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Advanced exergy-based analyses applied to a system including LNG regasification and electricity generation

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Abstract

Liquefied natural gas (LNG) will contribute more in the future than in the past to the overall energy supply in the world. The paper discusses the application of advanced exergy-based analyses to a recently developed LNG-based cogeneration system. These analyses include advanced exergetic, advanced exergoeconomic, and advanced exergoenvironmental analyses in which thermodynamic inefficiencies (exergy destruction), costs, and environmental impacts have been split into avoidable and unavoidable parts. With the aid of these analyses, the potentials for improving the thermodynamic efficiency and for reducing the overall cost and the overall environmental impact are revealed. The objectives of this paper are to demonstrate (a) the potential for generating electricity while regasifying LNG and (b) some of the capabilities associated with advanced exergy-based methods. The most important subsystems and components are identified, and suggestions for improving them are made.

Keywords: LNG, Exergy analysis, Advanced exergy analysis, Exergoeconomics, Advanced exergoeconomic analysis, Exergoenvironmental analysis, Advanced exergoenvironmental analysis

Background

Several concepts of a system for generating electricity while vaporizing liquefied natural gas (LNG) have been developed by Griepentrog et al. [1,2]. These concepts have some thermodynamic and economic advantages over systems proposed in the past. A detailed discussion of the advantages and disadvantages of these concepts has been given in [3].

In this paper, advanced exergy-based methods, including advanced exergetic and exergoenvironmental analyses, are applied to the base case of the LNG regasification system. The exergy destruction within components as well as the cost and environmental impact associated with each component is split into avoidable and unavoidable parts to help engineers identify the potential for improvement from the viewpoints of thermodynamics, cost, and environmental impact.

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Methods

Simulation

The base case is shown in Figure 1. The overall system consists of three subsystems with the following initial data and assumptions:

- LNG subsystem (process 1–2 – 3–4) - LNG from the storage system is (a) compressed by an LNG pump (P), (b) vaporized in heat exchanger II (HE II) using the waste heat from the nitrogen power system, and (c) expanded in expander III (EX III).
- N2 subsystem (process 11–12 – 13–14) - The N2 subsystem is a closed-cycle gas-turbine power system. After being cooled in HE II, the nitrogen is compressed in compressor III (CM III), heated in heat exchanger I (HE I) using the waste heat from an open gas-turbine power system, and expanded in expander II (EX II).
- Open gas-turbine power subsystem (process 21 through 28) - Air after compression in compressor I (CM I) is cooled in the cooler (CL) transferring thermal energy to the environment and is compressed in compressor II (CM II). After the combustion process in the combustion chamber

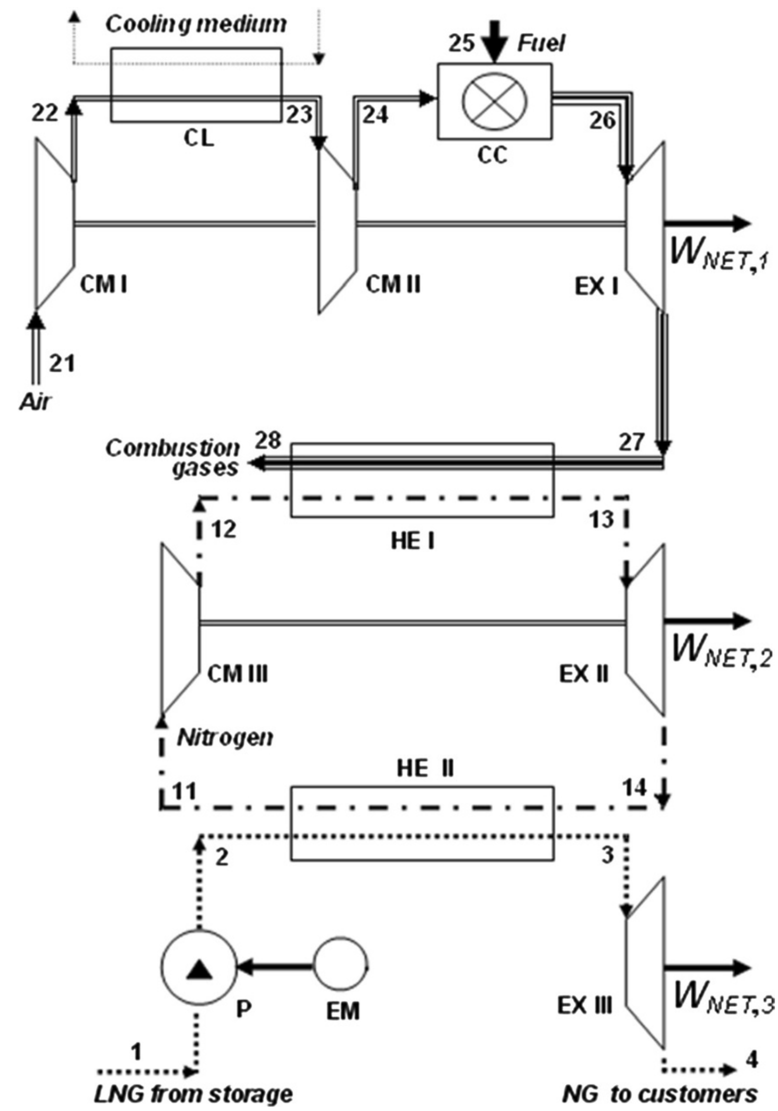

Figure 1 Schematic of the cogeneration system for vaporizing LNG.

(CC), the combustion gases are expanded in expander I (EX I) and rejected to the atmosphere after being cooled in HE I. The open gas-turbine power subsystem is based on an LMS 100 gas turbine (General Electric Company, Fairfield, CT, USA) [4].

For the simulation and the exergetic analyses, the softwares GateCycle (General Electric Company, Fairfield, CT, USA) [5], Gatex (Institut für Energietechnik, Technische Universität Berlin, Germany) [6], and EES (F-Chart Software, LLC, Madison, WI, USA) [7] were used. Table 1 presents some results obtained from the simulation [3]. The following assumptions were used: η_{CMI} = 90 %, η_{CMII} = 90 %, $p24/p21$ = 42, T_{26} = 1,290°C, $\eta_{EX\ I}$ = 94 %, $\Delta T^{min}_{HEI} = 20$ K, Δp_{HEI} = 3 %, $\eta_{CM\ III}$ = 85 %, $p12/p11$ = 15, $\eta_{EX\ II}$ = 88 %, $\Delta T^{min}_{HEI} = 15$ K, Δp_{HEII} = 3 %, η_P = 66.5 %, and $\eta_{EX\ III}$ = 85 %.

Exergy-based analyses

Exergoeconomics is a unique combination of exergy analysis and cost analysis conducted at the component level to provide the designer or operator of an energy conversion system with information crucial to the design or operation of a cost-effective system. Decisions are made, however, at the plant component level [8,9]. A complete exergoeconomic analysis consists of (a) an exergetic analysis, (b) an economic analysis, and (c) an exergoeconomic evaluation.

Table 1 Thermodynamic data for the material streams in the base case

Material stream	State	$\dot{m}$(kg/s)	T(°C)	p(bar)	e^T(kJ/kg)	e^M(kJ/kg)	e^{PH}(kJ/kg)	e^{CH}(kJ/kg)	e(kJ/kg)
LNG	1	65.03	−160	10	669.7	339.3	1,009	-	1,009
LNG	2	65.03	−144	272	250.5	778.5	1,029	-	1,029
NG	3	65.03	86	270	25.3	777.7	803	-	803
NG	4	65.03	2	80	1.0	630.0	631	-	631
N_2	11	217	−129	2.85	58.6	88.4	147	-	147
N_2	12	217	70	42.75	5.0	319.0	324	-	324
N_2	13	217	415	40.61	162.2	314.8	477	-	477
N_2	14	217	101	2.99	11.4	92.6	104	-	104
Air	21	209	15	1.013	-	-	0	1	1
Air	22	209	242	6.66	-	-	217	1	218
Air	23	209	117	6.53	-	-	170	1	171
Air	24	209	416	43.47	-	-	468	1	469
CH_4	25	5.1	15	45	-	-	566	51,534	52,100
Combustion gases	26	214.1	1,290	41.95	-	-	1,281	9	1,290
Combustion gases	27	214.1	435	1.08	-	-	190	9	199
Combustion gases	28	214.1	90	1.025	-	-	18	9	27

An *exergoenvironmental analysis* is considered as one of the most promising tools to evaluate energy conversion processes from an environmental point of view [10]. Exergoenvironmental analysis is a proper combination of exergy analysis and life cycle assessment (LCA). The exergoenvironmental analysis consists of three steps: The first step is an exergy analysis. In the second step, an LCA of (a) each relevant system component and (b) all relevant input streams to the overall system is carried out. In the last step, the environmental impact obtained from the LCA is assigned to the exergy streams in the system.

Exergy analysis

Table 1 shows the value of exergy for each material stream. The chemical exergies for material streams of the N_2 and the LNG subsystems do not need to be considered in the exergetic analysis because only the physical exergy of the working fluid is used in the corresponding subsystems. We considered the chemical exergies only in the open gas-turbine subsystem, where combustion takes place. The physical exergies of LNG, NG, and N_2 are split into their thermal and mechanical parts according to the approach presented in [11].

The exergetic analysis has been conducted at the component level using the 'exergy of the fuel' and the 'exergy of the product' [8,9]. The definitions of $\dot{E}_{F,k}$ and $\dot{E}_{P,k}$ for each system component are given in [3]. Table 2 shows some data obtained from the conventional exergetic analysis.

Exergoeconomic analysis

The exergoeconomic model for an energy conversion system consists of *cost balances* written for the kth component and auxiliary equations based on the P and the F rules [8,9]. The cost balances can be written as

$$\dot{C}_{P,k} = \dot{C}_{F,k} + \dot{Z}_k \tag{1a}$$

or

$$c_{P,k}\dot{E}_{P,k} = c_{F,k}\dot{E}_{F,k} + \dot{Z}_k, \tag{1b}$$

where

$$\dot{Z}_k = \dot{Z}_k^{CI} + \dot{Z}_k^{OM}. \tag{2}$$

Table 2 Results obtained from the conventional exergetic analysis [3]

Component	$\dot{E}_{F,k}$(MW)	$\dot{E}_{P,k}$(MW)	$\dot{E}_{D,k}$(MW)	ε_k(%)
CM I	48.418	45.434	2.984	93.84
CL	Dissipative component		9.993	-
CM II	65.224	62.458	2.766	95.76
CC	267.603	178.131	89.466	66.57
EX I	233.661	227.569	6.092	97.39
HE I	36.926	33.091	3.834	89.83
CM III	57.021	51.222	5.799	89.83
EX II	80.956	72.829	8.127	89.96
HE II	19.722	14.427	5.295	73.15
P	34.295	28.582	5.713	83.34
EX III	11.249	9.479	1.770	84.26
Overall system ($\dot{E}_{L,tot} = 5.768$ MW)	311.415	163.801	141.846	52.60

To simplify the discussion, we assume that the contribution of $\dot{Z}_k^{\mathrm{OM}}$ remains constant when the design changes, and therefore, the changes in the value of $\dot{Z}_k$ are associated only with changes in the capital investment cost $\dot{Z}_k^{\mathrm{CI}}$.

The real cost sources in an energy conversion system are the (a) capital investment (and operating maintenance expenses) for each component, (b) cost of exergy destruction within each component, and (c) cost of exergy loss from the overall system. The last two terms can be revealed only through an exergoeconomic analysis:

- The cost rate associated with exergy destruction within the kth component is

$$\dot{C}_{\mathrm{D},k} = c_{\mathrm{F},k} \cdot \dot{E}_{\mathrm{D},k}. \quad (3)$$

- The cost rate associated with exergy loss from the overall system is

$$\dot{C}_{\mathrm{L,tot}} = \dot{C}_{28}. \quad (4)$$

The exergoeconomic model for the base case has been discussed in detail in [12]. Table 3 shows selected data obtained from the conventional exergoeconomic analysis. Here, the cooler is considered together with the cooling tower ($\dot{Z}_{\mathrm{CT}} = 3.25$ \$/h), and the pump is considered together with the electrical motor ($\dot{Z}_{\mathrm{EM}} = 1.33$ \$/h).

For the economic analysis, the methodology presented in [8] is applied using the following assumptions and sources:

- The purchased equipment cost of turbomachinery is based on data from [8,13].
- The purchased equipment cost of heat exchangers is based on data from [8].
- The cost of LNG is equal to \$12/GJ [14].
- The average cost of money is $i_{\mathrm{eff}} = 10$ %.

Table 3 Exergoeconomic variables for the LNG-based cogeneration systems

Component	$\dot{Z}_k$(\$/h)	$\dot{C}_{\mathrm{D},k}$(\$/h)	$\dot{Z}_k + \dot{C}_{\mathrm{D},k}$(\$/h)	$c_{\mathrm{F},k}$(\$/GJ)
CM I	64.67	554	619	51.63
CL	11.10	Dissipative component		
CM II	97.01	514	611	51.63
CC	92.39	9,493	9,585	29.47
EX I	207.90	1,097	1,305	50.04
HE I	16.04	691	707	50.04
CM III	16.23	3,007	3,023	144.00
EX II	20.49	4,133	4,154	14.13
HE II	13.76	920	934	48.26
P	7.01	783	788	38.06
EX III	2.65	432	435	67.76

- The plant economic life is $n = 15$ years with 7,300 h/year.
- The average general inflation rate is $r_n = 2.5$ %

Exergoenvironmental analysis

Exergy analysis provides a powerful tool for assessing the quality of a resource as well as the location, magnitude, and causes of thermodynamic inefficiencies. In addition, LCA supplies the environmental impacts associated with a component or an overall system during its entire useful life. In the exergoenvironmental analysis, the environmental impacts obtained by LCA are apportioned to the exergy streams pointing out the main system components with the highest environmental impact and possible improvements associated with these components. Finally, exergoenvironmental variables are calculated, and an exergoenvironmental evaluation is carried out.

Life cycle assessment is a technique for assessing the environmental aspects associated with a product over its life cycle. The LCA process consists of goal definition and scoping (defining the system under consideration), inventory analysis (identifying and quantifying the consumption and release of materials), and interpretation (evaluation of the results) [15].

In general, any of recently introduced indicators can be used for LCA. For this exergoenvironmental analysis, an impact analysis method called Eco-indicator 99 [16] has been selected because it considers many environmental aspects and uses average European data.

In order to identify the raw material inlet flows, it is first necessary to perform a sizing of the plant components and to collect information about the weights, main materials, production processes, and scrap outputs of all relevant pieces of equipment needed to build the plant. This information is usually not very widely published (compared with the corresponding cost information). In this way, only rough calculations of the employed main materials and corresponding weights can be conducted.

The data collected in [17,18] were generalized in the form of equations (Tables 4 and 5) and used for estimating the component-related environmental impact that occurs during the construction phase. If the materials of a component correspond to the data given in Table 4, then the values of $\bar{b}$ (relative environmental impact) and $\bar{m}$ (relative mass) are equal to 1. If the selected material is different, then $\bar{b} = \frac{b_{\text{given material}}}{b_{\text{new material}}}$ and $\bar{m} = \frac{\rho_{\text{given material}}}{\rho_{\text{new material}}}$ (where ρ is the density of the material, kg/m^3).

For the LCA of the system being analyzed, we assumed in analogy with the economic analysis a life time of 15 years and 7,300 working hours per year at full capacity.

The exergoenvironmental model for an energy conversion system consists of *environmental impact balances* written for the kth component and auxiliary equations

Table 4 Eco-indicator 99 values and material composition of components

Equipment	Construction material	Eco-indicator 99 (mPoints/kg)	Material composition (% *w/w*)
CM I, CM II	Steel	86	33.33
	Steel low alloy	110	44.45
	Cast iron	240	22.22
CL	Steel	86	100
CT	Concrete	3.8	91.00
	PVC	280	9.00
CC	Steel	86	33.34
	Steel high alloy	910	66.66
EX I, EX II, EX III	Steel	86	25.00
	Steel high alloy	910	75.00
HE I, HE II	Steel	86	25.00
	Steel low alloy	110	75.00
CM III	Steel	86	33.33
	Steel low alloy	110	44.45
	Cast iron	240	22.22
P	Steel	86	35.00
	Cast iron	240	65.00

based on the P and F rules [10]. The environmental impact balances can be written as

$$\dot{B}_{\mathrm{P},k} = \dot{B}_{\mathrm{F},k} + \left(\dot{Y}_k + \dot{B}_k^{\mathrm{PF}}\right) \tag{5a}$$

or

$$b_{\mathrm{P},k}\dot{E}_{\mathrm{P},k} = b_{\mathrm{F},k}\dot{E}_{\mathrm{F},k} + \left(\dot{Y}_k + \dot{B}_k^{\mathrm{PF}}\right), \tag{5b}$$

where $\dot{Y}_k$ is the environmental impacts that occur during the three life-cycle phases: Construction $\dot{Y}_k^{\mathrm{CO}}$, operation and maintenance, $\dot{Y}_k^{\mathrm{OM}}$, and disposal $\dot{Y}_k^{\mathrm{DI}}$ constitute the component-related environmental impact associated with the kth component $\dot{Y}_k$:

$$\dot{Y}_k = \dot{Y}_k^{\mathrm{CO}} + \dot{Y}_k^{\mathrm{OM}} + \dot{Y}_k^{\mathrm{DI}}. \tag{6}$$

To simplify the discussion, we assume in this paper that the value of $\dot{Y}_k$ is mainly associated with $\dot{Y}_k^{\mathrm{CO}}$.

To account for *pollutant formation* within the kth component, a new variable was recently introduced $\dot{B}_k^{\mathrm{PF}}$ [19,20]. This term $\dot{B}_k^{\mathrm{PF}}$ is zero if no pollutants are formed within a process, i.e., for processes without a chemical reaction (compression, expansion, heat transfer, etc.). For components, where chemical reactions occur (combustion, for example), the value of $\dot{B}_k^{\mathrm{PF}}$ is

$$\dot{B}_k^{\mathrm{PF}} = \sum_i b_i^{\mathrm{PF}}\left(\dot{m}_{i,\mathrm{out}} - \dot{m}_{i,\mathrm{in}}\right), \tag{7}$$

where only pollutant streams which will finally be emitted to the environment are taken into account: CO, CO_2, CH_4, N_2O, NO_x, and SO_x [10].

The environmental impact of exergy destruction $\dot{B}_{\mathrm{D},k}$ identifies the environmental impact due to the exergy destruction within the kth component [10]:

$$\dot{B}_{\mathrm{D},k} = b_{\mathrm{F},k}\dot{E}_{\mathrm{D},k}. \tag{8}$$

To identify the most important components from the viewpoint of formation of environmental impacts, the

Table 5 Environmental impact functions of components for the construction phase

Component	Environmental impact function, Y_k(Pts of Eco-indicator 99)	Variables
CM 1, CM 2, CM 3	$Y_{\mathrm{CM}} = (0.0039\cdot\dot{W}_{\mathrm{CM}}^2 - 2,070.68\cdot\dot{W}_{\mathrm{CM}} + 2.62\cdot10^6)\times(0.3333\cdot\bar{b}_S\cdot\bar{m}_S + 0.4445\cdot\bar{b}_{\mathrm{SLA}}\cdot\bar{m}_{\mathrm{SLA}} + 0.2222\cdot\bar{b}_{\mathrm{CI}}\cdot\bar{m}_{\mathrm{CI}})$	$\dot{W}_{\mathrm{CM}}$ (kW)
CL	$Y_{\mathrm{CL}} = (0.703\cdot A + 12.03)\cdot\bar{b}_S\cdot\bar{m}_S$	Heat exchange area, A (m^2)
CT	$Y_{\mathrm{CT}} = 3098\cdot\dot{m}_{\mathrm{water}}\cdot\left(0.09\cdot\bar{b}_{\mathrm{PVC}}^{\mathrm{fill}}\cdot\bar{m}_{\mathrm{PVC}}^{\mathrm{fill}} + 0.91\cdot\bar{b}_{\mathrm{CON}}\cdot\bar{m}_{\mathrm{CON}}\right)$	$\dot{m}_{\mathrm{water}}$ (m^3/h)
CC	$Y_{\mathrm{CC}} = \left(-0.2965\cdot\dot{m}^2_{\mathrm{comb.\,gas}} + 454.12\cdot\dot{m}_{\mathrm{comb.\,gas}} - 60909.11\right)\times(0.3334\cdot\bar{b}_S\cdot\bar{m}_S + 0.6666\cdot\bar{b}_{\mathrm{SHA}}\cdot\bar{m}_{\mathrm{SHA}})$	$\dot{m}_{\mathrm{comb.\,gas}}$ (kg/s)
EX I, EX II, EX III	$Y_{\mathrm{EX}} = \left(0.2457\cdot\dot{W}_{\mathrm{EX}} + 15,538\right)\left(0.25\cdot\bar{b}_S\cdot\bar{m}_S + 0.75\cdot\bar{b}_{\mathrm{SHA}}\cdot\bar{m}_{\mathrm{SHA}}\right)$	$\dot{W}_{\mathrm{EX}}$ (kW)
HE I, HE II	$Y_{\mathrm{HE}} = (11.28\cdot A + 119.07)\times\left(0.75\cdot\bar{b}_{\mathrm{SLA}}^{\mathrm{tubes}}\cdot\bar{m}_{\mathrm{SLA}}^{\mathrm{tubes}} + 0.25\cdot\bar{b}_S^{\mathrm{casing}}\cdot\bar{m}_S^{\mathrm{casing}}\right)$	Tubes of SLA Casing of steel Heat exchange area, A (m^2)
P	$Y_{\mathrm{P}} = \left(0.0016\cdot\dot{W}_{\mathrm{P}}^2 - 0.5559\cdot\dot{W}_{\mathrm{P}} + 12.66\right)\cdot\bar{b}_{\mathrm{CI}}\cdot\bar{m}_{\mathrm{CI}}$ (for $p_{\mathrm{discharge}} > 5$ bar)	$\dot{W}_{\mathrm{P}}$ (kW)

sum of environmental impacts $\left(\dot{Y}_k + \dot{B}_k^{PF} + \dot{B}_{D,k}\right)$ is used.

The detailed exergoenvironmental model for the LNG-based cogeneration system (Figure 1) will be presented in a future publication. In this paper, some data obtained from the conventional exergoenvironmental analysis are given in Table 6. Here, the cooler is considered together with the cooling tower ($\dot{Y}_{CT} = 0.065\text{Pts/h}$), and the pump is considered together with the electrical motor, $\dot{Y}_{EM} = 0.363\text{Pts/h}$.

Advanced exergy-based analyses

The real potential for improving the system from a thermodynamic, economic, and environmental impact point of view can be estimated when the following are split into avoidable/unavoidable parts [17,21-23]:

- exergy destruction within each (important) system component,
- investment cost and environmental impact associated with such component, and
- cost of exergy destruction and environmental impact associated with the exergy destruction for each (important) system component.

The *unavoidable* exergy destruction cannot be further reduced due to technological limitations such as availability and cost of materials and manufacturing methods. The difference between total and unavoidable exergy destruction for a component is the *avoidable* exergy destruction. Only this value and not the total exergy destruction should be considered during the improvement procedure.

$$\dot{E}_{D,k}^{AV} = \dot{E}_{D,k} - \dot{E}_{D,k}^{UN} \tag{9}$$

The unavoidable investment cost ($\dot{Z}_k^{UN}$) and unavoidable component-related environmental impact ($\dot{Y}_k^{UN}$) for a component can be calculated by assuming the minimum values of $\left(\frac{\dot{Z}_k}{\dot{E}_{P,k}}\right)^{UN}$ and $\left(\frac{\dot{Y}_k}{\dot{E}_{P,k}}\right)^{UN}$, respectively. These values will always be exceeded as long as such a component is used in a real system. The avoidable investment cost and component-related environmental impact are the differences between the total value and unavoidable part of this variable, i.e.,

$$\dot{Z}_k^{AV} = \dot{Z}_k - \dot{Z}_k^{UN} \tag{10}$$

$$\dot{Y}_k^{AV} = \dot{Y}_k - \dot{Y}_k^{UN}. \tag{11}$$

The value of the unavoidable exergy destruction within the kth component is calculated using the ratio $\left(\frac{\dot{E}_{D,k}}{\dot{E}_{P,k}}\right)^{UN}$ that refers to the case where only unavoidable exergy destruction occurs:

$$\dot{E}_{D,k}^{UN} = \dot{E}_{P,k}^{real}\left(\frac{\dot{E}_{D,k}}{\dot{E}_{P,k}}\right)^{UN}. \tag{12}$$

The values of unavoidable capital investment cost and component-related environmental impact can be calculated using similar equations:

$$\dot{Z}_k^{UN} = \dot{E}_{P,k}^{real}\left(\frac{\dot{Z}_k}{\dot{E}_{P,k}}\right)^{UN} \tag{13}$$

$$\dot{Y}_k^{UN} = \dot{E}_{P,k}^{real}\left(\frac{\dot{Y}_k}{\dot{E}_{P,k}}\right)^{UN}. \tag{14}$$

The approaches for estimating the values of $\left(\frac{\dot{E}_D}{\dot{E}_P}\right)_k^{UN}$, $\left(\frac{\dot{Z}}{\dot{E}_P}\right)_k^{UN}$, and $\left(\frac{\dot{Y}}{\dot{E}_P}\right)_k^{UN}$ are given in [3,12].

Selected data obtained from the advanced exergy-based analyses for the LNG regasification system are given in Table 7. In this paper, we assumed that components of the open gas-turbine subsystem cannot be improved because

Table 6 Exergoenvironmental variables for the LNG-based cogeneration systems

Component	$\dot{Y}_k$ (Pts/h)	$\dot{B}_{D,k}$ (Pts/h)	$\dot{B}_k^{PF}$ (Pts/h)	$\dot{Y}_k + \dot{B}_{D,k} + \dot{B}_k^{PF}$ (Pts/h)	$b_{F,k}$ (Pts/GJ)
CM I	1.254	90.718	-	91.972	8.443
CL	0.090	Dissipative component			
CM II	1.054	84.085	-	85.139	8.443
CC	1.200	1,128.000	1,345.320	2,474.520	3.501
EX I	4.175	180.241	-	184.416	8.218
HE I	19.732	114.450	-	134.182	8.218
CM III	1.307	185.565	-	186.871	8.880
EX II	1.953	283.449	-	285.402	9.678
HE II	6.828	31.053	-	37.881	1.643
P	1.454	1.913	-	3.367	0.114
EX III	1.043	2.650	-	3.693	0.416

Table 7 Selected data obtained from the advanced exergy-based analyses

Component	$\left(\frac{\dot{E}_D}{\dot{E}_P}\right)_k^{UN}$	$\dot{E}_{D,k}^{UN}$ (MW)	$\dot{E}_{D,k}^{AV}$ (MW)	$\left(\frac{\dot{Z}}{\dot{E}_P}\right)_k^{UN}$ ($/MJ)	$\dot{Z}_k^{UN}$ ($/h)	$\dot{Z}_k^{AV}$ ($/h)	$\dot{C}_{D,k}^{UN}$ ($/h)	$\dot{C}_{D,k}^{AV}$ ($/h)	$\dot{Z}_k^{AV}+\dot{C}_{D,k}^{AV}$ ($/h)	$\left(\frac{\dot{Y}}{\dot{E}_P}\right)_k^{UN}$ (Pts/MJ)	$\dot{Y}_k^{UN}$ (Pts/h)	$\dot{Y}_k^{AV}$ (Pts/h)	$\dot{B}_{D,k}^{UN}$ (Pts/h)	$\dot{B}_{D,k}^{AV}$ (Pts/h)	$\dot{B}_{D,k}^{AV}+\dot{Y}_k^{AV}$ (Pts/h)
HE I	0.0451	1.492 (39%)	2.342 (61%)	0.231	7.66 (48%)	8.38 (52%)	269	422	430(61%)	0.3290	10.879 (55%)	8.835 (45%)	44.140	70.309	79.144 (58%)
CM III	0.0593	3.037 (52%)	2.762 (48%)	0.098	5.03 (31%)	11.20 (69%)	1,574	1,433	1,444(48%)	0.0063	0.323 (25%)	0.984 (75 %)	97.087	88.478	89.462 (48%)
EX II	0.0511	3.722 (46%)	4.405 (54%)	0.114	8.29 (40%)	12.20 (60%)	1,901	2,232	2,244(54%)	0.0059	0.433 (23%)	1.520 (77%)	129.677	153.772	155.292 (54%)
HE II	0.0973	1.404 (27%)	3.891 (73%)	0.469	6.77 (49%)	6.99 (51%)	244	676	623(73%)	0.0740	1.071 (16%)	5.757 (84%)	8.304	22.748	28.505 (75%)
P	0.0874	2.498 (44%)	3.125 (56%)	0.082	2.33 (33%)	3.35 (67%)	342	441	444(56 %)	0.0155	0.444 (30%)	1.010 (70%)	0.842	1.071	2.081 (62%)
EX III	0.0913	0.865 (49%)	0.905 (51%)	0.126	1.20 (45%)	1.45 (55%)	211	221	222(51%)	0.0240	0.228 (22%)	0.815 (78%)	1.298	1.351	2.166 (59%)

this subsystem represents an already commercially available unit.

Results and discussion

Conventional exergy based analyses

The conclusions which can be obtained from the conventional exergetic analysis of the N_2 and LNG subsystems are based on the values of $\dot{E}_{D,k}$ (Table 2). The components with the highest potential for improvement are EX II, CM III, and HE II.

The economic analysis (value $\dot{Z}_k$ in Table 3) shows that EX II is the most expensive component among the N2 and LNG subsystems followed by HE I and CM III.

The results from the exergoeconomic analysis (values of $\dot{Z}_k + \dot{C}_{D,k}$ in Table 3) show that EX II and CM III are by far the most important components from the economic viewpoint and that the high costs ($\dot{Z}_k + \dot{C}_{D,k}$) for these components are caused primarily by the exergy destruction ($\dot{C}_{D,k}$). This demonstrates (a) the importance of the N_2 subsystem for the economics of the overall system and (b) the necessity to keep the thermodynamic inefficiencies occurring within the N_2 subsystems to a minimum.

The results obtained from the LCA (value $\dot{Y}_k$ in Table 6) demonstrate that the component-related environmental impact associated with HE I and HE II is the highest among all components of the overall system.

The exergoenvironmental analysis (value $\dot{B}_{D,k}$ in Table 6) shows that for all components, the environmental impact associated with the exergy destruction is much higher than the component-related environmental impact ($\dot{B}_{D,k}+\dot{Y}_k$). Only for the pump and EX III are these values comparable. Based on the sum ($\dot{Y}_k + \dot{B}_{D,k} + \dot{B}_k^{PF}$), the most important components are again EX II and CM III. They can be improved by decreasing the exergy destruction and, therefore, decreasing the environmental impact associated with the exergy destruction.

The conventional exergy-based analyses suggest to initially decrease the exergy destruction within the N_2 subsystem and mainly within EX II and CM III. This decrease of exergy destruction will not only increase the overall efficiency, but will also simultaneously reduce both costs and environmental impact associated with the overall system.

Advanced exergy-based analyses

The advanced exergy-based analyses (results shown in Table 7) refine and correct the results from the conventional analyses. From the thermodynamic point of view, for example, CM III does not have the importance that the conventional exergetic analysis suggests because most of the exergy destruction in CM III is unavoidable. HE II and P are thermodynamically more important than CM III when only avoidable exergy destruction within each component is considered. Thus, improvement efforts should focus more on EX II, HE II, and P (where the potential for improvement is higher) than in CM III.

However, from the cost viewpoint, CM III is much more important than HE II or P because the cost per unit of exergy supplied to the compressor (cost of fuel) has the highest value among all components (see $c_{F,k}$ values in Table 3). The highest potential for reducing the cost of the overall product is still associated with EX II and CM III that exhibit the highest value of $\dot{C}_{D,k}^{AV} + \dot{Z}_k^{AV}$.

The values of $\dot{B}_{D,k}^{AV} + \dot{Y}_k^{AV}$ indicate that the highest potential for reducing the overall environmental impact is associated with EX II, CM III, and HE I. Thus, the advanced exergoenvironmental analysis emphasizes the importance of component HE I compared with the conventional exergoenvironmental analysis.

The advanced analyses confirm the conclusion from the conventional analyses that by decreasing the exergy destruction within the N_2 subsystem, the efficiency of the overall system would increase while the cost and the environmental impacts would decrease.

Conclusions

The present work identified the importance of the N_2 subsystem in improving the overall system and demonstrated the advantages of splitting thermodynamic inefficiencies, cost, and environmental impacts into unavoidable and avoidable parts.

Results show that efforts should focus on EXII, HEII, and P in order to improve the thermodynamic efficiency and reduce the environmental impact. To improve the cost effectiveness, effort should focus on EXII and CMIII. Thus, EX II is the most important system component regardless of the viewpoint of the analyst.

Even more accurate information is obtained when these variables are split into their endogenous and exogenous parts because, then, the interactions among components become transparent. The results from complete advanced exergy-based analyses will be presented in subsequent publications.

Nomenclature

b specific environmental impact per unit of exergy (Pts/J) or per unit of mass (Pts/kg)
$\dot{B}$ environmental impact rate associated with exergy (Pts/s)
C cost associated with an exergy stream ($)
c cost per unit of exergy ($/J)
$\dot{E}$ exergy rate (J)
e specific exergy (J/kg)
k kth component
$\dot{m}$ mass flow rate (kg/s)
p pressure (Pa)
$\dot{Q}$ heat rate (W)
T temperature (K)
$\dot{W}$ power (W)
$\dot{Y}$ component-related environmental impact rate (Pts/s)
$\dot{Z}$ cost rate associated with investment expenditures ($)

Greek symbols

ε exergetic efficiency (%)
η isentropic efficiency (%)

Superscripts

AV avoidable
CH chemical
CT cooling tower
M mechanical
PF pollutant formation
PH physical
T thermal
UN unavoidable

Subscripts

PI cast iron
CON concrete
D exergy destruction
F exergy of fuel
k kth component
L exergy loss
P exergy of product
PVC polyvinylchlorid
S steel
SHA high alloy steel
SLA low alloy steel
tot overall system
0 thermodynamic environment (reference state)

Abbreviations

CC, Combustion chamber; CL, Cooler; CM, Compressor; CT, Cooling tower; EM, Electrical motor; EX, Expander; HE, Heat exchanger; P, Pump.

Competing interests

The authors declare that they have no competing interests.

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Authors' contributions

TM co-supervised the work, conducted the exergy analysis, and drafted the manuscript. GT co-supervised the work, conducted the economic analysis, and corrected the manuscript. AB conducted the life cycle assessment. CG conducted the calculations according to the instructions provided by the supervisors. All authors read and approved the final manuscript.

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