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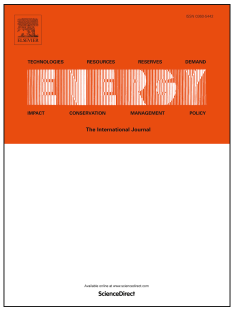

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Advanced exergy-based performance enhancement of heat pump space heating system

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Abstract:

Heat pump technologies for space heating can contribute to substantial economic, environmental and energy saving benefits. However, their performance is generally evaluated through energy-based methods.

The distinguish feature of the exergy-based approaches is that, unlike to the energy-based ones, they are more powerful and convenient tools for developing, evaluating, understanding and improving energy conversion systems without the need of additional analysis and iterations.

Exergy-based estimation (i.e. exergy, exergeconomic and exergoenvironmental analysis) has been applied to an air-source R134a heat pump unit for space heating, being this solution widely employed worldwide.

According to the results obtained 63% and 20% of the avoidable exergy destruction within the heat pump belongs to inefficiencies within the evaporator and the condenser respectively. For the investigated heat pump the biggest parts of the avoidable cost associated with investment expenditures and exergy destruction belong to the compressor (56%) and the evaporator (35%). For the compressor this is caused mostly by capital investment and for the evaporator - mostly by its thermodynamic inefficiency. About 70% of the total avoidable environmental impact associated with construction and exergy destruction belongs to the evaporator and can be decreased mostly by improving thermodynamic efficiency of this component.

For simultaneous improvement of thermodynamic, economic and environmental performance of the investigated solution the irreversibilities occurring in the evaporator and in the condenser has to be decreased. In addition, it is found that, to achieve such a target, reducing the temperature differences through both heat exchangers is a more suitable measure compared to the replacement of the existing emission heating system.

The derived exergy-based conclusions are confirmed with objective functions based on a set of energy, economic and environmental criteria. Compared with the initial case the improved solution provides the reduced value of annual exergy destruction by 31%. The annual cost of exergy of the product of the improved system is also decreased by several percent. The annual environmental impact associated with the product of the system is decreased by 9.5 %.

Keywords:

Advanced exergy analysis; Advanced exergoeconomic analysis; Advanced exergoenvironmental analysis; Heat pump system; Improvement; Performance

Nomenclature

A	heat transfer area (m^2)

b	environmental impact per unit of exergy (mPts·kWh^{-1})
B	environmental impact associated with exergy (mPts)
c	cost per unit of exergy (€·kWh^{-1})
C	cost associated with an exergy stream (€)
E	exergy (kW) or (kWh)
f	exergoeconomic factor (%)
f_b	exergoenvironmental factor (%)
m	mass (kg)
N	total number of time steps within the heating season (day)
p	pressure (Pa)
Q	heat (kWh)
r	relative cost difference (%)
r_b	relative environmental impact difference (%)
τ	time step (day)
T	temperature (K)
W	power (kWh)
Y	component-related environmental impact (mPts)
Z	cost associated with capital investment (€)

Greek symbols

ε	exergetic efficiency (-)
η	isentropic efficiency (-)
Δ	difference

Subscripts and superscripts

·	time rate
AV	avoidable
UN	unavoidable
UN, EN	unavoidable endogenous
UN, EX	unavoidable exogenous
AV, EN	avoidable endogenous
AV, EX	avoidable exogenous
D	exergy destruction
F	exergy of fuel
k	k-th component
n	number of time steps within the heating season
P	exergy of product
r	r-th component
year	annual
tot	overall system

Abbreviations

CM	compressor
CD	condenser

COP	coefficient of performance (-)
HP	heat pump
PH	peak heater
PEC	purchase equipment costs
ES	emission system
EV	evaporator
SI	sustainability index
TV	throttling valve

1. Introduction

Although space heating is fundamental to human life, its environmental impact is massive. Heat pump technologies can play crucial role in the future decarbonisation of this sector and thus in that of the global energy system as well. However, in order to considerably reduce the greenhouse gas (GHG) emissions related to the heating sector, the adoption of highly (thermodynamically) efficient heat pump units needs to be promoted. Such a target can be appropriately achieved through the implementation of advanced exergy-based tools [1-3]. In fact, unlike the conventional energy- and exergy-based assessments, the application of these thermodynamic tools can bring to light the actual thermodynamic, economic and environmental enhancement potential of the investigated solution and the mutual interdependencies among its components [1-3]. Table 1 summarizes the main findings of advanced exergy-based works related to heat pump and refrigeration equipment.

Table 1. Summary of the outcomes of the main studies related to advanced exergy-based analyses applied to heat pump and refrigeration units.

Reference	Investigated energy system	Main outcomes
[4]	Wall heating systems fed by vertical ground source heat pump	The exergy efficiency of the entire system is 27.4%. The value of the exergoenvironmental and exergoeconomic factors of the entire system are 33% and 75% respectively
[5]	Ground-source heat pump drying system	The most important system components are the drying duct and the condenser with respect to reducing the costs
[6]	Ground-source heap pump drying system	The condenser followed by the drying duct need to be significantly improved
[7]	Gas-engine-driven heat pump drying system	Most of the exergy destructions in the system components are avoidable with the exception of the compressor, evaporator and drying cabinet
[8]	Gas-engine-driven heat pump drying system	The most important components based on the total avoidable costs are drying ducts, the condenser and the expansion valve

[9]	Ground-source heat pump food dryer	The condenser is the most important system component from the efficiency improvement point of view
[1, 2]	Simple air refrigeration machine	Decreasing the inefficiencies within the expander and the refrigerator is of first priority.
[3]	Vapor-compression refrigeration machines	The evaporator should be improved first and the compressor second.
[10]	Absorption refrigeration machine	Absorber and generator should be improved first.
[11]	Air-source heat pump food dryer	The heat recovery unit provides the highest avoidable costs.
[12]	Vapor-compression refrigeration machines	The condenser and the evaporator have the highest potential for reducing inefficiencies, costs and environmental impact.
[13]	Wastewater source heat pump for space heating	The evaporator and the condenser have the highest potential for reducing inefficiencies.

As highlighted in Table 1 and to the best of the authors' knowledge, conventional and advanced exergetic, exergoeconomic and exergoenvironmental evaluations have been applied mostly to (industrial) heat pumps and refrigeration machines in which only the design operating conditions have been investigated. A distinguish feature of the heat pump systems providing thermal comfort in buildings is variation of operational modes due to weather conditions. Temperature of the environment varies during the season and can be below, above or equal to the operating temperature of the working fluids taking place in energy conversion processes.

The scope of the paper is, for the first time ever, to simultaneously improve the thermodynamic, economic and environmental performance of an air-source R134a heat pump system providing space heating in varying operational modes caused by fluctuating in outdoor conditions. This has been achieved with the aid of advanced exergy-based methods, i.e. advanced exergetic, exergoeconomic and exergoenvironmental analysis. It is worth highlighting that air-source R134a heat pumps are currently the most employed solution for space heating worldwide. Finally, the work is organized as follows: Section 2 provides the methodology of applied advanced exergy-based analyses and general relations used in the estimation, while Section 3 presents the description of the investigated system. Furthermore, the results obtained are presented and discussed in Section 4, while the conclusions and the needed future developments are summarized in Section 5.

2. Methodology

According to the methodology of advanced exergy-based analysis the total exergy destruction, the total investments costs and the component-related environmental impact in each system component can be split into endogenous/exogenous, unavoidable/avoidable parts and combined ones according to the two approaches of splitting [1-3, 10].

The thermodynamic-cycle-based approach has been applied for the calculations of the split values of exergy-based parameters (namely, exergy destruction, the investments costs and the component-related environmental impact) [1-3, 10].

For ideal or theoretical thermodynamic cycle irreversibilities within each component are excluded or minimized. The assumed operation conditions of the theoretical cycle of the heat pump are given in Table 2. The throttling process is replaced by an ideal expansion process [3].

Cycle with unavoidable exergy destructions ($\dot{E}_{D,k}^{UN}$) considers only unavoidable irreversibilities. The made assumptions for this cycle in the nominal mode of the heat pump are presented in Table 2.

The avoidable exergy destruction is calculated as

$$\dot{E}_{D,k}^{AV} = \dot{E}_{D,k} - \dot{E}_{D,k}^{UN} \tag{1}$$

and should be considered during the improvement procedure.

For calculating the endogenous part of the exergy destruction ($\dot{E}_{D,k}^{EN}$) within each component of the heat pump the hybrid cycles with only one irreversible component is analysed.

The exogenous exergy destruction is obtained as

$$\dot{E}_{D,k}^{EX} = \dot{E}_{D,k} - \dot{E}_{D,k}^{EN}. \tag{2}$$

In case of calculation of the additional components of exergy destruction, only the value of the unavoidable endogenous exergy destruction ($\dot{E}_{D,k}^{UN,EN}$) needs to be obtained using the thermodynamic-cycle-based approach.

The remaining parts of the exergy destruction are then calculated as follows

$$\dot{E}_{D,k}^{UN,EX} = \dot{E}_{D,k}^{UN} - \dot{E}_{D,k}^{UN,EN}, \tag{3}$$

$$\dot{E}_{D,k}^{AV,EN} = \dot{E}_{D,k}^{EN} - \dot{E}_{D,k}^{UN,EN}, \tag{4}$$

$$\dot{E}_{D,k}^{AV,EX} = \dot{E}_{D,k}^{AV} - \dot{E}_{D,k}^{AV,EN}. \tag{5}$$

The same thermodynamic-cycle-based approach has been used for the evaluation of the components of the investments costs ($\dot{Z}_k^{EN}$, $\dot{Z}_k^{EX}$, $\dot{Z}_k^{AV}$, $\dot{Z}_k^{UN}$, $\dot{Z}_{D,k}^{UN,EN}$, $\dot{Z}_{D,k}^{UN,EX}$, $\dot{Z}_{D,k}^{AV,EN}$, $\dot{Z}_{D,k}^{AV,EX}$) and the component-related environmental impact ($\dot{Y}_k^{EN}$, $\dot{Y}_k^{EX}$, $\dot{Y}_k^{AV}$, $\dot{Y}_k^{UN}$, $\dot{Y}_{D,k}^{UN,EN}$, $\dot{Y}_{D,k}^{UN,EX}$, $\dot{Y}_{D,k}^{AV,EN}$, $\dot{Y}_{D,k}^{AV,EX}$).

The values of the unavoidable investment cost and the component-related environmental impact ($\dot{Z}_k^{UN}$, $\dot{Y}_k^{UN}$) are determined assuming an extremely inefficient version of the considered component. These values will always be exceeded as long as a similar component is used in a real system [1, 2, 11]. The unavoidable conditions for the investment cost and the component-related environmental impact are listed in Table 2. Endogenous (capital investment cost $\dot{Z}_k^{EN}$ and construction-of-component-related environmental impact $\dot{Y}_k^{EN}$) are the parts of variables within a component obtained when all other components operate ideally and the component being considered operates with the same efficiency as in the real system [1, 2, 11, 12].

Table 2. Values of parameters assumed used for the advanced exergetic analysis [1, 2]

Component	Parameter, unit	Real process	Theoretical process	Unavoidable thermodynamic inefficiency	Unavoidable investment cost	Unavoidable environmental impact
CM	η_{CM} [-]	0.7	1	0.88	0.49	0.49
CD	ΔT_{MIN} [K]	5	0	1	10	10
EV	ΔT_{MIN} [K]	12	0	3	17	17

To better understand the interactions among components, the exogenous exergy destruction within the k-th component should also be split.

For obtaining a deeper understanding of the interactions among components, the exogenous exergy destruction (as well as the exogenous unavoidable and the exogenous avoidable exergy destruction) within the k-th component is split [1, 2, 12]

$$\dot{E}_{D,k}^{EX} = \sum_{\substack{r=1 \\ r\neq k}}^{n-1} \dot{E}_{D,k}^{EX,r} + \dot{E}_{D,k}^{mexo}, \tag{6}$$

where $\dot{E}_{D,k}^{AV,r}$ represents part of the exogenous exergy destruction within the k-th component that is caused by the irreversibilities occurring within the r-th component;

$\dot{E}_{D,k}^{mexo}$ – the remaining part is called mexogenous exergy destruction (from mixed exogenous exergy destruction) within the k-th component and is caused by the combined interactions of three or more components.

To identify the importance of the components from the thermodynamic viewpoint and priorities for improving the components the investigator should use the sum of the avoidable endogenous exergy destruction within the k-th component $\dot{E}_{D,k}^{AV,EN}$ and of the avoidable exogenous exergy destructions within the remaining components caused by the k-th component $\sum_{\substack{r=1 \\ r\neq k}}^{n-1} \dot{E}_{D,r}^{AV,EX,k}$ [1, 2, 12]

$$\dot{E}_{D,k}^{AV,\Sigma} = \dot{E}_{D,k}^{AV,EN} + \sum_{\substack{r=1 \\ r\neq k}}^{n-1} \dot{E}_{D,r}^{AV,EX,k}, \tag{7}$$

where $\dot{E}_{D,r}^{AV,EX,k}$ represents the part of the exogenous exergy destruction within the remaining r-th component that is caused by the irreversibilities occurring within the k-th component.

Similarly, the cost rates and environmental impact rates caused by the irreversibilities within the kth component can be estimated as [1, 2, 12]

$$\dot{C}_{D,k}^{AV,\Sigma} = c_{F,k} \cdot \dot{E}_{D,k}^{AV,EN} + \sum_{\substack{r=1 \\ r\neq k}}^{n-1} c_{F,r} \cdot \dot{E}_{D,r}^{AV,EX,k}; \tag{8}$$

$$\dot{B}_{D,k}^{AV,\Sigma} = b_{F,k} \cdot \dot{B}_{D,k}^{AV,EN} + \sum_{\substack{r=1 \\ r\neq k}}^{n-1} b_{F,r} \cdot \dot{E}_{D,r}^{AV,EX,k}, \tag{9}$$

where $c_{F,k}$, $c_{F,r}$, $b_{F,k}$, $b_{F,r}$ represent the cost and environmental impacts per unit of exergy for fuel of the k-th and r-th component, respectively.

The sum of the avoidable capital investments and construction-of-component-related impact caused by the irreversibilities within the kth can be defined as [1, 2, 12]

$$\dot{Z}_{k}^{AV,\Sigma} = \dot{Z}_{k}^{AV,EN} + \sum_{\substack{r=1 \\ r\neq k}}^{n-1} \dot{Z}_{r}^{AV,EX,k}, \tag{10}$$

$$\dot{Y}_k^{AV,\Sigma} = \dot{Y}_k^{AV,EN} + \sum_{\substack{r=1 \\ r\neq k}}^{n-1} \dot{Y}_r^{AV,EX,k} , \tag{11}$$

where $\dot{Z}_r^{AV,EX,k}$ and $\dot{Y}_r^{AV,EX,k}$ represents the part of the exogenous investments and construction-of-component-related impact within the r-th component but caused by the irreversibilities occurring within the k-th component.

Taking into account the potentials for improving the system, the overall importance of the k-th component from the viewpoints of cost and environmental impact can be presented with the variables: $\dot{Z}_k^{AV,\Sigma} + \dot{C}_{D,k}^{AV,\Sigma}$ and $\dot{Y}_k^{AV,\Sigma} + \dot{B}_{D,k}^{AV,\Sigma}$ [1, 2, 12].

In case of applying exergy-based approach to the heating and cooling systems in buildings, one of the challenging issue is the definition and selection of the reference environment [14]. In this research selection of an appropriate reference state corresponds to the selection of an appropriate reference temperature. Pressure and humidity as other parameters of the reference environment have not been taken into account as having neglegible effect in the climate conditions specified in the study. The reference temperature exactly follows the fluctuations of ambient (outdoor) conditions [15]. So, exergy always cancels out for the ambient air temperature.

For the sensitivity analysis the following cost equations were used for estimating the purchase equipment costs as functions of the thermodynamic parameters of the heat pump components [1, 2]

$$PEC_{CM} = \frac{k_{CM} \cdot \dot{m}_{CM}}{\eta_{CM}^{UN} - \eta_{CM}} \left(\frac{p_2}{p_1} \right) ln \left(\frac{p_2}{p_1} \right) \text{ - for compressor} \tag{12}$$

$$PEC_{CD} = k_{CD} \left(A_{CD} \right)^{0.6} \text{ - for condenser} \tag{13}$$

$$PEC_{EV} = k_{EV} \left(A_{EV} \right)^{0.6} \text{ - for evaporator} \tag{14}$$

where k_{CM}, k_{CD}, k_{EV} are constants; $\dot{m}_{CM}$ is mass flow rate of the working fluid through the compressor; p_2 / p_1 - pressure ratio in the compressor; η_{CM} and η_{CM}^{UN} are isentropic efficiencies of the compressor in real cycle and unavoidable conditions, respectively; A_{CD} and A_{EV} are the heat transfer areas of the condenser and evaporator calculated for the design mode, respectively. All these values are estimated for the design operating conditions (nominal mode) of the system.

A life cycle assessment (LCA) is applied for the estimation of the relative importance of each component with respect to environmental impact occuring during construction (manufacturing, transport and installation), operation and maintenance, and disposal. An impact assessment is performed using an environmental indicator – the Eco-indicator 99, which is based on the definition of three damage categories: human health, ecosystem quality and natural resources [12, 16, 17]. The result is expressed as Eco-indicator points.

For exergetic, exergoeconomic and exergoenvironmental assesment of the heat pump providing space heating it is proposed to consider annual (seasonal) values of parameters [13, 18].

For different operational modes ambient temperature can be referred in a different manner to temperatures of working fluids of the heat pump. The reference temperature can be above, below or cross the temperatures of the heat source medium and the refrigerant. In such conditions different formulas should be used for calculating exergy associated with the fuel and product in the components of the system and associated costs per unit of exergy of the fuel and product respectively. Taking into account this features it is proposed to apply the exergoeconomic model for the every 24-hour time step of the assumed quasi-steady state approximation. In calculation of annualized exergoeconomic parameters the averaged for the heating season values of cost per unit of exergy associated with the fuel and product for the kth component have been estimated using the formulas [18]

$$c_{F,k}^{year} = \frac{\sum_{\tau_n=1}^{N} c_{F,k}\left(\tau_n\right)\cdot E_{F,k}\left(\tau_n\right)}{\sum_{\tau_n=1}^{T} E_{F,k}\left(\tau_n\right)}; \quad (15)$$

$$c_{P,k}^{year} = \frac{\sum_{\tau_n=1}^{N} c_{P,k}\left(\tau_n\right)\cdot E_{P,k}\left(\tau_n\right)}{\sum_{\tau_n=1}^{T} E_{P,k}\left(\tau_n\right)}, \quad (16)$$

where $E_{F,k}\left(\tau_n\right)$ and $c_{F,k}\left(\tau_n\right)$ are the exergy of fuel and the cost per unit of exergy associated with the fuel of the kth component for the specified time step τ_n; $E_{P,k}\left(\tau_n\right)$ and $c_{P,k}\left(\tau_n\right)$ are the exergy of product and the cost per unit of exergy associated with the product of the kth component for the specified time step τ_n; N - the total number of time steps within the heating season.

The same approach is applied in the exergoenvironmental model.

The following objective functions based on a set of energy, economic and environmental criteria has been used for the simultaneous assessment of thermodynamic, economic and environmental performance of the investigated heat pump system:

- the annual value of exergy efficiency

$$\varepsilon_{tot}^{year} = \frac{E_{P,tot}^{year}}{E_{F,tot}^{year}}; \quad (17)$$

- the annual value of coefficient of performance of the heat pump

$$COP^{year} = \frac{Q_{HP}^{year}}{W_{HP}^{year}}; \quad (18)$$

- the annual value of sustainability index [19]

$$SI_{tot}^{year} = \frac{1}{1-\varepsilon_{tot}^{year}}, \quad (19)$$

where $E_{P,tot}^{year}$ and $E_{F,tot}^{year}$ are the annual values of exergy of the system product and fuel, respectively; Q_{HP}^{year} and W_{HP}^{year} are the annual values of heat generated in the condenser and electricity consumed in the heat pump, respectively.

3. System description

The analysis is performed for a typical Ukrainian house. The dwelling has two floors with a gross floor area of 170 m² and a volume of 470 m³. The weighted average insulation U-value of non-glazed external surfaces is 0.5 W·m^{-2}·K^{-1}. U-value of windows including frames is 1.67 W·m^{-2}·K^{-1}. Internal heat gains are defined with a constant value of 5 W·m^{-2}. Setpoint for the indoor temperature is 18 ^{o}C. The fraction of east and west oriented glazing is 30%, of the south one – 50%, of the north one – 20%. Natural ventilation is used in the dwelling. The design heating capacity of the house is 25 kW. Hydronic system is used for space heating. The heat pump is a basic heater covering 12 kW of heating demand in the design mode and uses outside air as a low temperature heat source. R134a is chosen as a working fluid in the heat pump.

In the design operating conditions (nominal mode) of the heat pump the following parameter values are set: the low temperature heat source medium (air) is cooled in the evaporator from -10 ^{o}C to -15

^{o}C. The temperature the heat source in off-design modes varied in a range from +10^{o}C to -16^{o}C. The supply and return temperatures in a constant-flow space heating system for the design mode are equal to 70 ^{o}C and 50 ^{o}C rspectively.

In order to determine thermodynamic parameters of the vapor compresion heat pump cycle in different operating modes (off-design modes) during a heating season, which is typical for such kind of solutions, the mathematical model proposed in [20] is used. The model is based on quasi-steady state approach. A set of nonlinear equations, involving heat, mass balances, heat transfer and equations for calculation of thermodynamic properties of working fluids, have been utilized. The equations, solved simultaneously with a gradient numerical method, have been established to describe the behaviour of each component and of the system as a whole. CoolProp software [21] providing functions for calculations of thermodynamica properties and inserted in MathCad math environment [21] is used in the calculations. Daily weather data within a heating season for the city of Rivne located in the western part of Ukraine were used for the analyses. So, 24-hour time step was assumed for quasi-steady state modelling. The weather data were provided by the Ukrainian Hydrometeorological Institute [22]. The total value of heating degree days was 3500°C·day.

4. Results and discussion

Fig. 1 illustrates values of annual exergy destructions $E_{D,k}^{year}$ in the investigated heat pump, peak heater and emission space heating system. It can be observed that the highest exergy destruction is found for the heat pump and equal to 5254 kWh and the lowest – for the peak heater and equal to 390 kWh. The annual exergy destruction in the emission system is 1514 kWh which is by 72% lower compared to the heat pump.

The results of the conventional exergy analysis (see Fig. 1) suggest that the biggest exergy destructions (1752 kWh and 1632 kWh, respectively) belong to the compressor and the throttling valve. The evaporator and condenser are of the third and the forth order of importance with seasonal exergy destructions of 1144 kWh and 726 kWh respectively. These results are misleading to some extent. For example, the conventional exergetic analysis identifies the compressor as the most important component from the thermodynamic viewpoint. Thus, improvement efforts should focus on this component. However, a more detailed analysis shows that exergy destruction within the compressor depends on pressure ratio in it and can be reduced by decreasing irreversibilities taking place in the evaporator and the condenser due to temperature differences. The same conclusion can be obtained concerning the throttling valve. Moreover the throttling process is completely irreversible and there are no ways of improving this process with the help of decreasing irreversibilities in it.

The main results for the base case of the investigated system obtained through the conventional exergoeconomic and exergoenvironmental analyses are presented in Tables 3 and 4, respectively.

The presented results demonstrate that from the exergoeconomic point of view the heat pump is the most important component of the space heating system because of the highest value of the sum $Z_{HP}^{year}+C_{D,HP}^{year}$, which is equal to 2072 €· year^{-1}. The sum $Z_{ES}^{year}+C_{D,ES}^{year}$ for the emission system is by 57% lower compared to the heat pump. The total sum $Z_{tot}^{year}+C_{D,tot}^{year}$ of the system is 2623 €· year^{-1}. The high value of the exergoeconomic factor for the overall system (91%) suggests that its cost effectiveness can be improved by reducing the investment cost of the system.

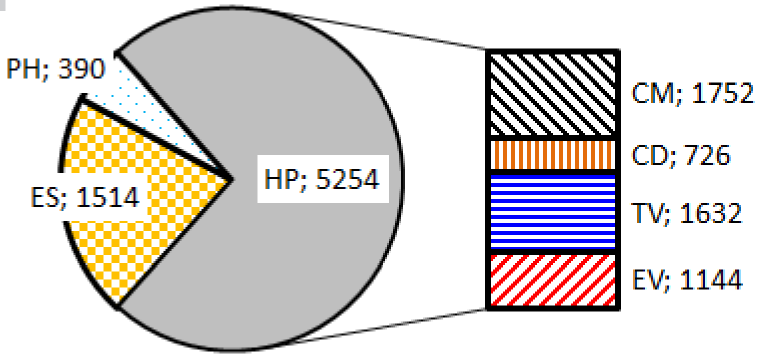

Figure 1. Annual exergy destructions $E_{D,k}^{year}$ *(kWh) in the investigated heat pump, peak heater and emission space heating system (base case).*

Table 3. Conventional exergoeconomic analysis of the base case of the system

Component	$c_{F,k}^{year}$, €·kWh^{-1}	$c_{P,k}^{year}$, €·kWh^{-1}	Z_{k}^{year}, €·year^{-1}	$C_{D,k}^{year}$, €·year^{-1}	$Z_{k}^{year}+C_{D,k}^{year}$, €·year^{-1}	r_{k}^{year}, %	f_{k}^{year}, %
HP	0.035	0.379	1889	183	2072	989	91
PH	0.035	2.280	199	13.6	212	6451	94
ES	0.430	0.905	285	651	937	110	30
Overall system	0.035	0.905	2374	249	2623	2501	91

As for the exergoeconomic analysis the heat pump is the component with the highest value of the sum $Y_{HP}^{year}+B_{D,HP}^{year}=151423mPts\cdot year^{-1}$ (see Table 4).

From exergoenvironmental viewpoint the emission system is also of the second order of priority ($Y_{ES}^{year}+B_{D,ES}^{year}=73820\,mPts\cdot year^{-1}$). As a result the total sum $Y_{tot}^{year}+B_{D,tot}^{year}$ of the overall system is equal to 209395mPts·year^{-1}. On the contrary to the exergoeconomic analysis, the low values of the exergoenvironmental factor for all components of the system (<20%) indicate that its environmental impact can be decreased by increasing thermodynamic efficiency of the system components.

Based on the above findings, it can be concluded that for the simultaneous thermodynamic, economic and environmental improvement of the investigated system the changes to the design of the heat pump and the emission system should be applied. It is recommended to decrease exergy destruction in the emission system. In case of the heat pump there are two opposite findings. From the exergoeconomic viewpoint the capital investment of this component should be decreased. On the other hand, the exergoenvironmental analysis indicates that thermodynamic efficiency of the heat pump should be increased.

The works [4, 5, 9] also demonstrate that highest values of the sums $Z_{k}^{year}+C_{D,k}^{year}$ and $Y_{k}^{year}+B_{D,k}^{year}$ belong to the heat pump. The high value of exergoeconomic factors and low value of the exergoenvironmental factor for the entire system using ground source heat pump are also reported in [4].

Table 4. Conventional exergoenvironmental analysis of the base case of the system

Component	$b_{F,k}^{year}$, mPts/kW·hr	$b_{P,k}^{year}$, mPts /kW·hr	Y_{k}^{year}, mPts· year^{-1}	$B_{D,k}^{year}$, mPts· year^{-1}	$Y_{k}^{year}+B_{D,k}^{year}$, mPts· year^{-1}	$r_{b,k}^{year}$, %	$f_{b,k}^{year}$, %
HP	27	43	9577	141846	151423	59	6.3
PH	27	166	2677	10520	13197	516	20.3
ES	46	84	3905	69915	73820	81	5.3
Overall system	27	84	16159	193236	209395	210	7.7

For a further analysis of the heat pump the advanced exergy-based evaluation was applied. The values of endogenous $E_{D,k}^{AV,EN,year}$ and exogenous $E_{D,k}^{AV,EX,year}$ avoidable parts of seasonal (annual) exergy destruction and the values of appropriately grouped endogenous/exogenous avoidable parts of seasonal (annual) exergy destruction $E_{D,k}^{AV,\Sigma,year}$ in the compressor, condenser, throttling valve and evaporator of the investigated heat pump are introduced in Fig. 2.

It can be observed from Fig. 2 that 448 kWh or 34 % of avoidable exergy destruction in the compressor can be reduced by improving this component. Another part (66 %) of avoidable exergy destruction in the compressor is caused by the irreversibilities that occurs in the remaining components. These data are in a good agreement with the results presented in [3, 12] where depending on the working fluids 40…56% of exergy destruction which can be avoided in in the compressor is due to irreversibilities within the remaining components.

The results obtained from the advanced exergetic analysis indicate that the endogenous avoidable exergy destruction in the throttling valve is zero. This means that the exergy destruction within this component can be reduced through changes in the remaining components (evaporator, condenser and compressor) or in the structure of the overall system. This conclusion completely coincides with the data provided in [3, 12, 13].

According to the results presented in Fig.2 565 kWh or 84 % of avoidable exergy destruction in the evaporator is endogenous. Moreover the evaporator significantly affects the exogenous avoidable exergy destruction associated with the remaining components (mostly in the compressor and the throttling valve). The big role of improvement of this component for possible thermodynamic savings is also confirmed in [3, 10].

234 kWh or 75 % of avoidable exergy destruction within the condenser is endogenous (Fig. 2). Irreversibilities taking place within this component also affect thermodynamic efficiency within the remaining components (mostly in the compressor and the throttling valve).

Some amount of exergy destruction within the heat pump components is mexogenous and caused by the combined interactions of more than two components (Fig. 2).

It can be observed from Fig. 2 that decreasing the irreversibilities within some components also leads to some increase exergy destruction in the others. Negative sign of several parts of avoidable exogenous exergy destruction confirms that. The mexogenous avoidable exergy destruction within the evaporator is equal to -61 kWh. -17 kWh of the avoidable exergy destruction within throttling valve also depends on combined interactions of more than two components. The avoidable parts of exogenous exergy destruction within the evaporator and the throttling valve and caused by compressor are also negative and equal respectively to -13 kWh and -16 kWh.

The similar information concerning negative values of exogenous exergy destruction is obtained in a series of works: [3] for a vapour-compression refrigeration machine with R407C, [10] for an absorption refrigeration machine, [13] for a water source heat pump providing space heating, [23, 24] for geothermal district heating systems, [25] for a combined cycle power plant. Negative values of exogenous exergy destruction provides negative values of costs and environmental impact due to exergy destruction. This is is confirmed in [26, 27, 28, 29].

It can be seen from the Fig. 2 that the biggest value of exergy destruction in the air-source heat pump can be removed with the help of improving evaporator because the sum of avoidable endogenous and avoidable exogenous exergy destruction $E_{D,EV}^{AV,\Sigma,year}$ in this component is equal to 1609 kWh or 63 %. These parts of avoidable endogenous and avoidable exogenous exergy destruction in the condenser and compressor are equal 506 kWh and 435 kWh, respectively (i.e. 3 and 3.7 times lower than in the evaporator).

The advanced exergoeconomic analysis provides a possibility to group the avoidable costs caused by the analyzed component but associated with both of this and the remaining components $Z_{k}^{AV,\Sigma,year}+C_{D,k}^{AV,\Sigma,year}$ (Table 5).

According to the results presented in Table 3 for the investigated air-source heat pump the highest value of the sum $Z_{k}^{AV,\Sigma,year}+C_{D,k}^{AV,\Sigma,year}$ belongs to the compressor and is equal to 690 Euro·year^{-1} (56 %). This sum is caused mostly by capital investment and can be reduced at the expense of the compressor efficiency. For the evaporator this part of the costs is equal to 434 Euro·year^{-1} (35 %) and caused mostly by its thermodynamic inefficiency.

Additional analysis shows that some amount of investment expenditures of the most expensive component (compressor) can be decreased by increasing the thermodynamic efficiency of the evaporator and condenser. This can be explained with a more detailed evaluation of the exogenous part of the capital investments for the compressor (Table 6). It can be seen that endogenous capital investment costs of the compressor are equal to 1205 Euro·year^{-1}. Furthermore, this is the biggest share of capital investment for the heat pump. However, 426 Euro·year^{-1} belong to the exogenous part of the capital investment costs and refer to the irreversibilities distributed within other components: 116 Euro·year^{-1} due to the condenser, 236 Euro·year^{-1} due to the evaporator and 74 Euro·year^{-1} due to the mixed influence of more than one component.

According to the methodology of advanced exergoeconomic analysis [1, 2, 12] the exogenous part of the capital investment cost is the difference between the value of the variable within the component in the real system and the endogenous part. Furthermore, the endogenous capital investment cost is the part of a variable within a component obtained when all other components operate ideally (with excluded or minimized irreversibilities) and the component being considered operates with the same efficiency as in the real system. Therefore, if the exogenous capital investment cost of the compressor caused by irreversibilities taking place within some component is positive, it means that investment cost of the compressor can be decreased by reducing the irreversibilities within the other component (evaporator or condenser). On the other hand, if the exogenous part of capital investment cost is negative, it means that in order to decrease the investment cost of the considered component the irreversibilities within the other components needs to be increased This is mentioned in [18] for a water source heat pump providing space heating, in [26] for a trigeneration system using a diesel-gas engine and in [28, 29] for a power plants with CO2 capture.

The advanced exergoenvironmental analysis (Table 7) shows that the environmental impact associated with the heat pump can be significantly reduced by increasing the thermodynamic performance of the evaporator. For the investigated heat pump about 70074 mPts·year^{-1} or 70% of the the total avoidable environmental impact associated with construction and exergy destruction belongs to the evaporator and can be decreased mostly by improving thermodynamic efficiency of this component. Decreasing irreversibilities occurring within the condenser is of the second priority. The condenser provides 16178 mPts·year^{-1} or 16% of the avoidable environmental impact within the heat pump.

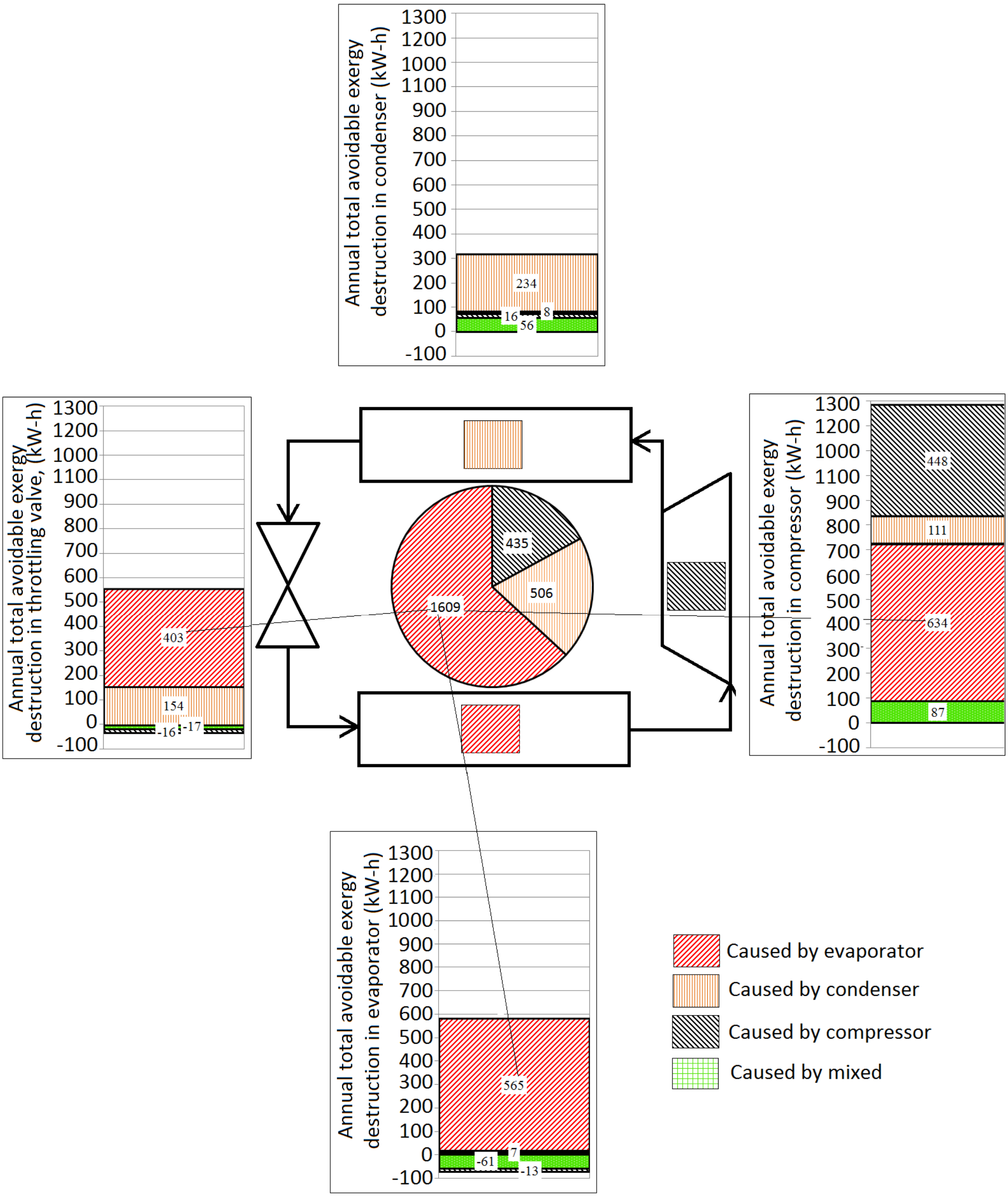

Figure 2. Values of endogenous/exogenous avoidable parts of seasonal exergy destructions $E_{D,k}^{AV,\Sigma,year}$ *(kWh) in the components of the investigated heat pump (base case).*

Table 5. Advanced exergoeconomic analysis of the heat pump (base case)

Component	$Z_k^{AV,\Sigma,year}$, €· year^{-1}	$C_{D,k}^{AV,\Sigma,year}$, €· year^{-1}	$Z_k^{AV,\Sigma,year} + C_{D,k}^{AV,\Sigma,year}$, €· year^{-1}
CM	681	9	690
CD	1,4	105	107
TV	0,0	6,1	6,1
EV	-6,3	441	434

Table 6. Splitting the capital investment cost for components of the heat pump (base case)

Component	$Z_k^{EN,year}$, €· year^{-1}	$Z_k^{EX,year}$, €· year^{-1}		
CM	1205	426	CD	116
			TV	0
			EV	236
			mexo	74

Table 7. Advanced exergoenvironmental analysis of the heat pump (base case)

Component	$Y_k^{AV,\Sigma,year}$, mPts· year^{-1}	$B_{D,k}^{AV,\Sigma,year}$, mPts· year^{-1}	$Y_k^{AV,\Sigma,year} + B_{D,k}^{AV,\Sigma,year}$,mPts· year^{-1}
CM	2128	11285	13413
CD	675	15503	16178
TV	0	823	823
EV	1257	68817	70074

Therefore, for the simultaneous thermodynamic, economic and environmental improvement of the base case of the investigated heat pump, irreversibilities within the evaporator and the condenser should be reduced by decreasing temperature differences in these elements.

Taking into account the results obtained above and possible interactions between other components of the heating system (peak heater, emission system), four additional cases for improving the analysed system were investigated: case 1 – reduction of the minimal temperature differences in the condenser of the heat pump to 1 K; case 2 – reduction of the minimal temperature differences in the evaporator of the heat pump to 3 K; case 3 – reduction of the minimal temperature differences in the evaporator and the condenser of the heat pump to 3 K and 1 K, respectively; case 4 - replacement of the existing emission heating system with 70 ^{o}C/50 ^{o}C to the low temperature one with 60 ^{o}C/40 ^{o}C, which requires increasing the surface of the emission system.

Sum of the cost associated with capital investment and operating and maintenance expenses for the components of the each proposed cases are shown in Fig. 3. This data is introduced for additional confirming conclusions concerning possibilities of decreasing investment expenditures for the compressor due to reduction of the temperature differences in heat exchangers. It can be observed that in the case 1 with reduction of the minimal temperature differences in the condenser to 1 K the investment costs associated with the compressor are decreased from $1631€ \cdot year^{-1}$ to $1480€ \cdot year^{-1}$. However, this causes comparatively smaller increase in investment expenditures for the condenser (from $130€ \cdot year^{-1}$ to $194€ \cdot year^{-1}$) and the evaporator (from $127€ \cdot year^{-1}$ to $132€ \cdot year^{-1}$). The similar results are obtained for the case 2 in which the minimal temperature differences in the evaporator is decreased from 15 K to 3 K. In this case the investment costs for the compressor are decreased by $275€ \cdot year^{-1}$ (from $1631€ \cdot year^{-1}$ to $1365€ \cdot year^{-1}$). Again compared to the base case smaller changes in investment expenditures for the evaporator (by

$255€\cdot year^{-1}-128€\cdot year^{-1}=127€\cdot year^{-1}$) and the condenser (by $-1€\cdot year^{-1}$) take place. In the case 3 (i.e. reduction of the minimal temperature differences in the evaporator and the condenser of the heat pump to 3 K and 1 K, respectively), the lowest value of the investment costs associated with the compressor is obtained ($1256€\cdot year^{-1}$). Increase in investment expenditures for the evaporator (from $128€\cdot year^{-1}$ to $261€\cdot year^{-1}$ or by $133€\cdot year^{-1}$) and the condenser (from $130€\cdot year^{-1}$ to $195€\cdot year^{-1}$ or by $65€\cdot year^{-1}$) is not higher compared to the increase in investment expenditures for the compressor (from $1631€\cdot year^{-1}$ to $1256€\cdot year^{-1}$ or by $375€\cdot year^{-1}$). In the base case and cases 1, 2, 3 the values of Z_k^{year} associated with the peak heater and emission system remains unchanged. For the case 4 in which switching from high to low temperature heating is proposed, investment expenditures associated with the compressor are again decreased by $180€\cdot year^{-1}$ (from $1631€\cdot year^{-1}$ to $1451€\cdot year^{-1}$). The increase in investment costs for the emission system are comparatively lower in the case 4 and equal to $95€\cdot year^{-1}$. The investment expenditures associated with the condenser, evaporator and peak heater remains almost the same.

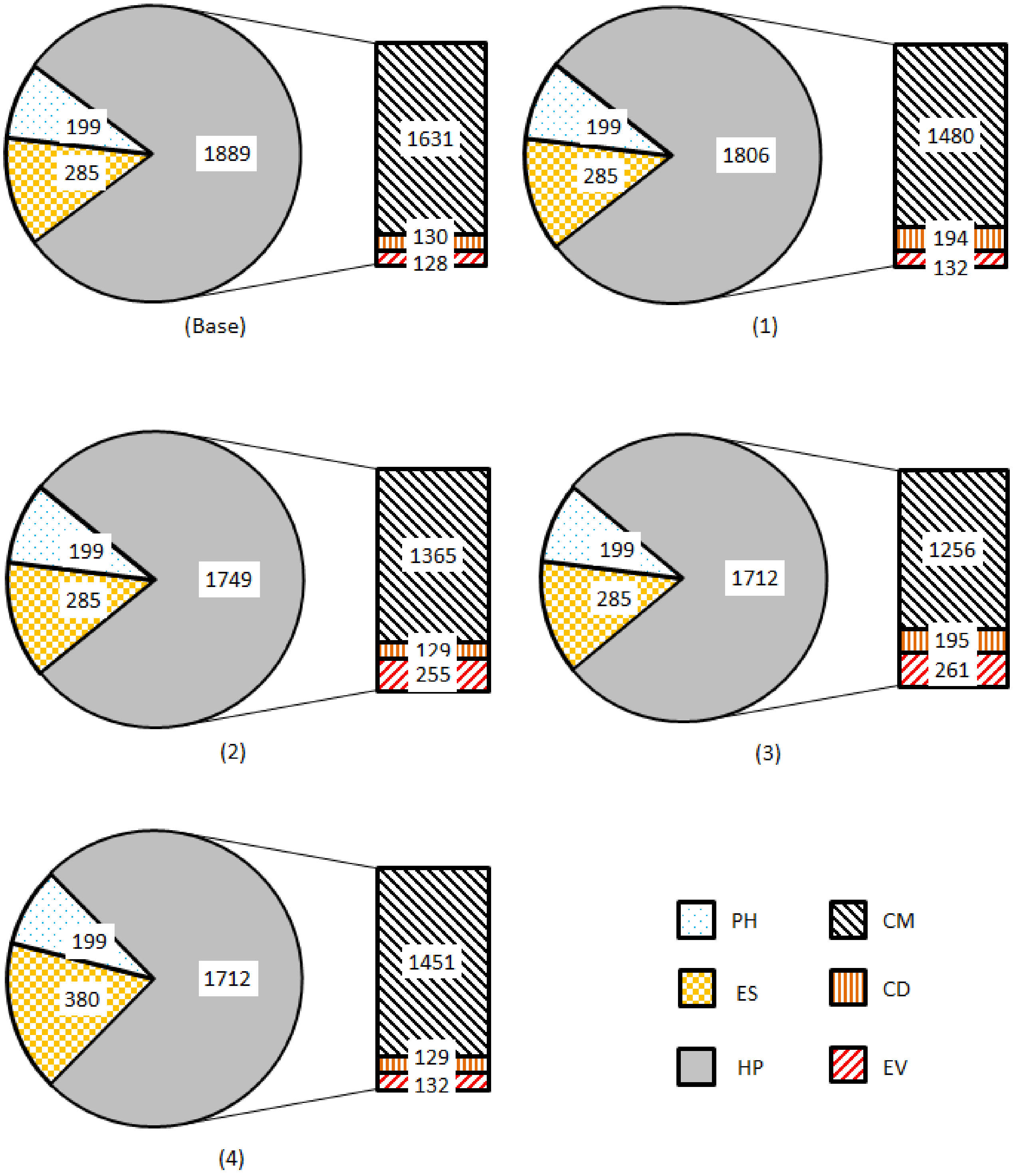

Figure 3. Investment costs Z_k^{year}*, €·year*$^{-}$*,*^{1} *for components of the investigated cases of space heating heat pump system*

The estimated values of the exergoeconomic and exergoenvironmental variables for the proposed cases are listed in Tables 8 and 9, respectively.

As it can be seen from the obtained results, from exergoeconomic and exergoenvironmental viewpoints, the case 3 is the most appropriate one for improvement of the system under analysis. The sums $Z_{tot}^{year} + C_{D,tot}^{year} = 2368\ € \cdot year^{-1}$ and $Y_{tot}^{year} + B_{D,tot}^{year} = 162014 mPts \cdot year^{-1}$ are the lowest ones for the case 3. The case 2 is of the second priority in which the total cost associated with investment expenditures and exergy destruction is equal to $2421\ € \cdot year^{-1}$ and total cost associated with environmental impact and exergy destruction is equal to $171282\,€\cdot year^{-1}$. Cases 1 and 4 are very close from the viewpoint of exergoeconomic and exergoenvironmental analyses. For these two cases the total sum $Z_{tot}^{year}+C_{D,tot}^{year}$ is equal to $2520\ €\cdot year^{-1}$ and $2514\ €\cdot year^{-1}$ respectively and the sum is equal to $197308 mPts\cdot year^{-1}$ and $190600 mPts\cdot year^{-1}$, respectively.

Table 8. Exergoeconomic estimation of the proposed cases of the system

Component	$c_{F,tot}^{year}$, €· kWh^{-1}	$c_{P,tot}^{year}$, €· kWh^{-1}	Z_{tot}^{year}, €· year^{-1}	$C_{D,tot}^{year}$, €· year^{-1}	$Z_{tot}^{year}+C_{D,tot}^{year}$, €· year^{-1}	r_{tot}^{year}, %	f_{tot}^{year}, %
Base	0.035	0.905	2374	249	2623	2501	91
1	0.035	0.885	2290	230	2520	2442	91
2	0.035	0.884	2233	188	2421	2443	92
3	0.035	0.876	2196	172	2368	2418	93
4	0.035	0.887	2291	223	2514	2448	91

Table 9. Exergoenvironmental estimation of the proposed cases of the system

Component	$b_{F,tot}^{year}$, mPts· kWh^{-1}	$b_{P,tot}^{year}$, mPts· kWh^{-1}	Y_{tot}^{year}, mPts·year^{-1}	$B_{D,tot}^{year}$, mPts·year^{-1}	$Y_{tot}^{year}+B_{D,tot}^{year}$, mPts·year^{-1}	$r_{b,tot}^{year}$, %	$f_{b,tot}^{year}$, %
Base	27	84	16159	193236	209395	210	7.7
1	27	80	18732	178577	197308	197	9.5
2	27	79	25656	146166	171822	191	14.9
3	27	76	28689	133325	162014	180	17.7
4	27	78	17462	173138	190600	188	9.2

Fig. 4 summarizes the most important objective functions of the investigated system. The presented values confirms that the case 3 is the most attractive among others. The annual exergy destruction in the case 3 is equal to 4938 kWh and lower by 31%, 25%, 9% and 23% respectively compared with the base, 1st, 2nd and the 4th cases. The annual exergy efficiency of the case 3 is the highest and equal to 0.29. The base and the cases 1, 2 and 4 are characterized by annual exergy efficiency equal to 0.22, 2.23, 0.27 and 0.24, respectively. Accordingly the sustainability index [25] for the case 3 is also the highest among others. The case 3 is characterized by the highest value of the annual coefficient of performance for the heat pump, which is equal to 4.3. For the base, 1st, 2nd and 4th cases this parameter is equal to 3.21, 3.42, 4.00 and 3.51, respectively. The annual cost of exergy of the product of the system for the all cases is not very different. In all proposed cases this parameter is decreased by only several percent. However, according to the results obtained above the cases 1, 2, 3 and 4 are better options for simultaneous improvement of the thermodynamic, economic and environmental performance of the investigated system. For the case 3 the annual cost of exergy of the product of the system is equal to 1728 €·year^{-1}. The annual environmental impact associated with the product of the system for the case 3 is decreased by 9.5%, 5.6%, 3.6% and 2.5 % compared to the base, 1st, 2nd and the 4th cases, respectively.

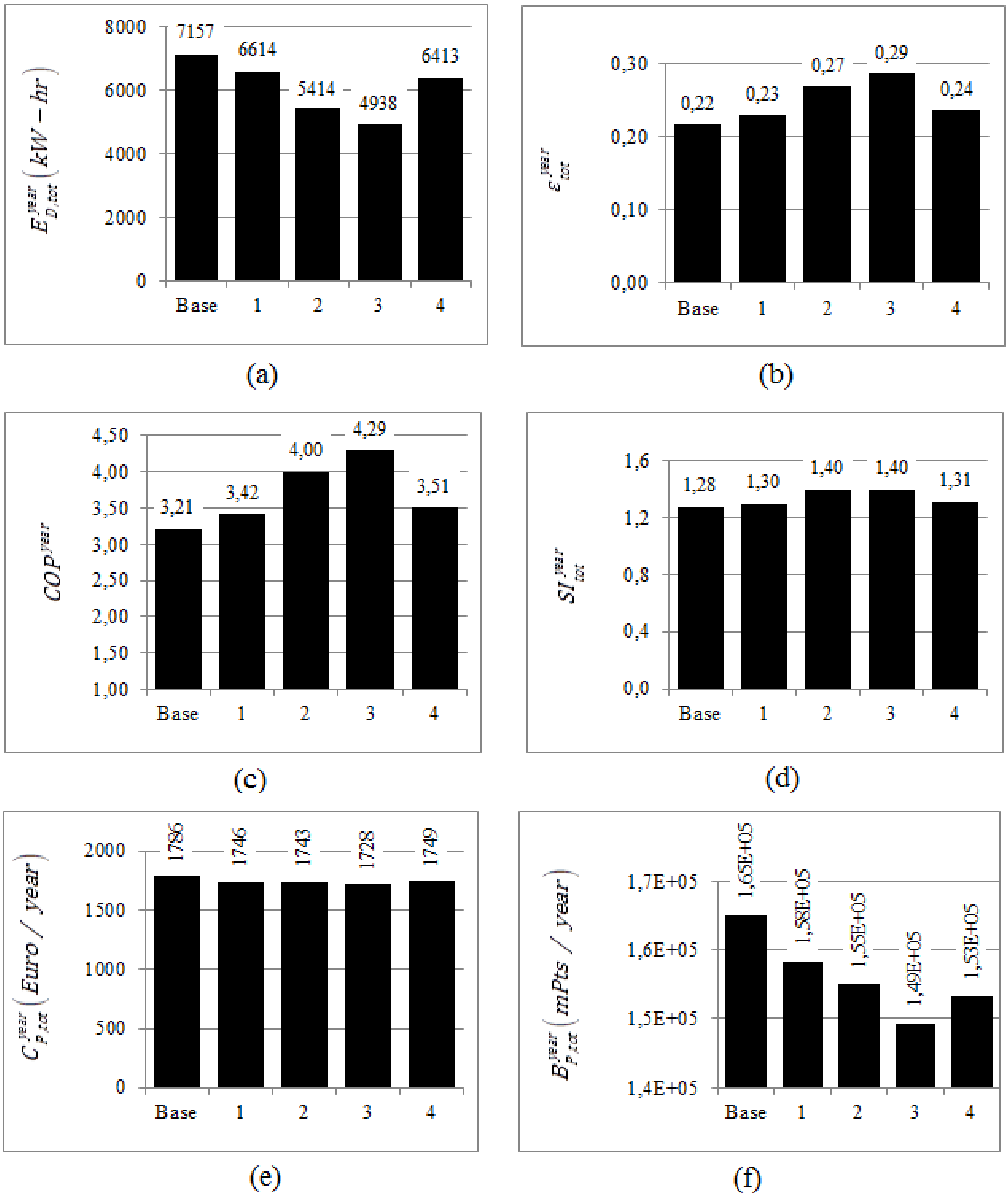

Figure 4. Objective variables of the investigated system: a) annual exergy destruction, b) annual exergy efficiency, c) annual coefficient of performance, d) annual sustainability index, e) annual cost of exergy of the product, f) annual environmental impact associated with the product

4. Conclusions and future developments

Heat pump units for space heating are expected to play a key role in significantly reducing the environment impact of such a fundamental sector. However, the performance of these systems including off-design operations has never been evaluated by means of the currently most powerful thermodynamic tools, i.e. advanced exergetic, exergoeconomic and exergoenvironmental analyses.

According to the obtained results the biggest value of exergy destruction in the investigated heat pump can be removed by improving evaporator. The sum of avoidable exergy destruction within the heat pump belongs to this component and is equal to 1609 kWh or 63 %.

The highest value of the avoidable cost associated with investment expenditures and exergy destruction belongs to the compressor and is equal to 690 Euro·year^{-1} (56 %). This sum is caused mostly by capital investment and can be reduced at the expense of the compressor efficiency. For the evaporator this part of the cost is equal to 434 Euro·year^{-1} (35 %) and caused mostly by its thermodynamic inefficiency.

About 70074 mPts·year^{-1} or 70% of the the total avoidable environmental impact associated with construction and exergy destruction belongs to the evaporator and can be decreased mostly by improving thermodynamic efficiency of this component. The condenser provides 16178 mPts·year^{-1} or 16% of the avoidable environmental impact within the heat pump.

The proposed design changes involved minimizing the irreversibility within the evaporator, condenser and emission system by reducing temperature differences. This decision only slightly increased capital investments and construction-of-component-related impact. Also, additionally to the thermodynamic objective functions the final objective economic and ecological ones were also improved.

Compared with the initial case the improved solution provides the reduced value of annual exergy destruction by 31%. The annual cost of exergy of the product of the improved system is also decreased by several percent. The annual environmental impact associated with the product of the system is decreased by 9.5 %.

Future research will involve the selection of the most appropriate low Global Warming Potential (GWP) working fluid for heat pump units aimed at space heating based on advanced exergy methods as well as the use of field measurements.

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Highlights

- Exergy-based analysis has been applied to an air-source heat pump for heating.
- The system performance was investigated based on its off-design operational modes.
- Reducing the irreversibilities through the evaporator and condenser is proposed.
- The thermodynamic, economic and environmental performance of the system was evaluated.

Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: