Valorization of low-temperature heat: impact of the heat sink on performance and economics

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Abstract

Low-grade heat is available everywhere; consequently, the valorization of this heat seems to be attractive in terms of economics. However, irrespective of the form of energy which is produced, any valorization comes along with the production of another stream of waste heat with even lower value. The dumping of this reject heat often turns out to be the issue which determines cost.

This presentation will elaborate on the influence of the heat sink temperature both on conversion efficiency and cost. It first will give a frame on a very generic level. Then, an example will be given especially for an absorption cooling system.

Keywords

First cost, operating cost, thermodynamics, temperature, characteristic equation

Introduction

Valorization of low-temperature heat is a broad area. It covers heat recovery by compression heat pumps, sorption heat pumps, and heat transformers, as well as conversion into cold or mechanical energy. The means to do so are abundant as well: conventional conversion systems use thermodynamic mono-fluid cycles (closed steam cycles, open steam cycles, or even gas cycles), or dual-fluid cycles such as sorption cooling processes or sorption power processes. Some options which are state of the art, or technically feasible, or at least in discussion, are listed in Table 1.

Table 1: Options for valorization of low-temperature heat

Mono-fluid		Multi-fluid		No fluid	
Air cycle	#1	Absorption cycle	#2, 4, 5	Peltier cooler	#1
Rankine cycle	#3	Adsorption cycle	#2, 4, 5	Magnetocaloric cooler	#1
Steam jet cycle	#2, 5	Chemical cycle	#2, 4, 5	Thermoelectric generator	#3
Stirling cycle	#1, 3	Hybrid sorption cycle	#1		
Vapor compression cycle	#1	Rankine sorption cycle	#3		
Vuilleumier cycle	#2, 4, 5				

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The numbers (#1, 2, etc.) which are listed in Table 1, refer to Figure 1, in which the nature of the duty to be fulfilled by these cycles is depicted on a temperature scale.
The first aim of this paper is to give an order to the said options and then to elaborate on the impact of the heat sink, and that of the other temperatures, too. It has to be distinguished between the impact on power density, efficiency, and cost. This will be done using generic equations. In a more technical approach, absorption chillers will be discussed in more detail.

Generic thermodynamic approach

Options for revalorisation

These options could be discussed in terms of exergy, but we keep using energy and temperature as describing parameters.
First two definitions or clarifications are in order: low-temperature heat is heat with a temperature above ambient (at least two times the temperature gradient across a heat exchanger!). The heat sink is defined by the ambient, as well. It may include humidity, so it may be the dry bulb temperature or the wet bulb temperature. In order not to complicate things, in this paper we do not distinguish this.

Figure 1 schematically shows the thermodynamic options; the only scale used is a temperature scale with temperature rising from bottom to top.

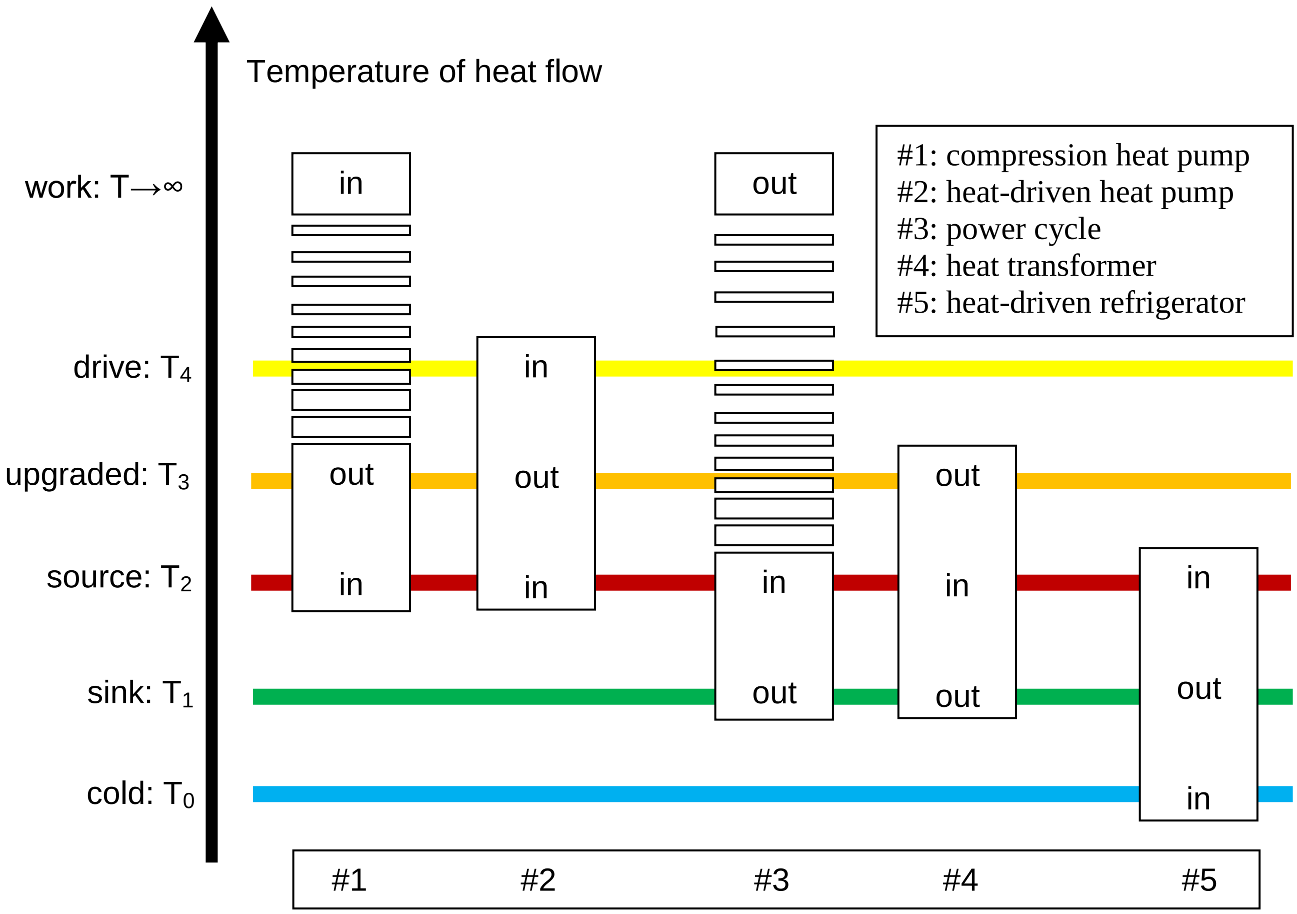

Figure 1: Generic options to valorise heat of temperature T_2

Each box denotes another generic conversion process. The words "in" or "out" are related to the energy flow on the respective temperature level, entering or leaving the device. Box #1 depicts a compression heat pump which upgrades heat from T_2 to T_3 with input of mechanical work.

Process #2 does the same upgrading, albeit with using heat of temperature T_4 as drive. It depicts a heat driven heat pump.
Box #3 stands for a power cycle which works between T_2 and T_1. Box #4 represents a heat transformer cycle which upgrades heat from T_2 to T_3 with degrading part of the heat to the heat sink at T_1. Box #5, finally, shows a heat driven refrigerator. So, summarising, #1, #2, and #4 are heat pumps of different nature.
In any case, the low-temperature heat source at T_2 conveys heat into the box. Energy flows out at a higher level (#1 to 4) or flows in at a lower level (#5). The focus of this paper should be on the processes #3 to #5 because they have to reject heat to a heat sink at a temperature T_1. However, we will discuss processes #1 and #2 also.

Performance

Table 2 gives the definition of efficiency or COP and an equation to determine it in the most simple way, which is to calculate the reversible limit and multiply this with a rough measure for thermodynamic quality, g. A numerical example is given also, just for orientation. This example uses the temperatures from Table 4 and a quality of g=0.5.

Table 2: Performance of generic valorisation processes

		Efficiency	Example
#1	Work-driven heat pump	$COP = \frac{Q_3}{W} = g\ \frac{T_3}{T_3 - T_2}$	$COP = 4.9$
#2	Heat-driven heat pump	$COP = \frac{Q_3}{Q_4} = g\ \frac{T_3}{T_4}\frac{T_4 - T_2}{T_3 - T_2}$	$COP = 1.1$
#3	Power cycle	$\eta = \frac{W}{Q_2} = g\ \frac{T_2 - T_1}{T_2}$	$\eta = 0.06$
#4	Heat transformer	$COP = \frac{Q_3}{Q_2} = g\ \frac{T_3}{T_2}\frac{T_2 - T_1}{T_3 - T_1}$	$COP = 0.29$
#5	Heat-driven refrigerator	$COP = \frac{Q_0}{Q_2} = g\ \frac{T_0}{T_2}\frac{T_2 - T_1}{T_1 - T_0}$	$COP = 0.43$

All these equations are well-known and will not be discussed here. The sensitivity of the efficiencies on the temperatures will be investigated by using the derivatives. Table 3 gives the derivatives with respect to all the relevant temperatures, normalised with the respective efficiency.
From these equations it is obvious that, e.g., the impact of the source temperature, T_2, on the heat pump COP is always somewhat larger than that of the sink, T_3 , in the work driven case (#1), whereas it is smaller in the heat driven case #2. For a power plant (#3) the impact of the heat sink, T_1, always is somewhat larger than that of the heat source, T_2. In the case of the heat transformer (#4) it is the other way round, again. This is understood easily, as a shift in the intermediate temperature T_2 changes temperature lift and temperature thrust of the process at the same time. For the same reason, the impact of the heat sink in the case of refrigeration (#5) is the largest one.
In order to quantify these findings, the derivatives according to Table 3 are plotted against the heat sink temperature for a set of other temperatures (see Table 4) in Figures 2 to 6. The absolute value of the derivatives is shown. The dashed lines display negative derivatives.

Table 3: Relative change in COP or efficiency due to a change in one temperature

	$\left\lvert\frac{\partial COP}{\partial T_i}\right\rvert \Big/ COP$ or $\left\lvert\frac{\partial \eta}{\partial T_i}\right\rvert \Big/ \eta$, derivative with respect to...				
	T_4	T_3	T_2	T_1	T_0
#1		$-\frac{T_2}{T_3(T_3-T_2)}$	$\frac{1}{T_3-T_2}$		
#2	$\frac{T_2}{T_4(T_4-T_2)}$	$-\frac{T_2}{T_3(T_3-T_2)}$	$\frac{T_4-T_3}{(T_3-T_2)(T_4-T_2)}$		
#3			$\frac{T_1}{T_2(T_2-T_1)}$	$-\frac{1}{T_2-T_1}$	
#4		$-\frac{T_1}{T_3(T_3-T_1)}$	$\frac{T_1}{T_2(T_2-T_1)}$	$-\frac{T_3-T_2}{(T_3-T_1)(T_2-T_1)}$	
#5			$\frac{T_1}{T_2(T_2-T_1)}$	$-\frac{T_2-T_0}{(T_1-T_0)(T_2-T_1)}$	$\frac{T_1}{T_0(T_1-T_0)}$

Table 4: Set temperatures according to Figure 1

Temperature level	T_4	T_3	T_2	T_1	T_0
Value [°C]	180	120	80	35	-5

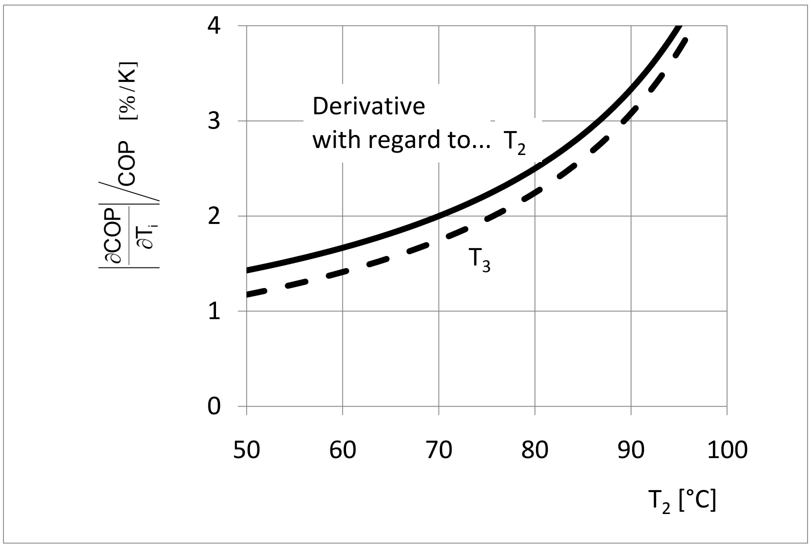

Figure 2: Relative change of the COP of a compression heat pump (#1) with temperatures

The impact of the temperatures on the COP of a compression heat pump (Figure 2) between T_2 and T_3 is the larger, the smaller the temperature lift, (T_3-T_2), to be accomplished is. It is in the order of some %/K for realistic temperatures. The difference between the impact of the two temperatures is marginal.

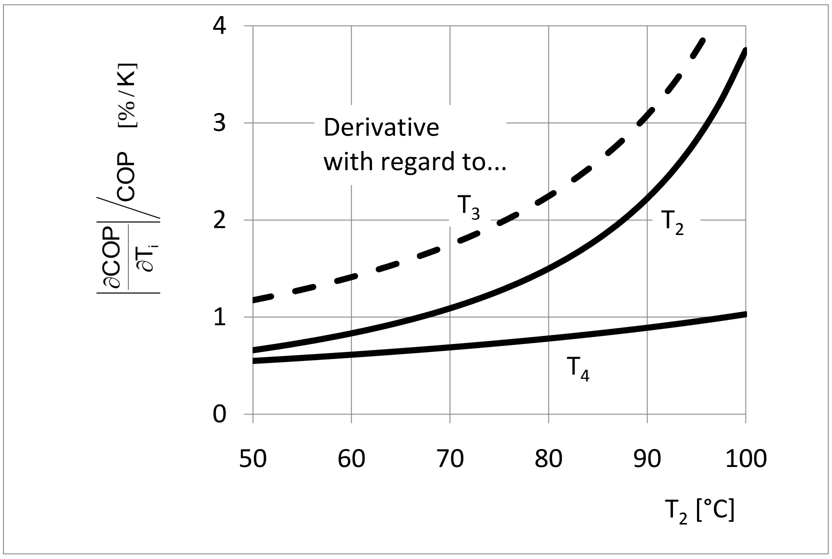

Figure 3: Relative change of the COP of a heat driven heat pump (#2) with temperatures

For heat driven heat pumps (#2, Figure 3), the impact of the temperatures on the COP is in the same order of magnitude as for a compression heat pump. However, the influence of the driving temperature T_4 is the smallest and does not vary much. For intermediate temperatures, the impact of the sink T_3 is the strongest, as discussed before.

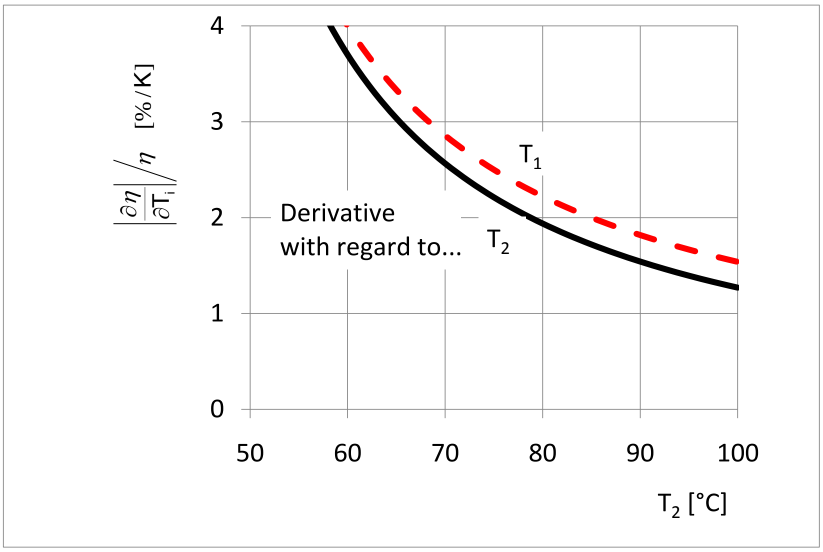

Figure 4: Relative change of the efficiency η of a power station (#3) with temperatures

For a power station which is operated by low temperature heat (#3, Figure 4), the impact of the temperatures is reverse as compared to Figure 2, naturally.

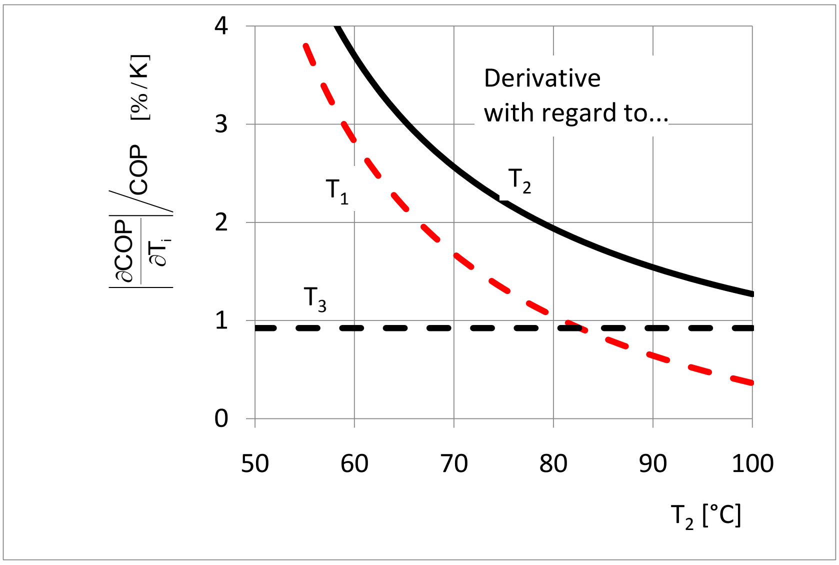

Figure 5: Relative change of the COP of a heat transformer (#4) with temperatures

An unusual result is found for the heat transformer (Figure 5): the relative impact of the high temperature heat sink temperature T_4 does not change with temperature T_2. Therefore, it is comparably small for small heat source temperatures, but for high heat source temperatures it becomes important. Then however, all derivatives are in the order of 1%.

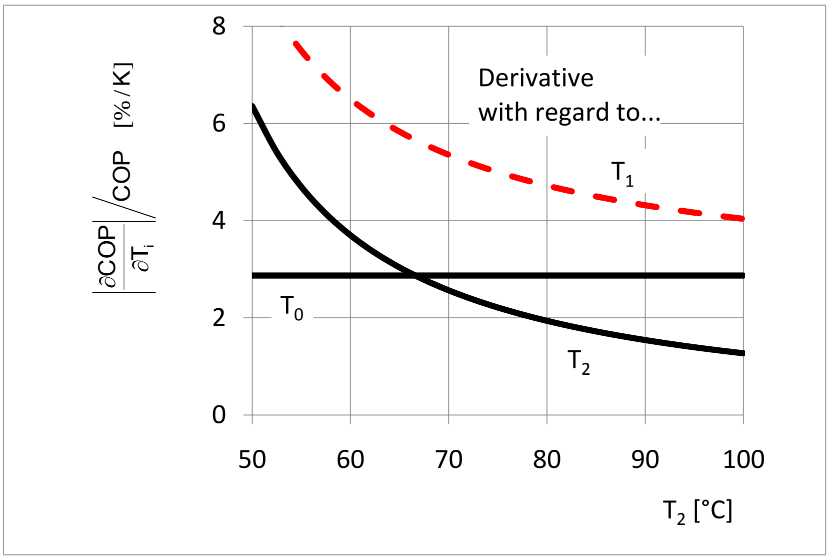

Figure 6: Relative change of the COP of a heat driven refrigerator (#5) with temperatures

The most important result may be found in Figure 6 for the refrigerators (#5): all derivatives are about a factor of 2 larger than for the other processes (be aware that the scale of the ordinate is doubled!). So, it may be stated that waste heat driven chillers are most sensitive to the respective temperatures. The impact of the heat sink temperature T_1 is by far the largest. We will elaborate on these findings in a later chapter. Before we do so, we use the equations from above for another short discussion with the focus on first cost.

Impact on first cost

It is very well known that low efficiency drives operating cost. However, low efficiency also drives first cost: the amount of heat which has to be put through an energy conversion system, of course, depends on its efficiency. Especially in processes which are driven by low-temperature heat the cost for heat exchange becomes a decisive issue. In Table 5 equations for a specific cost ratio σ are given which is defined as the ratio of the overall heat turnover to the useful energy (which may be heat or work):

$$\sigma = \frac{\sum |Q_i|}{Q_{USE}} \qquad (1)$$

These equations may be combined with the equations for efficiency in Table 2; then the derivatives in Table 3 can be applied. This will not be exemplified here because it is a straightforward exercise. It shall be sufficient to state that those temperatures which have a large impact on efficiency will have a large impact on cost, also.

Table 5: Specific cost ratio: relative heat turnover

		Relative heat turnover	Example (see Table 2)
#1	Work-driven heat pump	$\sigma = \frac{\sum \lvert Q_i \rvert}{Q_3} = 2 - \frac{1}{COP}$	1.8
#2	Heat-driven heat pump	$\sigma = \frac{\sum \lvert Q_i \rvert}{Q_3} = 2$	2
#3	Power cycle	$\sigma = \frac{\sum \lvert Q_i \rvert}{W} = \frac{2}{\eta} - 1$	32
#4	Heat transformer	$\sigma = \frac{\sum \lvert Q_i \rvert}{Q_3} = \frac{2}{COP}$	6.9
#5	Heat-driven refrigerator	$\sigma = \frac{\sum \lvert Q_i \rvert}{Q_0} = 2 + \frac{2}{COP}$	6.7

It is interesting to note that the relative heat turnover in the case of the heat driven heat pump (#2) does not depend on the COP. In all other cases, the turnover of heat can only and will be reduced by increasing efficiency. The numerical examples drastically show the problem of producing power from low-temperature heat: as the efficiency of the power plant will be relatively small, the turnover of heat as compared to the power output will be large. The heat pumps (#1 and 2), from this point of view, definitely show the best result. So we can conclude at this stage that valorization of waste heat by pumping it to a useful, higher temperature level may be the most attractive option.

Absorption chillers

The discussion up to now, of course, suffers from the fact that the specific features of the processes which are used do not show up in the fundamental thermodynamic relationships. Therefore, in order to check the validity, a more applied approach will be shown now.

The performance of absorption chillers can be presented most easily with using the characteristic equations. The cooling power, Q_0, as well as the driving heat input, Q_2, can be represented as a linear function of a temperature functional, the characteristic temperature function $\Delta\Delta t$, which, in turn, depends on the mean temperatures of the external heat carriers, driving heat t_2, cooling water t_1, and chilled water t_0:

$$\Delta\Delta t = a t_0 - b t_1 + c t_2 \quad (2)$$

$$Q_0 = S_0 + M_0 \, \Delta\Delta t \quad (3)$$

$$Q_2 = S_2 + M_2 \, \Delta\Delta t \quad (4)$$

The benefit of this representation is the fact that the impact of the temperatures is directly seen. As an example a single-effect LiBr absorption chiller with a nominal cooling capacity of 10 kW shall be used. In order to bring cost into the play the heat flows are normalised by a first cost of 10,000€ for this device. This, of course, is not the real price of the chiller but it is in the right order of magnitude. It renders a specific price of 1000€/kW of cooling capacity. The cost-specific heat flows (W/€) then are given by:

$$q_0 = s_0 + m_0 \, \Delta\Delta t \quad (5)$$

$$q_2 = s_2 + m_2 \, \Delta\Delta t \quad (6)$$

The COP consequently is the ratio

$$COP = \frac{q_0}{q_2} = \frac{s_0 + m_0 \, \Delta\Delta t}{s_2 + m_2 \, \Delta\Delta t} \quad (7)$$

The coefficients are given in Table 6 [1]. The coefficient b gives the impact of the heat sink. It, obviously is the largest one, and it is about double the size as the others. The same order of magnitude resulted from the generic approach (Figure 6) also. The respective characteristic curves are shown in Figure 8. The vertical line marks the design point of the chiller with a cooling capacity of 1W/€ at a characteristic temperature difference of about 22K. Any changes in temperatures may be seen as influencing cooling power or specific cost, respectively.

Table 6: Coefficients for characteristics of an absorption chiller

Coefficient	a	b	c	s_0	m_0	s_2	m_2
Value	1.8	2.5	1	0.09W/€	0.042W/€K	0.2W/€	0.051W/€K

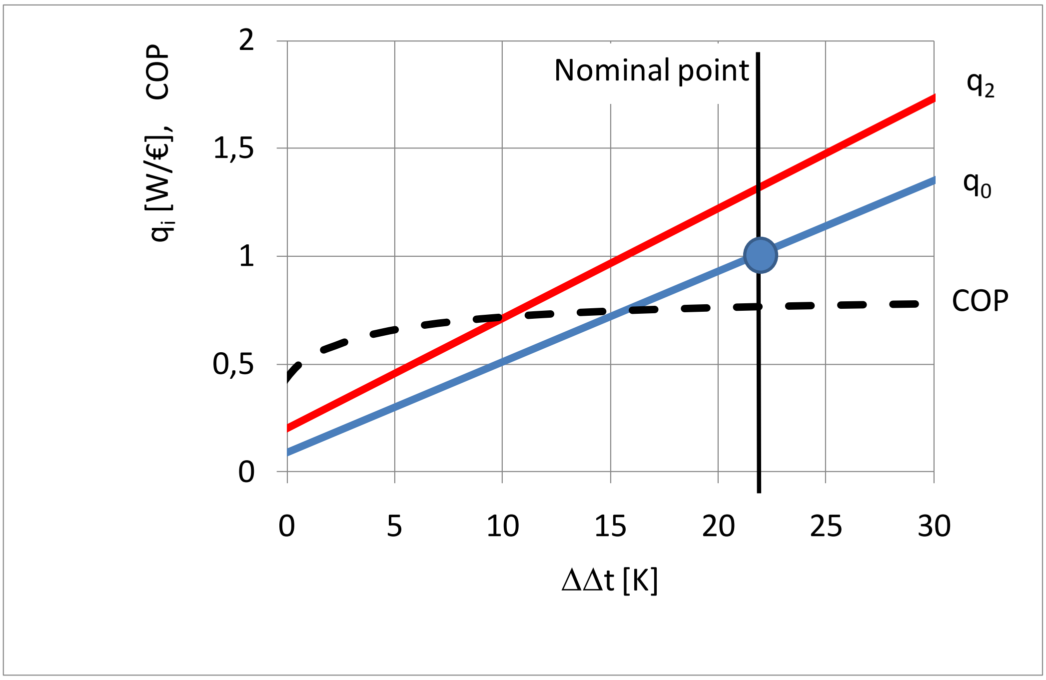

Figure 7: Characteristic curves of a single-effect absorption chiller

In order to see the influence of the temperatures on heat flows and the COP, again the derivatives have to be calculated. The results for the heat flows are given in Table 7. The impact of the temperatures on the driving heat are stronger than on the cooling power. The influence of the heat sink temperature is the largest of the three.

Table 7: Derivatives of the specific heat flows with respect to the temperatures

i	0		1		2	
$\frac{\partial q_0}{\partial t_i}$	a m_0	0.076	-b m_0	-0.105	c m_0	0.042
$\frac{\partial q_2}{\partial t_i}$	a m_2	0.092	-b m_2	-0.128	c m_2	0.051

The impact of the temperatures on the heat flows is almost linear, but it is a non-linear impact on the COP. Moreover, the relative impact is more interesting than the absolute one. Therefore, the relative influence of each temperature on relative cooling capacity and COP is plotted against the cost-specific cooling power q_0 in Figures 8 and 9. Again, a negative value of the derivative is indicated by a dashed line. The nominal point is marked by a vertical line.
The impact of the temperatures on specific power is in the order of 5%/K (driving heat), 8%/K (chilled water), and over 10%/K (heat sink) in the nominal point. It increases strongly when the specific power is reduced. This happens in the case of part load, or in the case of the characteristic temperature difference being small. In this case, the required heat exchange area is relatively large, the chiller will be expensive, and the sensitivity on the temperatures will be high.

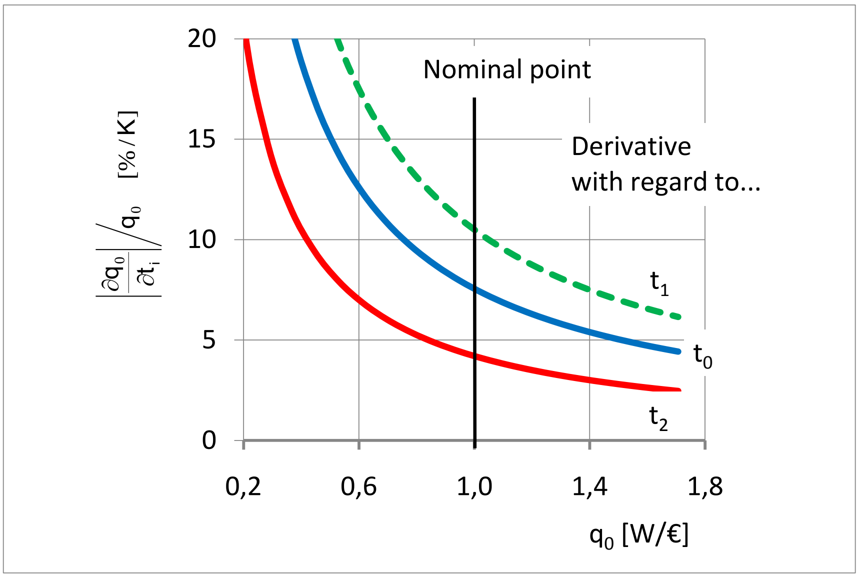

Figure 8: Sensitivity of the specific cooling power on the temperatures

The impact on the COP is significantly less, as long as the specific load is not too small. This can be seen in Figure 7 as well as in Figure 9, where the impact of the temperatures on the COP is plotted against the specific cooling load, again. Once more, the derivative with respect to the heat sink temperature, t_1, is the largest.

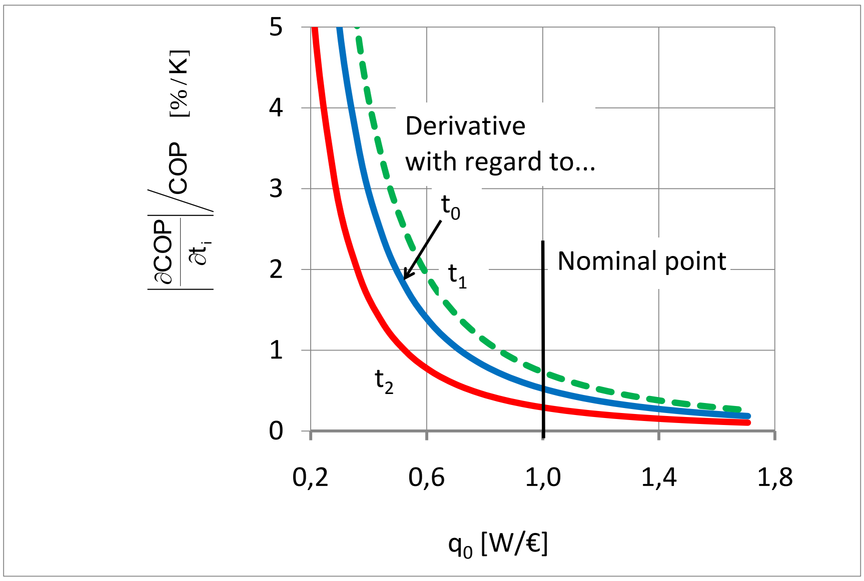

Figure 8: Sensitivity of the COP on the temperatures

Conclusion

From the fundamental relationships which have been presented in this communication it can be concluded that the impact of the temperature and nature of the heat sink on performance and economics in the field of valorization of low-temperature heat is predominant - except, of course, in the case of simple heat pumps. In all other cases the heat flow into this sink accounts for a large fraction of the energetic turnover. For the sake of efficiency, the driving temperature difference must be small which in turn necessitates large heat transfer areas. Heat pumps seem to be the most cost-efficient devices for valorization of low-temperature heat.
Of course a rising ambient or heat sink temperature in any case reduces efficiency. This effect is especially large for heat driven cooling machines. These devices have been studied in more detail using the approach of the characteristic functions. The impact of the heat sink temperature on heat flows (capacity) and performance (COP) is about twice as large as that of the other temperatures.
It can be stated that the research which is dedicated to this field does not match the overall importance within the area of energy engineering.

Nomenclature

a,b,c:	Coefficients [-]
COP:	Coefficient of Performance [-]
g:	Thermodynamic quality [-]
M:	Coefficient [kW/K]
m:	Coefficient [W/€K]
Q:	Heat flow [kW]
q:	Specific heat flow [W/€]
S:	Coefficient [kW]
s:	Coefficient [W/€]
T:	Temperature (process) [K]
t:	Temperature (heat carrier) [K]
W:	Mechanical power [kW]
η:	Efficiency [-]
σ:	Relative heat turnover [-]

Reference

[1] Kühn, A., Ziegler, F. 2005, "Operational results of a 10 kW absorption chiller and adaptation of the characteristic equation", Proceedings of the International Conference Solar Air Conditioning, 6.-7. October 2005, Bad Staffelstein.