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LNG – Based Cogeneration Systems: Evaluation Using Exergy-Based Analyses

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1. Introduction

The liquefied natural gas (LNG) market was established in the 1960s. During its over 50 years history, this market has grown significantly and the growth is expected to continue in the future. New technologies that lead to an increased efficiency in each step of the LNG chain are permanently in the focus of consideration. The information given in this section is based on many References (for example, EIA, 2003 and 2004; NTL, 2005; IIF-IIR, 2006; PFC Energy, 2011; GIIGNL, 2011; PLATTS, 2011; EUROGAS, 2011; Foss, 2003; Patel, 2005; Dorigoni & Portatadino, 2008; Maxwell & Zhu, 2011; Kumar et al., 2011).

The LNG chain (Figure 1) is divided into two main blocks: (a) Export terminal with associated technology for a liquefaction process, and (b) import terminal using a regasification process. Export and import terminals are connected by the LNG transport.
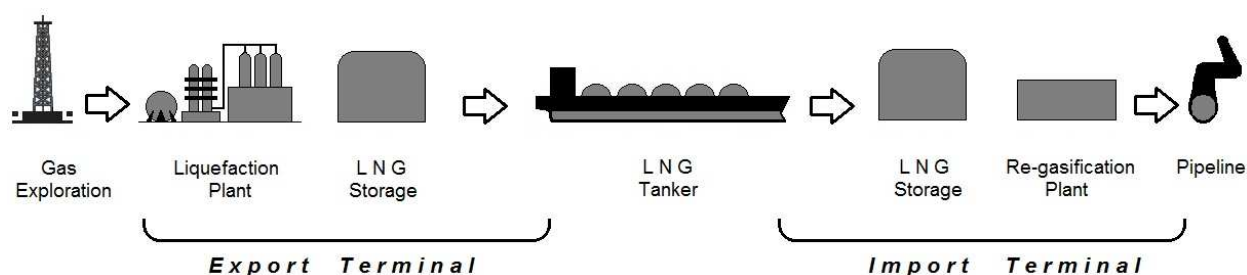

Figure 1. LNG chain

At the end of the year 2010, the World LNG market contained:

- 25 LNG liquefaction plants in 18 countries. Some of the first LNG liquefaction plants are still in operation (for example, in Algeria since 1964, in USA since 1969, and in Libya since 1970). New liquefaction plants that started operation during the year 2010 include two in Qatar, one in Yemen and one in Peru.

- 360 vessels (the oldest is in operation since the year 1969), and
- 83 LNG regasification plants (including 10 floating structures) with a total storage capacity of 38.5 million m^3 of LNG in 363 tanks. The oldest regasification plants are in operation since 1969 in Spain and Italy, and since 1972 in France and Japan. Many of the old regasification plants have been reconstructed during the last decade. The newest regasification plants include those completed in 2009 (in China, UK and Canada), and 2010 (in USA, Japan and Chile).

The average life cycle of a liquefaction and regasification plant is around 20 to 25 years. In the year 2010, the LNG trade rose with a growth rate of 21.2% compared with 2009, whereas the pipeline trade of natural gas increased only by 7%.

The following economic data can be found in the literature for the period 1992-2002. The price of LNG depended on the region and time (all values are given in constant US$ 2010 per million BTU):

- For the USA − between a minimum of 4.45 (1993) and a maximum of 5.84 (2001);
- For Europe − between a minimum of 3.06 (1999) and a maximum of 5.14 (2001); and
- For Japan − between a minimum of 4.73 (1998) and a maximum of 5.00 (2000).

In the year 2010 the LNG price was 3.75, 6.20, and 7.70 for USA, Europe, and Japan, respectively. Note that all the above cost numbers represent average annual values, while the average monthly price can vary by more than ± 1.5 US$/per million BTU. The price of LNG, obviously, depends on the price of natural gas. However, the price of LNG is also affected by the cost of the liquefaction, shipping and regasification processes.

The total capital investment associated with the LNG chain can be divided as follows: Exploration − 15% to 20%, liquefaction and storage − 30% to 45%, shipping − 10% to 30%, and storage and regasification − 15% to 25%. The capital investment for LNG storage in an import terminal is 30% to 50% of the capital investment of the import terminal, i.e. 5% to 10% of the overall capital investment of the LNG chain.

The specific values of the capital investment for the export terminals are: For the second generation (1980s) – US$ 600/ton$_{LNG}$ and for the last generation (2000s) – US$ 200/ton$_{LNG}$. Significant differences are associated with the energy consumption for the liquefaction of one ton LNG, which depends on the used liquefaction process.

The range of deviation in the total capital investment cost for the import terminals is larger than that for the export terminals. For example, the total capital investment of a small import terminal constructed in the middle of 1980s is approximately US$ 100 million, while the new generation of middle-capacity import terminals (4.0 to 8.0 million ton LNG/year) have a total capital investment of US$ 200 to 300 million. Modern technologies used for the regasification process lead to an increase in the capital investment of the import terminals up to US$ 400 million (USA, 2009-2010) and they even can be higher than US$ 2 billion for a state-of-the art Japanese import terminal.

In the middle of 1990s the cost of the liquefaction process was US$ 0.8 to 1.20/million Btu, the cost of shipping was US$ 0.4 to 1.0/million Btu, and that of regasification and storage

US$ 0.3 to 0.5/million Btu. The result of various improvements in all LNG-chain processes is that the overall cost of LNG delivery has been reduced by almost 30 % in the last 20 years.

During the last decade and through significant technological advancements, the cost of the liquefaction processes has been decreased to around US$ 0.5/million Btu. Improvements in the LNG tankers, the facilities, and the import terminals led to a decrease in the cost of LNG to only approximately US$ 0.1/million Btu for each mentioned process. Note that the cost per unit of energy is higher for the import terminals than for the export terminals. Therefore, improving the regasification process contributes significantly to a reduction in the final cost of natural gas at the end of the LNG chain.

At present, the following regasification processes are widely used in import terminals:

- Open rack vaporizers using sea water. The energy consumption is approximately 0.008 kWh/kg$_{(LNG)}$ for driving the sea water circulating pumps.
- Submerged combustion vaporizers that are water baths heated by burning fuel gas. Between 1.5 and 2% of the imported gas is used as fuel gas for LNG vaporization.
- Intermediate fluid vaporizers (for example, warm/hot water/glycol case)
- Seawater heating added to the water/glycol heaters with shell and tube vaporizers, and
- Other heating sources, such as using wastewater effluent from a treatment plant, or recovering waste heat from an existing industrial facility.

Using supplemental heat from seawater, or from a wastewater treatment plant, a power plant or another industrial facility (if available), might be economically attractive as the operating costs are significantly reduced. However, the capital cost is substantially increased. Both the hot water/glycol system and the submerged combustion vaporizers have relatively low capital costs, but high operating costs. The submerged combustion vaporizers are used quite often.

Since the beginning of the LNG history, the fifth type of the regasification processes has been discussed in the literature. By using heating sources that originate from an existing industrial facility, the dissipative process of LNG regasification is converted to a productive cogeneration process. Some import terminals are already using such a technology. New related concepts are still under development. The interest in the investigation of effective regasification technologies remains unchangeably high.

2. State of art in the regasification technologies

The studies in the field of the regasification of LNG follow studies on regasification of cryogenic liquids. The main difference between these technologies lies in the mass flow rates of the working fluids: relative small and temporary for the cryogenic liquids and large and continuous for the LNG. The widely used so-called atmospheric evaporators, with direct heat transfer between environmental air and cryogenic liquids, have never been used for LNG regasification.

Direct and indirect heat transfer processes (including submerged combustion vaporizers) between water (sea water, glycol case, etc.) and LNG are known as dissipative systems because no efficiency can be defined for these processes.

The vaporization of LNG becomes part of a productive system only when the low-temperature energy (and exergy) of LNG is used for cooling purposes in another system that may or may not need to reject thermal energy to the environment. One of the first ideas to combine the regasification of LNG with the storage of food (including deep frozen products) or with air conditioning systems cannot be realized, because of the distance between an import terminal and a place where the cooling is required.

A modification of this idea is to create an industrial complex consisting of an LNG import terminal and different chemical plants. These industrial complexes, in which the LNG low-temperature energy is used, are characterized by very strong interdependencies among processes as well as high capital investment costs and operating and maintenance expenses. However, the primary energy consumption of the industrial complex is low. This makes such systems attractive for practical applications.

For example, in a project developed by Osaka Gas in Japan (Otsuka, 2006), the LNG import terminal is combined with refinery and petrochemical plants. The regasification of LNG takes place during four stages: (a) Separation of light hydrocarbons produced as a byproduct in the oil refining process (temperature level is around −100ºC; an energy source to separate olefin used as a raw material of polymer products at the petrochemical plant); (b) liquefaction of carbon dioxide produced as a byproduct in the manufacture of hydrogen (temperature level is around −55ºC), (c) low-temperature storage of butane (−8 ºC), and (d) cooling of water used to cool the intake air for gas turbines (10 ºC).

A more interesting idea is to create an LNG-based cogeneration system. The thermodynamic analysis of a power system operating as a closed cycle shows that decreasing the temperature level of heat rejection to the environment leads to an increase in efficiency. Using the low-temperature heat during the LNG regasification enables engineers to decrease significantly the lower temperature level of a power system. One of the first publications, where this idea has been described, was a paper published by Angelino, 1978.

Since the end of the 1970s several approaches for cogeneration systems for electricity generation and LNG vaporization have been developed. For example, the gas-turbine-based concepts that can be found in literature include the following:

- German scientists developed a relative simple and efficient system for vaporization of LNG using closed-cycle gas turbines (Griepentrog & Sackarendt, 1976; Krey, 1979). The factors discussed in these publications include the effects of working fluid for the closed-cycle gas turbines, cycle pressure level, compressor and turbine inlet temperature, and efficiency values of the components. The reported value of the overall energetic efficiency is around 80%. This idea had a practical background, i.e. the development of a power system in Oberhausen (Germany) based on a closed-cycle gas turbine with helium as a working fluid (Griepentrog & Sackarendt, 1976; Frutschi, 2005).

- A similar idea but with hydrogen as the working fluid has been described by Najjar, 1991.
- Japanese scientists proposed to use the low-temperature heat coming from LNG for pre-cooling and interstage cooling of air for the so-called mirror gas-turbine system (Kaneko et al., 2004). The reported energetic and exergetic efficiencies amount to 56% and 60%, respectively.
- The idea of a cogeneration system with cascade arrangement of an open-cycle gas-turbine system as a topping cycle and a closed-cycle gas-turbine system as a bottoming cycle for electricity generation and LNG vaporization has been proposed and proved in Italy at the end of 1970s by Snamprogetti ENI Group (SNAMPROGETTI, 1978). A very brief description of this system can be found in a recent publication of Italian scientists from the University of Palermo (Dispenza et al., 2009 a, 2009 b). They improved the old idea and focused the research on the use of different working fluids (helium, nitrogen and carbon dioxide) in the closed-cycle gas-turbine system. However, open track vaporizers are also involved in these schematics. The electric efficiency of the cogeneration system is between 43% and 45% and the overall efficiency is 69%. The specific electricity generation is 0.38 kW$_{el}$/kg$_{LNG}$ and 0.29 kW$_{el}$/kg$_{LNG}$ for helium and nitrogen, respectively. For the economic analysis no clear data can be found; the authors tried to estimate the payback time under the assumption that the cost of the generated electricity is lower than the price in the Italian market of 74.75 Euro/MWh for the year 2006. The environmental analysis is based only on CO_2 emissions: 137.22 g/MJ of electricity generated and 55.28 g/MJ of regasified LNG. The avoided emissions amount to 26.71 kt for helium and 6.49 kt for nitrogen.
- The concepts based on combined-cycles for cogeneration systems are discussed only in recent publications, for example: In a typical combined-cycle power plant, the low-temperature energy of LNG is used for pre-cooling and interstage cooling of air for the gas-turbine system and for cooling in the steam condensation process (Shi et al., 2010). Typical thermodynamic data for this cogeneration system include (a) an energetic efficiency of the conventional plant of 56.5% and of the combination with LNG of 59.3%, and (b) net generated power of $\dot{W}_{net}$ =212 MW and $\dot{W}_{net}$ =288 MW for the conventional and the LNG-combined plant, respectively.
- The discussions in the field of combined-cycle power plants with Organic Rankine Cycle (ORC) mainly focus on the selection of a working fluid for the ORC:
- The case of propane is discussed by Najjar & Zaamout, 1993. An evaluation of a 200 MW gas-turbine power plant shows that addition of a cryogenic circuit may save about 62.595 tons/yr of LNG and 39 MW of power. This idea has been applied to one import terminal (Otsuka, 2006).
- Results using ammonia have been reported by Querol et al., 2011. The cogeneration system consists on a gas-turbine system, an ORC with ammonia as working fluid and an open track vaporizer (sea water first comes to the open track vaporizer, and after that enters the condenser of the ORC). The main data include: $\dot{W}_{net}$ =8 to 13 MW, energetic efficiency 44.5 to 46.6%, and cost of the generated electricity 76.7 to 54.8 Euro/MWh.

- A mixture of CF_4 and C_3H_8 was considered as an alternative to the water-ammonia mixture (i.e., a Kalina process, but with a mixture of CF_4 and C_3H_8 as working fluid) by Liu & Guo, 2011. The energetic efficiency of this cogeneration system is equal to 66%, and the exergetic efficiency is 23.5%.

- The MATIAN cycle (supercritical Rankine cycle with CO_2 as working fluid and integrated oxy-fuel combustion) has been combined with LNG vaporization (where the heat of the condensation process is used for the LNG) by Deng et al., 2004. The reported energetic efficiency is approximately 80%, and the exergetic efficiency is 49 to 50%.

- CO_2 is used as working fluid for the cogeneration system where the so-called "CO_2 Rankine-like cycle" (term used in these publications) is combined with a closed-cycle gas turbine system. Oxy-fuel combustion and CO_2 storage are integrated in the overall system. Several schematics of such a cogeneration system have been discussed by Zhang & Lior 2006a and 2006b; Liu et al., 2009. The by-products of this cogeneration system are water (subtracted from combustion gases), nitrogen and argon (after the air separation unit). The mass flow rate of LNG is 54.7 ks/s. The energetic efficiency of the cogeneration system without LNG integration is approximately 50% and with LNG 64% to 67% (for different schematics). The corresponding exergetic efficiency is equal to 51% (without LNG integration) and 53.6 to 67.5% (with LNG integration). The specific capital investment cost is around US$ 1100/kW$_{el}$ and the cost of the generated electricity is around US$ 0.04/kWh (The economic analysis has been conducted in CHY - the currency of the People's Republic of China, and the obtained data were converted in US$).

A different idea for the systems generating electricity and gasifying LNG has been published recently: Heat from the environment (air or sea water) is used as a high-temperature source for a power system, whereas the LNG represents the low-temperature reservoir:

- The Polish scientists (Szargut and Szczygieł, 2009) proposed such a system with a cascade (binary) of organic Rankine cycles using acetylene and ethane as working fluids. Depends on many parameters, the maximal exergetic efficiency of such a cogeneration system varies between 45% and 47%. The conclusion from the economic analysis is that the pay-back time of the investment expenditures is sufficiently short.

- Italian scientists from the University of Palermo (Dispenza et al., 2009c; La Rocca, 2010) have reported a similar but simpler (regular) organic Rankine cycle with ethane or ethylene. In these publications the value of the Coefficient of Performance (*COP*) is used as a variable for the efficiency. According to the definition of *COP* given by the authors, this value is around 1.6 for the analyzed systems.

Almost in all mentioned publications the concept of exergy is used. Not always the definition of energetic and exergetic efficiencies are given; therefore it is difficult to compare these cogeneration systems. Note that in the publications where the exergetic (second-law, availability) efficiency has been defined, the authors used the concept of "exergy output over exergy input", which is inferior to the product-over-fuel concept.

Only few of the above-mentioned publications deal with an economic or environmental analysis. The environmental analyses focus only on the CO_2 emissions through the fuel consumption.

There are some publications and technical reports (for example, IHV-2025, 2003; Malacic et al., 2008; EPA, 2010; PETRONAS, 2010; EIA, 2010) that discuss environmental issues associated with LNG terminals. These publications consider factors such as the CH_4 emissions through the leaking of LNG and NG, the CO_2 emissions through fuel consumption, the effect of decreasing the temperature of sea water after using open rack vaporizers, and the increase in the concentration of chlorine (to control bio-fouling in the open rack vaporizers). The information is always given for the entire terminal (existing or planned) without discussing the re-gasification process.

Since 2007 a group at the Institute for Energy Engineering at Technische Universität Berlin has been studying cogeneration systems for the simultaneous generation of electricity and re-gasification of LNG (Griepentrog et al., 2008a and 2008b; Tsatsaronis & Morosuk, 2009; Tsatsaronis et al., 2009; Tsatsaronis & Morosuk, 2010; Morosuk & Tsatsaronis, 2011; Morosuk et al., 2012). The research aims at developing thermodynamically efficient processes, and conducting economic and environmental-impact evaluations of these processes by using the so-called exergy-based methods. In the following sections we demonstrate how to evaluate an LNG-based cogeneration system using these methods.

3. The authors' concept

The system shown in Figure 2 represents a novel cogeneration system for generating electricity and vaporizing LNG. This cogeneration system is an advanced case of the gas-turbine-based approach.

The overall system consists of three sub-systems:

- *LNG sub-system* (process 1-2-3-4) – LNG from the storage system is (a) compressed by an LNG pump (PM), (b) vaporized in heat exchanger II (HE II) using the thermal energy rejected from the closed-cycle power sub-system, and (c) expanded in an LNG expander (EX III).
- *Closed-cycle gas-turbine power sub-system* (cycle 11-12-13-14) – After removing the thermal energy in HE II, the working fluid (a working fluid that can be used in a closed-cycle gas-turbine system) is compressed in compressor III (CM III), heated in heat exchanger I (HE I, using the thermal energy rejected from the open-cycle gas-turbine power system), and expanded in expander II (EX II).
- *Open-cycle gas-turbine power sub-system* (process 21-22-23-24+25-26-27-28) – Air after compression in compressor I (CM I) is cooled in a cooler (CL) by removing thermal energy to the environment, and is compressed in compressor II (CM II). After the combustion process in the combustion chamber (CC), the combustion gases are expanded in expander I (EX I) and rejected to the atmosphere after being cooled in HE I.
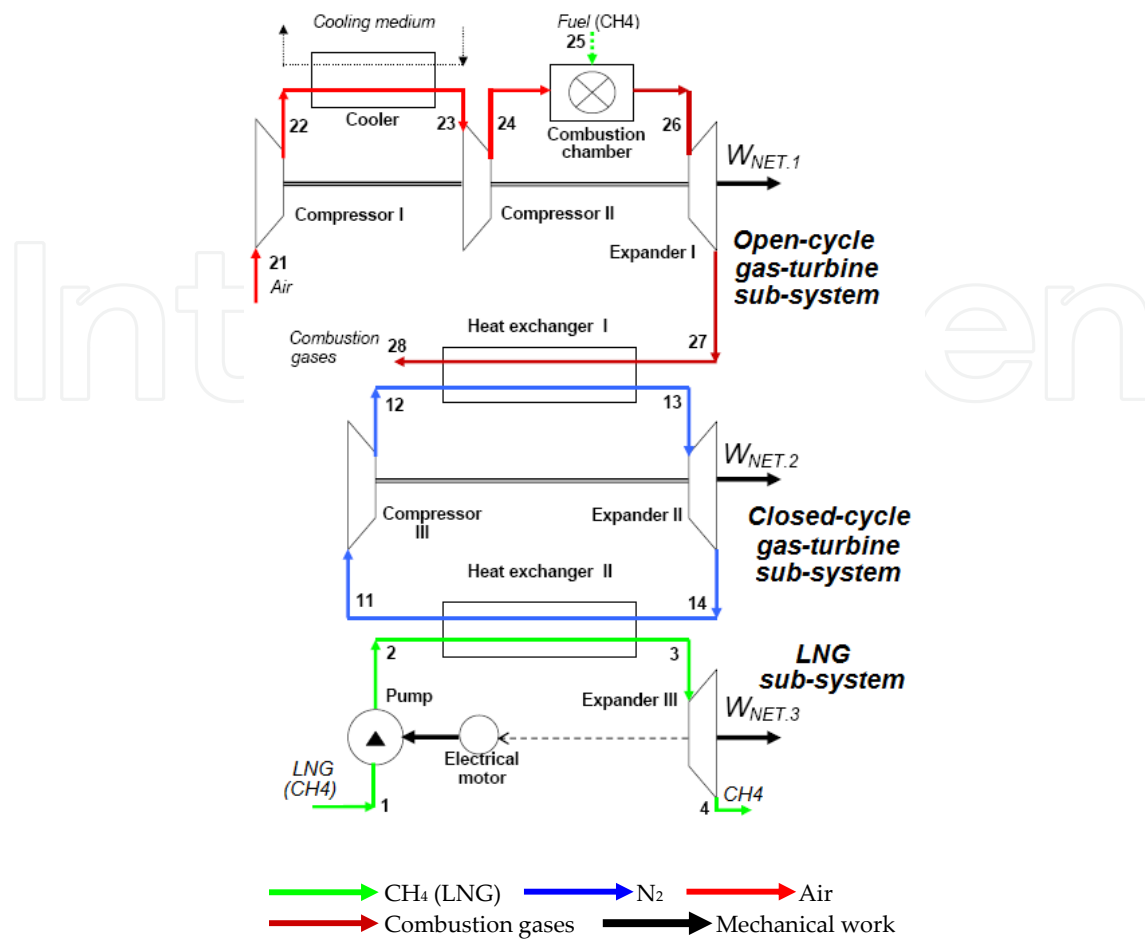
Figure 2. Schematic of the LNG-based cogeneration system

The following advantages are associated with the cogeneration system proposed by the authors:

- Complete independency of seawater. This means that for an import terminal the technical, economical and environmental aspects associated with the treatment, transport and use of seawater are irrelevant.
- The area of the import terminal that is necessary for the regasification process is relatively small (compared with other cogeneration systems using a Rankine cycle).
- The LNG storage within the import terminal is not important. For the *open-cycle gas-turbine power sub-system* the authors considered an efficient gas-turbine system (LMS-100™ (Reale, 2004)) that can reach 100% capacity within approximately 10 minutes.

3.1. Simulation

For the simulation of the cogeneration system, we assumed the following:

- The *open-cycle gas-turbine power sub-system* is based on a LMS 100 gas turbine, with T_{21}=15°C; p_{21}=0.1013 MPa; T_{26}=1290°C; pressure ratio 42:1 (Reale, 2004), $\eta_{CM,I}$ =90%, $\eta_{CM,II}$=90%, $\eta_{EX,I}$ =94%. The heat loss in the combustion chamber amounts to 2% of the lower heating value of the fuel.

- *For the closed-cycle gas-turbine power sub-system* we assumed $\eta_{CM,III}$=85%, $\eta_{EX,II}$=88% (Frutschi, 2005). Five working fluids have been considered for the analysis: Nitrogen, dry air, argon, helium and carbon dioxide.
- In the *LNG sub-system*, LNG is leaving the storage space as a subcooled liquid at T_1 = −160°C and p_1 = 1.0 MPa. After vaporization, superheated vapor at p_4 = 8.0 MPa and $T_4 \approx 2$°C is obtained. The isentropic efficiencies assumed for the LNG pump and the expander III are η_P=66.5%, and $\eta_{EX,III}$=85%, respectively. For the analysis, the LNG pump is considered together with the required electrical motor.

The generators required for producing the electric power were not considered in the analysis.

For the simulation and the energetic and exergetic analyses, the following software were used: GateCycle (GE, 1989), Gatex (GATEX, 2002), and EES (EES, 2012).

The operation conditions for the closed-cycle gas-turbine power sub-system are fixed by the temperatures at states 11 (415°C) and 14 (−129°C). Carbon dioxide cannot be used as a working fluid because of its thermodynamic properties: The temperature of −129°C cannot be achieved at the state of superheated vapor at $p_{11}(p_{14})$>0.1 MPa.

State	Working fluid	T [°C]	p [MPa]	v [m³/kg]	$\dot{E}$ [MW]	$\dot{m}$ [kg/s]
1	LNG	-160	1.0	–	124.3	64.96[*)] for air;
2		-144	27.2	–	126.8	65.02[*)] for nitrogen;
3		86	27.0	–	98.9	67.36[*)] for argon;
4		2	8.0	–	77.7	67.56[*)] for helium
11	Air	-129	0.28	0.142	31.7	222.50
12		71	4.27	–	69.7	
13		415	4.06	0.049	102.9	
14		103	0.30	–	22.4	
11	Nitrogen	-129	0.28	0.147	60.6	217.20
12		70	4.27	–	133.4	
13		415	4.06	0.051	196.1	
14		101	0.3	–	42.7	
11	Argon	-129	0.28	0.103	40.9	445.30
12		64	1.94	–	79.4	
13		415	1.84	0.078	112.1	
14		102	0.3	–	31.4	
11	Helium	-129	0.28	1.052	41.2	45.32
12		66	1.94	–	81.2	
13		415	1.84	0.779	114.0	
14		102	0.3	–	32.0	
21	Air	15	0.101	–	0.62	209.00
22		242	0.67	–	86.7	

State	Working fluid	T [°C]	p [MPa]	v [m³/kg]	$\dot{E}$ [MW]	$\dot{m}$ [kg/s]
23		117	0.65	–	67.8	
24		416	4.35	–	186.1	
25	Methane	15	4.5	–	507.0	5.14
26		1290	4.19	–	523.6	
27	Comb. gases	435	0.11	–	80.9	214.14
28		90	0.102	–	10.9	

*) Depends on the working fluid used for the closed-cycle gas-turbine sub-system

Table 1. Thermodynamic data for the material streams

3.2. Energetic analysis

Selected energetic variables of the LNG-based cogeneration system with different working fluids (that can be used in the closed-cycle gas-turbine sub-system) are given in Figure 3. Note that the variables of the open-cycle gas-turbine sub-system remain unchanged. The calculated values using dry air, nitrogen, argon and helium demonstrate that all these working fluids do not affect significantly the energetic efficiency of the overall system. The most significant differences refer to (Table 1):

- The mass flow rate of the re-gasified LNG air amounts to 64.96 kg/s, for nitrogen to 65.02 kg/s, for argon to 67.36 kg/s und for helium to 67.56 kg/s,
- The mass flow rate of the working fluid for the closed-cycle gas-turbine sub-system, is for air, nitrogen, argon, and helium 222.50 kg/s, 217.20 kg/s, 445.30 kg/s, und 45.32, respectively.
- The pressure ratio within the closed-cycle gas-turbine sub-system is $p_{12}/p_{11} = 6.8$ for argon and helium and $p_{12}/p_{11} = 15$ for nitrogen and air.

Based on these data for the closed-cycle gas-turbine sub-system we excluded argon as a potential candidate, and we looked closer to helium.

A new definition of the energetic efficiency for the LNG-based cogeneration system has been proposed (Tsatsaronis & Morosuk, 2010) as

$$\eta_{tot} = \frac{\dot{W}_{NET,tot} + \left(\dot{H}_4 - \dot{H}_1 \right)}{\dot{m}_{25} HHV} =$$

$$\frac{\dot{W}_{NET,tot}}{\dot{m}_{25} HHV} + \frac{\left(\dot{H}_4 - \dot{H}_1 \right)}{\dot{m}_{25} HHV} = \eta_{el} + \eta_{LNG} \tag{1}$$

where the lower heating value (HHV) of methane is 55.5 MJ/kg and $\dot{W}_{NET,tot} = \dot{W}_{NET,1} + \dot{W}_{NET,2} + \dot{W}_{NET,3}$. The values of $\dot{W}_{NET,1}$, $\dot{W}_{NET,2}$ and $\dot{W}_{NET,3}$ represent the net mechanical power generated in the open-cycle gas-turbine sub-system, the closed-cycle gas-turbine sub-system, and the LNG sub-system, respectively. $\dot{H}_4$ and $\dot{H}_1$ represent

the enthalpy flow rates at the thermodynamic states 4 and 1, respectively. The values of η_{el} and η_{LNG} are given in Figure 4.

An interesting conclusion can be obtained if the values of the specific volume at states 11 (intake to the CM III) and 13 (intake to the EX II) are analyzed. For the three working fluids (air, nitrogen and argon) these values are quite similar. Much higher values are observed for helium. This significantly affects the size of compressor III and expander II and, therefore the costs of these components. The price of the working fluid is also an important factor: The prices for nitrogen and dry air are similar; argon is approximately 25 times more expensive and helium is even more. Taking into account these economic aspects, both argon and helium cannot be recommended as working fluids for these systems.
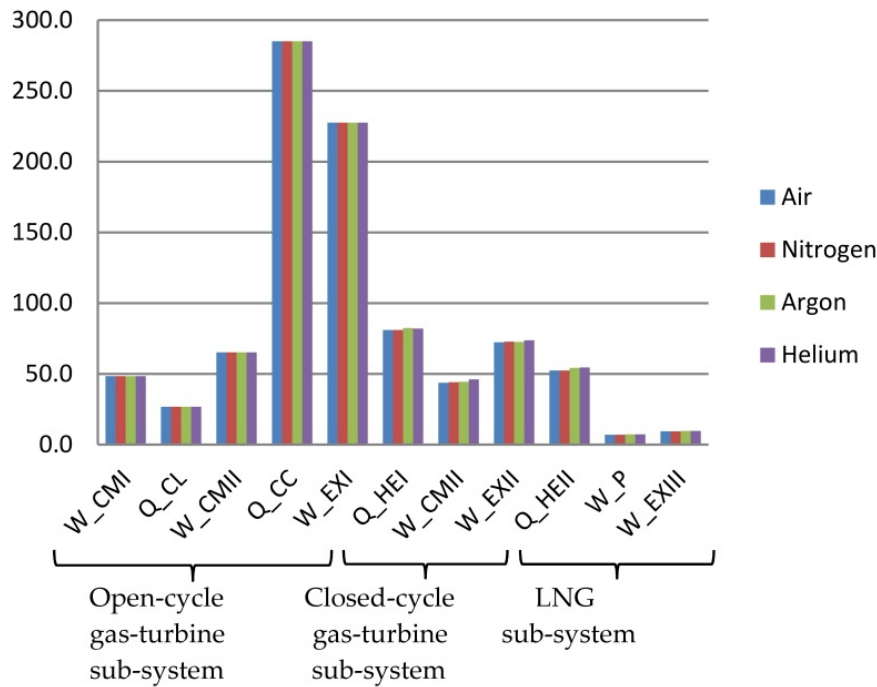
(a)
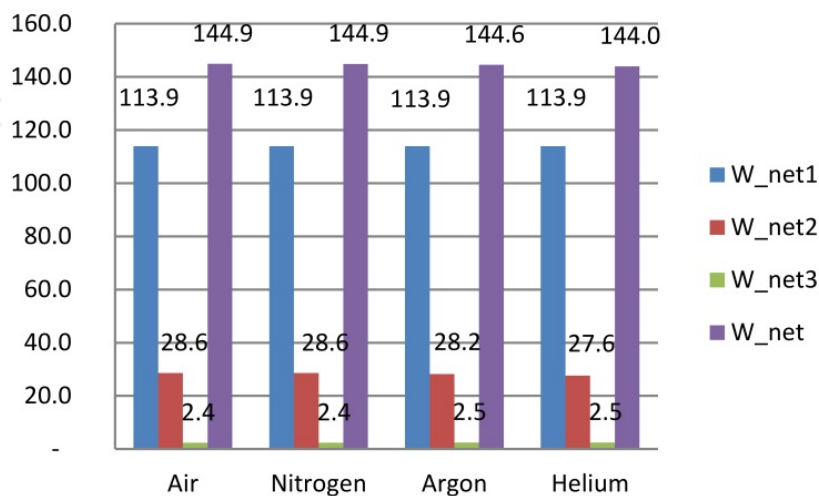
(b)

Figure 3. Results of the energetic analysis (all values are given in MW): (a) Component characteristics; (b) sub-system characteristics.
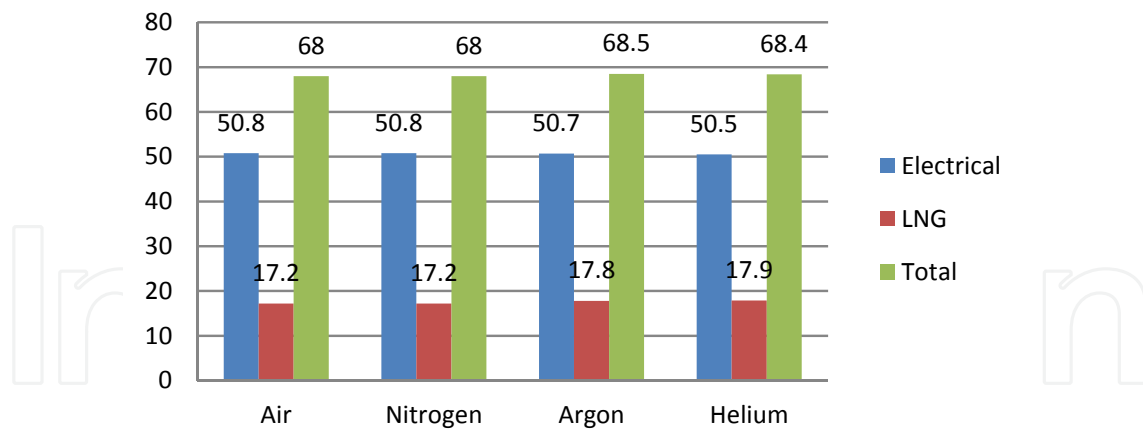
Figure 4. Electrical, LNG and overall energetic efficiency (%) of the LNG-based cogeneration systems.

4. Exergy-based analyses

4.1. Exergetic analysis

Exergy is defined as the maximum theoretical useful work (shaft work or electrical work) obtainable from an energy conversion system as this is brought into thermodynamic equilibrium with the thermodynamic environment while interacting only with this environment (Tsatsaronis, 2008).

An *exergy-based* thermodynamic *analysis* identifies the location, the magnitude, and the causes of thermodynamic inefficiencies, which are the *exergy destruction* (due to irreversibilities within the system), and the *exergy loss* (exergy transfer to the environment). In an exergy analysis we calculate the exergy associated with each energy carrier (stream) in the overall system, the exergy destruction within each system component and process, and the *exergetic efficiency* (for each process, component, or system).

The exergy balance for the overall cogeneration system is

$$\dot{E}_{F,tot} = \dot{E}_{P,tot} + \sum_k \dot{E}_{D,k} + \dot{E}_{L,tot} \qquad (2)$$

and for the *k*th component

$$\dot{E}_{F,k} = \dot{E}_{P,k} + \dot{E}_{D,k} \qquad (3)$$

The variables used for the conventional exergetic evaluation of the *k*th component in a system include the following:

- Exergy destruction rate that is calculated from the exergy balance
- Exergetic efficiency

$$\varepsilon_k = \frac{\dot{E}_{P,k}}{\dot{E}_{F,k}} = 1 - \frac{\dot{E}_{D,k}}{\dot{E}_{F,k}} \qquad (4)$$

- Exergy destruction ratio

$$y_k = \frac{\dot{E}_{D,k}}{\dot{E}_{F,tot}} \tag{5}$$

The definition of the exergetic efficiency for the LNG-based cogeneration system is

$$\varepsilon_{tot} = \frac{\dot{E}_{P,tot}}{\dot{E}_{F,tot}} = \frac{\dot{W}_{NET,tot} + \left(\dot{E}_4^M - \dot{E}_1^M\right)}{\dot{E}_{25} + \dot{E}_{21} + \left(\dot{E}_1^T - \dot{E}_4^T\right)} \tag{6}$$

The modern approaches for the exergetic analysis use the general concepts of *fuel* and *product* introduced over 25 years ago (Tsatsaronis, 1984): The *exergy of product* is the desired result (expressed in exergy terms) achieved by the system (e.g., the *k*th component) being considered, and the *exergy of fuel* represents the exergetic resources expended to generate the exergy of the product. These concepts are used in a consistent way for the exergy-based analyses (Lazzaretto & Tsatsaronis, 2006; Meyer et al., 2009).

The following definitions of the exergy of fuel ($\dot{E}_{F,k}$) and the exergy of product ($\dot{E}_{P,k}$) are used for the overall system and for the components (Bejan et al., 1996; Lazzaretto & Tsatsaronis, 2006):

- Overall system – $\dot{E}_{F,tot} = \dot{E}_{25} + \dot{E}_{21} + \left(\dot{E}_1^T - \dot{E}_4^T\right)$, $\dot{E}_{P,tot} = \dot{W}_{NET,tot} + \left(\dot{E}_4^M - \dot{E}_1^M\right)$ and $\dot{E}_{L,tot} = \dot{E}_{28}$
- Compressor I – $\dot{E}_{F,CMI} = \dot{W}_{CMI}$ and $\dot{E}_{P,CMI} = \dot{E}_{22} - \dot{E}_{21}$
- The cooler is a dissipative component, therefore we calculate $\dot{E}_{D,CL} = \dot{E}_{22} - \dot{E}_{23}$ without defining for this component an exergetic efficiency or the exergies of fuel and product.
- Compressor II – $\dot{E}_{F,CMII} = \dot{W}_{CMII}$ and $\dot{E}_{P,CMII} = \dot{E}_{24} - \dot{E}_{23}$
- Combustion chamber – $\dot{E}_{F,CC} = \dot{E}_{25}$ and $\dot{E}_{P,CC} = \dot{E}_{26} - \dot{E}_{24}$
- Expander I – $\dot{E}_{F,EXI} = \dot{E}_{26} - \dot{E}_{27}$ and $\dot{E}_{P,EXI} = \dot{W}_{EXI}$
- Heat exchanger I – $\dot{E}_{F,HEI} = \dot{E}_{27} - \dot{E}_{28}$ and $\dot{E}_{P,HEI} = \dot{E}_{13} - \dot{E}_{12}$
- Expander II – $\dot{E}_{F,EXII} = \dot{E}_{13} - \dot{E}_{14}$ and $\dot{E}_{F,EXII} = \dot{W}_{EXII}$
- The pump operates below the reference temperature: $e_2^{PH} > e_1^{PH}$, but $e_2^T < e_1^T$, and $e_2^M > e_1^M$. Therefore, $\dot{E}_{F,P} = \dot{W}_P + \left(\dot{E}_1^T - \dot{E}_2^T\right)$ and $\dot{E}_{P,P} = \dot{E}_2^M - \dot{E}_1^M$
- In heat exchanger II the reference temperature is crossed: $T_2 < T_0$, $T_3 > T_0$ and $T_{14} > T_0$, $T_{11} < T_0$. Because of the pressure drop on both sides of heat exchanger II the mechanical exergy at the inlet of each stream is larger than the mechanical exergy of the same stream at the outlet: $e_2^M > e_3^M$ and $e_{11}^M < e_{14}^M$. In this way, $\dot{E}_{F,HEII} = \left(\dot{E}_{14}^T + \dot{E}_2^T\right) + \left(\dot{E}_{14}^M - \dot{E}_{11}^M\right) + \left(\dot{E}_2^M - \dot{E}_3^M\right)$ and $\dot{E}_{P,HEII} = \left(\dot{E}_{11}^T + \dot{E}_3^T\right)$
- In Compressor III the reference temperature is crossed: $\dot{E}_{F,CMIII} = \dot{W}_{CMIII} + E_{11}^T$ and $\dot{E}_{P,CMIII} = \dot{E}_{12}^M - \dot{E}_{11}^M + \dot{E}_{12}^T$
- In expander III the reference temperature is also crossed. Thus, $\dot{E}_{F,EXIII} = \dot{E}_3^M - \dot{E}_4^M + \dot{E}_3^T$ and $\dot{E}_{P,EXIII} = \dot{W}_{EXIII} + \dot{E}_4^T$

The chemical exergies of LNG, and NG and of the working fluid of the closed-cycle gas-turbine sub-system do not need to be considered in the exergetic analysis of this system because only the physical exergy of the working fluid is used in the corresponding sub-systems. Only the chemical exergies in the open-cycle gas-turbine sub-system, where combustion takes place, need to be considered. The chemical exergy of air is not zero because of the humidity (60%) considered in it. The physical exergies of LNG, NG and N$_2$ are split into their thermal and mechanical parts according to the approach presented in (Morosuk & Tsatsaronis, 2008).

For the exergetic analysis we assumed: $T_0 = T_{21}$ =15ºC (288.15 K) and p_0 =1.013 bar. The results from the exergetic analysis are given in Tables 1 and 3. Figure 4 shows the exergy destruction ratio within components of the overall cogeneration system and Figure 5 shows the exergetic efficiency of the overall system. Note that the exergetic efficiency cannot be split is analogy to the energetic efficiency.
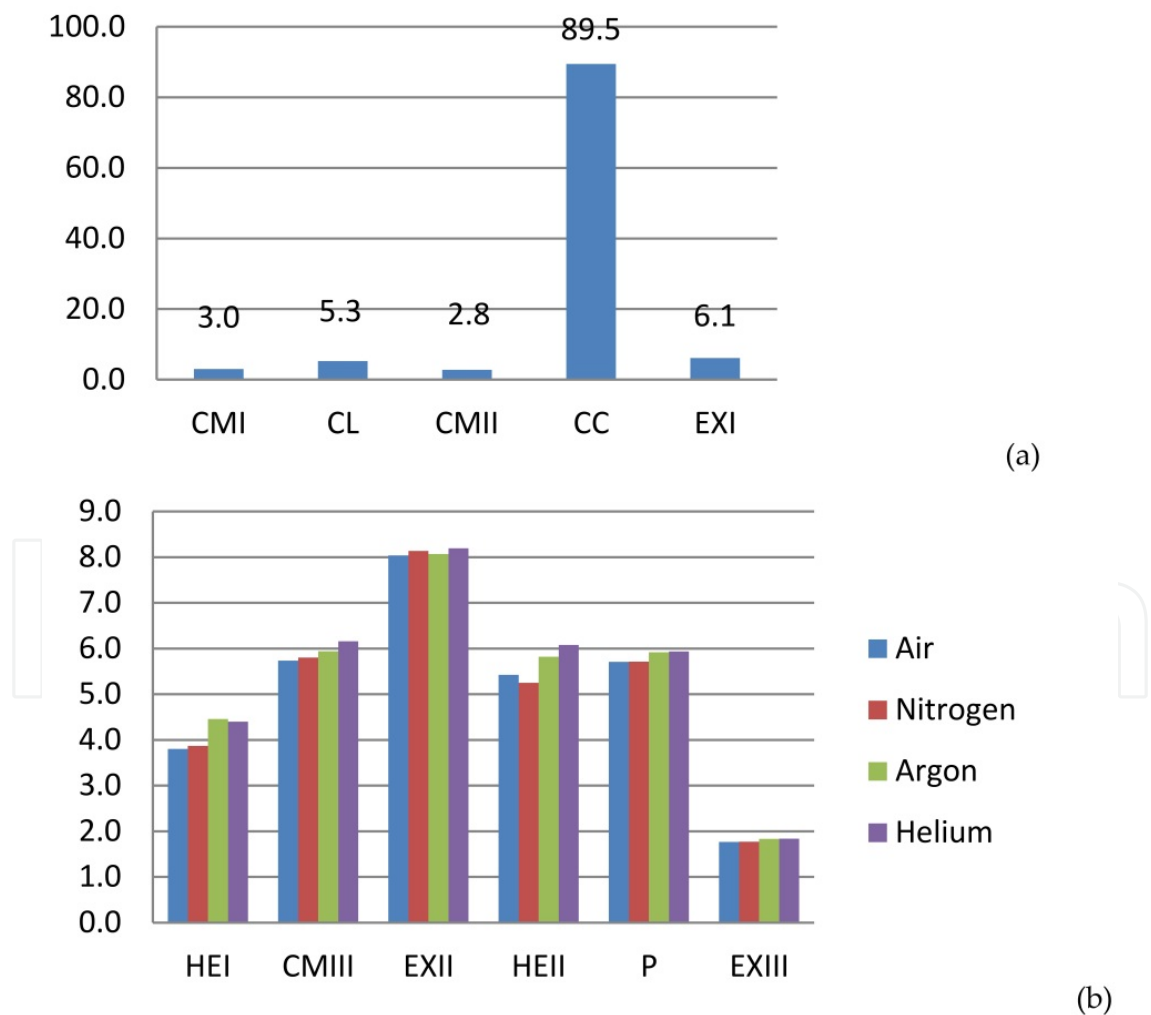

(a)

(b)

Figure 5. Exergy destruction rate (all values are given in MW) (a) within the components of the open-cycle gas-turbine sub-system, and (b) the remaining components.

The calculated overall efficiency (η_{tot} = 68% (HHV-based) or η_{tot} = 75.5% (LHV- based)) and exergetic efficiency (ε_{tot} = 52.6%) demonstrate the thermodynamic advantages of this novel cogeneration concept that combines LNG regasification with the generation of electricity, particularly if air or nitrogen is used for the open-cycle gas-turbine sub-system.

The results obtained from the conventional exergetic analysis are based on the value of $\dot{E}_{D,k}$ (Figure 5). Assuming that no changes can be conducted in the open-cycle gas-turbine sub-system (Figure 5a), the priorities for improving the components of the LNG and the closed-cycle gas-turbine sub-systems (Figure 5b) are the following:

- Expander II should be considered first because it exhibits the highest exergy destruction among all components of the considered sub-systems.
- Compressor III, heat exchanger II, and pump have comparable (values of $\dot{E}_{D,k}$), therefore they have the same relative importance for the improvement procedure. Note that the cogeneration system with nitrogen has the lowest exergy destruction within heat exchanger II.
- The exergy destructions within heat exchanger I (note the significant difference between air and nitrogen on one side and argon and helium on the other side) and expander III are relatively low, therefore these components, especially expander III, cannot significantly affect the efficiency of the overall cogeneration system.

The detailed results from the exergetic analysis and the sensitivity exergetic analysis for this LNG-based cogeneration system with nitrogen as working fluid for the closed-cycle gas-turbine sub-system have been reported by (Tsatsaronis and Morosuk, 2010; Morosuk and Tsatsaronis 2011). In this paper only the values of the exergetic efficiency of the overall cogeneration system with different working fluids for the closed-cycle gas-turbine sub-system is given (Figure 6). The exergetic analysis assists us to conclude that nitrogen should be used as the working fluid of the closed-cycle gas-turbine sub-system. In the further analyses only the case with nitrogen is considered.
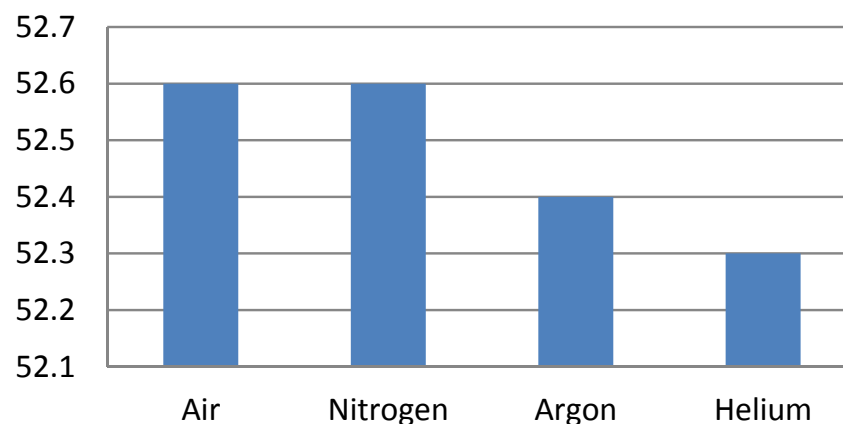

Figure 6. Exergetic efficiency of the overall cogeneration system with different working fluids for the closed-cycle gas-turbine sub-system.

4.2. Exergoeconomic analysis

Exergoeconomics (for example, Tsatsaronis, 1984; Bejan et al., 1996; Tsatsaronis 2008) 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. A complete exergoeconomic analysis consists of (a) an exergetic analysis, (b) an economic analysis, and (c) an exergoeconomic evaluation.

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. The cost balances can be written as

$$\dot{C}_{P,k} = \dot{C}_{F,k} + \dot{Z}_k \tag{7}$$

or

$$c_{P,k}\dot{E}_{P,k} = c_{F,k}\dot{E}_{F,k} + \dot{Z}_k \tag{8}$$

where

$$\dot{Z}_k = \dot{Z}_k^{CI} + \dot{Z}_k^{OM} \tag{9}$$

To simplify the discussion, we assume, that the contribution of $\dot{Z}_k^{OM}$ 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 $\dot{Z}_k^{CI}$.

The real cost sources in an energy conversion system are (a) the capital investment (and the operating & maintenance expenses) for each component, (b) the cost of exergy destruction within each component, and (c) the 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

$$\dot{C}_{D,k} = c_{F,k} \cdot \dot{E}_{D,k} \tag{10}$$

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

$$\dot{C}_{L,tot} = \dot{C}_{28} \tag{11}$$

The exergoeconomic model for the Base Case of the LNG-based cogeneration system is:

- Compressor I:

$$\dot{C}_{W1,CMI} + \dot{Z}_{CMI} = \dot{C}_{22} - \dot{C}_{21} \tag{12}$$

with $c_{21} = 0$.

- The cooler (dissipative component) was considered together with a cooling tower (which is not shown in Figure 1):

$$\dot{C}_{22} + \left(\dot{Z}_{CL} + \dot{Z}_{CT}\right) = \dot{C}_{23} \tag{13}$$

- Compressor II:

$$\dot{C}_{W1,CMII} + \dot{Z}_{CMII} = \dot{C}_{24} - \dot{C}_{23} \tag{14}$$

- Combustion chamber:

$$\dot{C}_{25} + \dot{Z}_{CC} = \dot{C}_{26} - \dot{C}_{24} \tag{15}$$

where $c_{25} = c_4$

- Expander I:

$$\dot{C}_{26} - \dot{C}_{27} + \dot{Z}_{EXI} = \dot{C}_{W1,EXI} \tag{16}$$

the auxiliary equation for EX I according to the F-rule is $c_{26} = c_{27}$. Note that c_{W1} is the specific cost of electricity generated within open-cycle gas-turbine sub-system.

- Heat exchanger I:

$$\dot{C}_{27} - \dot{C}_{28} + \dot{Z}_{HEI} = \dot{C}_{13} - \dot{C}_{12} \tag{17}$$

$c_{26} = c_{27}$ (F-rule)

- Expander II:

$$\dot{C}_{13} - \dot{C}_{14} + \dot{Z}_{EXII} = \dot{C}_{W2,EXII} \tag{18}$$

$c_{27} = c_{28}$ (F-rule), and $c_{14} = c_{14}^T = c_{14}^M$. The value of c_{W2} represents the specific cost of electricity generated within closed-cycle gas-turbine sub-system.

- Compressor III:

$$\dot{W}_{W2,CMIII} + \dot{C}_{11}^T + \dot{Z}_{CMIII} = \dot{C}_{12}^M - \dot{C}_{11}^M + \dot{C}_{12}^T \tag{19}$$

with $\dfrac{\dot{C}_{12}^T}{\dot{E}_{12}^T} = \dfrac{\dot{C}_{12}^M - \dot{C}_{11}^M}{\dot{E}_{12}^M - \dot{E}_{11}^M}$ (P-rule).

- Heat exchanger II:

$$\left(\dot{C}_{14}^T + \dot{C}_2^T\right) + \left(\dot{C}_{14}^M - \dot{E}_{11}^M\right) + \left(\dot{C}_2^M - \dot{C}_3^M\right) + \dot{Z}_{HEII} = \dot{C}_{11}^T + \dot{C}_3^T \tag{20}$$

where $c_{14}^M = c_{11}^M$ and $c_2^M = c_3^M$ according to the F-rule, and $c_3^T = c_{11}^T$ according to the P-rule.

- Expander III:

$$\dot{C}_3^M - \dot{C}_4^M + \dot{C}_3^T + \dot{Z}_{EX\,III} = \dot{C}_{W3,EX\,III} + \dot{C}_4^T \qquad (21)$$

with $c_3^M = c_4^M$ (F-rule) and $c_4^T = c_{W3}$ where c_{W3} is the specific cost of electricity generated within LNG sub-system.

- Pump I is considered together with the required electrical motor

$$\dot{C}_W + \left(\dot{C}_1^T - \dot{C}_2^T\right) + \left(\dot{Z}_{PI} + \dot{Z}_{EM}\right) = \dot{C}_2^M - \dot{C}_1^M \qquad (22)$$

with $c_1^T = c_2^T$ (F-rule) and $c_1 = c_1^{CH} = c_1^{PH} = c_1^T = c_1^M$. The chemical exergy of LNG does not change within the processes of sub-system 3, therefore $c_1^{CH} = c_2^{CH} = c_3^{CH} = c_4^{CH}$.

The value of c_W is the average specific cost of electricity generated by the overall cogeneration system

$$c_W = \frac{\dot{C}_{W1} + \dot{C}_{W2} + \dot{C}_{W3}}{\dot{W}_{NET,1} + \dot{W}_{NET,2} + \dot{W}_{NET,3}} \qquad (23)$$

Figure 6 shows selected data obtained from the conventional exergoeconomic analysis. Here the cooler is considered together with the cooling tower ($\dot{Z}_{CT}$ =3.25 \$/h) and the pump is considered together with the electrical motor ($\dot{Z}_{EM}$ =1.33 \$/h).

For the economic analysis, the methodology presented by Bejan et al., 1996 is applied using the following assumptions and sources (Bejan et al., 1996 and GE, 2008):

- The cost of LNG is assumed to be 12 US\$/GJ
- The average cost of money is i_{eff}= 10 %
- The plant economic life is n=15 years with 7300 hours/year
- The average general inflation rate is r_n=2.5 %.

The data are given in US\$ for the year 2009.

The total purchased equipment cost of the LNG-based cogeneration system is around US\$ 40.5 million. For the comparison with other systems for regasification of LNG, specific values of the purchased equipment cost should be used: (a) per kg of regasified LNG is equal to US\$ 0.62 million, and (b) per MW of generated electricity is equal to US\$ 0.28 million. The data obtained from the exergoeconomic analysis of the LNG-based cogeneration system have been discussed in detail by (Tsatsaronis et al., 2009).

The following conclusions regarding priorities of improvement for the LNG-based cogeneration system can be drawn from the

- economic analysis (based on the values of $\dot{Z}_k$, Figure 7a) – the capital investment cost of the open-cycle gas-turbine system is dominating, and the values of $\dot{Z}_k$ for all components of the closed-cycle gas-turbine system are comparable,
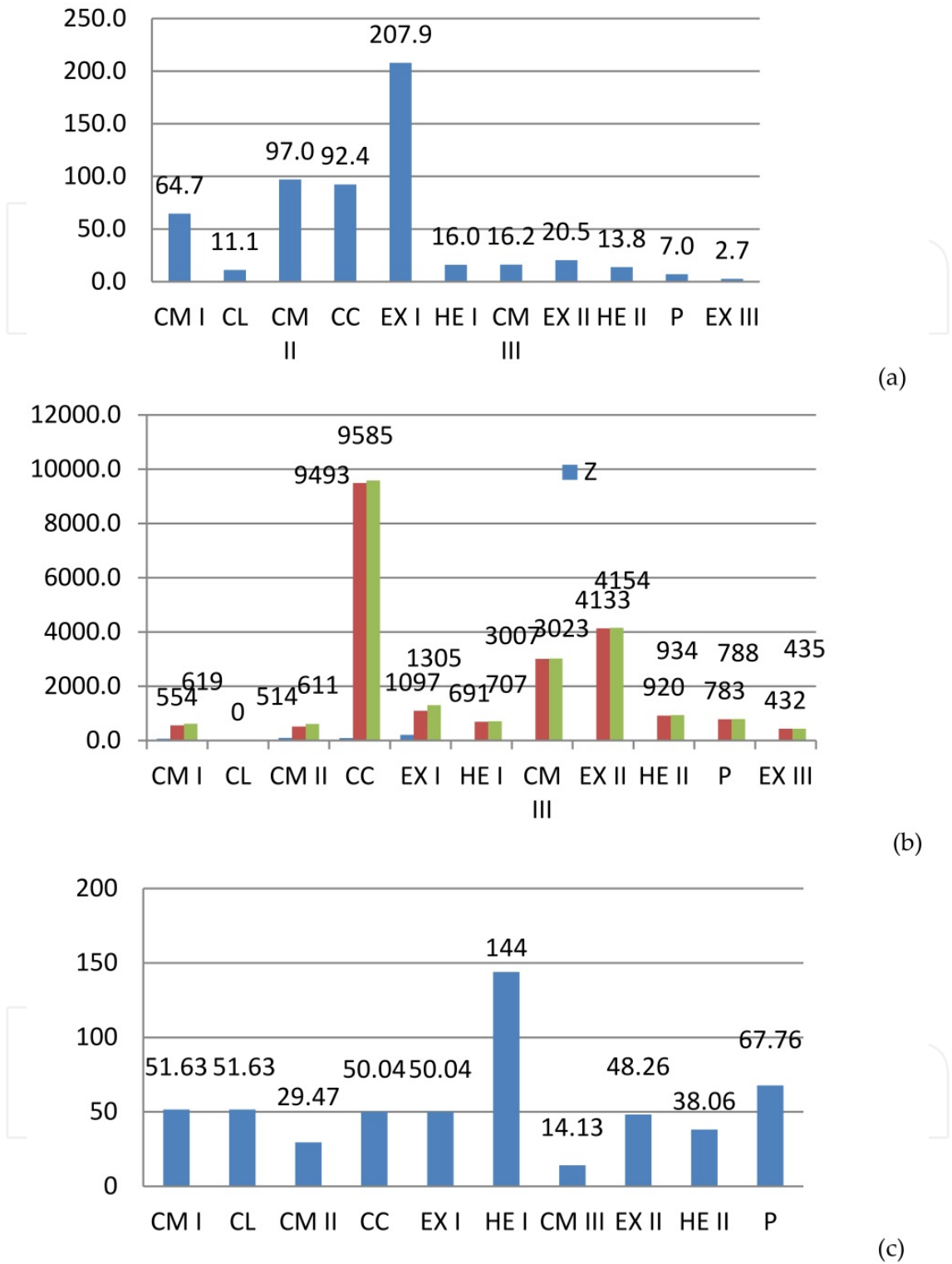
(a)

(b)

(c)

Figure 7. Selected exergoeconomic variables: (a) capital investment cost for each component ($\dot{Z}_k$, US\$2009/h), (b) total cost associated with each component ($\dot{Z}_k + \dot{C}_{D,k}$, US\$2009/h), and (c) specific cost of the exergy of fuel for each component ($c_{F,k}$, US\$2009/GJ).

- exergoeconomic analysis (based on the values of ($\dot{Z}_k + \dot{C}_{D,k}$), Figure 7b) – the total cost associated with each component mainly depends on the cost of the exergy

destruction ($\dot{C}_{D,k}$) while the capital investment cost is negligible. For reducing the overall cost associated with both products of the cogenerations system, we should focus on reducing the exergy destruction within the turbomachinery of the closed-cycle gas-turbine sub-system, i.e. within EX II and CM III.

The "net" cost of the generated electricity is:

- for the open-cycle gas-turbine sub-system 0.18 US\$/kWh,
- for the closed-cycle gas-turbine sub-system 0.28 US\$/kWh,
- for the LNG sub-system 0.16 US\$/kWh, and
- the average for the overall system is 0.20 US\$/kWh (Eq. 23).

Note that the cost of the exergy losses (stream 28) should always be charged to the product, i.e. the value of $\dot{C}_{28}$ should be added to the nominator of Eq. (15).

We have two possibilities to estimate the cost of the generated electricity and regasification of LNG:

- *Assumption 1* − cost of the LNG is equal to the cost of the natural gas (i.e. all costs associated with the regasification process are charged to the cost of the generated electricity)

$$c_W = \frac{\dot{C}_{W1} + \dot{C}_{W2} + \dot{C}_{W3} + \dot{C}_{28}}{\dot{W}_{NET,1} + \dot{W}_{NET,2} + \dot{W}_{NET,3}} \tag{24}$$

Using this assumption the average specific cost of the electricity is 0.23 US\$/kWh.

- *Assumption 2* – the average cost (per unit of exergy) of the total product of the cogeneration system is calculated from

$$c_{p,tot} = \frac{\dot{C}_{W1} + \dot{C}_{W2} + \dot{C}_{W3} + \dot{C}_{28}}{\dot{W}_{NET,1} + \dot{W}_{NET,2} + \dot{W}_{NET,3} + \left(\dot{E}_4^M - \dot{E}_1^M\right)} \tag{25}$$

In this way the average specific cost of the electricity is 0.20 US\$/kWh and the difference between the cost of LNG and natural gas (after regasification) is 0.06 US\$/GJ.

4.3. 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 (Tsatsaronis, 2008; Meyer et al., 2009), 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).

In general, any of recently introduced indicators can be used for LCA. For this exergoenvironmental analysis, an impact analysis method called Eco-indicator 99 (Goedkoop & Spriensma, 2000) has been selected because it considers many environmental aspects and uses average European data.

In order to identify the raw materials 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), neither is given what materials are used for each equipment item. In this way, only rough calculations of the employed main materials can be conducted.

For the LCA of the system being analyzed (a detailed discussion is presented in (Morosuk et al., 2012)), we assumed in analogy with the economic analysis a life time of 15 years and 7300 working hours per year at full capacity.

The exergoenvironmental model for an energy conversion system consists of *environmental impact balances* written for the *k*th component and auxiliary equations based on the P and F-rules. The environmental impact balances can be written as

$$\dot{B}_{P,k} = \dot{B}_{F,k} + \left(\dot{Y}_k + \dot{B}_k^{PF} \right) \tag{26}$$

or

$$b_{P,k}\dot{E}_{P,k} = b_{F,k}\dot{E}_{F,k} + \left(\dot{Y}_k + \dot{B}_k^{PF} \right) \tag{27}$$

where $\dot{Y}_k$ is the environmental impact that occurs during the three life-cycle phases: Construction $\dot{Y}_k^{CO}$, operation & maintenance, $\dot{Y}_k^{OM}$, and disposal, $\dot{Y}_k^{DI}$ constitute the component-related environmental impact associated with the *k*th component $\dot{Y}_k$:

$$\dot{Y}_k = \dot{Y}_k^{CO} + \dot{Y}_k^{OM} + \dot{Y}_k^{DI} \tag{28}$$

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

To account for *pollutant formation* within the *k* th component, a new variable was recently introduced $\dot{B}_k^{PF}$ (Boyano et al., 2011). This term $\dot{B}_k^{PF}$ 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 (for example, combustion), the value of $\dot{B}_k^{PF}$ is

$$\dot{B}_k^{PF} = \sum_i b_i^{PF} \left(\dot{m}_{i,out} - \dot{m}_{i,in} \right) \tag{29}$$

where only pollutant streams which finally will be emitted to the environment are taken into account: CO, CO_2, CH_4, N_2O, NO_x and SO_x (Meyer et al., 2009).

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

$$\dot{B}_{D,k} = b_{F,k} \dot{E}_{D,k} \tag{30}$$

To identify the most important components from the viewpoint of formation of environmental impacts, the sum of environmental impacts $\left(\dot{Y}_k + \dot{B}_k^{PF} + \dot{B}_{D,k} \right)$ is used.

In this paper some data obtained from the exergoenvironmental analysis are given in Figure 7. Here the cooler is considered together with the cooling tower ($\dot{Y}_{CT}$ = 0.065 Pts/h) and the pump is considered together with the electrical motor, $\dot{Y}_{EM}$ = 0.363 Pts/h.

The results obtained from the LCA (value $\dot{Y}_k$ in Figure 8a) demonstrate that the component-related environmental impact associated with HE I and HE II are the highest among all components of the overall system. The exergoenvironmental analysis demonstrates that the value of the environmental impact associated with the exergy destruction dominates for all components ($\dot{B}_{D,k} \gg \dot{Y}_k$). Only for the combustion chamber the value of the environmental impact of the pollutants formation ($\dot{B}_k^{PF}$) is comparable with the value of the environmental impact associated with exergy destruction ($\dot{B}_{D,k}$) (Figure 8b). 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 (assuming that the open-cycle gas-turbine sub-system cannot be improved). The environmental impact associated with the exergy destruction within EX II and CM III can be improved by decreasing the exergy destruction within these components.

The environmental impact associated with the generation of electricity and regasification of LNG can be estimated in analogy with cost (Eqs. (23)-(25)):

- The average "netto" environmental impact of the generated electricity is 31 mPts/kWh (by open-cycle gas-turbine sub-system 30.4 mPts/kWh, by closed-cycle gas-turbine sub-system 30.4 mPts/kWh, and by LNG sub-system 1.88 mPts/kWh).
- After charging the environmental impact associated with the exergy losses, we have the following data:
- If the environmental impact of the LNG is equal to the environmental impact of the natural gas (i.e. the environmental impact associated with the regasification process is charged to the environmental impact of the generated electricity), then b_W = 32.83 mPts/kWh, or
- If the average environmental impact (per unit of exergy) of the total product of the cogeneration system is calculated, then the average specific environmental impact of the electricity is 29.05 mPts/kWh and the difference between the environmental impact of LNG and natural gas (after regasification) is 0.013 mPts/kWh.
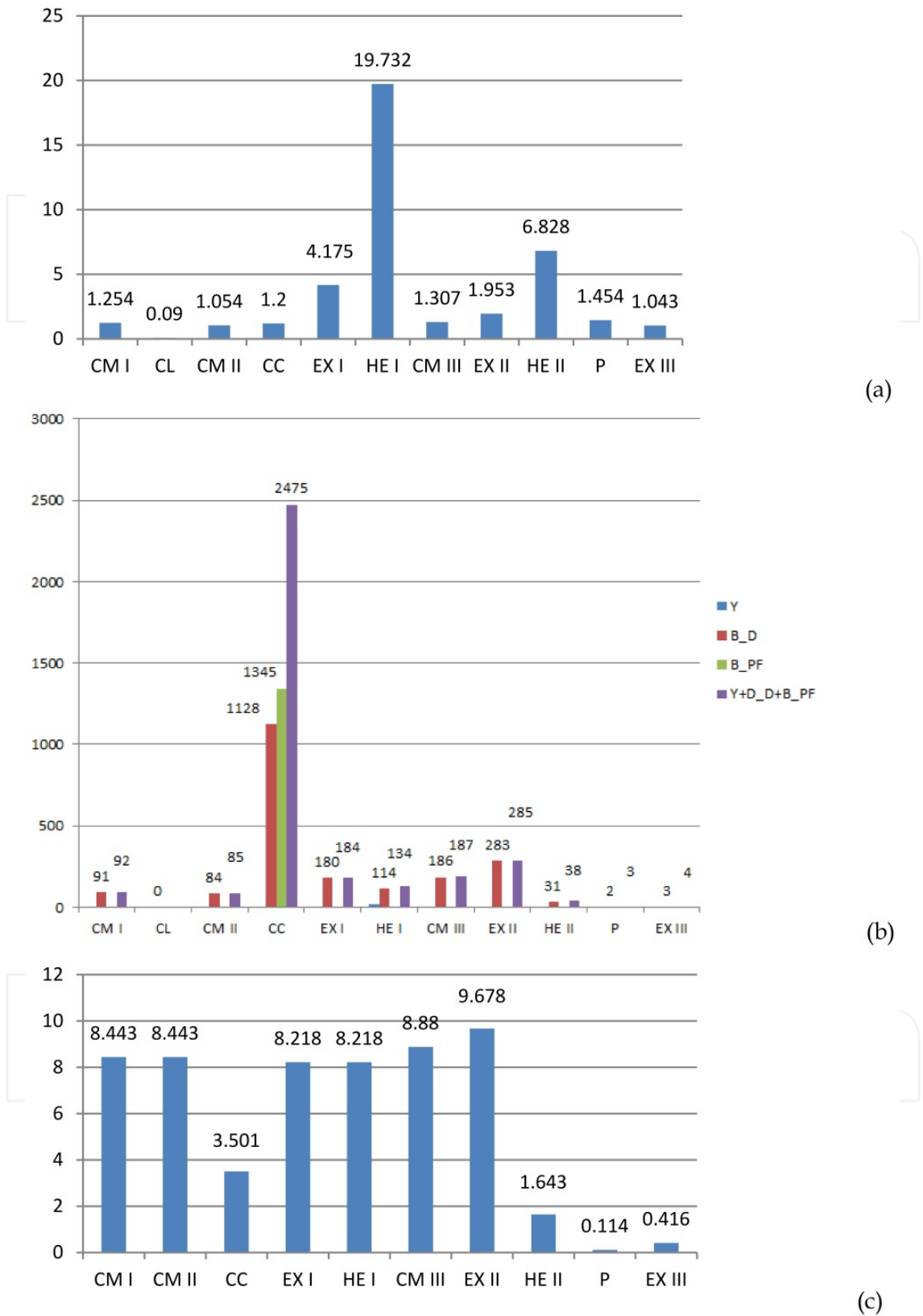
Figure 8. Selected exergoenvironmental: (a) component-related environmental impact ($\dot{Y}_k$, Pts ECO-99/h), (b) total environmental impact associated with the component ($\dot{Y}_k + \dot{B}_{D,k} + \dot{B}_k^{PF}$, Pts ECO-99/h), and (c) specific environmental impact of the exergy of fuel for the component ($b_{F,k}$, Pts ECO-99/GJ).

Note that the average value of the environmental impact associated with the electricity generation in Europe is 23 mPts/kWh (and, in general is varied between 10 and 62 mPts/kWh) as reported by Goedkoop & Spriensma, 2000.

None of the mentioned publications in the field of LNG-based cogeneration systems discussed neither LCA nor exergoenvironmental analysis. In order to compare the analyzed system with others, let us simplify the environmental analysis by considering only CO_2 generation within the open-cycle gas-turbine sub-system. Specific values of the $CO2$ generation include: (a) per kg of regasified LNG is equal to 90 g/kg, and (b) per MW of generated electricity is equal to 40 g/MW.

5. Advanced exergy-based analyses

In order to improve this energy conversion system, we should answer the following questions:

- What is the potential for decreasing (a) the exergy destruction within each component, (b) the cost and/or the component-related environmental impact of each component as well as the cost of exergy destruction and/or environmental impact associated with the exergy destruction?
- How an improvement in one component affects (positively or negatively and by how much) the remaining components?

Advanced exergy-based methods have been developed especially as a tool to find correct answers for these questions. The interactions among different components of the same system can be estimated and the quality of the conclusions obtained from an exergetic, an exergoeconomic, or an exergoenvironmental evaluation can be improved significantly, when the

- exergy destruction in each (important) system component,
- investment cost associated with such component, and
- component-related environmental impact associated with such component,

as well as the

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

are split into endogenous/exogenous and avoidable/unavoidable parts (all publications up to date in the field of the advanced exergy-based methods are summarized and generalized in (Tsatsaronis 2008; Tsatsaronis & Morosuk, 2008a and 2009b).

We call the analyses based on these procedures *advanced* (*exergetic*, *exergoeconomic*, or *exergoenvironmental*) *analyses*.

Endogenous exergy destruction is the part of exergy destruction 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. The *exogenous* part of the variable is the

difference between the value of the variable within the component in the real system and the endogenous part:

$$\dot{E}_{D,k} = \dot{E}_{D,k}^{EN} + \dot{E}_{D,k}^{EX} \qquad (31)$$

Such a splitting shows the interconnections between the components.

The *unavoidable exergy destruction* ($\dot{E}_{D,k}^{UN}$) 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* ($\dot{E}_{D,k}^{AV}$) that should be considered during the improvement procedure

$$\dot{E}_{D,k} = \dot{E}_{D,k}^{UN} + \dot{E}_{D,k}^{AV} \qquad (32)$$

Combining the two splitting options gives analysts an opportunity to calculate

- the *avoidable endogenous exergy destruction* ($\dot{E}_{D,k}^{AV,EN}$), which can be reduced by improving the kth component from the exergetic point of view, and
- the *avoidable exogenous exergy destruction* ($\dot{E}_{D,k}^{AV,EX}$) that can be reduced by a structural improvement of the overall system, or by improving the efficiency of the remaining components.

This methodology can also be applied to the splitting of the values of capital investment cost and to cost of exergy destruction as well as to component-related environmental impact and to environmental impact associated with the exergy destruction.

The conventional exergy-based analyses suggest to initially decrease the exergy destruction within turbomachinery of the closed-cycle gas-turbine sub-system. This decrease of exergy destruction will not only increase the overall efficiency, but will simultaneously reduce both costs and environmental impact associated with the overall system.

The detailed advanced exergy and exergoeconomic analyses of the LNG-based cogeneration system have been reported by Tsatsaronis et al., 2009. Here only selected data for the compressor III and the expander II are given (Table 2).

Splitting the exergy destruction into its endogenous and exogenous parts (first two columns of Table 2) shows, that $\dot{E}_{D,k}^{EN} > \dot{E}_{D,k}^{EX}$ for CM III and EX II, therefore the interconnections among these (and the remaining) components are not very strong.

The results from splitting the exergy destruction into its avoidable and unavoidable parts show that the avoidable exergy destruction that occurs in expander II is larger than the unavoidable one, while for compressor III we have a different arrangement.

The real potential for improving the components can be obtained using the values of $\dot{E}_{D,k}^{AV,EN}$ and $\dot{E}_{D,k}^{AV,EX}$. For both analyzed components the value of $\dot{E}_{D,k}^{AV,EX}$ is much smaller than the value of $\dot{E}_{D,k}^{AV,EN}$. This means that the irreversibilities within such components can be reduced by improving the components themselves, and not other components.

Component	$\dot{E}_{D,k}^{EN}$ (MW)	$\dot{E}_{D,k}^{EX}$ (MW)	$\dot{E}_{D,k}^{UN}$ (MW)	$\dot{E}_{D,k}^{AV}$ (MW)	$\dot{E}_{D,k}^{AV}$ (MW)	
					$\dot{E}_{D,k}^{AV,EN}$ (MW)	$\dot{E}_{D,k}^{AV,EX}$ (MW)
CM III	4.461	1.338	3.037	2.762	2.273	0.489
EX II	7.693	0.434	3.722	4.405	4.182	0.223

Table 2. Selected data obtained from the advanced exergetic analysis

6. Exergy-based improvement

By summarizing all information obtained from the exergy-based methods, we know that the LNG-based cogeneration system can be improved (from the thermodynamic, economic and environmental points of view) by improving the efficiency of the turbomachinery within the closed-cycle gas-turbine sub-system. As before we assumed that the open-cycle gas-turbine sub-system is a standard unit and, therefore, cannot be improved.

Let us assume that the isentropic efficiency within turbomachinery will increase up by 0.5 percentage points (realistic assumption), i.e. with $\eta_{CM,III}$=85.5%, $\eta_{EX,II}$=88.5%. As we already found out, the values of the capital investment cost and the component-related environmental impact are very small compared with the value of the total cost associated with the component and total environmental impact associated with the component, respectively. Therefore, for the improvement we assume that $\dot{Z}_k$ and $\dot{Y}_k$ for both components, CM III and EX II, remain unchanged.

The selected data for the comparison analysis are given in Table 3. We would like to emphasize that only by using the exergy-based methods including the advanced ones, the LNG-based cogeneration system could be easily improved – through the thermodynamic improvement of the turbomachinery of the closed-cycle gas-turbine sub-system. The cost of the generated electricity and the environmental impact associated with the electricity generation decrease significantly by 10% and 12%, respectively.

Variables, units	Case 1	Case 2
$\eta_{CM,III}$ [%]	85	85.5
$\eta_{EX,II}$ [%]	88	88.5
$\dot{W}_{net.2}$ [MW]	28.6	29.5
$\dot{W}_{net.tot}$ [MW]	144.9	146.7
η_{tot} (HHV-based) [%]	68.0	68.7
ε_{tot} [%]	52.6	52.8
$\dot{E}_{D.CMIII}$ [MW]	5.8	5.6
$\dot{E}_{D.EXII}$ [MW]	8.1	7.9

$\dot{m}_{Nitrogen}$ [kg/s]	222.50	218.9
$\dot{m}_{LNG}$ [kg/s]	65.02	65.03
$\dot{W}_{net.tot}$ / $\dot{m}_{LNG}$ [kW/kg$_{LNG}$]	2.23	2.26
c_W [1)] [US\$/kWh]	0.23	0.20
b_W [1)] [mPts/kWh]	32.83	28.89

[1)] All costs are charged to the electricity (Assumption 1)

Table 3. Selected data for the LNG-based cogeneration system to demonstrate the results of the improvement.

7. Conclusions

LNG will have in future a significantly larger contribution to the energy supply in the world than it had in the past. Thus, applying thermodynamically efficient, cost effective, and environmentally benign plants for the regasification of LNG is of particular importance for the use of LNG.

The concepts of the LNG-based cogeneration system developed by the authors (a) use gas turbines to keep the investment costs low and the efficiency high, (b) minimize the irreversibilities within the plant components and the losses to the environment, and (c) maximize the capability of LNG to generate electrical energy.

The application of advanced exergy-based methods to this concept allowed us to better understand their operation, i.e. how the thermodynamic inefficiencies are formed and how they affect the cost and the environmental impact of both products – electricity and regasified LNG. In this chapter, exergy-based methods for the evaluation and the improvement of an LNG-based cogeneration system were successfully applied.

8. Nomenclature

$\dot{B}$ environmental impact rate associated with an exergy stream (Points/s)
b environmental impact per unit of exergy (Points/J) or per unit of mass (Points/kg)
$\dot{C}$ cost rate associated with an exergy stream (US\$/h)
c cost per unit of exergy (US\$/J) or per unit of mass (US\$/kg)
$\dot{E}$ exergy rate (W)
e specific exergy (J/kg)
f exergoeconomic factor [-]
$\dot{H}$ entropy rate (W)
h specific entropy (J/kg)
HHV higher heating value (J/kg)
LHV lower heating value (J/kg)
k kth component
$\dot{m}$ mass flow rate (kg/s)

p pressure (bar)

$\dot{Q}$ heat rate (W)

r relative difference (%)

T temperature (ºC)

v specific volume (m^3/kg)

$\dot{W}$ power (W)

$\dot{Y}$ construction-of-component-related environmental impact rate (Points/s)

y exergy destruction ratio (%)

$\dot{Z}$ cost rate associated with investment expenditures (US$/h)

Greek symbols

Δ difference

ε exergetic efficiency (%)

η energetic efficiency for the overall system (%), or isentropic efficiency of a pump, compressor or expander (%)

Superscripts

AV avoidable; *EN* endogenous; *EX* exogenous; *M* mechanical; *PH* physical; *T* thermal; *UN* unavoidable

Subscripts

b refers to environmental impact; *D* exergy destruction; *F* exergy of fuel; *k* *k*th component; *L* exergy loss; *P* exergy of product; *tot* overall system; 0 thermodynamic environment (reference state)

Abbreviations

CL cooler; *CC* combustion chamber; *CM* compressor; *EM* electrical motor; *EX* expander; *HE* heat exchanger; *P* pump

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