Projet DRIVER du Fonds de Transition Energétique octroyé dans le cadre de l'appel de Novembre 2020

Délivrable 1 (D1) :

Rapport technique sur les émetteurs et utilisateurs de CO_2 belges et européens, incluant le référencement des infrastructures de capture, purification et transport de CO_2

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Date : 28 Octobre 2022

D1: émetteurs et utilisateurs de CO_2 belges et européens, infrastructures de capture, purification et transport de CO_2

Note : en accord avec les représentants du SPF Economie, il a été convenu lors de la kick off meeting du projet DRIVER qui s'est tenue le 25 Octobre 2021, que les délivrables du projet peuvent être rédigés soit en français soit en anglais moyennant un résumé en français. Le présent document comprend donc cette section introductive en français, qui résume le contenu du rapport technique quant à lui rédigé en anglais.

1. Description générale du projet DRIVER

Le projet DRIVER (**D**éveloppement d'un modèle de ma**R**ché, **I**nfrastructurel et régulatoire, du CO_2 comme **V**ecteur pour le stockage d'**E**nergie **R**enouvelable) vise le développement d'un modèle de marché du CO_2 en vue de la production de fuels synthétiques défossilisés permettant de réduire la dépendance aux combustibles fossiles et à terme tendant vers une indépendance énergétique. Le projet intègre les volets économiques, infrastructurels et régulatoires, et prend en compte les spécificités belges tant au niveau énergétique (p. ex. coordination avec la production d'éolien offshore) que de l'infrastructure (p. ex. pour le transport de gaz). Le modèle développé permettra *in fine* la définition d'une roadmap pour la future gestion du marché CO_2 belge, ainsi que pour le développement ultérieur d'une plateforme digitale.

Le CO_2 étant au centre du projet DRIVER, une attention particulière est portée sur la chaîne de capture, purification et transport de CO_2, ce dernier pouvant ensuite servir à la production d'autres vecteurs énergétiques tel que par exemple le gaz naturel synthétique (SNG). Une telle chaîne de procédés est couramment appelée « CCU » (Carbon Capture & Utilisation). Le CO_2 est donc l'un des éléments d'un réseau énergétique global aux côtés des dispositifs de stockage d'énergie renouvelable, de la production et du transport d'hydrogène et de tous les éléments nécessaires pour fabriquer, à partir de ce CO_2, des e-fuels et les transporter.

Les différents Work Packages (WP) du Projet DRIVER sont illustrés à la Figure 1.

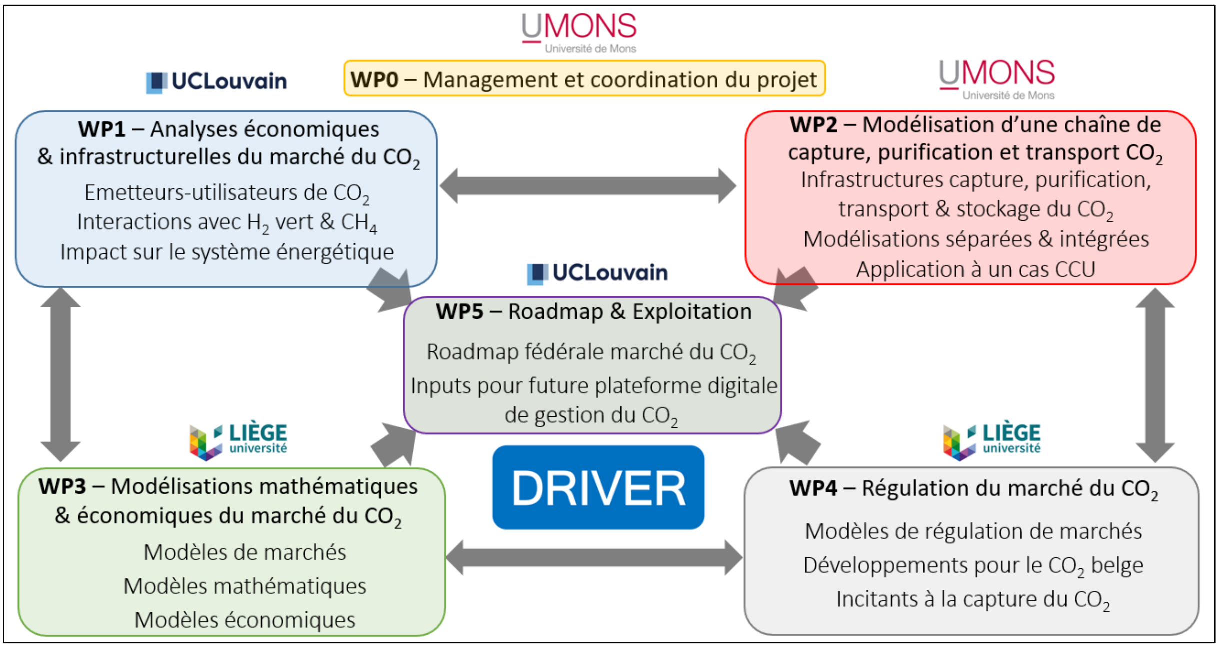

Figure 1 : Work Packages du Projet DRIVER

D'un budget total de 1 121 659 €, le projet DRIVER, a démarré au 1^er^ Octobre 2021 pour une durée de 4 ans.

Le consortium est composé de 3 universités belges qui mutualisent leurs expertises, à savoir l'Université de Mons (UMONS), l'Université de Liège (ULiège) et l'Université Catholique de Louvain (UCLouvain).

2. Résumé du rapport technique D1

2.1. Contenu général du rapport

L'objectif général du rapport est de fournir une vision globale en termes :

- de localisation et de caractérisation des principales sources d'émissions de CO_2, en Europe et en Belgique : différentes bases de données d'émissions de gaz à effet de serre sont reprises (p.ex. UNFCC, IEA, E-PRTR, …), ainsi que les évolutions durant ces dernières années, la répartition par localisation et types de gaz, ainsi qu'un focus plus particulier sur la répartition des émetteurs de CO_2 belges;

- de description des diverses voies de capture du CO_2 : à la fois au niveau des types d'intégration de procédés de capture du CO_2 (pré/post/oxy-combustion), mais également au niveau des principales technologies utilisables (absorption, adsorption, membranes et cryogénie), une liste de fournisseurs de technologies de capture du CO_2 étant fournie ;

- de transport de CO_2 : les différents moyens de transport du CO_2 sont repris (gazoduc, trains, camions ou bateaux), ainsi que les principales impuretés présentes dans le CO_2 capturé ;

- des potentialités actuelles et futures pour l'utilisation du CO_2 : une synthèse du marché actuel du CO_2 est présentée, ainsi que les futures pistes d'utilisation du CO_2 capturé ;

- de projets CCUS en Europe et en particulier en Belgique : permettant de juger le niveau de maturité des développements en la matière actuellement.

Bien que n'étant pas exhaustif, ce rapport permet de juger du statut actuel du développement du CCUS eu Europe et en Belgique, tant au niveau technologique qu'en termes de projets actuels et futurs.

2.2. Résumé des principaux enseignements du rapport

Il est tout d'abord important de rappeler que l'attention portée sur le CO_2 parmi les gaz à effet de serre (GES) est notamment liée au fait que **c'est le GES le plus émis** (entre 70% et 90% de l'ensemble des GES, 85% pour la Belgique).

Le système de gestion du marché du CO_2 (ETS – Emission Trading Scheme), dont les différentes étapes sont résumées dans le rapport, a vu le **prix du CO_2** grimper ces dernières années pour même approcher les 100 €/t_{CO2} à certains moments, ce prix fluctuant le plus souvent **entre 70 et 80 €/t_{CO2}**.

Au niveau des émetteurs de CO_2 belges, l'ensemble des **secteurs industriels** (production d'énergie et industries comme les cimenteries, raffineries, usines sidérurgiques, chimiques, etc.) conduisent à près de **50% des émissions de CO_2**, le plus important émetteur belge étant une centrale électrique avec plus de 5000 kt_{CO2} émises annuellement (2019). Dans le top-20 des plus gros émetteurs de CO_2 belges, on retrouve plusieurs cimenteries et un producteur de chaux, **la particularité de ces industries étant que près de deux tiers de leurs émissions sont dites « inévitables »**, à savoir liées à la décarbonatation de la matière première nécessaire à la production.

Différentes voies de capture du CO_2 existent, à savoir la pré-combustion, l'oxy-combustion et la **post-combustion**, cette dernière (**la plus développée** actuellement) présentant l'avantage de ne pas nécessiter une modification des procédés en amont (technologie dite « end-of-pipe »).

Au niveau des **technologies de capture du CO_2**, **quatre opérations unitaires** sont identifiées : procédés par absorption gaz-liquide, procédés par adsorption gaz-solide, l'utilisation de membranes séparatives (gaz-gaz) et enfin les procédés cryogéniques. La technologie par **absorption gaz-liquide**, et en particulier utilisant les **solvants aminés**, est **la plus mature** actuellement (TRL[1] de 9) et la plus disponible parmi les fournisseurs de technologie (dont plusieurs sont communiqués dans le rapport), bien que les autres technologies disposent d'un potentiel intéressant à moyen ou long terme, en particulier en termes de réduction des coûts et d'impacts environnementaux.
Dans tous les cas, que cela soit pour la capture, la purification ou la liquéfaction du CO_2, le développement de **systèmes cryogéniques** semble nécessaire.

Pour ce qui est du **transport du CO_2**, la pureté du CO_2 et l'impact éventuel des impuretés sur ses propriétés physico-chimiques sont des paramètres importants. Pour le transport continental, le CO_2 peut être transporté par **gazoduc** (cf. les développements de Fluxys en la matière), par **barges fluviales**, en **train**s ou en **camions**, le transport off-shore se limitant bien évidemment aux canalisations et aux bateaux.

Pour ce qui est de l'**utilisation du CO_2**, le marché mondial représente **230 Mt_{CO2} annuellement** (2018) dont **16% au niveau de l'Europe**. Près de **60% du CO_2 mondial** est actuellement utilisé dans la production d'**urée**, **34%** pour la **récupération assistée de pétrole** (EOR) et enfin tout ce qui concerne l'alimentaire et les **boissons gazeuses** (principales utilisations en Europe), ainsi que d'autres industries. Conjointement avec le développement de la filière hydrogène vert, d'**autres marchés** viendront à se développer dans le futur, tels que par exemple le **méthanol**, le **gaz naturel de synthèse (SNG)**, l'éthanol, l'e-kérozène, ainsi que d'autres produits à plus hautes valeurs ajoutées mais dont les marchés sont sensiblement plus réduits comme ceux des polycarbonates, de l'acide formique, du polyuréthane, etc.

Enfin, le rapport illustre les différents **projets CCUS** actuellement en développement en Europe, ainsi qu'en Belgique plus particulièrement, aussi bien dans la production d'énergie que dans des industries comme les cimenteries ou producteurs de chaux.

3. Cas spécifique de la capture du CO_2 dans l'air ambiant (DAC)

3.1. Résumé de l'étude réalisée

Comme indiqué dans le rapport D1, la technologie de capture directe du CO_2 dans l'air ambiant (DAC – Direct Air Capture) a fait l'objet d'un travail spécifique réalisé par L. Dubois (en collaboration avec R. Chauvy) et qui a conduit à une publication scientifique dans la revue International Journal of Energy Research (fournie en annexe). Pour rappel, à la différence de la capture du CO_2 appliquée aux fumées issues de points d'émissions (centrales électriques, cimenteries, fours à chaux, verreries, etc.) où celui-ci est concentré classiquement entre 3% et 30%, la concentration du CO_2 dans l'air ambiant est plutôt de l'ordre de 0.042%. Sa capture demande donc plus d'énergie (contrainte thermodynamique : travail maximum nécessaire à la séparation) et il convient dès lors de se poser la question si l'implémentation de cette technologie garde un sens, tant d'un point de vue économique qu'environnemental. La publication « Life cycle and techno-economic assessments of direct air capture processes: An integrated

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[1] TRL : échelle TRL (en anglais *Technology Readiness Level*) est un système de mesure employé pour évaluer le niveau de maturité d'une technologie. De 1 (plus bas niveau de maturité technologique) à 9 (application réelle de la technologie sous sa forme finale et en conditions réelles).

review » R. Chauvy & L. Dubois, Int J Energy Res. 2022;46:10320–10344, permet d'y apporter des éléments de réponse.

Il est ressorti de cette étude que les technologies DAC sont à des niveaux de maturité très différents (TRL de 1 à 3 pour certaines, jusque 9 pour d'autres) et impliquent diverses opérations unitaires (adsorption, absorption, …), utilisent différents types de matériaux (liquides ou solides) et types d'énergie (électrique et/ou thermique). La plupart des procédés utilisent l'adsorption (p.ex. Climeworks), l'absorption (p. ex Carbon Engineering), même si des solutions plus innovantes existent qui ne sont pas un niveau TRL suffisant pour envisager leur commercialisation.

En ce qui concerne les performances environnementales des technologies DAC, le caractère « **carbone-négatif** » de cette technologie a été souligné, en particulier lorsqu'elle est combinée à la séquestration du CO_2. Cependant, la construction de grandes installations de DAC a un impact sur d'autres aspects environnementaux concernant l'empreinte au sol, l'eau et l'utilisation des matériaux.

Pour ce qui est du volet économique, les études de la littérature fournissent de larges fourchettes de coûts, à savoir de 80 €/t_{CO2} à 1133 €/t_{CO2} pour les estimations actuelles, tandis que les coûts futurs des DAC devraient diminuer et se situer entre 34 €/t_{CO2} et 260 €/t_{CO2}.

Les leviers clés qui contribueront à améliorer les performances des DAC et à réduire leurs coûts sont également discutés dans l'étude publiée. Ceux-ci sont liés aux développements technologiques (p. ex., l'utilisation de sorbants liquides ou solides, le contacteur gaz-liquide/solide), à la consommation d'énergie (p. ex. la possibilité d'utiliser la chaleur résiduelle, la disponibilité d'électricité à faible coût et à faible émission de carbone), ainsi qu'aux caractéristiques de mise en œuvre (p. ex., la modularité et la mise à l'échelle, l'intégration énergétique avec un ou d'autres procédés) ;

3.2. Conclusions et perspectives

En conclusion, au-delà de la récupération du CO_2 atmosphérique, les technologies DAC pourraient, à termes, fournir du CO_2 dans des zones où des industries (émettrices de CO_2) ne sont pas présentes mais où de grandes quantités d'énergie bas carbone sont produites (p.ex. solaire, éolien, géothermique, …), et permettraient à la fois de capturer le CO_2 dans l'air, mais également (par exemple) de produire de l'hydrogène vert, combinable au CO_2 afin de produire un vecteur énergétique plus facilement transportable et gérable, tel que le gaz naturel synthétique (SNG).

Pour ce qui est de l'éventuelle application du DAC en Belgique, il semble clair qu'à l'heure actuelle la priorité doit être la limitation des émissions de CO_2 à la source (beaucoup plus concentrées, et donc aux performances de capture bien plus avantageuses), et donc la capture du CO_2 des fumées industrielles. Néanmoins, certaines technologies DAC pouvant s'ajouter à des installations existantes (p.ex. tours de refroidissement) ou profiter de chaleurs fatales actuellement perdues, il n'est pas à exclure que certains projets pourraient voir le jour dans le futur, en parallèle notamment des infrastructures relatives à l'hydrogène (production et transport) permettant alors d'utiliser ce CO_2 pour produire un autre vecteur énergétique.

4. Conclusions pour la suite du projet DRIVER

Les aspects étudiés dans ce premier rapport feront l'objet d'un suivi et d'une veille technologique tout au long du projet DRIVER, à savoir les évolutions du marché du CO_2 et sa régulation (ETS notamment), ainsi que l'évolution des projets CCUS et DAC en général (projets actuels et nouveaux projets).
Au niveau des chaînes CCUS en général, il a été noté que des **technologies cryogéniques** interviennent très régulièrement, que cela soit pour la capture, purification ou liquéfaction du CO_2. Pour le démarrage des modélisations et simulations de procédés, le choix s'est donc porté sur les techniques cryogéniques, celles-ci pouvant se combiner ensuite avec d'autres techniques de préconcentration (p.ex. adsorption ou membranes) afin d'obtenir des puretés et taux de récupération de CO_2 suffisants.

Belgian and European CO_2 emitters and users, CO_2 capture, purification and transport infrastructures

A. Costa, L. Dubois, D. Thomas and G. De Weireld

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Table of abbreviations

Acronym	Complete Name
ASU	Air Separation Unit
AWAC	Agence Wallonne de l'Air et du Climat
BAHX	Brazed Aluminium Heat Exchanger
CAIT	Climate Analysis Indicators Tool
CAPEX	CAPital EXpenditure
CCUS	Carbon Capture, Utilization and Storage
COP	Conference of the Parties
CO_2e	Carbon Dioxide equivalent
CPU	Carbon Purification Unit
DAC	Direct Air Capture
EEA	European Environment Agency
ETS	Emissions Trading System
EU	European Union
EUTL	European Union Transaction Log
E-PRTR	European Pollutant Release and Transfer Register
GHG	Greenhouse gas
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
LT-LEDS	Long-Term Low greenhouse gas Emission Development Strategies
LULUCF	Land Uses, Land Use Changes and Forestry
MOF	Metal-Organic Frameworks
MSR	Market Stability Reserve
$MtCO_2e$	Million metric tonnes of Carbon Dioxide equivalent
NDCs	Nationally Determined Contributions
OECD	Organisation for Economic Co-operation and Development
OPEX	OPerating EXpenses
PSA	Pressure Swing Adsorption
UNFCCC	United Nations Framework Convention on Climate Change

Molecule	Nomenclature
N_2O	Nitrous Oxide
NF_3	Nitrogen Trifluoride
SF_6	Sulphur Hexafluoride
CH_4	Methane
CO_2	Carbon Dioxide

1 Review of Belgian and European CO_2 emitters and users

1.1 General context of the work

Strategies to reduce greenhouse gas (GHG) emissions are a hot topic all over the world. Indeed, the majority of countries that have signed the Kyoto Protocol (192 Parties) have committed themselves to reducing the amount of GHG emitted into the atmosphere. The first commitment period (2008 – 2012) had the goal to reduce the emission below 5% compared to 1990 levels. At the end of this first period at the COP18 in Doha, on 8 December 2012, the second commitment period (2013-2020) was adopted extending the Kyoto Protocol. During this period, Parties aim to reduce GHG emissions by 18% always compared to 1990 levels. However, the Parties are not the same as in the first period with Canada leaving in December 2012 (UNFCCC, 2021b). For its part, the European Union is making even stronger commitments to the Kyoto Protocol. In the first period, the member countries (EU-15[2] when voting on the legislation) commit themselves to reducing the emissions of the global bloc by 8%. Subsequently, countries joining the EU were given targets for reducing GHG emissions (European Commission, 2014). In the second period, the target is to reduce emissions by 20%. 29 countries (EU-28[3] and Iceland) share this target (European Commission, 2021b).

At the COP21 in Paris, on 12 December 2015, the Paris Agreement was adopted by 196 Parties. This agreement aims to limit global warming to a level well below 2°C, for the best scenario to 1.5°C, compared to the pre-industrial period. Parties must submit by the end of 2020 climate action plans called nationally determined contributions (NDCs) explaining the measures taken to reduce their GHG emissions. Countries are also invited to provide a long-term low greenhouse gas emission development strategy (LT-LEDS) that represents an opportunity to develop the long-term horizon to the NDCs (UNFCCC, 2021a).

For its part, the European union shared at the end of 2018 its report (Runge-Metzger, 2018) on the long-term strategy to rich the neutral carbon dioxide emissions. Figure 1 shows the scenario to avoid a temperature increase above 1.5 °C. This scenario presents a drastic decrease of GHG emissions and a global balance in this GHG of zero tCO_2e thanks to carbon capture processes and land uses, land use changes and forestry (LULUCF).

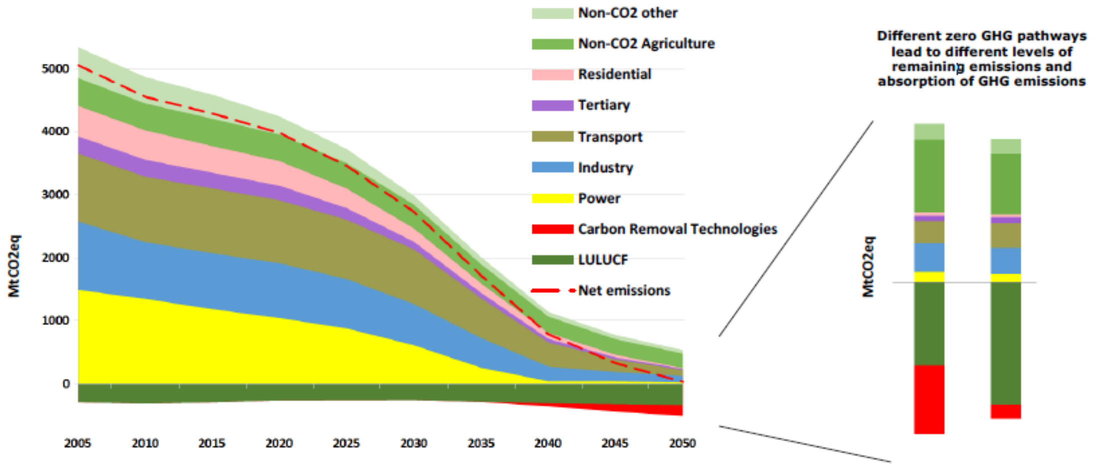

Figure 1 : GHG emissions trajectory in a 1.5°C scenario (Runge-Metzger, 2018)

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[2] EU-15: Austria, Belgium, Denmark, Finland, France, Germany, Greece, Ireland, Italy, Luxembourg, the Netherlands, Portugal, Spain, Sweden, the United Kingdom (EEA, 2004)

[3] EU-28: EU-15 and Bulgaria, Croatia, Cyprus, Czech Republic, Estonia, Hungary, Latvia, Lithuania, Malta, Poland, Romania, Slovakia, Slovenia (Yenilmez & Kılıç, 2016)

In this scenario, the objective is to reduce emissions directly at the source by finding a non-emitting alternative. However, in some cases there is no alternative, which implies the use of capture processes or the equivalent in LULUCF to balance the emissions.

Among the various GHG emitting sectors, one of the most important is that of energy production. In its report aiming at carbon neutrality, different scenarios are presented (Figure 2) for the 2050 energy mix from a "well below 2°C scenario" to one "limited to 1.5°C" scenario.

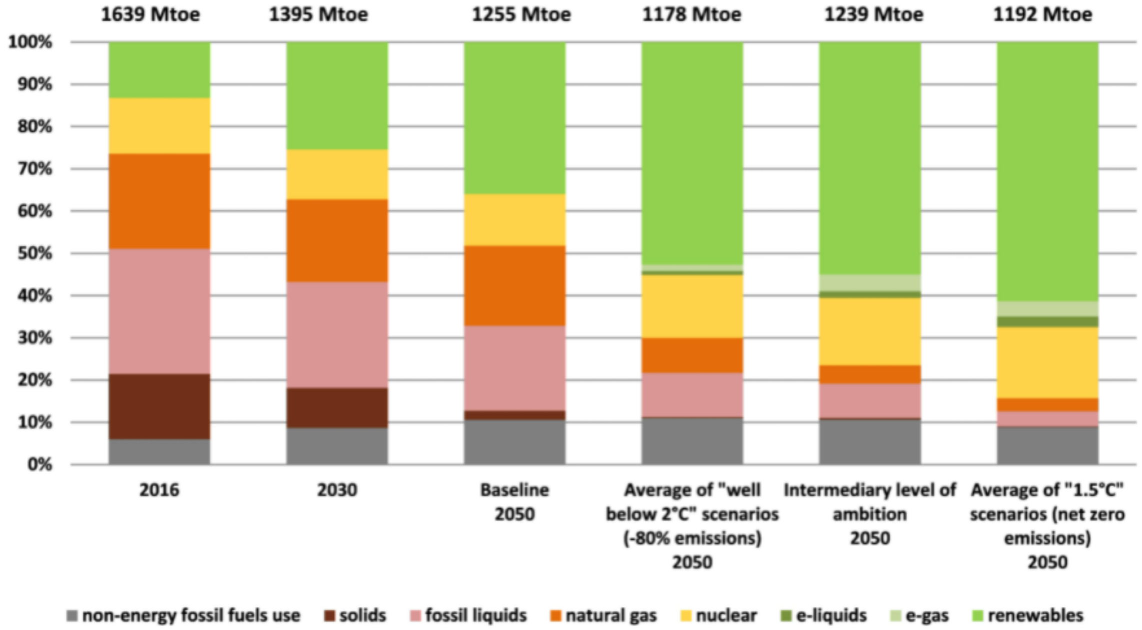

Figure 2 : Fuel mix in Gross Inland Consumption (Runge-Metzger, 2018). Note: as defined by the EU, the Gross Inland Consumption includes the overall supply of energy for all activities on the territory of a country, but excluding international maritime bunkers

Scenarios represent some perspective and some ways to reduce the GHG emissions for 2050. EU member states have committed themselves to reducing their GHG emissions in order to reach the forecasts of one of the different scenarios considered. However, the tools currently available do not allow major emitters to implement solutions to reduce their emissions in a more or less easy way.

1.2 Database for GHG

There are several databases about the gas quantity emitted . Therefore, there are some variations between the database values. In the following paragraph, an overview of the different database will be presented in the goal of choose the rightest database.

- UNFCCC includes only data from the annual GHG inventory submissions for Annex I Parties. For non-Annex I Parties, data provides from the National Communications and Biennial Update Reports. These inventory data are sent by countries. Since the reporting is not the same, the two groups can't be compared. Annex I Parties are members of the OECD since 1992 and countries with economies transition. Non-Annex I Parties are mostly developing countries (UNFCCC).
- CAIT is developed by the World Resources Institute. This tool includes data from several non-governmental sources to completed data given in the report provided by countries to the UNFCCC (World Resources Institute, 2015).
- IEA is a source of global energy data. Energy balance is made and based on the energy statistics on supply and demand. Data are collected for 150 countries and covers up to 95% of global energy supply. Regarding the CO_2 emissions are calculated following the 2006 IPCC guidelines using the energy balance (IEA, 2020).

- E-PRTR is the database linked to the regulation (EC) No 166/2006 of the European Parliament and of the Council of 18 January 2006 (EEA, 2006). An annual report is required to Member State (33 countries: EU 28, Iceland, Liechtenstein, Norway, Switzerland, and Serbia). Data should be provided by companies that are part of the relevant sectors of activity (Annex I) and are above the minimum emission threshold (Annex II) (EEA, 2020).
- The Union register is a database that lists installations covered by the EU ETS that is the European trading system of the emissions and keeps track of the emissions monitored by the ETS as well as the allowances issued to the different bodies. EUTL checks the validity of transactions between accounts in the Union register against the EU ETS rules (European Commission, 2021c).

The emissions analysed in this document will be based on 2019 figures for consistency and due to the impact on human activity during the COVID-19 crisis.

1.3 GHG emissions in Europe

Global warming is mostly due to greenhouse gases (GHG) that are discharged into the atmosphere such as carbon dioxide, methane, nitrous oxide, and fluorinated gases. GHG absorb infrared radiation (remits from the earth that increase the warm in the atmosphere. These gases do not have the same impact on the radiation balance. The CO_2 equivalent (CO_2e) is therefore used as the unit of measurement. This corresponds to the amount of CO_2 needed to have the same impact on IR absorption for a gap (usually 100 year) as the compared gas. Concerning methane and nitrous oxide, the global warning potential is respectively 25 and 298 (UNFCCC, 2007).

Since 1990, European Union has already reduced its emissions by 28% (Figure 3). There is still a lot of work to be done to achieve a zero GHG emissions balance. As a first step, an analysis of the different actors in the European Union is carried out to highlight their similarities and differences.

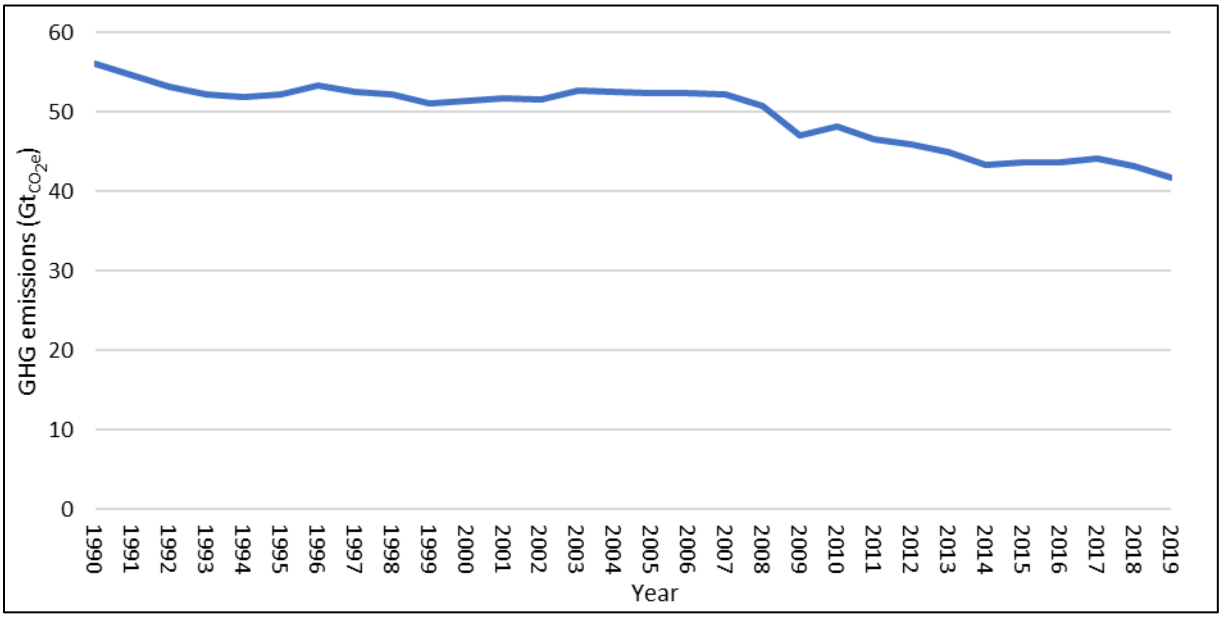

Figure 3 : GHG emissions for the EU 28 from 1990 to 2019 (EEA, 2021a)

The repartition of GHG (methane, carbon dioxide, hydrofluorocarbons, nitrous oxide, nitrogen trifluoride, sulphur hexafluoride, perfluorocarbons that are gases covered by the Kyoto protocol during the two-commitment period except for the NF_3 that is considered for the second commitment period) between the EU members.

The distribution of the different GHG emissions (Figure 4) for the EU countries has a large proportion in terms of CO_2 emissions ranging from 62% for the lowest to almost 91%. It is therefore clear that despite the greater impact on the greenhouse effect of other gases, CO_2 far outweighs other GHGs in terms of countries in the European Union.

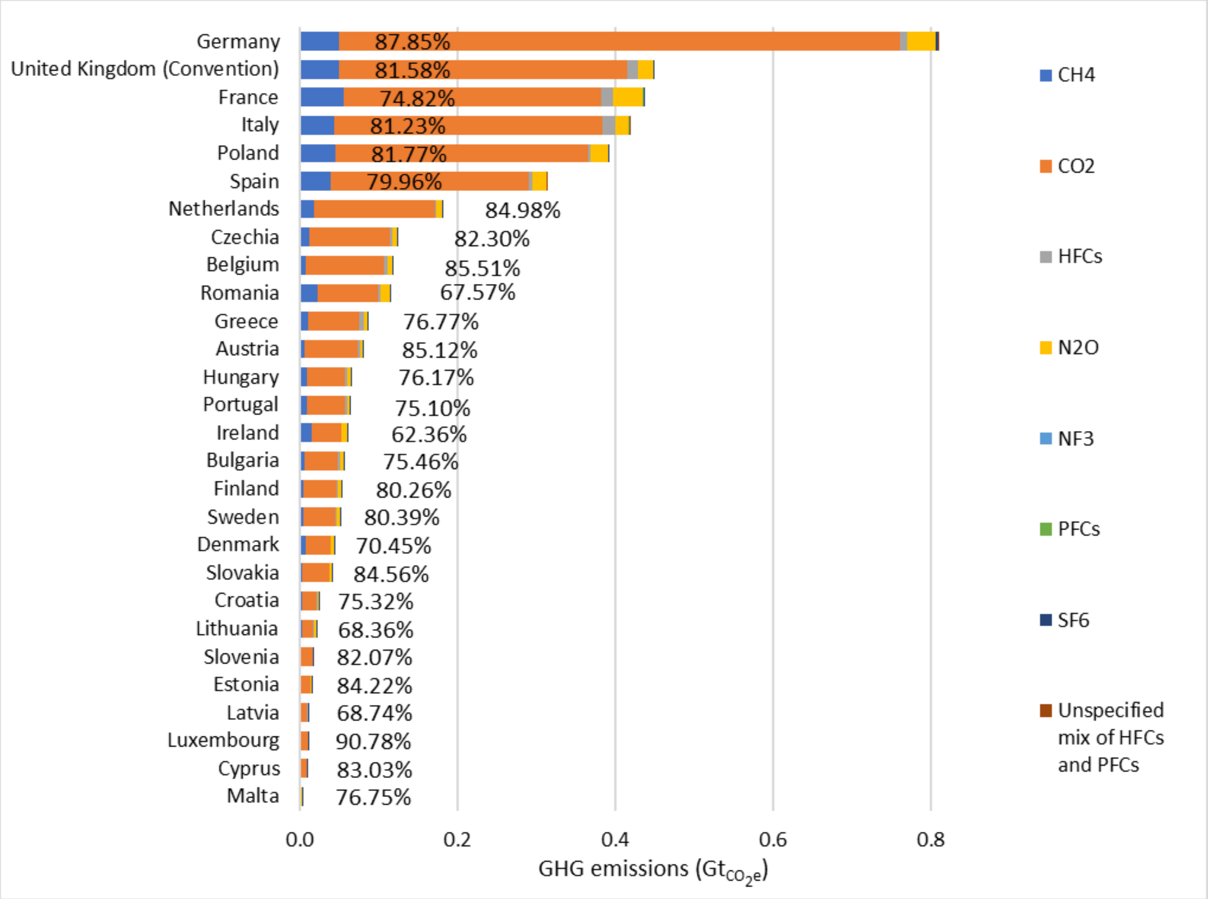

Figure 4 : Partition of the principal GHG for the EU 28 (2019) (the percentage is the CO_2 contribution) (EEA, 2021a)

To manage the CO_2 emissions of the various EU countries, an emissions trading system (ETS) was set up in 2005 according to the directive 2003/87/EC (European Parliament & Council, 2003). This system lists different sectors that have evolved over the years. The period up to 2020 is divided into three phases (2005-2007; 2008-2012; 2013-2020).

The first phase was a testing period for the energy production sectors and the largest energy consumers in industry. Quotas were given almost entirely free to companies, although a fine of 40€ per tonne was imposed for non-compliance. This test allowed the implementation of an infrastructure to monitor the companies involved as well as to have a price on carbon emissions and establish free trade across Europe.

For the second phase, the quotas have been revised downwards due to an excessive volume granted in phase 1. In addition, three countries outside the EU (Iceland, Liechtenstein, and Norway) have jointed the ETS. Nitrous oxide emissions from production of nitric, adipic and glyoxylic acids and glyoxal included by several countries. Only 90% of allowances were distributed freely and the penalty for non-compliance was increased to 100€ per tonne. For rest of quotas, some countries held auctions. Finally in 2012, the aviation sector is included in this carbon market, but the application is only to flights between airports located in the European Economic Area.

Phase 3 saw an increase in the sectors covered. Moreover, perfluorocarbons (PFCs) from production of aluminium are added to gases list. Auctioning became the default method of allocating allowances and for free allowances, a harmonisation of rules was applied. The latest change was to replace the national emissions cap with an EU-wide cap (AWAC, 2021; European Commission, 2021a).

On 1 January 2019, the Market Stability Reserve (MSR) was launched to reduce the surplus of allowances on the market to manage the CO_2 price correctly. Thus, 900 million allowances subtracted from the 2014 - 2016 auction have been placed in this reserve instead of being auctioned for 2019 - 2020. This market follows the rules set out in the EU Directive 2015/1814. If the number of allowances in circulation exceeds the threshold of 833 million, 24% of these allowances are placed in the MSR until 2023 with a minimum of 200 million of allowances. Beyond that year, only 12% of the surplus is placed with a minimum of 100 million of allowances. However, if the surplus is less than 400 million, allowances from the reserve are put back into circulation (European Parliament & Council, 2015). During the period from 1 September 2022 to 31 August 2023, the quantity of allowances placed in the MSR will be 347,811,404 (European Parliament & Council, 2022).

Currently, phase 4 (2021-2030) follows the EU target for 2030 of reducing GHG emissions by 40%. Thus, the emissions covered by the EU ETS must be reduced by 43%. One of the actions is to reduce the quantity of allowances by 2.2% per year, which is 0.5% more than before (2.2% instead of 2.7%). For 2021, the total allowances for the EU have been set at 1,571,583,007 for stationary enterprises. This implies an annual reduction of 43,003,515. The auction counts for about 57% of the Union-wide cap and the rest is provided for free.

Thus, the sectors covered by the EU ETS for CO_2 emissions are electricity and heat generation, energy-intensive industry sectors including oil refineries, steel works, and production of iron, aluminium, metals, cement, lime, glass, ceramics, pulp, paper, cardboard, acids, and bulk organic chemicals and the last is the commercial aviation within the European Economic Area.

The price of the CO_2 allocation has been evolving in this way since the beginning of Phase I. In 2007, the price fell to 0€ due to an overestimation of emissions and therefore an excessive total quantity of allowances. Figure 5 shows the variation in the price of CO_2 allowances from phase II until December 2021. The price remained relatively low during the period 2012 to 2018 (5 to 8€) due to the excess of CO_2 allowances. From 2019 onwards, the price started to increase and reached 75€ at the end of November 2021. In passing, it exceeded the 30€ mark one year earlier, which had never been reached since the beginning of the EU ETS. Since December 2021, the price is around 80€ with few peaks above €100 and a low point at the start of the war between Ukraine and Russia.

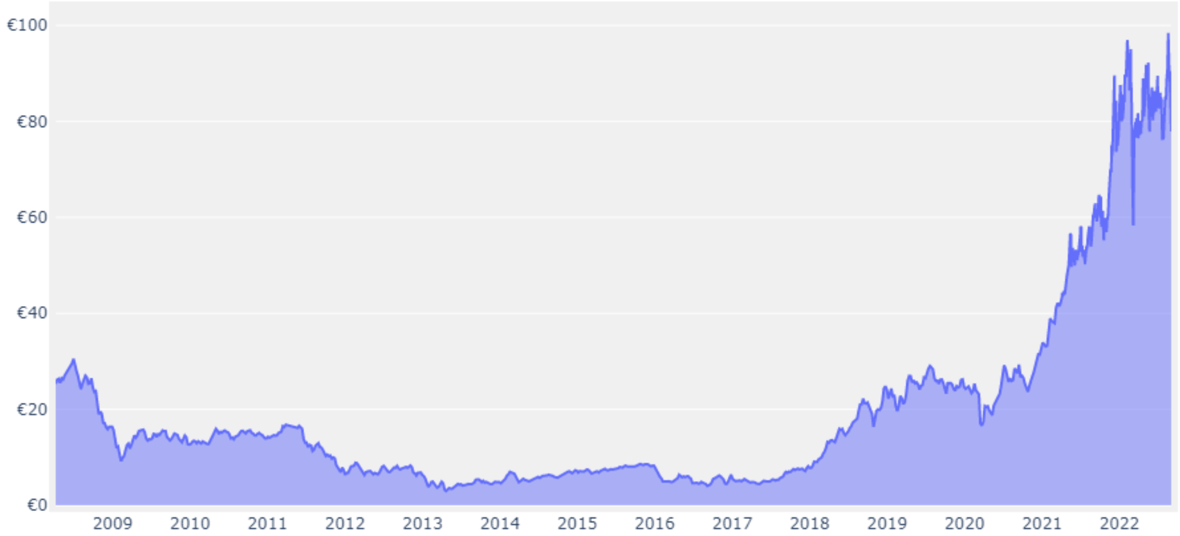

Figure 5 : CO_2 emission allowance EU ETS (Sandbag, 2015)

1.3.1 Study case: Belgium

The distribution of these gases varies from one sector to another. GHG quantities emitted in Belgium in 2019 is around 116.65 $MtCO_2e$ (EEA, 2021a). Figure 6 shows the distribution of the main GHG for this period. Carbon dioxide is the most emitted in the atmosphere with 85.5%. It is logical to search solution to reduce CO_2 emission. For the other GHGs, methane and nitrous oxide are gases to be monitored as they account for more than 10% of CO2e emissions.

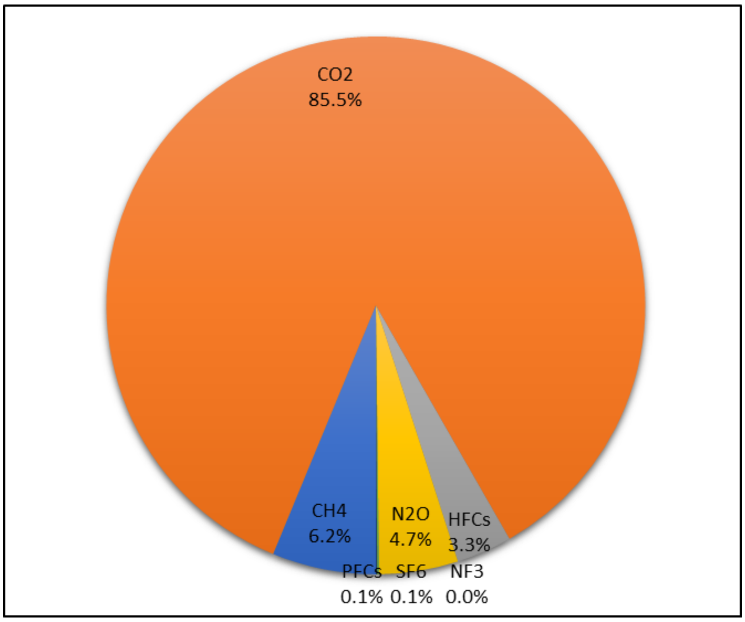

Figure 6 : Partition of the principal GHG in Belgium (2019) (EEA, 2021a)

As a first step, an analysis of the different sources of emissions can be made. The E-PRTR database and EU ETS database includes the different companies that are subject to the highest emissions of CO_2 or other pollutants. The data is therefore collected in relation to the sectors of activity of the companies. The sectors impacted by the collection of CO_2 emissions data are provided in Annex I of the "Document for the implementation of the European PRTR" (EEA, 2020) for the E-PRTR and in Annex I of the 2003/87/CE Directive (European Parliament & Council, 2003) and a supplement in the Annex of the 2009 Directive (European Parliament & Council, 2009) about aviation for the EU ETS.

One of the major differences between the two databases is that the former has thresholds depending on the pollutant. For CO_2, the threshold is 100 kt of CO_2/year. After a detailed analysis of both databases for Belgium in 2019, the data correspond to 70%. There are several reasons for these differences.

- The for the incineration of municipal and hazardous waste are not covered by the EU ETS. However, it is a significant source of emissions as the CO_2 release exceeds the threshold.
- Biomass energy is considered carbon neutral according to the IEA report (2011) (Tuerk et al., 2011). The EU ETS therefore does not consider such installations for the purpose of valorising their development since biomass is considered advantageous compared to fossil resources.

Due to this threshold in the amount of CO_2 emitted, the E-PRTR data (EEA, 2020) are far from covering all CO_2 emitters. The data reported by the EU ETS therefore contains a more comprehensive list of CO_2 emitters.

In Belgium, 299 companies in activity in 2019 (excluding aviation) are covered by the ETS. Figure 7 lists the different emission points according to their activity and CO_2 emission in 2019. For this year, emissions reach 44627 kt of CO_2 and the main emitters are located along the Walloon backbone (E42 highway) and around the port of Antwerp and the city of Ghent. Referring to the Pareto principle, which can be summarised as follows "80% of the consequences come from 20% of the causes", 48 companies (corresponding to a 16% share) account for 84% of CO_2 emissions. Ideally, it is these emitters that should reduce their CO_2 emissions as a priority.

Turning to activities from an ETS viewpoint, the default activity is the combustion activity with a total rated thermal input exceeding 20 MW. In addition, there are nine other specific activities that refer to production or firing capacity. However, only one activity category can be assigned per company. Thus, an enterprise exceeding the capacity as well as the thermal power threshold will have a specific activity. And therefore, enterprises not exceeding the capacity threshold but exceeding the combustion threshold are considered as a combustion activity. Of the 299 companies covered by the EU ETS in Belgium, 178 are involved in fuel combustion.

As described above, the incineration of municipal waste is not considered in the ETS. However, based on the E-PRTR data, there are 7 installations emitting more than 100 kt in 2019. The sum of the emissions of these different installations corresponds to 1920 kt for the same year.

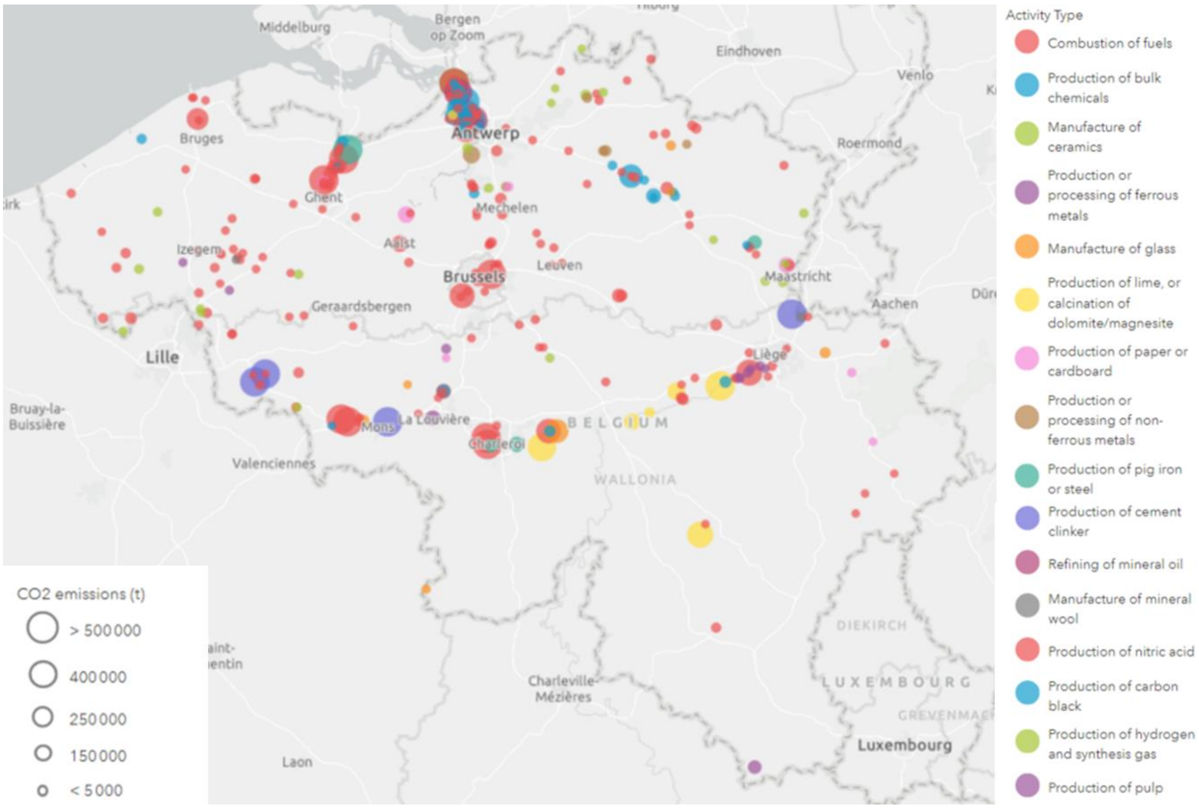

Figure 7 : CO_2 emitter by activity covered by EU ETS in Belgium (2019) (EEA, 2021b)

Among the largest emitters in the EU ETS (listed in the Table 1) are various companies with quite different activities. Thus, despite the high annual CO_2 emissions, the flue gases that cause these emissions are quite different. The composition of the gases depends on many factors such as the type of product manufactured by the company, the fuel burnt, the operating conditions, the type of process, etc. Thus, the data collected by the E-PRTR will give an initial idea of the other compounds present in the gaseous emissions.

Table 1: Emitters above 500 kt_{CO2}/year included in the EU ETS for 2019

	Company name (Plant type)	kt_{CO2}/year
1	Electrabel Knippegroen (Power plant)	5083.9
2	ArcelorMittal Gent (Steel plant)	4329.7
3	Total Antwerpen (Refinery)	4005.0
4	BASF Antwerpen (Chemical plant)	2358.6
5	Esso (Refinery)	2093.0

6	CCB Gaurain (Cement plant)	1376.0
7	Holcim Obourg (Cement plant)	1024.3
8	CBR Lixhe (Cement plant)	995.0
9	T-Power (Power plant)	964.1
10	Electrabel Amercoeur-Roux (Power plant)	842.7
11	Lhoist Hermalle (Lime plant)	808.6
12	Zandvliet-Power (Power plant)	800.9
13	Total Olefins Antwerp (Chemical plant)	768.1
14	CBR Antoing (Cement plant)	755.5
15	Yara Tertre (Chemical plant)	685.3
16	Centrale Ringvaart EDF Luminus (Power plant)	680.5
17	Centrale Marcinelle Energie (Power plant)	596.6
18	Electrabel Baudour (Power plant)	545.7
19	Evonik Antwerpen (Chemical plant)	529.7
20	Air Liquide Large Industry Antwerpen (Chemical plant)	504.8

UNFCCC database contains the values reported by the different countries according to the list of activities established in the annex to decision 24/CP.19.(UNFCCC, 2013). The CO_2 share in figure 5 corresponds to an emission of 99745.78 ktCO_2 for 2019.

It is interesting to show the different sectors producing carbon dioxide. The industrial sector corresponds to almost half of the CO_2 emissions in Belgium in 2019 (Figure 8). These emissions are divided between energy industries and other industries with a subdivision between process and energy done with combustion. By looking at the three sectors independently, there is a slightly higher percentage for the energy industries.

To compare these figures with those of the EU ETS, almost all industrial activities are covered. However, in relation to total emissions, only 45% is covered by the EU ETS. The sectors less affected by CO_2 management are transport and residential, commercial and agricultural heating. This is logical since most of the emissions are from point sources (home heating) or diffuse sources (car transport) which are therefore well below the thermal power required to be included in the EU ETS accounts.

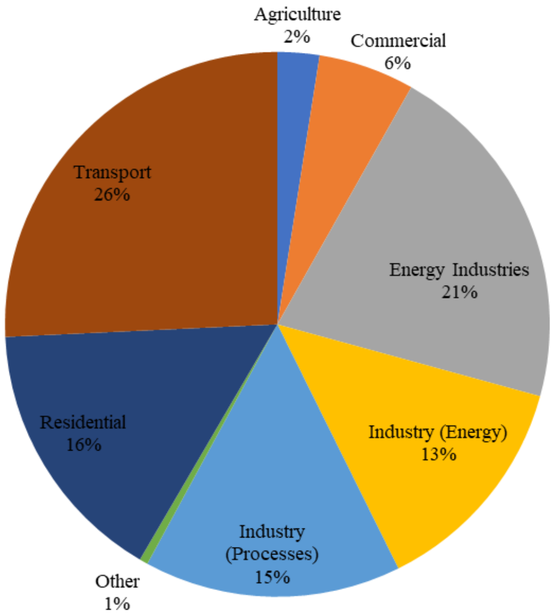

Figure 8 :Main sectors of CO_2 emissions in Belgium (2019) (EEA, 2021a)

When analysing the emission sectors of other European countries such as France, Germany or Poland (Figure 9), it can be seen that the distribution of these emissions is different. Indeed, Germany and Poland being coal-based electricity producing countries, the fraction linked to the "Energy industries" sector is more important. On the contrary, France being more dependent on nuclear energy which is low carbon in terms of emissions has a lower fraction. In France, the transport sector dominates in terms of emissions, accounting for more than total industrial emissions.

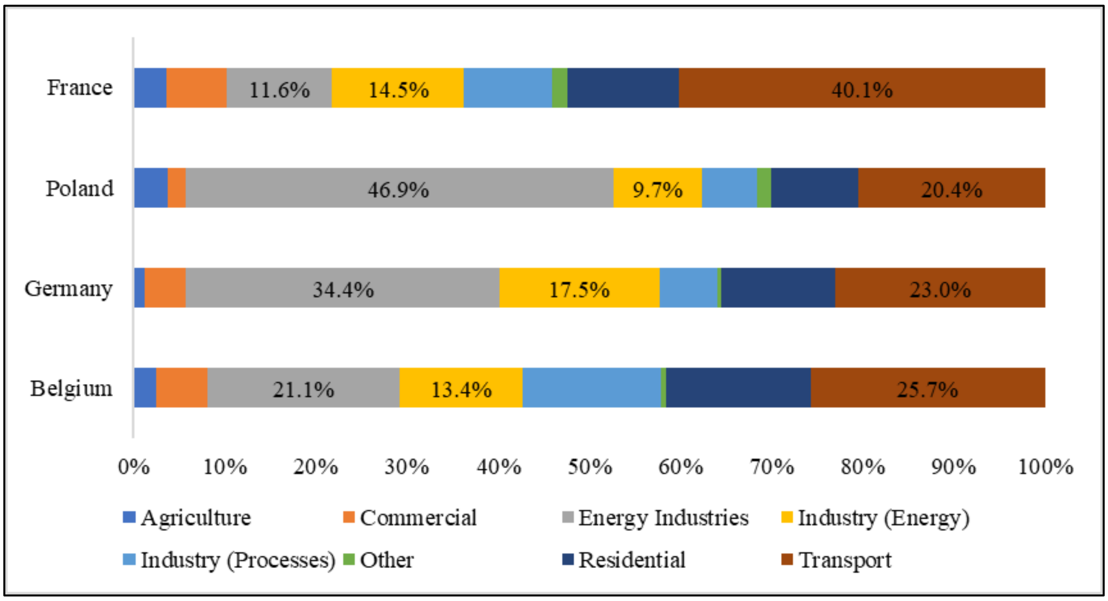

Figure 9 : Repartion between the differents sectors of the CO_2 emissions for Belgium, Germany, Poland and France (2019) (EEA, 2021a)

2 Carbon capture, utilization and storage

The objective of this section is to gather as main information on the different elements of the carbon capture, utilization and storage (CCUS) chain.

2.1 Integration of the capture unit in the process

The capture is possible along different ways that can be more or less easily integrated into the process. Of these ways, two correspond more to existing installations as they are end-of-pipe processes. These are post-combustion and partial oxy-combustion, which is a hybrid process between the former and oxy-combustion. Finally, there is a last possibility, which is pre-combustion. Figure 10 shows the different technologies available to integrate the carbon capture.

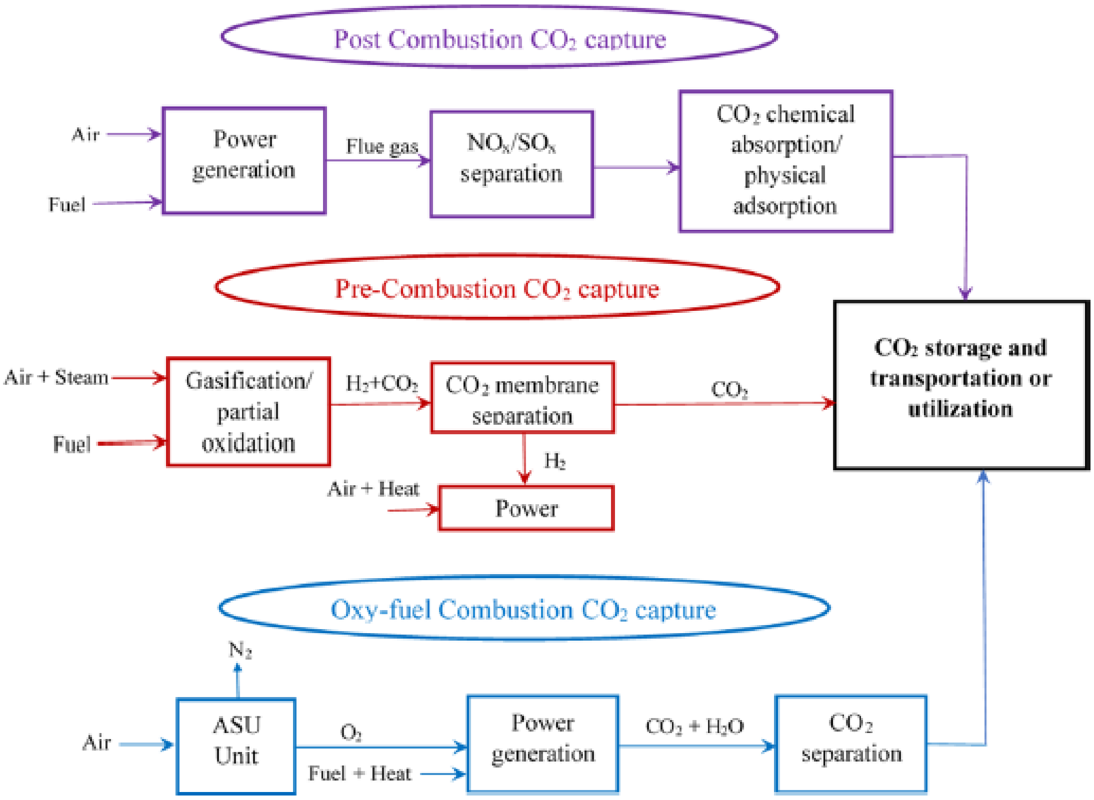

Figure 10 : Schema of technologies to capture CO_2 (Yadav & Mondal, 2022)

2.1.1 Pre-combustion

This process consists in burning a fuel decarbonised. In this process, the fuel is firstly converted in a syngas (mix gas composed of H_2 and CO) thanks to oxygen. Secondly, steam is injected with the products to react with CO to form CO_2 and more H_2. This reaction is known as the Water Gas Shift reaction. The CO_2 is then extracted from the gas stream using a capture technique to send only hydrogen into the combustion chamber. Thus, only water is produced during the combustion with oxygen that gives a clean flue gas containing only nitrogen, water and excess oxygen. This process is often associated with medium pressures (between 2 and 7 MPa) and high temperatures (range between 200 and 400°C) as operating conditions. In addition, CO_2 concentrations are generally between 20% and 40%. These operating conditions allow a wide range of possible separation. However, due to the difficulty of adaptation to existing plants, this technology is principally developed on new plants. Moreover, this technology only applies to CO_2 sources related to fuel combustion, which means that it is useless for process emissions.

2.1.2 Oxy-combustion

This process applies combustion fed by an oxygen-rich stream. The oxygen is produced in an air separation unit (ASU) using different methods (cryogenics, VSA (vacuum swing adsorption) or membranes). This combustion produces very high temperature flames which means that it is important to ensure that the chambers can tolerate these temperatures. This is one of the reasons, along with the modification of the air inlet to add a pipe from the ASU, that this process tends to be designed if the unit does not already exist. The recycled flue gas prior to combustion can sometimes be mixed with the oxidizer to control combustion. Usually, the concentration of the off-gas is at least 80% without air supply and 75% with more or less 5-10% of air supply.

This high CO_2 concentration in flue gases makes possible to use others capture techniques than these used usually in post-combustion process. The flue gas is conditioned by drying the CO_2, removing O_2

to prevent corrosion in the pipeline, and the other contaminants and inert gases (Ar, N_2, SO_2, and NO_x). However, the production of pure oxygen is very energy-intensive, making the operating cost high.

2.1.3 Post-combustion

Post-combustion capture is an end-of-pipe technology to capture the CO_2 from the flue gas produced with the conventional combustion of fossil fuel with air. In one hand the flue gas is decarbonated and in the other hand the CO_2 is concentrated. Usually, the effluent gases have a CO_2 concentration of 5 to 15% for power plants and a maximum CO_2 concentration of 30% for cement plant when the CO_2 is produced by a conventional combustion. However, this technology is very interesting since it can be added to an existing plan.

2.2 Carbon capture technologies

There are several available technologies to separate the carbon dioxide from other components of the flue gas. Below is a non-exhaustive list of them:

- absorption by a liquid phase tanks to the affinity of CO_2 for the solvent;
- adsorption on a solid to adsorb the CO_2 from the flue gas;
- membranes that are selective towards specific molecules like CO_2;
- cryogenics process to liquefy the CO_2;
- hybrid technologies are a combination of at least two other techniques.

All these technologies will be briefly described here after.

2.2.1 Absorption

Chemical absorption is a process for purifying gases at low and medium partial pressures during the regeneration phase. Generally, the gaseous component to be removed is absorbed by chemical reaction with an adequate solvent. In the present case this solvent is chosen for reacting with CO_2, forming a new chemical species, to transfer it efficiently into the liquid phase. By heating the solution, the solvent is regenerated from the species and the CO_2 is released in gas phase allowing it to concentrate. The most advanced and used solvent is MEA (monoethanolamine) with an aqueous solution containing 30 wt% in amine. However, various research and industrial works are studying the improvement of solvents (mixed amines, sterically hindered amines, demixing solvent, ionic liquids, hot potassium carbonate), equipment or processes in order to reduce operating costs by reducing regeneration energy. (Dubois & Thomas, 2018) show a reduction of up to 30% compared to MEA.

Physical absorption is not related to a chemical reaction but to absorption in a solvent (ex: alcohols) according to Henry's Law. A high partial pressure of the absorbed gas and a low temperature make the absorption more favourable. The energy required to regenerate the solvent is less than that for a chemical solvent, but the process conditions are significatively different (e.g. required temperature for Selexol is 0 - 5°C of Rectisol is -40°C) (Majeed, 2013; Olajire, 2010).

2.2.2 Adsorption

One of the adsorption characteristics impacting the CO_2 capture performances, the CO_2 adsorption capacity related to the affinity of the surface of an adsorbent for CO_2 molecules and the physical attraction between the surface and the CO_2. They are physically absorbed on the surface of the absorbent. The size of the pores also influences the absorption capacity. Separation is achieved by the size of the molecules or the binding forces.

The separation methods are Temperature Swing Adsorption and (Vacuum) Pressure Swing Adsorption (TSA & (V)PSA) to regenerate the sorbent. There are different materials available such as zeolites, activated carbon, silica gel, MOFs or carbon nanotubes to adsorb CO_2 (Chiang et al., 2019).

Furthermore, a high gas pressure differential improves the working capacity of the adsorbent that upgrade the process (Olajire, 2010).

2.2.3 Membranes

Membranes are semi-permeable barriers capable of separating substances by various mechanisms (solution/diffusion, adsorption/diffusion, molecular sieve and ion transport). A pressure gradient is exerted on the gas in order to be able to separate CO_2 from the other components. Two or three stages are necessary in order to have a good separation requesting a high energy consumption. Moreover, on the contrary to other technologies as absorption or adsorption, no other fluids (liquid or solid) are needed for performing the separation. There are different membrane materials available to work in different temperature ranges. The higher the operating temperature can be, the more resistant the material must be, but in return the cost is often high. There are therefore membranes made of organic materials (polymers) or inorganic materials (carbon, zeolite, ceramic or metal) (Olajire, 2010); the polymeric membranes are generally used due to the significantly lower costs.

There exist also gas-liquid membrane contactors that are used to separate CO_2 from the other components of the gaseous effluent. Depending on the nature of the liquid phase, the membrane must have more or less chemical and physical resistance to avoid degradation. In addition, the membrane must have a certain selectivity towards CO_2 to allow its diffusion and the liquid phase (solvent) must present a high affinity with CO_2 in order to reach a high absorption rate. For this type of membrane, there is no pressure gradient that is exerted but a concentration gradient. An advantage of this technology is the large gas-liquid exchange surface without flooding problems. However, in order to reach good performances, it is preferable that the pores of the membrane remain dry, which implies overcoming wetting problems (Nogalska et al., 2019).

2.2.4 Cryogenics

The cryogenic process allows the purification of a highly concentrated (> 60%) CO_2 gas stream. This purification is done by a succession of cooling and condensation steps in order to extract the other components of the gas. This method is carried out thanks to the difference in the condensation points of the different gases allowing an easy separation. An advantage of this technique is that the CO_2 can be available in liquid form which can facilitate its transport in some cases. However, since it is necessary to decrease the temperatures (-55°C), the energy consumed is high, which significantly increases the operating costs. This separation method can therefore be considered for pre-combustion or even oxy-combustion, which can be found under cryogenic operating conditions (Lockwood, 2014).

2.2.5 Hybrid technologies

Hybrid technologies are processes composed of at least two of the above-mentioned processes. More and more hybrid technologies are being studied in order to achieve good performance and overall cost reduction compared to a single technology. Thus, adsorption (VPSA) can be combined with cryogenics to achieve good recovery and excellent purity. In the case of oxy-combustion or flue gas with industrial by-products (hydrogen, carbon monoxide, etc.) a combination of membrane and cryogenics can be applied. It is also possible to mix adsorption with membranes to pre-concentrate the flue gas before purifying it if high purity is not required.

2.2.6 CO_2 capture technology providers

Most of the current technology providers are proposing post-combustion CO_2 capture processes, especially using amine(s)-based process. Among these providers, we can point out (non-exhaustive list):

- Mitsubishi Heavy Industries (MHI): especially KS-1/KS-21 solvent (e.g. Petra Nova plant, USA).

- Shell Cansolv (activated amines solution) (e.g. Boundary Dam, Canada). Partnership with Technip for conception and process installation.
- Aker Carbon Capture (ACC™ CO_2 capture process): (e.g. Norcem Brevik Cement plant, under construction, Norway).
- Linde/BASF (OASE solution). Note: OASE® blue technology for Post-Combustion CO_2 Capture covers a spectrum from 3 to 25 vol% CO_2 content in the flue gas). The technology allows for CO_2 capture rates higher than 95% and generates a CO2 product purity of 99.9 vol% (dry). Linde sells also adsorption, membranes, CPU (CO_2 Purification Unit) and liquefaction units.
- Carbon Clean (CycloneCC): CycloneCC™ uses a breakthrough combination of two proven process intensification technologies: Carbon Clean's advanced, proprietary amine-promoted buffer salt solvent (APBSCDRMax®) and rotating packed beds. As a result, the physical footprint of CycloneCC™ is up to 50% smaller than conventional carbon capture units and CapEx and OpEx costs are also reduced by 50%.
- IFPEN (IFP Energies Nouvelles, France): they propose a demixing solvent technology called "DMX process" (agreement with Axens company). In the framework of the EU Project "3D", this technology will be tested at Dunkirk on steel plant flue gas.
- Entropy company (e.g. Modular Carbon Capture & Storage™ MCCS™).
- Honeywell (chemical/physical solvents, but also adsorbents, cryogenics, membranes, etc.).
- IHI Corporation (post-combustion and oxyfuel combustion solutions).
- SAIPEM (former CO_2 Solutions) (K_2CO_3 solvent + carbon anhydrase enzyme).
- Several other companies proposing mainly amine(s)-based processes: Fluor, Toshiba, Hitachi, C-Capture, GEA, Babcock & Wilcox, CarbonOro, etc.

Beside the amine(s)-based technologies, other providers propose technology based on alternative solvents or alternative unit operations, such as:

- Air Liquide is proposing different solutions, especially "Cryocap" processes (Cryocap™ H_2, Cryocap™ FG for flue gases, Cryocap™ Oxy for oxy combustion Cryocap™ Steel for steel production, Cryocap™ NG for acid natural gas fields Cryocap™ XLL, for liquefying large volumes of CO_2.)
- Chilled ammonia process (CAP) (by GE): this was successfully demonstrated (TRL 7) at Technology Center Mongstad using flue gas streams with high (16% CO_2) and low (3.6% CO_2) CO_2 concentrations.
- CO_2 CAPSOL (CAPSOL EoP) with Hot Potassium Carbonate (HPC).
- Baker Hughes (solution licensed from SRI International): uses the Mixed-Salt Process (MSP) for CO_2 capture. MSP is a post-combustion carbon-capture process that uses a novel solvent formulation, which is based on potassium carbonate and ammonium salts.
- Air Products: for Blue H_2, CO_2 Purification Units (CPU), Syngas & CCUS
- Svante: Solid sorbent technology, especially a Rotating Adsorption Machine (RAM)).
- Kawasaki CO_2 capture (KCC): Temperature swing adsorption (TSA) process utilizing a granulated amine-coated porous sorbent.
- Honeywell (chemical/physical solvents, but also adsorbents, cryogenics, membranes).
- MTR (Membrane Technology and Research): proposing membranes separation processes.

In addition to these companies, it is worth mentioning that these last years, several start ups are also arriving on the market with innovative solutions, which is also particularly the case of the CO_2 capture from the air (Direct Air Capture – DAC), with companies like Climeworks, Carbon Engineering, Global Thermostat, Carbyon, etc.

Note: in the framework of the DRIVER project, a specific review was performed and published by L. Dubois on the Direct Air Capture processes (not addressed in the present report). This paper is provided in annex.

2.3 CO_2 transport

CO_2 transport is an important element to consider in CCUS chains but is often neglected. This section will review the various elements necessary to understand and properly use the different means of transportation available. CO_2 transport is either onshore or offshore. Onshore transport is carried out by pipelines, trains, trucks or barges along canals/rivers. For offshore transport, only pipelines and ships are available. In order to transport the CO_2, it must be conditioned after being captured while ensuring that it meets the specifications required by the network operator or carrier. Indeed, the impurities present in the gas have consequences on its physico-chemical properties as well as on the materials allowing its transport.

2.3.1 Impurities in the captured CO_2 flow

The impurities found in concentrated CO_2 are due to two factors. The first is industrial process emitting the flue gas and the gas treatments already in application. The second factor is the type of capture and its operating performance. Several papers (Daud, 2021; Li et al., 2009; Wetenhall et al., 2014) have studied their effects on physico-chemical properties such as density, viscosity and liquid-vapor phase envelope change.

The phase behaviour is modified as a function of temperature and critical pressure of the different impurities. Thus, the phase envelope is above that of the pure body for compounds such as N_2, O_2, H_2, CH_4, CO or Ar and it is below for H_2S, SO_2 or N_2O.

When CO_2 is pure, there is a discontinuity in density between the gas and liquid phase (Figure 11). Impurities change the region of this discontinuity by moving it to smaller values for a lower critical point and to higher densities for a higher critical point.

For viscosity, also has a discontinuity between the liquid phase and the gas phase. Impurities have an impact on the viscosity values of the liquid phase. If the critical temperature is lower, the viscosity decreases and conversely if the critical temperature is higher, the viscosity increases.

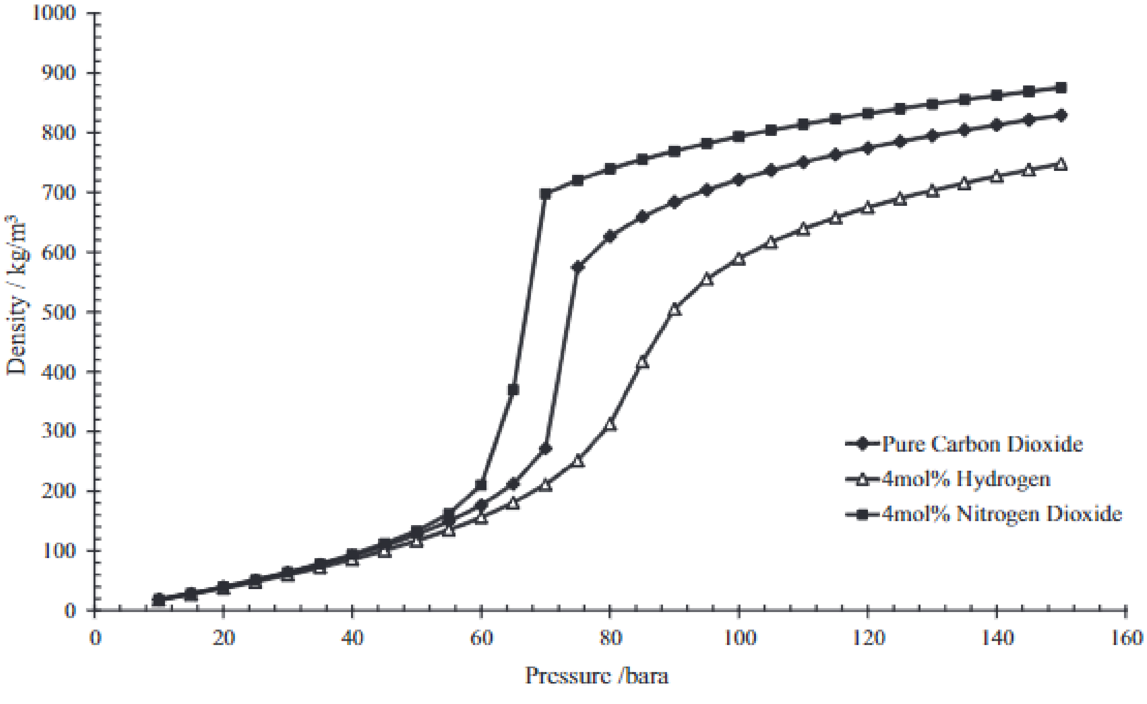

Figure 11 : Effect of impurities on the density of CO_2 for binary combinations of CO_2-4mol% H_2 and CO_2-4mol%NO_2 at 30◦C (Wetenhall et al., 2014)

Impurities also play other roles in transport. Some of them are to be limited in the 10 ppmv range in order to avoid any corrosion such as SOx, NOx, O_2, etc. and others such as H_2, N_2, Ar, etc. are to be limited in order to avoid high compression costs. In Belgium, Fluxys is a pipeline system operator. They have proposed two specifications for CO_2 pipeline transport (Table 2).

Table 2 : Fluxys CO_2 quality specification for pipeline transport (Fluxys, 2021)

Constituents	**Units**	**Specification95**	**Specification99**	**Note**
CO_2	% mol	> 95	> 99	1
Water	ppm v	< 40		2
H_2S	ppm v	< 5		3
O_2	ppm v	< 40		4
NOx	ppm v	< 5		3
NO	ppm v	< 2,5		3
NO_2	ppm v	< 2,5		3
SOx	ppm v	< 10		3
H_2	% mol	< 0,75	< 0,2	5, 9
N_2	% mol	< 2	< 0,5	6, 9
Argon	% mol	< 1	< 0,2	7, 9
CH_4	% mol	< 1	< 0,1	7, 9
CO	ppm v	< 100		8, 9
N_2+Ar+H_2+CH_4+CO+O_2	% mol	< 4	< 0,8	9
Amine	ppm v	< 10		10
$C_{2\text{-}6}$	ppm v	< 1200		11
VOC	ppm v	< 350		10
Aromatics (incl.BTEX)	ppm v	< 0,1		10
Ethylene	ppm v	< 1		10
HCyanide	ppm v	< 15		12
COS	ppm v	< 0,1		10
DimethylSulfide	ppm v	< 1,1		10
NH_3	ppm v	< 10		10
Impurities	The CO_2 delivered shall not contain any other elements or impurities (solid, liquid or gaseous) that might interfere with the integrity or operation of the pipelines or downstream systems.			13

These specifications may be modified according to other specifications imposed by the units after pipeline transport. Indeed, in the case of transport by ship, the CO_2 must be liquefied and certain impurities may be more restrictive in this state. Northern Lights (Phillips et al., 2022) recommends oxygen concentrations of less than 10 ppmv to avoid the risk of corrosion on the tank ship.

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1. Minimum CO_2 content (purity); 95%mol figure as per ISO 27913/ 2. To avoid the presence of free water and limit corrosion./ 3. Health and safety. To limit corrosion./ 4. To limit corrosion./ 5. Amount of “non-condensables” to be limited. 0,75%mol value as per ISO 27913/ 6. Amount of “non-condensables” to be limited. 2%mol value as per ISO 27913/ 7. Amount of “non-condensables” to be limited./ 8. Health and safety./ 9. Amount of “non-condensables” to be limited. 4%mol value as per ISO 27913/ 10. Compatibility with potential receiving parties./ 11. No heaviers than C7 to avoid liquids. Compatibility with potential receiving parties. / 12. Health and safety. Compatibility with potential receiving parties. / 13. Non-exhaustive list of impurities: Mercury, Glycol, Methanol, Ethanol, C7+, Acetaldehyde, Formaldehyde, Cadmium, Thallium

2.3.2 Transport type

There are different ways to transport CO_2. A distinction is made between onshore and offshore transports. For the onshore part, transport can be achieved by pipeline, train, truck or barge. Offshore, the choice is more succinct between pipeline and ship (Moe et al., 2020).

In the case of pipelines, the transport is continuous with the need for booster stations for long distances to maintain the flow under the minimum transport pressure. CO_2 can be transported in different phases such as liquid, gas or supercritical (pressure above the critical pressure of CO_2 (73.77 bar) in pipeline. The latter will be preferred if the pipeline network allows it due to the interesting properties of the supercritical fluid which has a density close to that of a liquid but a viscosity similar to that of a gas. Other transports are discontinuous, so intermediate storage is necessary. This storage is of the order of 1 to 2 times the transportable volume of a convoy (train, truck, ship, barge). Moreover, this transport takes place in liquid form, which means that the CO_2 does not have to be liquefied.

By land, CO_2 is preferentially transported by pipeline. Indeed, some studies show that transport by train or truck is only interesting for small quantities of CO_2 to be transported (Kegl et al., 2021; Psarras et al., 2020). This could be used by small companies or in DAC systems. Barges can only be considered if the capture site is close to a river system.

Currently, there are very few pipelines for the transport of CO_2. Some authors have proposed a pipeline grid to minimise the cost of transport (Hasan et al., 2014; Kegl et al., 2021; Leonzio et al., 2020; Zhang et al., 2018). When considering the cost of a transport network, different aspects have to be taken into account. As stated above, the type of transport will have different CAPEX and OPEX. The amount of CO_2 to be transported as well as the transport conditions such as temperature, pressure and quality of the CO_2 captured by the transport type. The distance between the place of capture and storage or use as well as the regions through which the transport passes will have an impact on the transport cost.

In the context of the cost of a pipeline, there are models such as the (Knoope et al., 2014) model which includes the cost of the material which is a function of the diameter, thickness and type of material, the labour cost of making the trench which is a function of the length, diameter and type of terrain as well as the Right of Way (ROW) fee and some miscellaneous costs. The diameter of the pipeline depends on the amount of captured CO_2 to be transported. (Luo et al., 2014) takes up the different possible relations to calculate the diameter of a pipe according to an equation based either on the speed or on the hydraulics or according to the model of (McCoy & Rubin, 2008).

In the case of Belgium, Fluxys will provide a pipeline network to cover areas with high CO_2 emissions. Part of the pipelines will be a conversion of a natural gas grid. Continuous interconnections between France, Germany and the Netherlands are possible. In addition, the ports of Ghent (Remy et al., 2022), Antwerp and Zeeburgge will have temporary storage sites to keep the CO_2 liquefied for transport by ship.

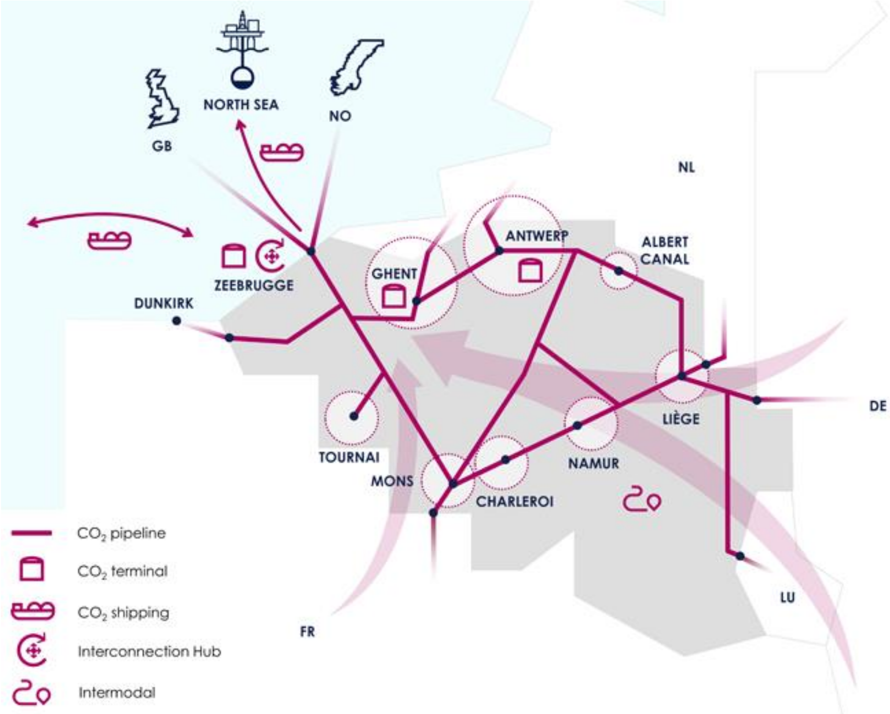


Figure 12 : Potential CO_2 pipelines grid in Belgium (Fluxys, 2022)

Potential connections to offshore pipelines can be considered if they are built. Indeed, this construction will depend on the rental of storage sites. Studies (Durusut & Joos, 2018; Nilsson et al., 2011) have shown that there is a cross point in the transport of CO_2 at sea between transport by ship and transport by pipeline.

2.4 Current utilizations of the CO_2

Following IEA report (IEA, 2019), the amount of CO_2 used in the world in 2015 is around 230 Mt with a part of 16% for the Europe.

Currently, the CO_2 market is mainly focused on the food industry (carbonated beverages, supercritical CO_2 to decaffeinate coffee, ...). Other common but smaller scale applications are the use of CO_2 in fire extinguishers, as dry ice or as a refrigerant. Figure 13 shows the distribution of the CO_2 market between the European countries and the different sectors. Belgium supplies this market with Yara's CO_2 from the purification of ammonia with an amine absorption-regeneration process.

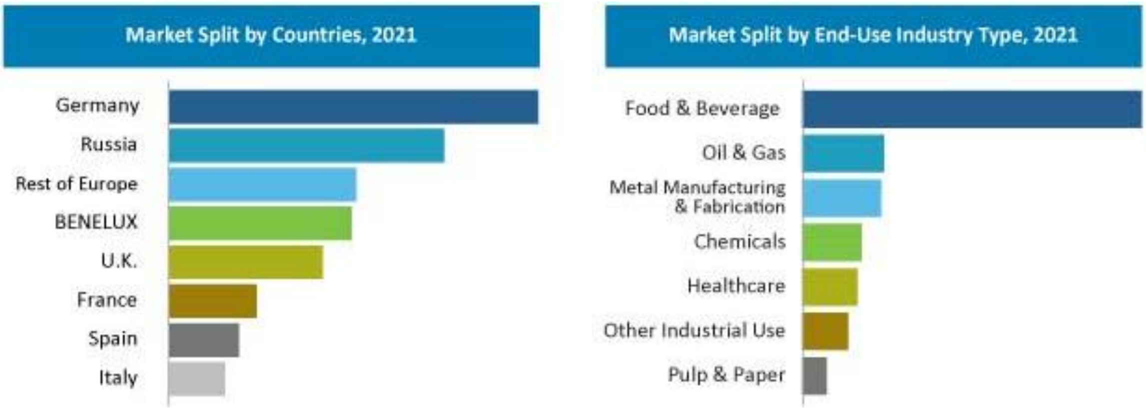


Figure 13 : Europe CO_2 market 2021 (Fact.MR, 2022)

However, as the CO_2 market increases in the future, more uses of CO_2 are expected. The following point summarizes the different possible ways.

2.5 Future utilizations of the CO_2

In the years to come, the captured CO_2 can be either used or stored. Among the uses, one way stands out. It is the conversion into e-fuels, including methane, methanol and kerosene. These compounds formed from CO_2 and hydrogen allow for easier storage than the latter. This is also the reason for which the hydrogen networks as well as its production is linked to the CCU. Furthermore, an important aspect of achieving carbon neutrality is the transition from fossil fuels to "green" energies. For example, e-methane from captured CO_2 and hydrogen generated from renewable energy sources would be fed back into the natural gas grid to power the citizen's boilers. This cycle allows to reduce by half the use of fossil gas (Chauvy & De Weireld, 2020; Chauvy et al., 2021).

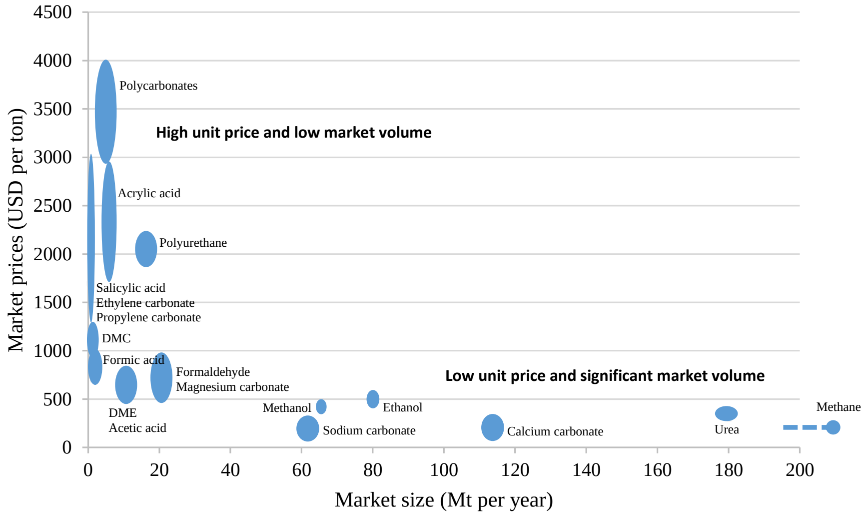


Figure 14 : Market sizes and market prices for the main CO_2-based compounds (non-exhaustive) (Chauvy et al., 2019)

However, use of CO_2 is not the only way to address the problematic. To remove CO_2 completely from the value chain and avoiding new CO_2 emissions, there is CCS. CO_2 storage is the main way. Potential storage sites have been studied in Europe in the CO2Stop project (Poulsen et al., 2013) by rescuing reservoirs that meet certain conditions in order to keep the CO_2 isolated from the atmosphere for the long term.

By analyzing Figure 15, it can be seen that the storage areas are mainly located in the north of Europe. Consequently, Belgium can be considered as a transit point for CO_2 stored in the North Sea. The European interconnections will therefore be just as important as the output hubs for storing CO_2.

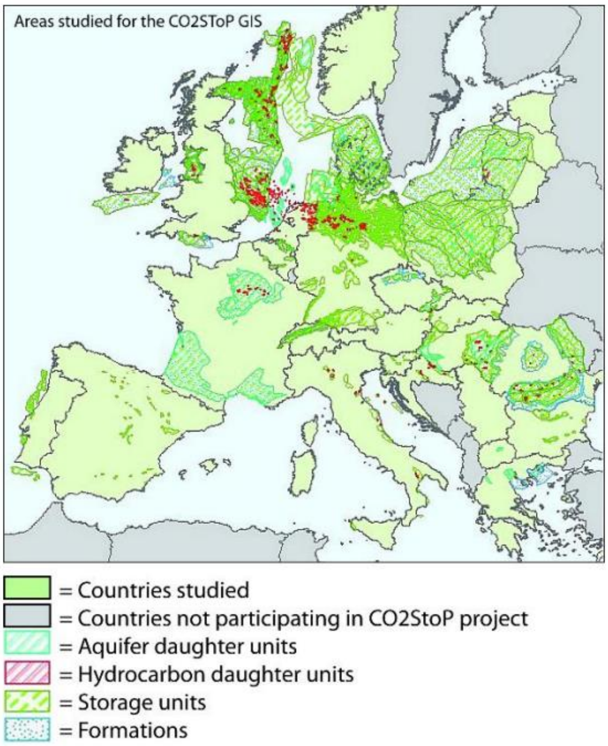
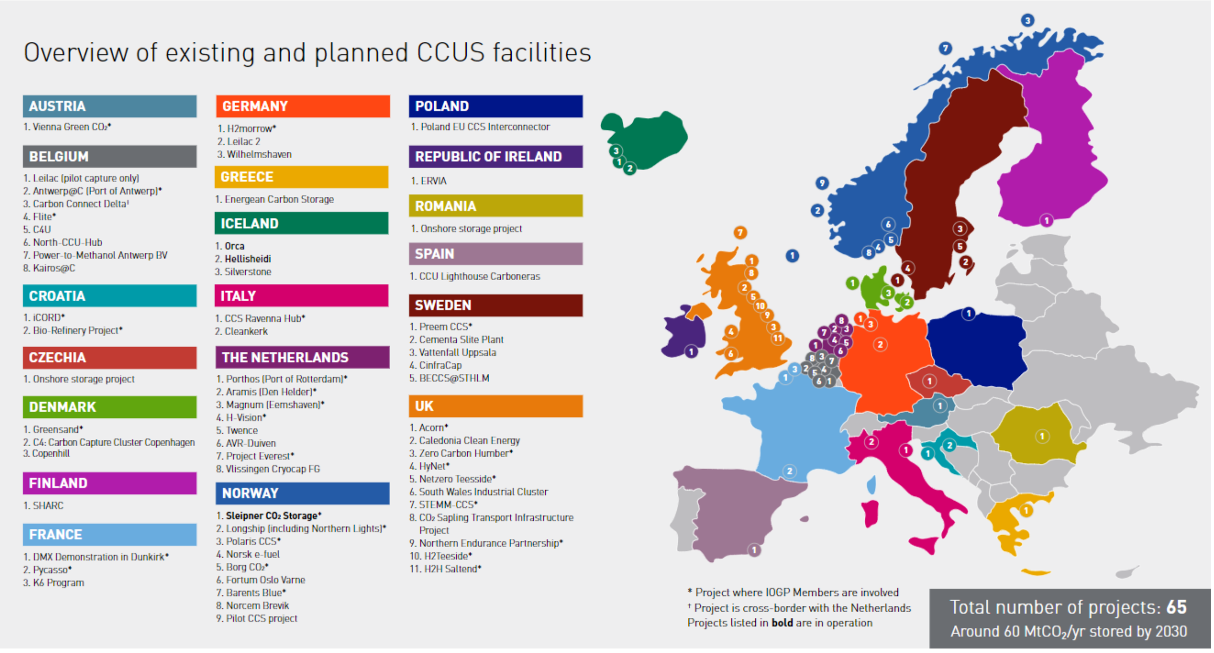


Figure 15 Potential reservoirs for the CO₂ storage (Poulsen et al., 2013)

2.6 CCUS project in Europe

For several years now, various projects around capture, transport, storage and/or conversion have emerged in Europe. This emergence continues with new projects announced for the coming years. This wave of projects covers different technologies and therefore different levels of technological advancement (TRL). Different databases collect most of the past, current and future projects with more or less information (CO₂ value Europe, 2022; International Association of Oil & Gas Producers, 2022; ZEP, 2022).



Overview of existing and planned CCUS facilities

AUSTRIA
1. Vienna Green CO₂*

BELGIUM
1. Leilac (pilot capture only)
2. Antwerp@C (Port of Antwerp)*
3. Carbon Connect Delta†
4. Flite*
5. C4U
6. North-CCU-Hub
7. Power-to-Methanol Antwerp BV
8. Kairos@C

CROATIA
1. iCORD*
2. Bio-Refinery Project*

CZECHIA
1. Onshore storage project

DENMARK
1. Greensand*
2. C4: Carbon Capture Cluster Copenhagen
3. Copenhill

FINLAND
1. SHARC

FRANCE
1. DMX Demonstration in Dunkirk*
2. Pycasso*
3. K6 Program

GERMANY
1. H2morrow*
2. Leilac 2
3. Wilhelmshaven

GREECE
1. Energean Carbon Storage

ICELAND
1. **Orca**
2. **Hellisheidi**
3. Silverstone

ITALY
1. CCS Ravenna Hub*
2. Cleankerk

THE NETHERLANDS
1. Porthos (Port of Rotterdam)*
2. Aramis (Den Helder)*
3. Magnum (Eemshaven)*
4. H-Vision*
5. Twence
6. AVR-Duiven
7. Project Everest*
8. Vlissingen Cryocap FG

NORWAY
1. **Sleipner CO₂ Storage***
2. Longship (including Northern Lights)*
3. Polaris CCS*
4. Norsk e-fuel
5. Borg CO₂*
6. Fortum Oslo Varne
7. Barents Blue*
8. Norcem Brevik
9. Pilot CCS project

POLAND
1. Poland EU CCS Interconnector

REPUBLIC OF IRELAND
1. ERVIA

ROMANIA
1. Onshore storage project

SPAIN
1. CCU Lighthouse Carboneras

SWEDEN
1. Preem CCS*
2. Cementa Slite Plant
3. Vattenfall Uppsala
4. CinfraCap
5. BECCS@STHLM

UK
1. Acorn*
2. Caledonia Clean Energy
3. Zero Carbon Humber*
4. HyNet*
5. Netzero Teesside*
6. South Wales Industrial Cluster
7. STEMM-CCS*
8. CO₂ Sapling Transport Infrastructure Project
9. Northern Endurance Partnership*
10. H2Teeside*
11. H2H Saltend*

* Project where IOGP Members are involved
† Project is cross-border with the Netherlands
Projects listed in **bold** are in operation

Total number of projects: **65**
Around 60 MtCO₂/yr stored by 2030

Figure 16 Belgium project on CCU/CCS (International Association of Oil & Gas Producers, 2022)

The projects are divided into different categories according to the sources. They include industrial capture, storage of CO_2, conversion of CO_2 into an energy vector, transport, etc.

In Belgium some projects are in feasibility studies like Antwerp@C, C4U, Carbon Connect Delta. Table 3 provides a brief description from the various databases of CCUS projects in Belgium.

Table 3 Belgium CCUS project (CO_2 value Europe, 2022; International Association of Oil & Gas Producers, 2022).

Project name	**Summary**	**Years**
BioRECO2VER	BioRECO2VER aims to demonstrate the technical feasibility of more energy efficient and sustainable non-photosynthetic biotechnological processes for the capture and conversion of CO_2 from industrial point sources into valuable platform chemicals, i.e. isobutene and lactate.	2018-2021
C2B	This project works on the implementation of a CO_2 capture system on a real and hot flue gasses. This is made possible by post-combustion flue gas by a membrane process. Next, its valorization in a sustainable process of production of sodium bicarbonate is assessed.	2013-2017
LEILAC	LEILAC (Low Emissions Intensity Lime And Cement) aims to develop a pilot technology that enables Europe's cement and lime industries to reduce their emissions while retaining, or even increasing international and cross sectorial competitiveness. A scaled-up carbon capture technology with direct CO_2 separation and decreased will be developed as this is an effective way of lowering the CO_2 emissions of lime and cement industries.	2016-2020
C4U	Demonstration of two highly energy-efficient high-temperature solid-sorbent CO_2 capture technologies for steel industries.	2024
FLITE	Sustainable Aviation Fuel (SAF) from ethanol produced from steel-mill off-gases. (44 millions litres of SAF using sustainable ethanol as feedstock).	2025
North-CCU-Hub	North-C-Methanol is the first large scale demonstrator project of North-CCU-Hub. It consists of an electrolyser plant with a power of 63 MW, splitting water in green hydrogen and oxygen, using renewable energy from off-shore wind. Oxygen will be used locally in the steel industry. Green hydrogen will be combined with captured CO_2, originating from industrial point sources, in a catalytic methanol synthesis plant with a production capacity of 45.000 ton methanol per year. The North-C-Methanol project will be the first implementation of the North-CCU-Hub Roadmap.	2024
Power-to-Methanol Antwerp BV	The Power to Methanol project in Antwerp will produce methanol from captured CO_2 combined with hydrogen that has been sustainably generated from renewable electricity. Currently, methanol is largely produced using fossil-based raw materials, which emits carbon dioxide from the process. With this innovative project, for each tonne of methanol produced at least one tonne of CO_2 emissions would be avoided. The 7 strong consortium comprises leading industrial and business partners: ENGIE, Fluxys, Indaver, INOVYN, Oiltanking, Participate maatshappij Vlaanderen (PMV) and Port of Antwerp. Future development could see increased volumes of sustainable methanol produced for wider industry use, including as a sustainable fuel for marine and road transport.	2023
Antwerp@C	CCS-equipped industrial cluster, CO_2 transportation and storage in the North Sea and reuse.	2025

Kairos@C	The joint project has been selected for funding by the European Commission through its Innovation Fund, as one of the seven large-scale projects out of more than 300 applications. The large-scale CO_2 capture layout will be a first-of-its-kind multi-feed scheme, which optimises and integrates CO_2 capture and purification from 5 different production units: 2 hydrogen plants, 2 ethylene oxide plants, and 1 ammonia plant. Kairos@C will use the services of the Antwerp@C consortium, which is developing a multi-modal infrastructure to transport CO_2 to multiple permanent storage sites around the North Sea.	N/A
Carbon Connect Delta	With CCUS, CO_2 emissions can be reduced by 30% in the port area of North Sea Port. A consortium of Belgian and Dutch companies expects to complete the Carbon Connect Delta feasibility study at the end of 2020, after which the project will be further developed for realization. The consortium works simultaneously across industrial sectors (chemicals, petrochemicals and steel), as well as with relevant governments in both countries to create unique synergies and opportunities.	2023
Carbon2Value	The objective is to demonstrate the potential of reduction of GHG emissions in the steel sector by 30+%, by implementing a cost efficient breakthrough solution for the separation of CO_2 & CO unavoidably emitted. This will be achieved by processing in a pilot line carbon rich gases into 2 streams, one rich in CO and another one in CO_2 that could be valorised into promising chemical building blocks in the future. We will also take into account the reuse of any by-products to further induce fossil fuels' replacement and GHG emissions reductions. Two valorisation routes will be studied during the project, i.e. ethanol as a drop-in transportation fuel and synthetic naphtha as a drop-in chemical building block.	2017-2021
CARMAT	This pilot plant uses carbonation/mineralization to manufacture construction products from two residual products, namely steel slag and CO_2.	2014-2015
CATCO2RE	The specific target of CATCO2RE is to investigate the conversion of CO_2 to solar fuels (methane and methanol) integrating new developments in the production of solar hydrogen, with the design and synthesis of selective catalysts active at milder reaction conditions, and effective CO_2 capture and purification technologies.	2018-2022
CO2ncrEAT	Production of construction materials through mineralisation of CO_2 emitted from the lime industry into by-products of the steel sector.	2022
COLUMBUS	The project, based on carbon capture and methanation technologies, aims to reduce carbon emissions by transforming CO_2 generated during the lime production process into e-methane, a renewable gas that can be injected into the gas network or used to power vehicles and industry. The process up-scales and combines existing and emerging technologies, such as the fabrication of hydrogen, using some of the world's largest electrolysers and a new type of lime kiln to generate purer CO_2	2020-2025
GENESIS	GENESIS develops and upscales some of the most promising material for CO_2 capture and demonstrate their performance, durability and reliability in industrial environments. The materials are IPOSS (polyPOSSimide hybrid organic-inorganic) and MOF (Metal-organic framework) membrane systems that have demonstrated great performances for CO_2 capture. Demonstrated at two different sites.	2018-2021

OCEAn	The OCEAN project aims to develop an integrated process for the production of high-value C2 chemicals from CO_2 using electrochemistry. OCEAN will bring this technology just one-step away from commercialization, by demonstrating this technology at the site of an industrial electricity provider. Overall, critical elements are addressed that are currently hindering new electrochemical processes: High value products that have the corresponding production margin to introduce this technology on the market are targeted, the cost is lowered by combining oxidation and reduction, and a trans-disciplinary approach is provided which is needed for the introduction of these advanced technologies.	2017-2021
SCOT	SCOT (Smart CO_2 Transformation) is the first ever collaborative European initiative in the area of CO_2 recycling/Utilisation. The main objective of the project is to define a Strategic European Research and Innovation Agenda for Europe in the field of integrated CO_2 Capture, Utilisation and Cycling (Energy Storage Technology). Through a stronger coordination of efforts among the consortium, the SCOT project will enable to: (i) define a Strategic European Research Agenda aimed at developing new breakthrough solutions and market applications; (ii) attract additional EU clusters, regions and investors to participate to multi-disciplinary research programmes and other collaborative actions defined in a Joint Action Plan, (iii) propose structural policy measures to favour the transition to a new European society based on the paradigm of “CO_2-as-a-resource”, thereby significantly improving the EU’s overall competitive position and environmental performance on the international scene.	2013-2016
Steelanol	The STEELANOL project is based on producing bio-ethanol via an innovative gas fermentation process using exhaust gases emitted by the steel industry.	2015-2021
VALCO2 II	The collaborative project VALCO2 II aims to develop three different largescale CO_2 valorization methods to produce raw materials for the chemical industry (such as hydrogen carbonates, alkyl carbonates and formic acid) or non-fossil sources of energy	2014-2018

3 Conclusions

This report highlighted different points that are summarized here below.

First of all, it was highlighted that the **CO_2 is the most emitted greenhouse gas** (GHG), namely between 70% and 90% of all GHG, 85% for Belgium.

The CO_2 market management system (ETS - Emission Trading Scheme), whose various stages were summarized, has seen the **CO_2 price rising in recent years**, even approaching €100/t_{CO2} at certain moment, with the price fluctuating **most often between €70 and €80/t_{CO2}**.

In terms of **Belgian CO_2 emitters**, all **industrial sectors** (energy production and industries such as cement plants, refineries, steel and chemical plants, etc.) account for **almost 50% of CO_2 emissions**, the largest Belgian emitter being the Knippegroen power plant with more than 5000 kt_{CO2} emitted annually (2019). In the top-20 of the largest Belgian CO_2 emitters are several **cement plants and a lime producer**, the particularity of these industries being that nearly **66% of the emissions are so-called "unavoidable"**, i.e. linked to the decarbonation of the raw material necessary for production.

Different ways of capturing CO_2 exist, namely pre-combustion, oxy-combustion and **post-combustion**, the latter (the most developed at present) having the advantage of **not requiring any modification of upstream processes** (so-called "end-of-pipe" technology). More specifically, in terms of CO_2 capture technologies themselves, four main categories have been identified: gas-liquid absorption processes, gas-solid adsorption processes, the use of separative membranes and finally cryogenic processes. The **gas-liquid absorption technology**, and in particular using **amin(es)-based solvents**, is the **most mature one** (Technology Readiness Level - TRL - of 9) and the most proposed among the technology providers, although the other technologies have an interesting potential in the longer term, in particular in terms of cost reduction. In all cases, whether for CO_2 capture, purification or liquefaction, **the development of cryogenic systems seems necessary**.

For **CO_2 transport**, the CO_2 purity and the possible impact of impurities on its physico-chemical properties are important parameters. For continental transport, CO_2 can be transported by **pipelines** (see Fluxys' developments in this area), by **river barges**, by **train** or by **truck**, with maritime transport obviously being limited to pipelines and **ships**.

Regarding the **use of CO_2**, the **global market represents 230 Mt_{CO2} annually** (2018), 16% of which is in Europe. Nearly 60% of the world's CO_2 is currently used in **urea production**, 34% for **enhanced oil recovery (EOR)** and finally everything related to **food and soft drinks** (main uses in Europe), as well as other industries. Together with the development of the green hydrogen sector, **other markets will develop in the future**, such as **methanol**, **methane**, **ethanol**, **E-kerosene**, as well as other products with higher added values but smaller markets, such as polycarbonates, formic acid, polyurethane, etc.

Finally, it was illustrated that **various CCUS projects are currently under development in Europe, and in Belgium in particular**, both in energy production and in industries such as steel, cement or lime producers.

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