Thermodynamic assessment of an integrated mild oxyfuel combustion power plant

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Abstract

The paper presents the advantages of a new boiler solution for the supercritical power plant with CO_2 capture. The mild oxyfuel combustion (MOFC) combines the advantages of mild (moderate and intensive low-oxygen dilution) combustion and oxyfuel combustion for the purpose of an effective CO_2 capture from fossil fuel based power generation. MOFC application could increase the efficiency of the boiler, increase the purity of the CO_2 in flue gases and reduce energy consumption for the recirculation of CO_2. It affects the overall net energy efficiency penalty associated with the CO_2 capture in comparison to the oxyfuel combustion technology. Thermodynamic analysis of an integrated MOFC power plant with CO_2 capture are presented. The data concerning the new design of the boiler are obtained from CFD modelling. Two case studies are performed, and in each of them three configurations of supercritical power plant are modelled. First two are the reference power plants, including the conventional power plant without CO_2 capture and oxyfuel combustion power plant with CO_2 capture. The third case is the MOFC boiler application within the same power plant. The thermodynamic parameters are compared, and detailed study of energy efficiency penalty is presented. Based on the presented results it can be noticed that the application of the MOFC technology allows to increase the overall net energy

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efficiency by about 2 percentage points. Additionally the usefulness of the proposed system approach (based on input-output analysis) for the energy analysis of complex energy systems have been proven.

Keywords:

Mild oxyfuel combustion, Mild combustion, Oxyfuel combustion, CO_2 capture, Thermodynamic analysis.

Nomenclature

Main symbols

A – matrix of the coefficients of the consumption of energy carriers and materials

a_{ij} – coefficient of consumption of energy carriers and materials

D – vector of external supplies

D – external supply

F – matrix of the coefficients of the by-production

f_{ij} – coefficient of by-production of energy carriers or materials

G – column vector of the main production

G – main production

I – unit matrix

K – column vector of the final production

K – final production

Subscripts and superscripts

ch – chemical

D – external supply not supplementing the main production

DG – external supply supplementing the main production

el – electricity

F – by-product

FG – by-product supplementing the main production

G – main product

Abbreviations

ASU – Air Separation Unit

CCS – Carbon Capture and Storage

CFD – Computational Fluid Dynamics

CPU – CO_2 Processing Unit

FGQC – Flue Gas Quality Control

HHV – Higher Heating Value

LHV – Lower Heating Value

MILD – Moderate and Intensive Low-oxygen Dilution

MOFC – Mild OxyFuel Combustion

OFC – Oxy-Fuel Combustion

OSA – Oxy System Analysis

p.p. – percentage point

REF – Reference

TRL – Technology Readiness Level

1. Introduction

In recent years interest has grown in the carbon capture and storage technologies (CCS) as the possible technology to mitigate the CO_2 emissions from both power sector and other industry branches. Generally three types of CCS technologies can be distinguished, viz. post-combustion, pre-combustion and oxy-fuel combustion (Fig. 1), which were briefly compared within Table 1.

The presented paper focus on the mild oxyfuel combustion (MOFC) technology, which is a next step within clean coal technologies, that combines the advantages of MILD (moderate and intensive low-oxygen dilution) combustion and oxyfuel combustion for the purpose of an effective CO_2 capture from fossil fuel based power generation. The CO_2 transport and storage (or utilization) are important and indispensable components of CCS, thus within this article the impact of the CO_2 transport and storage on the energy efficiency of the whole CCS chain is also discussed.

The oxyfuel capture technology is based on usage of high-purity oxygen in the combustion process instead of atmospheric air. Therefore flue gases have a high concentration of CO_2 (without nitrogen dilution), which allows to evade chemical post-combustion processes. Due to the limited adiabatic temperature of combustion part of CO_2 must be recycled to the boiler in order to maintain a proper flame temperature. Power plants constructed in this technology must comprise two main additional parts - the air separation unit (ASU) and the carbon dioxide processing unit (CPU), which latter can be divided into CO_2 purification and CO_2 compression units. Oxyfuel combustion is also taken into consideration in already existing retrofitting power plants, by adding ASU and CPU and adequate upgrading in the boiler island. Due to the higher cost of producing electricity, caused by implementing the CCS technology, process integration must be taken into consideration in order to lower the cost of carbon dioxide capture. One of the main ways of integration is the utilization of heat from compressor cooling systems concerning ASU and CPU with the steam cycle. The air separation unit and CO_2 purification unit are usually based on the cryogenic distillation system, because this technology is on the proper level of development to ensure the required performance of large-scale oxy-fired power plants with carbon dioxide capture. The utilization of nitrogen (e.g. drying of fuel) and application of the central water cooling system in individual cooling systems of the compressors are further examples of an integrated project.

Major challenges for current state-of-the-art oxyfuel combustion power plants are low-cost oxygen supply, developing high-temperature materials in new constructions and conversion schemes for existing air-fired power plants. Also preventing air infiltration is essential for both new and retrofitted power plants. Most of the worlds R&D project focus around new technologies for oxygen production, like e.g. membrane air separation units that can be integrated with boilers, for energy and cost effective oxygen supply. But within the oxyfuel combustion technology, there are other processes that are responsible for the net energy penalty associated with CO_2 capture and compression. Nowadays the drop of the net energy efficiency is predicted to be around 8 percentage points compared to the reference air-fired supercritical power plants.

Fig. 2 presents, the estimated within an interdisciplinary MIT study [5], parasitic energy requirements for oxyfuel pulverized coal generation with CO_2 capture. Both, air-fired and oxyfuel combustion power plants, have supercritical steam cycle. The 3 percentage point efficiency increase, for oxyfuel combustion compared to the air-fired power plant, is due to the improved boiler efficiency and reduced energy consumption for flue gas desulphurization. As mentioned already, the most significant net energy efficiency penalty is associated with the oxygen production. Within the other sources of energy efficiency drop, we may identify mainly the electricity consumption associated with the recycle of CO_2 to the boiler.

Mild oxyfuel combustion application could increase further the efficiency of the boiler, increase the purity of the CO_2 in flue gases and reduce energy consumption for the recirculation of CO_2. It affects the overall net energy efficiency penalty associated with the CO_2 capture in comparison to the oxyfuel combustion technology. Mild oxyfuel combustion boiler design gives also an opportunity to include the membrane air separation units with heat integration on required high temperature levels. Thus, within this paper, the preliminary thermodynamic analysis of an integrated MOFC power plant with CO_2 capture is presented, in order to investigate the potential of this technology. The successful implementation of CCS, and thus MOFC technology, will depend on economical factors, mostly the cost of electricity. Although post-combustion technology, based on chemical absorption by means of amine solutions, is now the only mature technology of CO_2 capture [2], nevertheless it has been considered that other CCS technologies are still considered, and some of them (as oxyfuel combustion) are even more promising [5].

2. Development pathway of mild oxyfuel combustion

Within this section the technology development pathway have been presented, from the point of view of the replacement of air with oxygen in the combustion process. Several concepts are briefly presented and discussed, pointing out the relevance to the development of the mild oxyfuel combustion technology.

2.1. Mixed air and oxygen combustion

Within the oxyfuel combustion several technological options and configurations were investigated in the literature. Most of them assumed elimination of the air in the combustion process in order to eliminate the dilution of the flue gases, so that the high concentration of CO_2 can be obtain (e.g. after just dehydration). Within [6] authors proposed a novel approach, in which the air can be used to carry the coal from the mills to the boiler (as in air-fired power plants), while oxygen is added to the secondary recycle flow and directly to the combustion zone. The presented concept, referred as CO2RE, could practically eliminate the problem with the primary recycle and air leakage into the CO_2 processing system.

Three configurations of the CO2RE technology were investigated within the paper [6], besides the conventional air-fired coal power plant. They differ with the amount of oxygen that is provided to the boiler. In first the air is used in the primary flow to the mills and whole secondary flow is composed of oxygen and recycled carbon dioxide. Second proposed the use of air also within the secondary flow, where the third assumes the use of the O_2/CO_2 mixture in the primary flow as well. Within the paper also two different purities of oxygen are analysed (viz. 95 vol.% and 99 vol.%). All those configurations result with different compositions of feedgas to the CO_2 processing unit, in which the CO_2 concentration vary from about 30 vol.% to almost 88 vol.%.

Within the results of this study [6] authors present several dependents of the air addition and energy consumption of air separation unit and CO_2 processing unit, as well the air separation plant size (which affects the investment cost of the system) and mentioned CO_2 concentration in the processed feedgas. Final results shows that the relatively small net power drop can be obtained for the third case (37 vol.% air addition), which authors find worthwhile to consider when the large-scale deployment of new power plants is taken into account in the future. Authors suggest also that their study provides an evidence to rethink the design of oxyfuel plants by adopting CO2RE concepts. However, the optimum choice for the CO2RE technology will depend on the overall cost analysis of the whole plant.

2.2. Oxyfuel combustion

Oxyfuel combustion technology has a long tradition with R&D projects, where the first concept (in context of providing a CO_2-rich stream for enhanced oil recovery) was proposed in the 80s [7]. This technology is based on the use of oxygen diluted with an recycle flue gases (mainly CO_2) rather then air. Thus a high concentration of CO_2 in the flue gases (next to the H_2O) can be obtained. The oxyfuel combustion technology may be combined with both sub-critical and super-critical (also ultra-super-critical) steam cycles. It is to be supposed, that in future advanced super-critical boilers will be applied in oxyfuel-based power plants. Both sub-critical and super-critical cycles with oxy-fired boilers and their influence on the performance and achieved thermo-economical indices have been dealt with in [8], respectively. Results of the analysis published in [8] showed a drop of the overall plant efficiency (LHV) of the sub-critical cycle from 38.14% (air-fired) to 30.45% (oxy-fired), and the super-critical cycle from 43.16% (air-fired) to 35.30% (oxy-fired). In both cases we have to do with efficiency losses due to CO_2 capture of somewhat less than 8 percentage points. The way aiming at a reduction of this efficiency drop is process integration.

Due to the necessity of using almost pure oxygen (usually around 95 vol.%) an air separation plant is needed as a part of the oxyfuel combustion power plant. The cryogenic air separation unit is presently only a market-mature technology for large-scale systems producing oxygen. It is a well-developed, most efficient and cost-effective technology, although there are still many possibilities to improve this process, mainly by process integration [8]. Although, due to productivity limitations of about 4,500 Mg O_2/day (up to 7,000 Mg O_2/day) it will be necessary to build parallel operating air separation units to cover the oxygen demands of oxy-fired power plants. It is estimated that a 500 MW_{el} power plant will need between 9,000 and 10,000 tons of oxygen per day, using two (or even three) parallel operating units. In most studies the purity level has been assumed as 95% [8,9], because at a higher oxygen purity the specific energy of separation grows rapidly after passing the aforesaid purity level. Higher values are not considered at present. The main producers of ASU for oxyfuel systems estimate the specific energy for separation of oxygen from air in the range of 200 down to 160 kWh/Mg O_2, but some of the studies suggest higher values around 220 kWh/Mg O_2. It is assumed that CO_2 will be transported to a storage reservoir by pipelines. Therefore it must be conditioned according to certain specifications (including the concentration of impurities and pressure). The suggested typical conditions and the purity of CO_2 at the delivery point are connected with the planned way of storing (or use, like enhanced oil recovery). The role of the CO_2 processing unit is to capture CO_2 from flue gases and to purify them in order to satisfy the mentioned specifications. The flue gas composition strongly depends on the oxygen purity and the amount of air infiltration in the process [1]. Carbon dioxide and vapour water are the main components of flue gases from the boiler, prior the capture plant, where the CO_2 concentration is around 80 up to 95 vol.% (dry basis) [1]. In the case of retrofit plants, due to higher air infiltrations, the shares can be much lower [10]. This specific energy for separation of CO_2 from the flue gases strongly depends on many factors, as the CO_2 share in flue gases, product pressure (usually around 15 MPa) and the type of the CO_2 purification unit. The net specific energy consumption of CO_2 processing unit is usually around 140 kWh/Mg captured CO_2 down to about 110 kWh/Mg captured CO_2. It is obvious, that with the drop of CO_2 product pressure results in a drop of the net specific energy consumption [10]. This indicates the importance of matching properly the CO_2 product conditions (concentration and pressure) for each site, keeping in mind the significant impact of the air infiltration, which lowers the CO_2 content in input flue gases.

Due to the high energy demands (mainly electrical within the air and carbon dioxide compressors), it is crucial to use every possible way to reduce internal energy demands of the power unit. Although new technologies with lower energy demands for oxygen production and CO_2 purification and compression are being developed, at the actual state of the technology the most effective way to improve the net efficiency is heat and process integration. In the case of heat integration for air separation and CO_2 compression units two main benefits can be achieved, viz. energy losses associated with compression and boiler feed water preheating can be reduced. Direct transfer of waste heat from the interstage cooling of the compressors is based on feed water preheating. Other options are indirect and can be achieved by oxygen preheating, coal drying or heating of any fluid of the cycle [11,12]. Most analysed oxyfuel combustion systems aim to find methods of heat integration in order to improve the overall net energy efficiency by integrating interstage cooling systems of the compressors with the steam-water cycle [13,14]. Within Table 2 the impact of the heat integration (based on [13,14]) have been presented. The heat integration, when the cryogenic air separation unit is considered, is responsible for about 0.5 percentage point increase in the net efficiency. In the case of membrane air separation unit, due to the additional possibility of heat integration of hot vent stream from the air separation with the steam cycle, the increase of the net energy efficiency is 4.4 percentage points.

In recent years many analyses have been performed concerning OFC power plants as a potential way in CCS technologies. The analysis performed, within last couple of years, by the National Energy Technology Laboratory (USA) focuses on the cost and performance concerning oxyfuel combustion power plants [15,16,17,18]. A techno-economical analysis of several different cases has been performed, including: biomass, lignite and hard coal use, conventional and advanced air separation units (with different O_2 purities), advanced CO_2 compression units (e.g. based on shock wave compression) and steam parameters (super-critical and ultra-super-critical). On the average, in all cases with CO_2 capture, the efficiency drop amounted to around 7 up to above 12 percentage points on a relative basis as compared to their reference cases (super-critical steam cycle without CO_2 capture). The target for CCS technologies the maximum increase in legalized cost of electricity has been assumed on the level of 35%, but none of these cases has reached that objective. The results of those studies, for the chosen configurations, have been presented in Table 3.

Basing on analyses of the National Energy Technology Laboratory, which assume for the oxyfuel combustion technology in new, as well as retrofitted power plants the achievement of 90% CO_2 capture at a less than 35% increase of cost of electricity and will be available for commercial application by the year 2020. The Department of Energy (USA) and National Energy Technology Laboratory are running several programs related to the oxyfuel combustion process, mainly connected with boiler development, oxygen supply and CO_2 compression. There are also several programs devoted to Chemical Looping Combustion, as a promising technology for CO_2 capture and storage [19].

2.3. Pressurized oxyfuel combustion

Another approach tries to gain energy savings by using pressured oxy-fuel combustion. It provides a chance to take advantage of the higher pressure of oxygen and nitrogen (heated up and directed to the expansion turbine, thus additional energy production is obtained), and the lower energy demand for CO_2 compression due to higher input pressure of the flue gases transported to CO_2 processing unit. It also allows to eliminate (or at least to reduce) the negative influence of air infiltration [20]. The pressurized oxyfuel combustion power cycle has been analysed in several studies. General conclusions in [21] show that according to several assumptions the pressurized oxyfuel combustion power plant reaches a higher net efficiency than the atmospheric one, viz. 34.9% and 31.5%, respectively. Besides the mentioned advantages of the pressurized oxyfuel combustion, also the increase of the boiler can be obtain due to the possible water condensation [22,23]. Within the Table 4, the results of studies conducted in [22,23] have been presented, concerning the impact of pressure within the boiler on its energy efficiency.

Further studies of an pressurized oxyfuel combustion power plant have been carried out. The results of those studies, presented in [24], refers to the pressure in the cycle, based on which we can conclude that the optimal pressure in the cycle is around 10 MPa [24]. Thus the advantages of the pressurized over atmospheric oxyfuel combustion can be summarized in the following points:

- the heat integration with the cycle allows to obtain a 2 percentage point increase in the gross energy efficiency, which correspond to a 3.4 percentage point increase in the net energy efficiency of the power plant,
- air separation unit, due to the higher oxygen pressure, consumes about 20% more electricity,
- CO_2 processing unit has lower energy consumption, due to the smaller quantities of the flue gases reaching it (possibility of water condensation in the heat integration unit),
- the energy consumption for the CO_2 recirculation is lower due to the lower compression ratios.

2.4. Moderate and intensive low-oxygen dilution combustion

Mild and intensive low-oxygen dilution (MILD) combustion, also called high temperature air combustion, excess enthalpy combustion or flameless oxidation, plays an important role in the mitigation of combustion based pollutants and greenhouse gases while maintaining the high energy efficiency regime of the boiler. The most characteristic feature of the MILD combustion technology is an intense recirculation of combustion products within the chamber, thus the temperature peaks are suppressed and both the temperature and the species concentrations fields are homogeneous. This result in low NOx and CO emissions and highly uniform heat fluxes within the boiler. So far, the MILD combustion technology have found its application in industrial furnaces, based on the combustion of gaseous fuels or light oils. Within last years, the attempts are made to introduce this technology into power plants pulverized boilers, as following advantages are foreseen [25]:

- reduction of the size of the boiler due to the increase of radiative heat fluxes,
- possibility of increase of the steam parameters, as high quality steel might be used (more compact and smaller boilers means less materials),
- stable combustion allows to use low rank coals,

- low excess air and low NO_x emissions.

Typically conventional air-fired boilers are composed of the radiative and convective section. Flue gases waste heat is recovered by air preheater and the economizer. In MILD combustion, the adiabatic flame temperature is much higher than that of a conventional boiler and the heat transfer inside the boiler is dominated by radiation. Thus, it is predicted that the design of a boiler without the convective section is possible with maintaining the same thermal output. The removal of the convective heat transfer region will lead to a significant reduction of boiler size and cost [25]. One of the main problems associated with the MILD combustion application to the power plant boilers is the need of providing high preheating of combustion air which is technically not easy. It is usually realised by regenerative heat exchangers. Within last years some new requirements for establishing the MILD combustion have been presented, which are less strict that expected previously [26]. Its expected that MILD combustion without preheating will have boarder range of use that now, also in the power plants pulverized boilers.

Two mechanisms for the MILD combustion to achieve increased thermal efficiency have been identified [26]:

- “when MILD combustion occurs, the furnace temperature is more uniform, which reduces irreversible loss of the combustion and heat transfer,
- although the peak temperature of MILD combustion is lower than that of conventional combustion, the former uses a smaller furnace to achieve a higher average furnace temperature, which increases the average heat transfer, especially the irradiative heat transfer”.

Therefore, as suggested by the Authors of [26], the thermal efficiency of MILD combustion is higher than that for conventional combustion notwithstanding considering the reversible thermal efficiency or heat transfer.

Most of the R&D projects concerning MILD combustion focus on the design of the boiler itself. Usually the CFD modelling is used (e.g. [25]). There have been also experiments conducted with the use of fossil fuels, which gave a very promising results (in terms of combustion stability and NOx concentrations in flue gases) [27]. In summary, the analysed papers confirms that MILD combustion technology could be an efficient and clean technology for fossil fuel fired boilers.

2.5. Mild oxyfuel combustion

Some drawback within the oxyfuel combustion process have be overcome, before the application of the technology can be made, which can be gathered in the following points [28]:

- an oxyfuel flame is less stable compared to the conventional air flame,
- NOx concentrations in flue gases can be on a high level, mainly due to the air infiltration and accumulation of nitrogen oxides due to the recirculation of flue gases,
- recirculation decrease the overall energy efficiency of the power plant.

As presented in Section 2.4, the MILD combustion technology could address some of those issues and improve the flame stability, as well as reduce the NOx formation due to the oxygen dilution and low temperature increment. The overall efficiency could also be increase by utilizing the hot recycled flue gases. As within the MILD combustion technology, most of the studies focus around the boiler design, including the CFD modelling. Nevertheless, the experiments with MOFC of pulverized coal have been conducted (0.4 MW pilot-scale facility), which were successful even without highly preheated oxidant [29]. Those research proved also, that with the in-furnace limestone injection, the costly desulphurization process can be neglected [26]. Those research indicates the feasibility of application of the MOFC technology in industrial application.

In summary the MOFC technology combines the advantages of the presented technologies, or is following the same pathway (is similar) for the reduction of the energy penalty associated with the carbon capture process, which was presented in Table 5. As the MOFC technology seeks it way to the application within the power plants boilers, it seems justified to investigate the potential overall efficiency improvements resulting from the introduction of this technology. The preliminary thermodynamic assessment of an integrated mild oxyfuel combustion power plant is the main goal of the paper.

3. Thermodynamic assessment of an integrated mild oxyfuel combustion power plant

Within the preliminary thermodynamic assessment of an integrated mild oxyfuel combustion power plant the system approach to the energy analysis of complex energy system (to which MOFC power plant belongs) have be used. The data concerning the new design of the boiler are obtained from first approach to the CFD modelling made within the Polish-Norwegian Research Programme in the frame of “Mild Oxy Combustion for Climate and Air” Project [30]. The scope of the project is a new combustion technology which links advantages of oxyfuel combustion and mild combustion and which might be used for CO_2 capture in a solid fuels combustion units.

Within the example two case studies with three configurations of supercritical power plant each are analysed. First two are the reference power plants, including the conventional power plant without CO_2 capture and oxyfuel combustion power plant with CO_2 capture. The third case is the MOFC boiler application within the same power plant.

3.1. System approach to the energy analysis of an integrated MOFC power plant

A power plant operating in compliance with the MOFC technology consists of such modules as a boiler island, steam cycle, cooling water system, water treatment module, air separation unit, flue gas quality control system and CO_2 purification and compression unit (within the whole CCS cycle also the CO_2 transport and storage system have to be included). The necessity of system approach to the energy analysis results mainly from the interdependence of technological modules, some part of which is of feedback character. Thus, the integrated MOFC power unit is a system consisting of energy branches (technological modules) connected with each other by interbranch relations.

Within the paper an complex approach of modelling the energy and material balance of an integrated power unit is briefly presented. It includes mathematical models of the "input-output" type evaluating the calculations of direct energy consumption. The algorithm presented in the paper is the component of the programme concerning system analysis of integrated oxyfuel power plants "OSA" (Oxy System Analysis). The presented programme has been developed as part of the Polish National Strategic Project co-realized by the corresponding author, called “Advanced Technologies for Energy Generation. Project no. 2: Oxy-combustion technology for PC and FBC boilers with CO_2 capture”. The main aim of the programme is to provide a tool for potential investors and analysts interested in oxyfuel technology, which allows to perform the analysis of direct and cumulative energy consumption, as well as cumulative exergy consumption, system exergy losses, thermoecological cost and life cycle assessment [31].

The presented approach have several advantages over the traditional approach to the process modelling of complex energy systems by mean of commercial software’s. First of all it is much less time consuming, as there is no need to build whole detailed process model in order to evaluate the thermodynamic performance. It also allows to combine the different process models developed in different software’s, which gives the opportunity to use most suitable one for each technological module (e.g. more detailed models of air separation unit in Thermoflex then Ebsilon Professional). The main disadvantage of the proposed approach is that it might lead to slightly under or overestimated results, as it’s based on the coefficients, but based on the Authors experience in construction of the input-output mathematical models this is being minimalized. In general the presented system approach to the energy analysis of complex energy system is suitable for the preliminary thermodynamic assessments of new concept of the power plants, which was presented in this paper.

Fig. 3 presents a simplified scheme of an oxyfuel power plant, for which the OSA programme was design. Seven main technological modules have been distinguished, which are also identified for the MOFC power plant. Within this paper the CO_2 transport and storage module will be taken into account in the additional example, as the main aim of this paper is to investigate the possibility of the reduction of energy penalty associated with CO_2 capture process itself. Three groups of energy carriers and materials are distinguished, viz. main production, by-production and external supplies. The main products corresponding to technological modules are presented in Fig. 3. Besides them 18 by-products (e.g. process heat, flue gases, make-up water, bottom and fly ash, nitrogen) and 7 external supplies (e.g. coal, raw water, limestone) are considered. The system approach bases on the “input-output approach” which is represented by the “input-output table” (Table 6) [32].

The mathematical model of direct energy (and material) consumption comprised of three matrix equations, referring to the three distinguished groups of energy carriers and materials, viz. main products, by-products and external supplies [32]:

- main products

$$\mathop{\Lambda}\limits_{i=1}^{n} : G_i + \sum_{j=1}^{n} f_{i,j}^{FG} G_j + D_{DGi} = \sum_{j=1}^{n} a_{i,j}^{G} G_j + K_{Gi} \tag{1}$$

$$\mathbf{G} + \mathbf{F_{FG}} \mathbf{G} + \mathbf{D_{DG}} = \mathbf{A_G} \mathbf{G} + \mathbf{K_G} \tag{2}$$

- by-products

$$\mathop{\Lambda}\limits_{l=n+1}^{m} : \sum_{j=1}^{n} f_{l,j}^{F} G_j = \sum_{j=1}^{n} a_{l,j}^{F} G_j + K_{Fl} \tag{3}$$

$$\mathbf{F_F} \mathbf{G} = \mathbf{A_F} \mathbf{G} + \mathbf{K_F} \tag{4}$$

- external supplies

$$\mathop{\Lambda}\limits_{p=m+1}^{s} : \sum_{j=1}^{n} f_{p,j}^{FD} G_j + D_{Dp} = \sum_{j=1}^{n} a_{p,j}^{D} G_j \tag{5}$$

$$\mathbf{F_{FD}} \mathbf{G} + \mathbf{D_D} = \mathbf{A_D} \mathbf{G} \tag{6}$$

Equations (1), (3) and (5) or in matrix notation equations (2), (4), (6) consist of the mathematical model on an integrated power plant. Based on the process models and the "input-output" table, the coefficients of production and consumption can been segregated of an integrated power plant and gathered in matrices and vectors, concerning respectively coefficients of:

- the consumption of energy carriers and materials manufactured as main products (matrix $\mathbf{A_G} = [a_{i,j}^G]$),
- the consumption of energy carriers and materials manufactured as by-products not supplementing the main production (matrix $\mathbf{A_F} = [a_{l,j}^F]$),
- the consumption of external supplies not supplementing the main production (matrix $\mathbf{A_D} = [a_{p,j}^D]$),
- the by-production of energy carriers and materials not supplementing the main production (matrix $\mathbf{F_F} = [f_{l,j}^F]$),
- the by-production of energy carriers and materials supplementing the main production (matrix $\mathbf{F_{FG}} = [f_{i,j}^{FG}]$),
- the by-production of energy carriers and materials supplementing the external supplies (matrix $\mathbf{F_{FD}} = [f_{p,j}^{FD}]$),
- the main production of energy carriers and materials (vector $\mathbf{G} = [G_i]$),
- the final production of main products (vector $\mathbf{K_G} = [K_{G\,i}]$),
- the final by-production of energy carriers and materials (vector $\mathbf{K_F} = [K_{F\,l}]$),
- the external supply of energy carriers and materials not supplementing the main production (vector $\mathbf{D_D} = [D_{D\,p}]$),
- the external supply of energy carriers and materials supplementing the main production (vector $\mathbf{D_{DG}} = [D_{DG\,i}]$).

The presented "input-output" approach, based on the universal structure of matrices and vectors, as well as the mathematical model of balancing the direct energy and material consumption constitutes the exploitation part of the life cycle inventory (LCI) for an integrated power plant.

In case of the matrix equation concerning the main production (Eq. 2) , the unknown value is vector G, which represents the global main production, thus we can obtain the following form:

$$\mathbf{G} = \left(\mathbf{I} - \mathbf{A_G} + \mathbf{F_{FG}}\right)^{-1}\left(\mathbf{K_G} - \mathbf{D_{DG}}\right) \tag{7}$$

The coefficients of the inverse matrix $\left(\mathbf{I} - \mathbf{A_G} + \mathbf{F_{FG}}\right)$ comprise direct and indirect connections existing in the integrated power plant. These coefficients may be called coefficients of cumulative energy consumption for the considered integrated power plant. Thanks to this inverse matrix the method of stepwise approximations in the procedure of setting up the balances of energy carriers can be avoided.

In general the MOFC power plant is similar in design to the conventional oxy-fuel combustion technology and consists of the same technological components. The main difference can be noticed in the boiler design, where the moderate and intensive low-oxygen dilution oxy-fuel combustion take place. Flue gas from the boiler are directed to the flue gas quality control module, where de-dusting and desulphurization take place. Then part of the CO_2 stream is recycled back to the boiler. In MOFC significantly lower recirculation rate is required in comparison with the classic oxy-fuel combustion technology. The remaining part of the CO_2 is directed into the CO_2 processing unit, where its further purified and compressed to the required pressure for transport. The CO_2 transportation is realised by pipelines and then the CO_2 is stored in saline formation (most common way of the CO_2 storage). Within the boiler island the primary steam is being produced, as well as reheat of the recycled steam takes place. The steam is used within the water-steam cycle in order to produce electricity. Oxygen for the MOFC power plant is provided by the air separation unit (most commonly by the cryogenic separation of air), where a small part of the produced O_2 is also used as oxidizer in the wet flue gas desulphurization instead of air (which prevent the dilution of the CO_2). Cooling water is provided to the condenser in water steam cycle, as well as the air separation unit and CO_2 processing unit for the interstage cooling of the air and CO_2 compressors, respectively.

3.2. Preliminary system analysis (case study no. 1)

Within the first case study, three cases are being analysed (Table 7). A detailed description of the proposed reference cases, including conventional air-fired and oxyfuel combustion power plants can be found in [15]. For them, the process models presented in [15], allowed to construct the "input-output" mathematical models. Within the MOFC case, the new coefficients of consumption and production of energy carriers and materials (including main products, by-products and external supplies) for the boiler island have been introduced into the OFC case. It allowed, within the system approach, to build a new mathematical model of an integrated power plant, which is considered within this study (MOFC case). Other technological modules have been left the same as in the OFC case, as the coefficients of production and consumption of energy carriers and materials should maintain the same.

With the MOFC case, the new column vector of the main production, based on Eq. (7), have been calculated, assuming the same net power of the power plant (through the column vector of the final production). The main changes within the MOFC case could be observe with the:

- coefficient of electricity consumption in the boiler island $a_{2,1}^{G}$ (drop of about 20% due to the lower recirculation rate),

- the coefficient of oxygen consumption in the boiler island $a_{5,1}^{G}$ (drop of about 5% due to the slightly lower oxidizer to coal ratio),
- the coefficient of fuel (coal) consumption in the boiler island $a_{26,1}^{D}$ (drop of about 2% due to the slightly higher thermal efficiency of the boiler).

All of those coefficients were estimated based on the literature review, additionally supported by the mathematical model of the MOFC boiler developed within the Engineering Equation Solver based on energy and mass balances. It have to been kept in mind, that those results are the first attempt of the MOFC boiler modelling. The results concerning the energy efficiencies, as well as power ratings for all three analysed cases have been presented in Table 8 and Fig. 4.

As presented in Table 8 and Fig. 4, the application of the MOFC technology within the power cycle of an reference oxyfuel combustion power plant results with almost 1 percentage point increase of the net energy efficiency. This results mainly from the higher boiler thermal efficiency and lower consumption of oxygen (which results in lower electricity consumption in air separation unit), as presented in Fig. 5.

3.3. Preliminary process and system analysis (case study no. 2)

Within the second case study three cases are being analysed (Table 9). The mathematical models of reference air-fired and oxyfuel combustion power plants were build based on the assumption made within on the final reports of the Polish National Strategic Project “Advanced Technologies for Energy Generation. Project no. 2: Oxy-combustion technology for PC and FBC boilers with CO2 capture” [33] and a PhD thesis of Jakub Tuka [34]. For the process modelling the Thermoflex and Ebsilon software were used, as well as preliminary results of the CFD modelling for the MOFC boiler. The system approach (“input-output” modelling) allows to build a new mathematical models of an integrated power plants, which are considered within this study (Table 9), combining data from different process models and other data (Fig. 6). As the example, the water-steam cycle modelled by means of Ebsilon Professional software was presented in Fig. 7. The data concerning the MOFC boiler were obtain from the preliminary results of CFD modelling, where the new industrial supercritical boiler running under mild oxyfuel combustion conditions is proposed. The basis for the design were: thermal input which is assumed to be 1000 MW_{ch} and composition of the oxidizer which contains 95 vol.% of O_2 and 5 vol.% of N_2. Comparing to classical oxyfuel combustion boilers where oxidizer is mixed with recirculated flue gases here oxidizer is supplied by separate jets. The transport of the pulverized coal is forced by recirculated flue gases which are dried, desulfurized and de-dusted. The origin of the boiler is taken from design proposed by Schaffel et al. [25] which is down fired mild combustion boiler. The fuel and oxidizer are supplied through the top wall of the boiler by set of specially arranged jets. The inlets are located in such way that fuel and oxidizer are separated by the distance which does not allow for fast mixing of both streams. Outlets from the boiler located at the top of the boiler forces to rise boiler internal gases recirculation. In order to develop flow profile which generate large internal recirculation and at the same time combustion products riches bottom of the boiler, what is required for long fuel residence time, fuel and oxidizer inlets cross section is selected to result in both fluxes velocity in a range of 40 to 70 m/s. Oxidizer inlets arrangement allow for oxidizer to be injected directly inside recirculated flue gases stream. The final location of the fuel and oxidizer jets is optimized. After number of numerical tests the final dimensions of the boiler are 36 m long, 19 m high, and 20 m depth, which are selected to keep firing density in range of 40 to 50 kW/m^3, and average wall heat flux in range of 140 to 160 kW/m^2. The boiler consist 8 identical segments separated by heat release screens what allows for firing each segment independently. Such design allow for easy control of boiler load. Each of the segment contains 2 fuel inlets, 2 oxidizer inlets and one outlet. Entire segment is surrounded by heat release screens which prevent mixing of combustion products with other (neighbouring) segments. Fuel jets are located close to the screen which creates symmetry plane along the length of the boiler. Oxidizers are located roughly in the middle of the 1/8th segment of the boiler. Outlet of the rectangular cross section is located near the side wall of the boiler at the top wall. The geometry of the new boiler design have been presented in Fig. 8, where on the left side the boiler dimension have been presented and on the right side the segment with 2 fuel and oxidizer inlets have been shown. The results of the first approach to the CFD modelling have been summarized in Table 9. Part of the heat was transferred to the steam cycle within the CFD modelled part of the boiler, where the rest was utilized in the economizer, superheaters and O_2 and CO_2 preheaters (modelled in Ebsilon Professional). As presented in Table 9, the NO_x have been neglected, but they will be taken into account in further studies. Other parameters of the analysed integrated power plant have been summarized in Table 10. The analysed MOFC cycle is not heat integrated, thus further studies within this topic are also necessary.

Based on the developed process models of the integrated power cycles the “input-output” mathematical models were constructed. The main differences between the OFC and MOFC could be noticed when the matrices of the consumption of energy carriers and materials manufactured as main products ($\mathbf{A_G} = [a_{i,j}^{G}]$) and the consumption of external supplies not supplementing the main production ($\mathbf{A_D} = [a_{p,j}^{D}]$) are compared for both cases:

- reference oxy-fuel combustion power plant (OFC_2):

$$\mathbf{A_G} = \begin{bmatrix} 0 & 1.9829 & 0 & 0 & 0 & 0 & 0 \\ 0.0023 & 0.0008 & 0.0173 & 100.96 & 739.08 & 508.76 & 0 \\ 0 & 1.0139 & 0 & 830.17 & 617.40 & 458.23 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1.1740 & 0 \\ 8.9\cdot 10^{-5} & 0 & 0 & 0.0065 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$

$$\mathbf{A_D} = \begin{bmatrix} 1.0739 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0.0004 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0.0157 & 0 & 0 & 0 \end{bmatrix}$$

- mild oxy-fuel combustion power plant (MOFC_2):

$$\mathbf{A_G} = \begin{bmatrix} 0 & 1.9834 & 0 & 0 & 0 & 0 & 0 \\ 0.0023 & 0.0008 & 0.0172 & 24.723 & 739.08 & 497.90 & 0 \\ 0 & 1.0141 & 0 & 207.54 & 617.40 & 447.37 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1.1740 & 0 \\ 8.9\cdot 10^{-5} & 0 & 0 & 0.0065 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$

$$\mathbf{A_D} = \begin{bmatrix} 1.0417 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0.0004 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0.0039 & 0 & 0 & 0 \end{bmatrix}$$

The most significant differences can be noticed in the consumption of energy carriers and materials manufactured as main products ($\mathbf{A_G} = [a_{i,j}^G]$) in column *4°* which represents the flue gas treatment plant, due to the lower energy consumption for recirculation ($a_{2,4}^G$) and lower cooling duty ($a_{3,4}^G$). In the case of the consumption of external supplies not supplementing the main production ($\mathbf{A_D} = [a_{p,j}^D]$), the value of $a_{26,1}^D$ represents the fuel (coal) unit consumption per unit of primary and secondary steam produced within the boiler.

The results of the thermodynamic assessment have been presented in Table 11. The net efficiency penalty associated with the carbon capture for the MOFC power plant are lower by 2.12 percentage point, which is mostly associated with higher boiler efficiency and lower electricity consumption for the CO_2 recirculation. Presented in Table 11 results exclude the CO_2 transport and storage, which will be included in the environmental analysis. The case description for the CO_2 transport and storage have been taken after [35] and summarized in Table 12. As presented in Fig. 9 the additional drop of net energy efficiency associated with the CO_2 transport and storage for assumed conditions is around 0.6 percentage point (Table 13).

4. Conclusions

The mild oxyfuel combustion is a new concept that combines the advantages of moderate and intensive low-oxygen dilution combustion and oxyfuel combustion for the purpose of an effective CO_2 capture from fossil fuel based power generation. Expected results of MOFC application (e.g. increase efficiency of the boiler, reduce energy consumption for the recirculation of CO_2) will affect the overall net energy efficiency penalty associated with the CO_2 capture in comparison to the oxyfuel combustion technology. Although several technical problems have to be dealt with before, as e.g. high temperatures and appropriate construction materials development.

Within the thermodynamic analysis of an integrated MOFC power plant with CO_2 capture the “OSA” programme have been used, which bases on the “input-output approach”. The data concerning the new design of the boiler are obtained from the first attempts of the CFD modelling. Three configurations of supercritical power plant are modelled for both investigated cases. The obtained thermodynamic parameters proves that the new concept of coal-fired boiler design could be a valid way to improve the overall net energy efficiency of the cycle. Detailed study of the net energy efficiency for the oxyfuel combustion power plant and MOFC in case study no. 1 shows that it is possible to increase it by almost 1 percentage point, for which the biggest share (0.61 percentage point) is associated with the increase of boiler thermal efficiency. When the process and system analysis have been combined within the case study no. 2 the 2.12 percentage point increase of the net energy efficiency have been obtained, which is directly associated with the MOFC boiler implementation.

Further studies are needed to obtain final results from the CFD modelling, that should also be validated based on laboratory test. When the final design of the MOFC boiler will be proposed, a detailed process analysis of the new boiler application within the power cycle should be done, preferable with the commercial process modelling tools. Further optimization within the MOFC cycle should be investigated, taking into account the positive effects proposed within the OFC technology, viz. interstage compressors (both ASU and CPU) heat integration with steam cycle, use of waste nitrogen to dry the coal (especially when brown coal is concern) and replacement of the cryogenic air separation unit with membrane one. Furthermore, the ecological and economic analysis should supplement those efforts to give a full picture of the new boiler design within the clean coal technology application.

Thus, two thesis were proven within the paper:

- the MOFC technology might be a suitable way to reduce the energy penalty associated with carbon capture and storage,
- the "input-output" approach can be a helpful tool for the preliminary assessment of the new technologies, and "OSA" programme can be used for the analysis of new design within the oxyfuel combustion technology.

Acknowledgments

The research leading to these results has received funding from the Polish-Norwegian Research Programme operated by the National Centre for Research and Development under the Norwegian Financial Mechanism 2009-2014 in the frame of Project Contract No Pol-Nor/232738/101/2014.

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Thermodynamic assessment of an integrated mild oxyfuel combustion power plant

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Abstract

The paper presents the advantages of a new boiler solution for the supercritical power plant with CO_2 capture. The mild oxyfuel combustion (MOFC) combines the advantages of mild (moderate and intensive low-oxygen dilution) combustion and oxyfuel combustion for the purpose of an effective CO_2 capture from fossil fuel based power generation. MOFC application could increase the efficiency of the boiler, increase the purity of the CO_2 in flue gases and reduce energy consumption for the recirculation of CO_2. It affects the overall net energy efficiency penalty associated with the CO_2 capture in comparison to the oxyfuel combustion technology. Thermodynamic analysis of an integrated MOFC power plant with CO_2 capture are presented. The data concerning the new design of the boiler are obtained from CFD modelling. Two case studies are performed, and in each of them three configurations of supercritical power plant are modelled. First two are the reference power plants, including the conventional power plant without CO_2 capture and oxyfuel combustion power plant with CO_2 capture. The third case is the MOFC boiler application within the same power plant. The thermodynamic parameters are compared, and detailed study of energy efficiency penalty is presented. Based on the presented results it can be noticed that the application of the MOFC technology allows to increase the overall net energy

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efficiency by about 2 percentage points. Additionally the usefulness of the proposed system approach (based on input-output analysis) for the energy analysis of complex energy systems have been proven.

Keywords:

Mild oxyfuel combustion, Mild combustion, Oxyfuel combustion, CO_2 capture, Thermodynamic analysis.

Nomenclature

Main symbols

A – matrix of the coefficients of the consumption of energy carriers and materials

a_{ij} – coefficient of consumption of energy carriers and materials

D – vector of external supplies

D – external supply

F – matrix of the coefficients of the by-production

f_{ij} – coefficient of by-production of energy carriers or materials

G – column vector of the main production

G – main production

I – unit matrix

K – column vector of the final production

K – final production

Subscripts and superscripts

ch – chemical

D – external supply not supplementing the main production

DG – external supply supplementing the main production

el – electricity

F – by-product

FG – by-product supplementing the main production

G – main product

Abbreviations

ASU – Air Separation Unit

CCS – Carbon Capture and Storage

CFD – Computational Fluid Dynamics

CPU – CO_2 Processing Unit

FGQC – Flue Gas Quality Control

HHV – Higher Heating Value

LHV – Lower Heating Value

MILD – Moderate and Intensive Low-oxygen Dilution

MOFC – Mild OxyFuel Combustion

OFC – Oxy-Fuel Combustion

OSA – Oxy System Analysis

p.p. – percentage point

REF – Reference

TRL – Technology Readiness Level

1. Introduction

In recent years interest has grown in the carbon capture and storage technologies (CCS) as the possible technology to mitigate the CO_2 emissions from both power sector and other industry branches. Generally three types of CCS technologies can be distinguished, viz. post-combustion, pre-combustion and oxy-fuel combustion (Fig. 1), which were briefly compared within Table 1.

The presented paper focus on the mild oxyfuel combustion (MOFC) technology, which is a next step within clean coal technologies, that combines the advantages of MILD (moderate and intensive low-oxygen dilution) combustion and oxyfuel combustion for the purpose of an effective CO_2 capture from fossil fuel based power generation. The CO_2 transport and storage (or utilization) are important and indispensable components of CCS, thus within this article the impact of the CO_2 transport and storage on the energy efficiency of the whole CCS chain is also discussed.

The oxyfuel capture technology is based on usage of high-purity oxygen in the combustion process instead of atmospheric air. Therefore flue gases have a high concentration of CO_2 (without nitrogen dilution), which allows to evade chemical post-combustion processes. Due to the limited adiabatic temperature of combustion part of CO_2 must be recycled to the boiler in order to maintain a proper flame temperature. Power plants constructed in this technology must comprise two main additional parts - the air separation unit (ASU) and the carbon dioxide processing unit (CPU), which latter can be divided into CO_2 purification and CO_2 compression units. Oxyfuel combustion is also taken into consideration in already existing retrofitting power plants, by adding ASU and CPU and adequate upgrading in the boiler island. Due to the higher cost of producing electricity, caused by implementing the CCS technology, process integration must be taken into consideration in order to lower the cost of carbon dioxide capture. One of the main ways of integration is the utilization of heat from compressor cooling systems concerning ASU and CPU with the steam cycle. The air separation unit and CO_2 purification unit are usually based on the cryogenic distillation system, because this technology is on the proper level of development to ensure the required performance of large-scale oxy-fired power plants with carbon dioxide capture. The utilization of nitrogen (e.g. drying of fuel) and application of the central water cooling system in individual cooling systems of the compressors are further examples of an integrated project.

Major challenges for current state-of-the-art oxyfuel combustion power plants are low-cost oxygen supply, developing high-temperature materials in new constructions and conversion schemes for existing air-fired power plants. Also preventing air infiltration is essential for both new and retrofitted power plants. Most of the worlds R&D project focus around new technologies for oxygen production, like e.g. membrane air separation units that can be integrated with boilers, for energy and cost effective oxygen supply. But within the oxyfuel combustion technology, there are other processes that are responsible for the net energy penalty associated with CO_2 capture and compression. Nowadays the drop of the net energy efficiency is predicted to be around 8 percentage points compared to the reference air-fired supercritical power plants.

Fig. 2 presents, the estimated within an interdisciplinary MIT study [5], parasitic energy requirements for oxyfuel pulverized coal generation with CO_2 capture. Both, air-fired and oxyfuel combustion power plants, have supercritical steam cycle. The 3 percentage point efficiency increase, for oxyfuel combustion compared to the air-fired power plant, is due to the improved boiler efficiency and reduced energy consumption for flue gas desulphurization. As mentioned already, the most significant net energy efficiency penalty is associated with the oxygen production. Within the other sources of energy efficiency drop, we may identify mainly the electricity consumption associated with the recycle of CO_2 to the boiler.

Mild oxyfuel combustion application could increase further the efficiency of the boiler, increase the purity of the CO_2 in flue gases and reduce energy consumption for the recirculation of CO_2. It affects the overall net energy efficiency penalty associated with the CO_2 capture in comparison to the oxyfuel combustion technology. Mild oxyfuel combustion boiler design gives also an opportunity to include the membrane air separation units with heat integration on required high temperature levels. Thus, within this paper, the preliminary thermodynamic analysis of an integrated MOFC power plant with CO_2 capture is presented, in order to investigate the potential of this technology. The successful implementation of CCS, and thus MOFC technology, will depend on economical factors, mostly the cost of electricity. Although post-combustion technology, based on chemical absorption by means of amine solutions, is now the only mature technology of CO_2 capture [2], nevertheless it has been considered that other CCS technologies are still considered, and some of them (as oxyfuel combustion) are even more promising [5].

2. Development pathway of mild oxyfuel combustion

Within this section the technology development pathway have been presented, from the point of view of the replacement of air with oxygen in the combustion process. Several concepts are briefly presented and discussed, pointing out the relevance to the development of the mild oxyfuel combustion technology.

2.1. Mixed air and oxygen combustion

Within the oxyfuel combustion several technological options and configurations were investigated in the literature. Most of them assumed elimination of the air in the combustion process in order to eliminate the dilution of the flue gases, so that the high concentration of CO_2 can be obtain (e.g. after just dehydration). Within [6] authors proposed a novel approach, in which the air can be used to carry the coal from the mills to the boiler (as in air-fired power plants), while oxygen is added to the secondary recycle flow and directly to the combustion zone. The presented concept, referred as CO2RE, could practically eliminate the problem with the primary recycle and air leakage into the CO_2 processing system.

Three configurations of the CO2RE technology were investigated within the paper [6], besides the conventional air-fired coal power plant. They differ with the amount of oxygen that is provided to the boiler. In first the air is used in the primary flow to the mills and whole secondary flow is composed of oxygen and recycled carbon dioxide. Second proposed the use of air also within the secondary flow, where the third assumes the use of the O_2/CO_2 mixture in the primary flow as well. Within the paper also two different purities of oxygen are analysed (viz. 95 vol.% and 99 vol.%). All those configurations result with different compositions of feedgas to the CO_2 processing unit, in which the CO_2 concentration vary from about 30 vol.% to almost 88 vol.%.

Within the results of this study [6] authors present several dependents of the air addition and energy consumption of air separation unit and CO_2 processing unit, as well the air separation plant size (which affects the investment cost of the system) and mentioned CO_2 concentration in the processed feedgas. Final results shows that the relatively small net power drop can be obtained for the third case (37 vol.% air addition), which authors find worthwhile to consider when the large-scale deployment of new power plants is taken into account in the future. Authors suggest also that their study provides an evidence to rethink the design of oxyfuel plants by adopting CO2RE concepts. However, the optimum choice for the CO2RE technology will depend on the overall cost analysis of the whole plant.

2.2. Oxyfuel combustion

Oxyfuel combustion technology has a long tradition with R&D projects, where the first concept (in context of providing a CO_2-rich stream for enhanced oil recovery) was proposed in the 80s [7]. This technology is based on the use of oxygen diluted with an recycle flue gases (mainly CO_2) rather then air. Thus a high concentration of CO_2 in the flue gases (next to the H_2O) can be obtained. The oxyfuel combustion technology may be combined with both sub-critical and super-critical (also ultra-super-critical) steam cycles. It is to be supposed, that in future advanced super-critical boilers will be applied in oxyfuel-based power plants. Both sub-critical and super-critical cycles with oxy-fired boilers and their influence on the performance and achieved thermo-economical indices have been dealt with in [8], respectively. Results of the analysis published in [8] showed a drop of the overall plant efficiency (LHV) of the sub-critical cycle from 38.14% (air-fired) to 30.45% (oxy-fired), and the super-critical cycle from 43.16% (air-fired) to 35.30% (oxy-fired). In both cases we have to do with efficiency losses due to CO_2 capture of somewhat less than 8 percentage points. The way aiming at a reduction of this efficiency drop is process integration.

Due to the necessity of using almost pure oxygen (usually around 95 vol.%) an air separation plant is needed as a part of the oxyfuel combustion power plant. The cryogenic air separation unit is presently only a market-mature technology for large-scale systems producing oxygen. It is a well-developed, most efficient and cost-effective technology, although there are still many possibilities to improve this process, mainly by process integration [8]. Although, due to productivity limitations of about 4,500 Mg O_2/day (up to 7,000 Mg O_2/day) it will be necessary to build parallel operating air separation units to cover the oxygen demands of oxy-fired power plants. It is estimated that a 500 MW_{el} power plant will need between 9,000 and 10,000 tons of oxygen per day, using two (or even three) parallel operating units. In most studies the purity level has been assumed as 95% [8,9], because at a higher oxygen purity the specific energy of separation grows rapidly after passing the aforesaid purity level. Higher values are not considered at present. The main producers of ASU for oxyfuel systems estimate the specific energy for separation of oxygen from air in the range of 200 down to 160 kWh/Mg O_2, but some of the studies suggest higher values around 220 kWh/Mg O_2. It is assumed that CO_2 will be transported to a storage reservoir by pipelines. Therefore it must be conditioned according to certain specifications (including the concentration of impurities and pressure). The suggested typical conditions and the purity of CO_2 at the delivery point are connected with the planned way of storing (or use, like enhanced oil recovery). The role of the CO_2 processing unit is to capture CO_2 from flue gases and to purify them in order to satisfy the mentioned specifications. The flue gas composition strongly depends on the oxygen purity and the amount of air infiltration in the process [1]. Carbon dioxide and vapour water are the main components of flue gases from the boiler, prior the capture plant, where the CO_2 concentration is around 80 up to 95 vol.% (dry basis) [1]. In the case of retrofit plants, due to higher air infiltrations, the shares can be much lower [10]. This specific energy for separation of CO_2 from the flue gases strongly depends on many factors, as the CO_2 share in flue gases, product pressure (usually around 15 MPa) and the type of the CO_2 purification unit. The net specific energy consumption of CO_2 processing unit is usually around 140 kWh/Mg captured CO_2 down to about 110 kWh/Mg captured CO_2. It is obvious, that with the drop of CO_2 product pressure results in a drop of the net specific energy consumption [10]. This indicates the importance of matching properly the CO_2 product conditions (concentration and pressure) for each site, keeping in mind the significant impact of the air infiltration, which lowers the CO_2 content in input flue gases.

Due to the high energy demands (mainly electrical within the air and carbon dioxide compressors), it is crucial to use every possible way to reduce internal energy demands of the power unit. Although new technologies with lower energy demands for oxygen production and CO_2 purification and compression are being developed, at the actual state of the technology the most effective way to improve the net efficiency is heat and process integration. In the case of heat integration for air separation and CO_2 compression units two main benefits can be achieved, viz. energy losses associated with compression and boiler feed water preheating can be reduced. Direct transfer of waste heat from the interstage cooling of the compressors is based on feed water preheating. Other options are indirect and can be achieved by oxygen preheating, coal drying or heating of any fluid of the cycle [11,12]. Most analysed oxyfuel combustion systems aim to find methods of heat integration in order to improve the overall net energy efficiency by integrating interstage cooling systems of the compressors with the steam-water cycle [13,14]. Within Table 2 the impact of the heat integration (based on [13,14]) have been presented. The heat integration, when the cryogenic air separation unit is considered, is responsible for about 0.5 percentage point increase in the net efficiency. In the case of membrane air separation unit, due to the additional possibility of heat integration of hot vent stream from the air separation with the steam cycle, the increase of the net energy efficiency is 4.4 percentage points.

In recent years many analyses have been performed concerning OFC power plants as a potential way in CCS technologies. The analysis performed, within last couple of years, by the National Energy Technology Laboratory (USA) focuses on the cost and performance concerning oxyfuel combustion power plants [15,16,17,18]. A techno-economical analysis of several different cases has been performed, including: biomass, lignite and hard coal use, conventional and advanced air separation units (with different O_2 purities), advanced CO_2 compression units (e.g. based on shock wave compression) and steam parameters (super-critical and ultra-super-critical). On the average, in all cases with CO_2 capture, the efficiency drop amounted to around 7 up to above 12 percentage points on a relative basis as compared to their reference cases (super-critical steam cycle without CO_2 capture). The target for CCS technologies the maximum increase in legalized cost of electricity has been assumed on the level of 35%, but none of these cases has reached that objective. The results of those studies, for the chosen configurations, have been presented in Table 3.

Basing on analyses of the National Energy Technology Laboratory, which assume for the oxyfuel combustion technology in new, as well as retrofitted power plants the achievement of 90% CO_2 capture at a less than 35% increase of cost of electricity and will be available for commercial application by the year 2020. The Department of Energy (USA) and National Energy Technology Laboratory are running several programs related to the oxyfuel combustion process, mainly connected with boiler development, oxygen supply and CO_2 compression. There are also several programs devoted to Chemical Looping Combustion, as a promising technology for CO_2 capture and storage [19].

2.3. Pressurized oxyfuel combustion

Another approach tries to gain energy savings by using pressured oxy-fuel combustion. It provides a chance to take advantage of the higher pressure of oxygen and nitrogen (heated up and directed to the expansion turbine, thus additional energy production is obtained), and the lower energy demand for CO_2 compression due to higher input pressure of the flue gases transported to CO_2 processing unit. It also allows to eliminate (or at least to reduce) the negative influence of air infiltration [20]. The pressurized oxyfuel combustion power cycle has been analysed in several studies. General conclusions in [21] show that according to several assumptions the pressurized oxyfuel combustion power plant reaches a higher net efficiency than the atmospheric one, viz. 34.9% and 31.5%, respectively. Besides the mentioned advantages of the pressurized oxyfuel combustion, also the increase of the boiler can be obtain due to the possible water condensation [22,23]. Within the Table 4, the results of studies conducted in [22,23] have been presented, concerning the impact of pressure within the boiler on its energy efficiency.

Further studies of an pressurized oxyfuel combustion power plant have been carried out. The results of those studies, presented in [24], refers to the pressure in the cycle, based on which we can conclude that the optimal pressure in the cycle is around 10 MPa [24]. Thus the advantages of the pressurized over atmospheric oxyfuel combustion can be summarized in the following points:

- the heat integration with the cycle allows to obtain a 2 percentage point increase in the gross energy efficiency, which correspond to a 3.4 percentage point increase in the net energy efficiency of the power plant,
- air separation unit, due to the higher oxygen pressure, consumes about 20% more electricity,
- CO_2 processing unit has lower energy consumption, due to the smaller quantities of the flue gases reaching it (possibility of water condensation in the heat integration unit),
- the energy consumption for the CO_2 recirculation is lower due to the lower compression ratios.

2.4. Moderate and intensive low-oxygen dilution combustion

Mild and intensive low-oxygen dilution (MILD) combustion, also called high temperature air combustion, excess enthalpy combustion or flameless oxidation, plays an important role in the mitigation of combustion based pollutants and greenhouse gases while maintaining the high energy efficiency regime of the boiler. The most characteristic feature of the MILD combustion technology is an intense recirculation of combustion products within the chamber, thus the temperature peaks are suppressed and both the temperature and the species concentrations fields are homogeneous. This result in low NOx and CO emissions and highly uniform heat fluxes within the boiler. So far, the MILD combustion technology have found its application in industrial furnaces, based on the combustion of gaseous fuels or light oils. Within last years, the attempts are made to introduce this technology into power plants pulverized boilers, as following advantages are foreseen [25]:

- reduction of the size of the boiler due to the increase of radiative heat fluxes,
- possibility of increase of the steam parameters, as high quality steel might be used (more compact and smaller boilers means less materials),
- stable combustion allows to use low rank coals,

- low excess air and low NO_x emissions.

Typically conventional air-fired boilers are composed of the radiative and convective section. Flue gases waste heat is recovered by air preheater and the economizer. In MILD combustion, the adiabatic flame temperature is much higher than that of a conventional boiler and the heat transfer inside the boiler is dominated by radiation. Thus, it is predicted that the design of a boiler without the convective section is possible with maintaining the same thermal output. The removal of the convective heat transfer region will lead to a significant reduction of boiler size and cost [25]. One of the main problems associated with the MILD combustion application to the power plant boilers is the need of providing high preheating of combustion air which is technically not easy. It is usually realised by regenerative heat exchangers. Within last years some new requirements for establishing the MILD combustion have been presented, which are less strict that expected previously [26]. Its expected that MILD combustion without preheating will have boarder range of use that now, also in the power plants pulverized boilers.

Two mechanisms for the MILD combustion to achieve increased thermal efficiency have been identified [26]:

- “when MILD combustion occurs, the furnace temperature is more uniform, which reduces irreversible loss of the combustion and heat transfer,
- although the peak temperature of MILD combustion is lower than that of conventional combustion, the former uses a smaller furnace to achieve a higher average furnace temperature, which increases the average heat transfer, especially the irradiative heat transfer”.

Therefore, as suggested by the Authors of [26], the thermal efficiency of MILD combustion is higher than that for conventional combustion notwithstanding considering the reversible thermal efficiency or heat transfer.

Most of the R&D projects concerning MILD combustion focus on the design of the boiler itself. Usually the CFD modelling is used (e.g. [25]). There have been also experiments conducted with the use of fossil fuels, which gave a very promising results (in terms of combustion stability and NOx concentrations in flue gases) [27]. In summary, the analysed papers confirms that MILD combustion technology could be an efficient and clean technology for fossil fuel fired boilers.

2.5. Mild oxyfuel combustion

Some drawback within the oxyfuel combustion process have be overcome, before the application of the technology can be made, which can be gathered in the following points [28]:

- an oxyfuel flame is less stable compared to the conventional air flame,
- NOx concentrations in flue gases can be on a high level, mainly due to the air infiltration and accumulation of nitrogen oxides due to the recirculation of flue gases,
- recirculation decrease the overall energy efficiency of the power plant.

As presented in Section 2.4, the MILD combustion technology could address some of those issues and improve the flame stability, as well as reduce the NOx formation due to the oxygen dilution and low temperature increment. The overall efficiency could also be increase by utilizing the hot recycled flue gases. As within the MILD combustion technology, most of the studies focus around the boiler design, including the CFD modelling. Nevertheless, the experiments with MOFC of pulverized coal have been conducted (0.4 MW pilot-scale facility), which were successful even without highly preheated oxidant [29]. Those research proved also, that with the in-furnace limestone injection, the costly desulphurization process can be neglected [26]. Those research indicates the feasibility of application of the MOFC technology in industrial application.

In summary the MOFC technology combines the advantages of the presented technologies, or is following the same pathway (is similar) for the reduction of the energy penalty associated with the carbon capture process, which was presented in Table 5. As the MOFC technology seeks it way to the application within the power plants boilers, it seems justified to investigate the potential overall efficiency improvements resulting from the introduction of this technology. The preliminary thermodynamic assessment of an integrated mild oxyfuel combustion power plant is the main goal of the paper.

3. Thermodynamic assessment of an integrated mild oxyfuel combustion power plant

Within the preliminary thermodynamic assessment of an integrated mild oxyfuel combustion power plant the system approach to the energy analysis of complex energy system (to which MOFC power plant belongs) have be used. The data concerning the new design of the boiler are obtained from first approach to the CFD modelling made within the Polish-Norwegian Research Programme in the frame of “Mild Oxy Combustion for Climate and Air” Project [30]. The scope of the project is a new combustion technology which links advantages of oxyfuel combustion and mild combustion and which might be used for CO_2 capture in a solid fuels combustion units.

Within the example two case studies with three configurations of supercritical power plant each are analysed. First two are the reference power plants, including the conventional power plant without CO_2 capture and oxyfuel combustion power plant with CO_2 capture. The third case is the MOFC boiler application within the same power plant.

3.1. System approach to the energy analysis of an integrated MOFC power plant

A power plant operating in compliance with the MOFC technology consists of such modules as a boiler island, steam cycle, cooling water system, water treatment module, air separation unit, flue gas quality control system and CO_2 purification and compression unit (within the whole CCS cycle also the CO_2 transport and storage system have to be included). The necessity of system approach to the energy analysis results mainly from the interdependence of technological modules, some part of which is of feedback character. Thus, the integrated MOFC power unit is a system consisting of energy branches (technological modules) connected with each other by interbranch relations.

Within the paper an complex approach of modelling the energy and material balance of an integrated power unit is briefly presented. It includes mathematical models of the "input-output" type evaluating the calculations of direct energy consumption. The algorithm presented in the paper is the component of the programme concerning system analysis of integrated oxyfuel power plants "OSA" (Oxy System Analysis). The presented programme has been developed as part of the Polish National Strategic Project co-realized by the corresponding author, called “Advanced Technologies for Energy Generation. Project no. 2: Oxy-combustion technology for PC and FBC boilers with CO_2 capture”. The main aim of the programme is to provide a tool for potential investors and analysts interested in oxyfuel technology, which allows to perform the analysis of direct and cumulative energy consumption, as well as cumulative exergy consumption, system exergy losses, thermoecological cost and life cycle assessment [31].

The presented approach have several advantages over the traditional approach to the process modelling of complex energy systems by mean of commercial software’s. First of all it is much less time consuming, as there is no need to build whole detailed process model in order to evaluate the thermodynamic performance. It also allows to combine the different process models developed in different software’s, which gives the opportunity to use most suitable one for each technological module (e.g. more detailed models of air separation unit in Thermoflex then Ebsilon Professional). The main disadvantage of the proposed approach is that it might lead to slightly under or overestimated results, as it’s based on the coefficients, but based on the Authors experience in construction of the input-output mathematical models this is being minimalized. In general the presented system approach to the energy analysis of complex energy system is suitable for the preliminary thermodynamic assessments of new concept of the power plants, which was presented in this paper.

Fig. 3 presents a simplified scheme of an oxyfuel power plant, for which the OSA programme was design. Seven main technological modules have been distinguished, which are also identified for the MOFC power plant. Within this paper the CO_2 transport and storage module will be taken into account in the additional example, as the main aim of this paper is to investigate the possibility of the reduction of energy penalty associated with CO_2 capture process itself. Three groups of energy carriers and materials are distinguished, viz. main production, by-production and external supplies. The main products corresponding to technological modules are presented in Fig. 3. Besides them 18 by-products (e.g. process heat, flue gases, make-up water, bottom and fly ash, nitrogen) and 7 external supplies (e.g. coal, raw water, limestone) are considered. The system approach bases on the “input-output approach” which is represented by the “input-output table” (Table 6) [32].

The mathematical model of direct energy (and material) consumption comprised of three matrix equations, referring to the three distinguished groups of energy carriers and materials, viz. main products, by-products and external supplies [32]:

- main products

$$\underset{i=1}{\overset{n}{\Lambda}}: G_i + \sum_{j=1}^{n} f_{i,j}^{FG} G_j + D_{DG\,i} = \sum_{j=1}^{n} a_{i,j}^{G} G_j + K_{G\,i} \qquad (1)$$

$$\mathbf{G} + \mathbf{F_{FG}}\mathbf{G} + \mathbf{D_{DG}} = \mathbf{A_G}\mathbf{G} + \mathbf{K_G} \qquad (2)$$

- by-products

$$\underset{l=n+1}{\overset{m}{\Lambda}}: \sum_{j=1}^{n} f_{l,j}^{F} G_j = \sum_{j=1}^{n} a_{l,j}^{F} G_j + K_{F\,l} \qquad (3)$$

$$\mathbf{F_F}\mathbf{G} = \mathbf{A_F}\mathbf{G} + \mathbf{K_F} \qquad (4)$$

- external supplies

$$\underset{p=m+1}{\overset{s}{\Lambda}}: \sum_{j=1}^{n} f_{p,j}^{FD} G_j + D_{D\,p} = \sum_{j=1}^{n} a_{p,j}^{D} G_j \qquad (5)$$

$$\mathbf{F_{FD}}\mathbf{G} + \mathbf{D_D} = \mathbf{A_D}\mathbf{G} \qquad (6)$$

Equations (1), (3) and (5) or in matrix notation equations (2), (4), (6) consist of the mathematical model on an integrated power plant. Based on the process models and the "input-output" table, the coefficients of production and consumption can been segregated of an integrated power plant and gathered in matrices and vectors, concerning respectively coefficients of:

- the consumption of energy carriers and materials manufactured as main products (matrix $\mathbf{A_G} = [a_{i,j}^{G}]$),
- the consumption of energy carriers and materials manufactured as by-products not supplementing the main production (matrix $\mathbf{A_F} = [a_{l,j}^{F}]$),
- the consumption of external supplies not supplementing the main production (matrix $\mathbf{A_D} = [a_{p,j}^{D}]$),
- the by-production of energy carriers and materials not supplementing the main production (matrix $\mathbf{F_F} = [f_{l,j}^{F}]$),
- the by-production of energy carriers and materials supplementing the main production (matrix $\mathbf{F_{FG}} = [f_{i,j}^{FG}]$),
- the by-production of energy carriers and materials supplementing the external supplies (matrix $\mathbf{F_{FD}} = [f_{p,j}^{FD}]$),
- the main production of energy carriers and materials (vector $\mathbf{G} = [G_i]$),
- the final production of main products (vector $\mathbf{K_G} = [K_{G\,i}]$),
- the final by-production of energy carriers and materials (vector $\mathbf{K_F} = [K_{F\,l}]$),
- the external supply of energy carriers and materials not supplementing the main production (vector $\mathbf{D_D} = [D_{D\,p}]$),
- the external supply of energy carriers and materials supplementing the main production (vector $\mathbf{D_{DG}} = [D_{DG\,i}]$).

The presented "input-output" approach, based on the universal structure of matrices and vectors, as well as the mathematical model of balancing the direct energy and material consumption constitutes the exploitation part of the life cycle inventory (LCI) for an integrated power plant.

In case of the matrix equation concerning the main production (Eq. 2) , the unknown value is vector G, which represents the global main production, thus we can obtain the following form:

$$\mathbf{G} = \left(\mathbf{I} - \mathbf{A_G} + \mathbf{F_{FG}}\right)^{-1}\left(\mathbf{K_G} - \mathbf{D_{DG}}\right) \qquad (7)$$

The coefficients of the inverse matrix $\left(\mathbf{I} - \mathbf{A_G} + \mathbf{F_{FG}}\right)$ comprise direct and indirect connections existing in the integrated power plant. These coefficients may be called coefficients of cumulative energy consumption for the considered integrated power plant. Thanks to this inverse matrix the method of stepwise approximations in the procedure of setting up the balances of energy carriers can be avoided.

In general the MOFC power plant is similar in design to the conventional oxy-fuel combustion technology and consists of the same technological components. The main difference can be noticed in the boiler design, where the moderate and intensive low-oxygen dilution oxy-fuel combustion take place. Flue gas from the boiler are directed to the flue gas quality control module, where de-dusting and desulphurization take place. Then part of the CO_2 stream is recycled back to the boiler. In MOFC significantly lower recirculation rate is required in comparison with the classic oxy-fuel combustion technology. The remaining part of the CO_2 is directed into the CO_2 processing unit, where its further purified and compressed to the required pressure for transport. The CO_2 transportation is realised by pipelines and then the CO_2 is stored in saline formation (most common way of the CO_2 storage). Within the boiler island the primary steam is being produced, as well as reheat of the recycled steam takes place. The steam is used within the water-steam cycle in order to produce electricity. Oxygen for the MOFC power plant is provided by the air separation unit (most commonly by the cryogenic separation of air), where a small part of the produced O_2 is also used as oxidizer in the wet flue gas desulphurization instead of air (which prevent the dilution of the CO_2). Cooling water is provided to the condenser in water steam cycle, as well as the air separation unit and CO_2 processing unit for the interstage cooling of the air and CO_2 compressors, respectively.

3.2. Preliminary system analysis (case study no. 1)

Within the first case study, three cases are being analysed (Table 7). A detailed description of the proposed reference cases, including conventional air-fired and oxyfuel combustion power plants can be found in [15]. For them, the process models presented in [15], allowed to construct the "input-output" mathematical models. Within the MOFC case, the new coefficients of consumption and production of energy carriers and materials (including main products, by-products and external supplies) for the boiler island have been introduced into the OFC case. It allowed, within the system approach, to build a new mathematical model of an integrated power plant, which is considered within this study (MOFC case). Other technological modules have been left the same as in the OFC case, as the coefficients of production and consumption of energy carriers and materials should maintain the same.

With the MOFC case, the new column vector of the main production, based on Eq. (7), have been calculated, assuming the same net power of the power plant (through the column vector of the final production). The main changes within the MOFC case could be observe with the:

- coefficient of electricity consumption in the boiler island $a^{G}_{2,1}$ (drop of about 20% due to the lower recirculation rate),

- the coefficient of oxygen consumption in the boiler island $a_{5,1}^{G}$ (drop of about 5% due to the slightly lower oxidizer to coal ratio),
- the coefficient of fuel (coal) consumption in the boiler island $a_{26,1}^{D}$ (drop of about 2% due to the slightly higher thermal efficiency of the boiler).

All of those coefficients were estimated based on the literature review, additionally supported by the mathematical model of the MOFC boiler developed within the Engineering Equation Solver based on energy and mass balances. It have to been kept in mind, that those results are the first attempt of the MOFC boiler modelling. The results concerning the energy efficiencies, as well as power ratings for all three analysed cases have been presented in Table 8 and Fig. 4.

As presented in Table 8 and Fig. 4, the application of the MOFC technology within the power cycle of an reference oxyfuel combustion power plant results with almost 1 percentage point increase of the net energy efficiency. This results mainly from the higher boiler thermal efficiency and lower consumption of oxygen (which results in lower electricity consumption in air separation unit), as presented in Fig. 5.

3.3. Preliminary process and system analysis (case study no. 2)

Within the second case study three cases are being analysed (Table 9). The mathematical models of reference air-fired and oxyfuel combustion power plants were build based on the assumption made within on the final reports of the Polish National Strategic Project "Advanced Technologies for Energy Generation. Project no. 2: Oxy-combustion technology for PC and FBC boilers with CO2 capture" [33] and a PhD thesis of Jakub Tuka [34]. For the process modelling the Thermoflex and Ebsilon software were used, as well as preliminary results of the CFD modelling for the MOFC boiler. The system approach ("input-output" modelling) allows to build a new mathematical models of an integrated power plants, which are considered within this study (Table 9), combining data from different process models and other data (Fig. 6). As the example, the water-steam cycle modelled by means of Ebsilon Professional software was presented in Fig. 7. The data concerning the MOFC boiler were obtain from the preliminary results of CFD modelling, where the new industrial supercritical boiler running under mild oxyfuel combustion conditions is proposed. The basis for the design were: thermal input which is assumed to be 1000 MW_{ch} and composition of the oxidizer which contains 95 vol.% of O_2 and 5 vol.% of N_2. Comparing to classical oxyfuel combustion boilers where oxidizer is mixed with recirculated flue gases here oxidizer is supplied by separate jets. The transport of the pulverized coal is forced by recirculated flue gases which are dried, desulfurized and de-dusted. The origin of the boiler is taken from design proposed by Schaffel et al. [25] which is down fired mild combustion boiler. The fuel and oxidizer are supplied through the top wall of the boiler by set of specially arranged jets. The inlets are located in such way that fuel and oxidizer are separated by the distance which does not allow for fast mixing of both streams. Outlets from the boiler located at the top of the boiler forces to rise boiler internal gases recirculation. In order to develop flow profile which generate large internal recirculation and at the same time combustion products riches bottom of the boiler, what is required for long fuel residence time, fuel and oxidizer inlets cross section is selected to result in both fluxes velocity in a range of 40 to 70 m/s. Oxidizer inlets arrangement allow for oxidizer to be injected directly inside recirculated flue gases stream. The final location of the fuel and oxidizer jets is optimized. After number of numerical tests the final dimensions of the boiler are 36 m long, 19 m high, and 20 m depth, which are selected to keep firing density in range of 40 to 50 kW/m^3, and average wall heat flux in range of 140 to 160 kW/m^2. The boiler consist 8 identical segments separated by heat release screens what allows for firing each segment independently. Such design allow for easy control of boiler load. Each of the segment contains 2 fuel inlets, 2 oxidizer inlets and one outlet. Entire segment is surrounded by heat release screens which prevent mixing of combustion products with other (neighbouring) segments. Fuel jets are located close to the screen which creates symmetry plane along the length of the boiler. Oxidizers are located roughly in the middle of the 1/8th segment of the boiler. Outlet of the rectangular cross section is located near the side wall of the boiler at the top wall. The geometry of the new boiler design have been presented in Fig. 8, where on the left side the boiler dimension have been presented and on the right side the segment with 2 fuel and oxidizer inlets have been shown. The results of the first approach to the CFD modelling have been summarized in Table 9. Part of the heat was transferred to the steam cycle within the CFD modelled part of the boiler, where the rest was utilized in the economizer, superheaters and O_2 and CO_2 preheaters (modelled in Ebsilon Professional). As presented in Table 9, the NO_x have been neglected, but they will be taken into account in further studies. Other parameters of the analysed integrated power plant have been summarized in Table 10. The analysed MOFC cycle is not heat integrated, thus further studies within this topic are also necessary.

Based on the developed process models of the integrated power cycles the “input-output” mathematical models were constructed. The main differences between the OFC and MOFC could be noticed when the matrices of the consumption of energy carriers and materials manufactured as main products ($\mathbf{A_G} = [a^G_{i,j}]$) and the consumption of external supplies not supplementing the main production ($\mathbf{A_D} = [a^D_{p,j}]$) are compared for both cases:

- reference oxy-fuel combustion power plant (OFC_2):

$$\mathbf{A_G} = \begin{bmatrix} 0 & 1.9829 & 0 & 0 & 0 & 0 & 0 \\ 0.0023 & 0.0008 & 0.0173 & 100.96 & 739.08 & 508.76 & 0 \\ 0 & 1.0139 & 0 & 830.17 & 617.40 & 458.23 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1.1740 & 0 \\ 8.9\cdot 10^{-5} & 0 & 0 & 0.0065 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$

$$\mathbf{A_D} = \begin{bmatrix} 1.0739 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0.0004 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0.0157 & 0 & 0 & 0 \end{bmatrix}$$

- mild oxy-fuel combustion power plant (MOFC_2):

$$\mathbf{A_G} = \begin{bmatrix} 0 & 1.9834 & 0 & 0 & 0 & 0 & 0 \\ 0.0023 & 0.0008 & 0.0172 & 24.723 & 739.08 & 497.90 & 0 \\ 0 & 1.0141 & 0 & 207.54 & 617.40 & 447.37 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1.1740 & 0 \\ 8.9\cdot 10^{-5} & 0 & 0 & 0.0065 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$

$$\mathbf{A_D} = \begin{bmatrix} 1.0417 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0.0004 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0.0039 & 0 & 0 & 0 \end{bmatrix}$$

The most significant differences can be noticed in the consumption of energy carriers and materials manufactured as main products ($\mathbf{A_G} = [a_{i,j}^{G}]$) in column *4°* which represents the flue gas treatment plant, due to the lower energy consumption for recirculation ($a_{2,4}^{G}$) and lower cooling duty ($a_{3,4}^{G}$). In the case of the consumption of external supplies not supplementing the main production ($\mathbf{A_D} = [a^D_{p,j}]$), the value of $a^D_{26,1}$ represents the fuel (coal) unit consumption per unit of primary and secondary steam produced within the boiler.

The results of the thermodynamic assessment have been presented in Table 11. The net efficiency penalty associated with the carbon capture for the MOFC power plant are lower by 2.12 percentage point, which is mostly associated with higher boiler efficiency and lower electricity consumption for the CO_2 recirculation. Presented in Table 11 results exclude the CO_2 transport and storage, which will be included in the environmental analysis. The case description for the CO_2 transport and storage have been taken after [35] and summarized in Table 12. As presented in Fig. 9 the additional drop of net energy efficiency associated with the CO_2 transport and storage for assumed conditions is around 0.6 percentage point (Table 13).

4. Conclusions

The mild oxyfuel combustion is a new concept that combines the advantages of moderate and intensive low-oxygen dilution combustion and oxyfuel combustion for the purpose of an effective CO_2 capture from fossil fuel based power generation. Expected results of MOFC application (e.g. increase efficiency of the boiler, reduce energy consumption for the recirculation of CO_2) will affect the overall net energy efficiency penalty associated with the CO_2 capture in comparison to the oxyfuel combustion technology. Although several technical problems have to be dealt with before, as e.g. high temperatures and appropriate construction materials development.

Within the thermodynamic analysis of an integrated MOFC power plant with CO_2 capture the “OSA” programme have been used, which bases on the “input-output approach”. The data concerning the new design of the boiler are obtained from the first attempts of the CFD modelling. Three configurations of supercritical power plant are modelled for both investigated cases. The obtained thermodynamic parameters proves that the new concept of coal-fired boiler design could be a valid way to improve the overall net energy efficiency of the cycle. Detailed study of the net energy efficiency for the oxyfuel combustion power plant and MOFC in case study no. 1 shows that it is possible to increase it by almost 1 percentage point, for which the biggest share (0.61 percentage point) is associated with the increase of boiler thermal efficiency. When the process and system analysis have been combined within the case study no. 2 the 2.12 percentage point increase of the net energy efficiency have been obtained, which is directly associated with the MOFC boiler implementation.

Further studies are needed to obtain final results from the CFD modelling, that should also be validated based on laboratory test. When the final design of the MOFC boiler will be proposed, a detailed process analysis of the new boiler application within the power cycle should be done, preferable with the commercial process modelling tools. Further optimization within the MOFC cycle should be investigated, taking into account the positive effects proposed within the OFC technology, viz. interstage compressors (both ASU and CPU) heat integration with steam cycle, use of waste nitrogen to dry the coal (especially when brown coal is concern) and replacement of the cryogenic air separation unit with membrane one. Furthermore, the ecological and economic analysis should supplement those efforts to give a full picture of the new boiler design within the clean coal technology application.

Thus, two thesis were proven within the paper:

- the MOFC technology might be a suitable way to reduce the energy penalty associated with carbon capture and storage,
- the "input-output" approach can be a helpful tool for the preliminary assessment of the new technologies, and "OSA" programme can be used for the analysis of new design within the oxyfuel combustion technology.

Acknowledgments

The research leading to these results has received funding from the Polish-Norwegian Research Programme operated by the National Centre for Research and Development under the Norwegian Financial Mechanism 2009-2014 in the frame of Project Contract No Pol-Nor/232738/101/2014.

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Figure
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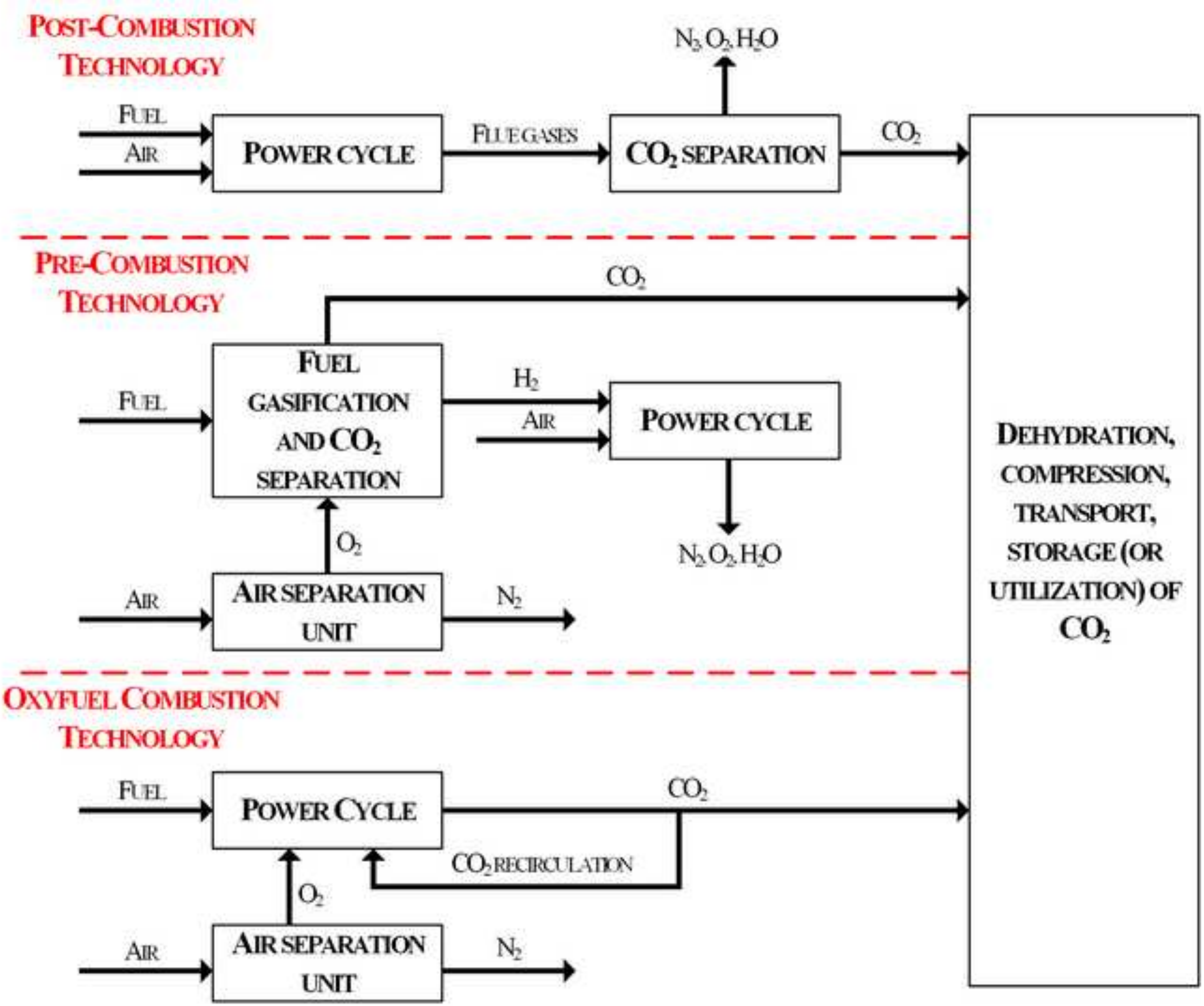

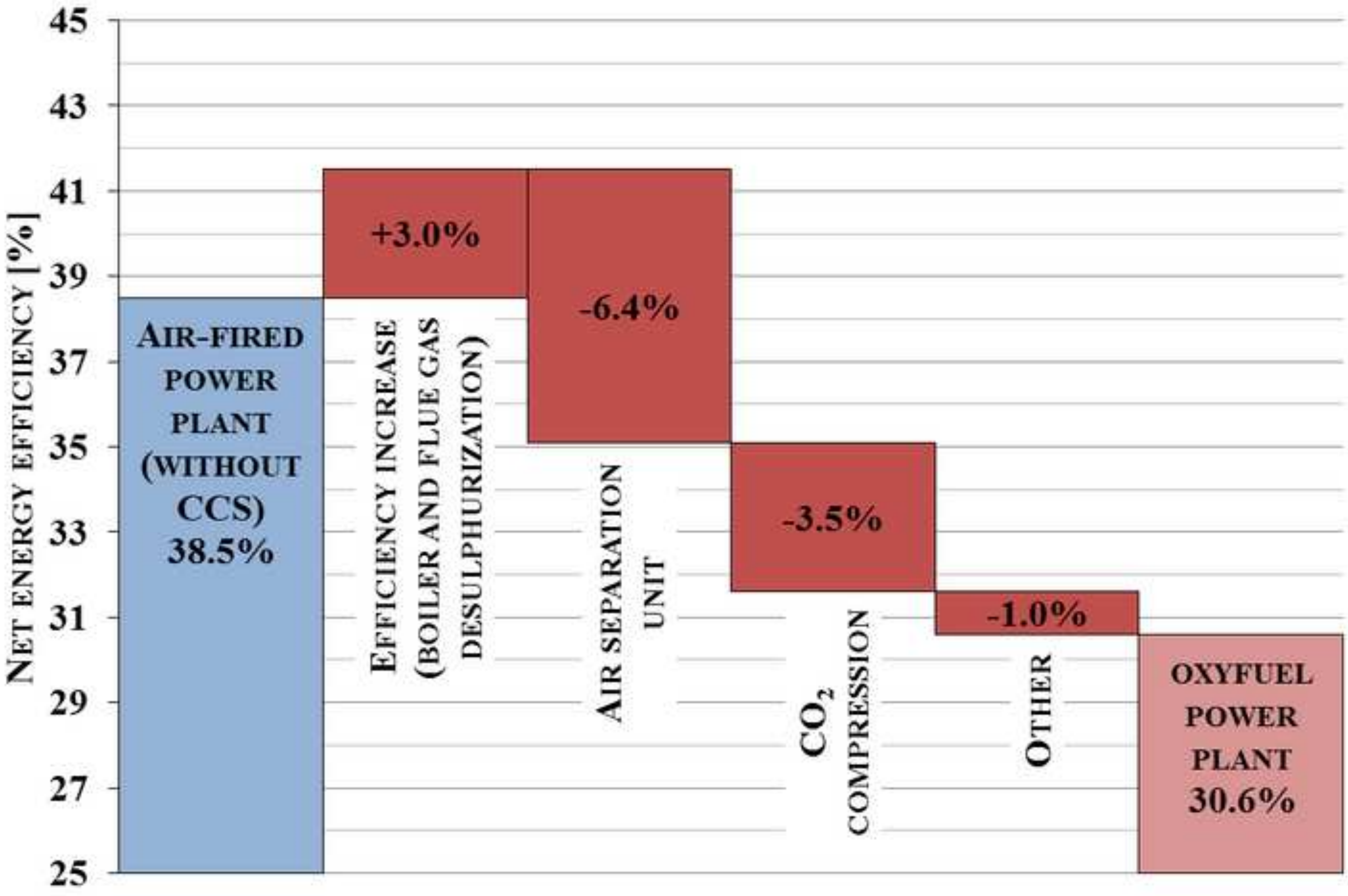
Net energy efficiency [%]
45
43
41
39
37
35
33
31
29
27
25
Air-fired power plant (without CCS) 38.5%
+3.0%
Efficiency increase (boiler and flue gas desulphurization)
-6.4%
Air separation unit
-3.5%
CO_2 compression
-1.0%
Other
Oxyfuel power plant 30.6%

Figure

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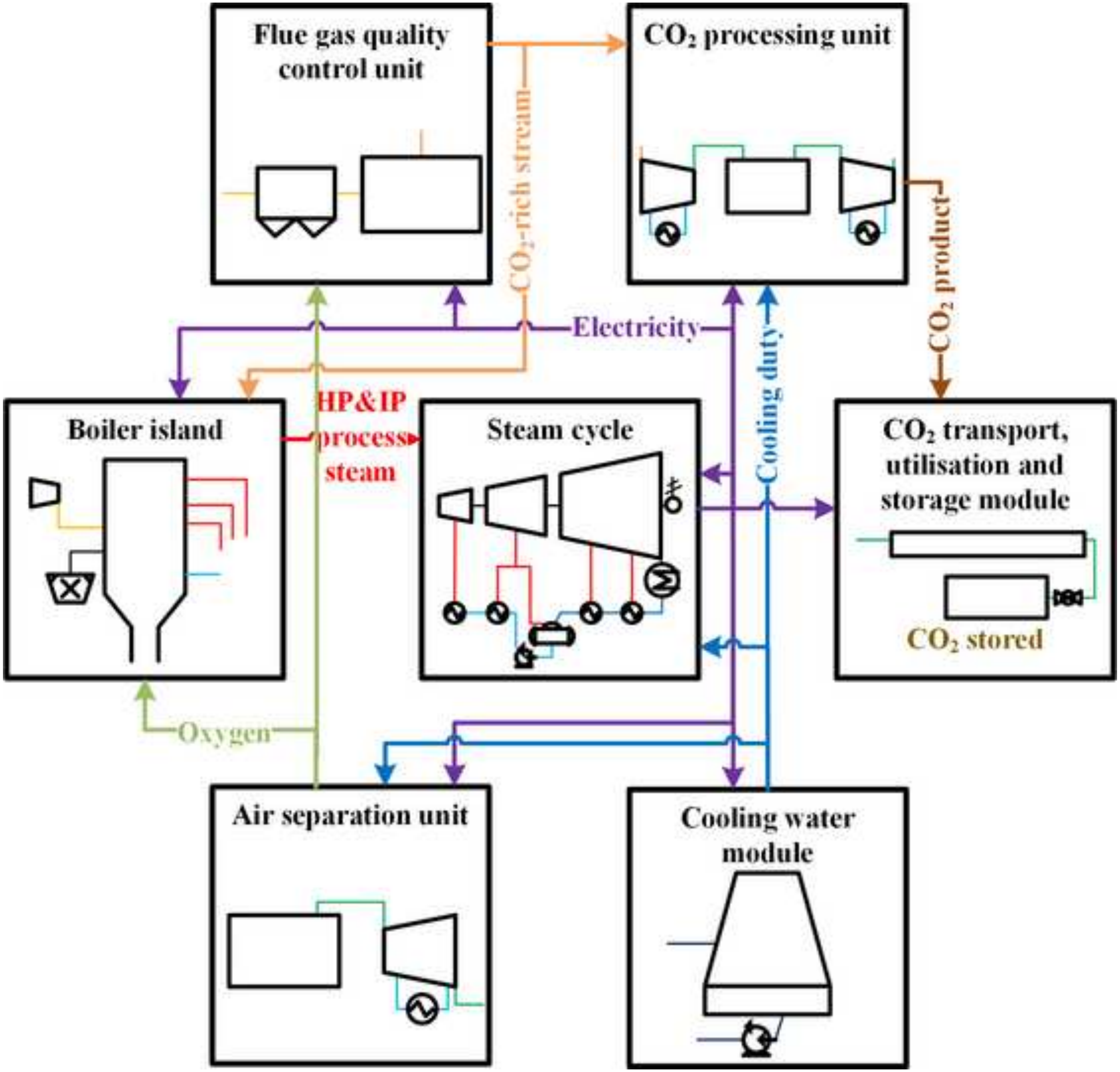

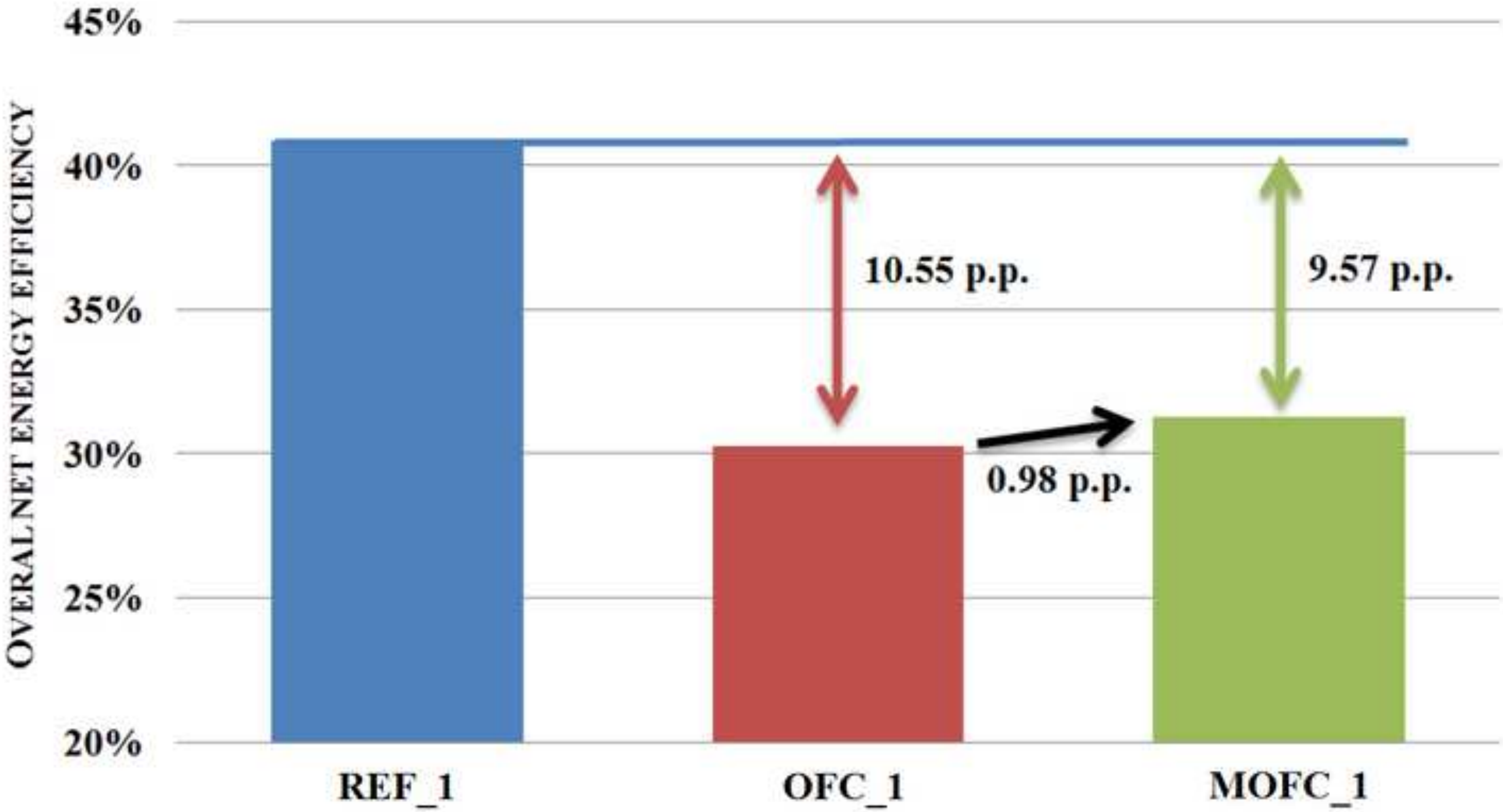
45%
40%
35%
30%
25%
20%
OVERAL NET ENERGY EFFICIENCY
10.55 p.p.
9.57 p.p.
0.98 p.p.
REF_1
OFC_1
MOFC_1

Figure

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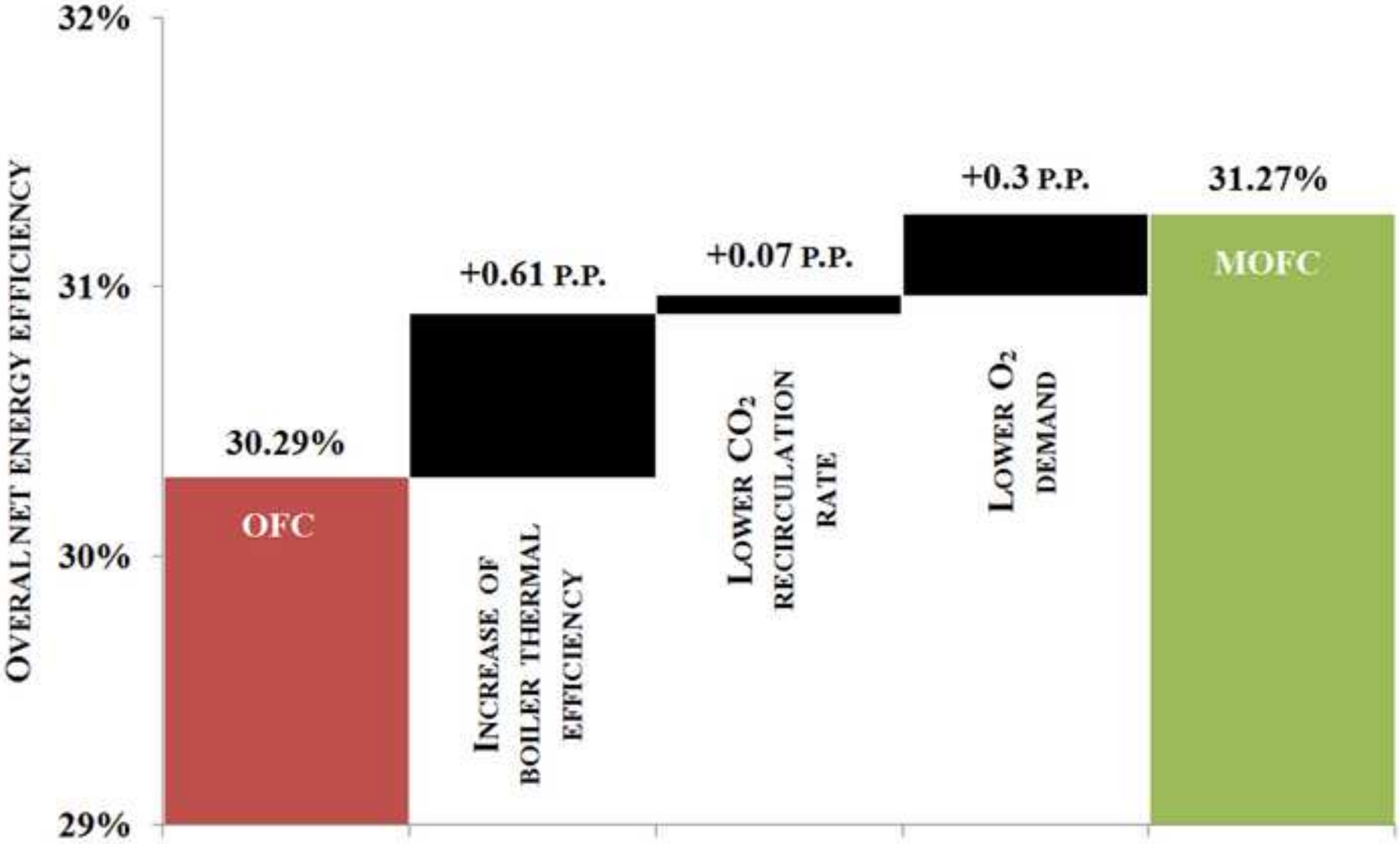
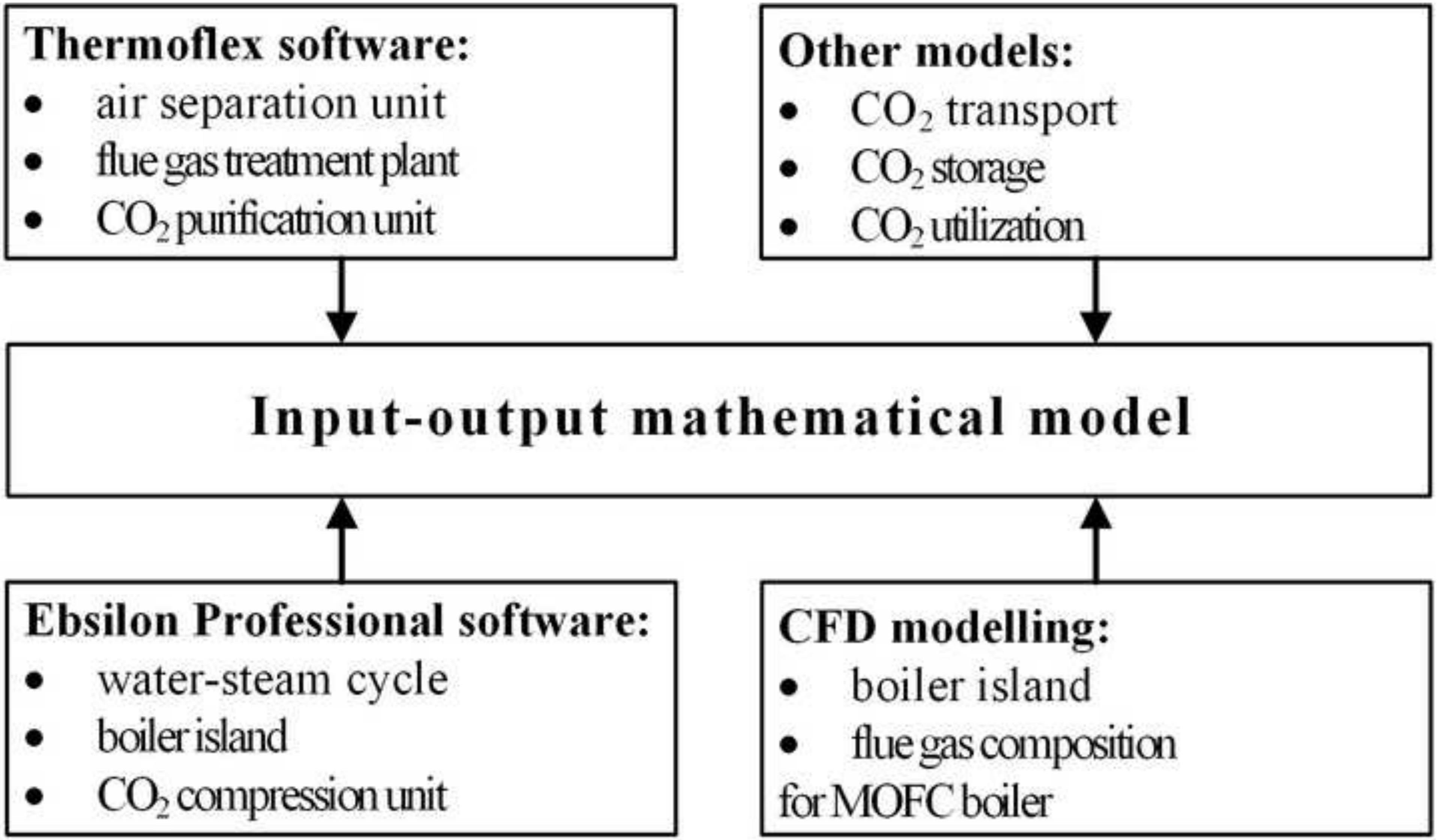
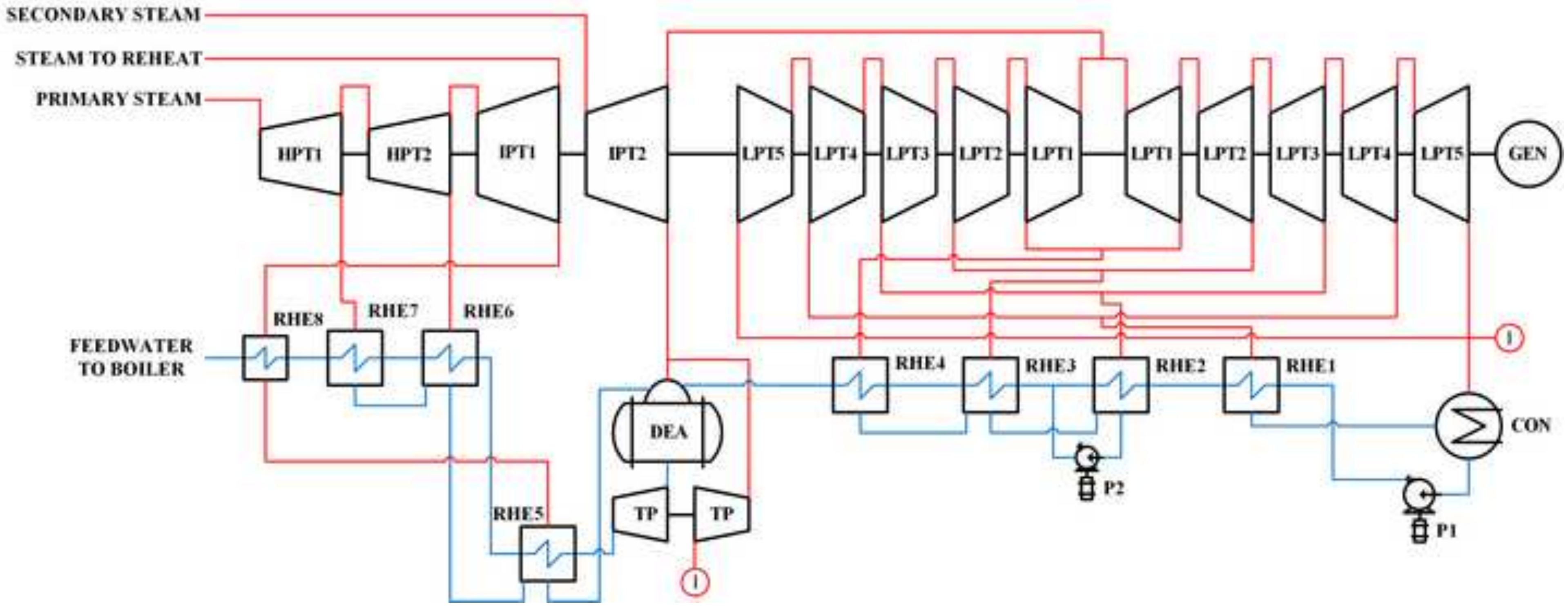
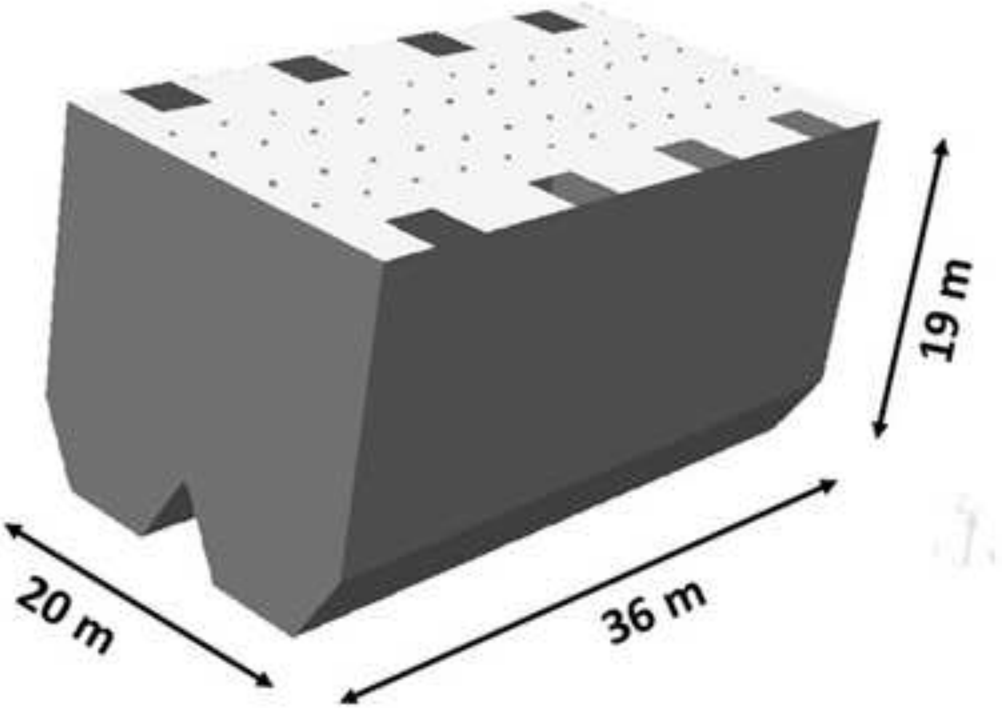



Thermoflex software:
air separation unit
flue gas treatment plant
CO₂ purificatrion unit
Other models:
CO₂ transport
CO₂ storage
CO₂ utilization
Input-output mathematical model
Ebsilon Professional software:
water-steam cycle
boiler island
CO₂ compression unit
CFD modelling:
boiler island
flue gas composition
for MOFC boiler


SECONDARY STEAM
STEAM TO REHEAT
PRIMARY STEAM
HPT1
HPT2
IPT1
IPT2
LPT5
LPT4
LPT3
LPT2
LPT1
LPT1
LPT2
LPT3
LPT4
LPT5
GEN
1
RHE8
RHE7
RHE6
FEEDWATER
TO BOILER
RHE4
RHE3
RHE2
RHE1
CON
DEA
P2
P1
RHE5
TP
TP
1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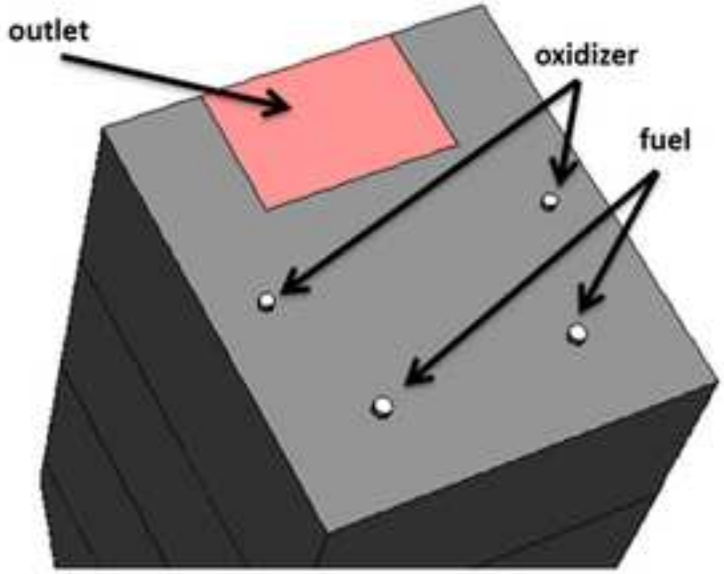
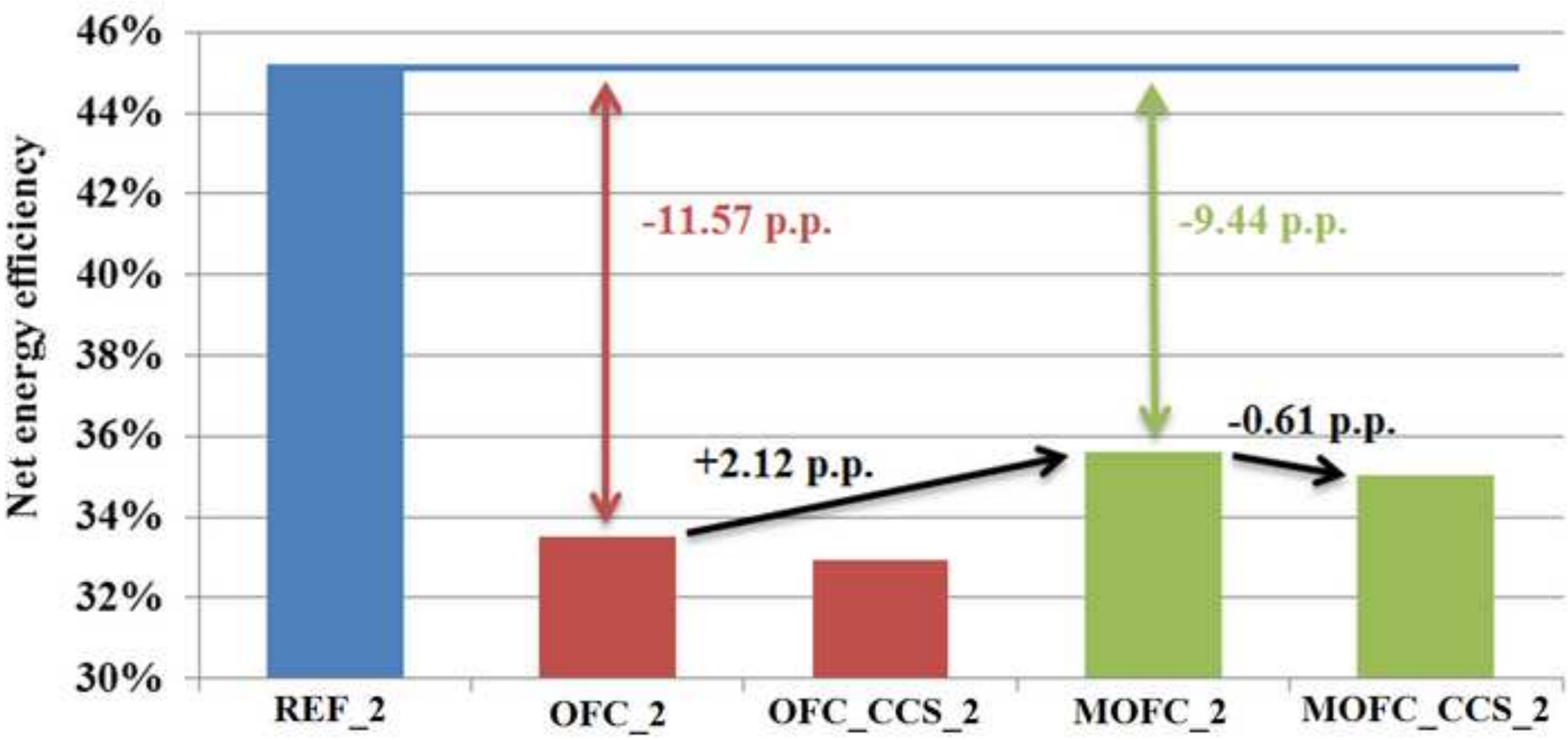

outlet
oxidizer
fuel


46%
44%
42%
40%
38%
36%
34%
32%
30%
Net energy efficiency
-11.57 p.p.
-9.44 p.p.
-0.61 p.p.
+2.12 p.p.
REF_2
OFC_2
OFC_CCS_2
MOFC_2
MOFC_CCS_2

Table

Table 1. Comparison of the CCS technologies including benchmark value of the Technology Readiness Level (based on [1,2,3])

Technology	Suitable for retrofit	Slip-stream applicable	Requires O_2 supply	Requires CO_2 removal	Generates other fuels	TRL
post-combustion	YES	YES	NO	YES	NO	9
pre-combustion	NO	YES	YES	YES	YES	9
oxyfuel combustion	YES	NO	YES	NO	NO	7

Table 2. Impact of the heat integration on the net efficiency drop (based on [13,14])

Steam parameters	supercritical (28.5 MPa/600°C/620°C)				
Heat integration	no	no	yes	no	yes
Air separation technology	none	cryogenic		membrane	
Net energy efficiency (LHV) [%]	45.9	36.1	36.6	36.4	40.8
Net efficiency drop (LHV) [p.p.]	-	9.8	9.3	9.5	5.1

Table 3. Comparison of the analysed oxyfuel combustion cases (based on [15,16,17,18])

Fuel	Boiler	Steam cycle*	ASU	CPU	Net efficiency drop (HHV)
hard coal	pulverized	super-critical	cryogenic	dehydration	10.1 p.p.
hard coal	pulverized	ultra-super-critical	cryogenic	dehydration	6.4 p.p.
lignite	pulverized	super-critical	cryogenic	cryogenic	7.6 p.p.
lignite	fluidized bed	super-critical	cryogenic	cryogenic	9.1 p.p.
biomass	pulverized	super-critical	cryogenic	dehydration	12.3 p.p.

*super-critical steam cycle (24.1 MPa/600°C/620°C) and ultra-super-critical (27.5 MPa/730°C/760°C)

Table 4. Impact of the pressure in the boiler on its efficiency (based on [22,23])

Type of combustion	air-fired	atmospheric oxyfuel	pressurized oxyfuel	
Pressure in the boiler	$\sim p_{atm}$	$\sim p_{atm}$	2.62 MPa	8.00 MPa
Boiler energy efficiency	86.68%	87.85%	94.38%	96.50%

Table 5. Relation and similarities between presented technologies and mild oxyfuel combustion

Technology	Specific correlation to MOFC
Mix air and oxygen combustion	• use of oxygen within the oxidizer to increase the CO_2 concentration in the flue gases • low or none CO_2 recirculation rate
Conventional oxy-fuel combustion	• O_2/CO_2 combustion atmosphere • CO_2 used as transport agent for coal • possibility of heat and process integration
Pressurized oxy-fuel combustion	• lower CO_2 recirculation rates • higher boiler efficiency
Moderate and intensive low-oxygen dilution combustion	• increase the flame stability • intense recirculation of combustion products within the combustion chamber • lower emissions of pollutants and CO_2

Table 6. “Input-output table” with the distinguished matrices and vectors

No	Energy carrier or material	Input part					Output part			
		Main production	By-production			External supplies	Interbranch flows			Final production
			1^o	...	7^o		1^o	...	7^o	
1^o	High and intermediate process steam	$\mathbf{G}$	$\mathbf{F_{FG}} = [f_{i,j}^{FG}]$			$\mathbf{D_{DG}}$	$\mathbf{A_G} = [a_{i,j}^{G}]$			$\mathbf{K_G}$
...	…									
7^o	Stored CO_2									
8^o	Low pressure process steam	$\mathbf{0}$	$\mathbf{F_F} = [f_{l,j}^{F}]$			$\mathbf{0}$	$\mathbf{A_F} = [a_{l,j}^{F}]$			$\mathbf{K_F}$
...	…									
25^o	Wastewater									
26^o	Coal	$\mathbf{0}$	$\mathbf{F_{FD}} = [f_{p,j}^{FD}]$			$\mathbf{D_D}$	$\mathbf{A_D} = [a_{p,j}^{D}]$			$\mathbf{0}$
...	…									
32^o	Limestone									

Table 7. Case description (case study no. 1) [15]

Case	Reference air-fired power plant (**REF_1**)	Reference oxyfuel combustion power plant (**OFC_1**)	Mild oxyfuel combustion power plant (**MOFC_1**)
Net power	~ 550 000 kW_{el}		
Steam cycle	super-critical steam parameters (24.1 MPa/600°C/620°C)		
Fuels and boiler	hard coal / pulverized boiler		
ASU	none	conventional cryogenic technology (O_2 purity 95%)	
FGQC	wet flue gas desulphurization, electrostatic precipitators		
CPU	none	only dehydration, no heat integration, CO_2 compressed to 15.3 MPa	

Table 8. Results of the thermodynamic assessment of the power plants without CO_2 transport and storage based on system approach (case study no. 1)

Case	Reference air-fired power plant (**REF_1**)	Reference oxyfuel combustion power plant (**OFC_1**)	Mild oxyfuel combustion power plant (**MOFC_1**)
Gross power	580 020 kW_{el}	785 900 kW_{el}	776 587 kW_{el}
Net power	550 030 kW_{el}	548 730 kW_{el}	548 730 kW_{el}
Gross energy efficiency	43.08%	43.37%	44.26%
Net energy efficiency	40.84%	30.29%	31.27%
Net efficiency drop	-	10.55 p.p.	9.57 p.p.

Table 9. Summary of the results concerning the new boiler design obtained from the preliminary CFD modelling (case study no. 2)

Parameter	**Value**
Stream of recycled CO_2	46.73 kg/s
Stream of O_2	83.8 kg/s
Temperature of CO_2 and O_2 to the boiler	100°C
Fuel input (chemical energy)	1 000 022 kW
Flue gas stream	173.1 kg/s
Flue gas temperature (from the modelled part)	1 150°C
Composition of flue gases (wet flue gases)	CO_2 = 56.81 vol.% O_2 = 6.68 vol.% H_2O = 32.63 vol.% N_2 = 3.81 vol.% SO_2 = 0.06 vol.% Ar = 0.01 vol.%
Amount of heat take within the modelled part of boiler	617 400 kW
Average temperature inside the boiler	1 220°C

Table 10. Case description (case study no. 2)

Case	Reference air-fired power plant (**REF_2**)	Reference oxyfuel combustion power plant (**OFC_2**)	Mild oxyfuel combustion power plant (**MOFC_2**)
Gross power	~ 460 000 kW_{el}		
Steam cycle	super-critical steam parameters (29 MPa/600°C 620°C)		
Fuels and boiler	hard coal / pulverized boiler / air ratio 1.15		
ASU	none	conventional cryogenic technology (O_2 purity 95 vol.%), no heat integration	
FGQC	wet flue gas desulphurization, electrostatic precipitators, no heat integration		
CPU	none	with CO_2 purification to 95 mol.%, CO_2 compressed to 13 MPa, no heat integration	

Table 11. Results of the thermodynamic assessment of the power plants without CO_2 transport and storage based on process and system approach (case study no. 2)

Case	Reference air-fired power plant (**REF_2**)	Reference oxyfuel combustion power plant (**OFC_2**)	Mild oxyfuel combustion power plant (**MOFC_2**)
Gross power	460.05 MW_{el}	460.10 MW_{el}	456.98 MW_{el}
Net power	437.71 MW_{el}	328.27 MW_{el}	338.62 MW_{el}
Gross energy efficiency	47.38%	46.96%	48.40%
Net energy efficiency	45.08%	33.51%	35.64%
Net efficiency drop	-	11.57 p.p.	9.44 p.p.

Table 12. Case description - CO_2 transport and storage (for case study no. 2) [35]

CO_2 transport and storage module	
Transport option	Onshore pipeline
Pipeline length	100 km
Pipeline diameter	~ 0.4 m
Electricity consumption	0 MWh/MgCO_2 (no recompression along the way)
Storage site	Saline aquifer
Electricity consumption	0.013 MWh/Mg CO_2
Brine water management	Reinjection without treatment
Brine water production	1.4 Mg/Mg CO_2
Electricity consumption	0.0033 MWh/Mg

Table 13. Results of the thermodynamic and environmental assessment of the power plants with CO_2 transport and storage based on process and system approach (case study no. 2)

Case	Reference oxy-fuel combustion power plant with CO_2 storage (**OFC_CCS_2**)	Mild oxy-fuel combustion power plant with CO_2 storage (**MOFC_CCS_2**)
Net energy efficiency	32.91%	35.03%
Net efficiency drop associated with CO_2 transport and storage	0.6 p.p.	0.61 p.p

Figure Captions

Fig. 1. Carbon capture and storage technologies (based on [4])

Fig. 2. Net energy efficiency (HHV) of referenced air-fired and oxyfuel combustion power plants (based on [5])

Fig. 3. Block diagram of an integrated MOFC power plant and its interconnections with domestic economy, domestic energy system and the environment

Fig. 4. Comparison of the net energy efficiency of all three analysed cases (case study no. 1)

Fig. 5. Net energy efficiency of referenced oxyfuel combustion and mild oxyfuel combustion power plants (case study no. 1)

Fig. 6. The construction of the “input-output” mathematical model of an integrated power plant

Fig. 7. Flow diagram of water-steam cycle (HPT - high-pressure turbine; IPT - intermediate pressure turbine; LPT - low pressure turbine; CON - condenser; P - pump; RHE - regenerative heat exchanger; TP - turbo-pump; DEA - deaerator)

Fig. 8. The mild oxyfuel combustion boiler (left side). The 1/8th segment of the mild oxyfuel combustion boiler with arrangement of fuel, oxidizer and outlet openings (right side).

Fig. 9. Comparison of the net energy efficiency of all three analysed cases, including also the cases with CO_2 transport and storage (case study no. 2)