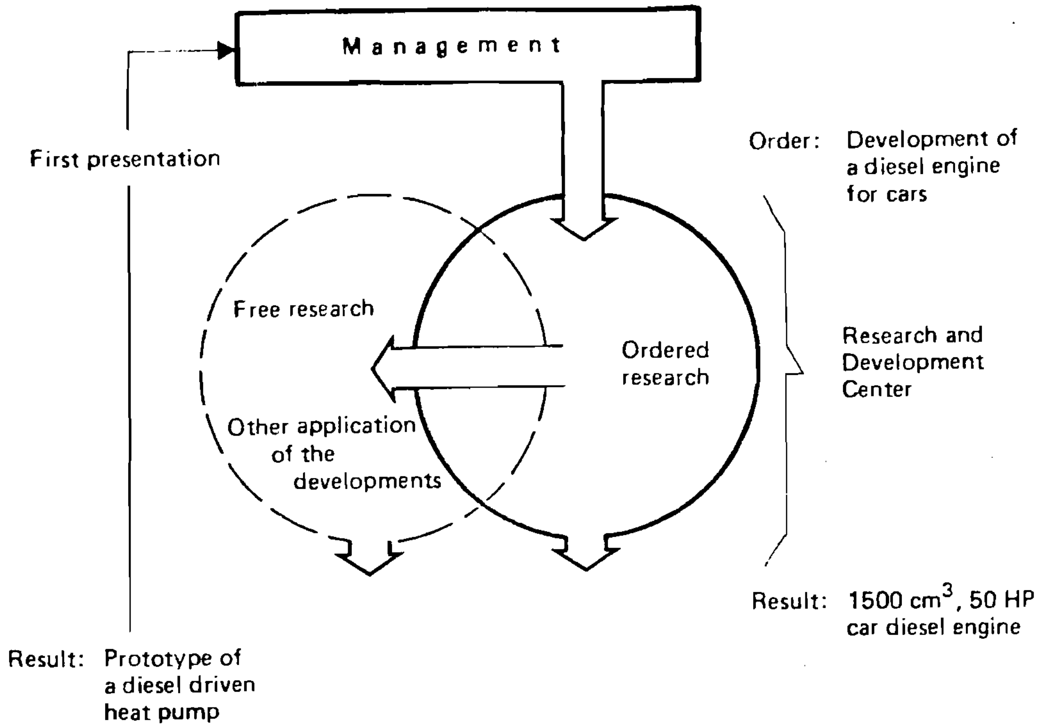


Figure 10. Interaction between Management and R&D Center.

The "free research" group in the R&D center built a proto-type combined from the self developed car diesel engine and a compressor heat pump, normally driven by an electro motor. This proto-type was presented to the management with the suggestion to start a development phase for this innovation with a possible mass production as the final goal.

2.2. Decision Phase: Further Development or Not?

2.2.1. First Presentation of the System

The result of the first presentation of the proto-type could have been:

- -- an immediate stop of further development;
- -- an order to the other departments of the company to consider, in cooperation with the R&D center, possible risks or benefits of the production system.

The decision of the management was to carry on with the technical development through the R&D center and to start a first analysis to investigate the difficulties and possible profits of a production. The following departments are involved:

- R&D center
- financial department
- marketing department
- production planning department.

2.2.2. Information Flow Between the Departments after First Presentation of the Proto-Type

To enable the other departments to start a first analysis of the possible benefits or risks of the production of heat pump systems, R&D had to provide the financial department with the following information:

- possible energy saving rate of the diesel heat pump system;
- service and maintenance costs during the time of operation;
- average lifetime of the whole system.

The financial department calculated a customers price based on a reasonable amortisation period in terms of cost advantages in relation to existing heating systems. This price is the estimated market price.

Furthermore R&D has to support the production planning department with data for:

- material and manpower volume of the self-manufactured parts of the system;
- volume of necessary prefabricated parts.

The production planning department calculated a provisional price from the data, first without information on the possible rate of production. This preliminary price is fed back to the financial department and compared there with the possible market price.

The financial department then gives the possible market price to the marketing department. This department estimates:

-- the size of the market for diesel driven heat pumps (domestic and foreign);
-- the speed of market penetration according to the price of the system and the energy cost advantage.

With the results of this analysis, the marketing department calculates the possible number of systems which could be sold annually. This figure is given to the production planning department to correct the necessary cost price by taking the production into consideration. This newly calculated price enables the financial department to make a first analysis of the possible loss or profit.

Figure 11 gives an overview of the whole information flow during the decision phase, including whether the development of the system should be carried on or not. In case costs of production and marketing are higher than the possible market price, further development could be stopped or postponed to a later date.

2.3. Development Phase

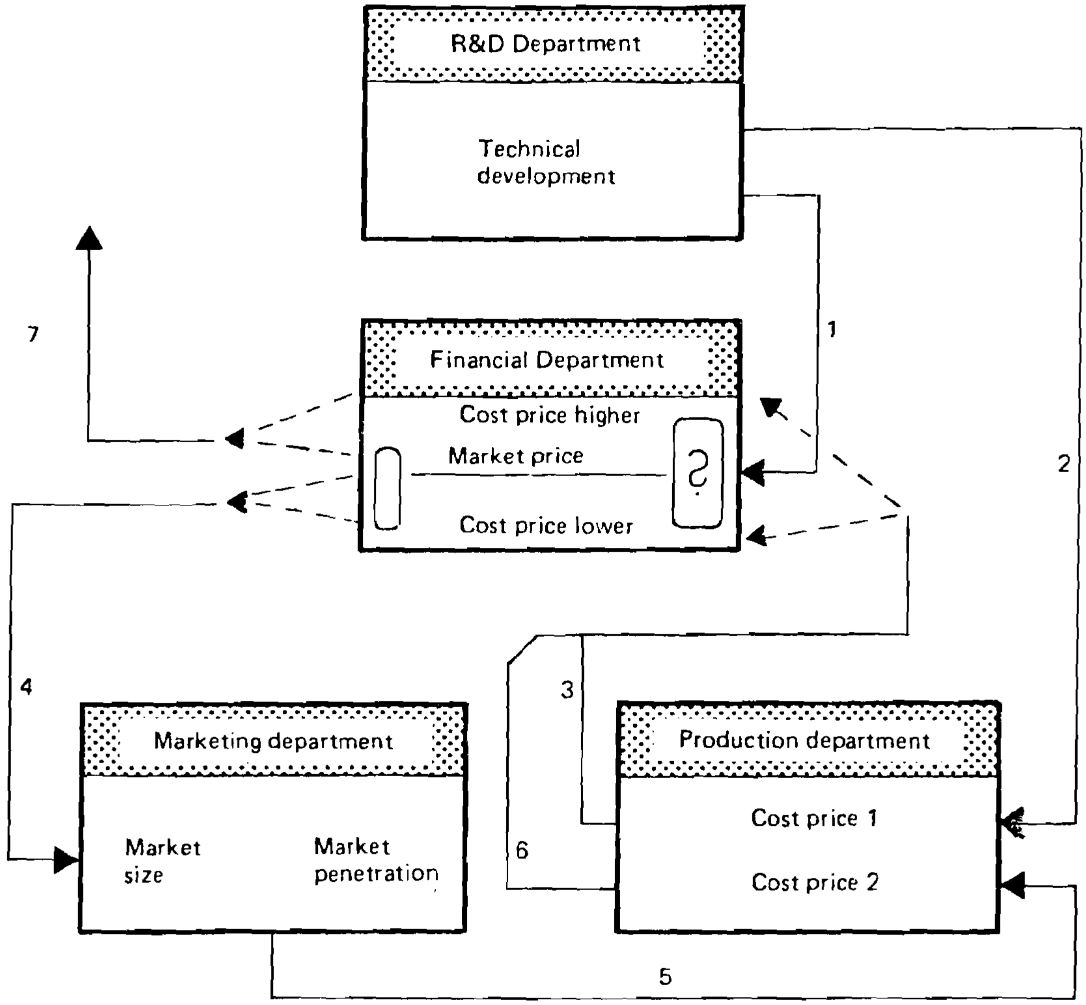
In case the first overlook shows a possible profit for the production of the system, all the departments involved begin a second analysis which is much more specific and precise than the first one. The following parts describe the different stages of this analysis during the development phase of the project.

2.3.1. Marketing Department

Market size estimation

In order to get more information about the size of the market for diesel driven heat pumps, the marketing department starts investigations on:

-- the structure of housing in the FRG and the other countries of the European Community;
-- the structure of domestic heating, especially the share of oil fueled heatings;
-- the age structure of the oil fueled domestic heating systems.



1 Possible energy cost reduction rate
2 Technical data of the system
3 Calculated first cost price
4 Estimated market price
5 Possible production rate
6 Calculated second cost price
7 stop or drive on further development

Figure 11. Overview of the Information Flow

Market diffusion

Together with the market price, estimated by the financial department (see 2.3.2.) the marketing department calculates a possible rate of replacement of the old systems. The higher the advantage in efficiency of the new system is for the user, the quicker would be the market penetration.

Environmental impacts

Furthermore, an analysis of the environmental law involved is done in order to avoid later difficulties. If necessary, some hints can be given to R&D to improve parts of the system in order to minimize the emittence of noise and flue gas.

Marketing strategies

The marketing department now also has to analyse in which way the final product will be sold. Several ways are possible and these are listed below:

-- the company sells only the diesel engine as a pre-fabricated part to all producers of heat pumps;
-- the company sells the total heat pump system (diesel motor and coupled heat pump) using their own automobile oriented trade mark;
-- the company is cooperating with a well known producer of heat pumps or boilers to sell the whole system (motor and heat pump) under two trade marks;
-- the company is taking over a well known producer of heat pumps or boilers and sells the system under the trade mark of this enterprise.

Service and maintenance system

The last two solutions seem to be the best way, especially to solve the problem of service personnel, which is a big problem in marketing the diesel driven heat pump system. Already in this stage of the development a decision must be taken whether service personnel should come from

-- skilled automobile servicemen, or
-- skilled plumbing servicemen.

The problem is that both types of servicemen are only familiar with one part of the whole system. While the diesel motor is known by automobile servicemen, the heat pump itself is more the traditional area of plumbing servicemen. As the whole system is for room heating, it should be better if the servicemen belongs to the plumbing area. In difference to the automobile service system, plumbing men traditionally come to the homes, are more familiar with the peripheric parts of the system (tubes, hot water tank, etc.) and also with the possibility to work during weekends, when something of the system turns out of order. As a whole, service intervals of the heat pump system are much shorter than for a traditional heating system and so the service costs are much higher. In order to avoid cost disadvantages which could hinder the success of the total system,the marketing department has to involve the R&D department to reduce the service intervals and to develop a service system which could help lower the necessary service costs.

2.3.2. Financial Department

Estimated market price

The most important task for the financial department is to calculate the possible market price of the heat pump system from the technical data and the possible energy cost saving rate. The energetic rate of efficiency of a diesel motor driven heat pump is dependent on the environmental temperature level and the temperature level of the effective energy output. The average energetic efficiency coefficient is 1.43 (see Figure 7) compared with only 0.75 (see Figure 6) of a traditional heating system. This means that the same energy output is possible with only 52.4% of the secondary energy input.

The energy cost saving rate (E) is thus

$$E = \frac{F * P}{2.102} \qquad (1)$$

where F is the quantity of fuel burned in a normal oil fueled heating system and P the actual price of one unit of fuel. This price will rise with an assumed percentage (i_1) over the amortisation time (t) of the heat pump system. The energy saving rate (E) will thus grow with the same ratio. The sum of the energy saving rates over the period t is thus

$$\sum_{1}^{t} E = E * \frac{\frac{(i_1 + 1)^t - 1}{100}}{\frac{i_1 + 1}{100} - 1} \quad . \tag{2}$$

The capital costs came from the interest rate and the linear depreciation rate. Depreciation rate (d) is

$$d = \frac{100}{t_1} \quad , \tag{3}$$

where t_1 is the average lifetime of the whole system. The annual depreciation (D) is thus

$$D = M \times \frac{d}{100} \quad , \tag{4}$$

where M is the unknown market price. The sum of the annual depreciation over an amortisation period is

$$\sum_{1}^{t} D = D \times t \quad . \tag{5}$$

The interest (J) is calculated yearly with the interest rate (i_2) on the rest of the invested market price, which is reduced by the depreciation

$$J = (M - D) \times \frac{i_2}{100} \quad . \tag{6}$$

The whole capital costs (C) in the amortisation period (t) are

$$\sum_0^t C = \sum_0^t \left[M \times \frac{d}{100} + \left(M - t \times M \times \frac{d}{100}\right) \frac{i_2}{100}\right] \qquad (7)$$

or

$$\sum_0^t C = (t + 1)\left[M \times \frac{d}{100} + M \times \frac{i_2}{100}(1 - D)\right] \quad . \qquad (8)$$

The capital cost difference (C_d) of the two systems is

$$C_d = C_h - C_b \quad , \qquad (9)$$

where C_h are the capital-costs of the diesel heat pump and C_b those of the normal burner.

The sum of the service costs difference (S_d), which is growing with the inflation rate (i_3) is over the amortisation period (t)

$$\sum_0^t S_d = S_d * \frac{\left(\frac{i_3 + 1}{100}\right)^t - 1}{\frac{i_3 + 1}{100} - 1} \quad . \qquad (10)$$

The market price (M) is calculated from the sums of the energy saving rate (E) minus capital cost difference (C_d) and service cost difference (S_d) plus the investment volume of the normal oil heating system (Z)

$$M = \sum_0^t E - \sum_0^t C_d - \sum_0^t S_d + Z \quad . \qquad (11)$$

<u>Financial volume bound by the production</u>

The financial department then has to calculate the investment volume of the production line. Investments in machinery and buildings must be taken into account. The possible rate of capital backflow dependent on the assumed value added has to be considered. Furthermore, the financial volume bound by the stock for raw material and prefabrics must be calculated. Thus the total financial volume of the production would be:

- production line investment
- stock of raw materials
- stock of prefabrics
- stock of final products
- retail system dept. volume.

Calculation of a cost price

The cost price has to consider all material and manpower costs of the self-fabricated parts of the system, the costs of the prefabrics and also shares of the general costs of the whole company. At least reasonable rebates for the selling organization must be considered. The cost price so calculated has to be compared with the market price.

2.3.3. R&D Department

Improvement of technical details

During the development phase, R&D has to improve the technical details of the system in order to fulfil the following standards:

- average lifetime of the diesel motor--20,000h; (8 yrs.)
- compact construction of the coupled components (motor and heat pump) in order to allow the working of the system in single-family-houses;
- noise emittence not higher than traditional heating systems;
- flue gas emittence comparable with traditional heating systems;
- service intervals at least two, better one per year;
- lay out of the load factor of the system to enable a reliable performance also under difficult climatic conditions;

-- development of electronical peripheric instruments to allow an automatic control of all functions.

Zero-initial series

At the same time, R&D has to build a zero-initial series of heat pumps to test the technical behavior under different conditions and to optimize the aggregates of the total system.

Long-term test program

A greater part of the so improved system must be given then to normal customers in order to get results of the systems behavior under normal working conditions. These customers should be situated in regions with different climate conditions.

2.4. Production Phase of the System

Presently, the innovation process of the system has reached the development phase (see 2.3.). The beginning of the production and market diffusion phase is planned for the year 1983, when the end of the long-term testing program is reached. The whole time period from the invention to the production phase thus amounts to 7 years.

Preparatory activities for the production phase are already started. This means that

-- the selection of the part delivering firms, and
-- the dimension of the production line (space under cover, skilled manpower, machinery and transportation facilities),

is already planned ahead.

3. Efficiency of the Diesel Driven Heat Pump System

3.1. Energetic efficiency

To compare the energetic efficiency of traditional heating systems and the diesel driven heat pump the exergy-anergy fluxes, shown in Figure 4, must be seen from the output side. For a given demand of effective energy for room heating the necessary input of secondary energy must be calculated.

Traditional oil fueled heating systems have an average rate of energetic efficiency of 0.75[1]. Thus for an average demand of i.e. 40,000 kWh/a effective energy for room heating and hot water of a single-family house, 53,333 kWh/a secondary energy input is necessary.

The efficiency factor of the diesel driven heat pump is depending on the outside temperature level. Figure 11 shows this dependency.

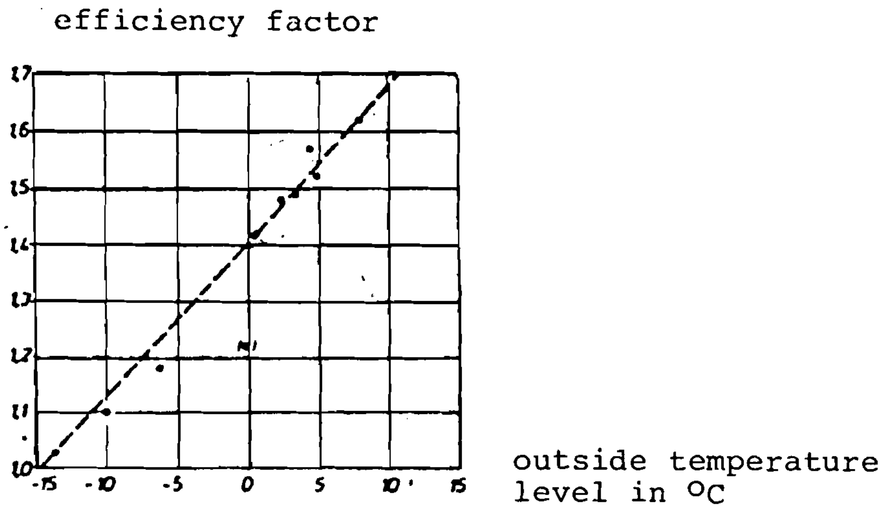


Figure 12. Efficiency Factor and Outside Temperature Level.

The used average efficiency factor of 1.43 is based on a medium outside air temperature level of + 2°C during the heating season (in West Germany normally from mid-September to the end of April).

To secure the same demand of effective energy, a diesel driven heat pump needs only a secondary energy input of 28,000 kWh/a. 18,000 kWh/a of the total demand of 40,000 kWh/a are coming from the motor heat, and 22,000 kWh/a from the heat pump, of which 14,000 kWh/a are external energy from the environment (see Figure 3).

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[1] See "BMFT-Bonn", Jahresbericht 1978 über rationelle Energieverwendung, S. 34.

Thus the secondary energy saving rate of the diesel driven heat pump in comparison with a normal oil fueled heating system is 47.5%. In this special comparison the energy saving rates related to the input of primary energy can be easily compared, because the input energy (fuel oil) is the same. The fuel oil quantities for the two systems are (1 kg fuel oil = 11.86 KWh).

oil fueled boiler	4497 kg
diesel driven heat pump	2360 kg

3.2. Monetary Efficiency

In most cases where energy is saved by new transformation technologies, the lower energy input induces a higher capital input. Furthermore the diesel driven heat pump needs higher service and maintenance costs. The monetary efficiency of the total system in relation to traditional systems thus must be calculated by comparison of

-- capital costs
-- fuel costs
-- service and maintenance costs.

Fuel cost comparison

In the present stage of the development, only the fuel cost advantage can be empiricly verified. If the price of fuel is rising more quickly than the average inflation rate, then the savings in fuel cost becomes increasingly important.

Table 1 shows how fuel prices would rise over a fifteen year period (1980-1995), if oil prices were to rise at a rate of 9.63% per year (a normal inflation rate of 4.5% plus a 5% rise in the real price of oil).

Table 1. Fuel Costs for an Oil Fueled Boiler System and a Diesel Driven Heat Pump 1980-1995.

Year	Oil Boiler US$	Diesel Heat Pump US$	Price of 1 kg Fuel Oil US$
1980	1484	779	.33
1985	2350	1233	.52
1990	3721	1953	.83
1995	5892	3093	1.31

The sum of fuel costs over the total period of 16 years is US$51,677 for the oil boiler and US$27,122 for the diesel heat pump. The difference in fuel costs amounts to US$21,753.

Capital cost comparison

In 1980 the price of a complete diesel driven heat pump system could be US$8,800[1]. On the other side, the price for a complete (together with all peripheric electrical equipment) oil fueled boiler is only US$4,200. Using a linear depreciation of 6.66% (lifetime 16 years) and an interest rate of 7.63% (3% real interest times 4.5% inflation equivalent), the 1980 capital costs for the two systems are:

oil fueled boiler	US$ 600
diesel driven heat pump	US$ 1,257.

Over the total lifetime of the two systems capital costs are:

oil fueled boiler	US$ 7,056
diesel driven heat pump	US$ 14,616.

The oil fueled boiler system thus has a capital cost advantage of US$7,560 over the diesel driven heat pump.

Service cost comparison

Service and maintenance costs of the two systems in 1980 are assumed to be:

oil fueled boiler	US$ 113 per year
diesel driven heat pump	US$ 250 per year.

After an operation period of approximately 8 years, it will be necessary to replace the diesel engine of the heat pump system. The price of this major part was US$1,400 in 1980. At a normal inflation rate of 4.5% per year the price for the engine will be US$1,991 in 1988. It is expected that the conventional boiler system will require no replacement parts during an operation period of 15 years.

Thus the cost of service and parts for the two systems over the 16 years period with the inflation rate of 4.5% would be

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[1] Price calculated assuming an annual production rate of 10^5 systems.

oil fuel boiler	US$ 2,553
diesel driven heat pump	US$ 8,671

The cost advantage of the oil fueled boiler system over the diesel driven heat pump for service and parts is US$6,118.

Overall monetary efficiency

An overall cost comparison is shown in Table 2.

Table 2. Overall Costs of the Oil Fueled Boiler System and the Diesel Heat Pump During a 16 Year Operation Period in US$.

	Oil Boiler	Diesel Heat Pump
Fuel costs	51,677	27,122
Capital costs	7,056	14,616
Service and spare part costs	2,553	8,671
	61,286	50,409

The total cost advantage of the diesel heat pump over a 15 year operation period is US$10,877, that means an average advantage of US$679 per year or 17% related to the costs of a normal oil boiler system.

If the price of fuel oil were to stabilize at the 1980 level of US$0.33 per kg of fuel oil, there would still be a final disadvantage for the diesel heat pump. The total development of all cost parts over the 16 years operation period is shown in Table 3. The heat pump system needs 11 years to pay back the investment surplus of US$4,600. With the assumed inflation rate of 4.5% in 1991 this amount represents a value of US$7,465. This inflated amount flows back to the investor after an operation time of 14 years.

Amortisation periods of more than 10 years are too long and hinder the speed of market penetration. To reduce this payback time it is necessary to

Table 3. Total Cost Comparison of an Oil Fueled Boiler and a Diesel Heat Pump.

Year	Oil Fueled Boiler		US$		Diesel Driven Heat Pump				Cost Advantage Cumulated	
	Fuel	Capital	Service	Total	Fuel	Capital	Service	Total	Burner	Pump
1980	1484	600	133	2197	779	1257	382	2418	221	
81	1627	579	118	2324	854	1212	399	2465	362	
82	1783	558	123	2459	936	1166	417	2519	432	
83	1955	537	128	2620	1026	1121	435	2582	394	
84	2143	515	134	2792	1125	1070	455	2650	252	
85	2350	494	140	2984	1233	1025	476	2734	2	
1986[1)]	2576	473	147	3196	1352	980	497	2829		365*
87	2824	452	153	3429	1482	935	520	2927		867
88	3096	431	160	3687	1625	890	543	3058		1496
89	3394	410	167	3971	1781	845	567	3193		2274
1990	3721	389	174	4284	1953	800	593	3346		3212
91[2)]	4080	367	182	4629	2141	755	619	3515		4326*
92	4473	345	190	5008	2347	710	647	3704		5630
93	4903	324	199	5426	2574	665	676	3915		7141
94[3)]	5376	302	208	5886	2821	620	707	4148		8879*
1995	5892	280	217	6389	3093	575	738	4406		10862

1) Heat pump system reaches relative profit zone after 6 years of operation.
2) Heat pump system reaches capital backflow of investment surplus after 11 years of operation.
3) Heat pump system reaches total capital backflow after 15 years of operation.

Inflation rate 4.5% p.a.
Interest rate 7.63% p.a.
Depreication 6.66% p.a. linear
Fuel oil price rising rate 9.63% p.a.

-- reduce the investment volume for the system

-- lower the annual service costs

-- enlarge the quantity of substituted fuel (not by an increasing energy efficiency coefficient but by a greater volume of delivered heat).

The general equation for the calculation of the market price (M in US $) is

$$M = \left[E x \frac{\left(\frac{i_1 + 1}{100}\right)^t - 1}{\frac{i_1 + 1}{100} - 1} \right] - \left[\left(M \times \frac{d}{100} \times t \right) - \left(Z \times \frac{d}{100} \times t \right) \right]$$

$$- \left[(M \times \frac{i_2}{100} \times t) - (Z \times \frac{i_2}{100} \times t) \right]$$

$$- \left[S \times \frac{\left(\frac{i_3 + 1}{100}\right)^t - 1}{\frac{i_3 + 1}{100} - 1} \right] + Z \quad ,$$

where i_1 = oil price rising factors 9.63% p.a.

E = energy saving rate of the heat pump in monetary terms in the first year US$705

d = depreciation rate over a lifetime of 15 years 6.66%

Z = price for a normal oil burner heating system in 1980 US$4,200

i_2 = interest rate for the capital investment 7.63% p.a.

S = difference in annual service costs of a normal oil burner and a diesel heat pump in the first year US$269

i_3 = average inflation rate over the total operation period 4.5% p.a.

If the repayment time t is set at 7 years in the equation we get after multiplying:

$$M = 6612 - (0.47M - 1958) - (0.53M - 2243) - 2157 + 4200$$

$$M = 8655 - (0.47M - 1958) - (0.53M - 2243)$$

$$2M - 4201 = 8655$$

$$M = 6438 \text{ US \$}$$

To reduce the repayment time from 11 to 7 years, the price for the heat pump system must be reduced to 6438 US$ (27%). Other possibilities to use the equation are to look for special rates of i_1 with a constant M or to minimize S. Also E might be changed if bigger quantities of oil are needed to settle a specific demand, i.e., in bigger houses.

The comparison of the efficiency of the two heating systems shows that at the end of 1980 the diesel heat pump is still in the first (I) zone of the general innovation cycle (see Figure 9). If fuel oil prices rise with a constant rate of 9.63% p.a. and all other parameters hold the value shown in Table 3, the system will reach the second (II) zone of the innovation cycle in 1983.

3.3. Environmental Efficiency

A comparison of the environmental efficiency of a normal oil fueled burner and a diesel driven heat pump must consider the following emissions:

Table 4. Emissions of Oil Burner and Diesel Heat Pump [10].

		Burner	Pump
Waste Heat	(in kWh, related to input enery)	0.25	0.13
CO_2	(g related to 1 kWh output energy)	360.00	188.00
SO_2	"	0.73	0.57
NO_x	"	0.13	5.52
CO	"	1.33	3.45
CH_x	"	0.07	0.69
Dust	"	0.04	0.11

The heat pump has lower emissions of CO_2 and SO_2 and higher emissions of NO_x, CO, CH_x and dust than the burner. A great problem could be the more than 40 times higher emission of NO_x of the heat pump, which results in the higher temperature level and the higher pressure of the diesel motor process compared with the normal burner process.

4. CONCLUSION

The analysis shows that the construction of a diesel heat-pump is justified from the point of view of energetic efficiency. The heat ouput in relations to primary energy input is unsurpassed by any other known system.

Construction and testing of the system require long lead time before production can actually start. This involves very high costs that can only be borne by large firms. Moreover large scale production of at least 105 systems annually is feasible only in large firms.

The substantial savings in fuel costs are facing high capital and service costs. Based on 1980 prices levels, the operation of a long Diesel heat pump is still just before take-off stage. As long as the difference in the initial investment between the diesel heat pump and the oil burner remains at 4600,- this investment differential can not be recovered in the next decade--even under the assumption that fuel oil prices would rise by 10% annually.

Environmental pollution through emission of CO_2 and SO_2 are smaller with the diesel heat pump than with the oil burner. However, with the diesel heat pump there is more NO_x,CO,HC and dust emission. It is not clear, which is the more dangerous pollution.

Thus, the total system has not yet reached phase II of the general innovation cycle. It could only be reached in the not too distant future if the investment of the diesel heat pump could be lowered.

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