Conventional and advanced exergoenvironmental analysis of an ammonia-water hybrid absorption-compression heat pump

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Abstract:

The ammonia-water hybrid absorption-compression heat pump (HACHP) is a technology suitable for industrial scale heat pumps in the process industry. A helpful tool in the design of cost effective and low environmental impact energy conversion systems, such as the HACHP, is the application of an advanced exergy-based analysis, comprised of both an advanced exergy, exergoeconomic and exergoenvironmental analysis. Recent studies have presented both the advanced exergy and advanced exergoeconmic analysis of the HACHP. An exergoenvironmental analysis combines exergy analysis with life cycle assessment to allocate the initial and operational environmental impact to the system components, thus revealing the main sources of environmental impact. The application of the advanced exergoenvironmental analysis improves the level of detail attained. This is achieved by accounting for technological and economic constraints as well as component interdependencies. The advanced exergoenvironmental analysis shows that the highest avoidable environmental impact stems from the compressor, followed by the absorber. Further, it is found that the initial environmental impact of the HACHP is negligible compared to the operational environmental impact.

Key Words:

Hybrid heat pump, ammonia-water heat pump, Life cycle assessment, Exergoenvironmental analysis, Advanced Exergoenvironmental analysis

1   Introduction

The hybrid absorption-compression heat pump (HACHP) or vapour compression heat pump with solution circuit is based on the Osenbrück cycle. The advantage of the HACHP is the reduction of vapour pressure and the temperature glides of the absorption and desorption processes. The reduction of vapour pressure allows the construction of high temperature heat pumps with standard pressure refrigeration components. The non-isothermal phase change in the absorber and desorber allow the matching of the temperature glides to those of the sink and source and thus a reduction of the entropy generation driven by heat transfer over a finite temperature difference. Consequently, the HACHP is a feasible measure of approaching the Lorenz cycle.

Jensen et al. [1] and Ommen et al. [2] investigate the technical and economic constraints of industrial scale vapour compression heat pumps [2] and HACHP [1] and compare the economic viability of the two technologies. This shows that the HACHP can attain both higher heat supply temperature and higher temperature lifts and further that the HACHP offers a higher net present value of the investment for most operating conditions.

Jensen et al. [3] investigates the economic and environmental benefit of replacing a natural gas boiler with a HACHP for heat supply in a spray-drying facility. It is shown that the HACHP installation is both economically and environmentally beneficial compared to a natural gas burner. However, the environmental benefit in [3] is based entirely on the reduction of CO_2 emission. Thus the environmental impact of construction, transportation and disposal of the system is not accounted for.

In the present study a life cycle assessment (LCA) of the HACHP is conducted to account for this. The LCA was then combined with the advanced exergy analysis to form an advanced exergoenvironmental analysis. This allows the environmental impact of both the operation of the HACHP and the construction, transportation and disposal of the HACHP to be allocated to the component that causes the environmental impact. Thus, it gives the system designer knowledge of which components have the highest environmental impact and thereby which components are of most interest for further improvement. Further, the exergoenvironmental analysis reveals whether the environmental impact of the component is dominated by operation or by the construction, transportation and disposal. Thereby, revealing whether the component is best improved by improving the exergy efficiency at the expense of an increased size or vice versa.

The total annual rate of environmental impact is comprised of two contributions: the non-exergetic environmental impact, associated with the construction, transportation and disposal, measured by $\dot{Y}_k$ and the environmental impact of operating the component, measured by the rate of environmental impact associated with the exergy destruction of the component, $\dot{B}_{D,k} = b_{F,k}\dot{E}_{D,k}$.

In recent years advanced methods have been introduced to the field of exergy-based analysis [4]. These improve the accuracy of the analysis as they account for component interdependencies and reveal the potential for environmental impact reduction [4, 5]. The component interdependencies are accounted for by splitting both, $\dot{B}_{D,k}$, and $\dot{Y}_k$, into an *endogenous* (EN) and an *exogenous* (EX) part [6]. The endogenous part is the environmental impact associated only with the design and operation of the component itself, while the exogenous part is the environmental impact associated with the remaining components. To determine the reduction potential, the rates of environmental impact $\dot{B}_{D,k}$ and $\dot{Y}_k$ are spilt into an *avoidable* (AV) and *unavoidable* (UN) part [7]. The unavoidable part of the $\dot{B}_{D,k}$ is the environmental impact of exergy destruction when the exergy efficiency of the component is increased to the technical and economic limitations. While the unavoidable part of $\dot{Y}_k$ is the non-exergetic environmental impact when the exergy efficiency of the component approaches 0.

In order to perform an advanced exergoenvironmental analysis, first an advanced exergy analysis must be applied. An advanced exergy analysis of the HACHP is performed and presented in [8]. The present analysis will be a direct extension of this work. In the present analysis conventional exergoenvironmental analysis on the HACHP will be presented and combined with the advanced exergy analysis in [8] to conduct the advanced exergoenvironmental analysis. Further, the results of the advanced exergoenvironmental analysis will be compared to the results of the advanced exergoeconomic analysis presented in [9].

2 Method
2.1 HACHP working principle & modelling

The general layout of the HACHP may be seen in Fig. 1a. In the desorber heat is supplied from a heat source in order to desorb the ammonia from the mixture. The phase change in the desorber is incomplete and thus the stream exiting the desorber is a liquid/vapour mixture. By separating the phases in a liquid-vapour separator (LVS), it can be ensured that only the vapour phase enters the compressor, while the liquid phase is supplied to the pump. The liquid stream will be lean in ammonia while the vapour stream consists mainly of ammonia. As the pressure increase in an incompressible fluid, such as the lean liquid, does not lead to any significant temperature increase it is useful to preheat the lean mixture by an internal heat exchanger (HEX). After preheating the lean mixture it is mixed with the vapour stream exiting the compressor. This causes an adiabatic absorption of the vapour phase into the lean liquid until thermodynamic equilibrium is reached. In the absorber a diabatic absorption of the ammonia vapour into the liquid is undertaken while releasing heat to the sink. The exiting stream is a saturated liquid mixture. It is beneficial to sub-cool this stream and therefore it is used as the heat source in the internal HEX. After this the sub-cooled liquid mixture, is throttled to the low pressure resulting in a two-phase stream that enters the desorber.
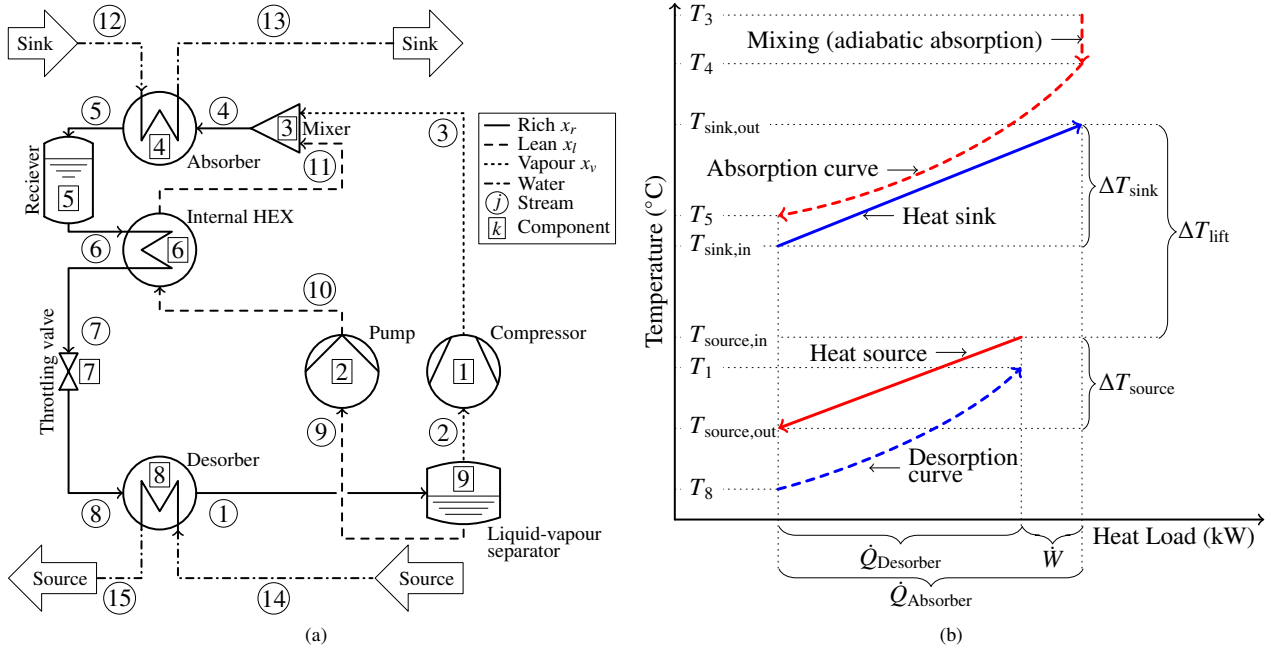
Fig. 1. (a) Principle sketch of the HACHP, (b) HACHP process sketched in a temperature - heat load diagram

Table 1. HACHP Operating condition and the design variables to determine the real cost, unavoidable exergy destruction cost and unavoidable non-exergetic cost

k^{th}	Unavoidable $\dot{B}_{D,k}$		Unavoidable $\dot{Y}_{D,k}$				Operating condition		
(1)	η_{is}^{UN}	= 0.95	TEI^{UN}	=	85% of TEI^{real}		T_{12}	=	80 °C
	η_{elec}^{UN}	= 0.99					$\Delta T_{glide,sink}$	=	20 K
(2)	η_{is}^{UN}	= 0.95	TEI^{UN}	=	85% of TEI^{real}		ΔT_{lift}	=	25 K
	η_{elec}^{UN}	= 0.99					$\dot{m}_{12}$	=	10 kg/s
(4)	ΔT_{pp}^{UN}	= 1 K	ΔT_{pp}^{UN}	=	35 K		$\dot{m}_{14}$	=	15 kg/s
(5)	ϵ^{UN}	= 0.98	ϵ^{UN}	=	0.25 -				
(7)	ΔT_{pp}^{UN}	= 1 K	ΔT_{pp}^{UN}	=	35 K				

The process described above is sketched in the temperature – heat load diagram shown in Fig. 1b. Here the temperature lift, ΔT_{lift}, is defined as the difference between the sink outlet temperature (heat supply temperature) and the source inlet temperature. The temperature glide, ΔT_{glide}, is defined as the temperature difference between the inlet and outlet of the sink and source, respectively. Further, it may be seen that the profiles of the equilibrium absorption and desorption processes are non-linear. Therefore, when modelling the HACHP it is not sufficient to ensure positive temperature difference at the inlet and outlet of the absorber and desorber. To ensure a feasible profile it is necessary to verify that there is a positive temperature difference over the entire heat transfer process.

The thermodynamic model of the HACHP was developed in Engineering Equation Solver [10] and follows the procedure presented in [8]. The inputs to the thermodynamic model may be seen in Table 1. Here the operating condition and the design variables used to determine the unavoidable exergetic and non-exergetic environmental impact are listed. The stated operating conditions result in a heat load of $\dot{Q}_4 = 837$ kW

All HEXs were assumed to be of a plate type with a chevron corrugation pattern. All three HEXs were modelled based on heat transfer and pressure drop correlations from the open literature. The applied calculation procedure and the correlations used are described in detail in [1].

2.2 Life cycle assessment of the HACHP

The LCA method is a generalized approach used to assess the environmental impact of all stages of a product, from construction to disposal. The process of conducting a LCA has been standardised in [11]. To conduct a LCA it is necessary to first compile an inventory analysis of the needed materials, energy inputs and releases (pollutants). Following, the environmental impact of all identified flows of materials, energy and pollutants are evaluated. From this the results can be interpreted, the main sources of environmental impact can be identified and measures to reduce them can be sought.

The main components used in the construction of a HACHP are identified in [1] in which costs are also correlated based on Danish intermediate trade business prices and individual consumers suggested retail prices. For the present study the mass of the components were correlated based on the aggregated data from [1]. The following assumptions were applied:

- The mass of a compressor was a function of the compressor displacement volume and the pressure limit [12].
- The mass of an electrical motor with a fixed efficiency was dependent only on the shaft power [13].
- The mass of a HEX was a function of the HEX area and the pressure limit [14].
- The mass of a pump was a function of the shaft power [15].
- The mass of a LVS was a function of the compressor suction line volume flow rate. The size was chosen to attain a vapour velocity of 0.4 m/s in the separator [13]. This corresponds to an entrained liquid droplet size with a maximum diameter of 0.25 mm.
- The mass of a high pressure receiver was a function of the volume and pressure limit [13].

The materials used for the construction of the components were also identified from these sources [12, 13, 14, 15]. The material inventory is stated in Table 2 along with the quantity of material needed to construct a HACHP with $\Delta T_{\text{pp},4} = \Delta T_{\text{pp},4} = 10$ K, $\epsilon_6 = 0.7$ $\eta_{\text{is},1} = 0.75$, $\eta_{\text{el},1} = 0.95$, $\eta_{\text{is},2} = 0.85$ and $\eta_{\text{el},2} = 0.95$. Further, Table 2 states the relevant production method for each component type. The type "vessels" covers both the liquid/vapour-separator and the high pressure receiver.

In order to quantify the environmental impact of the material inventory data the Eco-indicator 99 [16] has been applied. Eco-indicator 99 uses average European data and has been applied in several exergoenvironmental studies [17, 18]. It is thus assumed to be a suitable indicator for the study at hand. The Eco-indicator 99 points for each material and production method investigated are stated in Table 2. Further, the Total Environmental Impact (TEI) of all components is presented.

The technical lifetime of HACHP was assumed to be 15 years with 3500 operating hours per year.

2.3 Exergoenvironmental analysis

The basis of a conventional exergoenvironmental analysis is the association of environmental impact to all streams of exergy in the system. The exergy specific environmental impact is symbolized by: b_j. To determine b_j, an exergy analysis must be applied to the system such that the exergy flow rates, $\dot{E}_j$, of all streams are known. The exergy analysis of the HACHP is described in detail in [8]. Based on the exergy flow rates the environmental impact rate of each stream was calculated as: $\dot{B}_j = b_j \dot{E}_j$.

To determine b_j for each stream, environmental impact balances were applied to all system components. For a non-dissipative component the environmental impact balance can be formulated using fuel and product environmental impact, see Eq. (1).

$$\dot{B}_{P,k} = \dot{B}_{F,k} + \dot{Y}_k \tag{1}$$

The definition of the exergy fuel and product, as well as the fuel and product environmental impact for the non-dissipative components and for the total HACHP system are stated in Table 3. To ensure that the set of equations was specified, a number of auxiliary relations were needed. The applied auxiliary relations are listed in Table 3 (the F-rule [19] was applied).

For the dissipative components (mixer and throttling valve) and passive components (LVS and re-

Table 2. Estimation of the needed materials and the ECO 99 indicator points for the materials, production, transportation and disposal.

			ECO 99 (mpt/kg)	M^{real} (kg)	TEI^{real} (mpt)
Compressor	Materials				
		Cast Iron	240.0	937.6	$225 \cdot 10^3$
	Production				
		Milling	115.0	26.31	$302 \cdot 10^2$
Electric motor	Materials				
		88% Cast iron	240.0	889.6	$213 \cdot 10^3$
		12% Copper	1400	113.4	$159 \cdot 10^3$
Plate HEX	Materials				
		98% High alloy steel	910.0	96.01	$873 \cdot 10^2$
		2.0% Copper	1400	1.961	$274 \cdot 10^1$
	Production				
		Sheet production	30.00	96.01	$288 \cdot 10^1$
		Pressing	23.00	96.01	$221 \cdot 10^1$
Pump	Materials				
		69% Cast iron	240.0	51.19	$123 \cdot 10^2$
		25% Low alloy steel	110.0	18.55	$204 \cdot 10^1$
		6.0% Copper	1400	4.451	$623 \cdot 10^1$
Vessels	Materials				
		High alloy steel	910.0	304.1	$276 \cdot 10^3$
	Production				
		Sheet production	30.00	304.1	$912 \cdot 10^1$
Working fluid					
		Ammonia	160.0	11.90	$190 \cdot 10^1$
		Water	0.026	2.976	$773 \cdot 10^{-4}$
Transportation					
		Truck 16t (1000 km)	34.00	2431	$827 \cdot 10^2$
Disposal					
		Recycling ferro metals	−70.00	2278	$-159 \cdot 10^3$

Table 3. Component product and fuel definitions and auxiliary relations

k^{th}	Exergy fuel $\dot{E}_{F,k} =$	Exergy prod. $\dot{E}_{P,k} =$	Fuel cost $\dot{B}_{F,k} =$	Prod. cost $\dot{B}_{P,k} =$	Auxiliary relations
(1)	$\dot{W}_1$	$\dot{E}_3 - \dot{E}_2$	$b_w \dot{W}_1$	$\dot{B}_3 - \dot{B}_2$	-
(2)	$\dot{W}_2$	$\dot{E}_{10} - \dot{E}_9$	$b_w \dot{W}_2$	$\dot{B}_{10} - \dot{B}_9$	-
(4)	$\dot{E}_4 - \dot{E}_5$	$\dot{E}_{13} - \dot{E}_{12}$	$\dot{B}_4 - \dot{B}_5$	$\dot{B}_{13} - \dot{B}_{12}$	$b_4 = b_5$, $b_{12}=0$
(6)	$\dot{E}_6 - \dot{E}_7$	$\dot{E}_{11} - \dot{E}_{10}$	$\dot{B}_6 - \dot{B}_7$	$\dot{B}_{11} - \dot{B}_{10}$	$b_6 = b_7$
(8)	$\dot{E}_{14} - \dot{E}_{15}$	$\dot{E}_1 - \dot{E}_8$	$\dot{B}_{14} - \dot{B}_{15}$	$\dot{B}_1 - \dot{B}_8$	$b_{14} = b_{15}$, $b_{14}=0$
Sys.	$\dot{E}_{F,1} + \dot{E}_{F,2} + \dot{E}_{F,8}$	$\dot{E}_{P,4}$	$\dot{B}_{F,1} + \dot{B}_{F,2} + \dot{B}_{F,8}$	$\dot{B}_{P,4}$	$b_2 = b_9$

ceiver) exergy fuel and product could not be defined in a meaningful way and the environmental impact balance in Eq. (1) could not be applied. By applying the general form [19] the environmental

impact balance for these four components were derived, as seen in Eq. (2)-(5).

(3) Mixer :
$$\dot{B}_3 + \dot{B}_{11} + \dot{Y}_3 = \dot{B}_4 \tag{2}$$

(5) Reciever :
$$\dot{B}_5 + \dot{Y}_5 = \dot{B}_6 \tag{3}$$

(7) Throttling valve :
$$\dot{B}_7 + \dot{Y}_7 = \dot{B}_8 \tag{4}$$

(9) Liquid/vapour separator :
$$\dot{B}_1 + \dot{Y}_9 = \dot{B}_2 + \dot{B}_9 \tag{5}$$

Using the fuel and product definitions, the specific fuel and product environmental impact of the components , $b_{F,k}$ and $b_{P,k}$, were determined, as seen in Eq. (6).

$$b_{F,k} = \frac{\dot{B}_{F,k}}{\dot{E}_{F,k}}, \quad b_{P,k} = \frac{\dot{B}_{P,k}}{\dot{E}_{P,k}} \tag{6}$$

The value of $\dot{Y}_k$ was found as the sum of: $\dot{Y}_k^{\text{CO}}$, the environmental impact related to construction, $\dot{Y}_k^{\text{OM}}$ the impact related to maintenance and $\dot{Y}_k^{\text{DI}}$ the impact related to disposal of the component. $\dot{Y}_k^{\text{DI}}$ is a negative value which accounts for the benefit of recycling the used materials at the end of the life cycle.

$\dot{Y}_k^{\text{CO}}$, $\dot{Y}_k^{\text{OM}}$ and $\dot{Y}_k^{\text{DI}}$ were calculated as seen in Eq. (7). Here, H is the yearly operating time and L is the system lifetime. As seen $\dot{Y}_k^{\text{OM}}$ is assumed to be a 20% of $\dot{Y}_k^{\text{CO}}$ which is equivalent to the ratio applied in the exergoeconomic analysis [9].

$$\dot{Y}_k^{\text{CO}} = \frac{\text{TEI}_k^{\text{CO}}}{H \cdot L}, \quad \dot{Y}_k^{\text{OM}} = 0.2 \cdot \dot{Y}_k^{\text{CO}}, \quad \dot{Y}_k^{\text{DI}} = \frac{\text{TEI}_k^{\text{DI}}}{H \cdot L} \tag{7}$$

The value of b_w was set in accordance with the Eco-indicator 99 [16], to a value of 26 mpt/kWh corresponding to an average European value for low voltage electricity.

2.4   Advanced exergoenvironmental analysis

Splitting the environmental impact of the components into endogenous and exogenous quantifies the extent of the environmental impact, related to the inefficiency of that component (endogenous). Consequently, this also quantifies the environmental impact associated with inefficiencies of the remaining components (exogenous). This allows the system designer to focus on the components that actually causes the highest environmental impact, instead of the components in which the largest environmental impacts are located.

Splitting the environmental impact of the components into avoidable and unavoidable parts quantifies the extent of exergy related environmental impact and non-exergetic environmental impact that can be avoided. This is related to the technological and economic constraints specific to the component. The unavoidable exergy related environmental impact of a component is the environmental impact when implementing the "state of the art" technology regardless of the high investment. While the unavoidable non-exergetic environmental impact is the environmental impact when implementing the cheapest components on the market regardless of the their low exergy efficiency and thus high exergy related environmental impact. This split allows the system designer to focus on the components with large avoidable environmental impact, thus the components where savings can actually be achieved in the current technological and economic environment.

The concepts of endogenous and exogenous and avoidable and unavoidable can be combined, thereby giving the avoidable and unavoidable parts of both the endogenous and exogenous costs. Further, the exogenous environmental impact of the component can be split into the contribution specific to each of the remaining components. This allows the exogenous environmental impact of all components to be allocated to the component that is responsible for it. All equations applied are stated in Table 4.

Table 4. Equations applied to split $\dot{B}_{D,k}$ and $\dot{Y}_k$

Endogenous/Exogenous		
EN:	$\dot{B}_{D,k}^{\text{EN}} = b_{F,k}^{\text{real}} \dot{E}_{D,k}^{\text{EN}}$	$\dot{Y}_k^{\text{EN}} = \dot{E}_{P,k}^{\text{EN}} \left(\dfrac{\dot{Y}_k}{\dot{E}_{p,k}} \right)^{\text{real}}$
EX:	$\dot{B}_{D,k}^{\text{EX}} = \dot{B}_{D,k}^{\text{real}} - \dot{B}_{D,k}^{\text{EN}}$	$\dot{Y}_k^{\text{EX}} = \dot{Y}_k^{\text{real}} - \dot{Y}_k^{\text{EN}}$

Avoidable/Unavoidable		
UN:	$\dot{B}_{D,k}^{\text{UN}} = b_{F,k}^{\text{real}} \dot{E}_{D,k}^{\text{UN}}$	$\dot{Y}_k^{\text{UN}} = \left(\dfrac{\text{TEI}_k^{\text{UN}}}{\text{TEI}_k^{\text{real}}} \right) \dot{Y}_k^{\text{real}}$
AV:	$\dot{B}_{D,k}^{\text{AV}} = \dot{B}_{D,k}^{\text{real}} - \dot{B}_{D,k}^{\text{UN}}$	$\dot{Y}_k^{\text{AV}} = \dot{Y}_k^{\text{real}} - \dot{Y}_k^{\text{UN}}$

Combining Avoidable/Unavoidable & Endogenous/Exogenous		
EN/UN:	$\dot{B}_{D,k}^{\text{EN,UN}} = b_{F,k}^{\text{real}} \dot{E}_{D,k}^{\text{EN,UN}}$	$\dot{Y}_k^{\text{EN,UN}} = \dot{E}_{P,k}^{\text{EN}} \left(\dfrac{\dot{Y}_k}{\dot{E}_{p,k}} \right)^{\text{UN}}$
EN/AV:	$\dot{B}_{D,k}^{\text{EN,AV}} = \dot{B}_{D,k}^{\text{EN}} - \dot{B}_{D,k}^{\text{EN,UN}}$	$\dot{Y}_k^{\text{EN,AV}} = \dot{Y}_k^{\text{EN}} - \dot{Y}_k^{\text{EN,UN}}$
EX/UN:	$\dot{B}_{D,k}^{\text{EX,UN}} = \dot{B}_{D,k}^{\text{UN}} - \dot{B}_{D,k}^{\text{EN,UN}}$	$\dot{Y}_k^{\text{EX,UN}} = \dot{Y}_k^{\text{UN}} - \dot{Y}_k^{\text{EN,UN}}$
EX/AV:	$\dot{B}_{D,k}^{\text{EX,AV}} = \dot{B}_{D,k}^{\text{EX}} - \dot{B}_{D,k}^{\text{EN,UN}}$	$\dot{Y}_k^{\text{EX,AV}} = \dot{Y}_k^{\text{EX}} - \dot{Y}_k^{\text{EX,UN}}$

Splitting k^{th} component exogenous impact into the contribution from the rth component and mexogenous impact

$$\dot{B}_{D,k}^{\text{EX},r} = b_{F,r}^{\text{real}} \dot{E}_{D,k}^{\text{EX},r} \qquad \dot{Y}_k^{\text{EX},r} = \dot{E}_{P,k}^{\text{EN},r} \left(\frac{\dot{Y}_k}{\dot{E}_{p,k}} \right)^{\text{real}} - \dot{Y}_k^{\text{EN}}$$

$$\dot{B}_{D,k}^{\text{EX,UN},r} = b_{F,r}^{\text{real}} \dot{E}_{D,k}^{\text{EX,UN},r} \qquad \dot{Y}_k^{\text{EX,UN},r} = \dot{E}_{P,k}^{\text{EN},r} \left(\frac{\dot{Y}_k}{\dot{E}_{p,k}} \right)^{\text{UN}} - \dot{Y}_k^{\text{EN,UN}}$$

$$\dot{B}_{k}^{\text{EX,AV},r} = \dot{B}^{\text{EX},r} - \dot{B}^{\text{EX,UN},r} \qquad \dot{Y}_k^{\text{EX,AV},r} = \dot{Y}^{\text{EX},r} - \dot{Y}^{\text{EX,UN},r}$$

$$\dot{B}_{D,k}^{\Sigma} = \dot{B}_{D,k}^{\text{EN}} + \sum_{\substack{k=1 \\ k \neq r}}^{K-1} b_{F,r}^{\text{real}} \dot{E}_{D,k}^{\text{EX},r} \qquad \dot{Y}_k^{\Sigma} = \dot{Y}_k^{\text{EN}} + \sum_{\substack{k=1 \\ k \neq r}}^{K-1} \dot{Y}_{D,k}^{\text{EX},r}$$

$$\dot{B}_{D,k}^{\Sigma,\text{AV}} = \dot{B}_{D,k}^{\text{EN,AV}} + \sum_{\substack{k=1 \\ k \neq r}}^{K-1} b_{F,r}^{\text{real}} \dot{E}_{D,k}^{\text{EX,AV},r} \qquad \dot{Y}_k^{\Sigma,\text{AV}} = \dot{Y}_k^{\text{EN,AV}} + \sum_{\substack{k=1 \\ k \neq r}}^{K-1} \dot{Y}_{D,k}^{\text{EX,AV},r}$$
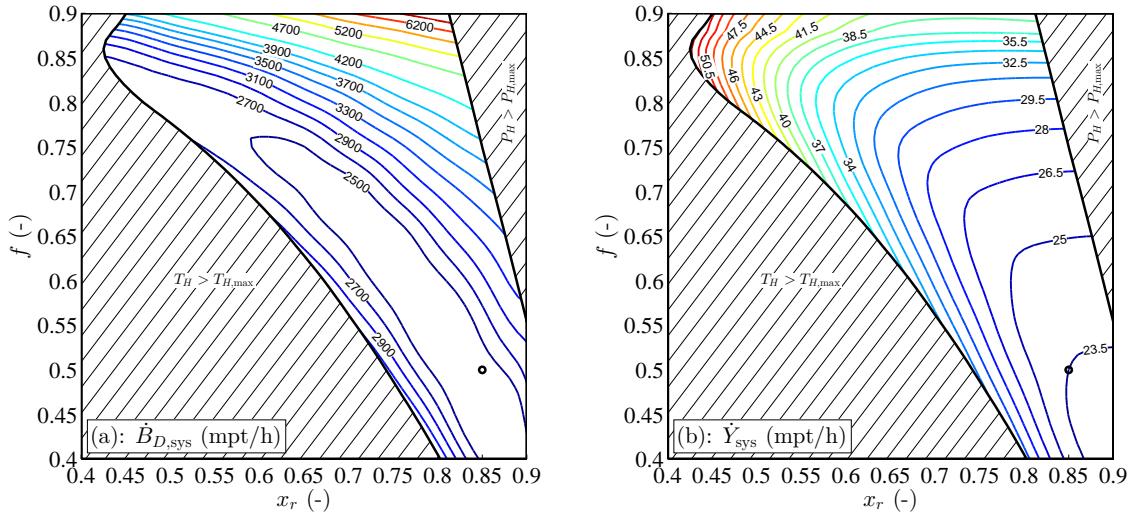

Fig. 2. Variation of the system environmental impact rates: $\dot{B}_{D,\text{sys}}$ (a) and $\dot{Y}_{\text{sys}}$ (b) with x_r and f

3   Results

As described in [1, 8, 9] applying the right combination of the rich ammonia mass fraction, x_r, and the liquid circulation ratio, f, is important to ensure a cost effective and efficient HACHP. Fig. 2 shows the variation of $\dot{B}_{D,\text{sys}}$ and $\dot{Y}_{\text{sys}}$ with the choice of x_r and f. The hatched areas indicate combinations for
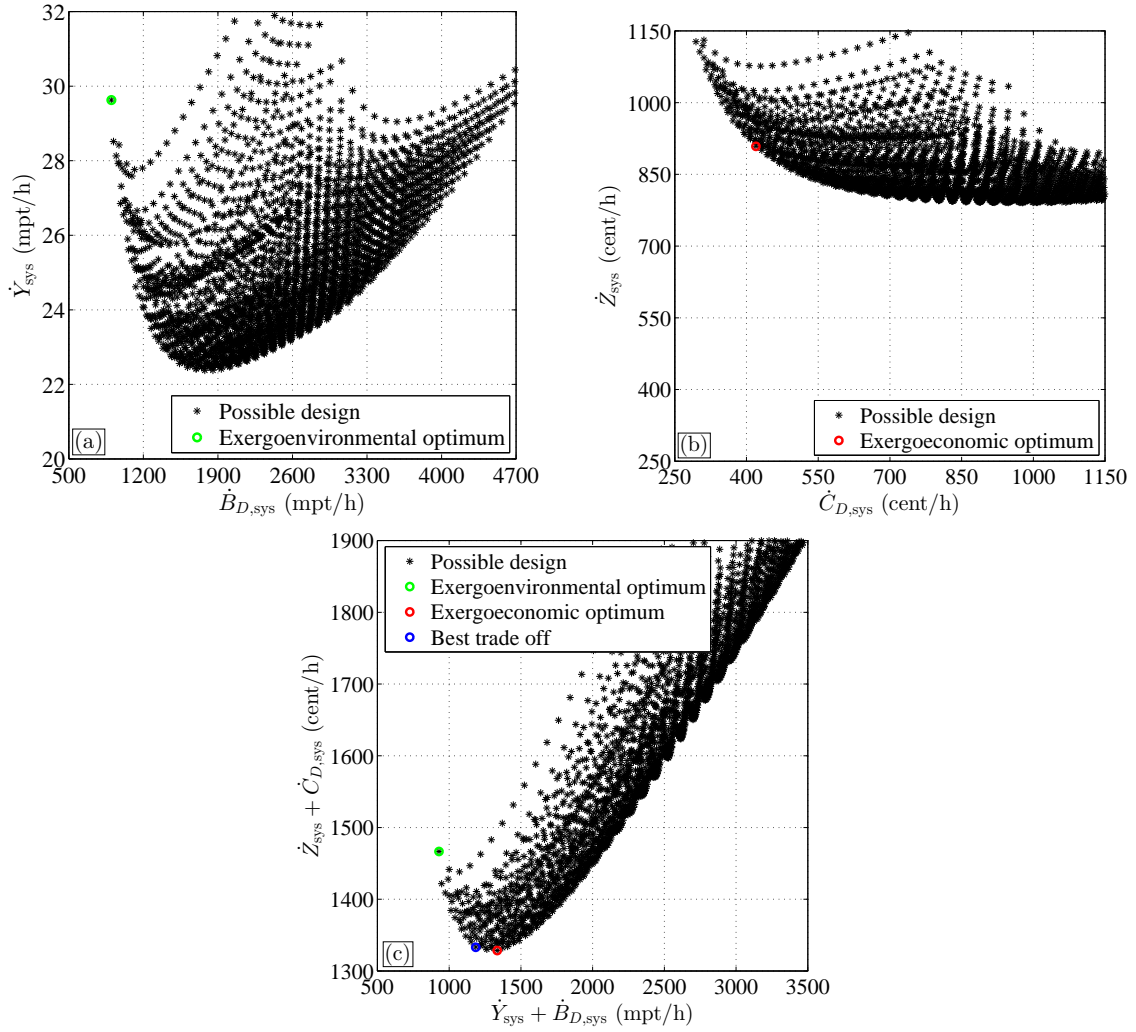
Fig. 3. System environmental impact rates: $\dot{B}_{D,\text{sys}}$ and $\dot{Y}_{\text{sys}}$ and system cost rates: $\dot{C}_{D,\text{sys}}$ and $\dot{Z}_{\text{sys}}$ for a variation of $\Delta T_{pp,4}$, $\Delta T_{pp,8}$ and ϵ_6

which commercial components are not applicable due to either temperature or pressure constraints. As seen, for all values of x_r there exists one value of f that minimizes $\dot{B}_{D,\text{sys}}$. Further, it is seen that the minimum value of $\dot{B}_{D,\text{sys}}$ increases slightly with a reduction of x_r. From Fig. 2 (b) it is seen that the $\dot{Y}_{\text{sys}}$ is more influenced by the choice of x_r than that of f, showing a large increase of $\dot{Y}_{\text{sys}}$ with the reduction of x_r. This is caused mainly by the increased size of the compressor but also due to the increased size of the absorber, desorber and internal HEX. However, it should be noted that the value $\dot{Y}_{\text{sys}}$ is two orders of magnitude lower than $\dot{B}_{D,\text{sys}}$ and thus seems to be of minor importance for the total environmental impact of the system. For the further analysis the value of x_r and f have been set to 0.85 and 0.5, respectively, as indicated by the dot on Fig. 2.

Fig. 3 (a) shows the variations of $\dot{B}_{D,\text{sys}}$ and $\dot{Y}_{\text{sys}}$ with the choice of $\Delta T_{pp,4}$, $\Delta T_{pp,8}$ and ϵ_6. $\Delta T_{pp,4}$ and $\Delta T_{pp,8}$ have been varied from 1 K - 20 K and ϵ_6 from 0.3 to 0.98. Fig. 3 (b) shows the variations of $\dot{C}_{D,\text{sys}}$ and $\dot{Z}_{\text{sys}}$ for the same parameter variations and thus gives an economic perspective. As seen from Fig. 3 (a) and (b) both the exergoenvironmental and exergoeconomic analyses result in a front of pareto optimal solutions. For the exergoenvironmental analysis it can again be noted that the values of $\dot{Y}_{\text{sys}}$ is two orders of magnitude lower than $\dot{B}_{D,\text{sys}}$. This results in an exergoenvironmental optimum at the unavoidable conditions, see Table 1. Hence, the increased component size at these conditions is not enough to counteract the benefit of the reduced exergy destruction.

For the exergoeconomic analysis in Fig. 3 (b) it can be seen that the cost related to the total capital investment and maintenance, $\dot{Z}_{\text{sys}}$, and the cost related to the operation of the system, $\dot{C}_{D,\text{sys}}$, are of

<p align="center">*Table 5. Results of the advanced exergoenvironmetal analysis.*</p>

k^{th}	$\dot{B}_{D,k}^{\text{real}}$	$\dot{B}_k^{\text{AV}}$	$\dot{B}_k^{\text{UN}}$	$\dot{B}_k^{\text{EN}}$	$\dot{B}_k^{\text{EX}}$	$\dot{B}_{D,k}^{\text{EN,AV}}$	$\dot{B}_{D,k}^{\text{EN,UN}}$	$\dot{B}_{D,k}^{\text{EX,AV}}$	$\dot{B}_{D,k}^{\text{EX,UN}}$	$\dot{B}_{D,k}^{\Sigma}$	$\dot{B}_{D,k}^{\Sigma,\text{AV}}$
	(mpt/h)	(mpt/h)	(mpt/h)	(mpt/h)	(mpt/h)	(mpt/h)	(mpt/h)	(mpt/h)	(mpt/h)	(mpt/h)	(mpt/h)
(1)	712	609	103	588	124	491	97.0	118	6.20	576	481
(2)	9.59	7.33	2.26	8.12	1.47	5.98	2.14	1.35	0.122	7.87	5.80
(4)	409	145	263	416	−7.34	150	266	−5.02	−2.32	492	216
(5)	-	-	-	-	-	-	-	-	-	-	-
(6)	24.3	13.5	10.9	12.3	12.1	4.77	7.49	8.76	3.37	30.5	17.1
(8)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	46.6	41.9
(9)	-	-	-	-	-	-	-	-	-	-	-

k^{th}	$\dot{Y}_k^{\text{real}}$	$\dot{Y}_k^{\text{AV}}$	$\dot{Y}_k^{\text{UN}}$	$\dot{Y}_k^{\text{EN}}$	$\dot{Y}_k^{\text{EX}}$	$\dot{Y}_k^{\text{EN,AV}}$	$\dot{Y}_k^{\text{EN,UN}}$	$\dot{Y}_k^{\text{EX,AV}}$	$\dot{Y}_k^{\text{EX,UN}}$	$\dot{Y}_k^{\Sigma}$	$\dot{Y}_k^{\Sigma,\text{AV}}$
	(mpt/h)	(mpt/h)	(mpt/h)	(mpt/h)	(mpt/h)	(mpt/h)	(mpt/h)	(mpt/h)	(mpt/h)	(mpt/h)	(mpt/h)
(1)	13.3	1.99	11.3	10.7	2.604	1.61	9.10	0.390	2.21	10.6	1.55
(2)	0.423	0.0634	0.359	0.359	0.0633	0.0539	0.306	0.00	0.0537	0.356	0.0516
(4)	2.98	2.67	0.318	2.98	0.00	2.67	0.318	0.00	0.00	4.46	42.89
(5)	1.44	-	-	-	-	-	-	-	-	-	-
(6)	0.294	0.278	0.0154	0.24	0.0560	0.225	0.0124	0.0531	0.00	0.414	0.2034
(8)	3.80	3.66	0.136	3.93	−0.132	3.79	0.141	−0.127	0.00	4.78	3.93
(9)	5.59	-	-	-	-	-	-	-	-	-	-

equal magnitude and thus that a trade off between the non-exergetic and exergetic cost exists. This is shown in Fig. 3 (b) by the red dot, indicating the exergoeconomic optimum.

Fig. 3 (c) shows the variation of the total environmental impact $\dot{B}_{D,\text{sys}} + \dot{Y}_{\text{sys}}$ and the total cost $\dot{C}_{D,\text{sys}} + \dot{Z}_{\text{sys}}$ for the same parameter variation. As seen this also results in a front of pareto optimal solutions. Both the exergoenvironmental and the exergoeconomic optimum are shown along with a suggested best trade off, indicated by the blue dot. The values of decision variables at this point will be used as the real conditions for the further analysis. The values at this point are, $\Delta T_{\text{pp},8}^{\text{real}} = 2$ K, $\Delta T_{\text{pp},4}^{\text{real}} = 4$ K and $\epsilon_6^{\text{real}} = 0.8$ -. For the compressor, the real conditions were $\eta_{1,\text{is}}^{\text{real}} = 0.75$ and $\eta_{1,\text{el}}^{\text{real}} = 0.95$, for the pump $\eta_{2,\text{is}}^{\text{real}} = 0.85$ and $\eta_{1,\text{el}}^{\text{real}} = 0.95$.

Table 5 shows the results of the advanced exergoenvironmental analysis at the best trade off conditions described above. It can be seen that for the real cycle, and thus for the results of the conventional exergoenvironmental analysis the largest exergy-related environmental impact stems from the compressor followed by the absorber. For the non-exergetic environmental impact it is seen that the highest impact also stems from the compressor followed by the liquid/vapour separator, desorber and absorber.

Splitting the environmental impact into avoidable and unavoidable parts shows that the largest avoidable exergy related environmental impact also stems from the compressor where 85% of $\dot{B}_{D,k}^{\text{real}}$ is avoidable. For the absorber this is only 35%. Conversely, the largest avoidable non-exergetic environmental impact is related to the desorber where 96% of the environmental impact is avoidable. The second highest stems from the absorber where 89% can be avoided while only 15% can be avoided in the compressor.

Splitting the environmental impact into endogenous and exogenous parts shows that the compressor environmental impact is mainly endogenous with 82% for $\dot{B}_{D,k}$ and 80% for $\dot{Y}_k$. A similar distribution is found for the pump. For the absorber, the exogenous environmental impact was found to be negative which means that an improvement of the exergy efficiency of the remaining components results in an increased environmental impact in the absorber. For the absorber the non-exergetic environmental impact is all endogenous. For the internal HEX $\dot{B}_{D,k}$ is evenly distributed between endogenous and exogenous, while $\dot{Y}_k$ is 90% endogenous. For the desorber, the exogenous non-exergetic environmental impact is negative and thus increasing the efficiency of the remaining components results in the
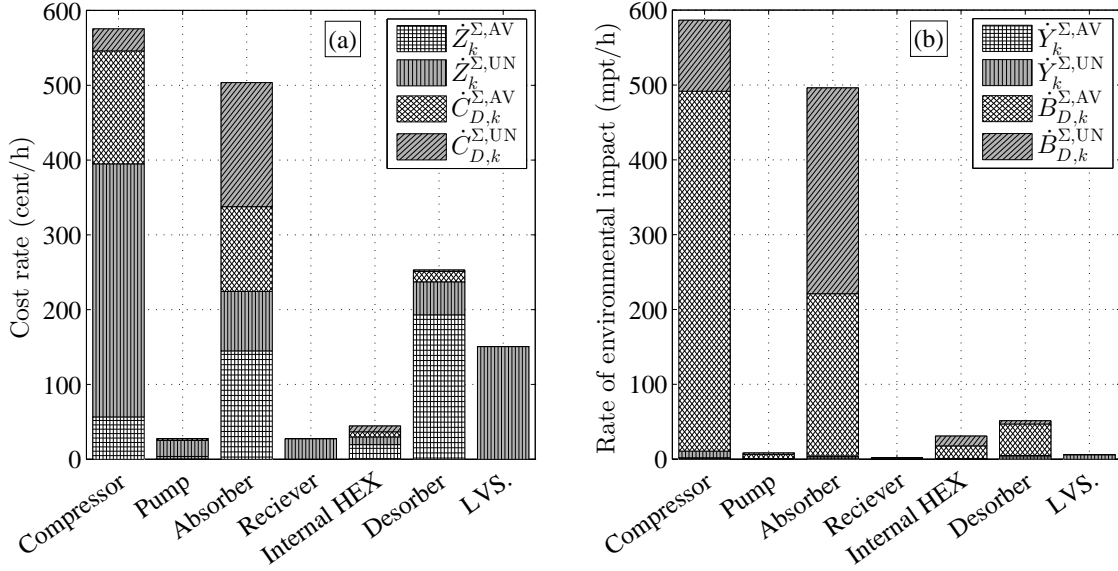
Fig. 4. Distribution of $\dot{C}_{D,k}$, $\dot{Z}_k$, $\dot{B}_{D,k}$ and $\dot{Y}_k$

need for a larger desorber.

Combining the split of avoidable and unavoidable with exogenous and endogenous and further splitting the exogenous part into a contribution specific to the rth component, results in the values of $\dot{B}_{D,k}^{\Sigma,\text{AV}}$ and $\dot{Y}_k^{\Sigma,\text{AV}}$ also stated in Table 5. These values represent the total avoidable environmental impact related to each component. As seen the highest value $\dot{B}_{D,k}^{\Sigma,\text{AV}}$ stems from the compressor followed by the absorber and desorber. Conversely, the highest values of $\dot{Y}_k^{\Sigma,\text{AV}}$ stem from the desorber followed by the absorber.

Fig. 4 summarizes the distribution of $\dot{B}_{D,k}^{\Sigma}$ and $\dot{Y}_k^{\Sigma}$ as well as $\dot{C}_{D,k}^{\Sigma}$ and $\dot{Z}_k^{\Sigma}$. As seen the component with the highest contributions are the compressor and absorber for both the exergoenvironmental and exergoeconomic analysis. Further, while the non-exergetic cost has a high impact on the cost of the system the non-exergetic environmental impact is negligible compared to the environmental impact related to the exergy destruction. Accounting for unavailabilities and interdependencies further showed that far from all costs or environmental impact can be removed by design improvements.

4   Conclusion

The environmental impact of installing a HACHP heat pump as heat supply in an industrial facility was investigated through the use of an advanced exergoenvironmental analysis. Further, the results where compared to those of an exergoeconomic analysis.

It was found that the environmental impact of the HACHP system was mainly driven by the operation of the system and thus linked to the electricity consumption. The environmental impact related to the construction of the system was found to negligible and for all cases the environmental impact related to the increased size of the components could be justified by the decreased energy consumption over the life time of the system. Thus, the exeroenvironmental optimum was found at the unavoidable conditions.

However, these conditions were found not to be economically viable, wherefore a trade off was suggested, that reduced the environmental impact to a close to optimal solution, without any significant increase in cost.

At this condition the advanced exergoenvironmental analysis was applied. This showed that 62% of the avoidable environmental impact was related to the compressor, followed by the absorber with 28%. 7% of the avoidable impact stems from the desorber while the last 3% were accounted to the internal HEX and pump.

Acknowledgements

Nomenclature

Abbreviations

HACHP Hybrid absorption compression heat pump

HEX Heat exchanger

LVS Liquid-vapour separator

LCA Life cycle assessment

Latin symbols

b Environmental impact per unit exergy (mpt/kWh)

$\dot{B}$ Exergetic environmental impact rate (mpt/h)

$\dot{C}$ Exergetic cost rate (cent/h)

$\dot{E}$ Exergy rate (kW)

f Circulation ratio (dimensionless)

H Yearly number of operating hours (h/year)

L Technical lifetime (years)

p Pressure (bar)

T Temperature (°C (difference K))

ΔT Temperature difference (K)

TEI Total environmental impact (mpt)

$\dot{W}$ Power (kW)

x_r Ammonia mass fraction of the rich mixture (kg/kg)

$\dot{Y}$ Non-exergetic environmental impact rate (mpt/h)

$\dot{Z}$ Non-exergetic cost rate (cent/h)

Greek symbols

ϵ Heat exchanger effectiveness

η Efficiency

Subscripts & Superscripts

AV Avoidable

CO Construction

D Destruction

DI Disposal

EN Endogenous

EX Exogenous

F Fuel

j Stream

k Component

OM Operation and maintenance

P Product

pp Pinch point

r Component

real Real cycle value

UN Unavoidable

w Work

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