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Published in:
Proceedings of the13th IIR-Gustav Lorentzen Conference on Natural Refrigerants

Link to article, DOI:
10.18462/iir.gl.2018.1380

Publication date:
2018

Document Version
Peer reviewed version

Heat pump COP, part 1: Generalized method for screening of system integration potentials

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ABSTRACT

Industrial heat pumps (IHP) are major contributors to the transformation towards a future energy system based on electrical power. The main barrier for IHP integration is the operating cost and thereby the COP. COP is highly dependent on the temperature difference between the source and the sink. Even in the first evaluation of IHP integration, a fairly correct COP is needed. Today, an estimation of the expected COP is often done by IHP suppliers, and it involves detailed choices such as working fluid, compressor technology, and configuration.

This paper (part 1) presents a simple, generic, and generalized method based on the theoretical maximum COP of the Carnot or Lorenz process. It does not involve any technological choices. Based on the model, the first system integration assessment including economic analysis can be done. This is often an iterative process of choosing temperature levels and heating capacity. The use of the model is demonstrated and the general conclusions are presented.

In part 2, the method is extended to account for real process parameters such as working fluid, and compressor and heat exchanger characteristics.

Keywords: Heat Pump, COP, System Integration, Generalized Model, Energy Efficiency, Economic

1. INTRODUCTION

To minimize CO_2 emissions from heat and power productions, the future energy system will to a large extend be based on electrical power from renewable sources as hydro, wind, and solar power. In order to have an efficient production of heat based on electrical power and utilizing low temperature waste heat, industrial heat pumps (IHP) are seen as major contributors to this transformation as they make it possible to produce more thermal power than the electrical power uptake from the grid with a ratio described by the Coefficient Of Performance (COP) higher than unity. Being an alternative to IHPs, an electrical heater will only have a COP of 1 at the best. The main barriers for IHP integration are the installation and operating costs and thereby the COP to compensate a potential higher investment cost by a better performance. The COP is highly dependent on the temperature difference between the source and the sink as well as the level of temperature change in the source and the sink. In most cases, a fairly correct estimation of the COP is needed even in the first evaluation of IHP integration into a process or energy system. According to Lorenz, H, 1895, a theoretically maximum COP (Carnot or Lorenz process) for the temperature set of a given source and sink exists, and Reinholdt *et.al.*, 2016, suggest that this is used as base for the first assessment analysis of heat pump implementation into a given process. A realistic COP for a given process is then estimates by reducing the theoretical maximum COP an efficiency factor covering all the losses in the heat pump system. Further by introducing the flow and thermal properties of one of the source or sink it is also possible to make a preliminary economical calculation as the power consumption and produced heat flow is then known. As the model is based on the theoretical maximum COP the choice of technology and working fluid for the IHP is not to be taken at this first assessment stage. In Ommen, T, et.al. 2018, the method is extended to account for real process parameters such as working fluid, and compressor and heat exchanger characteristics.

2. THEORETICAL HEAT PUMP COP

The theoretical limit for the COP of a heat pump operating between source and sink withconstant temperatures is defined by the Carnot process, which is given by

$$\mathrm{COP_{Car}} = \frac{T_H}{T_H - T_L} \tag{1}$$

where T is in [K].

Figure 1 shows a temperature set for a heat pump having a source cooled from 40 °C to 15 °C and the sink heated from 60 °C to 90 °C . In this case, the T_H and T_L is 90 °C (363 K) and 15 °C (288 K), respectively, shown as dashed lines in the figure. In other words, the heat pump will lift the heat from 15 °C to 90°C with a COP_{Car} = 4.84.

Figure 2 shows the same temperature set, but it has been split into five ideal heat pump processes, which are connected as indicated by the black lines. The five heat pump processes operate in series to fullfil the total heating of the sink and the cooling of the source. As shown in Reinholdt et.al., 2016, the maximum possible COP for this system is 6.62 or 37% higher.

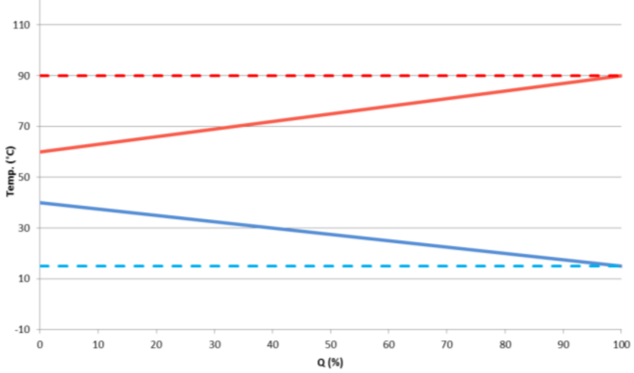

Figure 1: Temperature set for a heat pump in a temperature-heat diagram: Source (full blue) cooled from 40 °C to 15 °C. Sink (full red) heated from 60 °C to 90 °C (Reinholdt et.al., 2016).

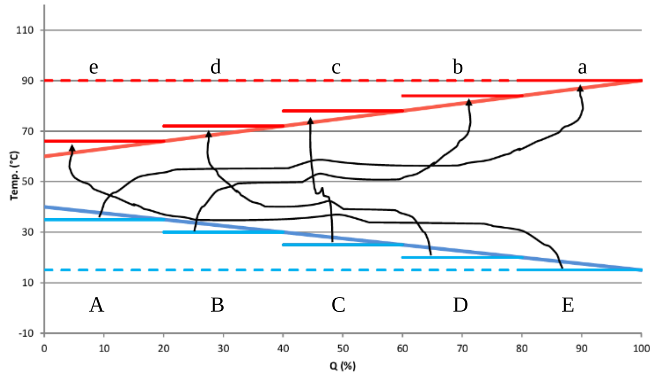

Figure 2: Temperature set from Figure 1 split into five heat pumps interconnected as illustrated by the black lines (Reinholdt et.al., 2016).

H. Lorenz (Lorenz, H., 1895) derived the COP for an infinite number of heat pump processes given by

$$COP_{Lor} = \frac{T_{lm,H}}{T_{lm,H} - T_{lm,L}} \tag{2}$$

Equation (2) is similar to the expression for COP_{Car} given in (1) with the constant temperatures substituted by the logarithmic mean temperature for the source and the sink, respectively, given by

$$T_{lm,L} = \frac{T_{L,o} - T_{L,i}}{ln\, T_{L,o} - lnT_{L,i}} \tag{3}$$

$$T_{lm,H} = \frac{T_{H,o} - T_{H,i}}{ln\, T_{H,o} - lnT_{H,i}} \tag{4}$$

Using the conditions in fig. 1, the COP_{Lor} is 7.33 or 51 % higher than COP_{Car}. Compared to this, the split into only five heat pumps in series reaches as much as 90.3 % of the theoretical maximum based on infinitely many heat pumps.

Tab. 1 shows the operating temperatures for typical applications and the corresponding theoretical maximum COP_{Car} and COP_{Lor} based on source and sink heat exchangers with no temperature difference (pinch temperature difference = 0 K), which corresponds to an infinite heat exchanger area. In other words, the shown COP_{Lor} is the maximum achievable COP for the given temperature sets for the source and the sink side.

Tab. 1 also lists the impact of the utilization of the temperature change in the source and the sink (COP_{Lor}) compared to operating between $T_{L,o}$ and $T_{H,o}$ (COP_{Car}), i.e. from +21 % for "Air conditioning system" having a rather low temperature change of the process streams to +145% for "Heat recovery from process waste water to heat up tap water". The latter also illustrates that the method does not automatically warn the user against possible bad system design as, in such cases, it would probably be more beneficial to make a direct heat exchange between the source and the sink for a part of the heating. For this part the theoretical maximum COP is infinite.

Table 1: Operating temperatures for typical applications and theoretical maximum COP_{Car} and COP_{Lor} based on source and sink heat exchangers with no temperature difference (pinch temperature difference = 0K).

Description		Chilled stream		Heated stream		Carnot	Lorenz	
Application	Season	$T_{L,i}$ (°C)	$T_{L,o}$ (°C)	$T_{H,i}$ (°C)	$T_{H,o}$ (°C)	COP_{Car} (-)	COP_{Lor} (-)	% of COP_{Car}
District heating from Geothermy	Winter	43	15	50	90	4,84	8,40	173,39
	Spring , fall	43	15	50	80	5,43	9,39	172,80
	Summer	43	15	50	70	6,24	10,70	171,55
District heating from Seawater	Winter	5	3	50	90	4,17	5,22	125,15
	Summer	20	10	50	70	5,72	7,41	129,61
Heat recovery from process waste water to heat up tap water	Industry	28	4	7	90	4,22	10,36	245,35
Flue gas condensation	Industry	40	15	42	46	10,30	19,03	184,80
Heat recovery from process water to district heating	Industry	18	6	37	67	5,58	8,16	146,36
District heating from wastewater	Winter	14	3	43	75	4,84	6,60	136,51
	Summer	18	3	43	75	4,84	6,87	142,08
District heating from ground water	Winter	9	2	35	90	4,13	5,95	144,24
	Summer	9	2	35	75	4,77	6,67	139,94
District heating from river water	Winter	5	2	30	70	5,05	7,00	138,76
	Summer	17	13	35	75	5,62	8,28	147,40
Air conditioning system	All year	12	7	30	35	11,01	13,29	120,75
Milk cooling	All year	20	4	20	65	5,54	10,49	189,23

The result up until now has been based on perfect heat exchangers with no temperature difference (pinch temperature = 0 K).

Fig. 3 illustrates a heat pump process having finite and constant temperature differences ΔT_{Pinch} on both the source and the sink side. The heat pump will operate between the evaporation temperature T_E on the source side and the condensation temperature T_C on the sink side. In other words, the heat pump will have a higher temperature lift which will lower the COP.

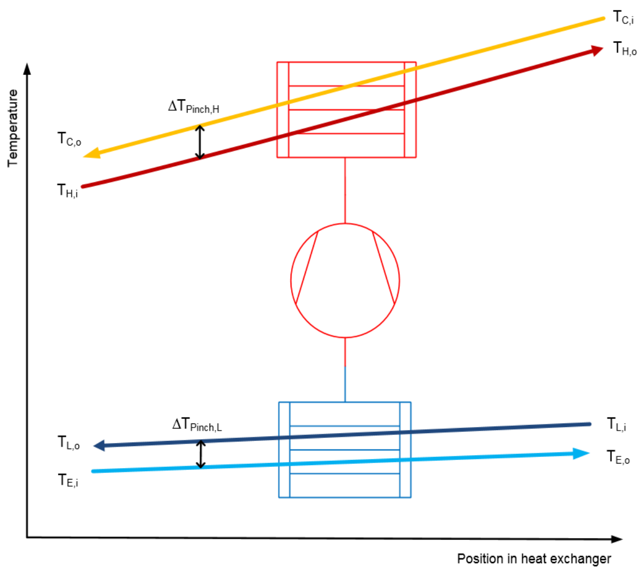

Figure 3: Heat pump process having finite and constant temperature difference ΔT_{Pinch} on both source and sink side.

Tab. 2 is identical to Tab. 1 except for the fact that a more realistic finite temperature difference of 3 K is introduced. As all other parameters are unchanged, the drop in COP is solely caused by the finite temperature difference in the heat exchanger on both the cold and the hot side of the heat pump. The relative drop in COP is in the range of 6% to 35%. Therefore, a first conclusion could be that the choice of heat exchanger has to be very carefully done in cases with the highest drop in COP. However, Tab. 2 also discloses that operating conditions with the highest drop also have the highest COP. In other words, in some cases, the theoretical COP will be so high that it leaves room for accepting higher losses (compared to the theoretical limit), still being a good business case for the real application.

Table 2: Operating temperatures for typical applications and theoretical maximum COP_{Car} and COP_{Lor} based on source and sink heat exchangers with a pinch temperature difference = 3 K. The drop in COP_{Car} and COP_{Lor} compared to Table 1 as well as the COP values from Table 1 are shown in the highlighted columns to the right.

Description		Chilled stream		Heated stream		COP_{Car}	COP_{Lor}		COP_{Car}	ΔCOP_{Car}	COP_{Lor}	ΔCOP_{Lor}
Application	Season	$T_{L,i}$ (°C)	$T_{L,o}$ (°C)	$T_{H,i}$ (°C)	$T_{L,o}$ (°C)	ΔT = 3K	ΔT = 3K	% of COP_{Car}	ΔT = 0K	%	ΔT = 0K	%
District heating from Geothermy	Winter	43	15	50	90	4,52	7,38	163	4,84	7%	8,40	14%
	Fall	43	15	50	80	5,02	8,12	162	5,43	8%	9,39	16%
	Summer	43	15	50	70	5,67	9,05	160	6,24	10%	10,70	18%
District heating from Seawater	Winter	5	3	50	90	3,94	4,83	123	4,17	6%	5,22	8%
	Summer	20	10	50	70	5,24	6,60	126	5,72	9%	7,41	12%
Heat recovery from process waste water to heat up tap water	Industry	28	4	7	90	3,98	8,75	220	4,22	6%	10,36	18%
Flue gas condensation	Industry	40	15	42	46	8,71	14,12	162	10,30	18%	19,03	35%
Heat recovery from process water to district heating	Industry	18	6	37	67	5,12	7,16	140	5,58	9%	8,16	14%
District heating from wastewater	Winter	14	3	43	75	4,50	5,95	132	4,84	8%	6,60	11%
	Summer	18	3	43	75	4,50	6,17	137	4,84	8%	6,87	11%
District heating from ground water	Winter	9	2	35	90	3,90	5,43	139	4,13	6%	5,95	10%
	Summer	9	2	35	75	4,44	6,00	135	4,77	7%	6,67	11%
District heating from river water	Winter	5	2	30	70	4,68	6,25	134	5,05	8%	7,00	12%
	Summer	17	13	35	75	5,16	7,25	140	5,62	9%	8,28	14%
Air conditioning system	All year	12	7	30	35	9,15	10,64	116	11,01	20%	13,29	25%
Milk cooling (Rø-Ka case)	All year	20	4	20	65	5,09	8,83	173	5,54	9%	10,49	19%
Tipical (Rø-Ka case)	All year	30	25	40	80	5,84	8,81	151	6,42	10%	10,36	18%

The close correlation between the high COP and the drop in COP when introducing finite temperature difference can be explained by comparing the temperature lift ΔT_{lift} of the heat pump with and without the finite temperature difference of 3 K as shown in Tab. 3. As ΔT_{lift} is lowered, the relative impact of the 3 K fixed temperature difference is raising, which gives a higher and higher drop in COP, but also results in a higher and higher COP. ΔT_{lift} is defined as

Table 3: The impact on theoretical maximum COP_{Car} and COP_{Lor} based on three temperature sets and source and sink heat exchangers with a temperature difference = 3K (pinch temperature).

	Chilled stream		Heated stream		Carnot			Lorenz		
ID	$T_{L,i}$ (°C)	$T_{L,o}$ (°C)	$T_{H,i}$ (°C)	$T_{H,o}$ (°C)	COP_{Car}	Δt_{lift} (K)	ΔCOP_{Car}	COP_{Lor}	Δt_{lift} (K)	ΔCOP_{Lor}
1	25	15	75	90	4,8	75	-	5,7	75	-
2	22	12	78	93	4,5	81	7%	5,2	81	8%
3	25	15	35	40	12,5	25	-	17,7	25	-
4	22	12	38	43	10,2	31	19%	13,3	31	25%
5	25	20	25	30	30,3	10	-	60,1	10	-
6	22	17	28	33	19,1	16	37%	27,6	16	54%

$$\Delta T_{lift} = T_{H,o} - T_{L,o} \tag{5}$$

3. REALISTIC HEAT PUMP COP

The above derivations are based on theoretical, loss free heat pump cycles. In Reinholdt et.al., 2016, it was suggested that an expected COP of a real system is estimated by introducing the Lorenz-Efficiency η_{Lor} given by

$$\eta_{Lor} = \frac{COP_{HP}}{COP_{Lor}} \tag{6}$$

, where COP_{HP} is the COP of the real heat pump taking all the losses in the heat pump system into account.

Based on the best industrial refrigeration system, Reinholdt et.al., 2016, suggest the use of η_{Lor} in the range of 50 % to 60 % for the maximum achievable COP_{Lor} for a first assessment analysis by using (2) and (6). In Ommen, T, et.al. 2018, a more qualified estimate of the maximum achievable η_{Lor} is derived. This estimate is based on real thermodynamic properties for the possible working media (refrigerant).

Using the Carnot limit (1) and the Lorenz limit (2), it is possible to draw a set of curves of the theoretical maximum COP for a given source and sink temperature set as shown in Fig. 4. A first estimation of the minimum required COP is the ratio between the price of energy for the alternative (e.g. natural gas) and the driving energy for the IHP (e.g. electric power). Having a ratio of 1:3, the IHP has to have a COP higher than 3 in order to deliver cheaper energy. Using a η_{Lor} = 60 % and a minimum COP = 3, the corresponding COP_{Lor} is 5 for an assumed efficiency of the alternative heating device (e.g. boiler) of 100%.

The marking of the area with a COP < 5 in Fig. 4 corresponds to an estimated real COP < 3. In other words, for the fixed sink outlet temperature ($T_{H,o}$), the source outlet temperature ($T_{L,o}$) has to be above the red area. Based on Fig. 4, it suggeeted that it will not be possible to reach a needed supply (sink) heated from 120 °C to 150 °C based on the ambient air or the ambient water at $T_{L,i}$ < 30 °C if the needed COP has to be minimum 3.

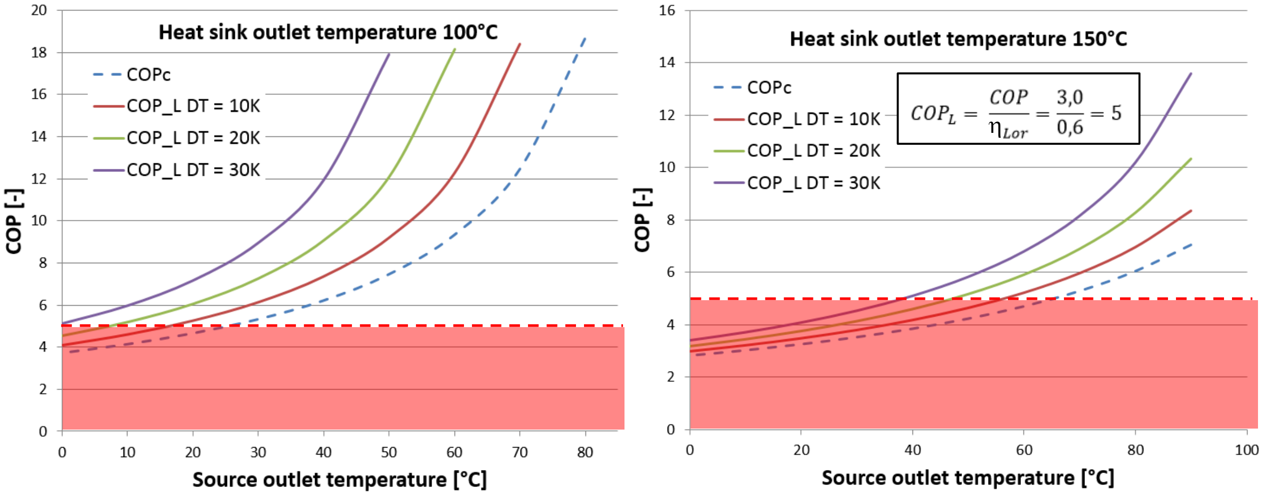

Figure 4: Theoretical maximum COP for a fixed $T_{H,o}$ = 100 °C and 150 °C, respectively, for a given $T_{L,o}$. COP_{Lor} (called COP_L in the diagram) is shown for a 10 K, 20 K, and 30 K temperature change in both source and sink. Red area marks the conditions having a COP < 3.

4. FIRST ASSESSMENT HEAT PUMP SIZING

The absolute main driver for the installation of IHP is to supply the needed heat in a "more appropriate way". In most cases, this will be the cost of the heat. As shown in (1), COP is very dependent on the operation temperatures given by the source and the sink temperature sets, which turn the analysis of the different possible implementations of IHPs in a given process into an iterative task and not a trivial task.

For a heat pump, COP_{HP} links the production of heat $\dot{Q}_H$ directly to the cost of producing it as given by (7):

$$COP_{HP} = \frac{\dot{Q}_H}{P} \tag{7}$$

, where the mechanical power uptake P by the heat pump is given by

$$P = \dot{Q}_H - \dot{Q}_L \tag{8}$$

When sizing a heat pump, the source flow or needed heat supply as well as the temperature sets are normally known to some extent. Knowing the heat capacity of the source and/or the sink, it is possible to calculate the heat input or output of the heat pump using (7) or (8).

$$\dot{Q}_L = Cp_L\, \dot{m}_L (T_{L,i} - T_{L,o}) \tag{9}$$

$$\dot{Q}_H = Cp_H\, \dot{m}_H\, (T_{H,o} - T_{H,i}) \tag{10}$$

Based on the temperature sets, the estimation of η_{Lor} COP_{HP} can be made, and by knowing the $\dot{Q}_L$(7) or the $\dot{Q}_H$ (8), it is now possible to estimate the power uptake using (9) and (10), which are equivalent to the electrical consumption if the heat pump is electrically driven. When estimating the yearly operating hours (N_{year}) of the heat pump, all parameters are hereby available in order to make an estimate of the operating cost O per year. Knowing the cost of an alternative supply of the needed heat, it is, furthermore, possible to estimate the profitability of a heat pump installation. The presented methodology has been implemented into a simple calculation tool "HP FAT" (Heat Pump First Assessment Tool) based on the EES programming environment

(F-Chart, 2017) of which the input/result screen can be seen in Fig. 5. HP FAT can be used without access to the EES programming environment, and it is available at website of Danish Technological Insitute (DTI, 2018).

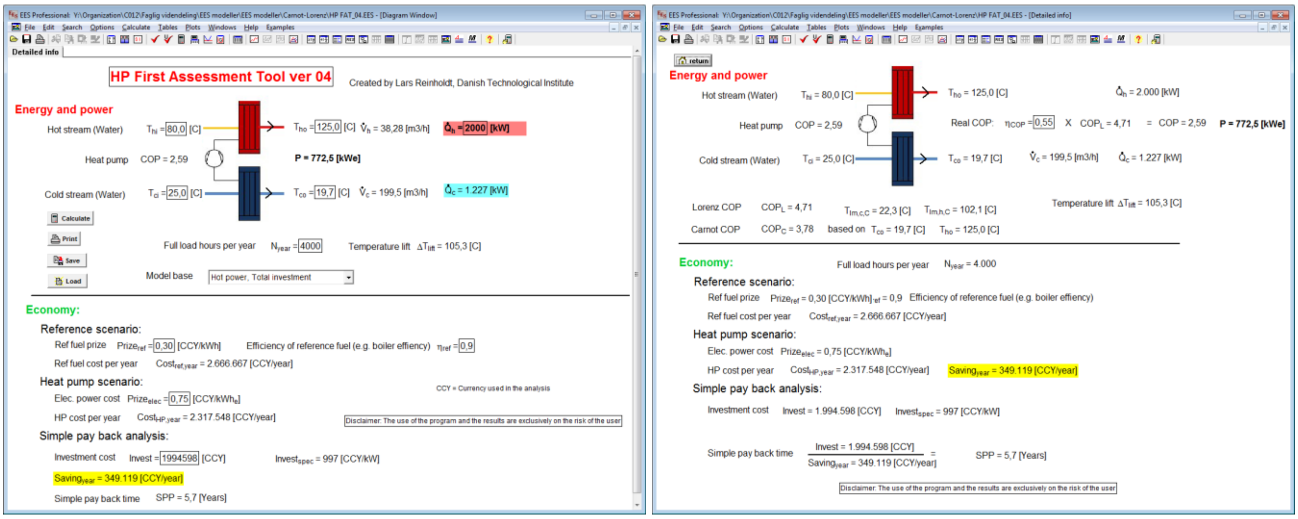

Figure 5: Heat Pump First Assessment calculation tool "HP FAT", ver. 04. Main input/result screen to the left and the detailed information screen to the right, where η_{Lor} can be changed.

A simple model for alternative heat supply is included in the tool, i.e. the "Reference scenario" has fuel costs (e.g. natural gas) and efficiency (e.g. 90% boiler efficiency) included. Moreover, by having the electrical costs (for running the heat pump) as an input as well, it is possible to calculate the savings in annual operating costs ($Saving_{year}$) when implementing an IHP (maintenance costs are not included in the model). The investment costs can be entered as total costs (*Invest*) or specific costs per delivered kW heat ($Invest_{spec}$). Base on this, the simple payback period (*SSP*) can be calculated as

$$SSP = \frac{Invest}{Saving_{year}} \tag{11}$$

Alternatively, the matching investment can be calculated based on a given (required) *SSP*.

Example: An industrial process needs 4000 h/year 2MW pressurized water heated from 80°C to 125°C, and the process has 200m^3/h cooling water at 35°C waste heat. Today, the process is heated by natural gas having a boiler efficiency of 90% and a cost of 0.30 CCY/kWh gas and 0.75 CCY/kWh electrical power (CCY being "Currency", the values are typically Danish energy prizes in DKK) and $SSP < 4$ for the first analysis. η_{Lor} is chosen to 0.55. The result is shown in Fig. 5 having a $SSP = 5.7$ year or 1.7 years too high.

Reducing the *SSP* to the required 4 years can be done in different ways. When using HP FAT in a iterative way and (for illustration) only changes one parameter at a time, some possible solutions are shown in Tab. 4.

Table 4: Some possible changes to the input conditions of "HP FAT" in Fig. 5 in order to reduce *SSP* from 5.7 years to 4.0 years.

Parameter: old > new value	**Remark**
N_{year}: 4.000 h > 5.700 h	If a future extension of the production is planned
η_{Lor}: 0.55 > 0.59	A very careful design of the IHP system and probably more costly installation will be needed
$T_{H,o}$: 125 °C > 112 °C	If only a part of the needed heating to 125 °C is done by the IHP. In this case, only 71 % of the heating is done by the IHP or 1422 kW and the rest is done by other means. This will also need other means as the SSP is affected as well
$T_{L,i}$: 25 °C > 30.2 °C	A more detailed analysis of waste heat sources can disclose other sources.

6. CONCLUSION

Even in the first evaluation of IHP integration into a process or energy system, a fairly correct COP is needed in an easy accessible way. The theoretical maximum COP for a heat pump is limited by the Lorenz COP. This fact combined with the expectations of how efficient heat pumps can be is used to make curves show the requirements of a heat source in order to reach a required delivery temperature and COP.

The method is used in the modelling tool HP FAT, which makes it possible also to make a basic economic analysis of the implementation of the IHP. The use of the tool to match the need from a given thermal process in an iterative way is demonstrated.

Moreover, as the tool can be used to illustrate the impact by changing operating parameters, the economic analysis is based on simple payback. However, it can be developed to include more detailed models and more detailed configurations of the energy system as well as be the base for economic analysis as well.

NOMENCLATURE

COP	*Coefficient Of Performance* (-), *based on the supplied heat (heat pump COP)*	$\dot{Q}$	*Heat flow (kW)*
T	*Temperature (K or °C)*	*Cp*	*Specific heat capacity (kJ/kg)*
$\dot{m}$	*Mass flow (kg/s)*	*P*	*Mechanical power (kW)*
n_h	*Operating hours (year^{-1})*	*O*	*Operating cost (CCY/year)*
Subscript:			
HP	*Heat Pump*	*Car*	*Carnot*
Lor	*Lorenz*	*H*	*High*
L	*Low*	*lm*	*Logarithmic mean*
i	*in*	*o*	*out*
C	*Condenser*	*E*	*Evaporator*

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