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Preliminary results of a techno-economic assessment of CO_2 capture-network configurations in the industry

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Abstract

This paper evaluated the techno-economic performance of several CO_2 capture-network configurations for a cluster of sixteen industrial plants in the Netherlands using bottom-up analysis. Preliminary findings indicate that centralizing capture equipment – instead of capture equipment at plant sites – shows lower average CO_2 avoidance costs for both post-combustion (central: 70 €/t; decentral: 86 €/t) and oxyfuel combustion (central: 63 €/t; decentral: 80 €/t) technology, because of economic scale effects, use of large-scale CHP plants and revenues from electricity sale to the grid. Centralizing capture equipment is particularly interesting for small point sources, since these plants benefit most from economies of scale.

Keywords: industry; techno-economic; regional case study; post-combustion; oxyfuel; system analysis; refinery; hydrogen; CHP

1. Introduction

Carbon capture and storage (CCS) can play a major role in mitigating CO_2 emissions in the industrial sector. According to the IEA [1,2], the deployment of CCS in the industrial sector can contribute to around 30-50% of the overall CO_2 emission reductions needed in the industrial sector to achieve a 450 ppm(v) stabilization target. However, carbon prices are currently well below CCS costs, and are not expected to increase sufficiently to make CCS a competitive CO_2 abatement option in the short term [3]. Reduction in CCS costs for the industry is, therefore, important. Previous research [4] has indicated that applying CCS to a cluster of industrial plants can be more cost-effective than a collection of individual CCS initiatives. Such configurations can be distinguished not only by the choice of the main CO_2 capture technology, but also by the way the capture technology is implemented. For example, by building the

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different units for the CO_2 capture and compression processes either at each individual plant or at a central location. However, the techno-economic performance of industrial clusters has, so far, hardly been evaluated in detail. This paper reports the methodology and preliminary results of research currently being conducted to investigate the techno-economic performance of several post- and oxyfuel combustion CO_2 capture-network configurations for a cluster of industrial plants by using a bottom-up analysis. A complete assessment, including pre-combustion configurations as well as the location and spatial footprint of the configurations, will be presented in a research paper which is under preparation.

2. Method

2.1 System boundaries, timeframe and CO_2 capture technologies

The scope of this study covers CO_2 capture and compression, the local network needed for transport of CO_2, O_2, flue gases and/or post-combustion amine solutions, the location and spatial footprint of the configurations, and the additional electricity and heat infrastructure required for CO_2 capture and local transport. This study does not consider the optimal CO_2 capture and transport configuration on the plant site itself. CO_2 transport through a trunk CO_2 pipeline, and CO_2 storage are outside the system boundaries. The time frame of this study is the short term (2020-2025) and therefore, the CO_2 capture routes investigated are based on commercially available technologies: post-combustion using amine absorption (monoethanolamine, MEA) and oxyfuel combustion using cryogenic oxygen production.

2.2 Case study: Botlek area

The analysis focuses on the industrial Botlek area in the Netherlands, which has a high concentration of small and large point sources from various industrial sectors. This study investigated the sixteen largest CO_2 emitters, together emitting around 7 Mt CO_2 yearly (see Table 1). For the year 2020-2025, we assumed the planned trunk CO_2 pipeline to operate at 110 bar.

Table 1. Main CO_2 point sources in the Botlek area and their respective annual CO_2 emissions in 2010 [5].

Plant type	CO_2 produced (kt/y)	Plant type	CO_2 produced (kt/y)	Plant type	CO_2 produced (kt/y)
Refinery	2,200	Chemical	228	Chemical	80
Waste processing	1,760	Utility	204	Chemical	61
Industrial gases	800	Chemical	181	Industrial gases	53
Utility	465	Chemical	133	Chemical	26
Chemical	411	Chemical	101	Biofuels	18
Industrial gases	403				
Total CO_2 emissions Botlek: 7,123 kt/y					

2.3 CO_2 capture-network configurations

Capture-network configurations were distinguished by varying the locations of the different units needed for CO_2 capture and compression (such as the flue gas conditioning units, amine-absorbers, strippers, CO_2 treatment units, compressors, energy plants, and air separation units). These units were either placed in a decentral location at a specific industrial site, or at a centralized location. As a consequence, the capture and utility units vary in scale: smaller scales at the industrial sites or larger at central locations where flows from different industrial sites are jointly treated. Also, the necessary infrastructure is completely different because different flows need to be transported, such as flue gas, low pressure CO_2, high pressure CO_2, O_2, CO_2-rich-amines, and/or CO_2-lean-amines.

Three main post-combustion configurations were investigated: a decentralized case with all capture units at individual plant sites (Post-decentral), a centralized case with most units at one central location

(Post-central), and a case in which the flue gas conditioning and absorption takes place at industrial plant level, but the regeneration and compression take place at a central location (Post-Recsor [†]) (see Figure 1). Sub-cases were designed based on the type of heat and electricity production unit used for the CO_2 capture process: a boiler without CO_2 capture (vent) and electricity import from the grid, an NGCC-CHP (CHP) without CO_2 capture, or by these technologies with CO_2 capture (CC).

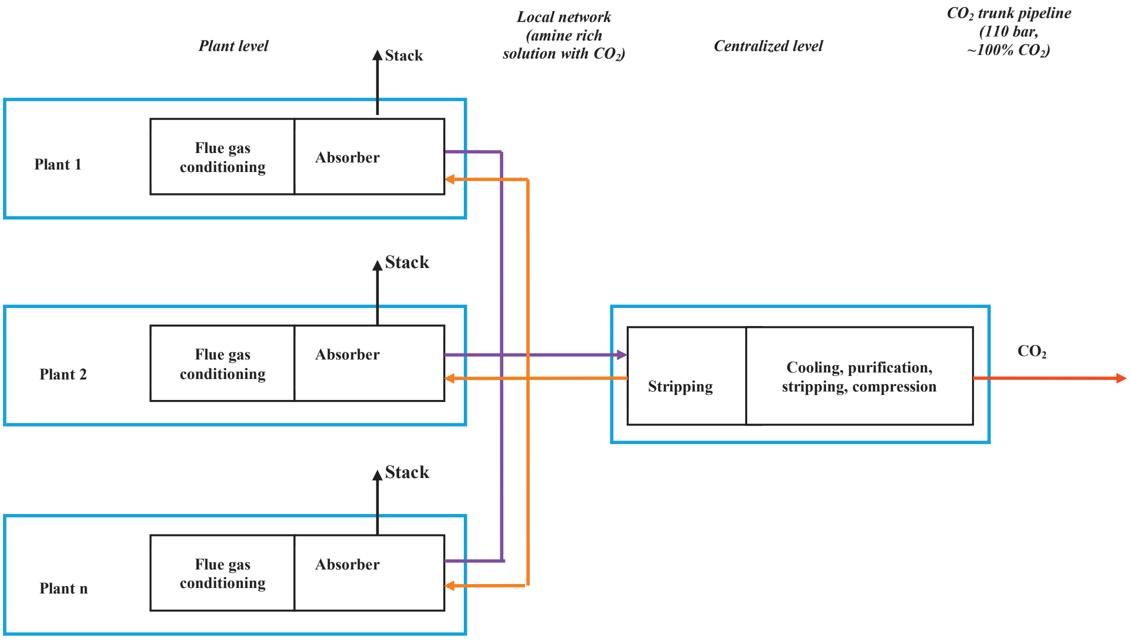

Figure 1 Schematic overview of CO_2 capture-network configuration with a separated absorption and stripping section. The purple, orange and red arrows denote the CO_2-rich amine flow, the CO_2-lean amine flow, and the CO_2 flows, respectively. The blue boxes represent the industrial plants' sites.

Two main oxyfuel combustion configurations were distinguished by having the ASU, CO_2 treatment units (drying, cooling, purification) and compressors: at plant level (Oxy-decentral), the ASU central and the CO_2 treatment and compression decentral (Comp-decentral), and all units at one or a few central locations (Oxy-central) (see Figure 2). Furthermore, the way of electricity production for the ASU and compressor was varied: either electricity import (EI), a gas turbine without CO_2 capture (GT/vent), or a gas turbine with CO_2 capture (GT/CC).

[†] Recsor stands for REmote Centralized SOlvent Regeneration

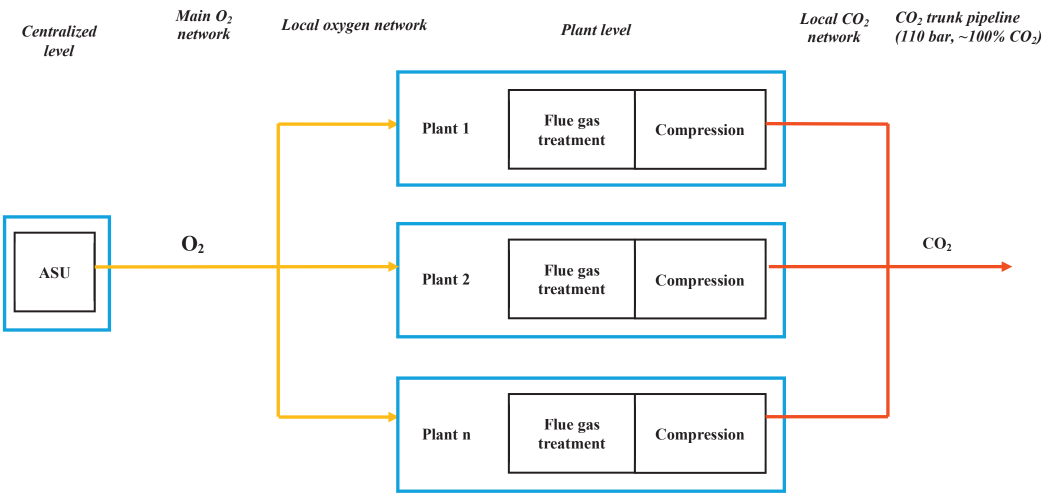

Figure 2 Schematic overview of oxyfuel combustion configuration with centralized oxygen production and flue gas purification and CO_2 compression at plant level. The yellow and red arrows denote the oxygen and the CO_2 flows, respectively. The blue boxes represent the industrial plants' sites.

2.4 Performance indicator and input data

A detailed description of the relevant equations used to calculate the technical and economic performance of the CO_2 capture-network configurations is given in [4] and [6]. Key performance indicators used in the analysis are shown in Table 2.

Table 2 Key performance indicators used in the analysis [4].

Performance indicator	Symbol	Unit
Electricity consumption	E_e	GJ_e/t CO_2 avoided
Heat consumption	E_{th}	GJ_{th}/t CO_2 avoided
Amount of CO_2 avoided	Y_a	t CO_2avoided/y
Specific capital costs	SC_{cap}	€/t CO_2 avoided
Specific O&M costs	$SC_{O\&M}$	€/t CO_2 avoided
CO_2 pipeline costs	C_p	€/t CO_2 avoided
CO_2 avoidance costs	C_{CO2}	€/t CO_2 avoided
Spatial footprint	A	m_2

Formula 1 presents the key economic performance indicator, CO_2 avoidance costs (€/t CO_2), which is particularly relevant for the results presented in this abstract.

$$C_{CO_2} = \frac{(El_{imp} - El_{exp}) * P_{el} + E_{ng} * P_{ng} + \alpha * I + C_{O\&M}}{Y_a} \quad (1)$$

with:

$$\alpha = \frac{r}{1-(1+r)^{-LT}} \quad (2)$$

where El_{imp} is the annual electricity import from the grid (GJ_e/y), El_{ex} is the annual electricity export to the grid (GJ_e/y), P_{el} is the electricity price (€/GJ_e), E_{ng} is the annual natural gas consumption (GJ_p/y), P_{ng} is the natural gas price (€/GJ_p), α is the annuity factor, I is the total capital expenditure (€/y), $C_{O\&M}$ is the annual operation and maintenance costs (€/y), Y_a is the annual CO_2 emissions avoided (t CO_2/y), r is the interest rate and LT is the economic life time (y). Table 3 presents general input parameters used for this study.

Table 3 General input parameters used in this study.

Parameter	Unit	Value	Source
Interest rate (r)	%	10	[6]
Economic lifetime (LT)	Years	20	[6]
Industrial energy price in 2025			
Natural gas (P_{ng})	€/GJ_{LHV}	9.3	[7,8,9]
Electricity (P_e)	€/GJ_e	18.5	
CO_2 emission factor			
Dutch electricity production (EF_{en})	kg CO_2 /GJ_e	88.9	[10]
Natural gas (EF_{ng})	kg CO_2 / GJ_{LHV}	56.7	[11]

Total capital costs were calculated by summing up the component costs that were estimated using data from open literature. Techno-economic input data for the post-combustion configurations were mainly taken from [12,13,14]; for the oxyfuel combustion configurations, data were mainly taken from [15,16]. Costs data found in literature were converted to €$_{2010}$. Inflation and material price increases were accounted for by applying the Chemical Engineering Plant Cost Index (CEPCI) [17]. Economic scaling factors from literature were used to adjust for differences in scale in the modeled component and the literature data. Uncertainty ranges were ±30%. Data on techno-economic performance of CHP plants and gas turbines was mainly taken from [18,19]. A more detailed overview on input data can be found in [4].

3. Preliminary results

3.1 Post-combustion

Table 4 presents the performance results for decentralized and centralized post-combustion CO_2 capture from the 16 industrial plants presented in Table 1. Figure 3 shows the *average* CO_2 avoidance cost as a function of total annual CO_2 emissions avoided. For the Post-decentral cases, the annual CO_2 emissions of the industrial plants on the x-axis are ordered from the lowest *average* CO_2 avoidance costs to the plant with the highest *average* CO_2 avoidance costs. For the Post-central cases, the plants are ordered from the plant with the highest amount of annual CO_2 emissions avoided (first plant) to the plant with the lowest amount of annual CO_2 emissions avoided (sixteenth plant).

Table 4 Key performance results for decentralized and centralized post-combustion CO_2 capture in the Botlek.

POST-COMBUSTION		Boiler				CHP			
		Decentralized		Centralized		Decentralized	Centralized		Recsor
		Vent	CC	Vent	CC	Vent	Vent	CC	CC
Total CO_2 emissions avoided	Mt/y	4.3	5.3	4.1	5.1	4.7	5.2	7.6	7.6
CAPEX	M€/yr	761	879	541	636	761	310	709	758
OPEX	M€/yr	87	107	87	107	87	87	122	122
Average CO_2 avoidance cost	€/t	124	123	136	133	86	77	70	71

As figure 3 shows, the centralized post-combustion capture configurations show lower average CO_2 avoidance costs than the decentralized capture configurations. The economic scale effects of centralized post-combustion capture outweigh the higher transport costs for the centralized cases, with the exception of the Post-central (boiler/vent) case, which is more expensive than the Post-decentral (boiler/vent) case due to limited economic scale effects of boilers and high electricity consumption needed for flue gas transport. The *average* CO_2 avoidance costs range from 135 €/t CO_2 (Post-decentral (boiler/vent)) to 70 €/t CO_2 (Post-central (CHP CC)). The Post-Recsor (CHP/CC) case shows slightly higher average CO_2

avoidance costs (71 €/t CO_2) compared to the Post-central (CHP CC) case. In general, the lower operational flue gas blowing expenses for the Post-Recsor (CHP/CC) case appear to outweigh the higher scale effects of the Post-central (CHP CC) case. However, the marginal avoidance costs of the Post-Recsor (CHP/CC) case increase rapidly for the smaller industrial plants, which is mainly due to the relatively high CAPEX of the local absorbers.

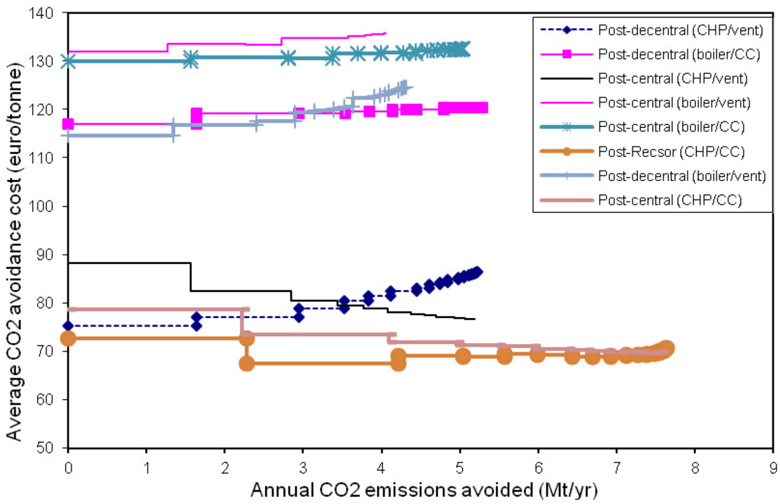

Figure 3 Average CO_2 avoidance costs as a function of annual total CO_2 emissions avoided for the post-combustion configurations.

3.2 Oxyfuel combustion

Table 5 presents the performance results for decentralized and centralized oxyfuel combustion CO_2 capture from point sources in the Botlek area. Figure 4 shows the *average* CO_2 avoidance cost as a function of total annual CO_2 emissions avoided.

Table 5 Key performance results for decentralized and centralized oxyfuel combustion CO_2 capture in the Botlek.

OXYFUEL COMBUSTION		Decentralized ASU	Centralized ASU	Centralized ASU		
		Local compression		Centralized compression		
		Electricity import		Electricity import	GT vent	GT CC
Total CO_2 emissions avoided	Mt/y	5.8	5.7	5.7	5.8	6.5
CAPEX	M€	2089	1609	1211	1211	1266
OPEX	M€/yr	107	107	107	107	107
Average CO_2 avoidance cost	€/t	80	77	69	66	63

The average CO_2 avoidance costs using oxyfuel combustion for the four Oxy-central cases (~63-77 €/t CO_2 avoided) appear more economical than the Oxy-decentral case (~80 €/t CO_2 avoided). However, for oxyfuel combustion, decentralized capture is still economically preferable over centralized capture up to about a cumulative amount of 2.0 Mt CO_2/y avoided, because the oxygen compression power for transport between the centralized ASU and the industrial plant is large and therefore costly. The *average* CO_2 avoidance costs of the Oxy-central (GT/vent) case are ~66 €/t CO_2 avoided and for the Oxy-central (GT/CC) case ~63 €/t CO_2 avoided. Note that the peaks in the cost supply curves (also for the post-combustion cases) are due to two reasons: (1) the addition of an extra CO_2 capture component results in lower economic scale effects (the amount of captured CO_2 is divided over the total amount of capture units), and therefore increases the capital costs per tonne of CO_2 avoided; (2) some industrial plants require more ducting/pipelines in terms of distance, and thus costs, than other.

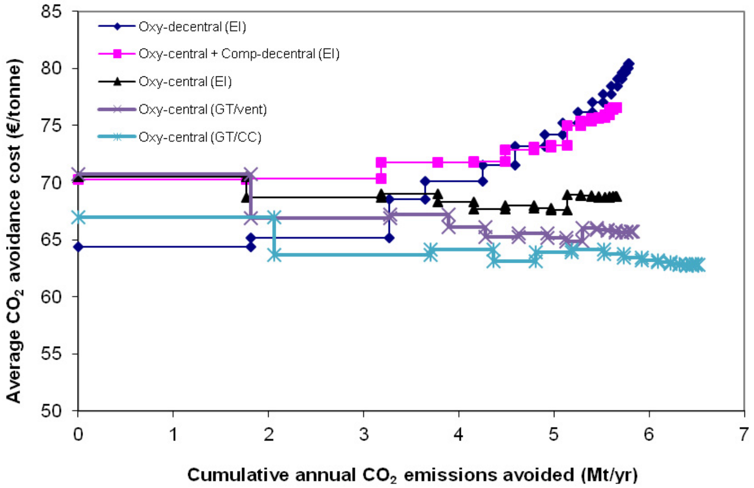

Figure 4 Average CO_2 avoidance costs as a function of annual total CO_2 emissions avoided for the post-combustion configurations.

4. Preliminary conclusions

This paper assessed the techno-economic performance of several CO_2 capture-network configurations for a cluster of 16 industrial plants, together emitting around 7 Mt CO_2 yearly, by using a bottom-up analysis. We presented the methodology and preliminary results of the post- and oxyfuel combustion configurations. A complete assessment, including pre-combustion configurations as well as the location and spatial footprint of the configurations, will be presented in a research paper that is under preparation.

Preliminary findings indicate that centralizing capture equipment (instead of placing capture equipment at industrial plant sites) results in lower average CO_2 avoidance costs for both post-combustion (Post-central (CHP/CC): 70 €/t; Post-decentral (CHP/vent): 86 €/t) and oxyfuel combustion (Oxy-central (GT/CC): 63 €/t; Oxy-decentral (El): 80 €/t) when capturing CO_2 emissions from all 16 industrial plants. Nevertheless, up to 2 Mt of avoided CO_2 emissions per year, decentralized oxyfuel combustion seems to be the most cost-efficient oxyfuel configuration. Overall, both for post- and oxyfuel combustion capture, the economic scale effects of centralized capture outweigh the higher transport costs for the centralized cases when capturing CO_2 from all 16 industrial plants. Centralizing CO_2 capture is particularly interesting for industrial plants with low CO_2 emissions, since these plants benefit most from economies of scale. Boilers are economically favorable for decentralized capture, while GT/CHP is economically favorable for centralized capture. The cases capturing CO_2 also from its own energy plants avoid significantly higher amounts of CO_2 compared to the other cases. This is not only because of the high capture rate, but also because of electricity export and thus the high amounts of CO_2 avoided in large-scale electricity plants. Currently, the research is being improved by using more specific data as well as by increasing the level of detail of particularly the local transport networks.

Further research is needed to investigate several aspects of the aforementioned capture network configurations in further detail, such as the impact of temporal fluctuations in flue gas and CO_2 streams on the techno-economic performance. Additionally, more attention needs to be given to the step-wise deployment of such configurations over time, the challenges it poses for the industrial plants and authorities, and the strategies needed to address these challenges in an adequate fashion.

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