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Oxygen enriched EGR in WtE plants: opportunities and challenges for enhanced CO₂ capture



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About ACCSESS

If CO₂ capture and storage (CCS) is to become a relevant, large-scale technology for cutting carbon dioxide (CO₂) emissions, several barriers need to be addressed, and its deployment must be accelerated.

ACCSESS works to address key challenges to the successful implementation of CCS across Europe: namely, challenges related to CO₂ capture, CCS chains, and societal acceptance. The project focuses on four industrial sectors with the potential to drastically reduce CO₂ emissions by implementing CCS: waste-to-energy, pulp and paper, cement, and biorefineries.

ACCSESS started in May 2021. Its consortium consists of 18 partners from eight different European countries.

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Abstract
<p>The CO₂ content in the flue gases of waste-to-energy plants can be increased using oxygen-enriched combustion with exhaust gas recirculation. It is expected that the energy consumption and sizes of equipment of the capture unit are reduced. However, the production of oxygen-enriched air increases energy consumption and CAPEX. This deliverable presents a techno-economic study on the performance of typical CO₂ capture processes for a waste to energy plant using oxygen-enriched combustion. The capture processes include (1) solvent capture using the CO₂ solutions by Saipem solvent technology, MEA and AMP-PZ, (2) membrane separation, and (3) oxy-fuel combustion. It is found that oxygen-enriched combustion increases the overall energy consumption for solvent capture processes since the reductions in energy consumption related to CO₂ capture are small. The overall energy consumption for the membrane capture is reduced by 17.5% when the CO₂ content of the flue gases increases to 27.5%. The oxy-fuel combustion is also competitive when considering energy consumption. Cost analyses have been performed for the MEA and for the membrane capture processes. It is found that the overall annualized cost increases for the MEA capture process while it is reduced for the membrane capture process. Trade-off between the reduction in cost for the membrane process and the increased complexity of the advanced oxygen enriched combustion configuration with recycle train must be considered when selecting a suitable configuration when considering membrane based processes for CO₂ capture from WtE plants. The oxygen-enriched combustion is thus more attractive for membrane capture processes in the range of CO₂ contents studied.</p>

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1 INTRODUCTION

1.1 Document Purpose

The purpose of this deliverable work is to investigate the opportunities and challenges of enhanced CO₂ capture for waste to energy plants using oxygen-enriched combustion with exhaust gas recirculation. The idea is to increase the CO₂ concentration in the flue gases so that energy consumption and also CAPEX of the capture processes can be reduced. However, the production of oxygen-enriched air increases energy consumption and CAPEX. This study evaluates the overall performance to understand the potential of using oxygen-enriched combustion in waste to energy plants for selected capture technologies that are relevant to this project.

1.2 List of Acronyms and abbreviations

AMP	Amino-methyl-propanol
ASU	Air separation unit
CEPCI	Chemical Engineering Plant Cost Index
CPU	Compression and purification unit
EGR	Exhaust gas recirculation
MEA	Monoethanolamine
MSW	Municipal solid waste
OEA	Oxygen-enriched air
PFD	Process flow diagram
PZ	Piperazine
SPC	Specific power consumption
SPCeq	Equivalent total specific power consumption
SRD	Specific reboiler duty
TCR	Total capital requirement
TDC	Total direct cost
TPC	total plant cost
WtE	Waste to energy

1.3 Relation to other deliverables

This deliverable is closely linked to the D 9.4 “Summary of blueprint design for pioneering CCUS chains”. The models and modelling results of the WtE plant and the AMP-PZ capture processes presented in the deliverable have been used in this study. The methodology for cost analysis has also been used in this work.

The results of this work will be relevant for deliverables D7.2 “Capture Ready Waste to Energy Plants” and D10.6 “Prospective WtE, Cement, pulp and paper, and biorefinery CCUS chains in Europe”

Reference [2], the framework document is not formally an ACCSESS deliverable, but will be uploaded to the ACCSESS community in Zenodo.org at the end of the project.

2 BACKGROUND

The generation of municipal solid waste (MSW) is expected to keep increasing due to growing population and prosperity. MSW incineration is a well-known technology for waste treatment. The process normally includes additional production of heat and/or power i.e. waste to energy (WtE) plant. Capturing CO₂ from WtE plants has attracted increasing interest for greenhouse gases control. Negative emissions may be achieved if the MSW contains sufficient biogenic materials. Both post-combustion and oxy-combustion technologies have been studied for WtE plants according to public literature [1]. A distinct advantage of post-combustion is that it is easier to install in existing plants. However, the CO₂ content in the flue gases is as low as around 11% according to the framework document of this project [2]. The energy consumption for capturing a unit of CO₂ decreases with higher CO₂ content in the flue gases although the extent of this decrease is dependent on the specific capture technology and on the ranges of CO₂ content. An approach to increase the CO₂ content in flue gases is the adoption of exhaust gas recirculation (EGR), which has been mostly studied for gas turbines with regards to CO₂ capture [3][4]. The EGR has also been used in WtE plants mainly for NO_x control. This is normally done by partly replacing the secondary combustion air with EGR [5]. The CO₂ can thus be slightly concentrated, e.g. according to [2], the CO₂ contents of Line 1 (without EGR) and Line 2 (with EGR) of the KVA Linth plant are ca. 11 vol% and ca. 13 vol% (wet basis), respectively.

Another approach to increase the CO₂ content is to use oxygen-enriched combustion, which has been used in industrial heating processes primarily for achieving higher temperatures e.g. metal or glass melting furnaces [6]. The oxygen content in the oxidant gases is higher compared to air but less than full oxy-combustion where nearly pure oxygen is used. As less nitrogen is introduced to the combustion system, the CO₂ can be concentrated in oxygen-enriched combustion. In addition, oxygen-enriched combustion can improve flame stability and reduce exhaust flows and pollutant emissions, e.g. NO_x [6]. When oxygen-enriched combustion is applied to WtE plants, EGR can be used for temperature control of the incineration furnaces to avoid too high temperatures. Oxygen-enriched combustion is an advanced configuration for WtE plants to increase the CO₂ concentration in its flue gas while also improving other associated plant performance characteristics. The application of oxygen-enriched combustion with calcium looping capture for a WtE plant has recently been reported [7]. It is found that the hybrid capture system consumes much less energy compared to the calcium looping capture process. In a study about hybrid oxygen-enriched combustion and MEA (Monoethanolamine) capture for coal-fired power plants [8], it is found that the hybrid capture system consumes less energy compared to the MEA capture process. Oxy-combustion has been found to consume even less energy, while the electrical power costs of the hybrid capture system turn out to be the lowest. However, in another study about hybrid oxygen-enriched combustion and MEA capture for coal-fired power plants, it was found that the hybrid system has the worst energy performance [9].

The primary motivation of this study is to investigate the opportunities and challenges of using oxygen-enriched combustion with EGR to enhance the performance of typical CO₂ capture technologies that are relevant to the WtE plant in this project. It should be noted that the study does not intend to make comparisons between different capture technologies. An illustration of the process is presented in Figure 2.1. The oxygen-enriched air (OEA) is produced from an OEA production unit and is mixed with the recycled flue gas before being sent to the furnace. The flue gases with concentrated CO₂ are sent to a capture unit for CO₂ capture after heat recovery and flue gas cleaning.

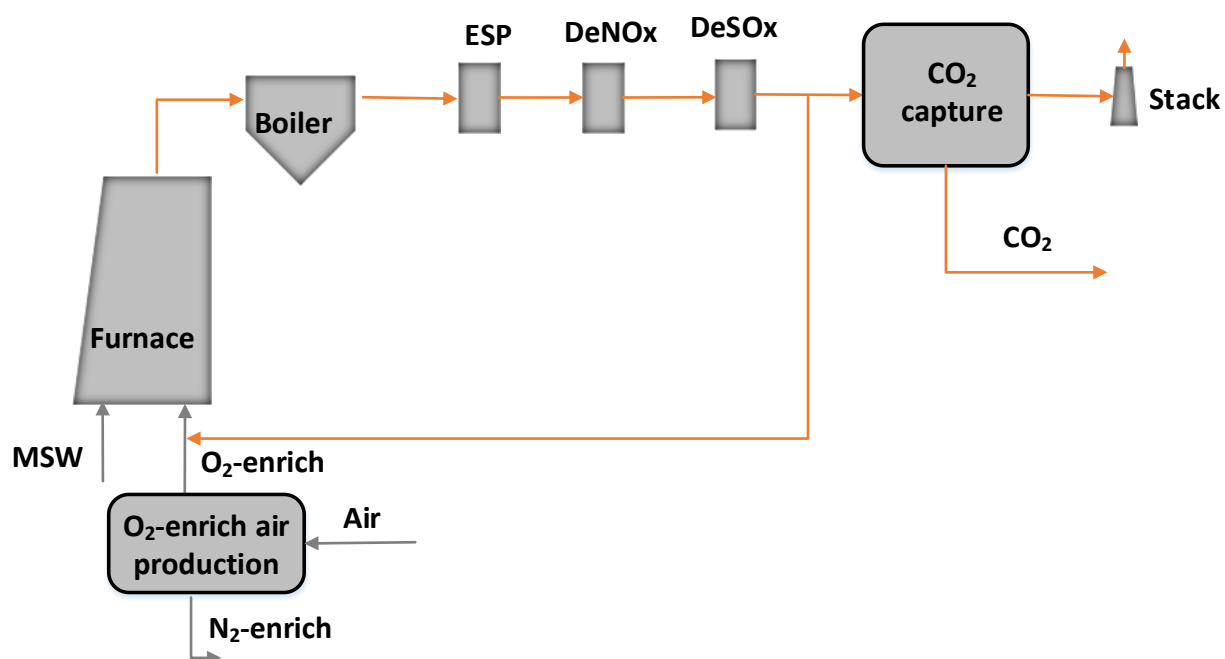


Figure 2.1: Illustration of enhanced CO₂ capture via oxygen enriched combustion in WtE plants.

3 PROCESS DESCRIPTION AND MODELLING

The oxygen-enriched combustion concept has been assumed to be applied to Line 1 of the KVA Linth WtE plant where the MSW is assumed to be supplied at 6 tonne/hr. More details about the description of the KVA Linth plant can be found in the framework document [2]. The flue gas is assumed to be recycled after SO_x removal. The following assumptions have been used to evaluate various cases in this study: (1) Adiabatic flame temperature of the furnace remains unchanged; (2) The amount of steam generated in the boiler remains unchanged; (3) the amount of heat recovered from "External economizer" and "Flue gas heat exchanger" (referred to Line 1 of the KVA Linth plant) remains unchanged; and (4) oxygen content in the flue gases of furnace outlet is specified to be 5 mole% in cases of oxygen-enriched combustion and oxy-combustion in order to ensure complete combustion of MSW. It should be noted that the existing temperatures of boiler, "External economizer" and "Flue gas heat exchanger" are higher in cases of oxygen-enriched combustion and oxy-combustion compared to air-fired cases mainly due to a larger specific heat capacity of CO₂ vs. N₂ since the N₂ is partially replaced by CO₂. Also, a higher acid dew point is expected at the outlet of the "Flue gas heat exchanger" due to higher SO_x concentrations.

3.1 Production of oxygen-enriched air

The following two options of producing oxygen-enriched air (OEA) have been evaluated: (1) Nearly pure oxygen is produced by cryogenic distillation (air separation unit - ASU) and is mixed with air as illustrated in Figure 3.1(a); and (2) direct production from polymeric membranes as illustrated in Figure 3.1(b). The oxygen content can reach up to around 39 mole% using polymeric membranes [7]. As a result, the CO₂ content in the flue gases is limited to ca. 28 mole%. A summary of the performance results of the two OEA supply has been presented in Table 3.1. The specific power consumption for oxygen supply is 0.23 kWh/kgO₂ (pure) [10] and 0.043 kWh/kgO₂ (39 mole%) for cryogenic distillation and polymeric membrane separation, respectively [7,11]. The oxygen supply from ASU and thus the power consumption for oxygen supply increases considerably in order to increase the CO₂ content from 15% to 27.5%. However, it should be noted that the increment becomes smaller for the range of higher CO₂ contents. The overall oxygen supply decreases with increasing CO₂ content since the O₂ content is assumed to be constant and the flow of flue gases decreases.

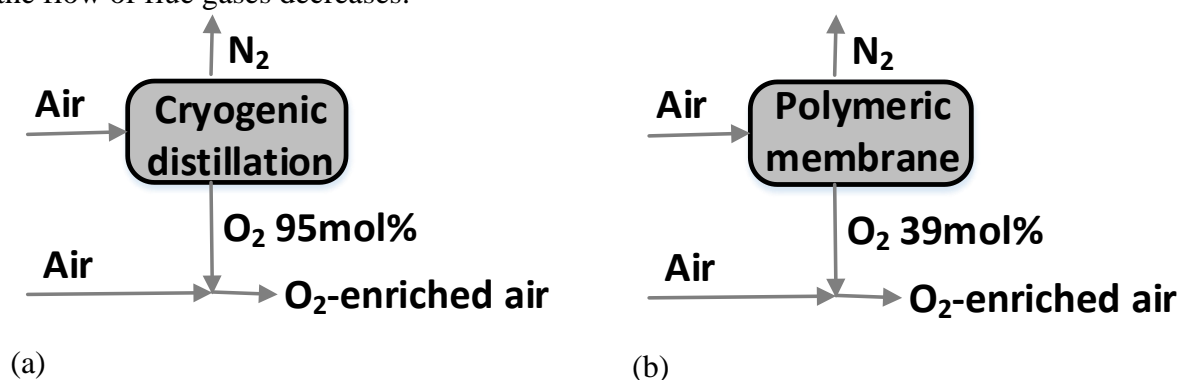


Figure 3.1: Illustration of production of OEA with oxygen supply from (a) cryogenic distillation and (b) polymeric membrane

Table 3.1: Performance of oxygen-enriched air supply.

	Cryogenic distillation			Polymetric membrane		
	15%	20%	27.5%	15%	20%	27.5%
CO ₂ molar content in flue gases (dry basis)						
Air supply, [kg/h]	30000	21000	13135	27000	12000	0
Oxygen supply from ASU, [kg/h]	1400	3100	4600	4600	12000	17000
Oxygen purity of ASU, [mole%]	95	95	95	0.39	0.39	0.39
Oxygen purity of ASU, [mass%]	0.96	0.96	0.96	0.43	0.43	0.43
Total oxygen supply, [kg/h]	8300	7800	7500	8300	7800	7400
Oxygen content in oxidant, [mole%]	0.24	0.3	0.39	0.24	0.3	0.39
Specific power consumption for ASU, [kWh/kgO ₂] [7,10]	0.23	0.23	0.23	0.043	0.043	0.043
Power consumption for oxygen supply, [MW]	0.31	0.68	1	0.2	0.50	0.75
Specific power consumption for oxygen supply, [kWh/kgO ₂]	0.037	0.087	0.135	0.024	0.064	0.101

3.2 CO₂ content and energy consumptions of CO₂ capture processes

This section presents the variation of energy consumption with CO₂ content in the flue gases for the following capture processes: (1) CO₂ Solutions by Saipem solvent, (2) Monoethanolamine (MEA) absorption, (3) solvent blend of Amino-methyl-propanol (AMP) and Piperazine (PZ), (4) membrane separation.

The key energy consumption data of each capture process is presented in Table 3.2. Energy for CO₂ capture processes are either supplied as heat, for instance to regenerate solvents and denoted as specific reboiler duty (SRD), and as work (power) denoted by specific power consumption (SPC). The performance data of CO₂ Solutions by Saipem solvent capture is provided by Saipem. The case of CO₂ content at 11% has slightly lower SRD since the case has been optimized to minimize the energy consumption. The changes in SRD are small with CO₂ content, however, the SPC reduces by 13% when the CO₂ content increases from 11% to 20%. The power consumption mainly includes the pumping and fan power including the compression of CO₂ up to 1.9 bara, which is close to the pressure of CO₂ captured in amine capture processes. Note that a distinct advantage of Saipem solvent is that much lower temperature heat (actually hot water instead of steam) can be used for regeneration therefore reducing the associated cost. The process and flowsheet of the MEA capture process are nearly the same as of the AMP-PZ capture process as presented in the framework document [2]. The performance results of MEA capture are taken from study [12] where the performance of MEA capture for CO₂ content ranges of 3.5% to 30% were presented for various volumetric flowrates of flue gases. The SRD slightly decreases when the CO₂ content increases from 11% to 27.5%. The changes of SRD for AMP-PZ capture are even smaller. The results are obtained using the capture models developed by SINTEF as presented in [2]. The SRD for AMP-PZ in the case with CO₂ content at 11% has slightly lower SRD than the other cases since it has been thoroughly optimized to minimize the heat consumption as the base case in [2]. As for membrane separation, a two-stage membrane process with recycle is assumed to be used. The process flow diagram (PFD) is presented in Figure 3.2. The performance results are obtained using SINTEF's in-house models for membrane separation [13]. The SPC of membrane separation decreases significantly with increasing CO₂ content. It is reduced by 52% when CO₂ content increases from 11% to 27.5%.

Table 3.2: Key energy consumption data for CO₂ capture processes

	CO ₂ content, [mole%]	11%	15%	20%	27.5%
Saipem solvent [14]	SRD (specific reboiler duty), [MJ/kgCO ₂] (around 80°C)	3.35	3.44	3.42	/(note 1)
	SPC (specific power consumption), [MJ/kgCO ₂]	0.47	0.44	0.41	/(note 1)
MEA [12]	SRD, [MJ/kgCO ₂] (around 120°C)	3.68	3.63	3.59	3.54
	SPC, [MJ/kgCO ₂]	0.1	0.08	0.06	0.02
AMP-PZ	SRD, [MJ/kgCO ₂] (around 120°C)	2.91	2.97	2.95	2.92
	SPC, [MJ/kgCO ₂]	0.1	0.08	0.06	0.02
Membrane	SPC, [MJ/kgCO ₂]	1.43	1.14	0.88	0.69

Note 1: 27.5% of CO₂ concentration is within the range of applicability for Saipem enzymatic solution technology. This case has not been simulated for the development of this specific report.

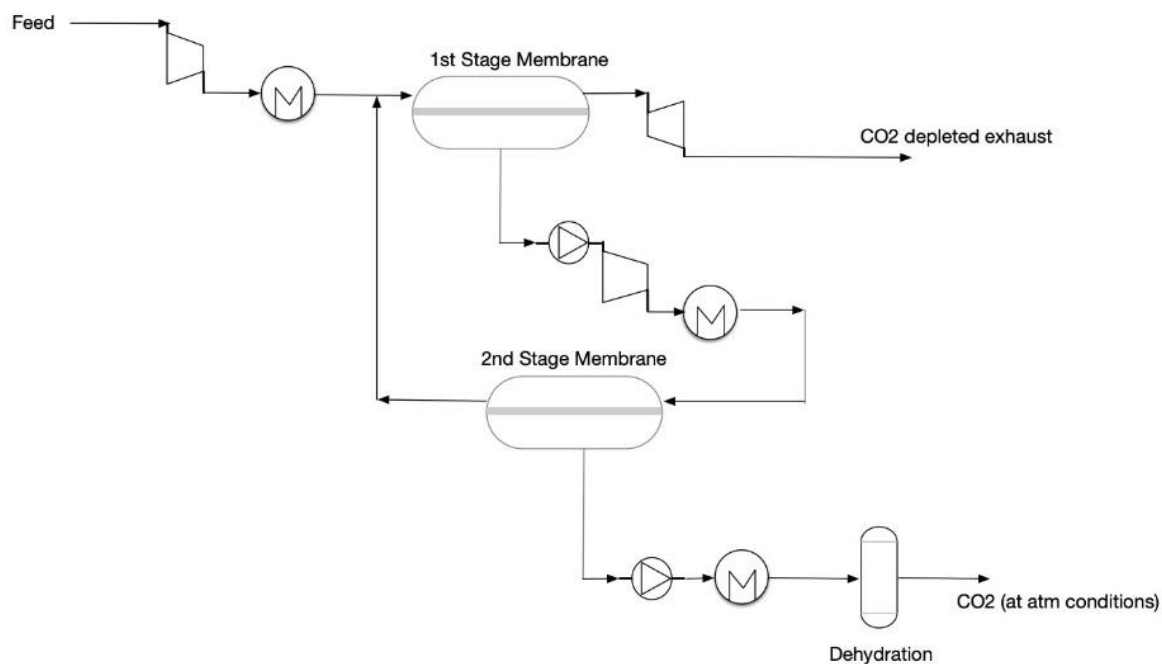


Figure 3.2: PFD of the two-stage membrane separation with recycling

4 PERFORMANCE SUMMARY

As presented in Section 3.2, the energy consumption of CO₂ capture generally decreases with increasing CO₂ content. However, the energy consumption of oxygen supply is also higher in order to achieve higher CO₂ content. This section presents the overall performance results. Since the pressure of CO₂ captured is somewhat different for each technology, the CO₂ is assumed to be compressed to the same target pressure (110 bara) for transport.

4.1 Heat to power ratio

Heat to power ratio is an “efficiency” factor to convert heat to work. In combined heat and power plants where steam is extracted from the steam cycle to supply heat, this is the amount of power that could have been generated if the steam was not extracted. Since both heat and power are consumed in solvent capture processes such as the CO₂ Solutions by Saipem solvent, MEA and AMP-PZ, heat to power ratio is used to estimate the equivalent power consumption of heat consumed. This equivalent power is defined as separation power in this study. The heat to power ratio is obtained based on the models of the KVA Linth WtE plant as developed in the framework study by evaluating the loss in power production by steam turbine when extracting the heat for solvent regeneration [2]. This factor is more practical than using exergy (or the Carnot factor) to determine the equivalent power consumption. For amine capture (MEA and AMP-PZ), the pressure of steam extracted for solvent regeneration is 3.5 bara. The heat to power ratio is determined to be 4.2. As for the CO₂ Solutions by Saipem solvent, the temperature of heat required is much lower and hot water is used, instead of steam. It is challenging to estimate the equivalent power consumption of hot water consumed. A heat to power ratio of 8.8 has been estimated using a similar approach, by assuming a virtual case that steam with a saturation temperature of 80°C is extracted from steam turbines for solvent regeneration.

Detailed heat integration of the WtE plant with the CO₂ capture process will provide the realistic heat to power ratio. However, for this work, a simple approach was used to identify the heat to power ratio. The trend of the effect of the power consumption with respect to CO₂ concentration is not expected to change when using a simple heat to power ratio factor, as done in this study, or using detailed integration. Thus, the absolute values of the specific power consumption of the different processes can, in theory, be lowered by optimal heat integration. This is particularly true for the CO₂ Solutions by Saipem technology where hot water is used rather than steam. This is one of the reasons why the results of this work should not be used to compare the technologies for post-combustion capture from WtE plants.

4.2 The oxy-combustion CO₂ capture process

A full oxy-combustion CO₂ capture process has been studied to further understand the potential of using oxygen-enriched combustion. Oxygen with a purity of 95 mole% is assumed to be supplied by cryogenic distillation. The CO₂ content in the flue gas is 74% (dry basis) while remaining components are mainly N₂ and O₂. The recycling ratio of EGR is 0.77. As a result, a compression and purification unit (CPU) is necessary to condition CO₂ to the required conditions for transport. The models of the CPU presented in [15] have been used in this study to evaluate the performance of the CPU.

4.3 Overall performance

The equivalent total specific power consumption (SPC_{eq}) for each capture technology is shown in Figure 4.1. The energy consumption depends on computational assumptions and the level of optimization applied. The purpose of this study is not to make direct comparisons between different capture technologies. The performance summary visually represented in Figure 4.1 is to give an overview of the potential for energy saving by using oxygen-enriched combustion for each capture technology. Details about the performance results can be found in Appendix Table 1.

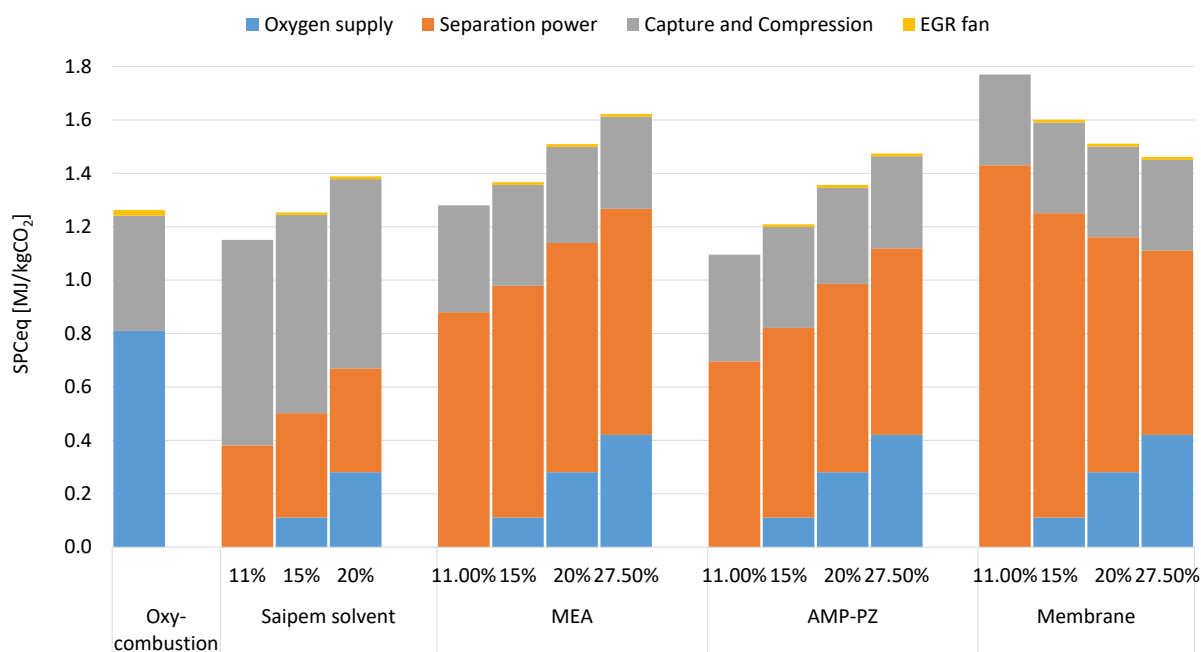
For CO₂ Solutions by Saipem solvent, the changes in separation power are negligible. The increased power consumption related to oxygen supply is more than the power savings related to CO₂ capture and compression. As a result, the overall equivalent SPC increases by 21% from 1.15 to 1.40 MJ/kgCO₂ when the CO₂ content increases from 11% to 20%. The total amount of flue gases to be processed in the capture unit is reduced by 40%. It is valuable to note that the separation power is less than the power consumption related to CO₂ compression since very low temperature heat has been used for solvent regeneration.

Similarly, the overall equivalent SPC increases by 27% and 35% respectively for MEA and AMP-PZ capture when the CO₂ content increases from 11% to 28%. The savings in heat consumption i.e. SRD and thus separation power, which dominates the total SPC, are small. The changes in power consumption of capture and compression are negligible. However, the power consumption for oxygen supply increases considerably. On the other hand, the amount of flue gases to be processed in the capture unit is reduced by 55%. The sizes of equipment, and thus CAPEX, of the capture unit are thus expected to be smaller.

For the membrane capture process, the separation power is considerably reduced by 52% from 1.4 to 0.69 MJ/kgCO₂ due to increased CO₂ content in the flue gases (from 11% to 28%). The savings in separation power are more than the increased power consumption of the oxygen supply. The changes in compression power and EGR fan power are negligible. As a result, the overall SPC decreases by 18%. In addition, the amount of flue gases to be processed in the capture unit is also reduced by 55%.

For oxy-combustion, the total SPC is around 1.3 MJ/kgCO₂, while the power consumption related to oxygen supply and CO₂ compression contributes 64% and 34% respectively. Cryogenic distillation is assumed to be used for oxygen supply. This option seems to be competitive from the viewpoint of total SPC.

Note that heat consumption for solvent regeneration is not required in the oxy-combustion and membrane capture cases. The capture technologies may be attractive for WtE plants where heat production should be maximized or other industrial plants where the availability of heat sources is limited for solvent regeneration.



Note: 27.5% of CO₂ concentration is within the range of applicability for CO₂ Solutions by Saipem enzymatic solution technology. This case has however not been simulated for the development of this specific report.

Figure 4.1: Equivalent total specific power consumption (SPC)

5 COST ANALYSES

Based on the results of Section 4, qualitative cost analyses can be concluded for solvent capture and membrane capture processes, as presented in Table 5.1. The plus and minus signs represent increasing and decreasing cost compared to the air-fired case i.e. 11% CO₂ in the flue gases. The CAPEX of CO₂ capture is reduced due to smaller amount of flue gases to be processed in the capture unit when EGR is considered. The OPEX of CO₂ capture is also reduced due to less energy consumption although the reductions in solvent capture processes are very small. The oxygen supply i.e. OEA production increases both CAPEX and OPEX. In addition, the EGR also increases CAPEX (and slightly OPEX). A qualitative cost estimation has been performed to further understand the potential of using oxygen-enriched combustion. Since the solvent capture processes show very similar trends in the changes of both energy consumption and equipment sizes with CO₂ content in the flue gases, the cost analyses focus only two capture processes: MEA and membrane capture. The objective is to understand how CAPEX and OPEX change with CO₂ content compared to air-fired cases.

Table 5.1: Qualitative cost analyses.

	Solvent capture	Membrane capture
CAPEX of oxygen supply	+	+
CAPEX of CO ₂ capture	-	-
CAPEX of flue gas recycling	+	+
OPEX of oxygen supply	+	+
OPEX of CO ₂ capture	-	-

5.1 Costing methodology

5.1.1 Costing of CAPEX

The costing of CAPEX is based on the most up-to-date guidelines published for cost evaluation of CCS [16]. The assumptions of costing analyses are presented in Table 5.2. The installation cost of equipment has been converted to total direct cost (TDC), total plant cost (TPC), total capital requirement (TCR) and eventually annualized CAPEX based on the approaches presented in [2] [15]. All the cost has been converted into the 2022 basis using the Chemical Engineering Plant Cost Index (CEPCI).

Table 5.2: Assumptions for cost analyses

Parameter	Value	References
Exchange between EUR and USD	1.14	[2]
Number of annual operating hours	8000	[15]
membrane price, USD/m ²	40	Estimated based on [17]
Price of electricity, [€/kWh]	0.076	[2]
Process contingency, [%]	15	[15]
Indirect cost, [% TDC]	14	[15]
Owner cost, [% TDC]	7	[15]
Project contingencies, [% TDC]	30	[2]
From TPC to TCR	15	[15]
Discount rate, [%]	8	[15]
Number of years of operation	25	[15]
Reference year, start of operation	1	[15]
Annualization factor	11.57	[15]

5.1.1.1 Costing of OEA production

The area and installation cost of membranes required for OEA supply are determined based on the total flow of OEA and the specific area and cost of a single membrane module in literature [17]. The installation cost of vacuum pumps is estimated based on the approach presented in [18]. The six-tenths rule has been used by taking as a reference vacuum pump with known suction flow rate and cost.

5.1.1.2 Costing of CO₂ capture section

For the MEA capture process, the changes in flowrate and CO₂ content of flue gases mainly change the cost of the absorber section including (1) the direct contact cooler including pumps and coolers, (2) the absorber column and (3) the water wash column including pumps and coolers. Since the amount of CO₂ to be captured is almost the same for the cases with different CO₂ contents, it is reasonable to assume that the changes in the cost of the regenerator and other units are negligible. The changes in cost of CO₂ compression process are also neglected. The CAPEX of the absorber section is estimated based on previous costing studies at SINTEF [19].

For the membrane capture process, the area and CAPEX of the membranes are obtained based on SINTEF's in-house models for membrane capture [13].

5.1.1.3 Costing of furnaces and flue gas recycling

One purpose of using flue gas recycling is to ensure that the temperature and the amount of flue gases are close to the air-fired cases. It is reasonable to assume that the changes in the cost of furnaces and flue gas cleaning units such as deSO_x, deNO_x and dust removal are negligible unless the EGR is recycled prior to flue gas cleaning (much less amount of flue gases will be processed in flue gas cleaning units then). The cost of the flue gas recycling fans is estimated using the approach presented in [20]. The cost of ducting is estimated based on [19] assuming a length of 70 meters.

5.1.2 Costing of OPEX

Since the study focuses on the trend of changes in cost of cases with different CO₂ contents, the dominant changes should be cost of equivalent power consumption. The changes in other OPEX costs such as fixed OPEX (maintenance, labour, insurance and location tax), and variable OPEX (MEA solvent, process water and cooling water) are neglected.

5.2 Results and discussions

Solvents and oxygen-enriched combustion:

The results of cost analyses for the MEA and membrane capture processes are presented in Appendix Table 2. For the MEA capture process, the total capital requirement (TCR) of the capture section is reduced by 2.1 m€ when the CO₂ content increases from 11% to 28% since the amount of flue gases to be processed is smaller with EGR. However, the overall TCR increases by 4.78 m€ mainly due to the high CAPEX of OEA production. In addition, the annual OPEX increases by 0.37 m€ due to increased power consumption. As a result, the overall annualized cost increases by 0.80 m€. The oxygen-enriched combustion thus seems to be less attractive for solvent capture processes presented in this study. The reductions in energy consumption of the capture processes are much less than the increased energy consumption for the OEA production. In addition, the CAPEX of the OEA production is larger than the reductions in the CAPEX of capture unit.

Membranes and oxygen-enriched combustion:

For the membrane capture process, the TCR of the capture section is reduced by 5.3 m€ when the CO₂ content increases from 11% to 28%, which is close to the increased TCR for the OEA production. The overall annualized cost decreases by 0.19 m€ due to reduced overall power consumption. The oxygen-enriched combustion seems to be promising for membrane capture particularly for plants where heat is limited or not available for solvent regeneration.

Trade-off considerations:

While the cost of capturing CO₂ decreases with increasing concentration when using oxygen enriched combustion, it is important to consider the increased complexity. The increased complexity comes from an additional separation process step for air that needs to be included and a flue gas recycle stream needs to be added. This may require modifications to the furnace. Thus this qualitative trade-off between the increased complexity of the process and the reduction in cost must be kept in mind if the advanced configuration is better for a given situation.

Oxygen-enriched air production:

The high energy consumption and CAPEX related to the production of OEA seems to be key challenges to implement oxygen-enriched combustion. It should be noted that the CO₂ content has been limited to 28% in this study since the oxygen content is limited to around 40% in the OEA based on current commercially available membrane technologies. As discussed in Section 3.1, the

increment in oxygen requirement becomes smaller for the range of higher CO₂ contents. This means that both power consumption and CAPEX related to the production of OEA increase less with the CO₂ content. Indeed, it is found that OEA with an oxygen purity of 70% can lead to considerable reductions in both total energy consumption and cost of CO₂ capture when oxygen-enriched combustion is combined with a membrane post-combustion process [18]. The study relies on upcoming developments of advanced membrane materials for the production of OEA.

It should be noted that the air used to be mixed with oxygen for producing OEA (as shown in Figure 3.1) can be used as sweet gases for the post-combustion membrane separation process [21]. This will increase the CO₂ content in the OEA and thus CO₂ content in the flue gases, which may further reduce the energy consumption of membrane CO₂ capture processes.

6 CONCLUSIONS

This study investigates the opportunities and challenges of enhanced CO₂ capture for waste to energy plants using oxygen-enriched combustion with exhaust gas recirculation. The CO₂ content increases from 11% to 28% when polymeric membranes are used to produce oxygen-enriched air with an oxygen purity up to 39%. The requirement of oxygen supply increases considerably within the low range of CO₂ contents. As a result, the energy consumption and CAPEX for producing oxygen-enriched air increases considerably. The amount of flue gases to be processed in the capture process is reduced by 55%. For the three solvent capture processes (CO₂ Solutions by Saipem solvent, MEA and AMP-PZ), the reductions in energy consumption related to CO₂ capture are small. As a result, the overall energy consumption increases. The reduction in the CAPEX of the MEA capture process is also smaller than the increased CAPEX for oxygen-enriched air production. As a result, both CAPEX and OPEX increases for the MEA capture process. For the membrane capture process, the overall energy consumption is reduced by 18% when the CO₂ content of the flue gases increases to 28%. The reduction in the CAPEX of the membrane capture process almost equals the increased CAPEX of oxygen-enriched air production. As a result, the overall annualized cost is reduced.

The following conclusions can be drawn:

- (1) Based on state-of-the-art technologies for oxygen-enriched air supply, oxygen-enriched combustion is competitive neither in terms of energy consumption nor in terms of costs for post-combustion CO₂ capture using the solvents evaluated in this study.
- (2) For the range of CO₂ content evaluated in this study, oxygen-enriched combustion seems promising for membrane capture processes. This is particularly attractive for plants where heat is limited or not available for solvent regeneration.
- (3) It is anticipated that the energy consumption and CAPEX of membranes for oxygen-enriched air production will decrease while the oxygen purity will increase with the development of advanced membrane materials. The CO₂ content in the flue gases will be much higher and thus the oxygen-enriched combustion will thus be more competitive.

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APPENDIX

A APPENDIX TABLES

Appendix Table 1: Performance Summary

	Air-fired without capture	Oxy- combustion	Saipem solvent (note 1)			MEA				AMP-PZ				Membrane			
CO2 content			11%	15%	20%	11.0%	15%	20%	27.5%	11%	15%	20%	27.5%	11%	15%	20%	27.5%
MSW, [kg/h]	6000	6000	6000	6000	6000	6000	6000	6000	6000	6000	6000	6000	6000	6000	6000	6000	6000
Air supply, [kg/h]	42073	0	42073	27090	12314	42073	27090	12314	0	42073	27090	12314	0	42073	27090	12314	0
Oxygen supply from ASU, [kg/h]	0	7002	0	4595	11640	0	4595	11640	17444	0	4595	11640	17444	0	4595	11640	17444
Oxygen purity of ASU	/	0.95	/	0.392	0.392	/	0.392	0.392	0.392	/	0.392	0.392	0.392	/	0.392	0.392	0.392
Total oxygen supply, [kg/h]	9676.8	6694	9676.8	8284	7824	9676.8	8284	7824	7413	9676.8	8284	7824	7413	9676.8	8284	7824	7413
Oxygen content in oxidant	0.21	0.95	0.21	0.236	0.297	0.21	0.236	0.297	0.392	0.21	0.236	0.297	0.392	0.95	0.24	0.297	0.21
Specific power consumption for ASU, [kWh/kgO ₂]	0	0.23	0	0.043	0.043	0	0.043	0.043	0.043	0	0.043	0.043	0.043	0	0.043	0.043	0.043
Power consumption for oxygen supply, [MW]	0.000	1.540	0	0.198	0.501	0.000	0.198	0.501	0.750	0.000	0.198	0.501	0.750	0.000	0.198	0.501	0.750
Specific power consumption for oxygen supply, [MJ/kgCO ₂]	0	0.810	0	0.111	0.281	0.000	0.111	0.281	0.421	0.000	0.111	0.281	0.421	0.000	0.111	0.281	0.421
Flue gas flowrate for CO ₂ capture or compression, [kg/h]	43801	8950.000	43801	34239	26360	43801	34239	26360	19725	43801	34239	26360	19725	43801	34239	26360	19725
CO ₂ content, [dry]	0.114	0.743	0.114	0.149	0.198	0.114	0.149	0.198	0.276	0.114	0.149	0.198	0.276	0.114	0.149	0.198	0.276
CO ₂ flowrate, [kg/h]	7133	7127	7133	7133	7132	7133	7133	7132	7132	7133	7133	7132	7132	7133	7133	7132	7132
CO ₂ capture rate	0	0.96	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9
CO ₂ captured, [kg/h]	0	6841.92	6419.7	6419.7	6418.8	6419.7	6419.7	6418.8	6418.8	6419.7	6419.7	6418.8	6418.8	6419.7	6419.7	6418.8	6418.8

SRD, [MJ/kgCO ₂]	0	0	3.35	3.44	3.42	3.68	3.63	3.59	3.54	2.91	2.97	2.95	2.92	0	0	0	0
Heat to power ratio	/	0	8.8	8.8	8.8	4.18	4.18	4.18	4.18	4.18	4.18	4.18	4.18	0	0	0	0
Separation power, [MW]	0	0	0.679	0.697	0.693	1.569	1.548	1.531	1.509	1.241	1.266	1.258	1.245	2.550	2.033	1.569	1.230
Specific separation power, [MJ/kgCO ₂]	0	0	0.381	0.391	0.389	0.880	0.868	0.858	0.846	0.696	0.710	0.705	0.698	1.430	1.140	0.880	0.690
Power consumption for capture and compression, [MW]	0	0.821	1.373	1.323	1.264	0.713	0.674	0.642	0.615	0.713	0.674	0.642	0.615	0.606	0.606	0.606	0.606
Specific power consumption for capture and compression, [MJ/kgCO ₂]	0	0.432	0.77	0.742	0.709	0.4	0.378	0.360	0.345	0.400	0.378	0.360	0.345	0.34	0.34	0.34	0.34
EGR ratio	0	0.768	0	0.187	0.356	0	0	0	0	0	0	0	0	0	0.187	0.356	0.506
Fan power for EGR, [MW]	0	0.04	0	0.018	0.018	0	0.018	0.018	0.018	0	0.018	0.018	0.018	0	0.018	0.018	0.018
Specific fan power for EGR, [MJ/kgCO ₂]	0	0.021	0.000	0.010	0.010	0.000	0.010	0.010	0.010	0.000	0.010	0.010	0.010	0.000	0.010	0.010	0.010
Total power consumption related to CO ₂ capture, [MW]	0	2.401	2.052	2.236	2.476	2.282	2.438	2.691	2.893	1.954	2.156	2.418	2.628	3.156	2.855	2.694	2.605
Total specific power consumption related to CO ₂ capture, [MJ/kgCO ₂]	0	1.263	1.151	1.254	1.388	1.280	1.367	1.509	1.622	1.096	1.209	1.356	1.474	1.770	1.601	1.511	1.461

Appendix Table 2: Results of cost analyses

	MEA				Membrane			
	11%	15%	20%	27.5%	11%	15%	20%	27.5%
CAPEX								
Oxygen supply								
OEA supply, [kg/h]	0	4595	11640	17444	0	4595	11640	17444
Membrane area, [m ²]	0	10726	27171	40719	0	10726	27171	40719
Installation cost of membrane, [kEUR]	0	509.2	1289.9	1933.1	0.0	509.2	1289.9	1933.1
Installation cost of vacuum pumps, [kEUR]	0	468.8	818.8	1043.7	0.0	468.8	818.8	1043.7
Increment in TDC, [kEUR]	0	1271.4	2741.3	3869.9	0.0	1271.4	2741.3	3869.9
Increment in TCR of oxygen supply section, [m€]	0	1.988	4.287	6.052	0.000	1.988	4.287	6.052
CO₂ capture								
Flue gas flowrate, [kg/h]	43801	34239	26360	19725	43801	34239	26360	19725
Absorber diameter, [m]	2.4	2.2	1.9	1.7	2.4	2.2	1.9	1.7
Increment in absorber section CAPEX, [m€]	0	-0.857	-1.562	-2.144	0	0	0	0
Regenerator diameter	0	0	0	0	0	0	0	0
Increment in regeneration & others section CAPEX, [m€]	0	0	0	0	0	0	0	0
Increment in TCR of CO₂ capture section, [m€]	0	-0.857	-1.562	-2.144	0.000	-2.722	-3.908	-5.322
Increment in TCR of CO₂ compression section, [m€]	0	0	0	0	0	0	0	0
Increment in TCR of EGR path, [m€]	0	0.819	0.847	0.865	0.000	0.819	0.847	0.865
Increment in overall TCR, [m€]	0	1.951	3.572	4.774	0.000	0.153	1.319	1.702
Increment in annualized CAPEX, [m€]	0	0.175	0.318	0.423	0.000	0.013	0.114	0.148
OPEX								
Equivalent power consumption, [MW]	2.282	2.438	2.691	2.893	3.156	2.855	2.694	2.605
Increment in annual cost of electricity, [m€]	0.000	0.094	0.249	0.371	0.000	-0.183	-0.281	-0.335
Total increment in overall annualized cost, [m€]	0.000	0.270	0.566	0.794	0.000	-0.170	-0.167	-0.188

Note 1: 27.5% of CO₂ concentration is within the range of applicability for Saipem enzymatic solution technology. This case has not been simulated for the development of this specific report