Journal of CO_2 Utilization 17 (2017) 50–59

Contents lists available at ScienceDirect

Journal of CO_2 Utilization

journal homepage: www.elsevier.com/locate/jcou

Region prioritization for the development of carbon capture and utilization technologies

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ARTICLE INFO

Article history:
Received 3 March 2016
Received in revised form 31 August 2016
Accepted 6 October 2016
Available online 24 November 2016

Keywords:
Carbon utilization
CO_2 emissions
Industries
Waste
Value chains
CO_2 reuse

ABSTRACT

In recent years several strategies have been developed and adopted to reduce the levels of the Greenhouse Gas Emissions released to the atmosphere. The adoption of Carbon Capture and Utilization (CCU) technologies may contribute towards carbon sequestration as well as to the creation of high value products. This study presents a methodology to assess the potential of CO_2 utilization across Europe, and to identify the European regions with the greater potential to deploy nine selected carbon dioxide utilization technologies. The results show that Germany, UK and France at the first level followed by Spain, Italy and Poland are the countries where the larger quantities of available CO_2 could be found but also where the majority of the potential receiving processes are located, and therefore with the greatest potential for CO_2 utilization. The study has also revealed several specific regions where reuse schemes based on CO_2 could be developed both in Central Europe (Dusseldorf and Cologne – Germany, Antwerp Province and East Flanders – Belgium and S'ląskie – Poland) and in Scandinavia (Etelä-Suomi and Helsinki-Uusimaa – Finland). Finally, among all the selected technologies, concrete curing and horticulture production are the technologies with the higher potential for CO_2 utilization in Europe.

1. Introduction

In 2011 the European Council announced that one of the environmental targets set in the Roadmap for 2050 is to reduce the levels of the Greenhouse Gas Emissions (GHG) at least by 80–95% below the values from 1990 by 2050 [12]. In the last couple of decades the European Union authorities together with all the EU member countries have made efforts to reduce emissions, with the following main pillars of their strategy towards a low carbon economy and society: (a) promotion of renewable energy sources, (b) implementation of energy saving measures and (c) development of carbon capture and storage (CCS) projects. All the efforts were also supported by the adoption of several regulations such as the EU Emissions Trading System (EU-ETS) EC [11].

This is the main reason why CCS has been rapidly developing worldwide during the last decade from pilot and demonstration plants to full scale projects, with geological and ocean storage being the main options for CO_2 storage. Indicative projects include the Sleipner CO_2 Storage Project (0.9 Mtpa) and the Snøhvit CO_2 Storage Project (0.7 Mtpa), in Norway, which already operate from 1996 and 2007 respectively, and the Don Valley Power Project and the Teesside Collective Project in the UK (both expected to operate during the next decade) [3,27].

By contrast, carbon capture and utilization (CCU), which includes the utilization of previously captured CO_2 as working fluid or as feedstock in industrial applications, has begun to get the same level of attention only during the last few years [40]. New CO_2-based value chains can be developed using CCU technologies and can play an important role in the future either through the development of sustainable energy carriers, as well as through the production of different types of carbon derived products [2]. In order to enable the development of such value chains, it is critical to gather detailed information both about the available CO_2 sources (e.g. purity, mass flow) and for the alternative CCU technologies (e.g. technology readiness level, cost, quality requirements). Then, it is necessary to identify the regions in which both sources and industries where CCU technologies could be installed co-exist in order to activate subsequently all the relevant stakeholders. Parallel to that, emphasis should also be given to the

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http://dx.doi.org/10.1016/j.jcou.2016.10.002

development of improved capture and purification technologies and more efficient transformation processes. Additionally, CO_2 used as raw material will be coupled with other sources and materials providing an opportunity to develop industrial symbiosis. For example, in Iceland a factory (Carbon Recycling International) produces methanol at a large scale, using CO_2 containing flue gas from a geothermal power plant as well as electricity geothermal [7].

The "enCO_2re" (Enabling CO_2 reuse) project, a flagship project financed by the European Institute of Innovation and Technology – Climate Knowledge Innovation Community, focuses on all the aspects of a successful CCU scheme; from mapping all potential CO_2 sources and sinks to developing new and improved carbon neutral products and educating its industrial partners, entrepreneurs, decision makers and researchers about recent developments and relevant issues.

1.1. State of the art

Due to the earlier development of CCS, there already exist several attempts to map on a global level the sites where CCS currenly takes place as well as sites with increased potential for investment. The Scottish Carbon Capture & Storage (SCCS) interactive world map of carbon capture and storage projects provides information about large-scale operating and planned projects with annual capacity greater than 0.5 Mt per annum (Mtpa) and also includes smaller scale but significant pilot projects from capture and storage to full-chain CCS [38]. Similar maps have been also created by the MIT Carbon Capture and Sequestration Technologies Program [27] and the IEA Greenhouse Gas R&D Programme [21]. Going one step further than simple mapping, the U.S. Department of Energy (DOE) Carbon Storage Atlas provides an estimate of the CCS potential across the United States and other portions of North America, by combining the available CO_2 stationary sources and the alternative storage points [44], whereas Szulczewski et al. [42] have performed a US-wide assessment of CO_2 storage capacity by using both analytical models and regional geological models and have estimated a total storage capacity of over 100 Gt in the continental US. Moreover, the Capacity Map developed by SETIS assesses the public and corporate R&D investment in Carbon Capture and Storage in the EU (among other low-carbon energy technologies), thus highlighting candidate countries for the development of such projects and providing a benchmark for future investments [6].

Similar studies, focusing on the CCU potential, are in their beginning. Pérez-Fortes et al. [32] analysed two different CCU options, methanol synthesis and accelerated aqueous carbonation of waste (fly ash), and assessed the role of CCU on the future European energy and industrial sectors, through a techno economic analysis. Process flow modelling was used to estimate all the relevant technical and economic values, assuming that the CO_2 source is a conventional power plant. Wei et al. [46] examined the potential of developing CCU projects in China, using technology readiness level (TRL) and geographic distribution as their two main criteria, and identified specific regions that are potential candidates to develop CCU technologies at different timeframes. A similar analysis was performed by Reiter and Lindorfer [36], who have evaluated the potential of using several alternative CO_2 sources within the power-to-gas industry in Austria, with the results revealing that the available CO_2 is enough to satisfy all the power-to-gas processes in the country. The ideal source has been identified as CO_2 from biogas upgrading facilities or bioethanol plants, based on capture cost, specific energy requirement and CO_2 penalty. A team led by Element Energy, and comprising Carbon Counts, PSE, Imperial College and the University of Sheffield, has carried out a study of industrial CO2 capture for storage or utilization and developed three alternative scenarios for the deployment of CCU technologies in the UK by 2025. The four technologies that were selected to be included in these scenarios are methanol production, mineral carbonation, polymer production and direct industrial use of CO_2. The annual CO_2 utilization ranged from 0.5 to 0.7 Mtpa for the moderate scenario to 9 Mtpa for the very high utilization scenario [14]. However, all these focus either on a few CO_2 end-receiving processes or on a specific country. von der Assen et al. [48] have mapped the available CO_2 sources greater than 0.1 Mtpa on a European level and have identified the favourable locations for CO_2 utilization with the lowest environmental impacts of CO_2 supply, the so-called CO_2 oases, by using environmental-merit-order curves.

The present paper will attempt to assess the potential of CO_2 utilization across Europe, and to identify the European regions with the greater potential to deploy nine selected carbon dioxide utilization technologies. The selection of these technologies is primarily based on their TRL and is validated by the industrial stakeholders involved in the project. The current production level of the goods that could potentially use CO_2 as raw material and the availability of by-products that could be combined with CO_2 in order to create new opportunities are retrieved from publicly available databases for the baseline year 2013. The countries with the higher potential are identified and a more detailed analysis at a regional level is carried out in order to pinpoint the regions that could be considered as candidates for the development of CO_2-based industrial clusters and thus for further study. Furthermore, a preliminary rough estimation of the amount of CO_2 than can be used by each technology is also performed. Section 2 briefly presents the methodology that will be followed for the estimation of CO_2 availability and potential for utilization, while Section 3 illustrates the results of the application of this approach in Europe. Section 4 summarizes the findings, highlights the most prominent regions for the development of CCU schemes but also enumerates several suggestions to improve the approach towards a more accurate estimation.

2. Methodology

A top-down methodological approach has been developed in order to identify the key European regions with potential for developing CCU partnerships (Fig. 1). The selection of a top-down approach is also driven by the possibility of using common available statistical data that allows the determination of maximum values of different flows [23].

The approach is divided in two blocks. In the first block, the current potential for CO_2 utilization at regional level in Europe is quantified and characterized. The calculated values represent what can be defined as the potential demand for CCU. The second block characterizes and quantifies CO_2 emitted by industrial stationary sources at a regional level and can be regarded as the potential availability of CO_2 as a feedstock or supplementary resource. The outputs of both blocks are estimated on a regional level and are juxtaposed in order to prioritize regions with potential to develop CCU business models. At this point the analysis is exclusively based on quantities and distances, whilst purities should be dealt with separately at a later stage, in opportunity development for the identified key areas. A detailed description of the top-down methodology is presented in the following sections.

2.1. Assessing the potential for CO_2 utilization

CO_2 is currently used as an input in several industrial processes with the various technologies and products being in different stages of development. For the purposes of this analysis, a list of CO_2-receiving processes has been compiled based on an extensive

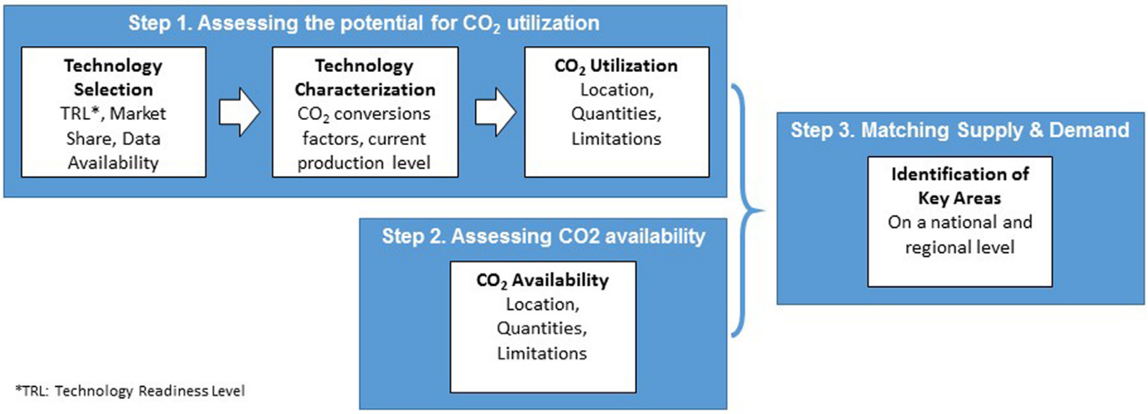

Fig. 1. Methodological Framework.

literature review and the TRL of each one has been determined. TRL is a systematic metric system used to assess the maturity level of a technology, which varies from 1 to 9, with 9 being the most mature process. The most promising processes have been selected for the estimation of the potential for CO_2 utilization, based on the TRL and on their inclusion in previous mapping attempts, presented in Section 1.1. This initial screening was further limited in certain cases due to lack of data for the estimation of CO_2 reuse potential. Table 1 summarizes all the CO_2-receiving processes considered in this study. It also provides information on the type of CO_2 use and the conversion factors, i.e. the ratio of CO_2 use per unit of product or per unit of raw material consumed. The following subsections present the three steps followed to estimate the regional potential for CO_2 utilization in Europe.

2.1.1. CO_2 potential for utilization at country level

CO_2 can be used in an industrial process either as a primary feedstock being its consumption proportional to the mass flow of the final product, or as a supplementary resource which reacts with a by-product of the main industrial process and its consumption is proportional to the mass flow of the by-product. Thus, the total amount of goods produced each year at country level or the amount of by-products that are produced during the production/extraction of a specific material needs to be estimated for all processes described in Table 1.

Industrial production is estimated using the Prodcom Database, provided by Eurostat, which includes statistics on the production of manufactured goods, and covers the mining, quarrying and manufacturing industries. The only exception is made when CO_2 is used as nutrient in industrial-scale bioprocesses (e.g. in the case of horticultural production) where the amount of CO_2 is proportional to the cultivated area and not to the final crop production. All the necessary values were collected from official publications and databases of various organizations and institutions. The following data sources were used to account the amounts of goods with CO_2 use at a country level:

- Industrial production classified by Prodcom codes disaggregated by EU28 Countries [17].
- Areas of crops under greenhouse areas disaggregated by EU28 Countries [18].
- Primary aluminium production at a country level, available in Nation Master [29]
- Crude steel production at a country level, available in World Steel Association [47]

The values collected were then combined with the conversion factors presented in Table 1 in order to estimate the annual potential for CO_2 utilization at country level in Europe.

2.1.2. Disaggregation at a regional level

According to European Comission [15], both countries and regional authorities should design smart specialization strategies to take advantage of the knowledge-based growth and diversify into technologies or products that are closely related to existing dominant technologies. Based on this, concept the present study defines key regions as regions that can take advantage of the existing technologies to promote CCU. Therefore, the values accounted at country level were subsequently allocated into regions, by using the ratio of the number of workers within a specific economic activity in the region to the number of workers for the same activity at a country level. In the cases where the data on the number of employees was not available, the same approach was applied by using the number of establishments. All values were retrieved from the Regional Statistics Database of Eurostat [17,18].

Table 1
Selected CO_2 end receiving processes.

Industrial Process	Type of use	TRL	Conversion Factor
Lignin Production	CO_2 used in black liquor pH regulation	7-8	0.22 tCO_2 per t of lignin produced [25,43],
Methanol Production	Electrochemical reduction of CO_2.	7	1.7 tCO_2 per t of methanol produced [45]
Polyurethane Production	CO_2 used as raw material to produce plastics and fibers	7	0.1–0.3 tCO2 per t of polyols [41]
Polycarbonate Production	CO_2 used as raw material to produce plastics and fibers	7	0.43 tCO_2 per t of PPC produced [8]
Concrete Curing (Concrete blocks)	CO_2 used for precast concrete curing	7–8	0.03 tCO_2 per t of block produced 0.12 tCO_2 per t of precast concrete [13]
Mineral Carbonation	CO_2 reacted with calcium or magnesium containing minerals	7–8	0.25 tCO_2 per t of steel slag [20]
Bauxite Residue Carbonation	CO_2 is used to neutralize bauxite residues	9	0.053 tCO_2 per t of red mud [49]
Horticulture Production	CO2 supplementation on plant growth	9	0.5–0.6 $kgCO_2/hr/100m^2$ [1] 160 tCO_2 per ha (for tomatoes in Sweden) [22]
Urea production	Urea production from ammonia and CO_2	9	0,74 tCO_2 per t of Urea [19]

2.2. Assessing CO_2 availability

The quantification of the CO_2 emissions for each region is based on the Regulation (EC) No 166/2006 of the European Parliament and of the Council [10], which establishes an integrated pollutant release and transfer registry at Community level (the European PRTR). Every year EU companies are required to report their emissions, if they exceed a certain threshold for the pollutants. For the case of CO_2 emissions, the limit from which the emissions have to be reported is 100 million kg/year to air. According to the European PRTR the thresholds are designed to capture 90% of European industrial releases [34]. Data was collected from the E-PRTR database, which covers all the values reported in 2013 for all EU Member States, Iceland, Liechtenstein, Norway, Serbia and Switzerland [16]. Based on this database, the total amount of CO_2 emissions released by stationary sources in 2013 is estimated. The CO_2 emissions at a facility level were aggregated into regional and national level. These values include both fossil fuels origin as well as biomass origin CO_2.

2.3. Matching availability and utilization potential

The last step of the proposed approach is to match the amount of available CO_2 per region with the potential for the utilization of CO_2. The matching is performed both on a country level and on a regional level and is done in absolute values, by comparing the total amount of CO_2 emitted by industrial sources, with the total amount of CO_2 that potentially could be utilized. The analysis on a country level helps to filter the countries and identify those with the most favourable quantitative characteristics for the development of CCU schemes. Such a screening can be useful to policy makers and decision makers in order to efficiently promote the development and the implementation of such schemes. The analysis on a regional level allows to narrow down the geographical area and could be helpful both for the industries searching for a partner and for technology developers, who could promote their innovations in a more targeted way.

2.4. Limitations

Industrial production data at the country level was not always available. In some cases, the data is confidential, when for example there is only one producer per country. Moreover, the maximum potential for CCU has been estimated by combining the annual CO_2 availability with the CO_2 quantity requirements for each process. However, these estimates include significant uncertainty because the CO_2 requirements for each conversion process represent an average value based on the most common product or the most technologically advanced process. The disaggregation into regional level is done using Eurostat data, only available at NACE 2 Digits (Sector Level), which for some cases can be considered as not detailed enough.

Some of the promising CO_2-feedstock receiving processes were not included due to lack of data. This is for instance the case of the power to gas technology. For this particular technology it was not possible to estimate the amount of CO_2 that could be utilized.

In this analysis, CO_2 emissions do not include minor industrial sources that emit less than 0.1 $MtCO_2$ per year. Despite the fact that minor sources contribute with only about 10% of the industrial emissions in the EU, some of them may represent an important source of CO_2 due to the high concentration of CO_2 in the effluent stream (such as fermentation plants, breweries. ethylene oxide industries or biogas purification plants). Furthermore, no additional capture/purification/treatment technologies are required. It is also cheaper to collect CO_2 from several small sources into a single pipeline than to transport smaller amounts separately.

The disaggregation at a regional level is done using the number of workers as reference parameter, an approach that showed to be efficient for regional data amputations [31]. Nevertheless, there are some drawbacks of using this approach, since industrial production also depends on other criteria such as the technology or market. The advantage of using the number of employees is that it is a commonly available figure in a detailed listing [37].

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 on a case by case basis and evaluate the importance of other critical variables such as the durability of the CO_2 in the new product or the potential substitution of raw materials by CO_2. However, this goes beyond the scope of this paper.

3. Results

3.1. Analysis on a national level

3.1.1. Availability of CO_2

In total, 1913 $MtCO_2$ were emitted in 2012 at a European level by 2215 stationary industrial sources. 935 were thermal power stations and other combustion installations, which were responsible for emitting 60% of the total amount of CO_2. Oil and gas refineries and installations for the production of pig iron or steel (108 and 65facilities respectively) emitted 7% and 5%. The majority of the emissions occurred in Germany (454.6 $MtCO_2$), United Kingdom (221.2 $MtCO_2$), Poland (192.3 $MtCO_2$) and Italy (154.1 $MtCO_2$) (Fig. 2a). The emissions from these countries represent more than 50% of the total CO_2 emissions.

3.1.2. Potential for CO_2 utilization

The following sections present a brief analysis for each one of the CO_2 receiving processes.

3.1.2.1. Methanol production. This category includes the production of methanol (Prodcom Code: 20.14.22.10). Currently, methanol is mostly manufactured from synthesis gas that is a mixture of carbon monoxide and hydrogen, which is produced by using natural gas as feedstock. Germany is the country with the highest methanol production in Europe (1.0 Mt), with its share reaching 65% of the total European Production (1.5 Mt) [17,18]. Based on the conversion factors presented in Table 1 (i.e. for every tonne of methanol produced, 1.375 t of CO_2 will typically be consumed) the maximum annual mass flow of CO_2 that would be required in order to produce methanol in Germany would exceed 1.3 $MtCO_2$ whereas in Europe would reach 2.0 $MtCO_2$.

3.1.2.2. Urea production. This category includes the production of urea containing >45% by weight of nitrogen on the dry anhydrous product (excluding in tablets or similar forms or in packages of a weight of less than 10 kg) (Prodcom Codes: 20.15.31.30 and 20.15.31.80). Urea can be used as solid nitrogen fertilizer or as feedstock by several chemical industries. Instead of using a source for capture CO_2, urea is commonly produced using coal-based products [4]. The market for urea production is slightly more balanced since 4 countries (Romania, Poland, Germany and Lithuania) share 75% of the annual European production, which reaches 2.5 Mt [17,18]. Given these values, the maximum annual potential of CO_2 utilization for urea production in Europe would exceed 3.9 $MtCO_2$.

3.1.2.3. Production of ethylene and propylene polymers. CO_2 can be used as feedstock to replace the current petroleum derived products used for polymers production. This category includes the

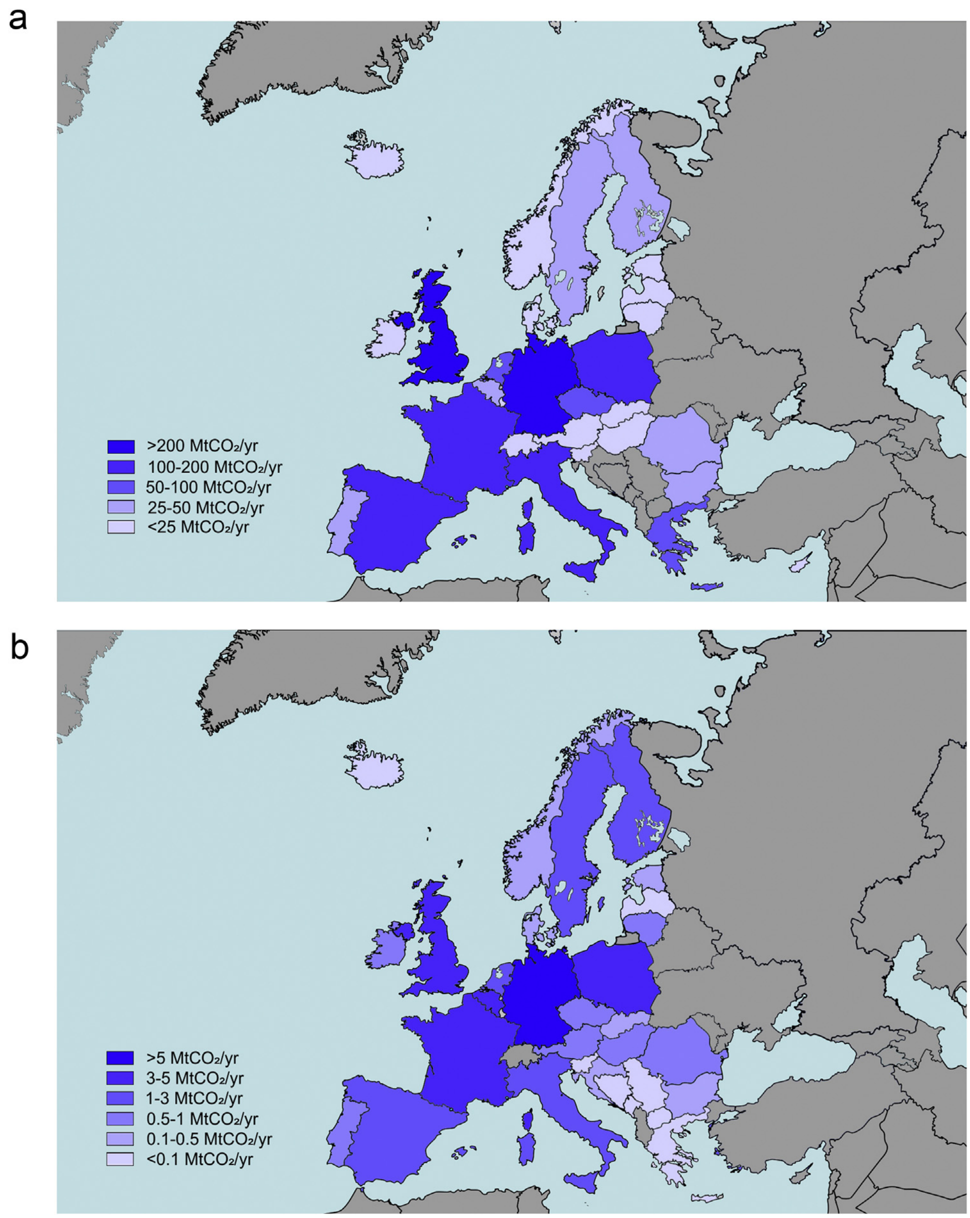

Fig. 2. Matching (a) CO_2 availability and (b) potential for CO_2 utilization on a Country level.

production of polymers of ethylene (Prodcom Code: 20.16.10.39 and 20.16.10.50), propylene or other olefins (Prodcom Codes: 20.16.51.30 and 20.16.51.50), in primary forms. The total amount of these polymers produced in Europe is approximately 19.4 Mt and national confidential values represent almost 23%. Among the available values, Belgium and Germany are the greater producers with respective shares (and quantities) 26% (3.9 Mt) and 23% (3.5 Mt) [17,18]. Assuming that the only polymers produced are polyethylene carbonate (PEC) and polypropylene carbonate (PPC), then the maximum annual mass flow of CO_2 that would be required in order to produce polymers in Europe would reach 8.3 MtCO_2. These estimates are probably less accurate compared to the other processes, due to the vast amount of polymers and the different production processes that can be applied. However, even such a rough estimation can indicate the countries where the analysis should be targeted.

3.1.2.4. Polyurethane production. The production of polyurethanes in primary forms (Prodcom code 20.16.56.70) is considered in this category. The annual production of polyurethanes in Europe is just over 3.0 Mt with Germany (40%), Belgium (24%) and Italy (13%) dominating the market [17,18]. An average estimation of the annual mass flow of CO_2 that would be required in order to produce polyurethanes in Europe would be approximately 0.25 MtCO_2.

3.1.2.5. Bauxite residue carbonation. Bauxite residue carbonation process involves the addition of CO_2 to the highly alkaline bauxite residue slurry (also known as “red mud”), which is the waste stream of the extraction of alumina from bauxite ore. Currently bauxite residue is classified by the European List of Waste as a non-hazardous waste and is normally disposed in landfills. Bauxite residue carbonation would permit to produce a more stable material, which could be used in the construction sector. The addition of CO_2 can reduce pH and simultaneously can lead to CO_2 sequestration. According to estimates, approximately 0.82 t of red mud are generated per tonne of alumina produced [24]. Various estimates can be found in the literature about the amount of CO_2 that is absorbed per tonne of red mud, ranging from 30 to 750 kg

CO_2/t red mud. For the purposes of the analysis, a relatively pessimistic value, proposed by Yadav et al. [49], will be used, equal to 53 kgCO_2 per tonne of red mud. This results in a lower potential for CO_2 utilization in Europe, around 0.22 MtCO_2. However, this estimation may increase by a factor of 10 (and reach 2.5 MtCO_2) if a more optimistic assumption is used. Concerning the spatial analysis, Norway is by far in the first place (with its share surpassing 27%) while Iceland and Germany follow with shares around 13–14% [29].

3.1.2.6. Mineral carbonation. Mineral carbonation involves the formation of solid carbonate products, based on a reaction between carbon dioxide and alkaline/alkaline-earth oxides, which can be found both in naturally occurring silicate rocks and in numerous sources of industrial waste, such as metallurgic slags, incineration ashes and mining tailings. For the purposes of this analysis, a rough estimation of the available potential for CO_2 utilization is made based on the estimated produced slag from the annual iron & steel production. The required data have been retrieved from the World Steel Association database [47]. It is assumed that in the course of liquid steel production in a basic oxygen furnace, for every ton of crude steel, about 100–150 kg of slag are generated in the form of waste, depending on the quality of the hot metal and the steel making process [35]. Based on this assumption, the total potential for CO_2 utilization is estimated approximately 5.3 MtCO_2 per year. Germany is the leading country in this category with a share surpassing 25% whereas Italy and France are the other two countries with shares over 10%. It should be noted that the potential is definitely underestimated since only one (e.g. iron and steel industry) out of many possible industrial waste sources has been considered in the analysis.

3.1.2.7. Concrete curing. A CO_2 stream can be used as a supplementary resource in the cement curing process in order to sequester CO_2 in manufactured concrete products. The use of CO_2 curing instead of the commonly used steam curing process allows the reduction of the energy consumption as well as the reduction of associated generation of CO_2 [30,39]. Using the annual production of concrete blocks in Europe, the potential for CO_2 utilization has been estimated. However, the potential is probably underestimated because although concrete blocks are the most widely used, long-lasting and cost-effective material used in building, they are not the only manufactured concrete product. The total estimated potential reaches 22.5 MtCO_2 per year and the country shares are quite balanced, with four countries having shares between 9 and 15%; United Kingdom (14%), Poland (12%), Germany (9.5%) and France (9%).

3.1.2.8. Lignin production. Lignin can be extracted from black liquor, which is a by-product of the pulp mill industry. Lignin extraction will not only allow to produce a valuable product, but will also increase pulp production. CO_2 needs to be added to the process in order to lower the pH of the black liquor. With the current technology, only high purity CO_2 streams are used but research is under way towards the possibility of using directly CO_2-containing flue gases [43]. According to estimates, approximately 0.3 t of lignin may be produced per tonne of air dried pulp produced [25]. Lignin production is estimated using the annual production of pulp in Europe [17,18]. Considering that 0.22 tCO_2 is necessary to produce one tonne of lignin [43], the annual potential for CO_2 utilization has been estimated at approximately 22.5 MtCO_2 per year. Sweden and Finland are the two countries with higher potential, with a share of just over 30% each, while Germany, Portugal and Spain follow with a share of approximately 10% each.

3.1.2.9. Horticultural production. For the majority of greenhouse crops, the net photosynthesis increases following the increase of CO_2 level in the air [28]. In general, when raising the CO_2 level from ambient values, about 340 ppm, to 1000 ppm, photosynthesis is improved by around 50% [1]. In Europe the production of vegetables (e.g. tomato, cucumber, sweet pepper) and fruits (e.g. watermelon, strawberries) in greenhouses represents 83% of the total greenhouse production area [17,18] while the remaining is used to produce flowers and ornamental plants. CO_2 utilization in Europe has been estimated using Eurostat data on the greenhouse cultivated area as well as a reference value of the amount of CO_2 required for the production of tomatoes (160 tCO_2 per ha of cultivated area). Tomato has been used as the representative plantation, since it is the vegetable which is more commonly produced in greenhouses in Europe. The estimated annual potential for CO_2 utilization in greenhouses is approximately 22.0 MtCO_2. Spain, Italy and the Netherlands are the countries with the highest potential with a share of 33%, 28% and 7%, respectively.

3.1.3. Overview

Table 2 presents the total amount of CO_2 that can be utilized by each industrial process in Europe. According to the results the most promising industrial technology is concrete curing with 22.5 MtCO_2, followed by horticulture production (22.0 MtCO_2) and lignin production (8.4 MtCO_2). There are other industrial processes with high potential for CO_2 capture and utilization that are not included in the Table. This is for instance the case of Power-to-Gas (PtG) that consists in converting surplus of energy into an energy carrier such as methane or methanol. Several demonstration projects can be found in Europe, especially in Germany with 20 plants operating in 2015 [9]. The largest project is located in Werlte in Germany (6 MW plant). Production of algae using CO_2 has also a limited market in Europe, but has very good perspectives to grow in the future, either to produce bio-fuels or other valuable products such as pharmaceutical or cosmetics. For both technologies the current prediction of potential CO_2 utilization is considered as inaccurate and therefore not considered further in the study.

It should be noted that all three technologies with the higher estimated potential can be found in the latter end of the innovation cycle, towards the adoption phase. They are all characterized by high TRL, namely horticultural production: 9, lignin production: 7–8, concrete curing: 7–8 and are only a few steps before commercialization, if not reached yet. Thus, in terms of innovation policy and practice, not many efforts related to fundamental science are required for their development. By contrast, local governments as well as national and European funding bodies could contribute significantly to the deployment of these options by targeting two relevant policy options. First, they are well placed to encourage the development of pilot and demonstration plant, which will allow such technologies to be tested and more widely adopted by increasing investor confidence. Second, public

Table 2
Potential CO_2 utilization in Europe by industrial process.

Industrial Process	CO_2 Utilization (Mtpa)
Concrete curing	22.5
Horticulture production	22.0
Lignin production	8.4
Ethylene and propylene Polymers	8.3
Mineral carbonation	5.3
Urea	3.9
Methanol	2.0
Polyurethane	0.3
Bauxite Residue Carbonation	0.2

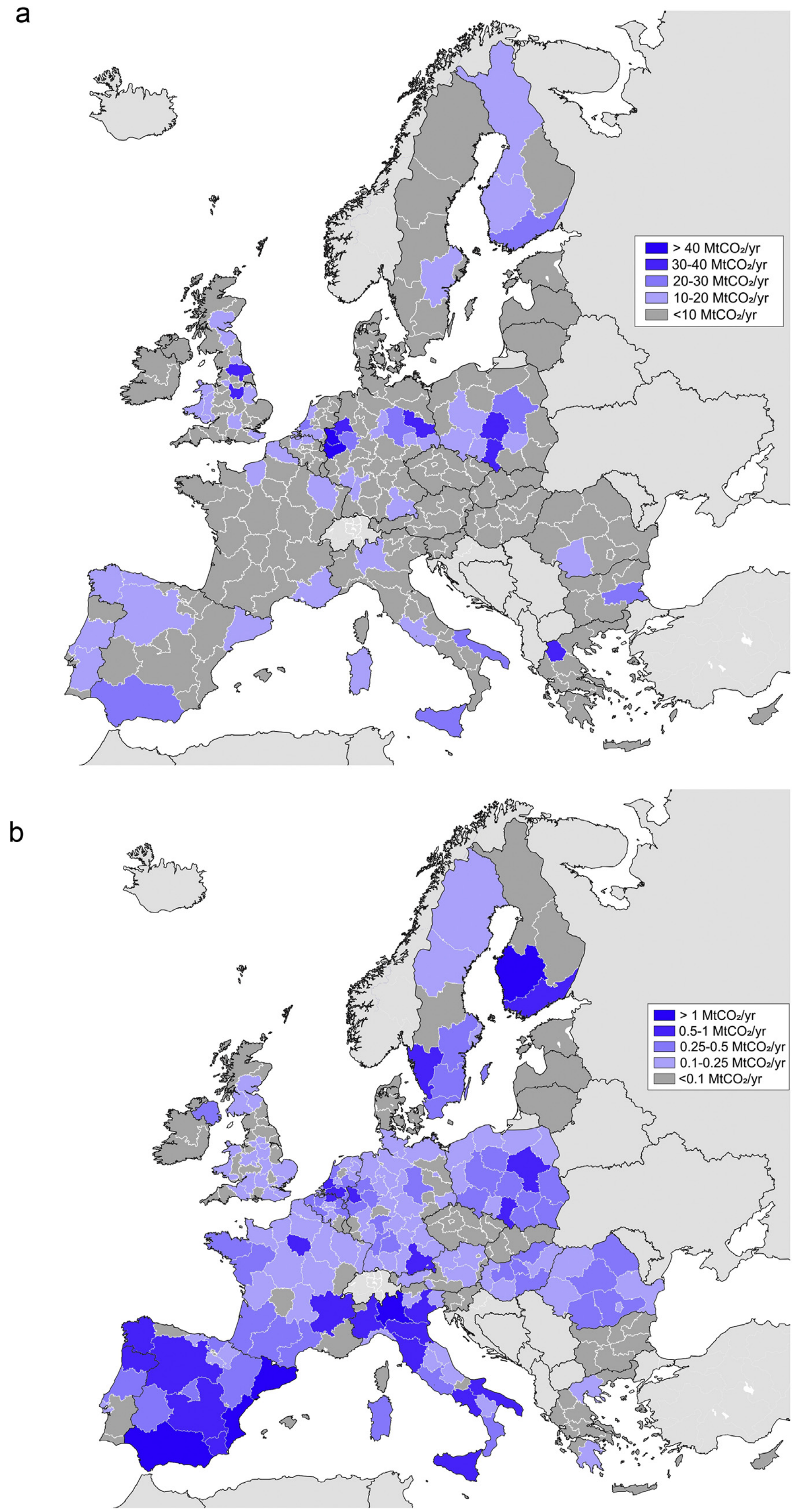

Fig. 3. Matching (a) CO_2 availability and (b) potential for CO_2 utilization on a regional level.

procurement could be considered to provide economies of scale to the emerging value chains and in particular to the new CO_2 end-receiving processes.

It is important to highlight that the same applies to a large extent to all the technologies assessed in the current paper. The methodological design stated that only technologies with high TRL (>7) were included in the estimation of the medium-term EU potential. However, there is a wide range of other CO_2 reuse technologies with much lower TRL (2–5), where the discussion of innovation theory and practice for their gradual adoption, would require a much broader approach to policy analysis according to the different alternatives in earlier stages of the innovation life-cycle, which is out of the scope of the present paper.

Fig. 2b maps the maximum potential for CO_2 utilization on a European level. It is apparent from the analysis that Germany is the country with the greatest potential, since it features among the top countries in almost all examined processes. Evidently, it is the preferred candidate for the development of partnership schemes focusing on the reuse of carbon dioxide, because it has a diverse range of conversion processes and can therefore absorb flows of different magnitude and purity. However, Germany should not be the sole focus of the analysis for developing successful CCU initiatives. Other countries with high potential are also included in the analysis, taking into account their specific characteristics. Sweden and Finland, for example, feature among the top countries with almost 3Mtpa each for the examined processes. However, the majority of the potential is related to lignin production, which at the moment requires high purity streams. By contrast, UK, France, Belgium and Poland are four countries with a more balanced CO_2 demand and can absorb flows of diverse purity and magnitude.

By comparing Fig. 2a and b, it is apparent that the countries with the larger quantities of emitted and available CO_2 and the greatest potential for CO_2 utilization in the nine selected processes are Germany, UK and France as the most promising followed by Spain, Italy and Poland. The fact that the countries with the largest emissions also have the highest potential for utilizing the CO_2, may potentially allow maintaining industrial production at the current level while simultaneously decreasing the net CO_2 emissions, by recycling CO_2 in the same region. However, the current potential for utilization is two orders of magnitude lower than the emissions. Therefore, a dramatic increase in CO_2 utilization capacity is required in order to decrease the net CO_2 emissions significantly.

3.2. Analysis on a regional level

The estimation of the potential utilization per country is useful, because it can guide decision makers and policy makers on a European level to identify countries, which should be the focus for the development of carbon dioxide reuse schemes. However, industrial stakeholders and technology developers require a more detailed analysis that narrows down the geographical area, where the former could find potential users/buyers of the carbon dioxide that they produce and the latter could promote relevant capture and purification technologies. Moreover, a more detailed mapping will help to identify key regions where (a) the methodology could be applied and a more detailed and case-specific analysis is necessary and (b) relevant potentially interested stakeholders could be sought.

Fig. 3 presents the CO_2 availability and the potential for the utilization of CO_2 on a regional level. A first observation from the comparison of the two maps is that the amount of available CO_2 is greater than the potential for CO_2 utilization in all regions. This proportion is expected, since the CO_2 availability includes all the large scale sources (without examining the feasibility of installing carbon capture technology) whereas the estimation of the potential for CO_2 utilization is based only on nine selected CO_2 receiving processes. However, the difference in the values is significant and it is almost certain that availability will be in most cases far greater than utilization. Thus, the identification of the candidate regions for the development of CCU schemes should be mainly based on the existing potential for CO_2 utilization.

The regions of Dusseldorf and Cologne (in North Rhine-Westphalia, Germany), Antwerp Province and East Flanders (in Vlaams Gewest, Belgium), Cataluña (in Este, Spain) and Śląskie (Silesia) in Poland are the six most promising regions in terms of both CO_2 availability and potential of CO_2 utilization. All of them are regions with significant industrial and/or port activities. The two regions of North Rhine-Westphalia (NRW) are expected to be among the most prominent candidates, since NRW is one of the most important industrial regions in Europe and one of the most important economical areas in the world. It also hosts Clean-TechNRW, an industrial cluster aiming to accentuate innovative potential and reduce CO_2 emissions across four industrial sectors, energy, steel, chemistry and biotechnology [5]. On the contrary, Vlaams Gewest in Belgium and Este in Spain host some of the most important ports in Europe (port of Antwerp and ports of Valencia, Barcelona and Tarragona respectively).

Moreover, the regions of Lombardia in Italy, Oberbayern (Upper Bavaria, with the Bavaria chemical cluster) in Germany, Łódzkie in Poland, South Holland and North Braband in the Netherlands and the southern part of Finland (specifically Etelä-Suomi and Helsinki-Uusimaa) have also been identified as favourable regions for the development of CCU schemes.

It should be pointed out that there are no regions which combine both high availability and high utilization potential (or at least the same level compared to the other countries) in France or the UK, two of the most developed economies and industrialized countries in Europe. However, there are a few regions with either high availability (e.g. Yorkshire and The Humber and East Midlands in the UK) or high potential utilization (e.g. Île de France). This may be explained from the fact that the nine selected CO_2 receiving processes are not significant for the industrial sector of those two countries or that the industrial sector is equally spread among all regions and no particular one stands out (although both countries were among those highlighted in the country-level analysis).

More detailed information is shown in Supplementary information, where the total amounts of available CO_2 as well the potential uptake, for each country and region are highlighted. As stated before, this study was performed to identify the total amount of CO_2 available and the potential CO2 utilization, both for countries and regions in Europe. Therefore, more populated countries or regions are more susceptible to have higher results. A comparison between countries or regions should be done based on the CO_2 reuse potential per capita ($MtCO_2$/capita) and on per available area ($MtCO_2/km^2$) for each region.

4. Conclusions and suggestions for further research

The current paper has presented a methodological approach in order to estimate the regional potential for utilization of CO_2 and to compare it with the distribution of available CO_2 due to industrial emissions. The annual amount of CO_2 released by industrial sources in Europe was approximately 1900 $MtCO_2$ while the potential utilization could reach 73 $MtCO_2$, based on nine selected technologies, which represents 2.8% of the total amount of CO_2 available. The results are in line with other recent studies [26], thus indicating that currently CCU can play a small role as a part of a wider strategy for carbon emissions reduction. There is a need to continue developing and testing emerging CCU technologies as well as other CCU technologies that are in an early stage of fundamental research [33]. Additionally, CCU should be considered a complementary strategy to other policies and sequestration options, such as CCS.

The study has shown that the countries with the largest emissions also have the highest potential for utilizing the CO2, with Germany, United Kingdom and France being the most promising followed by Spain, Italy and Poland. A more detailed analysis has also revealed several regions where CO_2 reuse schemes could be developed. The majority of them are located in Central Europe (Germany, Belgium and Poland) and Scandinavia (Sweden and Finland). These regions may take advantage of the available resources as well as technologies to increase the industrial production and decrease the dependence on fossil fuels based materials while simultaneously decreasing the net CO_2 emissions, by recycling CO_2 in the same region.

The regions of Dusseldorf and Cologne (in North Rhine-Westphalia, Germany), Antwerp Province and East Flanders (in Vlaams Gewest, Belgium), Cataluña (in Este, Spain) and Śląskie (in Poland) are the six most promising regions in terms of both CO_2 availability and potential of CO_2 utilization. Other promising regions can be found in Poland (Łódzkie), Finland (Etelä-Suomi and Helsinki-Uusimaa), Italy (Lombardia) and The Netherlands (South Holland and North Braband).

However, the application of the approach has also revealed some of its weaknesses. The fact that the main criterion for the definition of a region is its population has led to an overestimation of the potential of sparsely populated regions (such as Finland or Northern Sweden) and could also lead to the underestimation of the potential of small but densely populated regions. In order to resolve this issue two more maps will be created, based on the CO_2 reuse potential per capita ($MtCO_2$/capita) and on per available area ($MtCO_2/km^2$) for each region.

Concerning CO_2 availability, the small scale sources should be also included in the analysis. Although such sources may not play a significant role in the CO_2 emissions abatement if they are examined separately, they have some characteristics that can be very critical to the development of successful business models. They can be treated as an add-on to large scale sources and multiple small scale sources can be located close to each other thus providing opportunities for clustering. Moreover, small scale sources can be located closer to the CO_2 sink, and thus reducing the transport cost. Furthermore, the most popular carbon capture technologies are already proven on a small scale. Thus, their mapping is a necessary step towards their inclusion in a potential CO_2 reuse scheme.

A suggestion for future work would be to perform an uncertainty analysis of the obtained results. It would be also interesting to do a techno economic analysis of the necessary changes in the current infrastructure so that CO_2 could be used as raw material for each technology. Concerning the estimation of the CO_2 utilization potential, a couple of promising technologies (with relatively high TRL) but without any significant installed industrial unit across Europe, such as algae production were left out of the analysis intentionally, because the objective of the paper was to assess the current potential. In a next step of the analysis, our results could be combined with forecasts about the evolution of the involved industrial sectors in order to estimate not only the current but also the future potential for utilization.

Finally, a more detailed and case specific analysis should be performed for the most prominent regions. A high purity demand vs. low purity demand map should be created to highlight the requirements for specific capture and purification technologies and also, by comparing it with the available CO_2, the possibility and the feasibility to develop a reuse scheme.

Acknowledgements

The work presented in the paper arises from “enCO_2re – Enabling CO_2 Reuse”, a research project financed by the European Institute of Innovation and Technology – Climate Knowledge and Innovation Community (Climate-KIC).

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.jcou.2016.10.002.

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