archives
of thermodynamics
Vol. **35**(2014), No. 3, 39–57
DOI: 10.2478/aoter-2014-0020

System approach to the analysis of an integrated oxy-fuel combustion power plant

ANDRZEJ ZIĘBIK[1]
PAWEŁ GŁADYSZ

Silesian University of Technology, Institute of Thermal Technology,
Konarskiego 22, 44-100 Gliwice, Poland

Abstract Oxy-fuel combustion (OFC) belongs to one of the three commonly known clean coal technologies for power generation sector and other industry sectors responsible for CO_2 emissions (e.g., steel or cement production). The OFC capture technology is based on using high-purity oxygen in the combustion process instead of atmospheric air. Therefore flue gases have a high concentration of CO_2. Due to the limited adiabatic temperature of combustion some part of CO_2 must be recycled to the boiler in order to maintain a proper flame temperature. An integrated oxy-fuel combustion power plant constitutes a system consisting of the following technological modules: boiler, steam cycle, air separation unit, cooling water and water treatment system, flue gas quality control system and CO_2 processing unit. Due to the interconnections between technological modules, energy, exergy and ecological analyses require a system approach. The paper present the system approach based on the 'input-output' method to the analysis of the: direct energy and material consumption, cumulative energy and exergy consumption, system (local and cumulative) exergy losses, and thermoecological cost. Other measures like cumulative degree of perfection or index of sustainable development are also proposed. The paper presents a complex example of the system analysis (from direct energy consumption to thermoecological cost) of an advanced integrated OFC power plant.

Keywords: System approach; Input-output analysis; Oxy-fuel combustion; Cumulative energy and exergy consumption; System exergy losses; Thermoecological cost

---

[1] Corresponding Author. E-mail: andrzej.ziebik@polsl.pl

Nomenclature

a – coefficient of consumption
ASU – air separation unit
b – specific exergy, MJ_{ex},
b^* – index of cumulative exergy consumption, $\mathrm{MJ}_{ex}/\mathrm{MJ}$ or $\mathrm{MJ}_{ex}/\mathrm{Mg}$,
CCS – carbon capture and storage
CDP – cumulative degree of thermodynamic perfection
CEC – cumulative energy consumption
CExC – cumulative exergy consumption
CPU – $\mathrm{CO_2}$ processing unit
D – external supplies, MJ or Mg
e^* – index of cumulative energy consumption, MJ/MJ or MJ/Mg
F – by-production, MJ or Mg
f – coefficient of by-production
G – main production, MJ or Mg
HP – high pressure
IP – intermediate pressure
ISD – index of sustainable development
K – final production, MJ or Mg
LP – low pressure
LHV – lower heating value
OFC – oxy-fuel combustion
p_h – coefficient denoting the amount of harmful emissions released to the atmosphere
r – share of production supplementing the main production
TEC – thermo-ecological cost.
$\delta\mathrm{B}$ – exergy losses
δb^* – index of cumulative exergy losses

Greek symbols

ρ – unit thermoecological cost, $\mathrm{MJ}_{ex}/\mathrm{MJ}$ or $\mathrm{MJ}_{ex}/\mathrm{Mg}$
ξ – coefficient concerning additional consumption of exergy of non-renewable natural resources due to the necessity of compensation the environmental losses caused by the harmful emissions, $\mathrm{MJ}_{ex}/\mathrm{Mg}$ of harmful emission

Subscripts

D – external supply not supplementing the main production,
DG – external supply supplementing the main production,
el – electricity
ex – exergy
F – by-product not supplementing the main production
FG – by-product supplementing the main production
G – main product

1 Introduction

In recent years the interest has grown in the carbon capture and storage (CCS) technologies as the possible technology to mitigate the CO_2 emissions from both power sector and other industry branches. They are planned to be interim technologies which should help to meet the required CO_2 emission reduction goals, keeping the fossil fuel in use. Generally three types of CCS technologies can be distinguished, viz. post-combustion, pre-combustion and oxy-fuel combustion. The presented analysis focuses on the oxy-fuel combustion (OFC) technology applied to the power plants, for which practical application may occur first (e.g., White Rose Project [10]). The OFC technology has already been well described in the literature [5,9,11,22,26,27] and is developed in many scientific and commercial [21] projects around the world. Although several pilot plants have been launched, there isn't still a commercial one. Technology readiness level (TRL) for oxy-fuel combustion is between 6–7 (subcommercial scale) [21], where planted commercial scale projects like White Rose Project should bring the TRL to the level 8 and give the chance to make the OFC technology mature enough to be deployed worldwide (TRL-9).

Power plants constructed in OFC technology, compared to the conventional fossil-fuel based power plant, must comprise two main additional parts – the air separation unit (ASU) and the carbon dioxide (CO_2) processing unit (CPU). The OFC is also taken into consideration in already existing retrofitting power plants, by adding ASU and CPU and adequate upgrading in the boiler house. Due to the lower net efficiency of the OFC power plants, due to the additional energy consumption in ASU and CPU, several modification and upgrades are proposed. Beside obvious solutions like ultra-super-critical steam parameters and process integration (utilization of waste heat from the interstage cooling system of compressors) other options are being considered. Utilization of waste nitrogen from ASU for drying the lignite coal, advanced CO_2 compression processes (e.g., shock wave compression) or membrane based air separation units should help to degrees the overall net efficiency drop (about 8–12 pp. compared to the non-CCS power plants). The use of by-products of an ASU is considered to decrease the environmental impact of the whole power plant [8,9,11].

Although CO_2 transport and storage are important and indispensable components of CCS, this article discusses only OFC power plants. Accordance with the life cycle assessment (LCA) approach the analysis in principle should include the following main phases: construction phase, operation

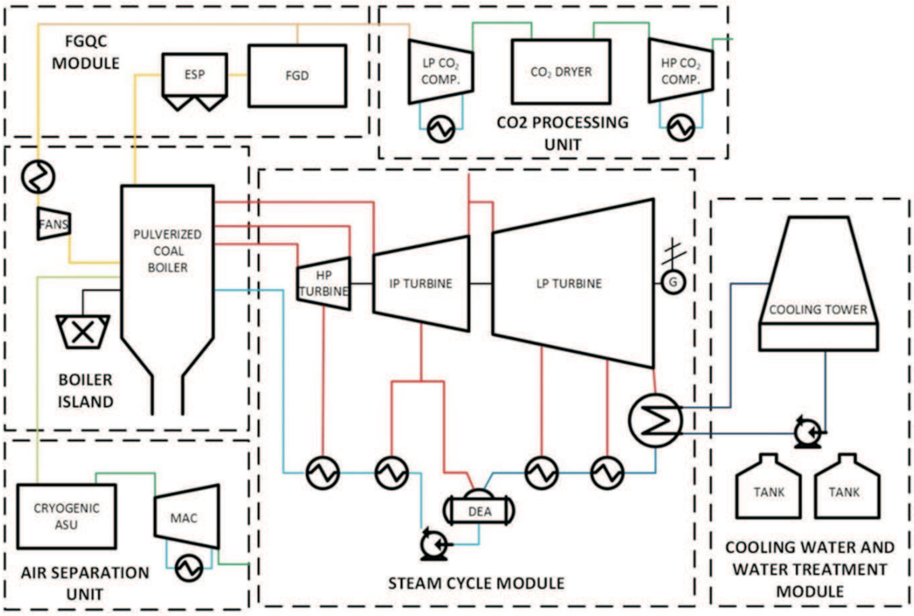

Figure 1: Block-diagram of an integrated OFC power plant; ASU – air separation unit, MAC – main air compressor, ESP – electrostatic precipitator, FGD – flue gas desulphurisation, DEA – deaerator, HP – high pressure, IP – intermediate pressure, LP – low pressure, respectively, FGQC – flue gas quality control, COMP. – compressors, G – generator.

phase and decommissioning phase. Based on the previous environmental analysis elaborated by the authors, the construction and decommissioning phase are responsible for about 0.3% of the life cycle thermoecological cost of electricity production [4], thus they will be neglected in this study. Figure 1 presents the scheme of oxy-fuel combustion power plant integrated with ASU and CPU.

2 System approach to the analysis of integrated OFC power plant — mathematical models

In this paper the system approach ('input-output' analysis [6,7]) in analysis is proposed to evaluate:

- direct energy and material consumption,
- cumulative energy and exergy consumption,

- system exergy losses,
- thermoecological cost,

of main products and net electricity production of the analysed OFC power plant.

‘Input-output’ model of direct energy and material consumption

The core of system analyses is the ‘input-output’ model of direct energy (and material) consumption, which was in detail described in [26,27]. In the structure of the ‘input-output’ table (Tab. 1) for an analyzed integrated OFC power plants the following three specific groups can be distinguished.

Table 1: The ‘input-output’ table of an integrated OFC power plant.

Energy carrier or material	Input part			Output part	
	Main production	By-production	External supplies	Interbranch flows	Final production
1	G_1	$\sum_{i=1}^{n} f_{1\,i}^{FG} G_i$	$D_{G\,1}$	$\sum_{i=1}^{n} a_{1\,i}^{G} G_i$	K_1
...	...	...	...	...	...
i	G_i	$\sum_{i=1}^{n} f_{i\,i}^{FG} G_i$	$D_{G\,i}$	$\sum_{i=1}^{n} a_{i\,i}^{G} G_i$	K_i
...	...	...	...	...	...
n	G_n	$\sum_{i=1}^{n} f_{n\,i}^{FG} G_i$	$D_{G\,n}$	$\sum_{i=1}^{n} a_{n\,i}^{G} G_i$	K_n
$n+1$	0	$\sum_{i=1}^{n} f_{n+1\,i}^{F} G_i$	0	$\sum_{i=1}^{n} a_{n+1\,i}^{F} G_i$	K_{n+1}
...	...	...	...	...	...
l	0	$\sum_{i=1}^{n} f_{l\,i}^{F} G_i$	0	$\sum_{i=1}^{n} a_{l\,i}^{F} G_i$	K_l
...	...	...	...	...	...
m	0	$\sum_{i=1}^{n} f_{m\,i}^{F} G_i$	0	$\sum_{i=1}^{n} a_{m\,i}^{F} G_i$	K_m
$m+1$	0	0	D_{m+1}	$\sum_{i=1}^{n} a_{m+1\,i}^{D} G_i$	0
...	...	...	...	...	...
p	0	0	D_p	$\sum_{i=1}^{n} a_{p\,i}^{D} G_i$	0
...	...	...	...	...	...
s	0	0	D_s	$\sum_{i=1}^{n} a_{s\,i}^{D} G_i$	0

The first group consist of energy carriers and materials being main products whose global production sometimes may be supplemented by the by-production or external supplies. The second group consists of energy carriers and materials manufactured as by-products not supplementing main products. The third group consists of energy carriers and materials which are external supplies not supplementing main products. These groups have been presented in Tab. 2.

Table 2: List of energy carriers and materials of an OFC power plant.

No.	Energy carrier or material	Unit	No.	Energy carrier or material	Unit
Main products; $i = 1 \dots n$			14^o	Fly ash	Mg
1^o	HP & IP process steam	MJ	15^o	Gypsum	Mg
2^o	Electricity	MJ	16^o	Liquid oxygen	Mg
3^o	Cooling duty	MJ	17^o	Gaseous nitrogen	Mg
4^o	CO_2-rich stream	Mg	18^o	Liquid nitrogen	Mg
5^o	Gaseous oxygen	Mg	19^o	Liquid argon	Mg
6^o	CO_2 product	Mg	20^o	Vent	Mg
By-products; $l = n + 1 \dots m$			21^o	Make-up water	Mg
7^o	Low pressure process steam	MJ	22^o	Wastewater	Mg
8^o	Low temperature process heat	MJ	External supplies; $p = m + 1 \dots s$		
9^o	Medium temperature process heat	MJ	23^o	Coal	MJ
10^o	High temperature process heat	MJ	24^o	Biomass	MJ
11^o	Preheated air process heat	MJ	25^o	Natural gas	MJ
12^o	Flue gases	Mg	26^o	Raw water	Mg
13^o	Bottom ash	Mg	27^o	Limestone	Mg

The mathematical model of balancing the direct energy (and material) consumption, based on the presented “input-output”, takes the form [7,27] of:

- balance of main products including by-production and external supplies supplementing the main production:

$$\mathbf{G} + \mathbf{F}_{FG}\mathbf{G} + \mathbf{D}_G = \mathbf{A}_G\mathbf{G} + \mathbf{K}_G \, , \tag{1}$$

- balance of by-product not supplementing the main production:

$$\mathbf{F}_F\mathbf{G} = \mathbf{A}_F\mathbf{G} + \mathbf{K}_F \, , \tag{2}$$

- balance of external supplies not supplementing the main production:

$$\mathbf{D}_D = \mathbf{A}_D\mathbf{G} \, , \tag{3}$$

where: $\mathbf{G}$ – vector of the main production, $\mathbf{F}_{FG}$, $\mathbf{F}_F$ – matrices of the coefficients of by-production supplementing and not supplementing the main production, respectively, $\mathbf{D}_G$, $\mathbf{D}_D$ – vectors of external supplies supplementing and not supplementing the main production, respectively, $\mathbf{A}_G$, $\mathbf{A}_F$, $\mathbf{A}_D$ – matrices of the coefficients of consumption the main products, by-products and external supplies, respectively, $\mathbf{K}_G$, $\mathbf{K}_F$ – vectors of final production of the main products and by-products, respectively.

‘Input-output’ models of cumulative energy and exergy consumption

Based on the ‘input-output’ model of direct energy and material consumption the mathematical model of cumulative energy and exergy consumption concerning the integrated oxy-fuel combustion power plant has been developed. The analysis of the direct consumption of energy does not include all the energy required for the production of any given useful energy carrier (or any other product). Other energy carriers used for its production (e.g., fuels) also require the consumption of energy in intermediate processes of production and transport. Thus, the energy carrier (or any other product) is produced not only as a result of direct but also indirect energy consumption in numerous preceding processes in the energy and technological set of interconnections. The sum of direct and indirect consumption of energy has been called the cumulative energy consumption (CEC). The methodology of cumulative exergy consumption (CExC) bases on the same fundamentals as calculations of indices of cumulative energy consumption. Cumulative exergy consumption charging the products of the process equals the sum of the cumulative exergy consumption of substrates of the process [1,17–19,30]. In the analysis of CEC and CExC we assume that the interconnections between the analyzed power plant and domestic energy system, as well as other sectors of domestic economy are rather weak. Such an assumption allows to apply in the calculations the indices of cumulative energy and exergy consumption of fuels, raw materials and semiproducts as quantities known *a priori* [24,25]. The indices concerning external supplies and by-production of main products are determined basing on the analysis of the entire economy of the given country. The by-products are charged by the indices of CEC and CExC resulting from the principle of a replaced process (the avoided cumulative energy or exergy consumption in a single-aimed process) [17,24,25].

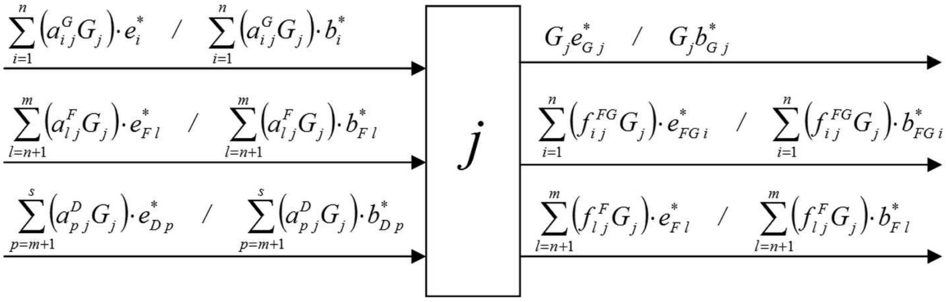

Figure 2: Cumulative energy/exergy balance of the jth branch; n, m, s -Õ number of main products, by-products and external supplies not supplementing the main products, respectively.

Figure 2 presents the block diagram of the jth technological module of the integrated OFC power plant.

The average-weighted index of the cumulative energy consumption, e_i^*, of an energy carrier is defined as follows:

$$e_i^* = r_{G\,i}e_{G\,i}^* + r_{FG\,i}e_{FG\,i}^* + r_{DG\,i}e_{DG\,i}^*\,, \tag{4}$$

where $r_{G\,i}$, $r_{FG\,i}$, $r_{DG\,i}$ denote the share of main production, by-production supplementing the main production and external supplies supplementing the main production in the input of the ith energy carrier and $e_{FG\,i}^*$, $e_{DG\,i}^*$ denote indices of cumulative energy consumption concerning the ith by-production supplementing the main production and external supply supplementing the main production.

The set of balance equations of cumulative energy consumption take the following form:

$$\begin{aligned}\mathop{\Lambda}_{j=1}^{n}:\ &\sum_{i=1}^{n}\left(a_{ij}^{G}G_j\right)\cdot e_i^* + \sum_{l=n+1}^{m}\left(a_{lj}^{F}G_j\right)\cdot e_{F\,l}^* + \sum_{p=m+1}^{s}\left(a_{pj}^{D}G_j\right)\cdot e_{D\,p}^* =\\ &= G_j e_{G\,j}^* + \sum_{i=1}^{n}\left(f_{ij}^{FG}G_j\right)\cdot e_{FG\,i}^* + \sum_{l=n+1}^{m}\left(f_{lj}^{F}G_j\right)\cdot e_{F\,l}^*\end{aligned} \tag{5}$$

from which the cumulative energy consumption of jth main product $e_{G\,j}^*$ can be calculated.

The similar equations for the cumulative exergy consumption can be presented, both for the average-weighted index of the cumulative exergy consumption, b_i^*, (based on Eq. (4)) and the set of balance of cumulative exergy consumption (based on Eq. (5)) [25].

‘Input-output’ model of the system exergy losses

The analysis of exergy losses in the integrated OFC power plant requires a system approach. As stressed by Szargut and Sama “consider the influence of the proposed changes in energy management on the exergy losses in other links of the system” [17,19]. This means that in a system consisting of many elements, the improvement of not merely the one of them should be considered, because the decrease of exergy losses in one element may involve in the system both positive and negative effects. This requirement can be satisfied if the exergy losses are assessed by means of the system analysis.

Based on the diagram of exergy balance concerning the jth module similar as Fig. 2, the set of exergy balances concerning all the modules takes the following form:

$$\begin{aligned} \underset{j=1}{\overset{n}{\Lambda}} : \sum_{i=1}^{n} \left(a_{ij}^{G} G_j\right) b_{G\,i} + \sum_{l=n+1}^{m} \left(a_{lj}^{F} G_j\right) b_{F\,l} + \sum_{p=m+1}^{s} \left(a_{pj}^{D} G_j\right) b_{D\,p} = \\ = G_j b_{G\,j} + \sum_{i=1}^{n} \left(f_{ij}^{FG} G_j\right) b_{G\,i} + \sum_{l=n+1}^{m} \left(f_{lj}^{F} G_j\right) b_{F\,l} + \delta B_j \end{aligned} \tag{6}$$

from which the local exergy losses δB_j can be calculated for each of the modules.

When the cumulative exergy losses are considered, they may be calculated by means of the expression [23]:

$$\delta b^{*}_{G\,i} = b^{*}_{G\,i} - b_{G\,i} \ , \tag{7}$$

where $\delta b^{*}_{G\,i}$ denotes the index of cumulative exergy loss associated with the production of the ith main product.

Then the cumulative exergy analysis, expressed by the ratio of the exergy of each main product to the cumulative exergy consumption, presents the cumulative degree of thermodynamic perfection (CDP) [14,17,19].

‘Input-output’ model of the thermoecological cost

The production of final energy carriers (e.g., electricity) is possible thanks to the consumption of nonrenewable primary energy resources the depletion of which is becoming more and more crucial for the sustainable development of the humankind. The production of final energy carriers is connected with harmful emissions. In order to compensate the environmental losses the additional consumption of primary energy is required. The sum of these consumption of primary exergy per unit of the useful product (energy carrier or another final product) is called the index of thermoecological cost (TEC) [13,15,16].

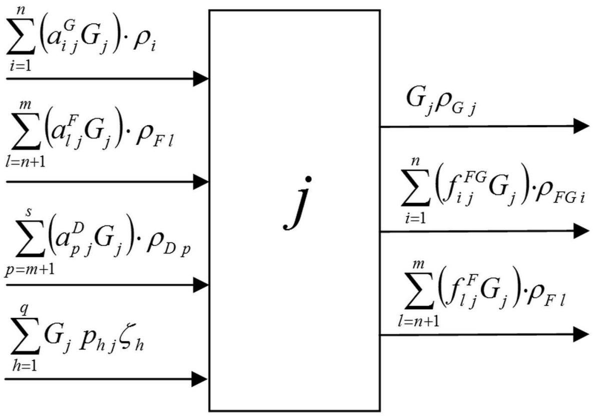

Figure 3: Diagram of calculating the indices of the thermoecological costs.

Figure 3 presents a diagram of calculating the index of thermoecological cost concerning the jth module of the integrated power plant. If the main product is supplemented by an external supply or a by-product we must apply the average-weighted index of the thermoecological cost, the same as in the case of the average-weighted index of cumulative energy and exergy consumption:

$$\rho_i = r_{G\,i}\rho_{G\,i} + r_{FG\,i}\rho_{FG\,i} + r_{DG\,i}\rho_{DG\,i}\,. \tag{8}$$

The set of balance equations used to calculate the indices of thermoecological costs takes the following form [29]:

$$\mathop{\Lambda}_{j=1}^{n} : \sum_{i=1}^{n}\left(a^G_{ij}G_j\right)\cdot\rho_i + \sum_{l=n+1}^{m}\left(a^F_{lj}G_j\right)\cdot\rho_{F\,l} + \sum_{p=m+1}^{s}\left(a^D_{pj}G_j\right)\cdot\rho_{D\,p} + \\ + \sum_{h=1}^{q} G_j p_{h\,j}\zeta_h = G_j\rho_{G\,j} + \sum_{i=1}^{n}\left(f^{FG}_{ij}G_j\right)\cdot\rho_{FG\,i} + \sum_{l=n+1}^{m}\left(f^F_{lj}G_j\right)\cdot\rho_{F\,l} \tag{9}$$

The Eqs. (8) and (9) present the algorithm of calculating the indices of thermoecological costs for an integrated power plant operating with oxy-fuel combustion. The indices ρ_D and ρ_{DG} concerning external supplies are preset *a priori* as average values in the country, whereas the indices ρ_F and ρ_{FG} are assessed basing on the principle of replaced processes.

The presented algorithm may be applied among others in the following investigations:

- assessment of the influence of operating parameters of an integrated OFC power plants on the depletion of nonrenewable natural resources,
- choice of optimal operating parameters from the point of view of minimization of the depletion of nonrenewable natural resources,
- assessment of the degree of sustainable development.

The index of sustainable development (ISD) is defined as a ratio of the thermoecological cost to the specific exergy of each given main product. The higher the value of the ISD is, the more disadvantageous is the effect of the production of given useful product on the depletion of nonrenewable natural resources. When it is economically justified, we should try to decrease the ISD in order to meet the goal set up by the idea of sustainable development [13].

3 Example

The example presented in this paper is based on [11], where several advanced OFC power plants concepts are presented. One of them – advanced pulverized coal (PC) oxy-combustion boiler case – has been chosen for the analysis. In the reference OFC power plant case, the boiler operates with a theoretical adiabatic flame temperature of 2031 °C, while in the analysed case the boiler accommodates a theoretical adiabatic flame temperature of 2308 °C. It results in reduction of recycled flue gases to around 63% (69% in reference OFC case), which leads to the increase of the oxygen concentration in the boiler. Introducing the advanced PC oxy-combustion boiler will require the use of materials that can handle the higher temperatures and sulphur concentration in the boiler. Details of proposed concept can be found in [11], other characteristic parameters are listed in Tab. 3.

The 'input-output' models of direct energy and materials consumption was elaborated based on the process model described in [11]. This model contains the matrices of the consumption of main products, $\mathbf{A}_G$, the by-production of energy carriers and materials not supplementing, $\mathbf{F}_F$, the main production, the consumption of energy carriers and materials manufactured as by-products, $\mathbf{A}_F$, and the consumption of external supplies, $\mathbf{A}_D$. Also the vectors of main production, $\mathbf{G}$, final production of main products, $\mathbf{K}_G$, and by-products, $\mathbf{K}_F$, and external supplies, $\mathbf{D}_D$, are elaborated.

Table 3: Case descriptions [11]

Source / case no.	DOE/NETL-2010/1405 [11] / case 7
Gross / net power	785 900 kW$_{el}$ / 549 450 kW$_{el}$
Gross / net efficiency (LHV)	43.89% / 30.69%
Boiler / fuel	advanced PC oxy-combustion boiler / hard coal
Live steam parameters	24.1 MPa / 600 °C / 620 °C
ASU / oxygen purity	conventional cryogenic technology / 95%
Flue gas quality control module	wet flue gas desulphurization (FGD) / an electrostatic precipitator (ESP) with baghouse
CO$_2$ processing unit	only dehydration and compression
CO$_2$ purity / capture rate / pressure	83.54%/100% / 15.3 MPa

For the analysed case of an integrated oxy-fuel combustion power plant the matrix $\mathbf{A}_G$ takes the following form:

$$\mathbf{A}_G = \begin{array}{cccccc|c} 1^\circ & 2^\circ & 3^\circ & 4^\circ & 5^\circ & 6^\circ & \\ 0 & 2.1146 & 0 & 0 & 0 & 0 & 1^\circ \\ 0.0036 & 0.0082 & 0.0114 & 22.132 & 845.18 & 391.31 & 2^\circ \\ 0 & 1.0082 & 0 & 238.15 & 806.39 & 807.88 & 3^\circ \\ 0.0002 & 0 & 0 & 0 & 0 & 1.0766 & 4^\circ \\ 0.0001 & 0 & 0 & 0.0038 & 0 & 0 & 5^\circ \\ 0 & 0 & 0 & 0 & 0 & 0 & 6^\circ \end{array}$$

As we see, in the matrix of the main production the intermodule flows are to be found in the case of the first five energy carriers (or materials). In the case of other matrices non-zero elements have been presented in Tab. 4.

In the analysed case there is not by-production or external supplies that supplements the main production, thus matrices $\mathbf{F}_{FG}$ and $\mathbf{D}_G$ are equal to zero. It also makes the average-weighted indices of cumulative energy and exergy consumption (Eq. (4)), as well as the average-weighted indies of thermoecological cost (Eq. (8)) equal to the values of those indices corresponding with the main production (e.g., $\rho_i = \rho_{G\,i}$).

Due to the assumed by the authors of [11] the 100% CO$_2$ capture rate, which implies no air emissions, the coefficients denoting the amount of harmful emissions released to the atmosphere, p_h, are also zero. This kind of assumption requires that the geological CO$_2$ sequestration can accommodate any amount of impurity in the sequestrated stream. Those assumptions lead to the simplification of the CPU, which in the analysed case consists of

Table 4: Nonzero elements of matrices $\mathbf{F}$, $\mathbf{A}_F$ and $\mathbf{A}_D$

Coefficient	Value	Unit	Coefficient	Value	Unit
matrix $\mathbf{F}$			matrix $\mathbf{A}_F$		
$f^F_{7\,2}$	0.0071	MJ/MJ	$a^F_{7\,5}$	37.005	MJ/Mg
$f^F_{8\,2}$	0.0034	MJ/MJ	$a^F_{7\,6}$	0.5497	[MJ/Mg]
$f^F_{12\,1}$	0.0003	Mg/MJ	$a^F_{8\,1}$	0.0016	MJ/MJ
$f^F_{13\,1}$	$8{\cdot}10^{-7}$	Mg/MJ	$a^F_{12\,4}$	1.0479	Mg/Mg
$f^F_{14\,4}$	0.0098	Mg/Mg	$a^F_{21\,2}$	$8{\cdot}10^{-6}$	Mg/MJ
$f^F_{15\,4}$	0.0197	Mg/Mg	$a^F_{21\,3}$	0.0003	Mg/MJ
$f^F_{17\,5}$	3.2039	[Mg/Mg]	$a^F_{21\,4}$	0.015	Mg/Mg
$f^F_{20\,6}$	0.00001	Mg/Mg	matrix $\mathbf{A}_D$		
$f^F_{21\,3}$	0.0003	Mg/Mg	$a^D_{23\,1}$	1.0774	MJ/MJ
$f^F_{22\,6}$	0.0767	Mg/Mg	$a^D_{25\,3}$	0.0003	Mg/MJ
			$a^D_{26\,4}$	0.0127	Mg/Mg

dehydration station and compression unit (8 stages with intercooling) [11]. It should although be noted here, that in real operation, the additional purification will be needed in order to meet the specifics of pipeline transport and utilization (e.g., enhance oil recovery) or storage (e.g., in saline formations) [20].

Table 5 presents the results of the balance of the analysed OFC power plant concerning the annual operation, with assumed capacity factor of 85% [11] for the final production and external supplies.

The indices concerning external supplies have been taken over from the literature and EcoInvent database, based on the average values for Poland [1–3,12,13]. Also the indices concerning by-production have to be preset and assessed basing on the principle to replaced processes. For the analysed cases, only the utilization of gypsum was considered (fly ash and bottom ash treated as wastes), where the value have been taken over from the EcoInvent database. Specific exergy of all energy carriers and materials have been calculated based on appropriate equations (presented in [28]) and data obtained from the process model [11]. The values of the indices of the CEC, CExC and TEC for the by-products and external supplies that are taken into account in the analysed case have been presented in Tab. 6.

Figure 4 presents the cumulative degree of thermodynamic perfection and the index of sustainable development of chosen main products (cor-

Table 5: Vector of global and final production and external supplies in annual operation phase.

No.	Energy carrier or material	Unit	Global production	Final production	External supplies
1°	HP & IP process steam	MJ/a	$44\ 548\times10^6$	0	–
2°	Electricity	MJ/a	$21\ 066\times10^6$	$14\ 728\times10^6$	–
3°	Cooling duty	MJ/a	$33\ 485\times10^6$	0	–
4°	CO_2-rich stream	Mg/a	$14\ 570\times10^3$	0	–
5°	Gaseous oxygen	Mg/a	$3\ 970\times10^3$	0	–
6°	CO_2 product	Mg/a	$4\ 967\times10^3$	$4\ 967\times10^3$	–
			⋱		
23°	Coal	MJ/a	–	–	$47\ 995\times10^6$
24°	Biomass	MJ/a	–	–	0
25°	Natural gas	MJ/a	–	–	0
26°	Raw water	Mg/a	–	–	$11\ 001\times10^3$
27°	Limestone	Mg/a	–	–	185×10^3

Table 6: The values of the indices of CEC, CExC and TEC of by-products and external supplies.

No.	Energy carrier or material	Cumulative energy consumption (CEC)		Cumulative exergy consumption (CExC)		Thermoecological cost (TEC)	
By-products; $l = n+1,\ldots,m$							
7°	LP process steam	1.292	MJ/MJ	1.237	MJ$_{ex}$/MJ	1.216	MJ$_{ex}$/MJ
8°	LT process heat	1.869	MJ/MJ	1.927	MJ$_{ex}$/MJ	1.821	MJ$_{ex}$/MJ
12°	Flue gases	273.4	MJ/Mg	308.3	MJ$_{ex}$/MJ	325.4	MJ$_{ex}$/MJ
15°	Gypsum	454	MJ/Mg	462	MJ$_{ex}$/Mg	425	MJ$_{ex}$/Mg
21°	Make-up water	31.22	MJ/Mg	34.8	MJ$_{ex}$/Mg	34.03	MJ$_{ex}$/Mg
External supplies; $p = m+1,\ldots,s$							
23°	Coal	1.064	MJ/MJ	1.17	MJ$_{ex}$/MJ	1.243	MJ$_{ex}$/MJ
26°	Raw water	31.22	MJ/Mg	31.22	MJ$_{ex}$/Mg	32.55	MJ$_{ex}$/Mg
27°	Limestone	176	MJ/Mg	338	MJ$_{ex}$/Mg	363	MJ$_{ex}$/Mg

responding with particular module). The obtained values of the ISD and CDP indicates that the higher potential for improvement is associated with the oxygen production (air separation unit).

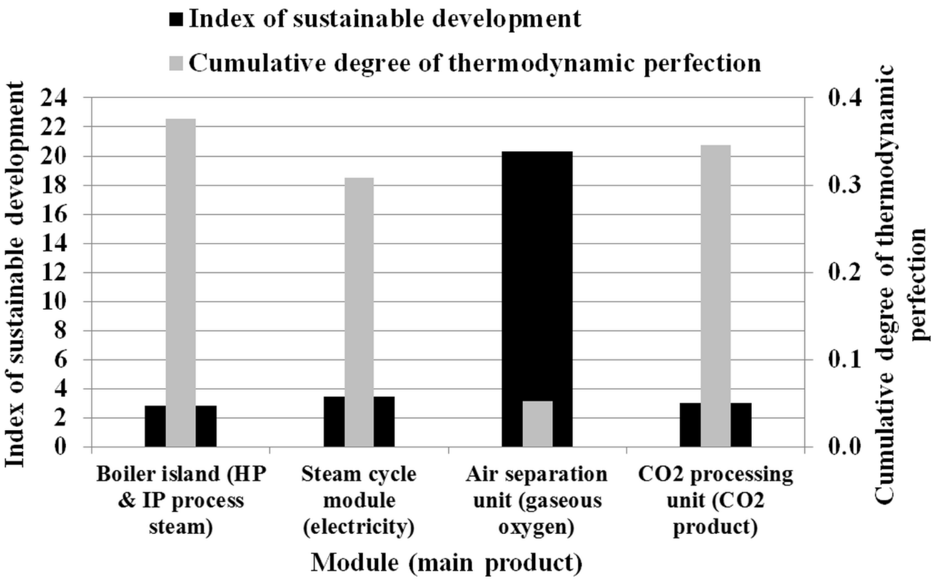

Figure 4: Index of sustainable development and the cumulative degree of thermodynamic perfection of chosen main modules (main products).

Based on the presented algorithms, the CEC, the CExC and the TEC of main products (e.g., gross electricity production, CO_2 product) and of the net electricity production was calculated for the analysed case. The results have been presented in Tab. 7. In Tab. 7 also the range of values for the coal fired power plants (lower values – best available technology) without CCS have been included, which were taken over from the literature [1–3,13] and EcoInvent database. Although, we have to keep in mind, that the presented values are usually calculated for certain location of power plant, thus they can be used in direct comparison between OFC power plant and reference one without CCS. Authors recommend to calculate the reference (without CCS) power plant with the same assumptions concerning by-products and external supplies in order to estimate the influence of the introduction of the OFC technology.

The results of CEC, CExC and TEC of net electricity production are slightly higher than the average values for Poland, which can be explained by the lower net efficiency of the analysed OFC power plant than the average for Poland. It may seem that the OFC technology, form the point of view from the depletion of nonrenewable resources is not favourable, but we have to

Table 7: Results of calculations of the CEC, CExC and TEC of main products and the net electricity production.

No.	Energy carrier or material	Cumulative energy consumption (CEC)		Cumulative exergy consumption (CExC)		Thermoecological cost (TEC)	
By-products; $l = n+1, \ldots, m$							
1º	HP & IP process steam	1.368	MJ/MJ	1.503	MJ_{ex}/MJ	1.595	MJ_{ex}/MJ
2º	Electricity	2.95	MJ/MJ	3.241	MJ_{ex}/MJ	3.433	MJ_{ex}/MJ
3º	Cooling duty	0.04359	MJ/MJ	0.04688	MJ_{ex}/MJ	0.04295	MJ_{ex}/MJ
4º	CO_2-rich stream	365.7	MJ/Mg	412.4	MJ_{ex}/Mg	435.3	MJ_{ex}/Mg
5º	Gaseous oxygen	2576	MJ/Mg	2823	MJ_{ex}/Mg	2981	MJ_{ex}/Mg
6º	CO_2 product	1584	MJ/Mg	1751	MJ_{ex}/Mg	1847	MJ_{ex}/Mg
Net electricity production (for analysed OFC power plant)		3.484	MJ/MJ	3.831	MJ_{ex}/MJ	4.056	MJ_{ex}/MJ
Net electricity production (values for coal fired power plants without CCS) [1-3,13]		3.3÷3.7	MJ/MJ	3.4–3.8	MJ_{ex}/MJ	3.8–4.1	MJ_{ex}/MJ

keep in mind that it will provide radical decrease of CO_2 emissions. Further studies are necessary in order to estimate the cumulative CO_2 emissions and global warming potential for the oxy-fuel combustion technologies.

4 Conclusions

Integrated OFC power plants are characterized by a complex system of interconnections, a part of which is of a feedback character. Thus the system approach to the energy analysis is an adequate approach. The presented system approach to the analysis of an integrated oxy-fuel combustion power plant is based on the 'input-output analysis'. The core of the system analysis is the direct energy and material consumption balance, but it is not sufficient tool for the assessment of entire consumption of energy carriers and materials. This results from the fact that energy carriers and materials supplied to the given process (in this case integrated OFC power plant) are already charged by the energy consumption in previous processes (e.g., extraction, transport and pre-processing of coal). Thus the cumulative energy and exergy analysis has been introduced. The exergy analysis, based on the 'input-output method', has also been proposed in order to point out the possible improvements of the thermodynamic imperfections of phenomena occurring in each module of the integrated OFC power plant. The ecological analysis, based on the idea of the thermoecological cost, has also been proposed in order to assess the proposed CCS technology from the sustainable development point of view.

The algorithms presented in the paper are the components of the authors programme (in preparation) concerning the system analysis of integrated oxy-fuel power plants oxy system analysis (OSA). The complete programme will comprise the system analysis of direct and cumulative energy and exergy consumption as well as LCA analysis applying thermoecological costs and cumulative emissions.

Acknowledgement This scientific work was supported by the National Centre for Research and Development, within the confines of Research and Development Strategic Program "Advanced Technologies for Energy Generation" project no. 2 'Oxy-combustion technology for PC and FBC boilers with CO_2 capture'. Agreement No. SP/E/2/66420/10. The support is gratefully acknowledged.

Received 18 June 2014

References

[1] Bibrowski Z.: *Cumulative Energy Consumption.* PWN, Warsaw 1983 (in Polish).

[2] Boustead I., Hancock G.F.: *Handbook of Industrial Energy Analysis.* Ellis Horwood Limited Publ., Chichester 1979.

[3] Czarnowska L., Stanek W., Pikoń K., Nadziakiewicz J.: *Environmental quality evaluation of hard coal using LCA and Exergo-Ecological Cost methodology.* Chem. Eng. Tran. (2014) (in press).

[4] Gładysz P., Ziębik A.: *Life cycle assessment of an integrated oxy-fuel combustion power plant with CO_2 capture, transport and storage.* In: Proc. 1st South East European Conference on Sustainable Development of Energy, Water and Environment Systems, 2014 (in press).

[5] Global CCS Institute: *CO_2 Capture Technologies oxy Combustion with CO_2 Capture.* 19 Jan. 2012.

[6] Klir G.J. (Ed.): *Trends in General Systems Theory.* WNT, Warsaw 1974 (in Polish).

[7] Leontief W.: *Input-output economics 2nd Edn.* Oxford Univer. Press, New York 1986.

[8] Liszka M., Szapajko G., Nowak G.T.: *Utilization of oxy-fuel waste nitrogen as a drying agent in a contact-type solid fuel dryer.* Fuel **113**(2013), 670–678.

[9] Liszka M., Ziębik A.: *Coal-fired oxy-fuel power unit – Process and system analysis.* Energy **35**(2010), 943–951.

[10] Lupion M., Herzog H.J.: *NER300: Lessons learnt in attempting to secure CCS projects in Europe.* Int. J. Greenhouse Gas Contr. **19**(2013), 19–25.

[11] Matuszewski M.: *Advancing Oxycombustion Technology for Bituminous Coal Power Plants: An R&D Guide.* Rap. DOE/NETL-2010/1405, Apr. 2012.

[12] Stanek W., Czarnowska L.: *Environmental externalities and its influence on the thermo-ecological cost.* Int. J. Susta. Water Env. Syst. **4**(2012), 1, 51–58.

[13] Stanek W.: *Methodology of Evaluation of Ecological Effects in Thermal Processes with the Application of Exergy Analysis.* Silesian UT, Gliwice 2009 (in Polish).

[14] Szargut J., Morris D.R.: *Cumulative exergy losses associated with the production of lead metal.* Int. J. Energ. Res. **14**(1990), 605–616.

[15] Szargut J., Stanek W.: *Fuel part and mineral part of the thermoecological cost.* Int. J. Thermodyn. **15**(2012), 4, 187–190.

[16] Szargut J., Ziębik A., Stanek W.: *Depletion of the non-renewable natural exergy resources as a measure of the ecological cost.* Energ. Convers. Manage. **43**(2002), 1149–1163.

[17] Szargut J., Ziębik A.: *Fundamentals of Thermal Engineering.* PWN, Warsaw 2000 (in Polish).

[18] Szargut J.: *Analysis of cumulative exergy consumption and cumulative exergy losses.* Adv. Thermodyn. **4(**1990), Finite-Time Thermodynamics and Thermoeconomics, Taylor&Francis.

[19] Szargut J.: *Exergy Analysis: Technical and Ecological Applications.* WIT, Southampton 2005.

[20] U.S. Department of Energy & National Energy Technology Laboratory: *Quality Guidelines for Energy System Studies. CO2 Impurity Design Parameters.* Rep. DOE/NETL-341/011212, Jan. 2012.

[21] U.S. Department of Energy & National Energy Technology Laboratory: *DOE/NETL Advanced Carbon Dioxide Capture R&D Program: Technology Update,* May 2013.

[22] Zheng L. (Ed.): *Oxy-fuel combustion for power generation and carbon dioxide (CO_2) capture.* Woodhead Publishing Series in Energy **17**(2011).

[23] Ziębik A., Gładysz P.: *Analysis of cumulative exergy losses of an integrated oxy-fuel combustion power plant.* Rynek Energii **1**(110)(2014), 82–89 (in Polish).

[24] Ziębik A., Gładysz P.: *Analysis of cumulative energy consumption in an oxy-fuel combustion power plant integrated with a CO_2 processing unit.* Energy Conversion and Management (2014), http://dx.doi.org/10.1016/j.enconman.2014.02.048.

[25] Ziębik A., Gładysz P.: *Analysis of the cumulative exergy consumption of an integrated oxy-fuel combustion power plant.* Arch. Thermodyn. **34**(2013), 3, 105–122.

[26] Ziębik A., Gładysz P.: *System analysis of oxy-combustion.* In: *Oxyfuel combustion for pulverized and fluidized boilers integrated with CO_2 capture.* W. Nowak , T. Czakiert, Eds. Częstochowa UT, Częstochowa 2012 (in Polish).

[27] Ziębik A., Gładysz P.: *System approach to the energy analysis of an integrated oxy-fuel combustion power plant.* Rynek Energii **101**(2012), 4.

[28] Ziębik A., Gładysz P.: *Systems analysis of exergy losses in an integrated oxy-fuel combustion power plant.* In: Proc. 25th Int. Conf. Efficiency, Cost, Optimization, Simulation and Environmental Impact of Energy Systems, Perugia, Jun. 26-29, 2012.

[29] Ziębik A., Gładysz P.: *Thermoecological analysis of an oxy-fuel combustion power plant integrated with a CO_2 processing unit.* In: Proc. 27th Int. Conf. Efficiency, Cost, Optimization, Simulation and Environmental Impact of Energy Systems, 2014 (in press).

[30] Ziębik A.: *Mathematical Modelling of Energy Management Systems in Industrial Plants.* Ossolineum, Wrocław 1990.