Open Access Journal

Journal of Power Technologies 95 (4) (2015) 239–249

journal homepage:papers.itc.pw.edu.pl

Utilization of heat recovered from compressed gases in an oxy-combustion power unit to power the Organic Rankine Cycle module

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Abstract

Oxy-combustion technology is a zero-emission technology with great potential for commercial use in the near future. Application of this technology is linked with high energy losses in oxygen production and preparation of captured CO_2 for transport to a storage place. In the analyzed oxy-combustion power plant with cryogenic air separation unit the compression of gases is responsible for most of the energy consumption. Compressed gases are sources of significant amounts of waste heat energy. Effective use of this energy is crucial to reducing the efficiency drop caused by additional installations. One method extensively examined in the literature for effective utilization of medium-grade and low-grade waste heat energy is the application of the Organic Rankine Cycle (ORC), which uses a low-boiling medium to produce additional electric power. The paper presents the results of analyses of the use of heat recovered from three sources identified in the oxy-combustion unit to power the ORC module. This includes heat from gases in the compression installations within the air separation unit, the CO_2 processing unit and the CO_2 compression installation. Thermodynamic and economic analyses were performed to assess the potential investment.

Keywords: oxy-combustion, gas compression, waste heat, heat recovery, Organic Rankine Cycle

1. Introduction

Oxy-combustion technology is an energy production technology with great potential in the campaign to reduce greenhouse gas emissions. The idea of the use of nitrogen-free oxidizer in the combustion process aims to eliminate nitrogen from flue gas, and thus, to reduce the energy demand for carbon dioxide separation from flue gas. Oxy-combustion is already being indicated as an alternative for post-combustion technology, with the chemical absorption method [1–3] being the nearest to commercial use.

The literature notes strong potential for the evolution of oxy-combustion technology, mainly as means for reducing the energy cost of oxygen production. The process of oxygen production is mainly responsible for the loss of net efficiency due to high energy consumption. High expectations in that field has led to the dynamic development of membrane techniques for oxygen separation, including separation using high-temperature membranes [4, 5]. To minimize the efficiency loss for any applied technology, despite the reduction in energy consumption, it is also important to reduce the heat losses to the ambient. Heat losses within a conventional air-combustion unit are primarily caused by high-temperature flue gas dispersing into the environment. It is possible to reduce the losses, but this requires the use of heat exchangers that are resistant to low-temperature corrosion. Heat leaving the condenser in the steam cycle is another key loss, but with little potential for useful utilization.

For oxy-combustion units the loss associated with driv-

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ing high-temperature flue gas into the ambient is significantly reduced. Fundamental here is the limitation of nitrogen ballast, which results in reduced flue gas mass flow. Moreover, the stream directed to the ambient contains no carbon dioxide, and the temperature of flue gas is lower than in the case of conventional units. However, for units with CO_2 separation installations there are additional sources of waste heat. The effective use of this heat is crucial for improving energetic efficiency indicators. Analyses of possible utilization of cooling heat from carbon dioxide, which after separation is compressed to prepare for transport to the storage place, are often presented in the literature [6–8]. The application of inter-section cooling is relevant in the aspect of energy consumption of the compression process. The analysis of deep cooling of flue gas before the separation installation is presented in [9]. In oxy-combustion units several significant sources of waste heat can be identified. In the system with cryogenic air separation unit (ASU), apart from the inter-cooling in the CO_2 compression installation, we can identify two other sources with similar specificity. This concerns the air compression installation operating within the cryogenic ASU and compression within the flue gas conditioning installation. Similar to the case of the CO_2 compression installation, here also the division into sections with inter-cooling reduces the electric power demand of compressors.

Heat recovered within the power unit can be effectively used in several ways. The operation of a supercritical combined heat and power plant with utilization of heat recovered from inter-cooling of CO_2 compressors to heat district heating water was analyzed by authors in [10, 11]. This heat may be also used within the steam cycle for condensate or feedwater heating, which leads to a decrease in steam extraction flows and, in consequence, to an energy efficiency increase [12, 13]. The literature considers variants of using additional thermal cycles in order to produce electric power, among others in [14–20]. For instance, the results of thermodynamic analyses for the Organic Rankine Cycle (ORC) powered by heat recovered in deep cooling of flue gas leaving the coal boiler are presented in [21].

This article presents the results of analyses of the use of heat recovered from three sources identified in the oxy-combustion unit to power the Rankine cycle with a low-boiling medium. To assess the feasibility of investing in such concepts, in addition to a thermodynamic analysis, economic analyses were also performed.

2. Description of the oxy unit

A schematic diagram of the oxy-combustion unit considered for integration with an ORC module is presented in Fig. 1. Three compression installations, which are the heat sources for the ORC module, are marked in gray. The considered plant without integration has gross power of 460 MW. In the boiler supercritical steam parameters are assumed: The temperature and pressure of live steam at the turbine inlet are 600°C and 29 MPa, respectively. The temperature and pressure of reheated steam are 600°C and 4.8 MPa, respectively. The oxygen for the needs of the boiler is produced in the cryogenic ASU.

It is assumed that the ambient air is compressed to a pressure of 0.6 MPa for the needs of the oxygen separation process. The basic elements of ASU are two cryogenic columns, expansion valves and a multi-stream heat exchanger. The purity of the produced oxygen is 95%. A dry recirculation loop of the boiler outlet flue gas is introduced to maintain the oxygen content in the combustion chamber at the level of 30%. The non-recirculated part of the flue gas is directed to the CO_2 processing unit (CPU), where at the first stage steam is extracted from the flue gas by compression and cooling. The heat produced by the compressors at this stage of the conditioning process is important for integration with the ORC module. At the second stage of CO_2 processing the non-condensing gases, such as argon, nitrogen and sulfur dioxide, are extracted. This stage is performed at low temperatures in 'cold boxes', which include heat exchangers, phase separators and expansion valves. The temperature of this process reaches –55°C. The conditioning process results in a higher content of carbon dioxide in the flue gas which is directed to the final compression stage, i.e. the CO_2 compression installation (CC). After that the gas is prepared for transport to the place of storage.

The pressure of the separated carbon dioxide stream leaving the cryogenic installation is 2.6 MPa. The pressure of the gas directed to the pipelines transporting it to the storage place is 15 MPa. The models of the analyzed components were built using the software GateCycle^{TM} [22] (a boiler island and a steam cycle) and AspenPlus [23] (air separation unit and carbon dioxide conditioning installation). Detailed characteristics of this unit and the specific assumptions used for thermodynamic calculations can be found in [13]. In this paper the authors focused mainly on the thermodynamic and economic aspects of the use of multi-

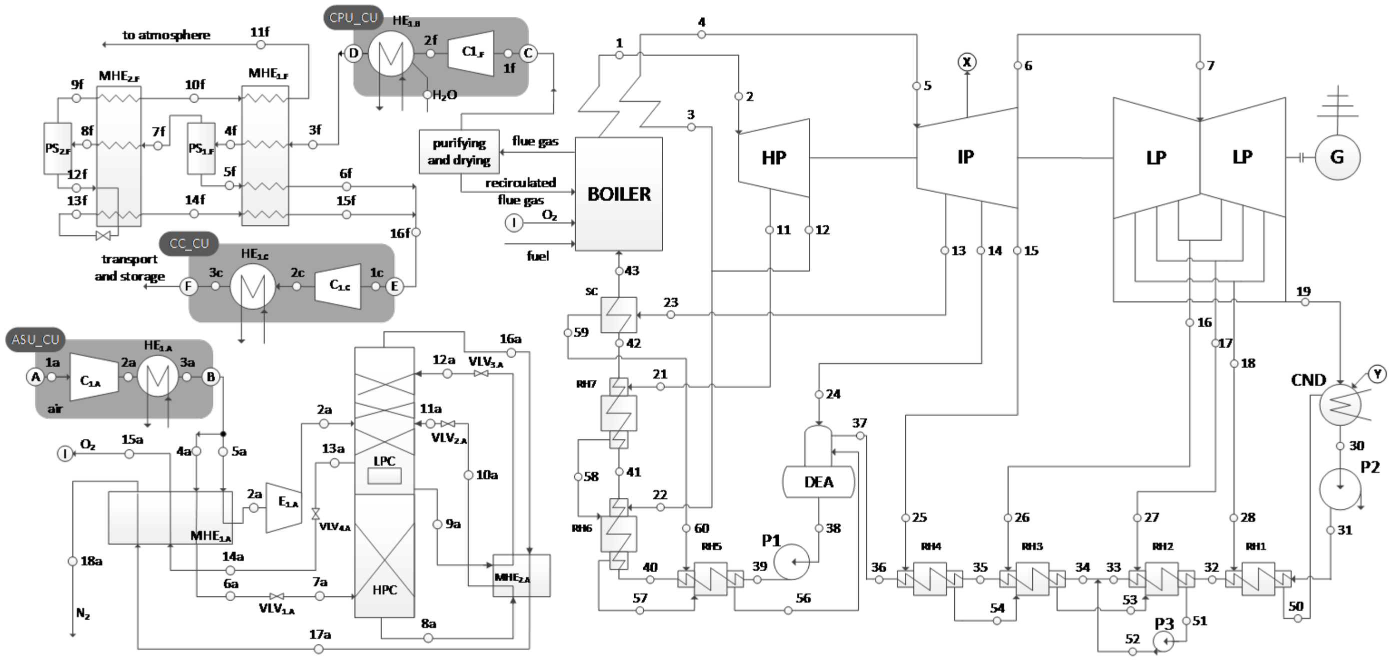

Figure 1: Schematic diagram of the oxy-combustion unit with compression installations marked by gray background

section compressors using inter-coolers and utilization of the recovered heat to replace the regenerative heat exchangers in the steam-water cycle.

The number of inter-cooled sections in compression installations is determined by the electricity consumption of the compressors, affecting the total auxiliary power of the unit. A crucial thermodynamic assessment index for power plants is the net efficiency of electricity generation. For oxy-combustion unit this efficiency can be defined by the relationship:

$$\eta_{\mathrm{el,n}} = \eta_{\mathrm{el,g}} (1 - \delta) = \frac{N_{\mathrm{el,g}}}{\dot{E}_{\mathrm{ch}}} (1 - \delta) \qquad (1)$$

where: $\eta_{el,g}$—gross electric efficiency, $N_{el,g}$—gross electric power, $\dot{E}_{ch}$—chemical energy flux of the fuel, δ—total auxiliary power rate.

The total auxiliary power rate is a sum of auxiliary power rates for particular installations within the unit:

$$\delta = \sum \delta_{\mathrm{i}} = \delta_{\mathrm{ASU}} + \delta_{\mathrm{B}} + \delta_{\mathrm{SC}} + \delta_{\mathrm{CPU}} + \delta_{\mathrm{CC}} \qquad (2)$$

where: δ_{ASU}—auxiliary power rate of the air separation unit, δ_{B}—auxiliary power rate of the boiler island, δ_{SC}—auxiliary power rate of the steam cycle, δ_{CPU}—auxiliary power rate of the CO_2 processing unit, δ_{CC}—auxiliary power rate of the CO_2 compression installation.

Each of these auxiliary power rates is defined as the ratio of the electrical power consumed by the particular installation and the gross electric power of the oxy unit:

$$\delta_{\mathrm{i}} = \frac{N_{\mathrm{aux,i}}}{N_{\mathrm{el,g}}} \qquad (3)$$

3. Description of the ORC module integration with the unit

The auxiliary power connected with compression of gases is important for achieved net efficiency of electricity generation. This concerns compression of gases within ASU, CPU and CC installations. The process of air compression required as part of the cryogenic ASU is essential here due to the very high energy consumption.

In one paper [13] five variants with different configurations of gas compression installations present in the oxy-combustion unit were analyzed. The basic variant provides one compression section in ASU, two sections in CPU and one section in CC installation (see Fig. 2). In subsequent variants the compression installations were more advanced - extended by a greater number of compression sections and, optionally, by a liquid CO_2 pump. In each case the final compressed gas was chilled in coolers located at the outlet of the installation. Three of the five variants were analyzed to determine the impact of inter-cooling of compressed gases on the thermodynamic and economic efficiency indicators. With the next two variants, additionally, the impact

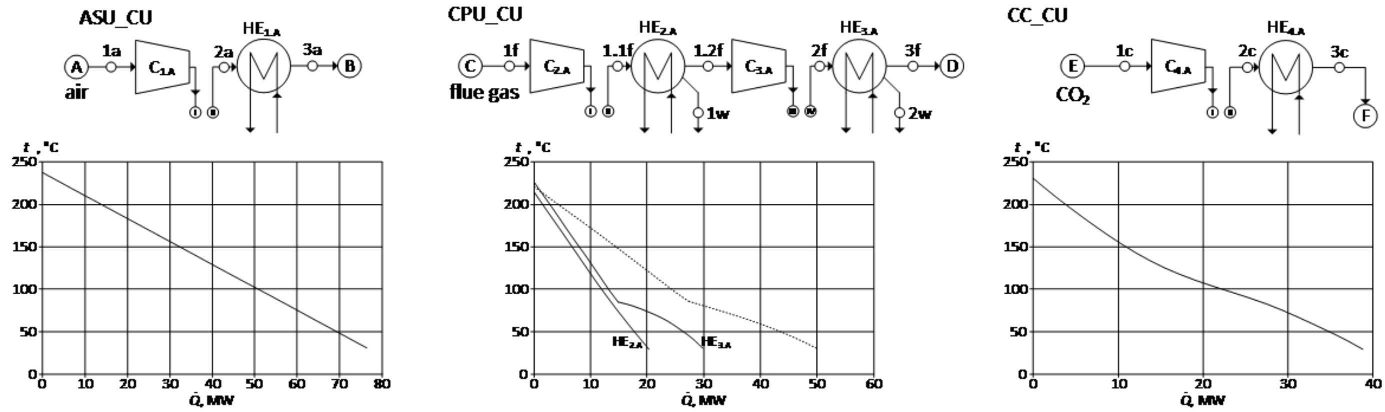

Figure 2: Structures of three compression installations in the oxy-combustion unit with cooled gases temperature distributions in inter-coolers as a function of exchanged heat energy flow (dashed line—the compositional curve)

Table 1: Auxiliary power rates for individual installations in the oxy-combustion unit

δ_{ASU}	δ_B	δ_{SC}	δ_{CPU}	δ_{CC}	δ
0.1810	0.0280	0.0343	0.0741	0.0344	0.3517

of the utilization of heat recovered from inter-cooling to replace the regenerative heat exchangers in the steam cycle was shown.

For the implementation of the studies whose results are presented in [13] it was assumed that the changes in the number of applied compression sections do not affect the thermodynamic parameters of gases leaving each compression installation. When the heat from inter-cooling is not effectively utilized, the only effect of changes in the number of cooling sections is a change of auxiliary electric power in the installations. The steam cycle and boiler island auxiliary power remain constant. When using inter-cooling heat to replace regeneration in the steam cycle, the additional effect is the increase in electric power of the unit. In that case, the change of denominator value in equation (3) affects the auxiliary power rates.

A consequence of the high power demand on the gases compression is a low value of net efficiency of the unit.

This parameter, calculated according to equation (1), is only 0.305 in this case. As shown in [10], increasing the number of compression sections significantly reduces the total auxiliary power rate. For example, the use of three compression sections in ASU, four sections in CPU, two sections and an additional liquid CO_2 pump in CC installation reduced the total auxiliary power rate to 0.297. This resulted in an increase in the unit's net efficiency to 0.330.

The number of compression sections entails several consequences. Thermodynamically, the primary consequence of a lower number of sections is higher energy demand for the compression process. The temperature of gas leaving the compression section is important in terms of the effective use of inter-cooling heat. Increasing the number of sections reduces that temperature and the potential for effective use of recovered heat. Depending on the manner of utilizing the considered heat, there is a limited number of sections where useful heat utilization is possible. Selection of the number of applied compression sections should be supported by economic analysis. In this aspect there is a compromise between the intention to minimize the power consumption of the compressors and minimization of investment costs for the compression installation, which mainly results from the increased number of inter-coolers and a significant increase in the total heat exchange surface in these coolers. In the case with the number of compression sections as in the considered variant, the obtained temperatures of gases at the outlet of each section are high, which creates the potential for use of inter-cooling heat in the Rankine cycle based on the use of low-boiling factors. Cooled gases temperature distributions within each inter-cooler as a function of obtained heat energy flow are presented in Fig. 2. As shown, regardless of the compression installation, the temperature of the gases at the inlet of each cooler exceeds the level of 200°C. It was assumed that in every inter-cooler the gases are back-cooled to the same temperature level: 30°C. Under this assumption, the thermal power of coolers working in the ASU, CPU and CC installation are 76.5 MW, 50.0 MW and 38.8 MW,

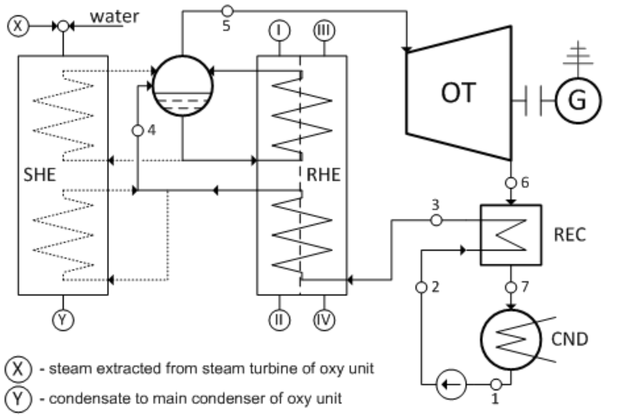

Figure 3: Structure of the ORC module with regenerative boiler utilizing inter-cooling heat and optional boiler fed by the steam extracted from steam turbine of the oxy unit

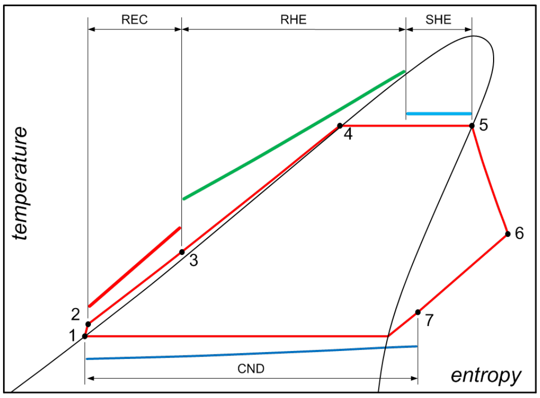

Figure 4: T-s diagram for the analyzed ORC module

respectively.

Three variants of the ORC module application are analyzed, respectively for its integration with three gas compression installations. A schematic diagram of the ORC module is shown in Fig. 3. It was assumed that the turbine is powered by saturated vapor of a low-boiling medium. Hexane is the working medium, as it is often considered in waste heat recovery installations, for example in [24, 25]. Expanded vapor leaving the turbine goes to a heat recuperator (REC) followed by a condenser (CND). The analyses include the influence of vapor pressure at the turbine inlet on the thermodynamic and economic indicators of the potential investment. In the first place the working medium in the module is heated in a regenerative heat exchanger (RHE) located in front of inter-coolers from compression installations. On one hand, the use of a high pressure, low-boiling factor is justified by obtaining higher cycle efficiency. On the other hand, at too high a pressure the inter-cooling heat level may be insufficient to produce

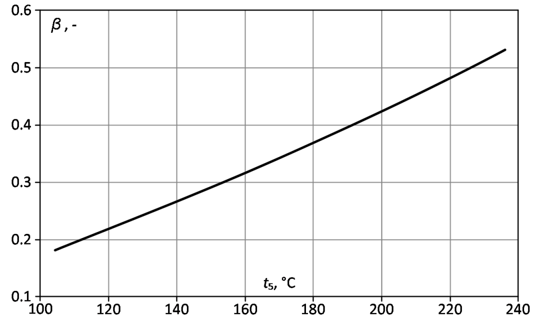

Figure 5: Power loss ratio caused by steam extraction from the steam turbine of the oxy unit to feed the ORC module as a function of the low-boiling medium vapor temperature

vapor in the RHE. The potential of inter-cooling heat utilization is limited here by the saturation temperature of the medium and by the assumed minimum temperature difference in RHE, equal to 5K. Optionally, due to the lack of sufficient potential of the inter-cooling heat, in order to produce vapor from the low-boiling medium the steam heat exchanger SHE is applied, which is supplied with steam from steam turbine extraction in the oxy unit. This concept of an additional power supply to the ORC module was proposed by the authors of the publication [18]. This steam extraction from the oxy unit provides additional heat energy to supply the ORC module. The negative effect of steam extraction would be a loss in power generated by the oxy unit. The thermal cycle realized in the ORC module is shown as a T-s diagram in Fig. 4. Steam at the required pressure is taken from additional steam turbine extraction and, before feeding the ORC module, is cooled by water injection in order to obtain saturation parameters. The power loss ratio is defined by the relationship:

$$\beta = \frac{\Delta N_{\mathrm{el\_ST}}}{\dot{Q}_{\mathrm{SHE}}} \tag{4}$$

where: ΔN_{el_ST}—steam turbine power loss due to the steam extraction, Q_{SHE}—heat energy flow of extracted steam feeding the ORC module.

The power loss ratio depends on the pressure of steam extraction, which is selected on the basis of the low-boiling medium vapor temperature and the minimum temperature difference in SHE:

$$p_{\mathrm{ex\_ST}} = p_{\mathrm{sat}}\left(t_5 + t_{\mathrm{pp\_SHE}}\right) \tag{5}$$

The minimum temperature difference in SHE is assumed at 5K. The power loss ratio as a function of the low-boiling medium vapor temperature is shown in Fig. 5. This distribution is determined based on the

Table 2: Analyzed vapor parameters at the turbine inlet in the ORC module and obtained characteristic parameters of the module

Symbol	a	b	c	d
p_5, kPa	405.4	825.2	1508.0	2564.0
t_5, °C	120.6	154.8	188.9	223.0
q_{ECON}, – $\left(\frac{\dot{Q}_{\mathrm{ECON}}}{\dot{Q}_{\mathrm{ECON}}+\dot{Q}_{\mathrm{EVAP}}}\right)$	0.3407	0.4537	0.5800	0.7665
q_{EVAP}, – $\left(\frac{\dot{Q}_{\mathrm{EVAP}}}{\dot{Q}_{\mathrm{ECON}}+\dot{Q}_{\mathrm{EVAP}}}\right)$	0.6593	0.5463	0.4200	0.2335
q_{REC}, – $\left(\frac{\dot{Q}_{\mathrm{REC}}}{\dot{Q}_{\mathrm{ECON}}+\dot{Q}_{\mathrm{EVAP}}}\right)$	0.1585	0.2287	0.2911	0.3241
η_{el,n_ORC}, – $\left(\frac{N_{\mathrm{el,n\_ORC}}}{\dot{Q}_{\mathrm{ECON}}+\dot{Q}_{\mathrm{EVAP}}}\right)$	0.1588	0.1984	0.2293	0.2486

analysis of the steam expansion line in the steam turbine of the oxy unit.

4. Assumptions and results of thermodynamic analysis

Analyses are performed for four different combinations of vapor parameters at the turbine inlet in the ORC module. The assumed pressures and temperatures, as well as the obtained values of characteristic parameters and net efficiency of the ORC module are summarized in Table 2. As can be seen, the rise in applied low-boiling medium vapor pressure is accompanied by an increase in the net efficiency of electricity generation of the ORC module. However, from a thermodynamic point of view, in the case of utilizing the inter-cooling heat in the ORC module, the rationality of maximizing the pressure is undermined by a change in the relationship of heat flows transferred to the low-boiling medium in its heating and evaporation (q_{ECON}/q_{EVAP}). Although with low pressure it is possible to power the ORC module with waste heat, then with increasing pressure the potential of the inter-cooled gases heat energy may become insufficient, which will lead to a need for additional power for the module from the extraction steam. With further increase of the low-boiling medium vapor pressure the share of heat flow supplied with the extraction steam in the total heat flow supplied to the module will increase, which will result in a greater loss in the steam turbine power of the oxy unit.

The expected result of the inter-cooling heat utilization within the ORC module is an increase in the power of the unit ($\triangle N$). If the module is powered only by inter-cooling heat, the power increase of the unit will be equal to the ORC module net power. When the module is additionally powered by the steam extracted from the steam turbine of the oxy unit, the power increase of the unit is the ORC module net power reduced by the loss of the steam turbine power of the oxy unit and, taking into account equation (4), can be defined by the relationship:

$$\Delta N = N_{\mathrm{el,n\_ORC}} - \beta \cdot \dot{Q}_{\mathrm{SHE}} \tag{6}$$

In terms of thermodynamic analysis of the integration, in addition to ambiguity about the optimal pressure level, there is the issue of optimizing the share of inter-cooled gas heat energy to be utilized within the ORC module. When discussing the problem it should be noted that the use of the recuperator in the ORC module on the one hand increases the cycle efficiency of the module, but on the other hand reduces the potential of utilizing the inter-cooling heat energy. Generally, the higher the temperature of the low-boiling medium at the inlet of the economizer, the less heat can be transferred from the cooled gas to the low-boiling medium. It should be noted that, due to the connection between the medium temperature at the recuperator outlet and its pressure at the turbine inlet, the discussed issue is related to a matter concerning the optimal pressure level. Since the gas temperature at the outlets of inter-coolers is lower than the temperature of the medium leaving the recuperator regardless of the applied pressure, it will not be possible to fully utilize the inter-cooling heat for any considered variant. Moreover, a high degree of inter-cooling heat utilization to power the ORC module may lead to a situation in which admittedly the module power is high, but the contribution of this heat to the total supplied heat flow is negligible. Hence the contribution of heat flow supplied with the extraction steam will be high. Theoretically, in consequence it may lead to a steam turbine power loss exceeding the ORC module net power.

Respectively for variants assuming the utilization in the ORC module of the inter-cooling heat of gases compressed in ASU, CPU and CC installations, Figs 6..8 present the power increases of the unit as a function of the degree of inter-cooling heat utilization. The greatest power increase is obtained in the case of ORC module integration with the ASU, while the lowest in the integration with the CC installation. Regardless of the variant, the possibility of utilizing the highest degree of inter-cooling heat exists for the application of the lowest

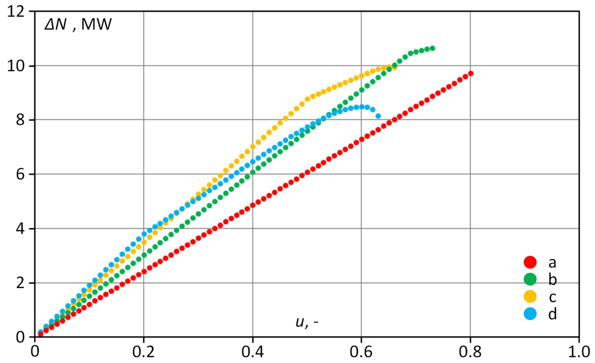

Figure 6: Power increase of the unit as a function of the degree of inter-cooling heat utilization from the ASU for four combinations of vapor parameters in the ORC module

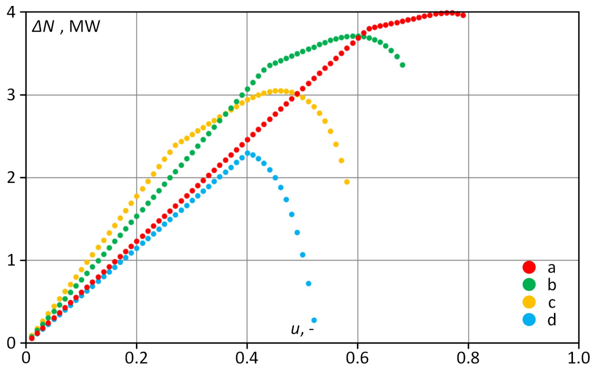

Figure 7: Power increase of the unit as a function of the degree of inter-cooling heat utilization from the CPU for four combinations of vapor parameters in the ORC module

low-boiling medium vapor pressure. The use of heat obtained from the air separation unit gives the highest power increase (10.6 MW) for the application of parameters presented in combination *b* (see Table 2). The same combination of parameters ensures the highest power increase (4.82 MW) also for the use of heat obtained from the CO_2 processing unit. In this case the increase in degree of the inter-cooling heat utilization above the value for which the highest power increase is achieved, results in a rapid reduction in obtained power increase. For the integration of the ORC module with a CO_2 compression installation the highest power increase is obtained for parameters in combination *a* (3.99 MW).

5. Assumptions and results of economic analysis

The results of thermodynamic analyses presented in Section 4 formed the basis for the economic analysis. The break-even price of electricity is chosen as an eco-

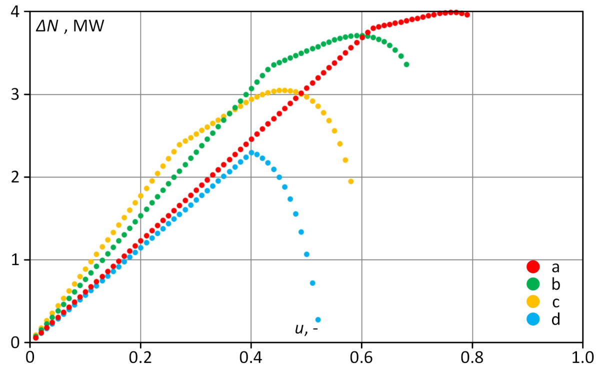

Figure 8: Power increase of the unit as a function of the degree of inter-cooling heat utilization from the CC installation for four combinations of vapor parameters in the ORC module

nomic effectiveness indicator. This is the price of electricity value designated from the condition of $NPV = 0$:

$$C_{\mathrm{el}}^{\mathrm{b-e}} = C_{\mathrm{el}}\,(NPV = 0) \tag{7}$$

NPV is the net present value described by the relationship:

$$NPV = \sum_{\mathrm{t=0}}^{\mathrm{t=N}} \frac{CF_{\mathrm{t}}}{(1+r)^{\mathrm{t}}} \tag{8}$$

In equation (8) r is the discount rate. The cash flow CF for a particular year t is calculated using the following formula:

$$CF_{\mathrm{t}} = \left[-J + S - \left(C_{\mathrm{op}} + T_{\mathrm{in}}\right) + A + L\right]_{\mathrm{t}} \tag{9}$$

where: J—investment costs, S—profit, C_{op}—operating costs (including fuel costs, operating and maintenance, exploitation and depreciation), T_{in}—income tax, A—depreciation, L—liquidation value referred to the last year of the investment.

Taking into account equations (7) - (9), as well as the relationship connecting net profit with the price of electricity:

$$S_{\mathrm{t}} = C_{\mathrm{el}} \cdot (\Delta E_{\mathrm{el}})_{\mathrm{t}} = C_{\mathrm{el}} \cdot \int_0^{\tau_{\mathrm{a}}} \Delta N d\tau \tag{10}$$

the equation for the break-even price of electricity may be written as follows:

$$C_{\mathrm{el}}^{\mathrm{b-e}} = \frac{\sum_{\mathrm{t=0}}^{\mathrm{t=N}} \frac{\left[-J+\left(C_{\mathrm{op}}+T_{\mathrm{in}}\right)-A-L\right]_{\mathrm{t}}}{(1+r)^{\mathrm{t}}}}{\sum_{\mathrm{t=0}}^{\mathrm{t=N}} \frac{(\Delta E_{\mathrm{el}})_{\mathrm{t}}}{(1+r)^{\mathrm{t}}}} \tag{11}$$

where $\triangle E_{el}$ is the total electric energy sold in the considered year t, and τ_a is the annual operation time of the unit.

Table 3: Key assumptions for the economic analysis

Quantity	Value
The annual operation time of the unit, τ_a, h	8000
The investment lifetime, N, year	20
Time of construction, τ_B, year	2
Share of own funds, u_{OF}, %	20
Share of commercial credit, u_{CC}, %	80
Commercial credit repayment period, T_{CC}, year	10
Commercial credit interest rate, r_{CC}, %	8
Depreciation rate, a_m, %	6.67
Income tax, T_{in}, %	19
Discount rate, r, %	5.7
The system operating costs, k_e, €/MWh	0.5
The system maintenance costs (% of investment expenditures), k_r, %	2.0

The basic assumptions for the economic analysis are summarized in Table 3.

In the economic effectiveness analyses of energy units with known thermodynamic analysis results the basic problem is to determine investment costs J. Literature in the field of economic analysis shows a number of ways to estimate these costs. One of them is to determine the investment by multiplying the cost of purchasing components of the unit (C_{eq}) by the building cost index (B). When determining the investment cost for the ORC module, this relationship is expressed in the form:

$$J_{\mathrm{ORC}} = C_{\mathrm{eq\_ORC}} \cdot B = B \cdot \sum_{\mathrm{i}} C_{\mathrm{eq\_ORCi}} \tag{12}$$

In performed analyses the building cost index is assumed at 2. The investment cost includes the cost of purchasing the following components with approximation relationships related to their basic characteristic parameters: Regenerative heat exchanger:

$$C_{\mathrm{RHE}} = 35000 \cdot \left[\left(\frac{\dot{Q}_{\mathrm{RHE/ECON}}}{\Delta t_{\mathrm{m\_RHE/ECON}}}\right)^{0.6} + \left(\frac{\dot{Q}_{\mathrm{RHE/EVAP}}}{\Delta t_{\mathrm{m\_RHE/EVAP}}}\right)^{0.6}\right] \tag{13}$$

Steam heat exchanger:

$$C_{\mathrm{SHE}} = 275.4 \cdot A_{\mathrm{SHE}}^{1.01} \tag{14}$$

Organic medium turbine:

$$C_{\mathrm{OT}} = -1.66 \cdot 10^4 + 716 \cdot N_{\mathrm{e\_OT}}^{0.8} \tag{15}$$

Generator:

$$C_{\mathrm{G}} = 3082 + 716 \cdot N_{\mathrm{e\_OT}}^{0.8} \tag{16}$$

Recuperator:

$$C_{\mathrm{REC}} = 35000 \cdot \left(\frac{\dot{Q}_{\mathrm{REC}}}{\Delta t_{\mathrm{m\_REC}}}\right)^{0.6} \tag{17}$$

Condenser:

$$C_{\mathrm{CND}} = 275.4 \cdot A_{\mathrm{CND}}^{1.01} \tag{18}$$

where: Q—heat power of the exchanger, kW, $\triangle t_m$–logarithmic mean temperature difference between exchanging factors in the heat exchanger, A—exchanger heat transfer area (calculated using the Peclet equation, with assumed heat transfer coefficient for SHE at the level of 0.93 kW/m^{2}K and for CND at 1.40 kW/m^{2}K), m^2, Ne_{OT}—organic medium turbine mechanical power, kW.

Equation (15) is taken from [26]. Equations used to estimate the cost of purchasing the other components are taken from [27]. The changes in value over time, using the Chemical Engineering Plant Cost Index (CEPCI), are taken into account when calculating the investment costs. However, it should be noted that this investment, in addition to the possibility of reducing steam turbine power in the oxy unit, brings other economic consequences.

The investment in the ORC module incurs costs, as specified using equation (12). This primarily involves a decrease in investment costs due to a reduction in the heat transfer area in the inter-coolers. Therefore, as well as the power decrease of the oxy unit, the total power change caused by applying the ORC module (AN) was considered. In the investment cost analysis a change in the investment cost for the oxy unit ($\triangle J_{oxy}$) is also taken into account. Consequently, for the economic analysis the investment cost for these technological solutions is defined as:

$$J = J_{\mathrm{ORC}} - \Delta J_{\mathrm{oxy}} \tag{19}$$

The investment costs calculated in accordance with presented methodology are presented in Figs 9..11 in similar terms as for the power increase of the unit, respectively for variants assuming the utilization of the inter-cooling heat of gases compressed in ASU, CPU and CC installations. The break-even prices of electricity are shown in Figs 12..14. The results indicate that the optimal parameters in terms of thermodynamic

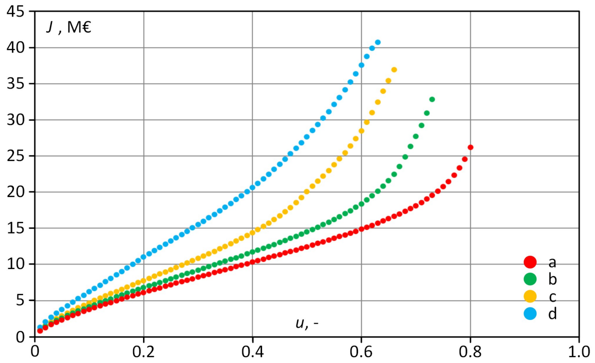

Figure 9: Investment cost related to the application of the ORC module as a function of the degree of inter-cooling heat utilization from the ASU for four combinations of vapor parameters in the ORC module

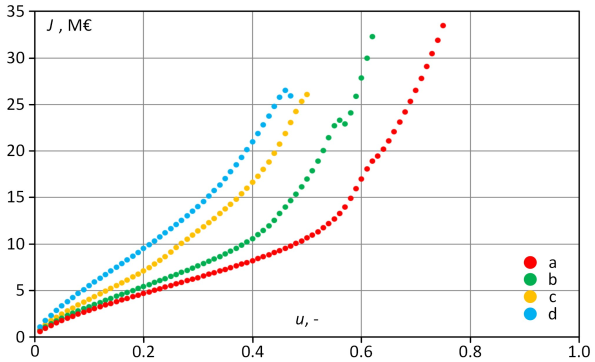

Figure 10: Investment cost related to the application of the ORC module as a function of the degree of inter-cooling heat utilization from the CPU for four combinations of vapor parameters in the ORC module

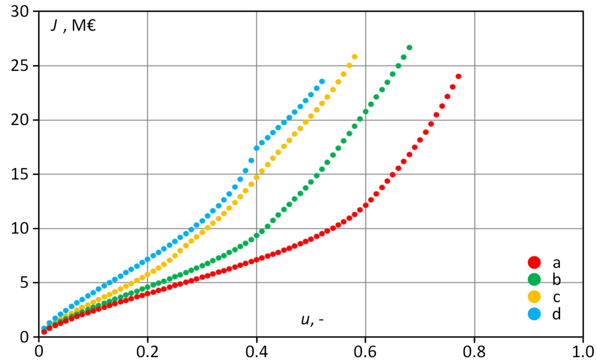

Figure 11: Investment cost related to the application of the ORC module as a function of the degree of inter-cooling heat utilization from the CC installation for four combinations of vapor parameters in the ORC module

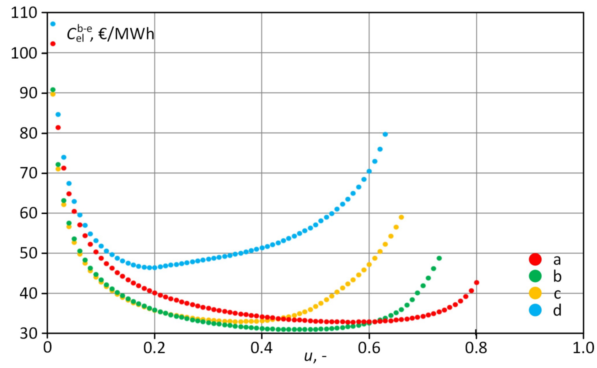

Figure 12: Break-even price of electricity as a function of the degree of inter-cooling heat utilization from the ASU for four combinations of vapor parameters in the ORC module

analysis are not optimal from the economic point of view. Since the ORC module is powered by waste heat, the investment cost is the most significant parameter for the economic analysis. A significant increase in investment costs at high degrees of heat utilization has a negative impact on the break-even price of electricity. Therefore, the optimal prices of electricity are obtained for slightly lower degrees of heat utilization.

6. Conclusions

The analyses presented in this paper showed that in the considered compression installations significant amounts of waste heat are available with a strong potential for use in the ORC module. Analyses were performed for different parameters of low-boiling medium as a function of degree of inter-cooling heat utilization. Depending on the needs, heat flow used within the ORC module is supplemented by extraction stream from the steam turbine of the oxy unit. The use of heat obtained from the air separation unit gives the highest power increase, up to 10.6 MW, while using the heat obtained from CO_2 processing unit gives up to 4.82 MW and from the CO_2 compression unit gives no more than 3.99 MW.

The economic analysis revealed that across a wide range of the degree of waste heat utilization it is possible to obtain low cost electricity production in the ORC modules, which is expressed in the form of the break-even price of electricity. This price for the ORC module powered by heat recovered from the ASU is slightly over 30 €/MWh, while for the CPU and the CC installation it is about 40-45 €/MWh. The results also indicate that the optimal parameters in terms of economic analysis are obtained for lower degrees of heat utilization than the optimal parameters identified by thermodynamic analysis. Thus, the high degree of waste heat utilization, even if technically available, is not always

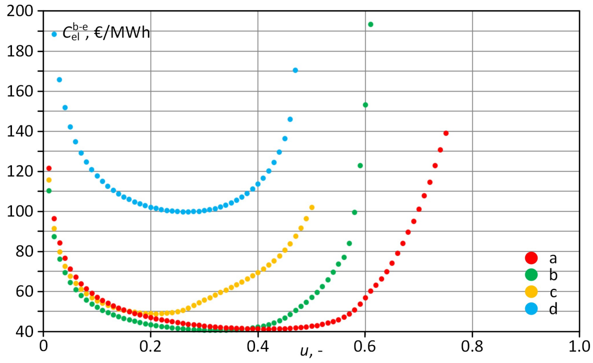

Figure 13: Break-even price of electricity as a function of the degree of inter-cooling heat utilization from the CPU for four combinations of vapor parameters in the ORC module

cost effective.

Acknowledgments

The results presented in this paper were obtained from research work co-financed by the National Centre for Research and Development within a framework of Contract SP/E/2/66420/10—Strategic Research Programme - Advanced Technologies for Energy Generation: Development of a technology for oxy-combustion pulverized-fuel and fluid boilers integrated with CO_2 capture.

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