Method to identify opportunities for CCU at regional level — Matching sources and receivers

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Abstract

Carbon Capture and Utilization is an attractive strategy not only due to its potential for CO_2 emissions reduction but also because it enables the creation of valuable products. The development of CO_2-based industrial symbiosis partnerships can contribute significantly towards achieving the goals of GHG emissions reduction on a European level by 2030, while at the same time it leads to an increased added value through the development of new production lines and carbon neutral products. The presented article focuses on identifying potential partnerships between companies that produce CO_2 and companies that may reuse CO_2 as input for their industrial process. A novel methodological framework is presented based on developing generic matrices for CO_2 sources and receivers and matching the industrial units based on geographical and technical criteria. Moreover, the paper provides the technical requirements of 17 CO_2 utilization technologies with relatively high technology readiness level, including the CO_2-to-product ratio, the required purity, pressure, temperature and the presence of a catalyst, as well as potential synergies and additional requirements. The methodology has been applied to the Västra Götaland region in West Sweden and the most promising CCU symbios~~i~~es have been identified. These include mineral carbonation (annual uptake: 59,600 tCO_2), greenhouses (26,000 tCO_2), algae production, methanol production (85,500 tCO_2), power to gas (66,500 tCO_2), pH control, lignin production, polymers synthesis and concrete curing (96,000 tCO_2). If all of them could be applied, the total annual CO_2 reduction would exceed 250,000 tCO_2 per year.

Keywords: Industrial symbiosis; CO_2 reuse; CCU logistics; CO_2 utilisation

1 Introduction

Global CO_2 emissions from fossil-fuel use and industry reached 35.7 billion tonnes in 2014 [1]. In 2015, during the Paris climate conference (COP21), 187 countries made commitments towards limiting the global temperature increase below 2 °C by 2100, as well as achieving zero net annual emissions of greenhouse gases (GHG) by the second half of the century. The European Commission has committed to reduce its GHG emissions by 40% below ~~their~~its 1990 level in 2030 [2].

Different strategies, policies and instruments ~~have to~~must be developed in order to meet these goals and Carbon Capture and Utilization (CCU) is an attractive one, not only because it contributes to CO_2 emissions reduction but also because it enables the creation of valuable products. In 2011, the Global CCS Institute and Parsons Brinckerhoff estimated that the global CO_2 reuse market ~~on a global level~~ was approximately 80 million tonnes per year [3]. Nevertheless, the various options for using CO_2 as input in industrial processes are in different stages of development and therefore their technology readiness level varies. Certain CO_2 technologies ~~CO_2~~ are already mature and widely used, such as the production of chemicals like urea, the carbonation of beverages, the direct use in refrigeration systems, welding systems and fire extinguishers or the use as an inert agent for food packaging, whereas there are other uses that are currently under development, such as the production of formic acid and polymers.

Several studies have been performed, focusing on a single CCU technology, including mineral carbonation [4], methanol production [5], power to gas [6], polymer production [7] formic acid [8] and enhanced oil recovery [9]. By contrast, studies focusing on the potential of CCU for the full range of available technologies are still at an early stage. In 2014, Element Energy together with Carbon Counts, PSE, Imperial College and the University of Sheffield, carried out a study of the technical potential of industrial CO_2 capture for storage or utilization for the deployment of CCU technologies in the UK by 2025 [10]. The study suggests four technologies that could be deployed in the UK: methanol production, mineral carbonation, polymer production, and direct industrial use of CO_2. Recently, the potential for CO_2 utilization technologies in China by 2020 and 2030 was assessed, with focus on 20 key CO_2 utilization technologies [11]. In 2016, Patricio and colleagues developed a methodology that identifies regions and countries in Europe with ~~the~~ higher CCU potential [12]. Nine different CCU technologies and the total amount of CO_2 released by large-scale industries in Europe were considered. Systemic methodologies for identifying and selecting potential CO_2 sources for CCU can also be found in the literature [13,9,14].

1.1 Industrial symbiosis and CCU

In order to take the next step and establish CCU symbiosis (industrial partnerships between carbon sources and sinks), it is necessary to formulate a methodology at the regional scale that identifies and connects prospective partners: the potential available sources of CO_2 and the potential CO_2 consuming industries (non-captive process), which can develop a cooperative relationship known as Industrial Symbiosis (IS). IS can be defined as inter-firm resource sharing, which includes physical exchange of materials, energy, water, and/or by-products among diversified clusters of firms. Such a co-operation has the potential to ~~should~~ minimize virgin material and energy input, as well as waste and emission output [15].

Several examples of CCU symbios~~i~~es have been established worldwide. In Iceland, Carbon Recycling International produces methanol at a large scale, having as input electricity and CO_2-containing flue gas from a geothermal power plant [16]. In the United Kingdom, a chemical company and a farmer have developed a collaborative scheme based on CO_2 and heat exchange, which allows the reduction of CO_2 emissions by 12.5 t a year and provides enough heat to support a new 38-acre greenhouse [17]. Moreover, Carbon8 uses CO_2 and waste heat to produce sustainable, carbon-negative construction aggregate since 2012 [18], whereas Novomer in the USA uses waste CO_2 to produce high performance and low cost polymers [19].

The process of developing and implementing industrial symbiosis is complex and can be divided in five development phases: (1) opportunity identification, (2) opportunity assessment, (3) barrier removal, (4) commercialization and adaptive management, and (5) documentation, review, and publication [20]. Our objective is to develop a systematic methodology for identifying opportunities for industrial symbiosis partnerships (Phase 1), but also delivering valuable information that can later contribute to the opportunity assessment (Phase 2). The methodology proposes an analytical tool that aims to facilitate the identification of potential partnerships between companies that produce CO_2 and companies that can in principle reuse CO_2 in their industrial process. To achieve this, our work uses both input-output matching as well as relationship mimicking and the knowledge can be used by third parties to identify promising opportunities for IS. A matrix of CO_2 sources, with their quantitative and qualitative characteristics, as well as a list of 17 different potential receivers of CO_2 as feedstock, are initially compiled. A top-down approach for the identification and matching of CO_2 sources and potential receivers is developed based on these matrices and is presented in Section 2. Section 3 describes its application to Västra Götaland, a region located in the western coast of Sweden and illustrates the main partnerships identified. Finally, Section 4 summarizes the conclusions of the analysis and presents suggestions for the next steps.

2 Methodology

The developed methodology consists of a top-down approach with three consecutive steps (Fig. 1). In the first step, a generic matrix of CO_2 sources by industry type is developed. It is populated based on a literature review and includes information on the typical physical and chemical characteristics of the effluent gases of the main CO_2 sources. ~~On a~~At the regional level, the CO_2 sources are mapped and classified based on this generic matrix. In the second step, the most promising technologies that could potentially reuse CO_2 (CO_2 receivers) are listed in a separate generic matrix, based again on literature review. The matrix of CO_2 receiving processes illustrates the requirements of each process, including the minimum acceptable level of CO_2 purity, the required quantity (CO_2 flow) and the appropriate conditions (temperature, pressure, presence of catalyst, auxiliary inputs). At the~~On a~~ regional level, the CO_2 receivers matrix can be used to identify existing companies that could potentially reuse CO_2, as well as new opportunities. Finally, the third step is performed at a regional level on a case by case basis. It involves matching the sources with the receivers, based on technical and geographical parameters. Each step of the methodology is explained in detail in the following subsections.

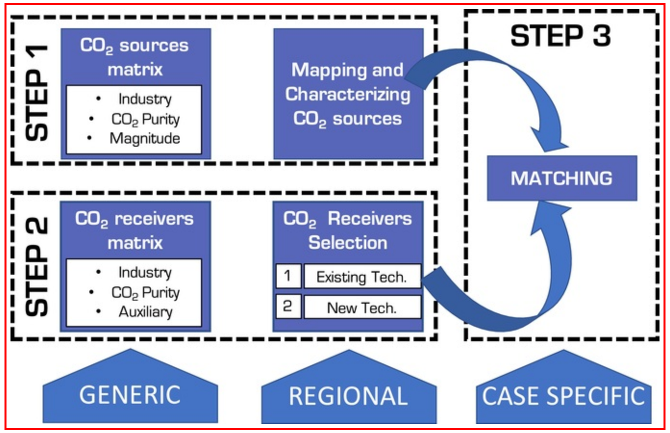

Fig. 1 Methodological framework for regional CCU.

alt-text: Fig. 1

2.1 CO_2 sources

For the purpose of this study, CO_2 sources are defined as stationary industrial sites that produce CO_2 during combustion (i.e., CO_2 flue gases) or as a by-product from an industrial process, e.g.: off-stream from a fermentation process [21]. The composition of the flue gases varies for each process, but typically includes nitrogen, carbon dioxide, carbon monoxide, hydrogen halides, oxides of nitrogen and sulfur, hydrogen sulfide, among others [22].

2.1.1 Developing a generic matrix of CO_2 sources

The two main characteristics of the CO_2 sources included in the developed matrix (Table 1) are the purity and the magnitude of the effluent gas flow. The purity is represented by the share of CO_2 in the flue gases of each source and the absence of critical contaminants. Both values were specified based on information on the typical off-gas composition by industry type, collected through a literature review. The magnitude of the flow for each type of industry was obtained using data from the European Pollutant Release and Transfer Database (E-PRTR). The maximum, minimum and average quantity of CO_2 released at the single installation level, for each industry type in Europe in 2012 was retrieved.

Table 1 Generic matrix of CO_2 sources.

alt-text: Table 1

Industry~~Field~~	NACE ~~C~~code	Source of emissions	Gas ~~C~~composition	Typical magnitude of the flow (Mtpa)			Source
				Min	Average	Max	
Biogas production	3521	During the purification process	CO_2: 99%, CH_4: 1%	<~~-~~0.1			[23]
Bioethanol ~~P~~production	1041	Fermentation process	CO_2: 100%	–	0.2	–	[24]
Energy, steam and air conditioning	3511	Natural gas fired boilers	CO_2: 7–10%, N_2: 78–80%, O_2: 2–3%	0.1	10.0	35.2	[25]; [26]
	3530						
	3511	Gas turbines	CO_2: 3–4%				
	3511	Oil fired boilers	CO_2: 11–13%, N_2: 78–80%, O_2: 2–6%				
	3511	Coal fired boilers	CO_2: 11%, O_2: 6%, N_2: 76%, H_2O: 6%, Ar: 1%, NO_x, Hg, Cd: 1%				
	3511	Integrated gasification combined cycle	CO_2: 12–14%				

Waste treatment/ Incineration	3821, other	Incineration of waste	CO_2: 10.0%, O_2: 9.5%, N_2: 80.4%, Other: 0.1%	0.2	0.4	0.5	[27]
Cement ~~I~~industries	2351	Cement ~~K~~kiln	CO_2: 22.4%, N_2: 68.1%, O_2: 2.3%, H_2O: 7.2%	0.1	0.5	2.1	[28]
Lime ~~P~~production	2352	Combustion of fuels in lime kilns	CO_2: 24–32%, CO: 2–7% SO_2 + NO_2: 1%, H_2O: 5–8%, O_2: 5–6%	0.1	0.3	2.0	[22]
Brick production	2332	Brick dryers and ~~K~~kilns	CO_2: 1.5-4.0%	–	0.4	–	[29]
Pulp ~~I~~industries	1711	Recovery boiler	CO_2: 13.3%, N_2: 63.3%, O_2: 4.4%, H_2O: 19%	0.1	0.9	1.8	[30]
Paper ~~I~~industries	1712	Energy production	CO_2: 13.3%, N_2: 63.3%, O_2: 4.4%, H_2O: 19%	0.1	0.5	2.6	[30]
Glass ~~I~~industries	2311		CO_2: 10%, O_2: 8–9%, H_2O: 10%, NO_X + SO_X + Dust: <1%	0.1	0.1	0.4	[31]
Petro-chemical ~~I~~industries	2013	Carbon ~~B~~black ~~M~~manufacturing	CO_2: 2–5%, CO: 10–11%, N_2: 36%, H_2O: 43%, CH_4: 0.2%, H_2:8%	–	0.2	–	[32]
	1920	Gas sweetening – ~~R~~refineries	CO_2: 96–99%, CH_4: 1–4%	–	1		[24]
	2011	Hydrogen production	CO_2: 100%	–	–	–	[33]
	2015	Ammonia ~~P~~production, Haber-Bosch process	CO_2: 30–99%	0.2	0.5	2.5	[24]
	2014	Ethylene oxide production	CO_2: 30–100%	0.1	0.2	6.8	[24]
	2016	Purified ~~t~~Terephthalic ~~a~~Acid (PTA) production	CO_2: 2%, H_2O: 12%, O_2: 3.5%, N_2: 83%	–	–	–	[34]
	2016	Polyethylene ~~P~~production~~.~~	CO_2: 5%, H_2O: 21%, O_2: 2%, N_2: 72%	0.2	0.6	4.8	[35]
		Cracker furnaces					
	1920	Gases coming from combustion, hydrogen plant, sulfur plant, flaring, coke burn off etc.	CO_2: 10–13%, H_2O: 10–12%, O_2: 1.7-4.5%, N_2: 73–75%	0.1	1.4	6.1	[36]; [37]
	1920	Oil ~~R~~refinery	CO_2: 8–24%, H_2O: 15%, O_2: 1–4%, N_2: 59–74% NO_X, SO_X < 1%	0.1	1.4	6.1	[38]
Beer and ~~W~~wine production	1105	Fermentation process	CO_2: 100%	<~~-~~0.1			[26]
Textile ~~I~~industry	1330	Heating energy and drying process	CO_2: 9%, H_2O: 19%, N_2: 72%	–	0.4	–	[39]
	1320						
Aluminum ~~P~~production	2442	Hall-Heroult process	CO_2: 3–10%, O_2: 18.8-20.7%, H_2O: 0.3-1%, N_2: 70.9-75.3%	0.1	0.3	0.5	[40]
Iron and Steel Industries(I am not able to change tis to: Iron and steel industries)	~~2593~~2410	Blast ~~F~~furnace	CO_2: 22%, N_2: 50%, H_2: 3%, CO: 20%, H_2O: 5%, SO_X ~~<~~≤2%, NO_X ~~<~~≤2%	0.1	0.3	11.4	[41–43,28]
	~~2561~~2410	TGRBF	CO_2: 22–38%, N_2: 3%, H_2: 8–24%, CO: 46–51%, SO_X ~~<~~≤2%, NO_X ~~<~~≤2%				
	2410	Corex	CO_2: 30%, N_2: 5%, H_2: 20%, CO: 40%, H_2O: 3%, SO_X ~~<~~≤2%, NO_X ~~<~~≤2%, CH4: 2%				

All the industrial types included in the matrix were also described using the Statistical Classification of Economic Activities in the European Community nomenclature (NACE), a standard unique code for each industry type. The NACE codes cover more than 900 different economic activities.

2.1.2 Mapping the CO_2 sources ~~on a~~at the regional level

~~On a regional level analysis, t~~The first step of the analysis is the identification of all the available local CO_2 sources at the regional level. For this purpose, the sources are classified into two groups according to the magnitude of their flows: (a) medium and large-scale sources, which emit more than 0.1MtCO_2~~*1~~ per year and (b) small-scale sources, which emit less than 0.1MtCO_2 per year.

Medium and large-scale sources are recorded in the ~~E-PRTR~~ publicly available E-PRTR database which includes information on the facility's name, its NACE code, geographical location and the annual quantities of released pollutants. It has been estimated that the facilities/emitters included in the E-PRTR cover approximately 90% of the CO_2 released by European industrial sources [44].

Small-scale sources are more difficult to identify. Some can be found in the E-PRTR database, as the activities they carry out are subject to emission reduction policies. However, the share of the facilities included is relatively small. Thus, additional data sources were included in the research, since it is important to ensure that small-scale, high-purity sources (30–100%) are identified for several reasons: (a) it is easier to capture CO_2 from high purity sources, due to their high partial CO_2 pressure [45]; (b) the commercial maturity of CO_2 capture technologies is higher for high purity CO_2 sources [10]; and (c) such sources can act as an add-on to nearby low purity sources to reduce the overall cost of capturing and transportation. These can include natural gas processing, biogas and bioethanol processing, ammonia production, ethylene oxide production, and wine and beer production [45,6]. The small-scale, high-purity sources are identified and geographically located using directories of companies or by directly contacting industry associations.

The inclusion of the NACE code in the regional catalogue of large and small-scale sources is critical. Based on this code, the regional industrial plants can be linked with the data, included in the generic matrix, and, in case of missing information, it is possible to use generic data for either the composition or the magnitude of the flow of the flue gas.

2.2 CO_2 receivers

There is a wide range of industrial processes, where CO_2 can be used as raw material or as a solvent. One of the reasons for the current low level of CO_2 consumption globally is due to the fact that CO_2 is considered a chemically inert compound, and therefore the majority of the processes that utilize CO_2 have substantial energy input requirements [46]. In the last decade, CCU has attracted worldwide attention and been used in pilot and demonstration plants, as well as in full-scale projects [47]. However, and despite existing examples, most of the technologies still need~~s~~ to be developed further~~further develop~~ and in most cases there is a need for added scalability and replication to ensure the widespread economic viability of the technologies [48].

2.2.1 Developing a generic matrix of CO_2 receivers

Based on an extensive literature review, a matrix of over forty CO_2-feedstock-receiving processes was compiled. However, the technologies to be studied in more detail were selected according to their maturity, as described by the Technology Readiness Level (TRL) value, and the size of the potential global market CO_2 for the resulting CO_2 containing product.

The maturity of the CO_2 receiving process is a critical parameter for the success of a potential CCU symbiosis. Each CO_2 consuming technology has thus been assigned a TRL, based on a literature review. The TRL is a system widely used to assess the maturity of a technology. Ranking ~~varies~~is scaled from 1 to 9, with 9 being the most mature process. According to the European Commission definition, technologies marked with TRL 1–3 are below proof of concept, those with TRL 4–6 have been tested in lab and demonstration scales, and those with higher than 7 are close to industrial production and commercial use. Only technologies with TRL ~~higher than 4~~5 or greater were chosen to be studied in more detail.

The second parameter is the quantity of CO_2 needed for the production of the intermediate chemical or the final product. There are several technologies that despite their high TRL, are considered to be low-volume applications, and are unlikely to substantially increase the CO_2 demand in their short to medium term. Examples include compressed CO_2 used in pneumatic energy sources, or CO_2 used for food packing or in refrigeration [49]. Thus, these technologies were not included in the developed matrix.

The final matrix contains ~~seventhen~~seventeen technologies (Table 2). For each ~~of the~~ technology, the matrix contains information on the NACE code of industries likely to use a particular technology, a short description of the CO_2 conversion methods and the TRL of each technology. It also provides information on the conversion quality requirements, including the conversion factor, i.e. the ratio of CO_2 use per unit of product or per unit of raw material consumed, the required CO_2 purity, and the operating conditions of the process such as temperature, pressure and presence of catalyst. Critical information on potential auxiliary inputs that may facilitate the implementation of the technology in a region can also be found in the matrix. Finally, the matrix informs whether the technology is a stand-alone technology or dependent on the presence of a specific industry.

Table 2 Generic matrix of CO_2 Receiving Processes.

alt-text: Table 2

NACE	CO2 utilization technology	Description	Reference	Conversion ~~Q~~quality ~~R~~requirements				
				TRL	Conversion ~~F~~factor	Purity	Pressure (P), ~~T~~temperature (T), ~~C~~catalyst	Potential ~~A~~auxi inputs
2014	Microalgae production	CO_2 used as a nutrient source to grow algae	[50]	4–7	~~1.8-2.0~~ 1.65 - 1.83 tCO_2 per t of dry algal biomass	5–22% of CO_2, ~~A~~avoid SO_X, NO_X & VOCs	Low temperature; No catalyst	- Munici and industr wastew (nutrie and wa source - Waste
0113	Horticulture ~~P~~production	CO_2 used as a nutrient source to grow crops	[51]	9	0.50–0.60 $kgCO_2/hr/100m^2$	Depends on crop. Avoid SO_X, NO_X & Heavy Metals	No catalyst	- Waste
2014	Methanol ~~P~~production	Electrochemical reduction of CO_2	[52]	7–8	$1tCO_2$ and 0,14 tH_2 produces 0.68 t of methanol	High pure CO_2	High P (5 MPa), High T (225 °C), Metal/metal oxide catalyst	- Hydrog source - Water excess energy supply - Low co electri
2014	Methane ~~P~~production (Power to Gas)	Hydrogen + CO_2	[53]	6–8	1 tCO_2 and 0.18 tH_2 produce 0.364 tCH_4	Concentrated CO_2 source	Nickel/~~C~~cobalt ~~C~~catalyst	- Hydrog source - Excess energy supply - Low co electri

2015	Urea ~~Y~~yield ~~B~~boosting	Ammonia + CO_2	[3]	9	0.735–0.75 tCO_2 per t of urea	High pure CO_2	High P, ~~H~~high T, ~~N~~no ~~C~~catalyst	
2452/ 3821	Carbon ~~M~~mineralization	Alkaline waste + CO_2	[54]	7–8	0.18 tCO_2 per t of steel slag 0.12 tCO_2 per t of municipal solid waste ash	Both low and high purity CO_2. Avoid S	Optimal P: 40–150 atm, Optimal T: 100–180 °C	
2442	Bauxite ~~R~~residue ~~C~~carbonation	Slurry + CO_2 to solid carbonates	[54,~~55,~~56]	7–9	30–50 $kgCO_2$ per t of red mud	High pure CO_2 (>85%)	High Pressure (4 MPa)	
2361	Concrete ~~C~~curing	Precast concrete curing	[55] (add the reference: Shao, Y., S. Monkman, and A. J. Boyd. "Recycling carbon dioxide into concrete: a feasibility study." In *Proceedings of the 2010 concrete sustainability conference*. 2010.)	7–8	0,06-0,19~~0.12~~ tCO_2 per t of precast concrete	Both low and high purity CO_2~~.~~	No ~~C~~catalyst	
	Propylene	Propylene			0.43 tCO_2 per t	High pure	~~c~~Catalyst ionic liquid-1-*n*-ethyl-3-	

2016	~~C~~carbonate ~~P~~production	Oxide + CO_2	[57]	7	of PC produced	CO_2	methylimidazolium chloride (EMImCl)	
2016	Polyurethane ~~P~~production	Epoxides + CO_2	[7]	7	0.1-0.3 tCO_2 per t of polyols	High pure CO_2	Zinc catalyst	
2016	Polycarbonate ~~P~~production (PEC and PPC)	Propylene Oxide + CO_2	[58]; [46]	7	0.43 tCO2 per t of PPC produced	High pure CO2	CrIIICl complex as catalyst	
1711	Lignin ~~P~~production	Black Liquor pH regulation	[59]	7–8	0.22 tCO_2 per t of lignin	High pure CO_2	No catalyst	
1081	Sugar ~~P~~production	Carbonation process using lime and CO_2	[60]	9	0.36 tCO_2 per tonne of white sugar produced	High pure CO_2	No catalyst	
3600	Desalination	Remove TDS using CO_2	[61]; [62]	9	0.024 kg CO_2 per liter of water produced	High pure CO_2	No catalyst	
3600	pH ~~C~~control	Neutralize alkaline using CO_2	Li(add the reference:Linde, 2017. Available at: https://www.linde-gas.nl/en/processes/water_and_wastewater_treatment/drinking_water_treatment/index.html)nde (2017~~5~~)	9	Variable	High pure CO_2	No catalyst	
0610	Enhanced Oil Recovery (EOR)	CO_2 is injected in oil reservoirs, increasing the quantity of crude oil that can be extracted	[63]	9		Dry (to avoid corrosion), pure, liquid carbon dioxide	No catalyst	
0610	Enhanced Coal Bed Methane Recovery (ECBM)	Process similar to EOR. CO_2 is injected into a unmineable coal seams leading to enhanced coalbed methane recovery	[63]	7		Preferably pure CO_2	No catalyst	

Note: Other technologies that may use CO_2 but have not been included in the detailed list are the following: Butanol Production, Isobutanol Production, Isoprene Production, Salicylic Acid Production, Fire Suppression, Pneumatics, Wine making, Beverage Carbonation, Coffee Decaffeination, Dry Ice, Food Refrigeration, Metal Working, Pulp & Paper Processing, Pulp & Paper Processing, Ethanol Production, Laser Cutting, Glycerol Carbonate Production, Sodium Acrylate Production, Dimethyl carbonate Production, Syngas production, Dimethyl ether (DME) Production.

2.2.2 Mapping the CO_2 receivers at the~~on a~~ regional level

The mapping of CO_2 receivers is a more complex task than the mapping of the sources, and is performed in two steps. As a first step, the potential CO_2 receivers already operating in the region are identified, by crosschecking a regional business registry with the generic matrix, and ~~identify companies with the same~~using the NACE code. As second step, the selected companies need to be analysed further, since some of the NACE codes are generic, and may include several different industries. Additional new opportunities for CO_2 reuse are also identified in this step. These include all stand-alone technologies that are not currently found in the region and therefore were not selected in the previous step. All of the other technologies that are dependent on the presence of a specific industry that cannot be found in the region, are not considered for further study.

2.3 Matching the sources with the receivers

After identifying and characterizing the available sources as well as the potential receivers by industry type, the next step is to identify potential industrial symbiosis by matching them, and adding to the symbiotic scheme other stakeholders that may be fundamental for its success. For the purpose of our analysis, the matching was performed according to the following information:

- Geographical location of receiving process;
- Identification of the purity requirements (Table 2);
- Estimation of the CO_2 needed for the receiver (using the conversion factor available in Table 2) ~~and~~;
- Selection of the most appropriate CO_2 source for the CO_2 receiving technology, according to the magnitude and purity (Table 1);
- Elimination of CO_2 sources based on geographical proximity;
- Identification of additional requirements, as for instance the need for catalyst (Table 2); and,
- Identification of auxiliary inputs that may facilitate, or be indispensable to, the symbiosis (Table 2);

2.4 Limitations

The assignment of the TRL value for each CO_2 receiving process was estimated based on a literature review and the authors' evaluation. The TRL provides a subjective assessment of maturity of each technology, which can change according to circumstances. It only assesses the technical readiness of a technology, and does not take into account the economic performance nor the environmental sustainability aspects [64]. Moreover, some of the technologies have a low TRL which indicates that these have not been tested in an operational environment and thus the reported data might not be realistic in a real CCU symbiosis, which contributes to the overall uncertainty of the analysis.

The percentage of CO_2 in the sources, as well as the purity needed in each CO_2 receiving process, were estimated based on average values available in the literature. Similarly, the assessment of the quantity of CO_2 that each technology can use, was estimated based on average conversion factors found in the literature. However, these factors reported by researchers usually correspond to the best values of their experiments, under optimal conditions, which might be different from the actual operational environment, which adds another layer of uncertainty to the analysis.

This study assumes that companies with the same NACE code use similar technologies in their industrial processes. However, as already mentioned, some NACE codes can be considered broad, including more than one type of industrial plant or final product, e.g. NACE code 2016 refers to all industries that produce plastics in primary forms, without specifying the type of plastic that is produced.

This study does not analyse the economic feasibility of implementing each proposed symbiosis. The authors acknowledge that such a study is extremely important for the success of subsequent implementation phases of potential CCU symbioses, and should be performed as a follow-on step using the results of deploying this method and on a case-by-case basis, involving relevant stakeholders that can benefit from the proposed synergy.

Finally, the environmental impact assessment of implementing a CCU technology is not included in the current analysis. For that purpose, it would be necessary to conduct a Life Cycle Assessment to properly evaluate the environmental impacts of the status quo and of proposed CCU on a case by case basis including critical variables such as the duration of fixation of the CO_2 in the new product and the potential substitution of raw materials using captured CO_2. However, this goes beyond the scope of the present work.

3 The Västra Götaland case study: results and discussion

The methodology has been applied ~~on the~~in Västra Götaland county, located on the western coast of Sweden, with a population of 1.6 million (17% of Sweden's total) (Supplementary Fig. 1). A wide range of industries from different sectors such as shipping, agriculture, forestry and manufacturing operate in the county [65]. The results of the analysis and the potential symbioses identified are presented in the following sections.

3.1 CO_2 sources

In total, approximately 6.6 Mt of CO_2 were emitted in 2012 by both large and small-scale sources, from a total of 69 CO_2 point sources. Using the matrix of CO_2 off-gas composition (Table 1) it was possible to classify the CO_2 sources operating in the study region based on their CO_2 content. The majority of the sources emitted low purity streams with CO_2 concentrations below 20%. These include oil refineries that typically emitted flue gases with CO_2 concentrations ranging between 8 and 24%, as well as three incinerators with approximately 10% of CO_2 in the effluent and thermal power stations fired with natural gas, oil and wood that generated emissions with a CO_2 content of 7–13%. In the region, there is also a steel mill with 22% of CO_2, as well as a cement plant with off-gas with approximately 22% of CO_2.

High purity CO_2 emissions mainly originated from small-scale (<0.1 Mtpa) biogas-to-biomethane upgrading plants. However, such quantities may be sufficient for a number of technologies included in the region-specific matrix of CO_2 receivers. An ethylene-oxide industry produces a CO_2 rich stream as a by-product, which is already shared with a manufacturer of industrial gases that purifies and liquefies the CO_2 for subsequent re-sale. Fig. 2 illustrates the location of the CO_2 point sources in the region, their size and their purity ~~(Fig. 3)~~.

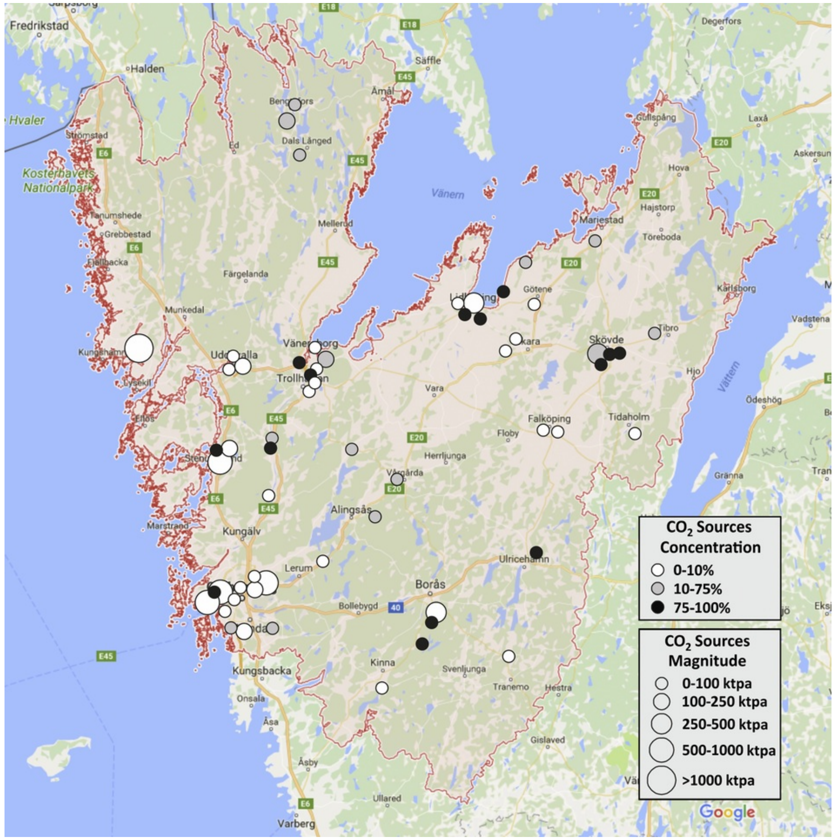

Fig. 2 CO_2 sources according to magnitude and purity.

alt-text: Fig. 2

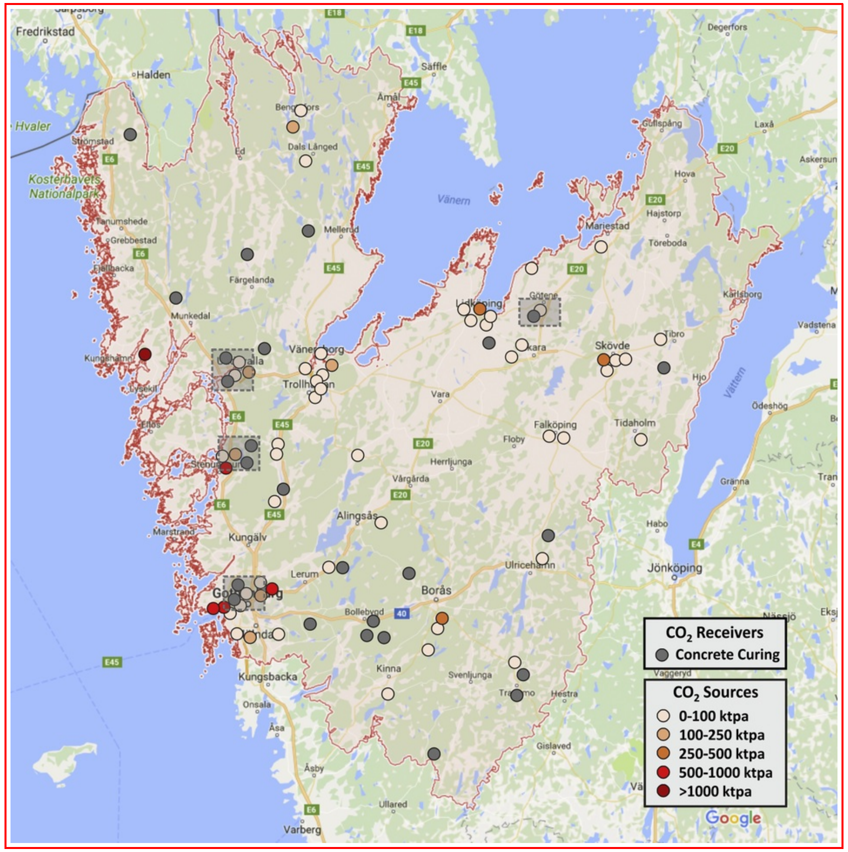

Fig. 3 Potential concrete curing based industrial symbios~~i~~es in the Västra Götaland Region. The squares show the potential industrial symbioses. (Figure 3 should be moved to chapter 3.3.2 Concrete curing)

alt-text: Fig. 3

3.2 CO_2 receivers

The selected technologies were divided into two groups: (a) existing technologies and (b) novel technical configurations in the area. The existing technologies operating in the region that may use CO_2 include mineral carbonation, concrete curing, polymers processing, lignin production and pH control, whereas new opportunities include algae production, methanol production and power-to-gas. The majority of these technologies require high purity CO_2, with the exception of algae technology, which may use CO_2 purity between 5 and 22% depending on the type of algae used. Similarly, mineral carbonation and concrete curing can work with either low or high CO_2 concentrations. The selected technologies are described in detail in the next subsections. Certain CO_2-receiving processes, among those presented in Table 2, were not considered in the matching process due to being dependent on the existence of a specific infrastructure or industry that is not currently present in the area, namely, red mud carbonation, sugar production, water desalination, urea yield boosting, enhanced oil recovery and enhanced coal bed methane recovery.

3.3 Matching and assessment for existing technologies

3.3.1 Mineral carbonation

Accelerated mineral carbonation is the formation of solid carbonate products, based on a reaction between carbon dioxide and alkaline materials composed by calcium and magnesium rich oxides and silicates [66]. ~~Indicative products~~Examples may include carbonated compounds such as magnesium carbonate ($MgCO_3$) and calcium carbonate ($CaCO_3$, commonly known as limestone). There are numerous sources of industrial waste that can be used in the mineral carbonation process, such as metallurgic slags, incineration ashes, mining tailings, asbestos containing materials, red mud and oil shale processing materials [67]. Nevertheless at~~t~~ the current time, the technology still has some drawbacks such as low CO_2-binding efficiency and large energy consumption [68]

Obviously, this route can contribute not only to the reduction of CO_2 emissions, but also to the reduction of the amount of waste currently sent to landfill and to the production of materials with commercial value. Commercial accelerated carbonation plants can already be found; for instance a company operating in the United Kingdom produces Air Pollution Control Residue-derived aggregate [69].

The maximum recovery potential of this technology is relatively low. When implemented in a waste incineration plant, approximately 2% of the CO_2 can be recovered using incinerated ash, which can be increased to up to 6% when implemented in a steel and cement industry using ash and slag as raw materials. This can be considered as one of the main drawbacks of this technology [70]. One of the main advantages of carbon mineralization is that it can operate on flue gases directly, without CO_2 pre-treatment. Although initial studies have shown that only high purity CO_2 sources can be used, more recent studies have been using successfully low purity flue gases with CO_2 concentration of 10% [71]. This would mean that long-distance CO_2 transport may not be needed and the industries would be able to capture and use CO_2 locally. The ashes would be carbonated locally, using the available CO_2 from the incinerator or the steel industries.

Several of the above-mentioned waste flows can be found in Västra Götaland Region. Furthermore, the majority of the waste-producing plants, also produce CO_2-containing flue gas. Incineration of urban waste with energy recovery (NACE Code 3821) is a common practice in Sweden. In the studied region, there are 5 incinerators that burned approximately 927,000 t of waste in 2013 [72] and generated approximately 56,700 t of fly ash and 140,000 t of bottom ash. For this case, a suitable solution could be to produce stable construction materials, such as aggregates used in lightweight concrete for insulation and lightweight formulated blocks.

Apart from the incinerators, other industries in the region that produce waste suitable for mineral carbonation include metallurgic companies and a cement plant. A local steel mill produces every year approximately 200,000 t of steel slag. According to Pan, Chang, & Chiang (2012) steel slag has the capacity to capture approximately 0.18kgCO_2/kg of slag, and Municipal Solid Waste (MSW) ash can capture approximately 0.12kgCO_2/kg ash. Therefore, CO_2 capture in the region could reach approximately 36,000 tCO_2 using steel slag and 23,600 tCO_2 using MSW ash.

3.3.2 Concrete curing

Concrete curing using CO_2 (carbonation curing) presents an alternative technology to the traditional steam and autoclave curing processes. It can be applied within the curing process or during manufacturing of building products, e.g. building blocks, masonry units, paving stones, cement boards and fiberboards [55]. Instead of using traditional energy-intensive steam curing methods, an alternative method, developed by Carbon Sense Solutions, uses CO_2-containing flue gases to cure precast concrete products, without affecting the quality of the final product [73]. This technology is currently moving towards small-scale demonstration implementation in the concrete sector.

In the region, there are 33 companies producing a collective total of approximately 800 kt of concrete products (NACE Code 2361) per year. Considering ~~the best-case scenario,~~ that each tonne of concrete produced can take up approximately 0.12 t of CO_2, it is estimated that 96,000 t of CO_2 could be consumed using concrete curing technology. Most of the mineral carbonation studies have been performed using high purity CO_2 sources, but flue gas CO_2 sources with lower CO_2 content have also shown promising results. This is the case of a study performed by Shao et al. [74] in which concrete curing was performed using a flue gas with 25% of CO_2.

The potential symbioses identified for this technology consider companies that produce concrete products and the closest company that produces CO_2 containing flue gas, because: (a) the required purity is quite low; and (b) in principle, the amount of available CO_2 will be more than enough to satisfy the demand for concrete curing. Fig. 3~~4~~ shows the location of both the companies that produce concrete products and the CO_2 sources in the region. The squares represent examples of matched companies that potentially could collaborate.

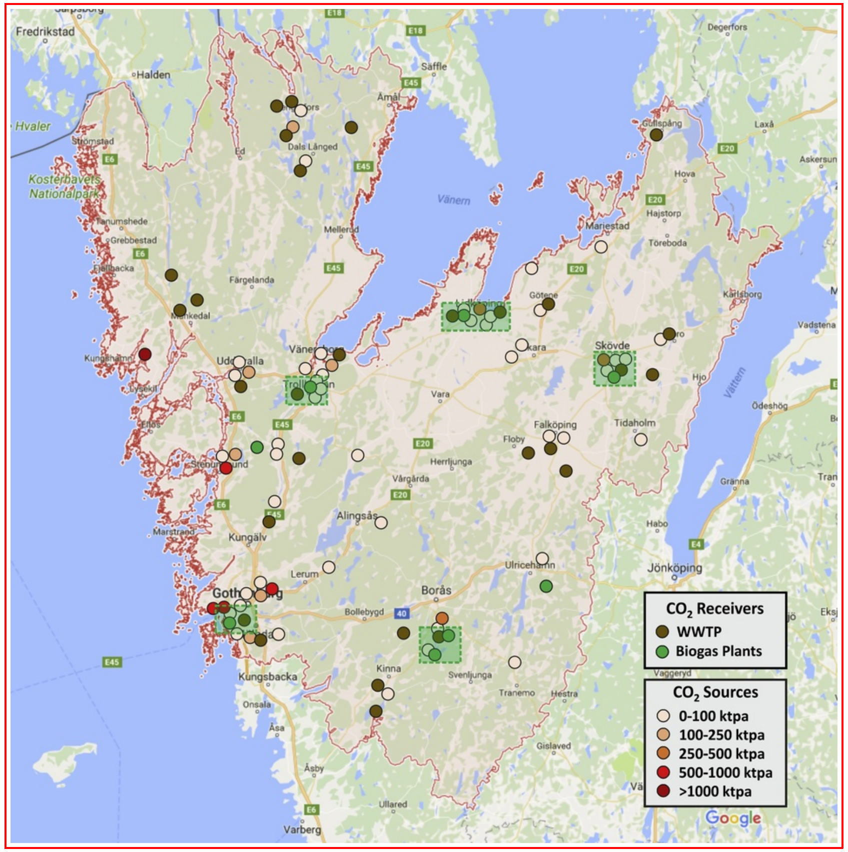

Fig. 4 Potential algae production based industrial symbioses in the Västra Götaland Region. The squares show the potential industrial symbioses. (This figure is to move to the chapter 3.4.1 Algae production.)

alt-text: Fig. 4

3.3.3 pH control (in this chapter, in the equation, the signs < - > are not appearing in the proof. I tried to replace and see but never worked.)

Carbon dioxide is used worldwide to neutralize alkaline flows in several industries. When dissolved in water, it forms carbonic acid ($CO_2 + H_2O \langle\text{-}\rangle H_2CO_3$), which is the compound that helps to neutralize the alkalinity of a solution. Waste-water neutralization is necessary in industries such as refineries, steel mills, paper and pulp mills, leather and textiles industries, and also in drinking water in water treatment facilities. In the latter case, CO_2 use has been gaining acceptance and has been gradually replacing mineral acids [75]. Currently, the two major drinking water treatment plants (NACE Code 3600) operating in the studied region, use locally captured CO_2 already (approximately 2000 tCO_2 per year). The CO_2 used in the drinking water plants is captured from a high purity CO_2 source produced by an ethylene-oxide plant (NACE 2014) operating in the region. Therefore, this technology can be considered as saturated in this region.

3.3.4 Polymer synthesis

The utilization of CO_2 as raw material in the polymer industry can be seen as an important route to reduce the dependence on petroleum-based materials and to create high value products, such as polyurethanes and polycarbonates. These polymers have become an important part of various industrial processes, and some of the technologies that use CO_2 are deployed at commercial scale (e.g.: [19]). Polymer processing requires a highly concentrated flow of CO_2. Thus, CO_2 captured from point sources such as syngas production, natural gas sweetening and coal fired power plants, should undergo an additional processing step to increase the concentration and purity of the CO_2.

In this case, the companies that already produce polymers and that may be interested in exploring a new technology using CO_2 as raw materials are considered. There are five companies that produce polymers in primary forms operating in the region (NACE Code 2016). The two largest companies produce polyethylene (PE) and polyvinyl chloride (PVC), respectively. The companies are both located in the Stenungsund Industrial Park, where a high purity CO_2 flow is also available. The quantity of

CO_2 needed will depend on the amount and type of polymers that will be produced, but will vary from 0.1 to 0.4 t of CO_2 per tonne of polymers produced.

3.3.5 Lignin production

Lignin is the second most abundant polymer and represents 30% of all the non-fossil carbon on the planet [76]. It can be used to replace fossil-derived raw materials. Currently, the most mature markets include the use for heating or for the production of dispersants, surfactants and vanillin. Lignin can be extracted from black liquor, a by-product of the pulp mill industry (NACE Code 1711). The addition of CO_2 is required in order to lower the pH of the black liquor. Current technology allows only for highly pure CO_2 to be used; however, recent developments have shown that it may~~will~~ be possible to use CO_2 containing flue gases directly [77]. The main benefits will be the increase of the production, reduction of cost and creation of new sources of income for the paper mills. In 2007, a pilot study started in Sweden, with a capacity of 6,000 to 10,000 t lignin/year [78].

There is currently a paper mill in ~~West Sweden~~Västra Götaland that produces pulp, and therefore could explore the production of lignin using CO_2. However, there are no high purity CO_2 sources located nearby. Thus, in this case, it would be necessary to further explore the potential use of flue gas from the paper mill that contains approximately 13% of CO_2 after a purification step or to even explore the direct use of the flue gas. Otherwise, the possibility to transport CO_2 from neighbouring counties through various means could be explored.

3.4 Matching and assessment for new opportunities

3.4.1 Algae production

Algae cultivation systems can exploit point source emissions effectively and can be installed on marginal land near power stations, which cannot be used for other forms of value creation or as agricultural land. Solar irradiance and available land are two key factors determining algae growth potential, the lack of which is limiting its use in many world regions. Municipal and industrial wastewater can be used as a nutrient source. One of the advantages is that it is also possible to simultaneously treat the wastewater by reducing nitrogen and phosphorus and produce biomass and lipids [79]. Paper and pulp industry wastewater usually comes with excess heat that can be also used in the CCU system, especially during the months when ambient temperature is lower than the optimal temperature to grow microalgae [80].

Algae can be used to produce several different products. The most likely use of the algae would be for the large-scale production of biofuels, which have a large potential market. Another solution is to produce biogas using an anaerobic digestion process (ADP), which does not require intense dewatering or further chemical extraction [81,82]. Therefore, energy consumption can be reduced, since the intense drying process is avoided. One other advantage is that algae can be used in anaerobic digestion plants already operating in the region. The algae biomass can be combined with organic waste from ~~such as~~ domestic, industrial and agricultural activities~~waste~~ and improve the Carbon:Nitrogen:Phosphorus balance of the process.

Thus, a symbiotic scheme based on algae production using CO_2 should at least include two different types of industries: (i) a CO_2 source and (ii) a source of the nutrient-rich water. The former includes companies from energy sector, refineries, as well companies from paper and pulp industry. Municipal and industrial wastewater treatment plants or food processing industries may supply the nutrient-rich water. Apart from the two essential parts, biogas plants are also considered as a potential receiver of the produced algae. Therefore, for the studied region, five possible algae symbioses have been identified (Fig. 4). Each of the symbiosi~~e~~s include a CO_2 emiter, a nutrient-rich water source including paper industry (NACE Code 1712), pulp industry (NACE Code 1711) or wastewater treatment facilities (NACE Code 3700), and a potential algae receicer, that in this case were the biogas production industries (NACE Code 3521). The increase of biogas production in the region is one of the Gotenburg municipality strategies for the future [83].

3.4.2 Agricultural production in greenhouse systems

Another mature option for CO_2 reuse is its application in agricultural production. In general, when raising the CO_2 level from ambient values (about 340 ppm) to 1,000 ppm, an increase of photosynthesis by ~~around~~approximatly 50% can be obtained [84]. The level of CO_2 purity required in a greenhouse is high, so not all flue gases can be directly used without proper treatment. It is well known that several flue gases may have impurities, such as sulphur oxides (SO_x), nitrogen oxides (NO_x) or heavy metals, which are toxic for the plants. In these cases, and before the flue gas is diluted into the ambient air of the greenhouse, it is important to ensure that the components present in the flue gas comply with safety requirements for the plants and workers. Moreover, the perfect combination occurs when, in addition to CO_2, heat can also be provided. Therefore, proximity to an industrial partner with waste heat is beneficial. Large areas as well as proper soils for crop cultivation are also needed.

Biogas upgrading ~~to biomethane~~ plants (NACE Code 3521) are a perfect CO_2 source for greenhouses (NACE Code 0113) because (i) even though they produce small amounts of CO_2, the quantities are enough to supply a large greenhouse, (ii) they produce highly concentrated CO_2 streams, which can therefore be used directly in the greenhouse; and (iii) they may produce excess heat, which can also be supplied to the greenhouse.

Worldwide there are several successful symbioses between companies that produce highly concentrated CO_2 and greenhouses. For the regional analysis, two options have been examined: (a) use CO_2 from the biogas upgrading plant directly in the greenhouse that already operates in the region and (b) build a new greenhouse in the vicinity of one of the biogas upgrading plants. Since the distance between the greenhouses operating in the region and the biogas purification plants in most cases was too large (more than 10 km), it was decided that the second option would be more suitable. Moreover, the number of greenhouses operating in the region is small, and there is a need defined by the Gothenburg municipality to increase the quantity of locally produced vegetables [83].

In this technology, the potential symbiosis considers a biogas upgrading company (CO_2 source) and a greenhouse operator (CO_2 receiver) that would be constructed in the vicinity of the biogas facility. In total, there are thirteen biogas upgrading facilities operating in the region, with variable capacities producing aproximatlly 26,000 t of CO_2 per year; the largest one being a biogas purification plant currently emitting 6,500 t of CO_2. A greenhouse that produces tomatoes in Sweden needs between 90 and 180 t of CO_2 per year per ha, to produce approximately 500 t of tomatoes [85]. Thus, the largest biogas plant could in principle supply a greenhouse of up to 40 ha. The total amount of CO2 emitted by all biogas upgrading facilities could pupply a total of 153 ha of greenhouses.

3.4.3 Methanol production

Methanol can be produced using CO_2 and H_2 as feedstock. The electrolysis of water produces hydrogen (H_2), which is compressed and reacts with CO_2 over a metal/metal oxide catalyst to produce methanol and water ($CO_2 + 3H_2 \rightarrow CH_3OH + H_2O$). The technology is typically highly energy intensive, mostly due to H_2 production, which in this case is already available in the region thus increasing the attractiveness of a potential scheme. Processes and catalysts for the efficient conversion of CO_2 are in various stages of development. The most commonly used catalyst is $Cu/ZnO/Al_2O_3$, produced in a high-pressure process (50–100 bar) and high temperatures (T = 200–300 °C) [86]. Methanol can be used as a transport fuel or as a resource for the production of dimethyl ether (DME) or biodiesel and methanol-to-power. Furthermore, methanol is an important intermediate chemical for the synthesis of various products such as pharmaceuticals, plastics, paints and solvents.

Production of methanol is possible anywhere in the proximity of a high-concentration CO_2 source and an appropriate water and energy supply. According to Goeppert et al. [87] the availability and price of the necessary electricity is the main limiting factor for scale-up of such processes. In order to render the process economically and environmentally viable, H_2 should be produced using electricity from renewable sources, which requires either compression to 350 to 700 bar or liquefaction at very low temperature (–253 °C).

At the moment, there is no production of methanol (NACE Code 2014) in Sweden. However, methanol is used as raw material in several industrial production lines. The current market for methanol in Sweden is approximately 180,000 t per year and a large part is consumed within the area studied. There are some companies operating in the region that could possibly be interested in using the methanol produced, such as producers of olefins (methanol to olefin), producers of fine chemicals or shipping fuel producers.

A specific industrial symbiosis would involve a company that produces hydrogen as by-product, and a highly pure CO_2 source.The most common industries that produce hydrogen as a by-product are chlorine, ethylene, acetylene, cyanide and styrene production units [88]. In the studied region, ~~there exist~~ three such industries exist and the most important one is an ethylene industrial site that produces approximately 9,230 t of hydrogen per year [88]. ~~However, it should be noted that most of it is currently used for process heat or electricity generation [53]. Nevertheless, t~~The previous hydrogen source is located in the Stenungsund Industrial Park, where a high-purity CO_2 source is also located, producing around 50,000 t of CO_2 per year (Fig. 5). In the same area operates another hydrogen source that produces approximately 2,740 t of hydrogen per year. Considering the two hydrogen sources, 85,500 t of CO_2 would be necessary to produce aproximatly 58,000 t of methanol per year. The next step would be to identify where the methanol production site could be located, and whether it would be economically feasible and environmentally sustainable~~friendly~~.

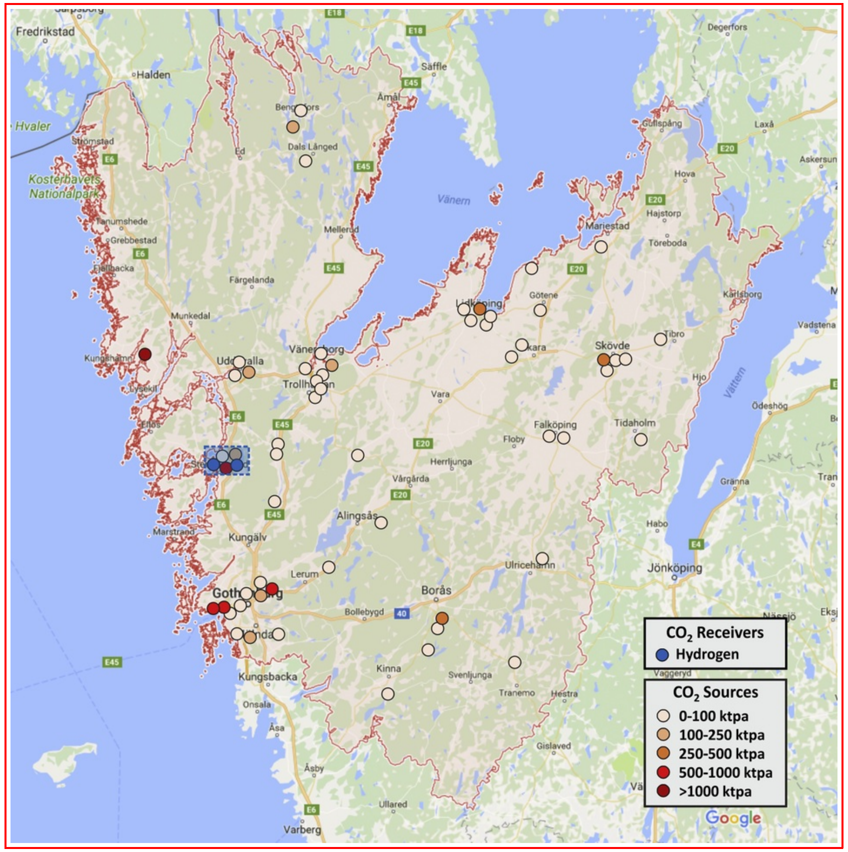

Fig. 5 Potential CCU symbiosis for methanol production in Stenungsund.The square shows the potential industrial symbiosis. ~~Circles represent CO_2 emitters and stars H_2 producers.~~

alt-text: Fig. 5

3.4.4 Power to gas

Power to gas technology focuses on the transformation of electrical energy to SNG (synthetic natural gas), by combining CO_2 with H_2, obtained from water electrolysis and further converted to methane, via the Sabatier reaction ($4H_2 + CO_2 \rightarrow CH_4 + 2H_2O$). Similar to methanol production, power to gas technology is highly energy intensive, especially because of the electrolysis process. So it can be applicable and economically viable if either surplus energy or hydrogen is available. The companies that could be involved in a power to gas CCU symbiosis would be the same as the ones described in the methanol production. Thus, a highly concentrated CO_2 source as well as a surplus of hydrogen would be required. Therefore, the industrial plants presented in Fig. 5, in the Stenungsund Industrial Park could be good candidates to implement a power to gas technology. Considering the available H_2, 66,500 t of CO_2 would be necessary to produce 24,000 t of methane per year.

3.5 Overall assessment

The aim of this paper was to find opportunities for CO_2 reuse through industrial symbiosis in the Västra Götaland region using nine selected technologies. For some of them, it was possible to assess the maximum quantity of CO_2 that could be used. These include mineral carbonation (annual maximum uptake: 59,600 tCO_2), greenhouses (26,000 tCO_2 splited by 13 biogas upgrading plants), methanol production (85,500 tCO_2), concrete curing (96,000 tCO_2) and power to gas (66,500 tCO_2). It should be noted that power to gas and methanol production could not be developed at the same time, because they have common resources required. Other technologies that were considered, but for which it was not possible to quantify the amount of CO_2 uptake, include algae production, lignin production and polymers synthesis. The main reason for that was that the amount of CO_2 needed will depend on the quantity of product intended to be produced. Furthermore, for each technology, several stakeholders that may be willing to implement~~promote~~ CCU in the region were identified. Table 3 summarizes briefly all the identified potential CCU symbioses in the region; it presents their advantages as well as the estimated CCU potential. Fig. 6 illustrates the overall results on the regional map. By combining all the different CCU symbiosis options, there could be five clusters where such partnerships would be easier to develop, including one near the port of Gothenburg and other close the Stenungsund Industrial park.

Table 3 Summary of all the potential CCU symbiosis identified in Västra Götaland.

alt-text: Table 3

Industrial ~~P~~process	Short ~~D~~description	Potential ~~R~~receivers	Potential ~~E~~emitters	Advantages	Potential CO_2 ~~U~~utilization
Mineral ~~C~~carbonation	Formation of solid carbonate products, based on a reaction between carbon dioxide and alkaline materials composed by calcium and magnesium rich oxides and silicates [66].	~~.~~Five waste incinerators (carbonation of the bottom and fly ash)~~;~~. One steel mill (carbonation of steel slag). ~~.One steel mill – carbonation of steel slag.~~	Low purity flue gases with CO_2 concentration of 10% can be used [71]. In this case, the CO_2 emitted by the incinerators or the steel mill would be the best option.	CO_2 emissions reduction; Reduction of the amount of waste that is currently sent to landfill (ash); Long-term storage of the CO_2; Use of ash to produce construction materials.	In total, approximately 36,000 tCO_2 using steel slag and 23,600 tCO_2 using Municipal Solid Waste ash.
Concrete ~~C~~curing	Applied within the curing process or during manufacturing of building products, e.g. building blocks, masonry units, paving stones, cement boards and fibreboards [55].	~~.~~Thirty-three manufacture of concrete products industries~~.~~; One cement industry. ~~. One cement industry.~~	Low purity flue gases with CO_2 concentration of 20% can be used. The closest CO_2 emitter from the concrete products industries would be appropriate.	Long-term storage of the CO_2; Water savings, if water was used in the curing process.	Estimated that 96,000 t of CO_2 could be used in concrete curing technology.
pH ~~C~~control	Carbon dioxide is used worldwide to neutralize alkaline flows in several industries.	~~.~~Two drinking water plants.	High pure CO_2 is needed.	Replaces mineral acids.	Already used locally captured CO_2 (approximately 2(,)000 tCO_2 per year).
Polymer ~~S~~synthesis	Utilization of CO_2 as raw material in the polymer. Different polymers can be produced, including Polyurethane or Polycarbonate.	~~.~~Five companies that produce polymers in primary forms operating in the region.	Polymer processing requires a highly-concentrated flow of CO_2.	Reduce the dependence on petroleum-based materials.	CO_2 needed will depend on the amount and type of polymers that will be produced (from 0.1 to 0.4 t of CO_2 per tonne of polymers produced).
Lignin ~~P~~production	Lignin can be extracted from black liquor, a by-product of the pulp mill industry.	~~.~~One pulp and paper industry in the region.	Pure CO_2 is necessary. The CO_2 emitted from the pulp and paper industry may be used, after CO_2 has been captured.	The main benefits will be the increase of the production, cost reduction and creation of new sources of income (lignin).	~~Only one industry may use this technology in the region.~~ No data on amount of pulp produced (confidential).
Algae production	Cultivation of algae using bioreactors, open pounds or a combination of both systems.	~~.~~The algae should be located close to the CO_2 emitter or a wastewater treatment facility.	Low CO_2 purity flue gases ~~with CO_2 concentration~~ can be used, including flue gases from power stations, refineries or paper industry.	~~No need for pure CO_2;~~ The large applications of algae; Would be beneficial to get the water from a wastewater treatment plant (rich in nutrients).	Depends on the quantity of algae produced. CO_2 will not be the limiting factor.
Agricultural ~~P~~production in ~~G~~greenhouse ~~S~~systems	Use of CO_2 in agricultural production. In general, when raising the CO_2 level from ambient values, about 340 ppm to 1,000 ppm, an increase of photosynthesis by around 50% can be obtained [84].	~~.~~The greenhouse would be installed close to a biogas upgrading plants, that produces high pure CO_2. There are thirteen biogas upgrading plants in the region.	High pure CO_2 is needed.	Could be a source to increase the quantity of agriculture products produced in the region; Heat and CO_2 exchanged at the same time would be the perfect combination.	Depends on the size of the greenhouse. A greenhouse in Sweden needs between 90 and 180 t of CO_2 per year per ha.
Methanol ~~P~~production	Methanol can be produced using CO_2 and H_2 as feedstock. The electrolysis of water produces hydrogen (H_2), which is combined with CO_2, compressed and reacted over a metal/metal oxide	~~-~~H_2 is needed. An alternative would be that the methanol producer would be close to an industry that produces H_2 as by product and a CO_2 high pure source.	High purity CO_2 is needed; Nearby the H_2 sources, exists a high pure CO_2 source.	Large applications of methanol; Avoids the need to import methanol from international	Considering the available H_2, 85,500 t of CO_2 would be necessary to produce 5~~5~~8,000 t of methanol per

	catalyst to produce methanol and water ($CO_2 + 3H_2 \rightarrow CH_3OH + H_2O$).	One symbiotic scheme was identified in the region.		markets.	year.
Power to gas	Power to gas technology focuses on the transformation of electrical energy to SNG (synthetic natural gas), by combining CO_2 with H_2.	H_2 is needed. An alternative would be that the methanol producer would be close to an industry that produces H_2 as by product and a CO_2 high pure source. One symbiotic scheme was identified in the region.		Conversion of renewable energy into storable energy (methane).	Considering the available H_2, 66,500 t of CO_2 would be necessary to produce 24,000 t of methane per year.

Mt = Million tonnes = 1,000,000,000 kg. In this study tonne (t) stand for metric tonnes.

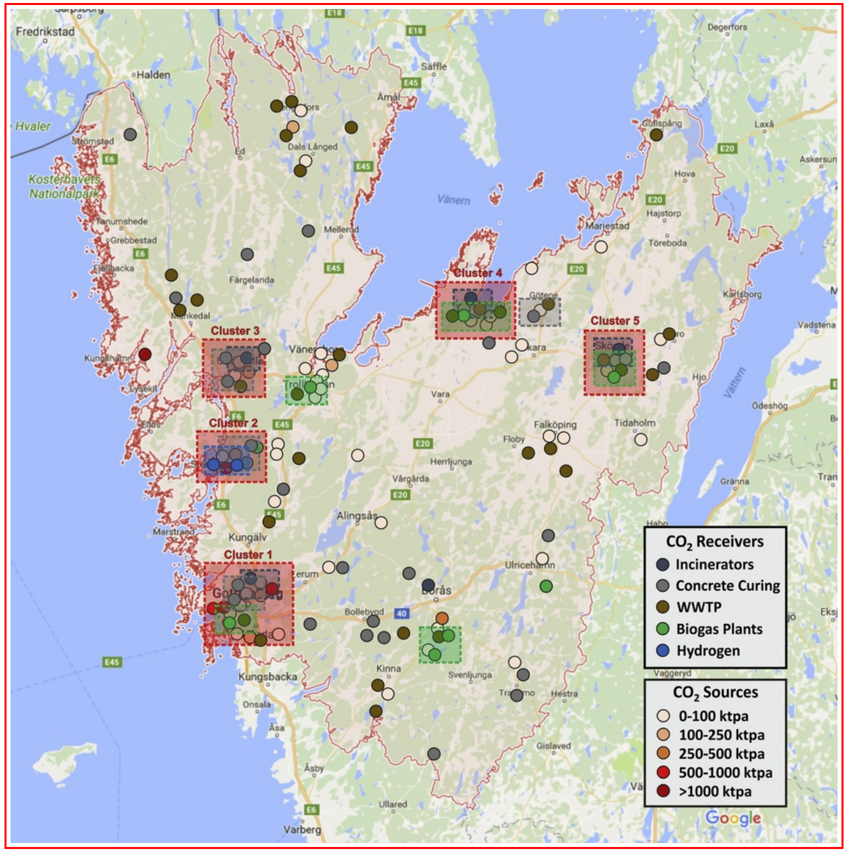

Fig. 6 Overall potential CCU symbiosis identified in Västra Götaland.

alt-text: Fig. 6

This work identifies opportunities~~has fulfilled the opportunity identification~~ for CCU symbioses. It provides elements needed to progress to the opportunity assessment and barrier removal stages. Such progress requires in addition to the potential identified, that regional priorities and trade-offs be analysed in relation to basic pre-conditions for regional symbioses.~~ The methodology allows for replicating the relationship between the findings and the pre-conditions elsewhere.~~ Stakeholders with a regional focus such as regional development agencies have the level of insight and influence needed for subsequent stages. The findings of this work inform regional facilitators in three key capacities. First, they can be combined with the overview of economic and environmental policy in the region. The feasibility of CCU can also depend on priorities in resource efficiency, climate change and energy set at the regional level. All ~~data~~ potential data and subsequent knowledge on trade-offs must be regarded in the context of regional investment and development plans as well as strategies for fostering employment in environmental technologies. Västra Götaland, for instance, has a priority to increase local food production and an interest in facilitating collaborations leading to that goal. Second, the practicality of the potential must be analysed from the perspective of regional spatial planning and infrastructure management. Important commodities and auxiliary inputs to CCU can only be planned at regional level such as transport, water, energy and waste management infrastructure. Planning and building permissions are also important procedures in meeting the needs for infrastructure, which can be foreseen from the geographical findings. Therefore, opportunities for CCU both influence and depend on the development of these assets which can be coordinated by regional development agencies. Finally, the findings must be combined with the insight of the regional facilitators into individual and collective business strategies in the area. Symbioses between companies require the trust and sense of common purpose that is best fostered by facilitators. Feasibility of single CCU schemes will depend on how compatible they are with individual strategies and the ability of companies to commit to a joint undertaking. Regional facilitators have the ability to convene the necessary dialogue and to develop incentives such as shared transport equipment and financial or fiscal support for purchase and insurance of shared infrastructure.

4 Conclusions

~~The current~~This paper has presented a methodological approach for the identification of CO_2 based symbioses, by defining guidelines to identify sources and receivers, and by matching and prioritizing them based on technical and geographical criteria. The methodology has been applied to the Västra Götaland region in Western Sweden. The most promising symbioses have been identified, both based on co-existence of ~~all~~ the stakeholders needed and the high TRL of ~~because~~ the respective CO_2 consuming technology ~~is characterized by high TRL~~. They include carbon mineralization (annual maximum uptake: 59,600 tCO_2), greenhouses (26,000 tCO_2), algae production, methanol production (85,500 tCO_2), power to gas (66,500 tCO_2), pH control, lignin production, polymers synthesis and concrete curing (96,000 tCO_2). If all of symbiosis were implemented~~them could~~ ~~be applied~~, the total annual CO_2 reuse potential would exceed 250,000 tCO_2 per year.

After the initial step, in which the opportunities for CO_2 symbiosis were identified, the subsequent step would be to do an opportunity assessment. This includes meetings, in which the findings from this project are shared with stakeholders operating in the region. These meetings would~~will~~ be a starting point to understand if there are stakeholders interested in doing a detailed technical study, in order to evaluate if the sources and receivers can start to collaborate, and assess the economic and environmental performance of the proposed scheme. The main parameters that should be taken into account will include the market price of the final product; the commercial price of CO_2; the cost of capture and transport CO_2; the cost of modifying the industrial process, and the carbon tax or cost of emitting CO_2.

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Highlights

- Matrix of CO_2 sources including magnitudes and flue-gas composition.
- Matrix of CCU technologies including processes, products and TRL.
- Analytical tool to facilitate the identification of potential CCU industrial symbiosis.
- Västra Götaland show potential for implementation of 9 types of CCU technologies.
- An annual abatement of 250,000 tCO_2/year can be potentially achieved in the region.

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