Zero emissions platform

Climate solutions for EU industry: interaction between electrification, CO_2 use and CO_2 storage

Policies have to be tailored to potential: EU energy intensive industry risks being left without a realistic pathway to decarbonise

This document has been prepared on behalf of the Advisory Council of the European Zero Emission Technology and Innovation Platform (ETIP ZEP). ZEP exists to advise the European Commission on Carbon Capture Utilisation and Storage Technologies and associated policies. The information and views contained in this document are the collective view of the Advisory Council and not of individual members, or of the European Commission. Neither the Advisory Council, the European Commission, nor any person acting on their behalf, is responsible for the use that might be made of the information contained in this publication.

The project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 727582

Contents

Executive Summary

In 2012-2013 European industry collaborated with the European Commission and civil society to develop sectoral Low-Carbon Economy Roadmaps for 2050. Despite being ground-breaking at the time, the Roadmaps have quickly become out-of-sync with European and global commitments on climate change mitigation as encapsulated in the Paris Agreement. This report, based on an initial analysis of what the Paris Agreement really means for European industry, evaluates the technical potential of electrification, Carbon Capture and Utilisation (CCU) and Carbon Capture and Storage (CCS) as solutions for industrial decarbonisation.

The Paris Agreement requires European industry to reduce emissions at a much greater rate than those implied in the Low Carbon Economy Roadmaps for 2050. Challenging the perception that electrification can deliver the majority of this abatement, the analysis shows that while electrification can reduce CO_2 emissions in some industries and locations, the abatement potential is limited in sectors where CO_2 emissions are a product of chemical processes and not the combustion of fossil fuels. Furthermore, the analysis shows that **the amount of electricity required for large-scale electrification of Europe's energy-intensive industry would necessitate levels of new low-carbon electricity generation that stretch the concept of feasibility**.

As an example, analysis of data published by chemical industry association CEFIC shows that **decarbonisation of Europe's chemical production – just one of the sectors in question – via electrification would require more than twice (+140%) the EU's current electricity generation.** Given the scale of the challenge in just decarbonising Europe's existing electricity supply, such a vast increase in demand could render power sector decarbonisation unachievable. **For this reason, ZEP has concluded that electrification alone is not a viable pathway for decarbonising Europe's heavy industry** within a relevant timeframe to the Paris Agreement goals. **Complementary methods of decarbonisation must be deployed; namely Carbon Capture and Storage (CCS) and, where it has climate benefit, Carbon Capture and Utilisation (CCU).**

The capture of carbon emissions from Energy-Intensive Industries (EIIs) for utilisation in new products is gaining traction as a potential cost-effective way of addressing industrial carbon emissions in Europe. Collectively, these processes are known as CCU. **In some instances, CCU can lead to a reduction in emissions by recycling CO_2 into products** that would otherwise use CO_2 generated solely for that purpose; this might also, in many cases, have resource efficiency benefits. **From a climate perspective however, the extent to which a CCU process can contribute towards climate change mitigation depends on the lifecycle of the product and whether and when the captured CO_2 is released into atmosphere**.

Furthermore, assessment of different types of CCU must be measured against a robust and transparent counterfactual, for example, whether a fuel produced from recycled fossil-derived CO_2 actually displaces conventional fossil fuel use, or whether it is likely to compete against other, more effective climate mitigation technologies and processes. This report concludes that treating all forms of CCU as *de facto* CO_2 abatement could have serious detrimental impacts on efforts to reduce emissions, and that **each application of CCU must be comprehensively assessed on its ability to contribute to long-term climate mitigation.**

Building on analysis of the 'Indicative Sink Factor' (ISF) of different types of CCU, the report also analyses the potential market size for different CCU products and processes in Europe. The analysis suggests that **the emerging markets for CO_2 (re)use will only be able to address a small proportion of the emissions that will need to be abated to meet climate targets** under EU legislation and the Paris Agreement. Looking at current trends in CO_2 utilisation, it can be estimated that 9 – 20% of total captured emissions from EIIs could be converted, corresponding to 40 – 120 MtonsCO_2/year, competing in a market with CO_2 from other sources.

As a result, **the majority of captured CO_2 emissions from EIIs will have to be geologically stored.** Based on the current product portfolio of energy-intensive sectors in Europe this would correspond to 360 – 540 MtonsCO_2/year.

It is recognised that while CCU applications, in many cases, have a limited potential for CO_2 abatement at scale, they could provide a valuable means of incentivising investment in enhanced CO_2 capture technology in the short term, reducing costs for industry and society. Notwithstanding, **it is imperative that current EU short-term focus on CCU does not lead to a further delay in large-scale CO_2 storage deployment, rendering delivery of the Paris Agreement infeasible.**

Taking into account the challenges around electrification and the limited scalability of CCU, it can be concluded that these solutions must be combined with making available large-scale permanent storage for captured CO_2 to meet the required level of reductions, thus **enabling the long-term sustainability of these key industries in a low carbon Europe.** Given the critical importance of CCS in enabling decarbonisation of Europe's EIIs, **this paper recommends that EU policy focuses on the rapid deployment of CO_2 transport and storage** infrastructure to support these important sectors. **A failure to provide such enabling infrastructure in the short term will increase CO_2 liability risk and undermine investments in jobs and economic activity.**

1. CCU and CCS classification

Carbon capture and storage

CCS is the capture, transport and permanent, deep geological storage of CO_2, which prevents the CO_2 entering the atmosphere. CCS is a large-scale climate mitigation technology. CO_2 storage sites can be characterised and developed both onshore and offshore. In Europe, storing CO_2 offshore, such as under the North Sea is likely to benefit from a greater public acceptability.

Recent ZEP reports have identified that:

1. CCS is a necessary tool for the decarbonisation of EIIs and other sectors. The absence of CO_2 transport and storage renders infeasible the current climate change mitigation ambition level of the EU.[1]

2. Increasing climate ambition, such as the more stringent objectives of the 2015 Paris Agreement to limit global temperature rise to "well below" two degrees Celsius, will rely even further on CO_2 transport and storage to address difficult to abate residual emissions, and to provide the infrastructure for large-scale carbon dioxide removal (CDR).[2]

3. CO_2 transport and storage networks are critical decarbonisation infrastructure, but require time for development and expansion. The development trajectory for large CO_2 transport and storage clusters may be several decades. Providing CO_2 transport and storage networks to enable EU industries to meet obligations under the Paris agreement will require staged infrastructure development beginning now.[3]

Carbon capture and something

Geological storage is one possible fate for carbon captured from industry. However, alternative proposed ends for captured CO_2 include a wide variety of CO_2 uses. CO_2 utilisation encompasses a diverse portfolio of direct uses for CO_2 as well as chemical conversion processes. Chemical conversion of CO_2 generally requires energy and/or mineral inputs with a wide range of full life cycle CO_2 abatement potential. This complex landscape of CO_2 utilisation has led to complex naming including (but not limited to):

- CCU – Carbon Capture and Utilisation,
- CCUF- Carbon capture for conversion into fuels
- CCR for Carbon Capture and Reuse
- CCV for Carbon Capture and Valorisation.

For the purposes of this report, CCU covers all the above.

Classes of CCU

CCU, where CO_2 may be used and subsequently emitted or used and stored for varying periods is different to carbon capture and geological storage where the CO_2 is always <u>permanently</u> stored.

Given the breadth of technologies and processes covered by the term CCU, it is necessary to evaluate different technologies, processes and projects on a case-by-case basis to determine their relative value in terms of CO_2 abatement and tackling climate change. A breakdown of CCU technologies into subsidiary types, technologies and processes is needed, supported by a robust assessment of the counterfactual in each instance.

A key component of the assessment of CCU classes will be the time span in which it is likely that the captured CO_2 will be released to the atmosphere. This is necessary to ensure that emissions reductions across the economy, in accordance with the EU's contribution towards the Paris

[1] CCS for industry: Modelling the lowest-cost route to decarbonising Europe, Zero Emissions Platform, 2016
[2] Fast Track CO2 Transport and Storage for Europe, Zero Emissions Platform, 2017
[3] Ibid.

Agreement, are delivered and that climate finance is not used to support technologies that do not lead to verified avoided emissions.

ZEP recommends that a classification system is developed, incorporating a so-called "**Sink Factor**", to indicate the proportion of CO_2 that is permanently abated in line with climate objectives (climate effective CO_2 storage), as proposed in ZEP's recent position paper.[4]

Thorough Lifecycle Analyses (LCAs) are required to understand how factors such as process energy input impact the CO_2 abatement potential. It should be noted that, aside from CO_2 abatement, products derived from anthropogenic CO_2 can, in some instances, contribute to at least a partial replacement of the same or similar products made by a conventional process and therefore yield benefits in terms of the conservation of resources. Particular attention is needed for CO_2 used for producing food or feed for people and animals – this might e.g. aid in reducing agricultural encroachment on forests and other carbon sinks in a world with continuing population growth.

ZEP has identified four classes for CCS and CCU, ranging from permanent to short term sequestration.

Table 1. Indicative applied sink factor to different types of CCU and CCS

Table 1 Indicative applied sink factor to different types of CCU and CCS

	Sequestration period of CO2	Use of materials in which CO2 is captured	Indicative Sink Factor	Examples
Bio-CCS	Permanent	Permanent storage, no use	>100%	Provided the biomass involved is sustainably sourced, the capture and storage of biogenic CO2 from any industrial bio- conversion or combustion process can yield negative emissions
CCS	Permanent	Permanent storage, no use	100%	
Enhanced Oil Recovery	Depending on project: permanent	Can be permanent storage, depending on project	95 – 100%	
CCU				
□ Long term	> 100 years	Building materials, aggregates	40 – 75%	mineralisation (CO_2 -Olivine), nanocarbon
□ Medium term	10 – 100 years	Building materials	10 – 40%	Carbon8, Blueplanet, Solida, CarbonCure
□ Short term	< 10 years	Fuels, feedstock, food, lightweight building materials, plastics	0 – 10%	Power to Fuels (e.g. methane, methanol). Biofuels (microalgae)

For CCU we see three classes:

1. **High sink factor:** *Long term, CO_2 prevented from entering the atmosphere for a century or more*
   CO_2 is locked away from the atmosphere for long time periods in stable products. CO_2 use in this way has direct climatic benefits by sequestering CO_2. High sink factor of technologies will sequester the captured CO_2 into materials that will be unchanged over a very long term, likely more than 100 years. The requirement is that the materials produced with the captured CO_2 are not changed during the normal lifetime and use of these materials.

[4] Briefing paper: CCU in the RED, Zero Emissions Platform, 2017 http://www.zeroemissionsplatform.eu/library/publication/274-ccu-in-the-red.html

2. **Intermediate sink factor:** *Medium term, 10 and 100 years before release of utilised CO_2.*
   CO_2 used in stable products that will typically release the CO_2 to the atmosphere after 10 and before 100 years, indicating that the CO_2 is sequestered in materials that in the longer term will on purpose (e.g. by incineration) or naturally fall apart into the original components.
   The technologies from this medium term CCU-class will solve the problem for today, but not forever. That means that in future solutions have to be found for these materials, but at this moment the application of these technologies leads to reduction of CO_2 emissions to the atmosphere.

3. **Low sink factor:** *Short term, 10 years or less before release of utilised CO_2.*
   CO_2 is released to the atmosphere nearly immediately with the normal use of the product manufactured with captured CO_2, for example in the case of conversion of CO_2 into products with a relative short life span such as fuels, food, disposable plastics etc. Low sink factor CCU technologies should be seen as single reuse of CO_2. The greenhouse gas reduction of these products is reliant on displacement of more CO_2 intensive products, e.g. replacing hydrocarbon derived plastics with CCU. Other considerations when assessing the GHG reductions include the resource intensity, such as electricity use required to manufacture products with a low sink factor.

Advantages of the classification of CCU technologies

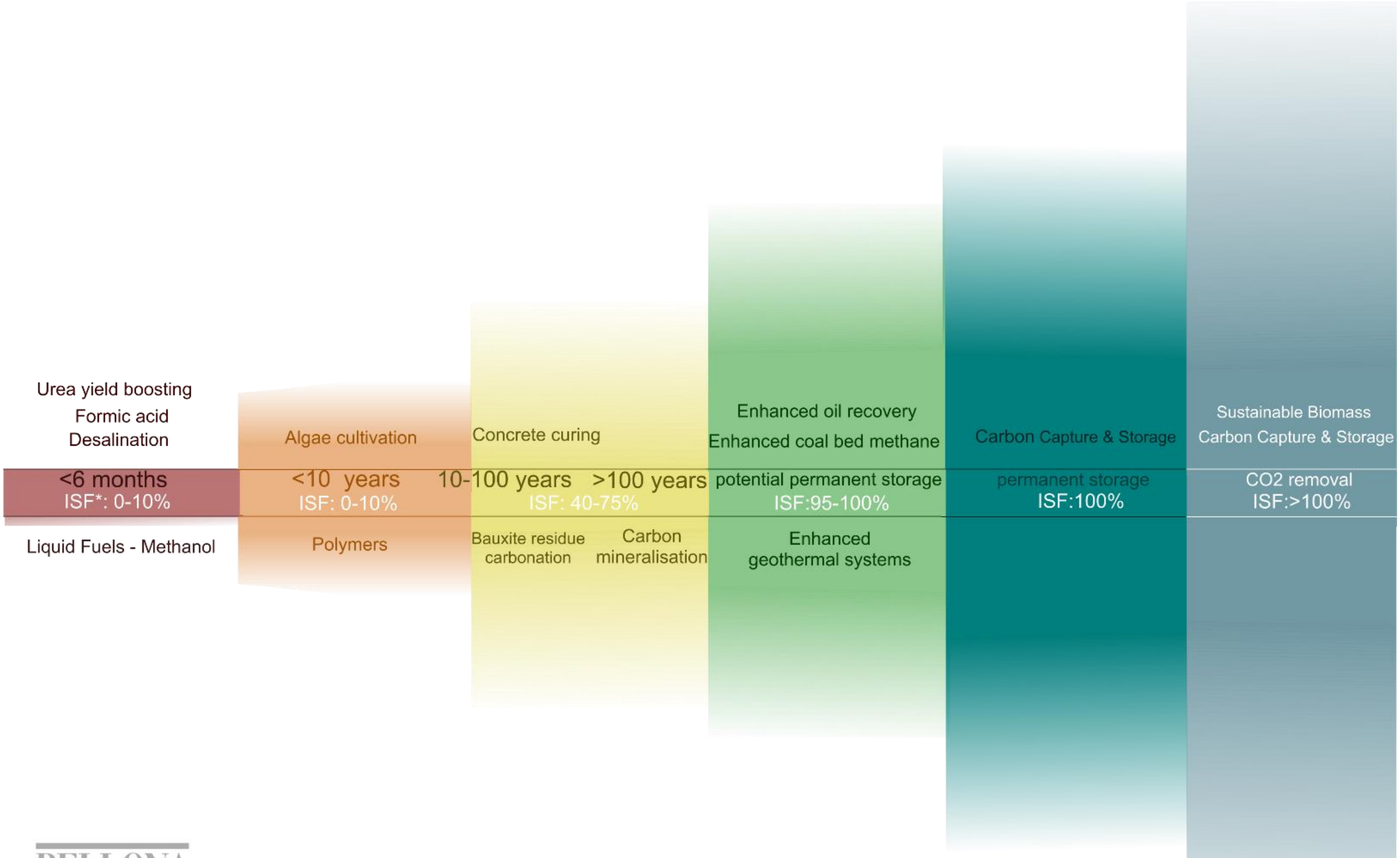
The classification of CCU technologies in relation to the expected timeframe of the release to the atmosphere of the captured CO_2 is needed because this classification provides clarity on each technology in discussions around climate change abatement tools and policies.

It is often mentioned[5] [6] that CCU will contribute to the Circular Economy, by using the fossil carbon two or more times. The question posed by this paper is whether this carbon recycling should be classified as circular unless a closed loop can be achieved, effectively prohibiting the CO_2 from entering the atmosphere.

A risk is that the reuse of captured industrial fossil C or CO_2 could contribute to a lock-in of carbon-intensity in sectors where other options exist or are being developed. It is also apparent that C or CO_2 recycling can only be done with considerable (fossil or renewable) energy input, due to the law of conservation of energy which states that the total energy of an isolated system remains constant.

The substantial additional pressure such increased energy demand would place on the decarbonisation of the EU power sector must be appropriately taken into account in CCU climate mitigation LCAs.

[5] https://setis.ec.europa.eu/setis-reports/setis-magazine/carbon-capture-utilisation-and-storage/challenges-of-ccu-industry
[6] Actions required to develop a roadmap towards a Carbon Dioxide Utilisation Strategy for Scotland. 9Wilson et.al.,2016)



BELLONA EUROPA

*Indicative Sink Factor (ISF): the proportion of CO_2 that is permanently abated in line with climate objectives - climate effective storage) (ZEP 2017)

**The values are an approximate indication of the CO_2 retention potential of available groups of CCU technologies. For a more precise measure, a case-by-case approach is needed.

2. The role of electrification in decarbonising EU industries

Electrification of significant parts of the economy, such as electromobility along with the smart and flexible use of variable renewable electricity, has the potential to greatly reduce the fossil fuel use and CO_2 emissions of the European economy. Many industrial processes can likewise be redesigned to avoid CO_2, through using low-carbon electricity directly or via the use of clean hydrogen, which can be manufactured from low-carbon electricity or by steam methane reformers (SMRs) with CCS.

CCU is also sometimes framed as electrification: CO_2 captured from industry can be combined with hydrogen from renewable electricity to produce transport fuels for the use in conventional combustion engines. Upon combustion, the CO_2 is then emitted to atmosphere.

Electrification of industry is electricity intensive

Wide scale electrification of large European industries such as steel, cement and chemicals manufacture will not provide deep emissions cuts in all sectors and will place unfeasibly large demands on renewable electricity. A comparative assessment of the electrical energy requirements and CO_2 abatement potential of the following major industrial electrification routes has shown that relying on electrification alone is not an achievable decarbonisation pathway for European industrial production.

- Electrifying European chemical process would require 140% of total current electricity generation in Europe. (0)
- Converting CO_2 to fuels requires very large electricity inputs. Power to fuels is electricity intensive, requiring many multiples the electricity input compared with direct electrification of industrial process. (0)
- CO_2 capture, transport and storage places comparatively small additional demands on low carbon electricity. Some low carbon electricity is required for CO_2 compression for transport and storage, but ongoing developments in CO_2 capture technology, such as Hisarna[7] for the steel industry, drastically drive down the energy penalty for capture.

Electrification does not always provide deep emissions cuts

Although electrification can reduce CO_2 emissions, in sectors with process CO_2 emissions not resulting from fossils fuels the abatement potential is limited. Manufacturing sectors such as cement and aluminium will not reduce emissions substantially through greater electrification alone. CO_2 transport and storage networks will be required for deep CO_2 reductions.

- A reference cement plant producing 1 million tonnes of cement a year would consume electricity equivalent to ~250,000 homes. The process CO_2 emissions (~60% of total emissions) would not be reduced through electrification. (0)
- Converting fossil CO_2 captured from industry into transport fuels results in the reuse of CO_2 once. Hence the best-case full life cycle CO_2 reduction is 50%. Real world reductions will be significantly less due to conversion efficiency losses and huge energy demand. For comparison, biofuels in Europe are required to achieve a CO_2 reduction of 60% when compared to petroleum, growing to 70% in 2022.
- CO_2 capture, transport and storage directly reduces both energy and process CO_2 emissions from industry.

[7] https://www.tatasteeleurope.com/en/innovation/case-studies-innovation/hisarna%E2%80%93pilot%E2%80%93plant

Box 1 – Example of electrification of cement industry

Providing the thermal energy requirements of a cement manufacture process with renewable electricity would reduce fossil fuel use, but would not reduce the majority of the CO_2 emission from the manufacturing process. A reference cement plant producing 1 million tonnes of cement a year would consume approximately 1TWh of electricity, equivalent to ~250,000 homes. Applied to all EU cement production[8], the cement sector would require the equivalent of all electricity produced in Poland today.

Alternatively, capturing and converting all CO_2 from the sector to synthetic diesel transport fuels (CCUF) would increase electricity consumption by six times again, and would displace industrial CO_2 emissions to the transport sector without actually stopping them from reaching our atmosphere.

For cement production, as with other sectors with non-fossil CO_2 emissions, CCS provides far greater CO_2 emissions reductions at a fraction of renewable electricity resources. Wide deployment of CCS in the EU cement sector requires development to urgently begin on an extensive CO_2 transport and storage infrastructure, ultimately capturing and storing 100 million tonnes of CO_2 per annum.

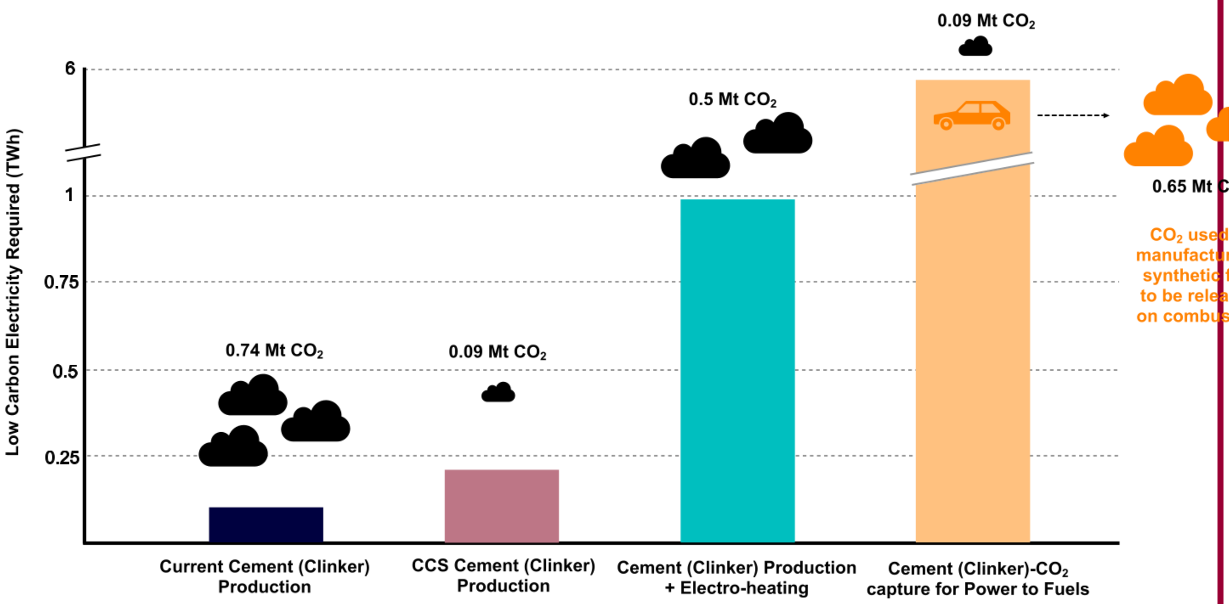


Figure 1 Reference cement production facility of 1 million tonnes per annum. Comparing the electricity requirements and CO_2 reduction of carbon capture and storage, electric heating, CO_2 conversion via power to fuels.[9]

[8] EU clinker production, 140 million tonnes in 2011 (cembureau, 2011)

[9] CCS, *Process emissions 0.507 tCO2/t Clinker* (Gibbs, et al., 2000)*, 3 GJe/t Clinker* (Moya, et al., 2010)*, 90% CO2 capture & Post Combustion, 2.7GJt/tCO2 thermal energy & additional fossil energy for capture process* (Hsiu Yu, et al., 2012)*, Compression 150 bar, 0.72 GJe/tCO2 electrical energy* (Hsiu Yu, et al., 2012)
Electro Heating. *3 GJt/t Clinker* (Moya, et al., 2010) *Process emissions 0.507 tCO2/t Clinker* (Gibbs, et al., 2000)
Power to Fuels, *Synthetic eDiesel fuel 3.81 tCO2/t Diesel* (Carbontrust, 2016)*, 42.8 GJe/t Diesel* (Laborde, 2011)*, 60% conversion efficacy of electricity to fuel*

Box 2 – Example of electrification of steel production

Steel mills are large and centralised, with a handful of integrated plants in Europe. The result of electrifying any single integrated steel plant will be a very large localised increase in electricity consumption. A reference integrated steel mill producing 7 million tonnes of steel a year with electrolysis of hydrogen for direct reduction and electric arc furnace would consume approx. 37 TWh of renewable electricity per annum. A single steel production site would consume as much electricity as 9 million European households or the total electricity demand of greater London[10].

Increasing electricity demand so dramatically from a single consumer in a small area would test the feasibility of both the electrical grid and renewable generation to meet the additional supply. Electrifying all new EU steel production[11] would have a dramatic effect on electricity consumption and demand for clean electricity resource; electricity demand would be equivalent to the total current generation of 19 EU member states. An electrolysis hydrogen based EU steel sector would monopolise some 50% of the total wind energy resource potential of the North Sea, renewable energy that will also be required to replace current carbon-intensive electricity generation as well as for the electrification in other sectors such as electromobility and residential heating and cooling.

CO_2 capture and use of fossil CO_2 from an integrated steel mill to synthetic diesel transport fuels would increase electricity requirement even further, without actually stopping the CO_2 from reaching our atmosphere.

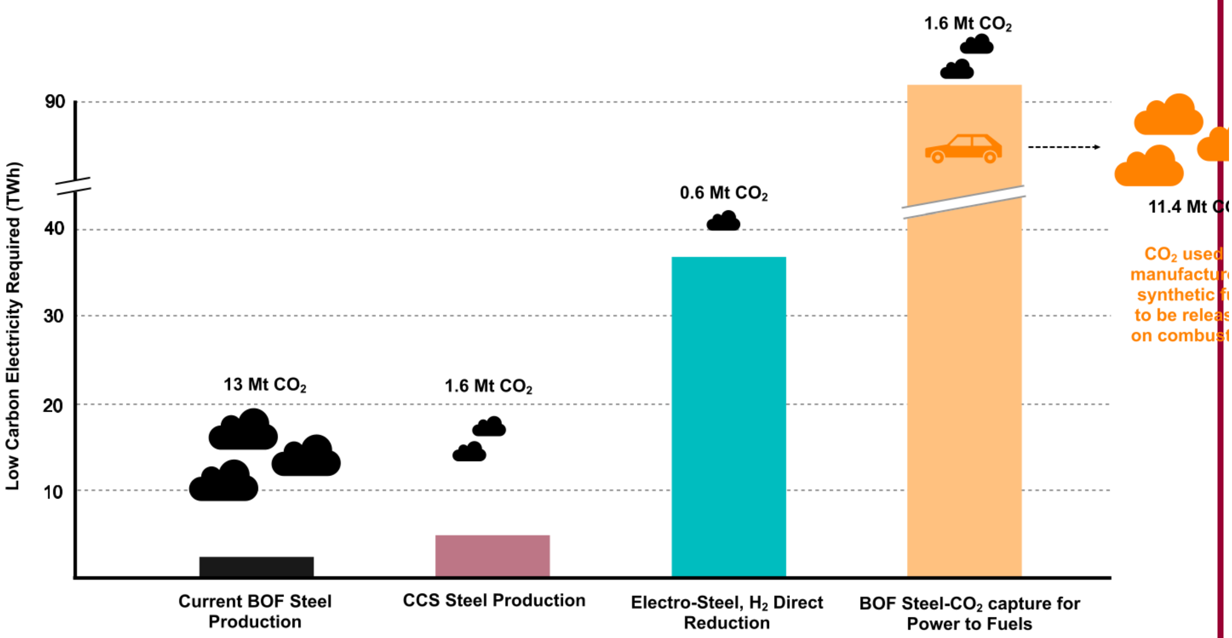


Figure 2 Reference integrated steel production facility of 7 million tonnes per annum. Comparing the electricity requirements and CO_2 reduction potential of Carbon capture and storage, Hydrogen direct reduction, CO_2 conversion via power to fuels.[12]

[10] Total greater London electricity demand in 2015 was 39.65 TWh.

[11] EU BOF steel production, 104 million tonnes (Wortler, et al., 2013)

[12] CCS: *EU average 1.88 tCO2/t BOFSteel* (Wortler, et al., 2013), *90% CO2 capture & Post Combustion, 2.7GJt/tCO2 thermal energy & additional fossil energy for capture process* (Hsiu Yu, et al., 2012), *Compression 150 bar, 0.72 GJe/tCO2 electrical energy* (Hsiu Yu, et al., 2012), *Other electrical 0.6 GJe/t BOF steel* (Friedrichsen,, et al., 2016)

Electro-Steel: 19.96GJe/t steel & 94kg CO2/t steel (Otto, et al., 2017)

BOF Steel Power to Fuels: Synthetic eDiesel fuel 3.81 tCO2/t Diesel (Carbontrust, 2016), 42.8 GJe/t Diesel (Laborde, 2011), 60% conversion efficacy of electricity to fuel, BOF Gas, available 4.719 GJ/tSteel (Otto, et al., 2017)

Box 3 – How much North Sea offshore wind electricity resource is needed to electrify steel production?

Reliance on electrification for decarbonisation of steel production in Europe will place massive, potentially infeasible demands on transmission grid strengthening and increased renewable electricity generation, leaving no renewable electricity for other sectors to decarbonise. Added to this is the requirement to redevelop all blast furnace integrated steel manufacture facilities. Large scale CO_2 transport and storage infrastructure will be a required element in achieving deep cuts in the European steel sector.

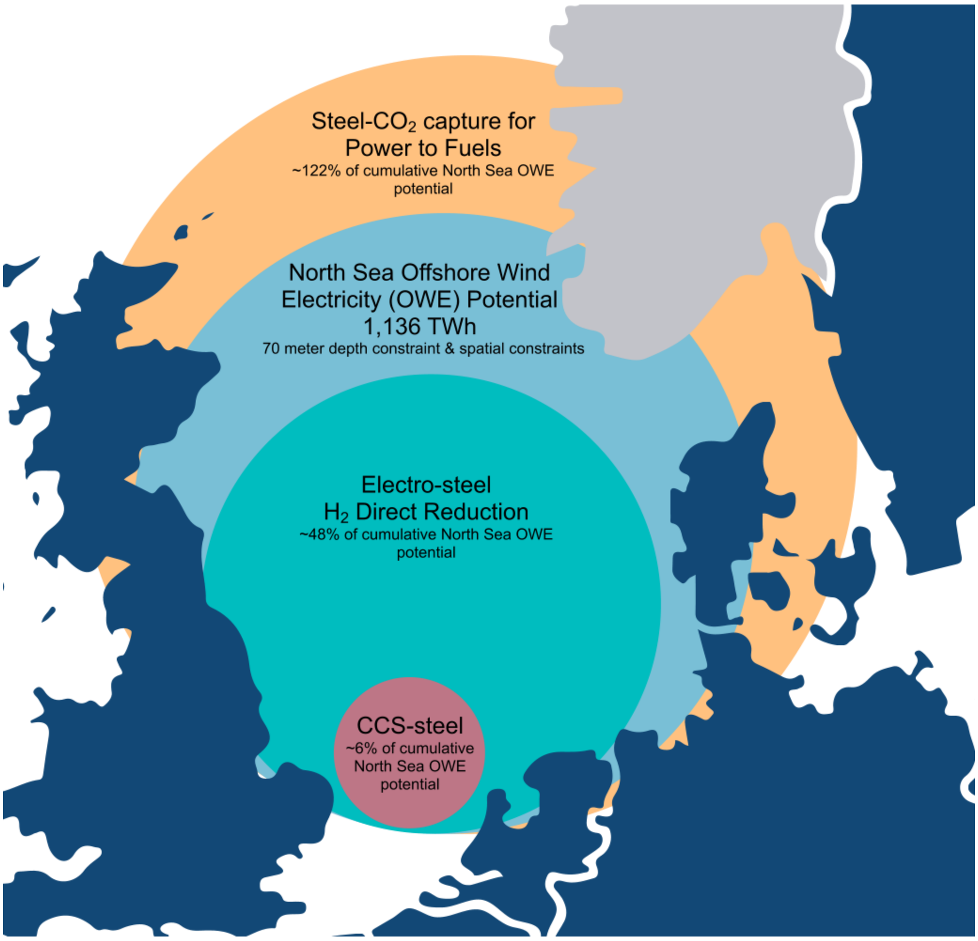


Figure 3 North Sea Offshore Wind Electricity (OWE) potential, 132,000 km2 with 1,136 TWh (Cameron, et al., 2011). Comparison of electricity requirement for EU low carbon steel manufacture with CCS, electrolysis of hydrogen and direct reduction, CO_2 conversion via power to fuels. Producing new electro-steel in Europe at current production volumes would monopolise almost 50% of the total practical renewable wind electricity potential of the North Sea. Production of power to fuels of EU new steel CO_2 would exceed all North Sea offshore wind generation potential [13]

[13] EU BOF steel production, 104 million tonnes (Wortler, et al., 2013)

Box 4 – European Chemical industry roadmap for electrification and CO_2 use.

In the EU, the production of base industrial chemicals including ammonia, urea, methanol, olefins, chlorine and BTX[14] emit approximately 80 million tonnes of CO_2 per annum. CEFIC, the Europeans chemicals association, commissioned a study to assess the electricity required to electrify the manufacture of these key chemical feedstocks and processes (Bazzanella, et al., 2017). Electrification of the sector requires redesigning the manufacture process to use low carbon hydrogen and CO_2 as the primary feedstock.

The electricity requirements for an industry-wide conversion are unfeasibly large. Low carbon electricity demand, dominated by the need to produce hydrogen via electrolysis, would surpass current total EU electricity generation. With the inclusion of power to fuels, EU electricity generation would be required to grow four-fold while simultaneously transitioning to low carbon and renewable electricity sources.

Even at such large low carbon electricity consumption, the CO_2 abatement potential is ill defined. Disposal of products manufactured with CO_2, such as plastics, would after disposal by incineration release the CO_2 to the atmosphere, unless waste incineration facilities were fitted with CCS. The use of power to transport fuels (for which CCS is not an option) would emit CO_2 to the atmosphere resulting in a low full life cycle CO_2 abatement.

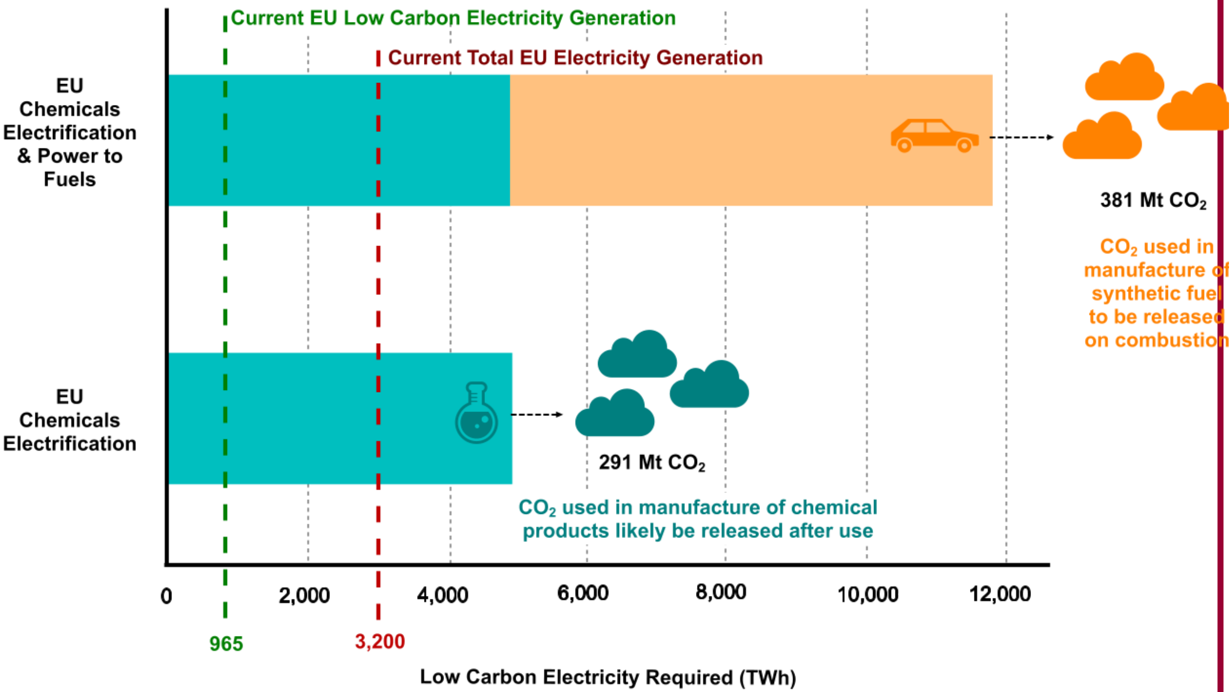


Figure 4 Manufacture electrification of key EU chemicals products. Full electrification of chemical manufacturing process requires 140% of all EU electricity generation. Electrification of manufacturing process and production of synthetic fuels 350% of all EU electricity generation. (Bazzanella, et al., 2017)[15]

[14] BTX (Benzene, Toluene, Xylene)
[15] Share of electrification of product manufacture in 2050:
Chemical Products: olefins 85%, BTX 100%, electric heating 100%.
Fuel Products: MeOH (methanol) 96.5% in gasoline, synthetic jet fuels 100%, synthetic diesel 100%

3. Decarbonisation roadmaps for European Energy Intensive Industries

Starting point: Industrial low carbon roadmaps for 2050

Responding to a request by the European Commission in its 2011 “Roadmap for moving to a competitive low carbon economy in 2050”, European Energy Intensive Industries (EEIIs) produced a set of sector-specific decarbonisation Roadmaps to 2050[16][17][18][19]. From these the following conclusions can be drawn.

1. Three sectors dominate in terms of emissions; steel, cement and chemicals. The emissions from the pulp and paper sector are significantly smaller, but are included here to account for the four largest CO_2 emitting industries.

2. EIIs, while being heavy emitters, are also crucial providers of building blocks for the decarbonisation of the European economy. For example, it is estimated that 100Mt of steel will be needed to meet demand for wind turbines in Europe to 2050[20]. The cement industry roadmap highlights that cement’s thermal mass properties make it a high performing material for construction of energy efficient buildings compared to alternatives[21].

3. Energy Intensive Industrial emissions demonstrate a clear downward trajectory, but the industry roadmaps also demonstrate the continuation of this trend will require implementation of both solutions that are known but currently not cost effective, and technologies that are not yet ready for deployment at scale. The former includes deep decarbonisation of the power system, maximized deployment of (for example) fuel switching and energy efficiency measures, and significant if not complete decarbonisation of the transport system. The latter includes CC[U]S, which will be crucial for these sectors to progress much beyond a 50% reduction on 1990 level emissions.

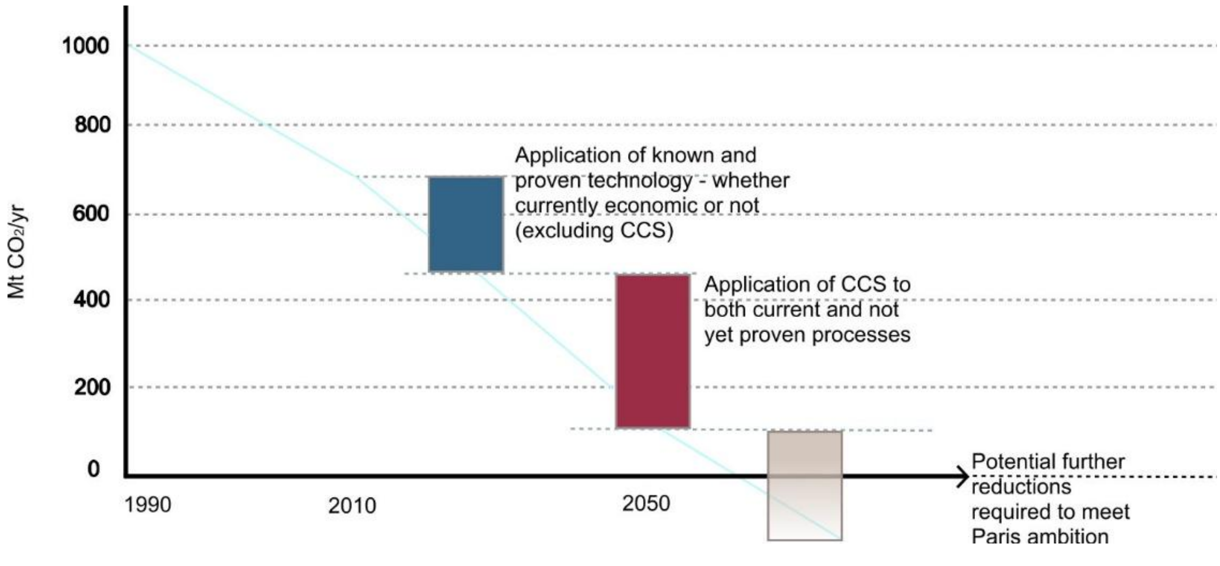


Figure 5 Combination of 4 Energy Intensive Industry roadmaps indicating the three levels of carbon reductions mentioned. The first bloc is based on application of known and proven technology without CCS. The main part has to come from future developments. Remaining is the “unsolved” bloc in the roadmaps 2012/2013. Includes EU Steel, Cement, Chemicals and Pulp & Paper Industrial emissions

[16] The role of Cement in the 2050 Low Carbon Economy (Cembeau, 2013)
[17] European chemistry for growth (cefic, 2013)
[18] Investing in Europe for Industry Transformation (cepi, 2013)
[19] A steel roadmap for a low carbon 2050 (Eurofer, 2013)
[20] Manufacturing Our Future: Industries, European Regions and Climate Action (Whiriskey, 2016)
[21] The role of Cement in the 2050 Low Carbon Economy (Cembeau, 2013)

Box 5 – Example of potential emission reductions in cement industry

The cement industry Roadmap (2013) estimates that a 32% emissions reduction on 1990 levels can be achieved through decarbonisation of power and transport, more efficient plant, fuel switching and use of new materials, such as novel cements. Further reductions will require CCS or a yet unproven breakthrough technology, the inclusion of which could lead to an up to 80% reduction in emissions from cement (Cembeau, 2013).

Paris: Current roadmaps are not ambitious enough

In order to reach 'Paris-level' commitments, i.e. below 2 degrees warming, the European Commission estimates an 83 to 87% emissions reduction will be required in industry by 2050[22]. The IEA estimates in its most recent Energy Technology Perspectives report that a below 2 degree scenario will require deployment of CCS at capture rates above 90%, as well as a significant amount of carbon dioxide removal (CDR) from bioenergy with CCS (BECCS). The report concludes that in a below 2 degree scenario 55% of steel and cement production is equipped with CCS, resulting in 1,007 million tonnes of CO_2 being captured and stored annually in 2060 from these sectors alone.[23]

Much more CO_2 will need to be stored than sold for use

A recent study of the potential uses for CCU that leads to permanent carbon abatement concluded that CCU is likely to be able to account for around 9% of the total carbon that needs to be sequestered to 2050, including 8% to be used for Enhanced Oil Recovery (EOR).[24] Given the high levels of carbon sequestration needed to achieve significant levels of decarbonisation within EIIs, provision of both infrastructure and market structures to enable deployment of CCS within these industries is crucial. Given that individual companies operating in these sectors do not have the expertise or currently the incentive to build CO_2 transport and storage (T&S) infrastructure[25], policy will need to be developed to build publicly available T&S which industrial emitters will be able to use via a "pay-at-the-gate" arrangement. It should be emphasized that focusing on CCS as the dominant route to enable the levels of sequestration required does not exclude emitters from choosing to sell CO_2 for use where there are opportunities to do so. However, as outlined in other areas of this report, any application for CCU must have a high sink factor to be comparable to the carbon abatement potential of CCS and as such, eligible for climate mitigation funding.

22 Energy Roadmap 2050 [COM/2011/885] (EC, 2011)
23 Energy Technology Perspectives 2017 (IEA, 2017)
24 The role of CO2 capture and utilization in mitigating climate change (Mac Dowell, et al., 2017)
25 Manufacturing Our Future: Industries, European Regions and Climate Action (Whiriskey, 2016)

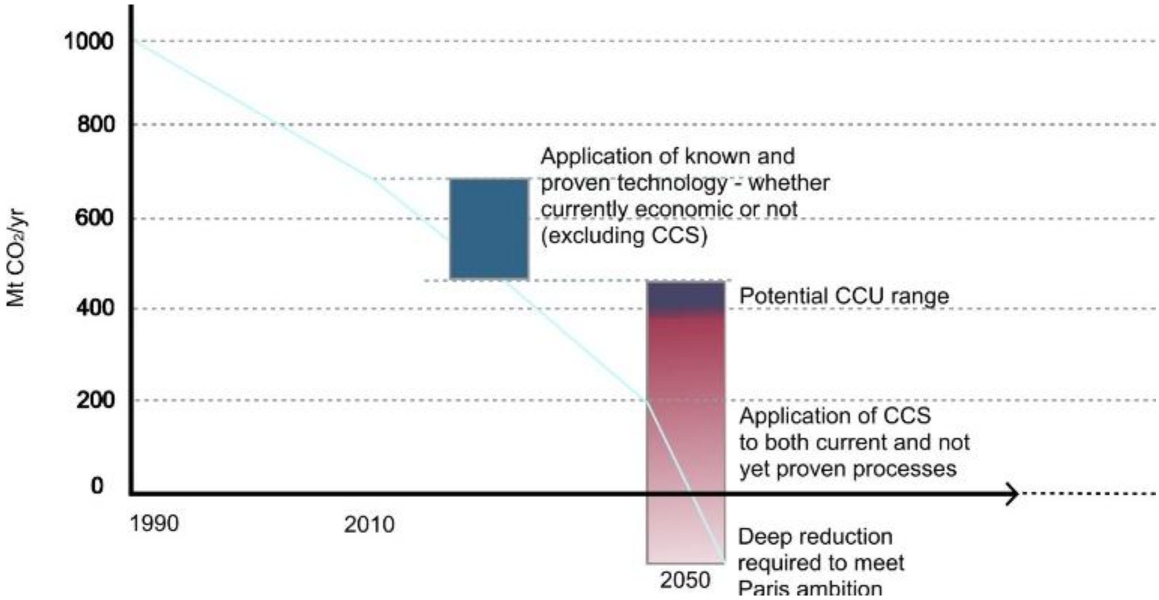


Figure 6 Potential in the Energy Intensive Industries within the Paris agreement target setting indicates that more emissions reductions are needed by CCS/CCU then before. Includes EU Steel, Cement, Chemicals and Pulp & Paper Industrial emissions

4. Economics of CCS and CCU

Interactions of CO_2 use and CO_2 storage

The European Emissions Trading Scheme (ETS) currently provides an insufficient price signal to incentivise deep emissions cuts from EIIs. In addition, the ETS alone will not stimulate development of shared CO_2 transport and storage infrastructure, as this requires long timescales and diverse beneficiaries[26] [27].

Commercial uses for CO_2 could incentivise investment in CO_2 capture at industrial sites, but will not direct resources to the timely development of shared CO_2 storage. Market demand for CO_2 can emerge from industrial CO_2 applications, although currently many CCU applications still require further innovation or subsidy to become market competitive[28]. Alternatively, greater demand may be created by legislation promoting use directly or indirectly. One potential example is the mandate for 'renewable' transport fuels, including power to fuels, in the proposed Renewable Energy Directive (REDII).

Industries that can extract value from CO_2 utilisation may be willing to purchase CO_2 at a price that is higher than that of EUAs. If that price were high enough to justify investment in CO_2 capture, CCU would be financially viable. In such circumstances, it should be expected that companies capturing CO_2 would aim to sell it for utilisation as opposed to permanently storing it, leading to limited carbon abatement.

A short-term focus prioritising only the use of CO_2 will disincentivise the required development of the shared CO_2 transport and storage necessary to abate the lion's share of CO_2 captured from industries. It is possible that under these circumstances no investment in CO_2 transport and storage would occur, severely delaying the development of industrial CO_2 clusters and sufficient CO_2 storage capacity which are essential for decarbonisation and the long-term competitiveness of, and employment in, European EIIs.

Box 6 – CO_2 Use, bridging ETS and non-ETS sectors

Currently industrial emitters surrender EUAs for CO_2 that is sold for use.[29] The CO_2 is therefore still classed as emitted under the ETS. An outcome of this is that relatively inexpensive CO_2 emissions can be moved from an ETS sector to be emitted freely in non-ETS sectors such as transport with a far higher effective CO_2 price. In this way, CO_2 use and conversion could be used as a form of CO_2 arbitrage, exploiting different CO_2 reduction legislation and compliance cost in different sectors.

It is estimated that the EU's 2021 transport CO_2 target of 95 grams/ CO_2 per kilometre results in an effective compliance cost of approximately €370 per tonne of CO_2, many times the CO_2 compliance cost applied to electricity and industry.

The production of synthetic transport fuels for internal combustion engines could allow for industrial CO_2 to be moved and emitted in the transport sector, greatly reducing the cost of compliance for vehicle manufactures. Synthetic fossil fuels could allow the continued use of current combustion technology with no technological change required by the vehicle manufacturer to meet transport CO_2 targets. Audi, a large German car manufacturer, is already pursuing with partners the production of power to fuels, sometimes branded E-Diesel.[30]

[26]Business models for commercial CO_2 transport and storage (ZEP, 2014)
[27]Fast Track CO2 Transport and Storage for Europe (ZEP, 2017)
[28] http://s3platform.jrc.ec.europa.eu/carbon-capture-and-utilization
[29] CO_2 from ammonia production is used as feedstock for the production of urea, the related amount of CO_2 shall be considered as emitted by the installation producing the CO_2 (Section 17 of Annex IV of the MRR) (EC, 2012)
[30] Norwegian company can be the first in the world to produce Audi's "wonderful diesel" (NILSEN, 2017)

Box 7 – CO_2 Use & CO_2 Storage are required to be developed in parallel

At present, there is no economic driver for timely development of CCS or enabling CO_2 transport and storage infrastructure. In the case where some forms of CCU become commercial or benefit from supporting legislation, such as REDII creating market demand for synthetic fuels, investment will be channelled solely to CO_2 use. Ultimately, such a development pathway will result in limited effective decarbonisation. CO_2 transport and storage will not be present to supplement the limited climate mitigation potential of CCU.

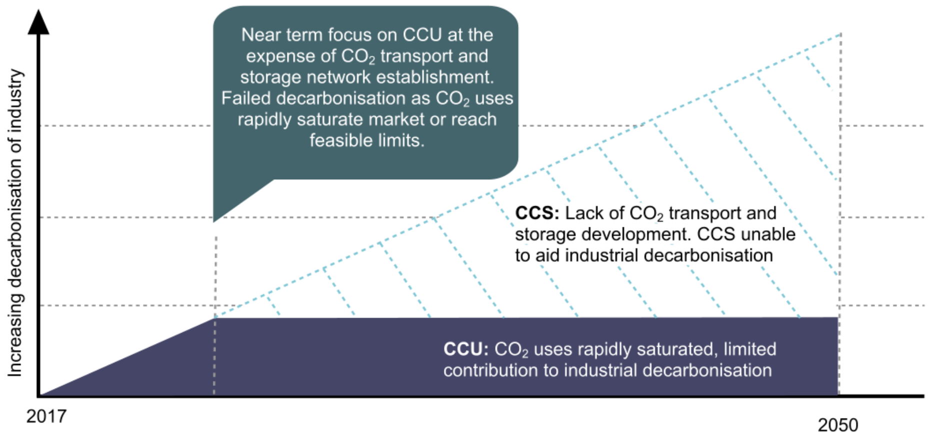


Figure 7 CCU implementation scenario without CCS strategy and policy support: results in prioritisation of CCU and a failure to develop required CO_2 transport and storage for deep decarbonisation of Energy Intensive Industries

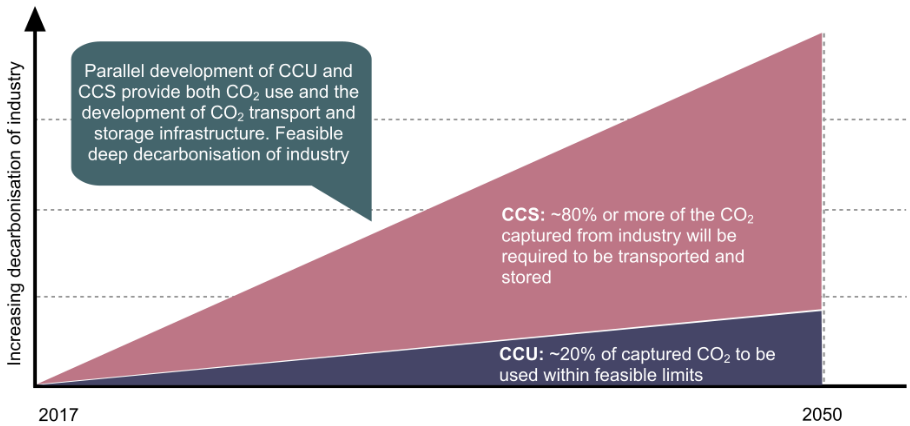


Figure 8 Co-development pathway of CCU and CCS provides a long-term pathway to deep emissions cuts in energy intensive industries

Financing

Despite the need for CCS at scale to meet Paris Agreement targets, a number of challenges currently hinder private investment. The low price of EU emission allowances (EUAs) offers limited motivation for industry investment in capture, the result being that EIIs will prefer to pay to emit[31] unless additional revenue streams can be found, such as a market premium for low carbon products.

Uncertainty on CO_2 pricing and the trajectory of industrial decarbonisation creates little incentive for private investment in CO_2 storage, leading to a "chicken-and-egg" situation where neither party is willing or able to make the first move. Further interdependencies between the various parts of the business chain add individual project risks that cannot adequately be managed by project developers and warrant intervention from government and independent regulators to unlock development in the early phase[32].

EIIs operate in global, highly commoditised markets. In markets where products are not differentiated by climate performance it is not possible to pass on increases in low carbon production cost to consumers.

Solutions to the challenges outlined above hinge on increased political certainty and regulatory stability. If these are addressed, investors could be convinced of the market opportunity implied in the stated climate goals, and thus choose to participate in future projects. Crucially, government funds are required in the short- to medium-term to complement the EUA sales revenues.

It is in this context that it is possible to understand the synergies between CCU and CCS: by providing revenues independent of the EUA price, CCU can enable investment in the capture of small CO_2 volumes and de-risk the integration of capture with industrial process, with a view to then scale-up the capture operations as permanent CO_2 storage becomes available.

[31] Emitters can pay an 'ETS wergild' (in ancient Germanic law, the amount of compensation paid by a person committing an offense to the injured party)

[32] An Executable Plan for enabling CCS in Europe (ZEP, 2015)

Conditions for success of CCU and CCS

Geological storage of CO_2 from EIIs in Europe is inevitable for reaching the global and European climate change targets. Ratification of the Paris Agreement has meant a further strengthening of these targets as the world attempts to limit warming to 1.5 degrees Celsius, putting even more pressure on the pace and scale of implementation. Cooperative actions between industrials, their host regions and CO_2 storage provinces is required to begin the rational deployment of CO_2 transport and storage infrastructure needed by industry to contribute to deep decarbonisation targets. Isolated and slow development of CO_2 infrastructure is contributing to a growing focus on near term CO_2 use by EIIs, who are facing a growing CO_2 liability risk, but lacking access to large-scale abatement options like storage.

The current focus of EIIs on CO_2 use is also the result of:

- The inability of a single industrial site to individually develop CO_2 transport and storage
- The fact that some form of limited-scale CCU applications may provide commercial opportunities in the short term due to their current high product value
- The prospect of supporting legislation to create wider commercial opportunities for CCU products, regardless of climate or economic performance.

CCU can help to mitigate a small proportion of emissions from sectors that have uses for CO_2 that result in real world full life cycle CO_2 emissions reductions. CCU products that have a high 'Sink Factor', i.e. products that a) do not rapidly rerelease CO_2 to the atmosphere and b) displace the use of a more carbon intensive product, should therefore be supported.
However, even the most climate effective CCU applications will only practically contribute to a minor part of the challenges EIIs face to mitigate their carbon emissions.

Opportunities for CCS

Carbon Capture and Storage is a series of technologies and infrastructure that must operate together. This value chain requires diverse conditions to be met to enable many distinct parties to invest in CO_2 networks and CO_2 capture. These conditions include robust financial models, technological development and commitments to sustained carbon reductions.

Economic and technical feasibility

Changes in industrial processes and products will only happen when economically and technically feasible. The key barrier for implementation of CCS (and many CCU) projects is that they will not result in economically feasible business cases in the current framework. In other words, there is limited or no added value (as sum of the values from profit and/or savings or other perspectives) for the involved companies. The second key barrier is that technologies are often not available at scale, or will benefit from cost reductions only with wider deployment and learning. There is a need for support for innovation in processes and products from government(s) and project developers, and the climate for innovation in the EU must be improved.

Competition

Imports from non- or less-carbon constrained exporters should be subject to appropriate constraints to ensure a level playing field, with a view to encourage vanguard decarbonising industry players. Vanguard low carbon industrial products must demonstrate significant CO_2 reductions whole life cycle, significant scale of deployment and responsible resource use.

Regulation and permitting

Innovation is only possible when there is room, of course within boundaries, to innovate. There is currently very little or no EU support, legislatively or financially, for developing accessible geological CO_2 storage to enable deep industrial decarbonisation. Without prospects for access to storage, industry is in turn unlikely to risk large investment in capture technology at scale, which given CCU market limitations would become stranded assets in the absence of transport and storage infrastructure.

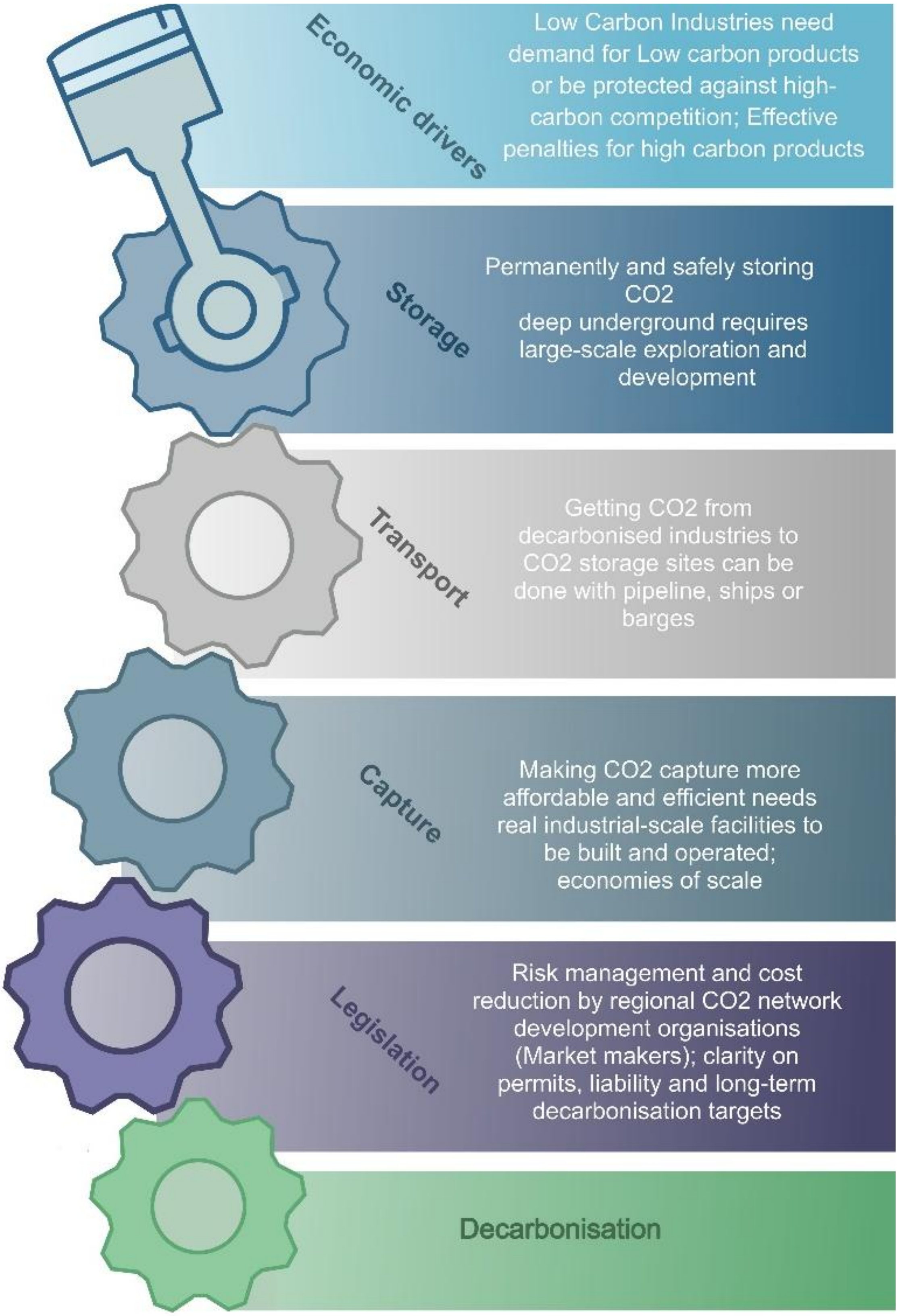


Figure 9 Driver and necessary elements for CCS implementation is EU

5. Policy recommendations

1. EU & Member States' climate policy must be linked to European commitments for climate change mitigation. As public funds for climate action will always be limited, **it is crucial that available funds are spent in a way which has high cost-efficiency**, in a way that **creates markets for solutions with a high impact**, and that can e**nable the achievement of long-term targets**.

2. Likewise, **resources are limited**. This also holds true for renewable energy supply, at least within a relevant time frame for the combat against disastrous climate change. **Climate solutions must therefore be merited not only on their impact in one specific sector, but on the pressure they place on resource use** that could be more efficiently spent in other sectors.

   An example of this is the production of hydrogen for synthetic fossil fuels. Aside from the limited climate impact explained in this report (due to the eventual emission of the CO_2 from a vehicle), **the vast input of renewable electricity required to produce the hydrogen means that policy support to such a process should be merited on its impact on other sectors** – and whether the support undermines market uptake of more efficient uses of the electricity in the sector in question, in this case electromobility. **It is critical that all uses of CO_2 that are considered for policy support mechanisms are judged on their Indicative Sink Factor**, taking into account both the **lifecycle analysis of the carbon** and also the mitigation impact compared to the **counterfactual scenario**.

3. **Policy support for climate measures should above all be merited** – based on best available knowledge when introducing the measures and subject to regular review **– on the role they will be able to play in bringing our economy to net zero emissions and beyond** in the longer term, in line with the Paris Agreement. **Failing to take this into account risks locking in emissions that will be extremely costly or even impossible to deal with later.**

4. Given the uncertainties in projecting future economic activity and unforeseen technology developments, a 100 % accurate answer to exactly how much CO_2 would need to be captured, utilised and stored from EU energy-intensive industries cannot be provided. **Providing EU industry with access to shared infrastructure networks for CO_2 transport and large-scale storage should** however **be seen as a no-regrets option**.

   Such infrastructure enables investment in economic Europe without growing uncertainty about CO_2 liability risk, and it would serve as a **basis for real conversation about deeply decarbonised industrial manufacturing at scale**, and hence as a driver for innovation and rapid cost reductions.

5. **As long as Europe fails to put in place such enabling infrastructure as a public good, industry will inevitably be looking for short-term, commercial opportunities to mitigate some of its CO_2 liabilities** – not mainly from a climate perspective, but for the purpose of retaining economic activity and jobs. **The EU, it's Member States and not least Europe's key industrial regions themselves need to act now to turn real, large-scale climate ambition in industry from being a risk into being an opportunity** for investors and industry.

References

{ BIBLIOGRA
Bazzanella and Ausfelder Low carbon energy and feedstock for the European chemical industry [Report]. - Frankfurt : DECHEMA Gesellschaft für Chemische Technik und Biotechnologie e.V., 2017.
Cameron, van Stralen and Veum Scenarios for offshore wind including spatial interactions and grid issues [Report]. - Amsterdam : SPatial Deployment of offshore WIND Energy in Europe (WINDSPEED), 2011.
Cameron, van Stralen and Veum Scenarios for offshore wind including spatial interactions and grid issues [Report]. - Amsterdam, : SPatial Deployment of offshore WIND Energy in Europe (WINDSPEED), 2011.
Carbontrust Conversion factors guide 2016 [Report]. - [s.l.] : Carbontrust, 2016.
Cefic European chemistry for growth [Report]. - [s.l.] : cefic, 2013.
Cembureau The role of cement in the 2050 low carbon economy [Report]. - Brussels : Cembeau, 2013.
Cembureau The Role of cement in the 2050 low carbon economy [Online]. - cembureau, 2011. - http://lowcarboneconomy.cembureau.eu/index.php?page=where-is-the-sector-now.
cepi Investing in Europe for Industry Transformation [Report]. - [s.l.] : cepi, 2013.
EC COMMISSION REGULATION (EU) No 601/2012 on the monitoring and reporting of greenhouse gas emissions pursuant to Directive 2003/87/EC of the European Parliament and of the Council [Report]. - Brussels : European Commission, 2012.
EC Energy Roadmap 2050 [COM/2011/885] [Report]. - [s.l.] : European Commission, 2011.
Eurofer A steel roadmap for a low carbon europe 2050 [Report]. - Brussels : Eurofer, 2013.
Friedrichsen, and Herbst Prices and costs of EU energy Annex 5 Industrial Case Studies [Report]. - [s.l.] : Ecofys, 2016.
Gibbs, Soyka and Conneely CO_2 Emissions from cement production [Report]. - [s.l.] : Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories , 2000.
Hsiu Yu, Hung Huang and Sung Tan A Review of CO_2 Capture by Absorption and Adsorption [Journal] // Aerosol and Air Quality Research. - 2012. - pp. 745–769.
IEA Energy Technology Perspectives [Report]. - [s.l.] : IEA, 2017.
Laborde Assessing the Land Use Change Consequences of European Biofuel Policies [Report]. - [s.l.] : International Food Policy Institute, 2011.
Mac Dowell [et al.] The role of CO_2 capture and utilization in mitigating climate change [Journal]. - [s.l.] : Nature Climate Change , 2017. - 243–249 : Vol. 7.
Mock and Tietge Road transport in the EU Emissions Trading System: An engineering perspective, [Report]. - [s.l.] : ICCT , 2014.
Moya, Pardo and Mercier Energy Efficiency and CO_2 Emissions: Prospective Scenarios for the Cement Industry [Report]. - [s.l.] : JRC, 2010.
NILSEN Norsk selskap kan bli først i verden til å produsere Audis «vidunderdiesel» [Online] // tu.no. - 10 06 2017. - https://www.tu.no/artikler/norsk-selskap-kan-bli-forst-i-verden-til-a-produsere-audis-vidunderdiesel/348424.
Otto [et al.] Power-to-Steel: Reducing CO_2 through the Integration of Renewable Energy and Hydrogen into the German Steel Industry [Journal]. - [s.l.] : Energies, 2017. - 451 : Vol. 10.
Whiriskey, Helseth Manufacturing Our Future: Industries, European Regions and Climate Action [Report]. - Brussels : Bellona, 2016.
Wortler [et al.] Steel's contribution to a low-carbon Europe 2050 [Report]. - [s.l.] : The Boston Consulting Group and Steel institute VDEh, 2013.
ZEP An Executable Plan for enabling CCS in Europe [Report]. - Brussels : Zero Emissions Platform, 2015.
ZEP Business models for commercial CO_2 transport and storage [Report]. - Brussels : Zero Emissions Platform , 2014.
ZEP Fast Track CO_2 Transport and Storage for Europe [Report]. - Brussels : Zero Emissions Platform, 2017.

Contributors

Name	Country	Organisation
Bruce Adderley	UK	UK CCS Research Centre
Nikki Brain	UK	Carbon Capture and Storage Association
Emrah Durusut	Belgium	Element Energy
Arthur Heberle	Germany	Mitsubishi Hitachi Power Systems Europe
Jonas Helseth	Belgium	Bellona Europe
Nora Lambrecht	Netherlands	HeidelbergCement
Theo Mitchell	UK	
Ana Serdoner	Belgium	Bellona Europe
Rob Van der Meer	Netherlands	HeidelbergCement
Keith Whiriskey	Belgium	Bellona Europe