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Method for a quick economic assessment of vapor compression heat pumps

Dominik Seliger^{a,*}, Daniel Lange^a, Veronika Wilk^b, Jürgen Fluch^c, Karl Ponweiser^a

^aTU Wien, Institute for Energy Systems and Thermodynamics (IET), Getreidemarkt 9/302, 1060 Wien, Austria

^bAIT Austrian Institute of Technology GmbH, Sustainable Thermal Energy Systems, Giefinggasse 2, 1210 Wien, Austria

^cAEE – Institute for Sustainable Technologies, Feldgasse 19, 8200 Gleisdorf, Austria

Abstract

Renewable energy systems play a major role in the reduction of CO₂ emissions in industrial processes. However, selecting a suitable renewable energy system is difficult since the development of standardized concepts for assessing the ecological and techno-economic performance of such a system is lagging behind the advances made in the technologies themselves.

This article introduces a diagram-based approach for the quick evaluation and comparison of energy systems by using the vapor compression heat pump cycle as an example. On the basis of known technical key parameters of the heat pump cycle, transparent and highly flexible performance indicators are deduced like the relative energy cost and CO₂ savings during heating operation. The proposed evaluation concept demonstrates efficient practical use for economic and ecological technology comparison in several example scenarios. A parameter study shows the influence of key parameters in the heat pump cycle with regards to the system savings.

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1. Introduction

The consumer driven demand for sustainable products is steadily increasing, forcing companies to overthink their ecological impact. Therefore, companies are faced with the task to develop business models with sustainable replacements for technologies that are affecting the environment [1-2]. However, there are currently no standardized tools to give comprehensive and reliable statements about the impact of switching between technologies. This slows down the implementation process and market penetration of renewable energy systems. Comprehensible performance indicators are needed to develop a common understanding of the economic potential of switches between technologies. Furthermore, time and money constraints rarely justify in-depth system studies like a pinch analysis during pre-projects and business case development. Industrial stakeholders and consultants therefore need easily accessible tools for the quick assessment of the economic and ecological potential of new technologies for their evaluation and decision making process.

This article formulates an effective approach to compare different heating technologies. The premise is to give a clear indication for the more beneficial system by calculating its potential relative savings. The proposed method expands on considerations made by Lange [3]. It is based on observations for energy technologies in general and is then refined for vapor compression heat pump systems. Key parameters are used to customize the method for heat pump cycles and a comprehensive graph is presented that further emphasizes the practicability of the approach. The approach can be used for either economic or ecological purposes by using suitable specific costs in the calculation which is demonstrated with several example scenarios. These scenarios

* Corresponding author. Tel.: +43-1-58801-302316; fax: +43-1-58801-302399.
E-mail address: dominik.seliger@tuwien.ac.at.

are examples for the effectiveness and comprehensibility of the relative savings as a key figure as well as the approach itself. Furthermore certain parameters are discussed to understand how these should be adapted to have positive impact on the overall relative savings.

2. Derivation of economic performance indicators

In order to evaluate and compare two different technologies the same framework must be applied: Every considered technology has the function to fulfill a certain heat demand, Q_D , in a certain time period Δt . During the defined time period Δt all considered technologies are working in a steady state, meaning that every process variable is assumed to be constant.

2.1. Comparison of two energy technologies

Any technology for heat supply causes costs mainly due to the consumption of other energy sources, Q_i . Each of these energy sources has a specific cost c_i . Therefore, the operating costs C to provide a certain heat demand Q_D are:

$$C(Q_D) = \sum_i Q_i(Q_D) c_i \quad (1)$$

However, most technologies only consume one type of energy to meet a certain heat demand. These technologies shall be named direct conversion technologies from this point onward. Operating costs as defined in equation 1 can be expressed for these direct conversion technologies as follows:

$$C = Q c \quad (2)$$

Equation 2 is also valid for technologies which use only one energy source with significant specific costs, making the costs for other energy sources negligible. Furthermore, for direct conversion technologies the efficiency η is defined as:

$$\eta = \frac{Q_D}{Q} \quad \text{or} \quad Q = \frac{Q_D}{\eta} \quad (3)$$

One indicator for a beneficial technology are lower operating costs in comparison to reference technologies. An easy criterion, that identifies technology A as superior to B is:

$$\frac{c^A(Q_D)}{c^B(Q_D)} < 1 \quad (4)$$

If this criterion is used to compare two direct conversion technologies, equation 2 and 3 can be used to transform equation 4 to a cost-efficiency-ratio:

$$\frac{\eta^B c^A}{\eta^A c^B} < 1 \quad (5)$$

Finally, the relative savings \hat{S} by using technology A instead of B can be calculated as:

$$\hat{S} = \frac{c^B - c^A}{c^B} = 1 - \frac{c^A}{c^B} \quad (6)$$

If only direct conversion technologies are considered, equation 6 can be modified by using the cost-efficiency-ratio:

$$\hat{S} = 1 - \frac{\eta^B c^A}{\eta^A c^B} \quad (7)$$

Equation 7 shows that the relative savings for switching between any two given technologies may be calculated using only the specific costs for input energies and efficiencies, regardless of the heat demand Q_D .

2.2. Relative savings with a vapor compression heat pump system

One of the main technical parameters for a vapor compression heat pump system is the coefficient of performance, COP . In a steady state the supplied heat, Q_D , and the required work, W^{HP} , are proportional to their process variables, \dot{Q}_D and \dot{W}^{HP} . Therefore the COP can be calculated as follows:

$$COP = \frac{Q_D}{W^{HP}} \tag{8}$$

For every vapor compression heat pump system exists an ideal reverse Carnot cycle for comparison [4] The ideal cycle is based upon isentropic changes of state in the compressor and throttle as well as upon isotherm changes of state in the condenser and evaporator. For this ideal system the coefficient of performance reaches its maximum, COP_{max} . Due to the first and second law of thermodynamics, COP_{max} can be calculated by using only the temperatures in the evaporator, T_{eva} , and the condenser, T_{con} :

$$COP_{max} = \frac{T_{con}}{T_{con} - T_{eva}} \tag{9}$$

Like most other efficiencies, the COP relates benefit to cost. However, typical values for the COP are above 1 and the range varies due to the temperature levels of the system, making a direct comparison difficult. As a universal performance indicator the second law efficiency η^{HP} is introduced. This factor compares the ideal performance, COP_{max} , to the actual performance of a heat pump system, COP :

$$\eta^{HP} = \frac{COP}{COP_{max}} \tag{10}$$

If equations 8 and 10 are combined, W^{HP} is calculated as follows:

$$W^{HP} = \frac{Q_D}{\eta^{HP} COP_{max}} \tag{11}$$

The relative savings \hat{S} can be derivated by combining considerations analogue to chapter 2.1 with the established technical parameters of a heat pump system and. The operating costs for a heat pump system are:

$$C^{HP} = W^{HP} c_W^{HP} + Q^{HP} c_Q^{HP} \tag{12}$$

Additionally to electrical work W^{HP} , each heat pump system is supplied with a low grade heat Q^{HP} that is either waste heat or taken from the environment. Therefore Q^{HP} causes no costs in most cases, reducing the specific costs c_Q^{HP} to 0. Equation 12 is then reduced to:

$$C^{HP} = W^{HP} c_W^{HP} \tag{13}$$

Inserting equation 11 into 13 leads to the operating costs for heat pumps with regards to heat demand Q_D :

$$C^{HP} = \frac{Q_D}{\eta^{HP} COP_{max}} c_W^{HP} \tag{14}$$

Equation 14 calculates the operating costs based upon general key technical parameters of a heat pump system. These costs may also be compared to other systems using equations 4 and 6. For a reference system based on a direct conversion technology, equation 4 yields:

$$\frac{1}{COP_{max}} \frac{\eta^{ref} c_W^{HP}}{\eta^{HP} c^{ref}} < 1 \quad \text{or} \quad \frac{\eta^{ref} c_W^{HP}}{\eta^{HP} c^{ref}} < COP_{max} \tag{15}$$

Finally, the relative savings \hat{S} for operating a heat pump system instead of a reference system are:

$$\hat{S} = 1 - \frac{1}{COP_{max}} \frac{\eta^{ref} c_W^{HP}}{\eta^{HP} c^{ref}} \tag{16}$$

Which can also be transformed to:

$$\hat{S} = 1 - \frac{1}{COP} \frac{\eta^{ref} c_W^{HP}}{c^{ref}} \tag{17}$$

Figure 1 shows a graph illustrating \hat{S} for higher practicability. The graph is based on the two main components of equation 16 and 17 which are a coefficient of performance, either COP or COP_{max} , as well as the according cost-efficiency-ratio. Note that the term for the cost-efficiency-ratio changes with the according coefficient of performance. Therefore the use of Figure 1 is more flexible depending on which technical key parameters for the heat pump system are known.

The linear nature of equations 16 and 17 makes Figure 1 easily to use. Straight lines for a constant COP or COP_{max} can be added at will due to the following rules:

- $\hat{S} = 1$: Relative savings of 100% are only possible if the relative cost savings are 0 regardless of the coefficient of performance. Therefore any straight line has to cross the y-axis exactly at 1.0.
- $\hat{S} = 0$: For relative savings of exactly 0%, the cost-efficiency-ratio is equivalent to the coefficient of performance. Consequently, a line for a constant value of COP or COP_{max} crosses the x-axis at that value.

These characteristics strongly increase the overall applicability of the diagram since it is also possible to make rough sketches and estimations on the go. Furthermore, several approaches to use the equations 16 and 17 or Figure 1 exist, depending on the required result. Aside from calculating relative savings it is possible to show necessary technological or economic thresholds to guarantee an economic benefit.

2.3. Ecological assessments and inclusion of a pollutant tax

The operational ecological costs of technologies are mainly represented by their production rate of environmental pollutants such as CO₂. For an ecological assessment the equation system above may be used by simply inserting the specific production rate p of a pollutant instead of the specific economic costs c of an energy source Q in equation 2. This amount for the ecological costs C_{ecol}

$$C_{ecol} = Q p \tag{18}$$

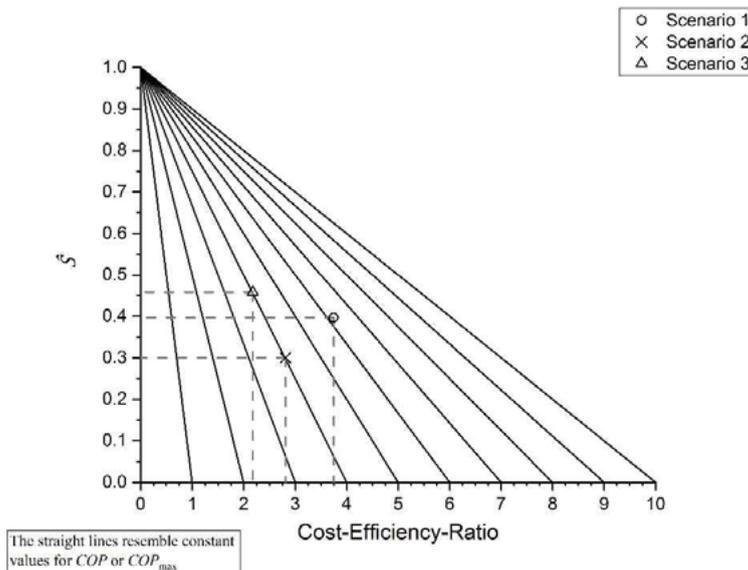


Fig. 1: The relative cost savings as a function the cost-efficiency-ratio for an array of constant COP_{max} or COP values as calculated with equation 16 or 17 respectively. The marked points show results for example scenarios given in section 3. By using the corresponding cost-efficiency-ratio, Figure 1 can be applied for equation 20 and 23 as well.

This allows the use of the same approach as shown in chapter 2.1 and 2.2 for the calculation of the relative savings in pollutant production, \hat{S}_{ecol} , resulting from a technology switch:

$$\hat{S}_{\text{ecol}} = 1 - \frac{\eta^B p^A}{\eta^A p^B} \quad (19)$$

$$\hat{S}_{\text{ecol}} = 1 - \frac{1}{COP} \frac{\eta^{\text{ref}} p_W^{\text{HP}}}{p^{\text{ref}}} \quad (20)$$

For future considerations the inclusion of a pollutant tax t might also be of relevance. By using the pollutant production rate p and the specific costs c of the energy source Q , the overall economic costs result in:

$$C_{\text{econ}} = Q (c + p t) \quad (21)$$

By using equation 21 instead of equation 2, the relative economic costs savings change to:

$$\hat{S}_{\text{econ}} = 1 - \frac{\eta^B (c^A + p^A t)}{\eta^A (c^B + p^B t)} \quad (22)$$

$$\hat{S}_{\text{econ}} = 1 - \frac{1}{COP} \frac{\eta^{\text{ref}} (c_W^{\text{HP}} + p_W^{\text{HP}} t)}{(c^{\text{ref}} + p^{\text{ref}} t)} \quad (23)$$

Equation 20 and 23 are of similar structure as equation 17 and therefore Figure 1 may also be used if the correct cost-efficiency-ratio is applied. However, note that equations 20 and 23 can be only applied if the used waste heat source for the heat pump, Q^{HP} , does not result in additional pollutant production.

To use this method it is necessary to know the specific production or emission rate of the considered pollutant for the used energy sources. Energy suppliers usually reference their used energy mix but not necessarily their specific impact on environmental resources. Aside from rough key figures about certain energy types it is possible to perform a system analysis for further information. Nevertheless, one of the more efficient approaches is to use tools like GEMIS. GEMIS is an open source database plus an analysis model to determine energy and resource flows. It considers the life-cycle for processes and scenarios and therefore includes secondary contributions like raw material and transportation. However, for quick calculations the GEMIS database delivers key figures for the main energy sources as well [5].

3. Evaluation of example scenarios

The set of equations derived in chapter 2 as well as Figure 1 can be used to examine possible applications for heat pumps. Depending on the requirements they may be used either to calculate the relative cost savings coinciding with a technology switch, or to determine the necessary technical boundaries for predefined minimum savings. Several predefined scenarios are analyzed in the following section to demonstrate the approach for practical applications.

3.1. Scenario 1 – comparison of a heat pump system and purchased saturated steam

The first scenario considers an industrial process that is currently supplied with saturated steam at 100 °C. The steam, which is bought from an external supplier at 10 cent/kWh, provides thermal energy for an industrial dryer at constant temperature. An unused waste heat source allows a theoretical evaporator temperature of 40 °C and enables the implementation of a heat pump system. The company pays 15 cent/kWh for electrical energy including secondary costs. Experimental data shows second law efficiencies for high temperature heat pumps between 0.40 and 0.60 [6], therefore it is safe to assume a minimum second law efficiency of 0.40. The relative cost savings are required to justify a technology switch.

To use Figure 1, the cost-efficiency-ratio and the according COP_{max} have to be calculated. Due to the fact that steam is bought and used directly for heating the dryer at a constant temperature, the corresponding efficiency is 1.

$$\frac{\eta^{\text{steam}} c_W^{\text{HP}}}{\eta^{\text{HP}} c^{\text{steam}}} = \frac{1.00 \cdot 15 \text{ cent/kWh}}{0.40 \cdot 10 \text{ cent/kWh}} = 3.75$$

$$COP_{\text{max}} = \frac{T_{\text{con}}}{T_{\text{con}} - T_{\text{eva}}} = \frac{(100 + 273) \text{ K}}{(100 - 40) \text{ K}} = 6.22$$

To evaluate the relative economic cost savings, either equation 16 or the graph for \hat{S} can be used. Inserting the calculated COP_{max} and cost-efficiency-ratio in Figure 1 shows that the implementation of a heat pump system instead of purchasing steam leads to relative cost savings of about 40% for the given boundaries. As shown in equation 15 the economic threshold for the implementation of a heat pump system is the equilibrium of COP_{max} and the cost-efficiency-ratio. In this particular case the specific costs for the electrical energy have to increase by approximately 66 % in order to reach this equilibrium. Furthermore, Figure 1 allows to identify the required cost-efficiency-ratio in order to meet a given relative economic saving. This procedure is shown in scenario 2.

3.2. Scenario 2 – comparison of a heat pump system and a natural gas heater

This scenario examines a heat pump system that may be used as an alternative to a natural gas heating system for a household. The gas furnace uses condensing technology and has an average fuel utilization efficiency of 0.90 [7] at a cost of 8 cent/kWh. Electrical power is supplied at a cost of 25 cent/kWh. The heat pump system must lead to relative cost savings of at least 30% to ensure a reasonable return of investment. Point of investigation is the COP .

Again the cost-efficiency-ratio is calculated first, but in regards to COP , not COP_{max} :

$$\frac{\eta^{\text{gas}} c_W^{\text{HP}}}{c^{\text{gas}}} = \frac{0.90 \cdot 25 \text{ cent/kWh}}{8 \text{ cent/kWh}} = 2.81$$

Using the graph for \hat{S} , and a calculated cost-efficiency-ratio of 2.81 leads to a minimum of 4.0 as COP for any profitable heat pump system as shown in Figure 1. At this point the versatility of the diagram based approach can be demonstrated. Assuming that the heat pumps available on the market only reach a COP of 3, the relative cost savings decrease to approximately 5%, making their implementation less feasible.

3.3. Scenario 3 –ecological evaluation of scenario 2

Aside from the relative energy cost savings it is also possible to evaluate the ecological impact of a technology switch as defined in scenario 2 by using the specific CO_2 production of the energy sources. Key figures taken from the GEMIS-database show that burning natural gas emits about 250 g_{CO_2}/kWh whereas using electric power produces 605 g_{CO_2}/kWh [8].

This can be translated into a cost-efficiency-ratio as well:

$$\frac{\eta^{\text{gas}} p_W^{\text{HP}}}{p^{\text{gas}}} = \frac{0.90 \cdot 605 \text{ } g_{CO_2}/kWh}{250 \text{ } g_{CO_2}/kWh} = 2.18$$

Using the minimum COP of 4.0 as estimated in scenario 2 and the new cost-efficiency-ratio of 2.18 leads to minimum CO_2 savings of about 45% during operation as seen in Figure 1. Due to the fact that the idea to give emissions a certain economic value is gaining popularity, it is important to make these upcoming changes quantifiable. Scenario 4 demonstrates the economic impact of a tax on emissions for a change of technology.

3.4. Scenario 4 –considering a pollutant tax for scenario 2 and 3

A CO_2 emission tax of 0.01 cent/ g_{CO_2} is introduced to study the impacts of a pollutant tax on the future profitability of the technology switch as demonstrated in scenario 2.

Considering equation 23, the cost efficiency ratio including a pollutant tax is as follows:

$$\frac{\eta^{\text{ref}} (c_W^{\text{HP}} + p_W^{\text{HP}} t)}{(c^{\text{ref}} + p^{\text{ref}} t)} = \frac{0.90 \cdot (25 \text{ cent/kWh} + 605 \text{ } g_{CO_2}/kWh \cdot 0.01 \text{ cent}/g_{CO_2})}{8 \text{ cent/kWh} + 250 \text{ } g_{CO_2}/kWh \cdot 0.01 \text{ cent}/g_{CO_2}} = 2.66$$

The new cost-efficiency-ratio is lower than without a CO₂ tax when compared with scenario 2. This leads to several main conclusion:

- Using the same COP as calculated in scenario 2, 4.0, leads to relative cost savings of about 33%, which is higher than without a CO₂ tax.
- With minimum savings of 30%, as suggested in scenario 2, and the new cost-efficiency-ratio, the new minimum COP is 3.8. A pollutant tax would therefore lower the technical requirements for the heat pump system.

These considerations clearly indicate, that the heat pump system is economically better when a CO₂ tax is introduced. However, this relates mainly to the higher CO₂ savings calculated in scenario 3. If the CO₂ tax would be raised indefinitely, the threshold for the relative cost savings would be the same as the relative CO₂ savings.

4. Parameter study

The presented example scenarios highlight the ease of the approach. However, the key parameters are further examined to develop an understanding how the system would behave if certain inputs are changed. These considerations can also be facilitated when analyzing potentials or optimizing systems in general.

4.1. Influence of condenser and evaporator temperature on relative cost savings

In regard to vapor compression heat pumps the main technical parameters are the temperatures in the condenser and evaporator, T_{con} and T_{eva} . These temperatures determine the ideal Carnot process that is used for comparison and therefore determine the COP_{max} as seen with equation 9. To understand the influence of the temperatures, equation 9 is combined with equation 16:

$$\hat{S} = 1 - \frac{T_{con}-T_{eva}}{T_{con}} \frac{\eta_{HP}^{ref} c_W^{HP}}{\eta_{HP} c_{ref}^{ref}} = 1 - \left(1 - \frac{T_{eva}}{T_{con}}\right) \frac{\eta_{HP}^{ref} c_W^{HP}}{\eta_{HP} c_{ref}^{ref}} \tag{24}$$

Equation 24 shows a linear dependence between the temperature ratio T_{eva}/T_{con} and the relative cost savings \hat{S} . This is also presented with various cost-efficiency-ratios in Figure 2. Several statements can be made by analyzing equation 24 and Figure 2:

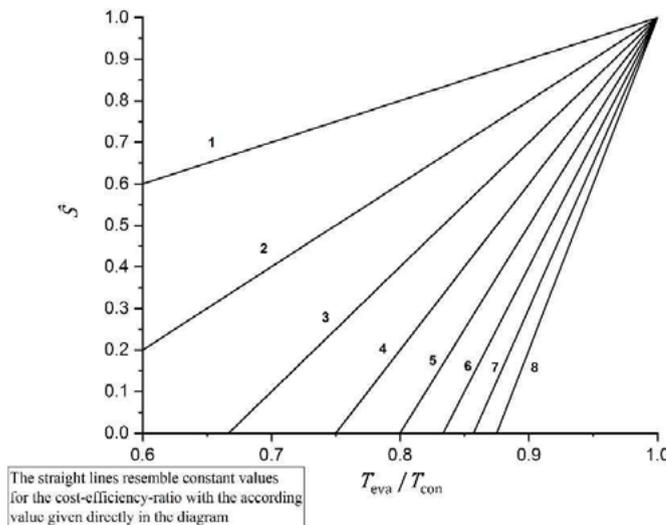


Fig. 2: Relative cost savings as a function of the temperature ratio of the vapor compression heat pump cycle for an array of constant cost-efficiency-ratios. $T_{eva}/T_{con} \leq 0.6$ is equivalent to $COP_{max} \leq 2.5$ which is currently outside of feasible heat pump applications.

Several statements can be made by analyzing equation 24 and Figure 2:

- Increasing T_{eva} or decreasing T_{con} improves the relative cost savings whereas decreasing T_{eva} or increasing T_{con} reduces the relative cost savings. More specifically, smaller differences between T_{eva} and T_{con} lead to higher cost savings.
- For $T_{eva} = T_{con}$ the relative cost savings are always 100% because the utilized waste heat can theoretically be used directly and without a heat pump.
- Each cost-efficiency-ratio has temperature combinations that allow positive relative cost savings. However, the maximum profitable temperature difference between T_{con} and T_{eva} may be very small, depending on the temperature level. More specifically, higher cost-efficiency-ratios reduce the economically beneficial temperature difference.
- The same temperature difference at higher temperature increases the temperature ratio and therefore results in better relative savings as long as the cost-efficiency-ratio remains constant.
- The theoretically lowest temperature ratio is 0 which coincides with a COP_{max} of 1. A COP_{max} below 1 is therefore impossible.

4.2. Considerations about the cost-efficiency-ratio

The cost-efficiency-ratio has a significant influence on relative savings aside from the temperatures of the heat pump cycle. Any change in the specific costs or technology efficiencies leads to a change in the overall ratio. Statements about changes in the cost-efficiency-ratio can therefore be translated to each of its parameters if their position in the numerator or denominator is considered.

Relevant for considerations about the cost-efficiency-ratio are equations 15 and 16. Moreover, equation 16 can be developed into a graph aside from Figure 1 as shown in Figure 3. This allows the following statements:

- Relative savings are guaranteed when equation 16 is used and the cost-efficiency-ratio is below 1 due to COP_{max} always being greater or equal to 1. However, the regular COP theoretically may still be below 1.
- In order to have positive relative cost savings, the coefficient of performance has to be higher than the respective cost-efficiency-ratio.
- Both, an increase of the coefficient of performance or a decrease of the cost-efficiency-ratio, lead to improved relative savings. However, it is more beneficial to lower the cost-efficiency-ratio by a certain percentage, e.g. 5%, than to improve the respective coefficient of performance by the same percentage.

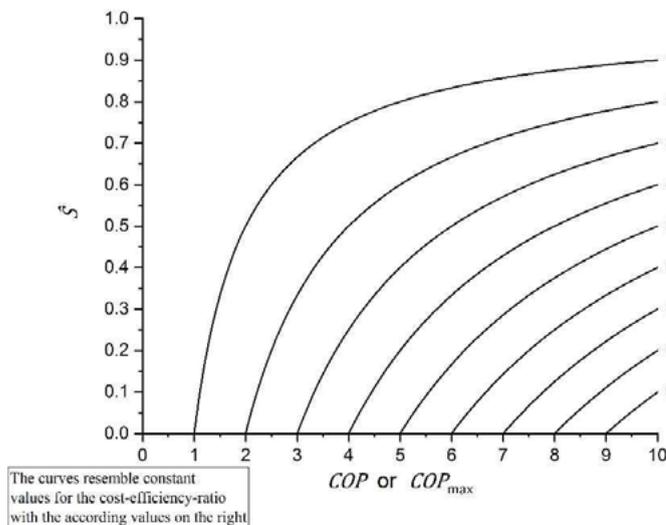


Fig. 3: Relative cost savings as a function of the COP or COP_{max} with an array of curves for constant cost-efficiency-ratios.

5. Conclusion

The derived equations are an accessible and fast tool for assessing and comparing vapor compression heat pump systems with other heating technologies. Based on general known key parameters the relative savings are a clear indicator for the more viable system. Companies may use either the established equation system itself or the graph shown in Figure 1 for estimations about economic potential and therefore for their decision making.

Aside from economic use, the here shown system may also be used for an ecological comparison. The structure of the cost-efficiency-ratio allows the comparison of any number of aspects, as long as the specific costs are of the same type. Comprehensive and reliable statements about ecological effects may be given in combination with databases like GEMIS. If taxes for CO₂-production are introduced in the future, the shown method for a fast economic and ecological evaluation will become even more useful.

Future research in the course of the project CORES (COmbind Renewable Energy Systems) will link the heat pump with other renewable energy technologies like solar thermal energy, photovoltaics and thermal energy storages for optimization in industrial applications. For further improvements the approach may be extended to include a comprehensible assessment about investment costs and amortization periods.

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