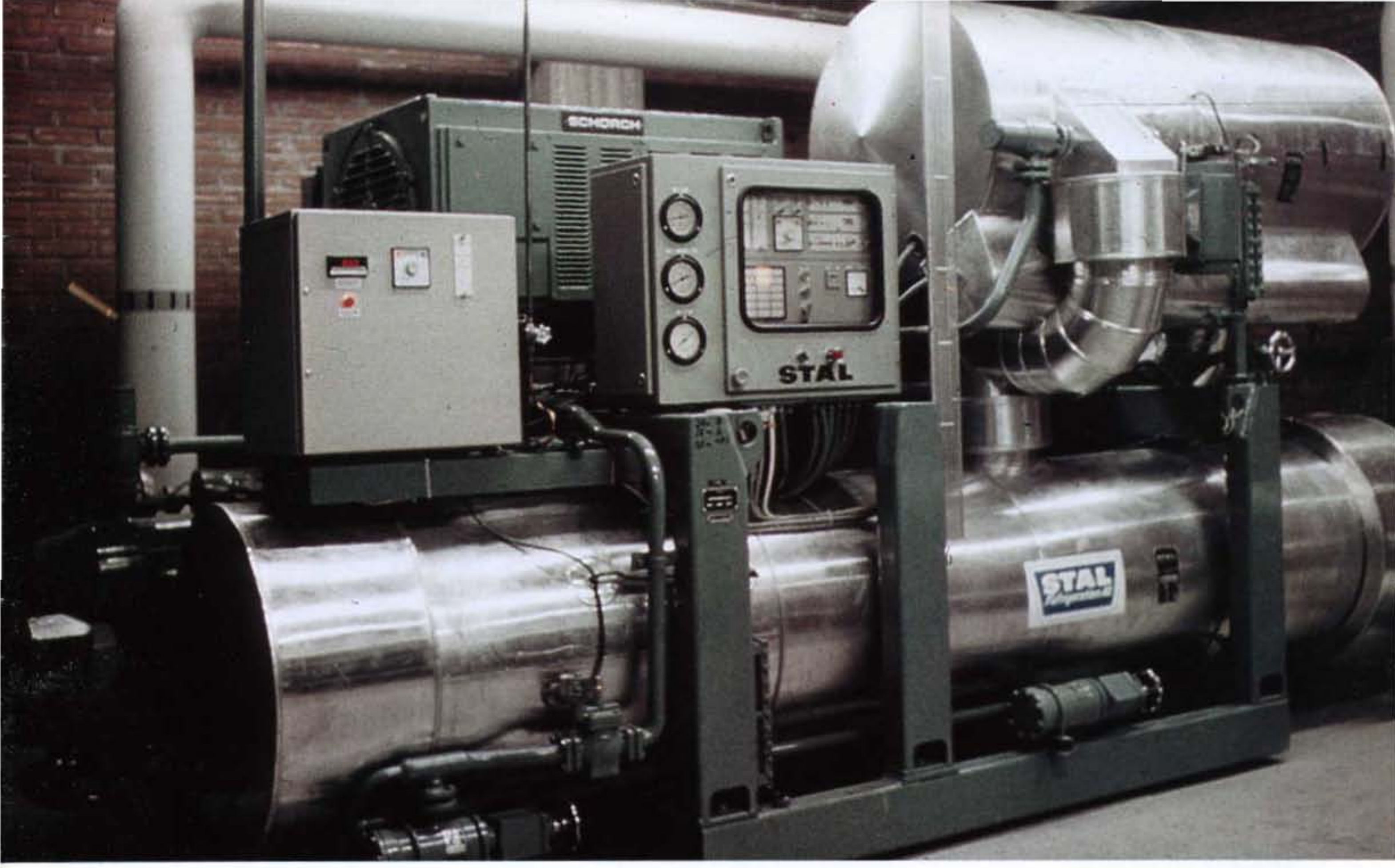

Thermoeconomic optimization of a heat pump process

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Thermoeconomics is an effective method of making technical systems efficient. The method finds the most economical solution within the limits of the technically possible. At the same time it can show how research should be directed. A simple heat pump process was chosen as an example to illustrate the method. The result shows among other things that the drive source should be made more efficient, thus saving both money and exergy.

Thermoeconomics

For several years Myron Tribus and Yehia M El-Sayed at the Center for Advanced Engineering Study, M.I.T., have been developing a method they call "Thermoeconomics", which optimizes the cost under prevailing thermodynamic conditions. The method has been applied with great success to industrial processes in the process industry. The purpose of thermoeconomics is to improve analyses of systems by introducing ways of concurrently suggesting improvements to the analysed system. One way Myron Tribus justifies the method is as follows:

"It is much more important to be able to survey the set of possible systems approximately than to examine the wrong system exactly. It is better to be approximately right than precisely wrong."

The starting point is to consider a system surrounded by both a physical and an economic environment; see Fig 1. The physical environment is described in terms of pressure, temperature and the chemical potentials of the substances involved. The economic environment is described in terms of the prices of the goods in question and the interest on loans.

The two environments are interconnected via cost relationships describing how the costs depend on physical quantities.

The method can be described briefly as follows:

1. Draw up a concise description of the process studied.

2. Define the system, the system limits, various system zones, components etc (detailed flow chart or sketch of the process).

3. Define the physical environment or alternatively the local physical environment.

4. State the sources of thermodynamic data.

5. Draw up a thermodynamic calculation algorithm with clearly identifiable

inflows and outflows. The algorithm is based, among other things, on material and energy balances for the system. It must constitute a complete thermodynamic description of the system (under the given conditions).

6. Indicate cost functions for the relevant zones or components and state the target function of the system (optimization conditions).

7. Calculate the exergy flows in the process and state the entropy sources, i e where exergy is lost in the system. Then relate these losses to the inflow and outflow of exergy.

8. Calculate the value flows (based on internal prices) in the process.

9. State any proposals, based on items 7 and 8, for improvements to the system configuration, and adjust the affected relationships (item 5).

10. Carry out an optimization of the process.

11. Carry out a sensitivity analysis.

12. Propose improvements and areas for research and development.

The initial stages of this working method are obviously self-explanatory and generally accepted. The most important improvement is the introduction of the environment and its effects on the process. The concept of exergy which can then be applied makes it possible, among other things, to calculate the technical losses in the system, item 7.

An engineer designing a system is expected to aim for the highest possible technical efficiency at minimum cost under the prevailing technical, economic and legal conditions (sometimes also with regard to ethical, ecological and social consequences). Scope for the following should be taken into account when doing this work:

- Different operating modes (different pressures, flow rates etc)
- Different configurations (addition or removal of components, rearrangements etc)
- Different purposes (by-products, sale of waste heat etc)
- Different environments (change of environmental conditions, energy price, environmental requirements etc)

Thermoeconomics is a method of analysis that makes this work a great deal easier.

The heat pump

Using a heat pump to produce heat is technically far superior to the traditional methods involving combustion or electrical short circuits, and heat pump systems have therefore become increasingly common for heating applications as the cost of energy has risen. The system studied is shown in Fig 2.

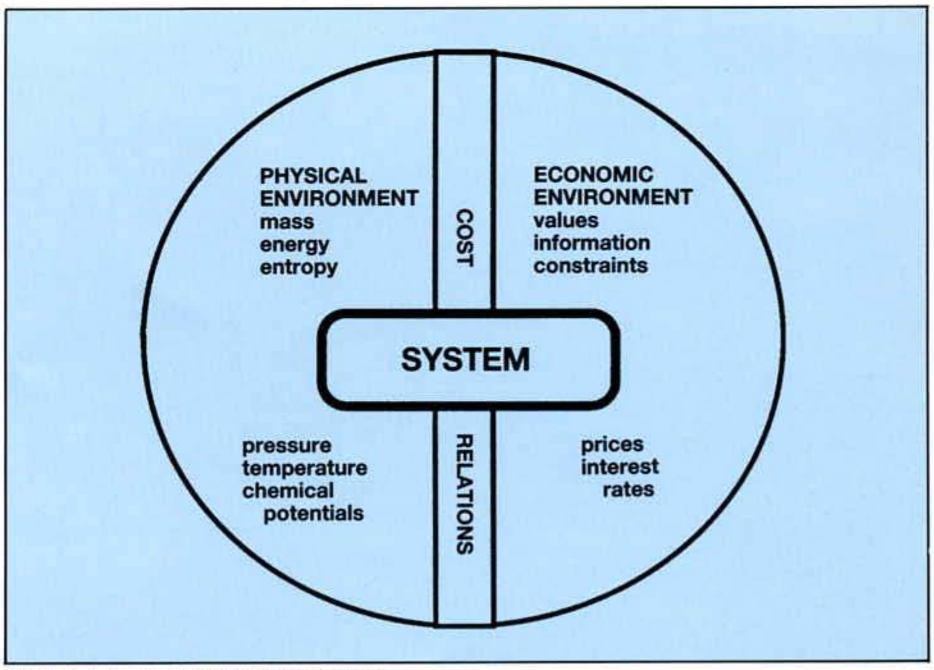

Figure 1. The system in two environments.

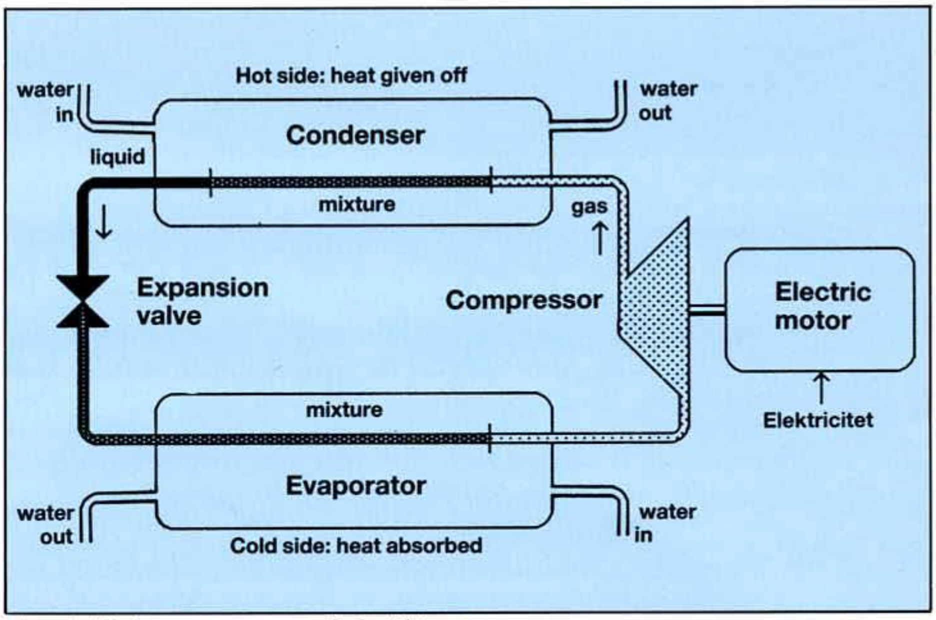

Figure 2. The heat pump system studied, with its components.

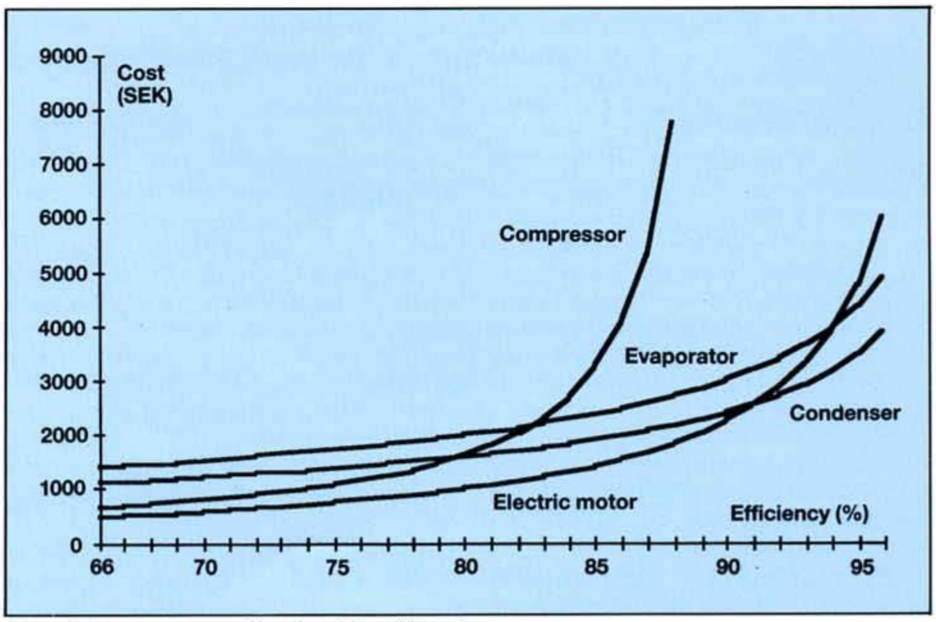

Figure 3. Investments as a function of the efficiencies.

It is made up of a compressor, condenser, expansion valve, evaporator and an electric motor as the drive source. The refrigerant is R12 and the heat transfer medium to the environment in the condenser and evaporator is water. The ambient temperature and pressure are assumed to be 0 °C and 1 atmosphere respectively. Since there are no chemical reactions in the process, other information about the surroundings is irrelevant.

The chosen free decision variables to be determined at optimality are the efficiencies of the compressor, the condenser, the evaporator and the electric motor. The system is completely determined except as far as these free decision variables are concerned. Each value of these locks the system to a given operating state in accordance with the state equations for the system. The exergy flows and exergy losses in each component are also calculated.

The aim is to minimize the total cost of the system for a given heat production. This cost is made up partly of a running cost (electricity) and partly of costs for investment for each component. The running cost increases if the investments decrease and vice versa. The revenues for the supplied product (heat) and given profitability conditions set a limit to the cost of the system and thus determine which systems are profitable. The problem is then to find among the profitable systems the apportionment on the one hand between running costs and investments and on the other hand between the various components of the system, that gives the lowest cost.

Figure 3 shows the assumed investments as a function of the efficiencies. The investments are written off on the annuity principle, which gives an annual cost for each component. The total cost per year is therefore the sum of these and the cost of electricity consumed annually.

In this example the values of the dimensioning parameters have been assumed to be: heat output produced 6 500 W (energy), running time of 5 000 hours per year, electricity cost SEK 0.25/kWh, temperature of produced heat of 60 °C and temperature of heat source 10 °C.

Let us now assume an arbitrarily operating system with all four efficiencies at 70 per cent. The calculated total cost will then be SEK 4 221/year, SEK 3 617/year of which is for electricity. Optimization now gives the following efficiencies instead: compressor 0.80, condenser 0.83, evaporator 0.73 and electric motor 0.91. The total cost will now be SEK 3 388/year instead, SEK 2 416/year of which is for electricity. So by increasing the investment cost from SEK 604/year to SEK 972/year we make a total saving of SEK 833/year compared with the assumed system; see Fig 4. At the same time the exergy

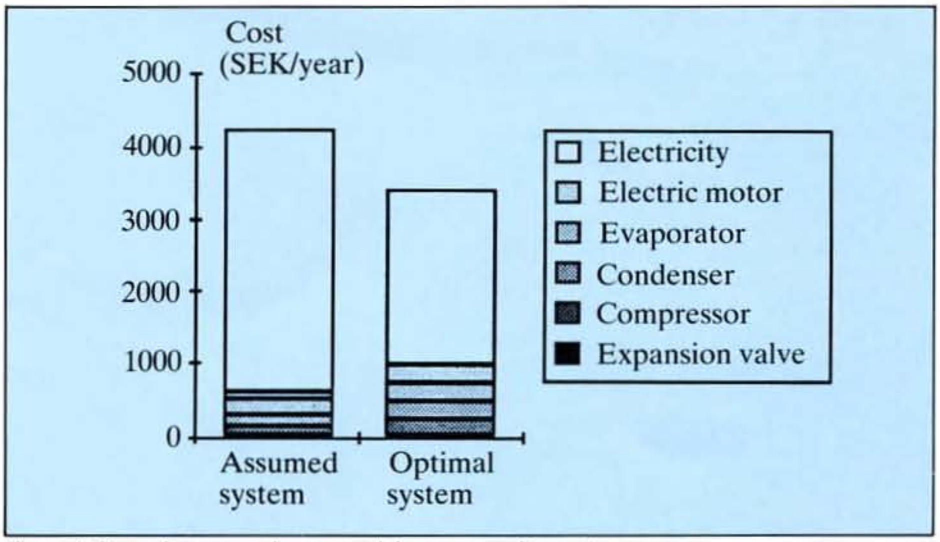

Figure 4. Costs of an assumed system and the corresponding optimum system.

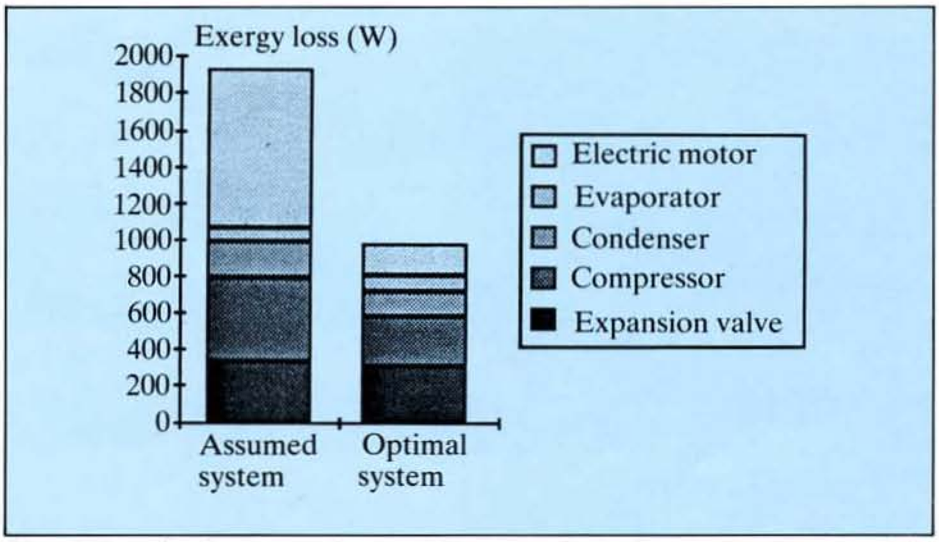

Figure 5. Exergy loss for an assumed system and a corresponding optimum system.

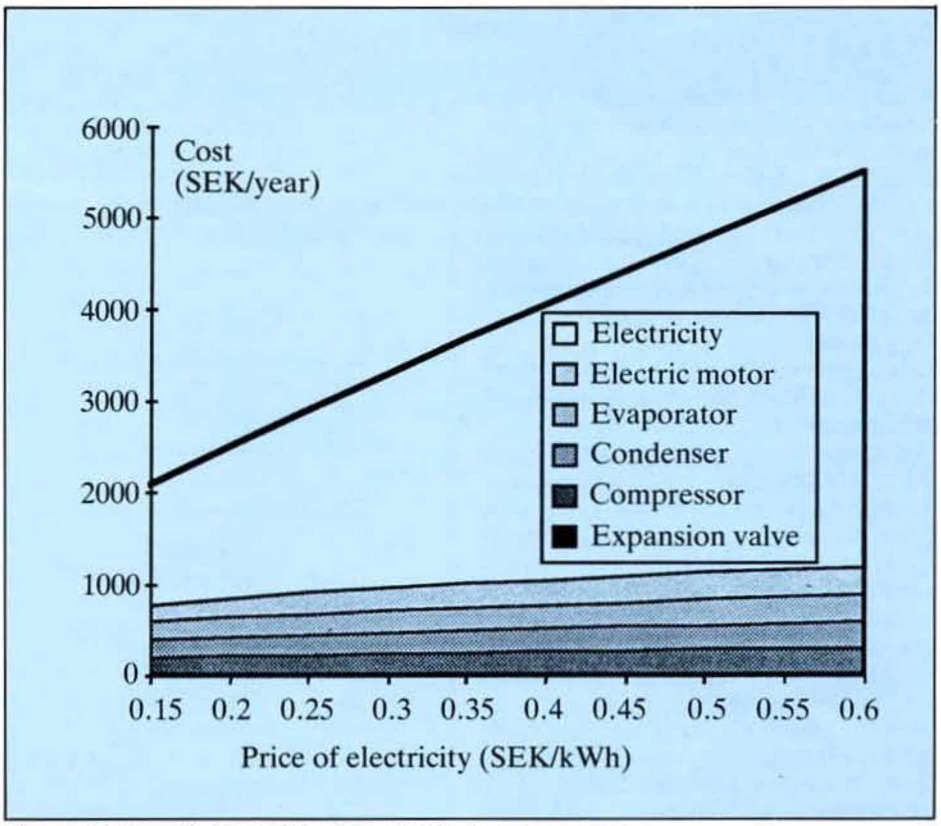

Figure 6. Costs as a function of electricity price for the optimum system.

losses are approximately halved from 1 933 W to 979 W, i e by 954 W. Fig 5 also shows that it is improvements in the electric motor that account for the largest single exergy saving, so that the optimization saves us both money and exergy.

In the optimum system, the expansion valve accounts for the largest single exergy loss, and this justifies research and development to improve it.

So the results indicate among other things that the electric motor should be made far more efficient. It has been assumed that the electric motor would cost three times as much if its efficiency could be raised from 70 to 91 per cent (Fig 3), a perfectly realistic target. (It could even cost nine times as much and still be profitable compared with the assumed system.)

Figure 6 shows the costs of an optimum system as a function of the electricity price when this varies between SEK 0.15 and 0.6/kWh. The total cost increases from SEK 2 073/year at SEK 0.15/kWh to SEK 5 522/year at SEK 0.6/kWh. By way of comparison, if the optimum system at SEK 0.15/kWh were used at SEK 0.6/kWh, the total cost would be SEK 5 947, i e more expensive by SEK 425/year. (For the assumed system the total cost would be 9 284, i e more expensive by SEK 3 762/year.

The choice of the optimum system is also influenced by the variation of the condenser temperature, i e the temperature of the heat produced (Figures 8 and 9). The total cost is doubled from 2 336 at 40 °C to 4 680 at 75 °C. The energy output produced is the same, i e 6 500 W, but the exergy output changes from 434 to 713 W, which provides a better explanation of the increase in cost. When the temperature increases from 40 to 75 °C, the efficiency requirements for the system as a whole becomes stricter, but not necessarily for each individual component. This is clearly shown by Figure 9. In the context of a total increase in component costs, therefore, it is more economical to choose an increasingly cheaper evaporator. The reason is simply that an investment gives a better return in other parts of the system. The method does show where an investment is most worthwhile.

All other relationships can be illustrated in the same way. Other refrigerants or cost relations can be assumed. The purpose of this study has been to illustrate the termoeconomics method by applying it to a heat pump process. The exact results are therefore secondary to the presentation and discussion of the suitability of the method. This method for improving technical systems can never replace long practical experience or high technical expertise, but it can be a useful complement to them.

There is a complete report in English with a computer program in Pascal.

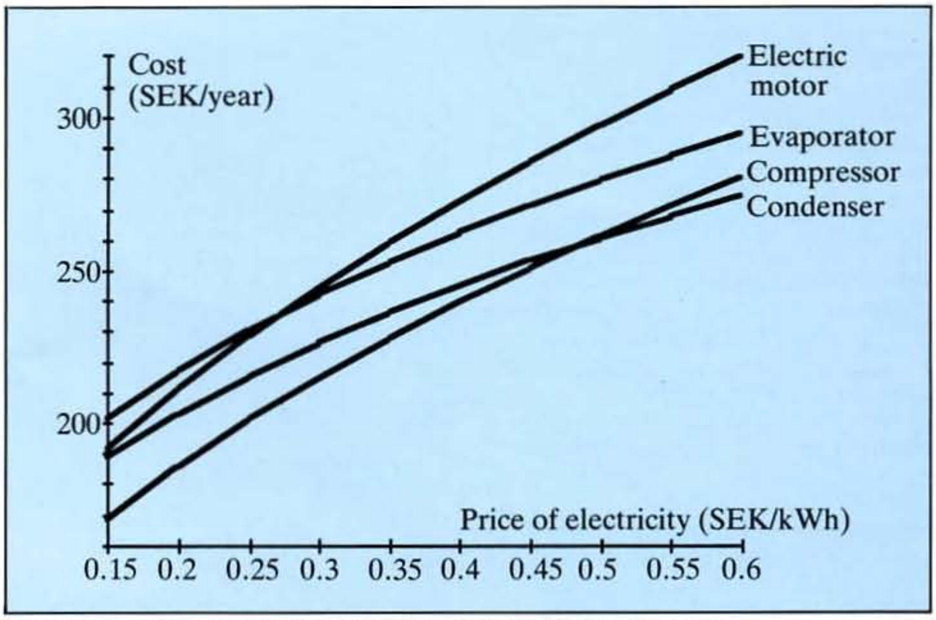

Figure 7. Component costs as a function of electricity price for the optimum system.

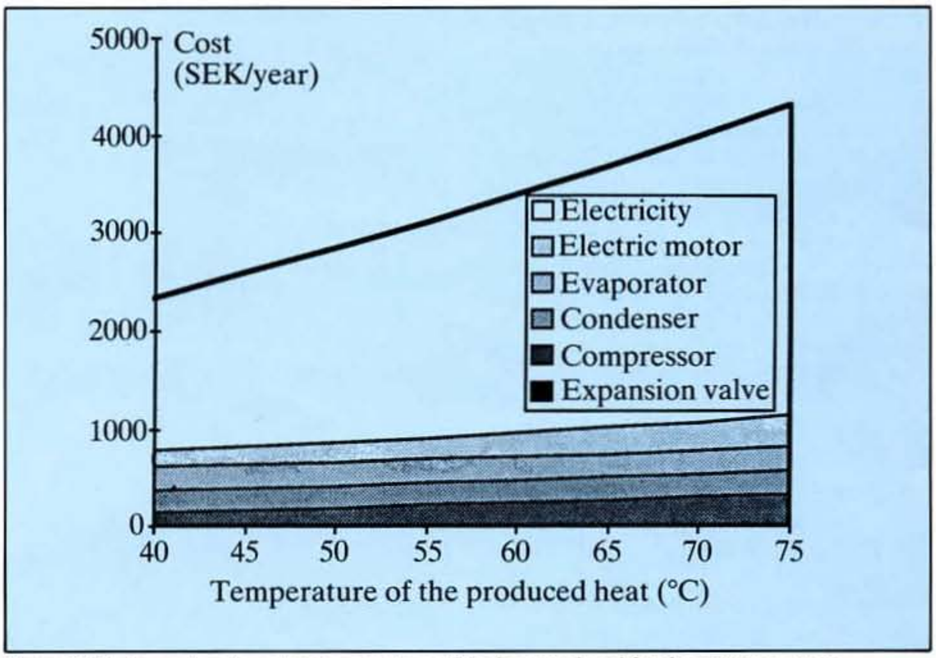

Figure 8. Costs as a function of the temperature of the heat produced for the optimum system.

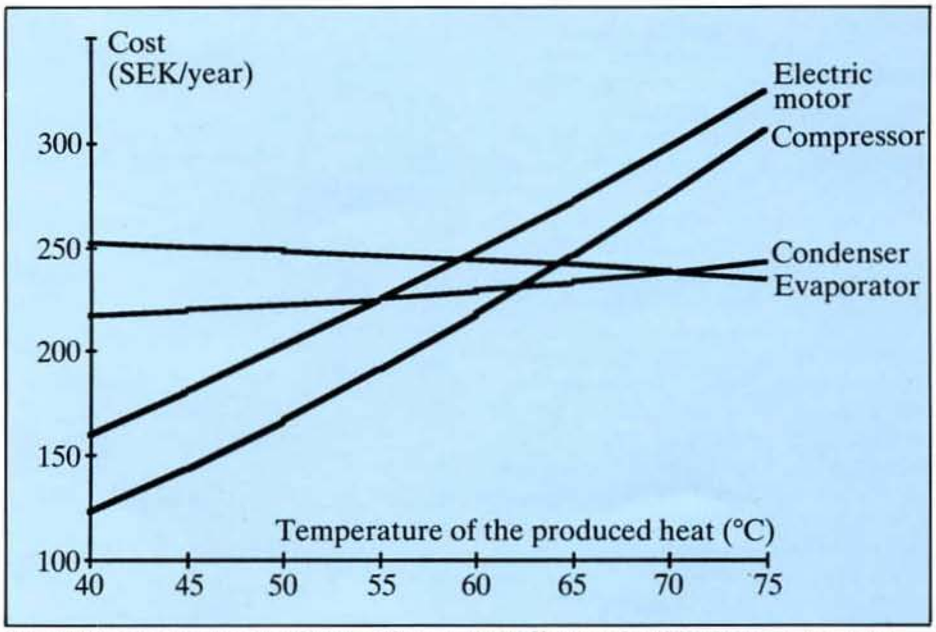

Figure 9. Component costs as a function of temperature of heat produced for the optimum system.