

## Analysis of the cumulative exergy consumption of an integrated oxy-fuel combustion power plant

ANDRZEJ ZIĘBIK\*  
PAWEŁ GŁADYSZ

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

**Abstract** In order to analyze the cumulative exergy consumption of an integrated oxy-fuel combustion power plant the method of balance equations was applied based on the principle that the cumulative exergy consumption charging the products of this process equals the sum of cumulative exergy consumption charging the substrates. The set of balance equations of the cumulative exergy consumption bases on the ‘input-output method’ of the direct energy consumption. In the structure of the balance we distinguished main products (e.g. electricity), by-products (e.g. nitrogen) and external supplies (fuels). In the balance model of cumulative exergy consumption it has been assumed that the cumulative exergy consumption charging the supplies from outside is a quantity known *a priori* resulting from the analysis of cumulative exergy consumption concerning the economy of the whole country. The byproducts are charged by the cumulative exergy consumption resulting from the principle of a replaced process. The cumulative exergy consumption of the main products is the final quantity.

**Keywords:** Exergy; Cumulative consumption; Oxy-combustion; Integrated power plant

### Nomenclature

- A** – matrix of the coefficients of the consumption of energy carriers and materials
- $a_{ij}$  – coefficient of consumption of energy carriers and materials
- b**\* – vector of indices of the cumulative exergy consumption

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\*Corresponding Author. E-mail: andrzej.ziebiak@polsl.pl

- $b^*$  – index of the cumulative exergy consumption
- $\mathbf{F}$  – matrix of the coefficients of the by-production
- $f_{ij}$  – coefficient of by-production of energy carriers or materials
- $G$  – main product
- $i, j$  – several number of main product
- $I$  – several number of by-product
- $\mathbf{I}$  – unit matrix
- $m$  – number of main and by-products
- $n$  – number of main products
- $p$  – several number of external supply
- $s$  – number of main, by-products and external supplies

#### Subscripts and superscripts

- $D$  – external supply
- $DD$  – external supply not supplementing the main production
- $DG$  – external supply supplementing the main production
- $Ex$  – exergy
- $F$  – by-product
- $FG$  – by-product supplementing the main production
- $G$  – main product

#### Abbreviations

- ASU – air separation unit
- CExC – cumulative exergy consumption
- CPU – CO<sub>2</sub> processing unit
- FGQC – flue gas quality control
- LHV – lower heating value
- OFC – oxy-fuel combustion
- PC – pulverized coal

## 1 System approach to the analysis of cumulative exergy consumption

An integrated oxy-fuel combustion (OFC) power plant constitutes a system consisting of the following technological modules: boiler, steam cycle, air separation unit, cooling water system, flue gas quality control system, water treatment unit, CO<sub>2</sub> processing unit. Due to the interconnections between technological modules, energy and exergy analyses require a system approach [1,2]. This concerns both direct energy (exergy) consumption, as well as cumulative energy and exergy consumption [3].

The methodology for 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 [4]. In the case of an integrated OFC power plant the ‘input-output method’ was applied assuming 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 indices of the cumulative exergy consumption of fuels, raw materials and semiproducts as quantities known a priori [5,6]. These indices are determined basing on the analysis of cumulative exergy consumption concerning the entire economy of the country as far as domestic products are concerned or evaluated according to cumulative exergy consumption of export goods if imported products are taken into account [4]. Usually in the calculation the investment component is neglected because it is very slight in comparison with the component of exploitation.

## 2 Mathematical model of the system method of the assessment of cumulative exergy consumption

The mathematical model of the system method of the assessment of cumulative exergy consumption of an integrated OFC power plant bases on the principle of the mathematical model of the ‘input-output’ type of direct energy consumption [7]. In the structure of the balance main products (e.g., electricity, oxygen) and by-products supplementing the main products (e.g., electricity from a nitrogen recovery turbine in the case of pressurised oxy-fuel combustion), by-products not supplementing the main products (e.g., nitrogen, gypsum) and supplies from outside supplementing the main products (e.g., oxygen) or not supplementing ones (e.g., fuels) are to be distinguished. The suggested model assumes that supplies from outside are charged by cumulative exergy consumption given a priori determined as an averaged value of the country. By-products are charged by the cumulative exergy consumption resulting from the principle of replacing (the avoided cumulative exergy consumption in a single-aimed process).

Figure 1 presents the block diagram of the  $j$ th technological module of an integrated oxy-fuel combustion power plant. Explanation of description symbols used in this figure

$$\sum_{i=1}^n (a_{i,j}^G G_j) \quad - \quad \text{consumption of the } i\text{th product belongs to main production in the } j\text{th module,}$$

- $b_i^*$  – average weighted index of cumulative exergy consumption of the  $i$ th product,
- $\sum_{l=n+1}^m (a_{l,j}^F G_j)$  – consumption of the  $l$ th by-product not supplementing the main production in the  $j$ th module
- $b_{Fl}^*$  – index of cumulative exergy consumption charging the  $l$ th by-product not supplementing the main production
- $\sum_{p=m+1}^s (a_{p,j}^D G_j)$  – consumption of the  $p$ th external supply not supplementing the main production in the  $j$ th module,
- $b_{DDp}^*$  – index of cumulative exergy consumption charging the  $p$ th external supply,
- $G_j b_j^*$  – cumulative exergy consumption of the  $j$ th main product,
- $\sum_{l=n+1}^m (f_{l,j} G_j)$  – production of the  $l$ th by-product in the  $j$ th technological module.

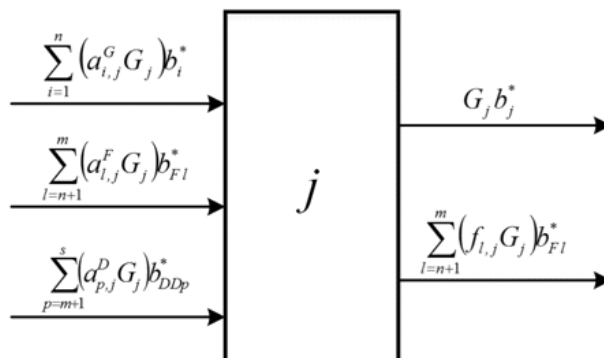


Figure 1. Calculating diagram of cumulative exergy consumption.

Average weighted index of cumulative exergy consumption concerning the  $i$ th product  $b_i^*$  results from equation

$$b_i^* = r_{Gi} b_{Gi}^* + r_{FGi} b_{FGi}^* + r_{DGi} b_{DGi}^*, \quad (1)$$

where

- $b_{Gi}^*$  – index of cumulative exergy consumption charging the  $i$ th main product,  
 $b_{FGi}^*$  – index of cumulative exergy consumption of the  $i$ th by-product supplementing the main production,  
 $b_{DGi}^*$  – index of cumulative exergy consumption of the  $i$ th supplementary supply of the main production,  
 $r_{Gi}, r_{FGi}, r_{DGi}$  – the share of main production, by-production and external supply supplementing the main production in the input of  $i$ th product.

The set of balance equations of cumulative exergy consumption in the form of the matrix has the following form:

$$\mathbf{A}_G^T \mathbf{b}^* + \mathbf{A}_D^T \mathbf{b}_{DD}^* = \mathbf{b}_G^* + (\mathbf{F}^T - \mathbf{A}_F^T) \mathbf{b}_F^*, \quad (2)$$

- where
- $\mathbf{A}_G^T$  – transposed matrix of indices of the direct consumption of main products,
  - $\mathbf{b}^*$  – vector of average weighted indices of the cumulative exergy consumption,
  - $\mathbf{A}_D^T$  – transposed matrix of indices of the direct consumption of external supplies,
  - $\mathbf{b}_{DD}^*$  – vector of indices of the cumulative exergy consumption of external supplies,
  - $\mathbf{b}_G^*$  – vector of indices of the cumulative exergy consumption of the main products,
  - $\mathbf{F}^T$  – transposed matrix of indices of by-production not supplementing the main production,
  - $\mathbf{A}_F^T$  – transposed matrix of indices of the direct consumption of byproducts not supplementing the main production,
  - $\mathbf{b}_F^*$  – vector of indices of the cumulative exergy consumption of by-products.

The vector of average weighted indices of cumulative exergy consumption is calculated by means of equation

$$\mathbf{b}^* = \mathbf{r}_G^d \mathbf{b}_G^* + \mathbf{r}_{FG}^d \mathbf{b}_{FG}^* + \mathbf{r}_{DG}^d \mathbf{b}_{DG}^*, \quad (3)$$

where  $\mathbf{r}_G^d$ ,  $\mathbf{r}_{FG}^d$ ,  $\mathbf{r}_{DG}^d$  denote diagonal matrices of the shares of the main production, by-production and external supplies supplementing the main production in the global production of system and  $\mathbf{b}_{FG}^*$  and  $\mathbf{b}_{DG}^*$  denote the vectors of supplementary by-products and external supplies, respectively.

The matrix Eqs. (2) and (3) constitute the general algorithm of calculating the indices of cumulative exergy consumption charging the main production of an integrated OFC power plant. In particular case the model may be simplified. If, e.g., by-production and external supplies supplementing the main production do not exist, then

$$\mathbf{b}^* = \mathbf{b}_G^* . \quad (4)$$

Including Eq. (4) into (2) and calculating vector  $\mathbf{b}_G^*$  we have

$$\mathbf{b}_G^* = (\mathbf{I} - \mathbf{A}_G^T)^{-1} [\mathbf{A}_D^T \mathbf{b}_{DD}^* + (\mathbf{A}_F^T - \mathbf{F}^T) \mathbf{b}_F^*] , \quad (5)$$

where  $(\mathbf{I} - \mathbf{A}_G^T)^{-1}$  denote inverse matrix and  $(\mathbf{I} - \mathbf{A}_G^T)$  is not a singular matrix.

### 3 Examples of calculating the indices of cumulative exergy consumption of an integrated power plant with oxy-fuel combustion

The examples presented in this paper are based on [8], where several advanced oxy-fuel combustion technologies for bituminous coal power plants are analyzed. The chosen case is based on the advanced CO<sub>2</sub> compression concept [9], where shock-wave compression technology is applied. Also the base case [8] (current technology) is analyzed in order to compare the results of cumulative exergy consumption.

The analyzed cases include a supercritical pulverized coal OFC power plant (24.1 MPa/600 °C/620 °C) with a wet flue gas desulfurization (FGD) unit and a baghouse to remove particles. The pulverized coal (PC) boiler design is based on a bituminous coal fired unit, where the theoretical adiabatic flame temperature of the boiler is controlled by varying the amount of flue gases recycled to the boiler. The oxidant is supplied by conventional cryogenic air separation unit (ASU) technology that produces 95% pure oxygen. The recycled flue gases (wet recycling is realized) are superheated by 9 K (where the condensate from the steam cycle is used – low temperature (LT) process heat) before entering the primary and induced draft fans in order to ensure that the primary and secondary streams do not produce a condensate in the ducts or enter the fans in saturated conditions. In the analyzed case the CO<sub>2</sub> compression system utilizes advanced shock

wave compression technology with a higher stage of compression efficiency that in the base case, where compression is accomplished in eight stages of centrifugal compression with intercooling between each stage. When shock wave compression is realized, the interstage compression heat is recovered in the boiler feedwater system (medium temperature (MT) and high temperature (HT) process heat), which reduces the amount of steam extracted from the steam cycle and can increase the power output of the steam cycle. In a conventional system (basic case) the intercooling of each stage is realized by cooling water without useful heat recovery. The main reason for not recovering the heat in a conventional system is that the temperature is too low and the recovery of it is economically unprofitable [8]. In both cases the CO<sub>2</sub> product is compressed to 15.3 MPa and satisfies the requirements concerning the purity to be sequestered in a saline formation [8].

All the data concerning matrices of the balance of CExC are presented for the advanced CO<sub>2</sub> compression based on the process model presented in [8]. Figure 2 presents the block diagram of an oxy-fuel combustion power plant in which seven technological modules are shown corresponding to seven main products (Tab. 1).

Table 1. Technological modules and the corresponding main products.

No.	Module	Main product
1°	Boiler island	HP & IP process steam
2°	Steam cycle	Electricity
3°	Cooling water system	Cooling duty
4°	Flue gas quality control system	CO <sub>2</sub> -rich stream
5°	Water treatment system	Make-up water
6°	Air separation unit	Oxygen
7°	CO <sub>2</sub> processing unit	CO <sub>2</sub> product

Figure 2 illustrates the system of the main energy-material interconnections between the respective technological modules in the analyzed case. The steam boiler is fired with coal and an oxidizer which is a mixture of oxygen and recycled CO<sub>2</sub>-rich flue gases. The boiler is supplied with feeding water prepared in the steam cycle module. Other energy carriers are electricity and condensate process heat (LT process heat – up to 100 °C) used to preheat the recycled stream of CO<sub>2</sub>-rich flue gases. The main product of the boiler is high pressure (HP) and intermediate pressure (IP) process steam passed to the steam cycle module. By-products are flue gases containing mainly CO<sub>2</sub> (about 66%) and bottom ash. The main product of

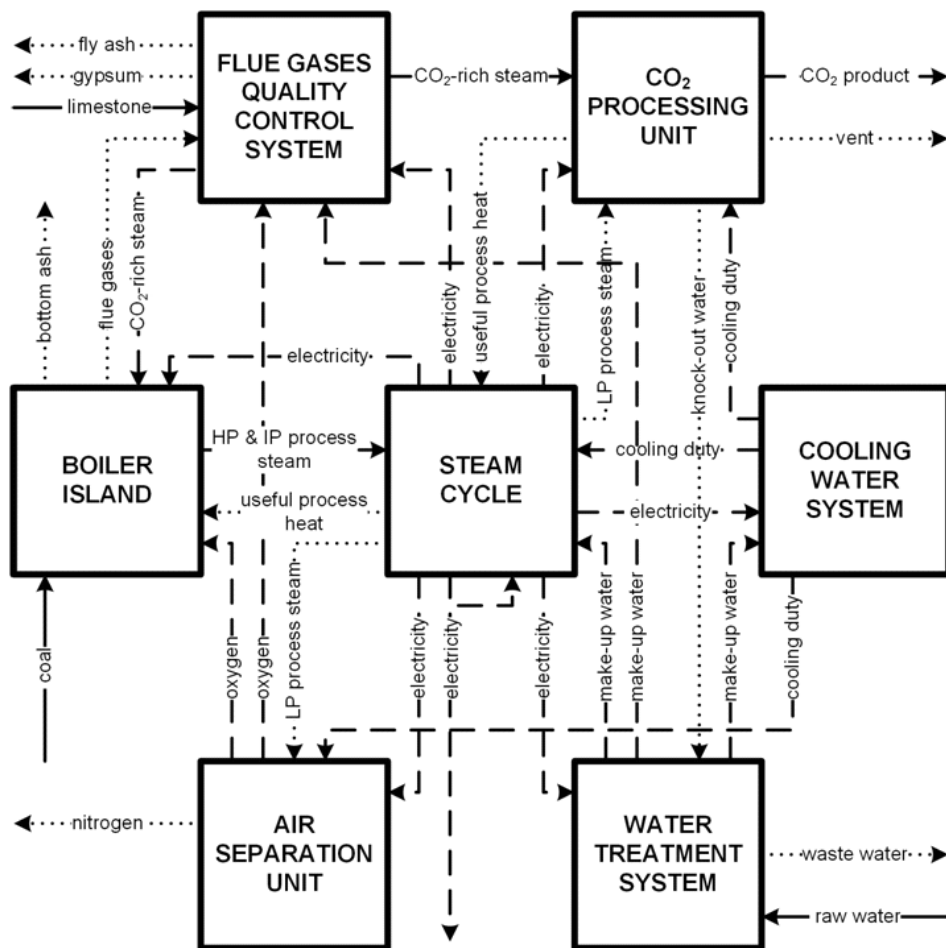


Figure 2. Block-diagram of an oxy-fuel combustion power plant (useful process heat consist of LT, MT and HT process heat).

the steam cycle module is electricity. The by-products are low pressure (LP) process steam and LT process heat. Besides the main driving steam (HP&IP process steam) the module is fed with interstage cooling heat from CO<sub>2</sub> processing unit (CPU) (MT process heat – up to 200 °C and HT process heat – up to 300 °C), as well as cooling duty and make-up water. The cooling water system is closely connected with the steam cycle module and also with ASU and CPU. The main product, cooling duty, is first of all applied in the steam condenser and the interstage cooling system of com-



pressors in ASU and CPU. In this module electricity and make-up water are consumed. The water treatment system is a module strictly connected with the steam cycle, cooling water system and flue gas quality control (FGQC) system, to which lead outputs from this module. The input part of this module comprises raw water, waste water and electricity. The module air separation unit is based on the cryogenic technology of separating oxygen from air. The fundamental part of input energy is electricity driving the air compressors. The ASU module is also fed with LP process steam from the steam cycle module and cooling duty from the cooling water system. The dominating consumer of oxygen is the boiler island. A small amount of oxygen is also consumed by the FGQC system. The aim of the FGQC module is the conditioning of flue gases from the boiler island. These flue gases comprise CO<sub>2</sub> (66%), H<sub>2</sub>O (20%), N<sub>2</sub>(8%), Ar (3%), O<sub>2</sub>(2%), SO<sub>2</sub> (0.3%) and fly ash. In this module the flue gases are dedusted in electrofilters and desulphurized. In result CO<sub>2</sub>-rich steam is obtained which is the input to the CO<sub>2</sub> processing unit and a large part is recycled to the boiler (about 70%). The module FGQC system is supplied with limestone, electricity, make-up water and oxygen. Besides the main product, CO<sub>2</sub>-rich stream, useful effects of FGQC module operation are by-products, namely gypsum and fly ash.

Table 2 contains a list of main products, by-products and external supplies not supplementing the main production. In considered example by-products and external supplies supplementing the main production do not exist. From among 13 by-products 9 are useful products and for the avoided cumulative exergy consumption have been estimated.

The energy carriers and materials numbered 1°–7° comprise the main production in the respective module (Tab. 1), number 8°–20° concern the by-production and number 21°–24° the external supplies.

Based on the ‘input-output’ table the matrices  $\mathbf{A}_G$ ,  $\mathbf{F}$ ,  $\mathbf{A}_F$  and  $\mathbf{A}_D$  have been segregated, concerning respectively:

- coefficients of the consumption of energy carriers and materials manufactured as main products,
- coefficients of the by-production of energy carriers and materials,
- coefficients of the consumption of energy carriers and materials manufactured as by-products,
- coefficients of the consumption of external supplies.

Table 2. List of energy carriers and materials.

No.	Energy carrier or material	Unit	No.	Energy carrier or material	Unit
Main products; $i = 1 \dots n$			By-products; $l = n + 1 \dots m$ (continuation)		
1°	HP&IP process steam	MJ	13°	Flue gases	Mg
2°	Electricity	MJ	14°	Bottom ash	Mg
3°	Cooling duty	MJ	15°	Fly ash	Mg
4°	CO <sub>2</sub> -rich stream	Mg	16°	Gypsum	Mg
5°	Make-up water	Mg	17°	Nitrogen	Mg
6°	Oxygen	Mg	18°	Vent	Mg
7°	CO <sub>2</sub> product	Mg	19°	Knock-up water	Mg
By-products; $l = n + 1 \dots m$			20°	Waste water	Mg
8° LP process steam MJ			External supplies; $p = m + 1 \dots s$		
9°	LT process heat	MJ	21°	Coal	MJ
10°	MT process heat	MJ	22°	Natural gas	MJ
11°	HT process heat	MJ	23°	Raw water	Mg
12°	Preheated air process heat	MJ	24°	Limestone	Mg

For the analysed case of an integrated oxy-fuel combustion power plant with advanced CO<sub>2</sub> compression matrix  $\mathbf{A}_G = [a_{ij}^G]$  takes the following form:

$$\mathbf{A}_G = \begin{bmatrix}
 & 1^\circ & 2^\circ & 3^\circ & 4^\circ & 5^\circ & 6^\circ & 7^\circ & \\
 1^\circ & 0 & 2.0256 & 0 & 0 & 0 & 0 & 0 & \\
 2^\circ & 0.004 & 0.0057 & 0.0129 & 20.097 & 3.3707 & 845.2 & 533.64 & \\
 3^\circ & 0 & 1.1596 & 0 & 0 & 0 & 806.46 & 187.73 & \\
 4^\circ & 0.0003 & 0 & 0 & 0 & 0 & 0 & 1.0767 & \\
 5^\circ & 0 & 7 \cdot 10^{-6} & 0.0005 & 0.0112 & 0 & 0 & 0 & \\
 6^\circ & 0.0001 & 0 & 0 & 0.0032 & 0 & 0 & 0 & \\
 7^\circ & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 
 \end{bmatrix} \quad (6)$$

As we see, in matrix of the main production interbranch the flows are to be found in the case of the first six energy carriers (or materials). Electricity is consumed in all the seven modules (branches). For instance, the coefficient  $a_{23}^G$  denotes the consumption of electricity for the production of cooling water (cooling duty) and the coefficient  $a_{32}^G$  the consumption of cooling water for the production of electricity. Both these elements, situated on either side of the main diagonal indicate a connection of feedback character. In other matrices nonzero elements have been presented in Tab. 3. The main production is accompanied by thirteen by-products, e.g., the coefficients  $f_{107}$  and  $f_{117}$  denote the amount of interstage cooling process heat which can be usefully used (respectively medium- and high-temperature process

Table 3. Nonzero elements of matrices  $\mathbf{F} = [f_{ij}]$ ,  $\mathbf{A}_F = [a_{ij}^F]$  and  $\mathbf{A}_D = [a_{ij}^D]$ .

Coefficient	Value	Unit	Coefficient	Value	Unit
matrix $\mathbf{F}$			matrix $\mathbf{A}_F$		
$f_{82}$	0.0068	MJ/MJ	$a_{86}^F$	37.005	MJ/Mg
$f_{92}$	0.0041	MJ/MJ	$a_{87}^F$	0.5491	MJ/Mg
$f_{107}$	514.44	MJ/Mg	$a_{91}^F$	0.0020	MJ/MJ
$f_{117}$	221.94	MJ/Mg	$a_{102}^F$	0.1169	MJ/MJ
$f_{131}$	0.0004	Mg/MJ	$a_{112}^F$	0.0504	MJ/MJ
$f_{141}$	$8.05 \cdot 10^{-7}$	Mg/MJ	$a_{134}^F$	1.0407	Mg/Mg
$f_{154}$	0.0083	Mg/Mg	$a_{195}^F$	0.0239	Mg/Mg
$f_{164}$	0.0167	Mg/Mg	matrix $\mathbf{A}_D$		
$f_{176}$	3.2496	Mg/Mg	$a_{211}^D$	1.0837	MJ/MJ
$f_{197}$	0.0767	Mg/Mg	$a_{235}^D$	1.0000	Mg/Mg
$f_{205}$	0.0239	Mg/Mg	$a_{244}^D$	0.0107	Mg/Mg

heat). This process heat is used in steam cycle (coefficients  $a_{102}^F$  and  $a_{112}^F$ ) to preheat the condensate and feedwater in the steam cycle, respectively low-pressure and high-pressure regenerative part. The analyzed system is fed by three external supplies. The supply of coal feeding the boiler is defined by the coefficient  $a_{211}^D$ . The preheated air process heat is not taken into account due to the lack of use in the analyzed cases. Also the supply of natural gas is equal to zero. Those energy carriers are taken into account when, for example, an integrated OFC power plant with membrane air separation unit is analyzed. Also the by-product vent is not taken into account, due to the fact, that there is not further gas separation of  $\text{CO}_2$ -rich stream in the CPU (only water separation and  $\text{CO}_2$  compression).

Equations (7)–(13) describe the balance equations of cumulative exergy consumption for all seven branches (Tab. 1), based on matrix equation, Eq. (2), for the analyzed integrated OFC power plant with advanced  $\text{CO}_2$  compression:

$$a_{21}^G b_2^* + a_{41}^G b_4^* + a_{61}^G b_6^* + a_{91}^F b_{F9}^* + a_{211}^D b_{DD21}^* = b_{G1}^* + f_{131} b_{F13}^* + f_{141} b_{F14}^*, \quad (7)$$

$$a_{12}^G b_1^* + a_{22}^G b_2^* + a_{32}^G b_3^* + a_{52}^G b_5^* + a_{102}^F b_{F10}^* + a_{112}^F b_{F11}^* = b_{G2}^* + f_{82} b_{F8}^* + f_{92} b_{F9}^*, \quad (8)$$

$$a_{23}^G b_2^* + a_{53}^G b_5^* = b_{G3}^*, \quad (9)$$

$$a_{24}^G b_2^* + a_{54}^G b_5^* + a_{64}^G b_6^* + a_{134}^F b_{F13}^* + a_{244}^D b_{DD24}^* = b_{G4}^* + f_{154} b_{F15}^* + f_{164} b_{F16}^*, \quad (10)$$

$$a_{25}^G b_2^* + a_{195}^F b_{F19}^* + a_{235}^D b_{DD23}^* = b_{G5}^* + f_{205} b_{F20}^*, \quad (11)$$

$$a_{26}^G b_2^* + a_{36}^G b_3^* + a_{86}^F b_{F8}^* = b_{G6}^* + f_{176} b_{F17}^*, \quad (12)$$

$$a_{27}^G b_2^* + a_{37}^G b_3^* + a_{47}^G b_4^* + a_{87}^F b_{F8}^* = b_{G7}^* + f_{107} b_{F10}^* + f_{117} b_{F11}^* + f_{197} b_{F19}^*. \quad (13)$$

In the example, Eq. (8) describes the balance equation of cumulative exergy consumption for the second branch (steam cycle), where  $a_{12}^G b_1^*$ ,  $a_{22}^G b_2^*$  and  $a_{32}^G b_3^*$  define the cumulative exergy consumption of the main products, HP&IP process steam, electricity and cooling duty, respectively. Also, the cumulative exergy consumption of by-production of interstage cooling heat ( $a_{102}^F b_{F10}^*$  and  $a_{112}^F b_{F11}^*$ ) is an input on this branch. The cumulative exergy consumption of electricity is the main product of the steam cycle ( $b_{G2}^*$ ); also the by-production of low-pressure process steam ( $f_{82} b_{F8}^*$ ) and low-temperature process heat ( $f_{92} b_{F9}^*$ ) are outputs of the second branch. The indices of cumulative exergy consumption of main products  $b_G^*$  are equal to the average-weighted indices of cumulative exergy consumption ( $b^*$ ) due to the lack of by-production or external supplies supplementing the main production in the considered cases.

Based on the ‘input-output’ model of the balance of direct energy consumption, the cumulative exergy consumption can be analyzed. In order to perform such an analysis the indices of cumulative exergy consumption of the external supply and the indices of cumulative exergy consumption of the by-products, both of which do not supplement the main production, have to be distinguished.

In the case of low-pressure process steam the index of cumulative exergy consumption is calculated from the equation:

$$b_i^* = e_i^* \frac{T_s - T_a}{T_s}, \quad (14)$$

where  $e_i^*$  is the index of cumulative energy consumption charging the process steam,  $T_s$  is the saturation temperature of process steam and  $T_a$  is ambient temperature.

The indices of cumulative exergy consumption of process heat (e.g., condensate process heat and interstage cooling heat) are calculated from the following equation:

$$b_i^* = e_i^* \frac{T_m - T_a}{T_m}, \quad (15)$$

where  $e_i^*$  denotes the index of cumulative energy consumption charging the process heat and  $T_m$  is the average thermodynamic temperature of preheated water defined as follows:

$$T_m = \frac{T_{pr} - T_{in}}{\ln \frac{T_{pr}}{T_{in}}}, \quad (16)$$

where  $T_{pr}$  and  $T_{in}$  denotes the temperature of preheated and inlet water.

It was assumed that the index of cumulative exergy consumption charging gypsum (and limestone) results from the consumption of electricity or mechanical work. Therefore the index of cumulative exergy consumption of gypsum is calculated from the formula

$$b_{gypsum}^* = b_{n\ gypsum} + e_{gypsum}^*, \quad (17)$$

where:

$b_{n\ gypsum} = 150$  MJ/Mg – standard chemical exergy of gypsum ( $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ ); the chemical standard enthalpy of gypsum (enthalpy of devaluation) is equal zero ( $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$  is the reference substance) [4],

$e_{gypsum}^* = 510$  MJ/Mg – index of cumulative exergy consumption for the production of gypsum [10].

In the case of other useful products of coal combustion the analysis of cumulative exergy consumption was performed with the certain assumptions concerning the substitution of other products [6,11,12]:

- bottom ash – aggregate (60% of use, rest is solid waste),
- fly ash – cement, aggregate, sand and gypsum (15% of use each, rest is solid waste).

Based on the literature review [11,12] the average share of use of those by-products has been estimated on the level of 60%. In the case of indices of the cumulative exergy consumption fly ash, bottom ash, aggregate, cement and sand were estimated based on literature [3,4,6,10] or from the equation similar to (17). In the case of flue gases ( $b_{F13}^*$ ), due to the further use of them in the FGQC system and CPU, the cumulative exergy consumption was calculated based on the products which can be obtained through the whole treatment process in an integrated OFC power plant (e.g.,  $\text{SO}_2$  in flue gases as one of the substrates of the process of gypsum production in

the wet flue gas desulfurization unit).

It was assumed that in the case of raw water the cumulative exergy consumption is equal to the cumulative energy consumption [13] due to the main share of electricity charging the raw water production. For the cumulative exergy consumption of fuels (coal, natural gas) the indices of cumulative exergy consumption were used based on [3,4] and brought to the appropriate unit. All the indices are expressed in the MJ unit of exergy per unit of energy carrier or material (Tab. 3).

Based on the literature review and calculations the presented vectors of indices of cumulative exergy consumption have been distinguished:

- vector of indices of cumulative exergy consumption of by-production not supplementing the main production:

$$\mathbf{b}_F^* = \begin{bmatrix} 0.415 & \text{MJ}_{\text{Ex}}/\text{MJ} & 8^\circ \\ 0.18 & \text{MJ}_{\text{Ex}}/\text{MJ} & 9^\circ \\ 0.257 & \text{MJ}_{\text{Ex}}/\text{MJ} & 10^\circ \\ 0.486 & \text{MJ}_{\text{Ex}}/\text{MJ} & 11^\circ \\ 0 & \text{MJ}_{\text{Ex}}/\text{MJ} & 12^\circ \\ 485.6 & \text{MJ}_{\text{Ex}}/\text{Mg} & 13^\circ \\ 176.8 & \text{MJ}_{\text{Ex}}/\text{Mg} & 14^\circ \\ 1484 & \text{MJ}_{\text{Ex}}/\text{Mg} & 15^\circ \\ 660 & \text{MJ}_{\text{Ex}}/\text{Mg} & 16^\circ \\ 0 & \text{MJ}_{\text{Ex}}/\text{Mg} & 17^\circ \\ 0 & \text{MJ}_{\text{Ex}}/\text{Mg} & 18^\circ \\ 0 & \text{MJ}_{\text{Ex}}/\text{Mg} & 19^\circ \\ 0 & \text{MJ}_{\text{Ex}}/\text{Mg} & 20^\circ \end{bmatrix},$$

- vector of indices of cumulative exergy consumption of external supply not supplementing the main production:

$$\mathbf{b}_{\text{DD}}^* = \begin{bmatrix} 1.17 & \text{MJ}_{\text{Ex}}/\text{MJ} & 21^\circ \\ 1.137 & \text{MJ}_{\text{Ex}}/\text{MJ} & 22^\circ \\ 31.22 & \text{MJ}_{\text{Ex}}/\text{Mg} & 23^\circ \\ 446 & \text{MJ}_{\text{Ex}}/\text{Mg} & 24^\circ \end{bmatrix}.$$

As we can see in the presented vector for by-production, not all energy carriers (or materials) have different values than 0. This means that only those energy carriers (or materials) are useful by-products, which can replace other energy carriers or materials in the analyzed case (avoided outlay

of energy in replaced processes). Also, the same approach as in case of coefficients of by-production, if each energy carrier (or material) is not used in the analyzed case (e.g., preheated air process heat  $b_{F12}^*$ ), will have values equal 0.

In result of the ‘input-output’ analysis based on the model of the balance of cumulative exergy consumption we get the vector of the indices of cumulative exergy consumption of the main products of an integrated OFC power plant (with advanced CO<sub>2</sub> compression):

$$\mathbf{b}_G^* = \begin{bmatrix} 1.473 & \text{MJ}_{Ex}/\text{MJ} & 1^\circ \\ 3.125 & \text{MJ}_{Ex}/\text{MJ} & 2^\circ \\ 0.062 & \text{MJ}_{Ex}/\text{MJ} & 3^\circ \\ 558.8 & \text{MJ}_{Ex}/\text{Mg} & 4^\circ \\ 41.75 & \text{MJ}_{Ex}/\text{Mg} & 5^\circ \\ 2707 & \text{MJ}_{Ex}/\text{Mg} & 6^\circ \\ 2041 & \text{MJ}_{Ex}/\text{Mg} & 7^\circ \end{bmatrix} .$$

In the analyzed integrated OFC power plant there are two main products characterized by the final production — electricity and CO<sub>2</sub> product. Those indices of cumulative exergy consumption correspond to the exergy required for the production, for example  $b_2^*$  expresses the cumulative exergy consumption charging the electricity production in an integrated OFC power plant.

In this paper, the basic and advanced CO<sub>2</sub> compression cases have been compared [8,9]. The results are presented in Tab. 4, where the relative change calculated in relation to the base case value of each index concerning the main product of cumulative exergy consumption is shown when advanced CO<sub>2</sub> compression is implemented.

Table 4. Comparison of cumulative exergy consumption for analysed cases.

No.	Main product	Unit	Base case	Advance CO <sub>2</sub> compression	Relative change, %
1°	HP&IP process steam	MJ <sub>Ex</sub> /MJ	1.525	1.473	-3.4
2°	Electricity	MJ <sub>Ex</sub> /MJ	3.314	3.125	-5.7
3°	Cooling duty	MJ <sub>Ex</sub> /MJ	0.065	0.062	-4.6
4°	CO <sub>2</sub> -rich stream	MJ <sub>Ex</sub> /Mg	525.7	558.8	6.3
5°	Make-up water	MJ <sub>Ex</sub> /Mg	42.1	41.75	-0.8
6°	Oxygen	MJ <sub>Ex</sub> /Mg	2869	2707	-5.6
7°	CO <sub>2</sub> product	MJ <sub>Ex</sub> /Mg	1915	2041	6.6

Figure 3 illustrates the change of the direct and cumulative net energy lower heating value (LHV) [6] and exergy efficiencies of the OFC power plants in both analyzed cases.

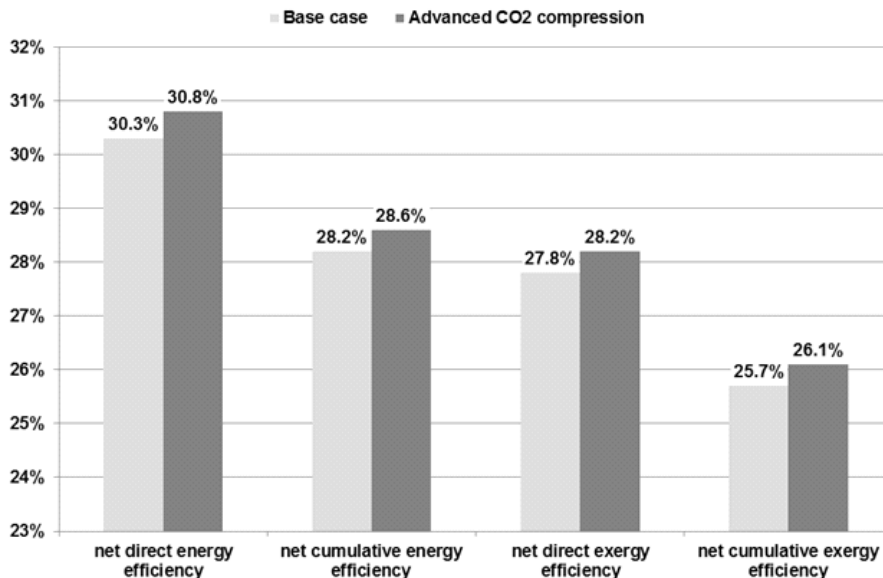


Figure 3. Direct and cumulative net energy and exergy efficiencies.

The obtained results confirm the correctness of the suggested ‘input-output’ models of the balance of the cumulative exergy consumption. The decrease of the net efficiencies of the OFC power plant results both from the direct process change, i.e., the change of the coefficient of electricity consumption per unit of the CO<sub>2</sub> product, and from all the changes due to indirect interconnections existing in an integrated OFC power plant. Similarly as in [6] a sensitivity analysis have been performed for the cumulative exergy carriers of by-products that can be used basing on the principle of the avoided outlay of energy in replaced processes. When the indices of cumulative exergy consumption of fly ash and bottom ash are equal to zero (there is no substitution of other materials) the index of the cumulative exergy consumption for electricity production is equal to 3.136 MJ<sub>Ex</sub>/MJ (in the case with advance CO<sub>2</sub> compression), which may reflect the small influence of useful development of those by-products for the indices of CExC of main product of an integrated oxy-fuel combustion power plant.



## 4 Conclusions

The obtained index of cumulative exergy consumption charging the production of electricity in an integrated oxy-fuel combustion power plant is lower than it has been assumed so far ( $3.74 \text{ MJ}_{Ex}/\text{MJ}$ ) [3]. This results, first of all, from the fact that up till now subcritical systems have been analyzed. Secondly also the application of solid waste products has been taken into account, although to a lesser degree, leading to a decrease of cumulative exergy consumption charging electricity.

In the case of oxygen the calculated index of cumulative exergy consumption is 2.7 times lower than presented in literature [3] because data quoted in literature are based on the ASU technology from more than 20 years ago. In the mean time the ASU technology has considerably advanced [9].

If the solid waste products (fly ash and bottom ash) are not utilised, the index of cumulative exergy consumption charging the production of electricity grows only slightly, amounting to  $3.136 \text{ MJ}_{Ex}/\text{MJ}$ , which proves that its influence is rather small. A similar result has been obtained in the case of cumulative energy consumption [6].

The algorithm presented in the paper is one of the components of the authors programme concerning system analysis of integrated oxy-fuel power plants OSA (oxy system analysis). The complete programme will comprise system analysis of direct and cumulative energy and exergy consumption as well as life cycle analysis applying thermoecological costs.

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