A method to calculate the positive effects of CCS and CCU on climate change

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Executive Summary

The value of CCS and CCU projects to climate change mitigation is crucial, however, how to assess the added value, to be more exact, is complex. There are many factors that could play a major role, such as which boundary conditions and assumptions to use. Fundamentally, Life Cycle Analyses is the instrument that should be used for these assessments, but the resources and time needed for such analyses are significant. There is need for a methodology for fast checks and comparisons.

In 2017, ZEP published a paper with the so-called Indicative Sink Factor (ISF). That approach was too simple. Now, we are introducing three fundamental characteristics for the classification of technologies for climate change abatement of CCU and CCS projects. Each characteristic has its own Key Performance Indicator:

1. Mitigation effect: CO_2 to the Atmosphere (C2A)
   The objective of climate change mitigation is to prevent or reduce greenhouse gas emissions into the atmosphere. The factor measuring the CO_2 emitted into the atmosphere (C2A) describes the net effect on the atmosphere per tonne of CO_2, intended to be captured and subsequently used or stored permanently. In short: Not all described as CO_2 emissions reductions are in reality CO_2 emissions reductions.

2. Net energy consumption: Net Energy Factor (NEF)
   CO_2 abatement by CCS or CCU cannot, due to thermodynamics, be done in an energy-neutral manner. The net energy factor (NEF) reflects how much extra energy needs to be added to the CCU and CCS technologies compared to the energy needed for the production process alone. The energy use and the linked emissions will be a key driver and limiting factor for CCU (and less for CCS).

3. Implementation period
   Technologies that are available now can already contribute to the climate neutrality ambitions. New technologies and improvements in existing technologies will come and reduce costs and improve the energy efficiency of CCUS in the future. Four periods have been identified to characterise the timeframe to 2050.

This report also includes examples showing the value of this concept. On the basis on these three KPIs, a simple and easy assessment of each technology is possible. The abatement potential of any CCS or CCU technology is dependent on:

1. The source of the CO_2: geological/fossil, biogenetic, atmospheric.

2. The phase to which the CO_2 is being converted: geological storage, short-term living product, long-term living product, fuel, atmosphere, etc.

3. The energy source used for the conversion.

Contents

1. Introduction

How to assess the climate change effects of carbon capture projects? This fundamental question can be answered (and perhaps should be answered) by performing a Life Cycle Analysis, but for a fast assessment, using an LCA will require too many resources. There is a need for a methodology for fast checks and comparisons.

In 2017, ZEP published a paper with the so-called Indicative Sink Factor (ISF). The ISF can be used to identify different types of CCU and CCS projects and their effect on climate change. This simple classification of CCU and CCS technologies in relation to the expected timeframe of the release of the captured CO_2 into the atmosphere, provides clarity on each technology in discussions around climate change abatement tools and policies. This report also highlighted the need for (renewable electrical) energy to decarbonise energy-intensive industries.

The 2017 ZEP report indicated the following policy recommendations:

1. EU and member states' climate policy must be linked to European commitments for climate change mitigation.

2. Climate solutions must also be merited on the pressure they place on resource use that could be more efficiently spent in other sectors.

3. Climate measures should be assessed on the role they will be able to play in bringing our economy to net zero emissions and beyond in the long term.

4. Providing EU industry with access to shared infrastructure networks for CO_2 transport and large-scale storage is a no-regrets option.

5. The EU, its 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.

These ideas put forward in 2017 were too simple and in the meantime several political developments have strengthened the need for a simple and fast "assessment model" for CCU and CCS technologies. For the EU ETS Innovation Fund, the avoided emissions concept, developed by the JRC, is a good instrument for concrete projects. But it doesn't solve the comparison between different technologies as such. It is also interesting that the Technical Expert Group on Taxonomy for Sustainable Finance has refrained from taking a position on the eligibility of CCU projects, given the wide range of types of projects.

Now is the time for an improved concept.

2. Scope and how to measure – Three characteristics

Developments continue: In March 2020, the European Commission proposed the Climate Law with the ambition to reach climate-neutrality by 2050. Discussions on the European Green Deal indicate higher ambitions for the 2030 targets than currently defined (today 40% reduction compared to 2005). The requirement for solutions is urgent, and therefore the need to make the right choice between all available and upcoming solutions becomes more important.

Carbon Capture and geological Storage (CCS) will have to play a major role in the decarbonisation of European society, and especially for the energy-intensive industries. In addition, the (re)use of captured CO_2 emissions – Carbon Capture and Use (CCU) – will become more important, highlighting which positions these technologies will have next to CCS, in the debate on solutions to achieve a climate-neutral Europe. Regardless of the volume of CO_2 to be used for CCS and CCU, some fundamental characteristics for the classification of technologies can be identified:

1. Mitigation effect

The objective of implementing CCU and CCS technologies is to prevent greenhouse gases (GHGs) from being emitted into the atmosphere by sequestering the CO_2 in products or in stable geological formations for a longer period (or even eternity, as is the case for CCS). Technologies with higher mitigation effects should be encouraged above others, and certainly above non-changed production processes without any emissions reduction.

Processes that extract GHGs from the atmosphere, so called Carbon Removals (e.g. biomass, DACs), will have higher mitigation effects than processes in which fossil-based CO_2 is captured and sequestered.

CCUS projects are energy intensive and consequently, depending on the local power supply, (may) cause additional emissions. These have to be integrated into the mitigation effect in order to have a fair comparison. In general, CCS projects will need less electrical energy than CCU projects and depending on the emissions factor of the electrical energy supply, significant differences in the mitigation effect appear.

2. Net energy consumption

CO_2 abatement by CCS or CCU cannot, due to thermodynamics, be done in an energy-neutral manner. On the other hand, synergies between production processes and capture of CO_2 will for some processes result in a much lower energy consumption than the separate processes.

Inevitably, energy is to be added: favourably renewable electrical energy. Each CCU and CCS technology will have its own associated "energy footprint". Choices on feasibility of technologies should take into account the energy footprint and the associated potential GHG emissions.

3. Implementation period

Technologies available now can already contribute to the climate neutrality ambitions, even when they are perhaps not the best from a mitigation effect and/or net energy consumption perspective. Continuous actions are needed in order not to wait for 2049 to do everything. Therefore, the implementation period is a crucial characteristic for any technology assessment. This should be based on the Technical Readiness Levels (TRLs, as defined in reference).

For each of these three characteristics, a Key Performance Indicator (KPI) can be defined. The combination of the three KPIs with the volume of CO_2 that is to be sequestered in any CCU and CCS projects will deliver a positive picture.

It is difficult to give clear numbers about the volumes of CCS and CCU to expect for 2050. However, the BDI-Klimapfade 2018[1], 95% scenario, showing the need to capture and store 93 Mt of CO2 per annum for Germany in 2050. This indicates that the volumes will be significant.

The methodology developed is not taking into account emissions to be reported under the EU ETS Monitoring and Reporting Regulation. The methodology is covering the total amount of emissions to the atmosphere.

[1] Klimapfade für Deutschland, 2018

3. KPI 1: Mitigation expressed as Carbon to Atmosphere Factor

The first KPI to be defined is to characterise the mitigation effect of technologies. This mitigation effect is to be measured in the Carbon to Atmosphere Factor (which as such is an improvement on the Indicative Sink Factor, introduced earlier). The Carbon to Atmosphere Factor (C2A) is intended to support decision makers and project developers to quickly and uniformly derive the emissions abatement potential of CO_2 capture projects in a directly comparable manner. The use of C2A calculation and process allows for a quick, indicative calculation of the climate impact of different combinations of CO_2 capture, use and storage (CCU, CCS and CDR).

It can be derived if a proposed CO_2 capture project will reduce emissions (Climate Mitigation) or remove CO_2 from the atmosphere (Carbon Dioxide Removal). From the perspective of a CO_2 capture project, the C2A will calculate the eventual CO_2 emissions released or removed from the atmosphere and, subsequently, the project's CO_2 emissions reduction. The C2A methodology also takes into account CO_2 replacement in the case of non-permanent CO_2 utilisation, such as if CO_2 is reused from an industrial source to produces a synthetic fuel.

C2A is a first estimation of the net effect to the atmosphere per tonne of CO_2 intended to be captured and subsequently used or stored, resulting in three categories as described in table 1.

Without taking into account emissions from energy production, the C2A will range from -1 to 1. (C2A above 1 means an increase of emissions.)

C2A	Explanation
C2A > 1	The process has increased emission. The capture of a tonne of CO2 has resulted in more than one tonne of CO2 to be added to the atmosphere.
C2A > 0	The process can be characterised as climate mitigating. CO2 emissions to the atmosphere still occur but emissions have been otherwise reduced.
C2A = 0	The process can be characterised as climate neutral, having no additive effect of CO2 to the atmosphere.
C2A < 0	The process removes CO2 from the atmosphere = Carbon Dioxide Removal (CDR)

Table 1 – Carbon to Atmosphere Factors ranges

Calculation

The C2A methodology may be applied to any technical CO_2 capture project, such as CO_2 capture from an industrial point source or direct capture of CO_2 from the atmosphere. The C2A methodology encompasses permanent geological storage and CO_2 use, such as permanent mineralisation of CO_2 and non-permanent storage of CO_2 in fuels.

Calculating the eventual emission or removal of CO_2 to the atmosphere from CO_2 captured and subsequently used or stored requires three functions/factors. The F terms in the formula are fractions (or eventually percentages).

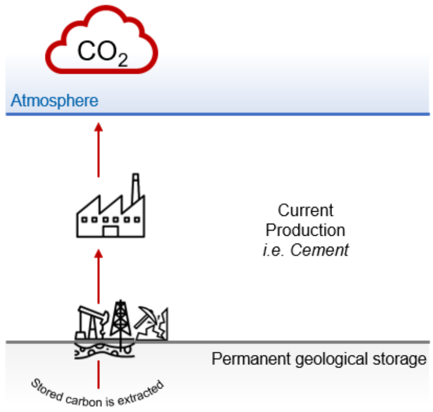
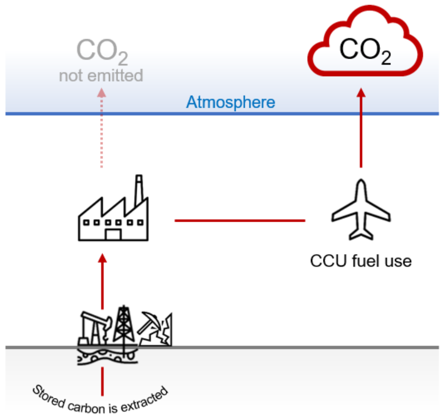
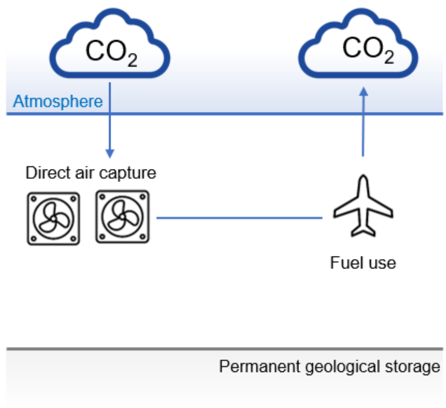
$$C2A = F_{CO2\ source} - (1 - F_{Emitted}) - \left(\frac{F_{Emitted} * F_{CO2\ source} * F_{Re-emitted}}{2}\right)$$

Factor	Explanation	(Theoretical) Examples
$F_{co2\ source}$	The type of CO_2 intended to be captured can be split into two groups: • CO_2 originating from a geological source or; • CO_2 from an atmospheric source. Mixtures are of course possible, e.g. when biomass and fossil fuels are combined. $F_{CO2\ source}$ = Is the carbon to be captured Geological origin Y/N? = Percentage of carbon that is of geological origin	$F_{CO2\ source}$ Geological = 1 Geological CO_2 sources include the majority of CO_2 streams considered for CO_2 capture use or storage. These include CO_2 emissions resulting from traditional fossil fuel combustion, fossil fuel conversion, industrial process emissions such as traditional cement and steel manufacture and fossil derived wastes such as plastic combustion. $F_{CO2\ source}$ Atmospheric = 0 Atmospheric CO_2 sources is CO_2 that originates from the atmospheric system and is not geological in origin. These include processes that capture CO_2 directly from the atmosphere, known as Direct Air Capture. Biological sources of CO_2 are also considered atmospheric in origin, as the biomass grows, CO_2 from the atmosphere is incorporated into the biomass. Upon combustion or conversion of biomass this atmospheric CO_2 is released and can be captured.
$F_{Re\text{-}emitted}$	After CO_2 is captured it may be stored permanently or used in a way that it is stored temporarily before being emitted to the atmosphere. Again, mixtures are possible as not necessarily all CO_2 captured is sequestered permanently. $F_{Re\text{-}emitted}$ = Will the carbon be re-emitted to the atmosphere Y/N? = Percentage of captured CO_2 that will be re-emitted to the atmosphere within a timescale of 100 years	$F_{Re\text{-}emitted}$ Yes = 1 CO_2 will be re-emitted to the atmosphere when it is not permanently stored. Some forms of CO_2 utilisation convert CO_2 into a product that on use will emit CO_2 to the atmosphere. A synthetic aviation fuel, manufactured from CO_2, will on combustion in a plane re-emit this CO_2 to the atmosphere. Uses of CO_2 that will re-emit the CO_2 include all synthetic fuels such as methanol, synthetic gas and aviation fuel. $F_{Re\text{-}emitted}$ No = 0 For CO_2 not to be re-emitted to the atmosphere it must be permanently stored. Permanent storage of CO_2 can be achieved through permanent geological CO_2 storage or though the mineralisation of CO_2 in permanent stable products.
$F_{Emitted}$	$F_{Emitted} = \Sigma CO_2 + F_{Re\text{-}Emitted}$ The application of CCU and CCS technologies will result in additional CO_2 emissions that must be accounted for. Additional emissions are calculated per tonne of CO_2 intended to be captured and subsequently used or stored. Major additional CO_2 sources include emissions from increased energy and electricity use for per tonne of CO_2 capture, conversion or compression. The CO_2 that is not captured as a result of the CO_2 capture rate should also be included. Also, to be included are fugitive emissions during compression and transport. Upstream emissions from feedstocks should also be included, such as the emissions to the atmosphere for the production of biogenetic-based fuels or materials.	$F_{Emitted}$ = ΣCO_2 resulting from capture, conversion, use or storage + $F_{Re\text{-}Emitted}$ ΣCO_2 resulting from capture, conversion, use or storage = the CO_2 emitted, in tonnes per tonne of CO_2 captured, due to fugitive emissions and energy used in the process of capture, transport and storage or conversion

Table 2 – Calculation of C2A including theoretical examples

Examples

The examples below show idealised cases of the combination of different CO_2 sources ($F_{CO2\ source}$) and different CO_2 use or storage ($F_{Re\text{-}Emitted}$). The simple examples provided are "best case" and show minimum C2A that can be achieved for a given combination. The idealised examples in table 3 omit emissions from CO_2 capture, use and conversion.

C2A value	Description	Illustration
C2A = 1	Traditional production process with emissions to the atmosphere. No capture technology is applied. (Other technologies for emissions abatement are not considered.)	
C2A = 0.5 **$F_{CO2\ source}$ = 1** **$F_{Re\text{-}emitted}$ = 1**	Geological CO_2 is captured and converted in a product that when used will emit CO_2 directly into the atmosphere. (Assumed is both 100% capture and no emissions from the additional energy needed.) In practice the C2A will deviate from the 0.5.	
C2A = 0 **$F_{CO2\ source}$ = 0** **$F_{Re\text{-}emitted}$ = 1**	Atmospheric CO_2 is captured and converted in a product that when used will emit CO_2 directly into the atmosphere. (It is assumed that the production of the biogenetic fuel does not result in emissions to the atmosphere.)	

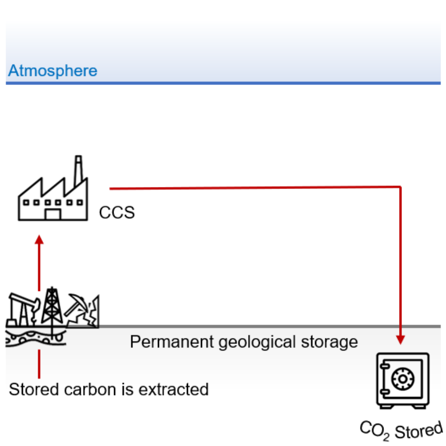
C2A = 0

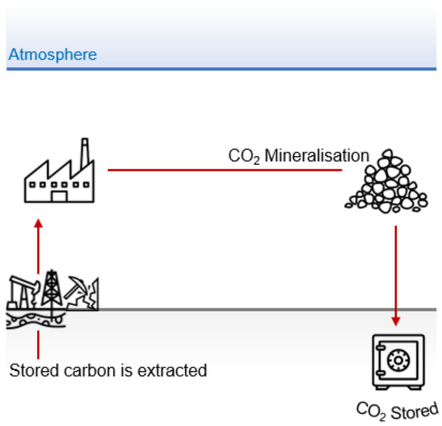
$F_{CO2\ source}$ = 1

$F_{Re\text{-}emitted}$ = 0

Carbon capture in industry followed by geological storage or use as a product with a lifetime above 100 years. (Assumed is both 100% capture and no emissions from the additional energy needed.)

In practice the value of C2A will deviate from 0 due to other emissions, etc.





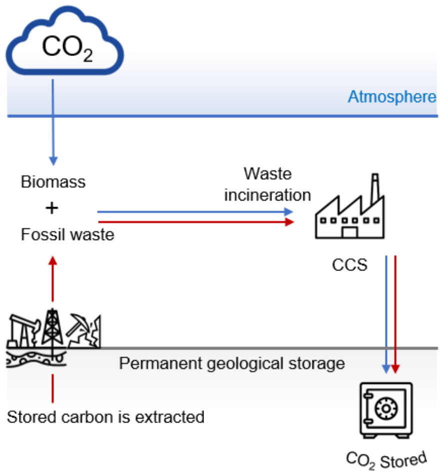
C2A = - 0.5

$F_{CO2\ source}$ = 0.5

$F_{Re\text{-}emitted}$ = 0

Waste incineration with mixed CO_2 source of 50% geological origin and 50% atmospheric origin.

(Assumed 100% capture, no emissions from the additional energy needed and no emissions from biomass waste component.)



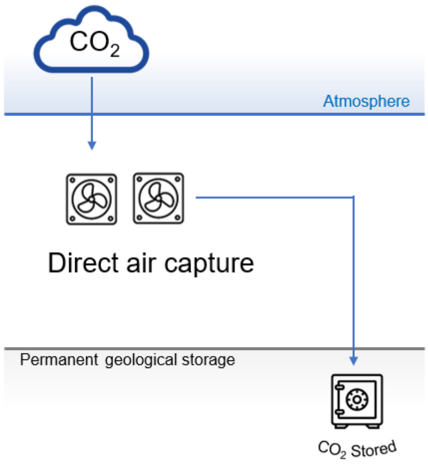
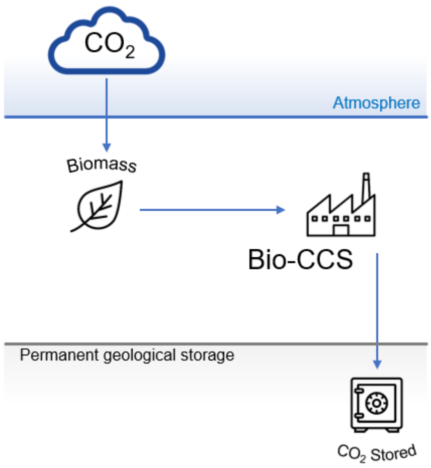
C2A = - 1 $F_{CO2\ source} = 0$ $F_{Re\text{-}emitted} = 0$	Direct Air Capture of CO_2 to permanent storage. (It is assumed that application of DAC does not result in emissions to the atmosphere.)	
C2A = - 1 $F_{CO2\ source} = 0$ $F_{Re\text{-}emitted} = 0$	Biogenetic materials as fuels in combination with long term sequestration (BECCS). (It is assumed that the production of the biogenetic fuel does not result in emissions to the atmosphere.)	

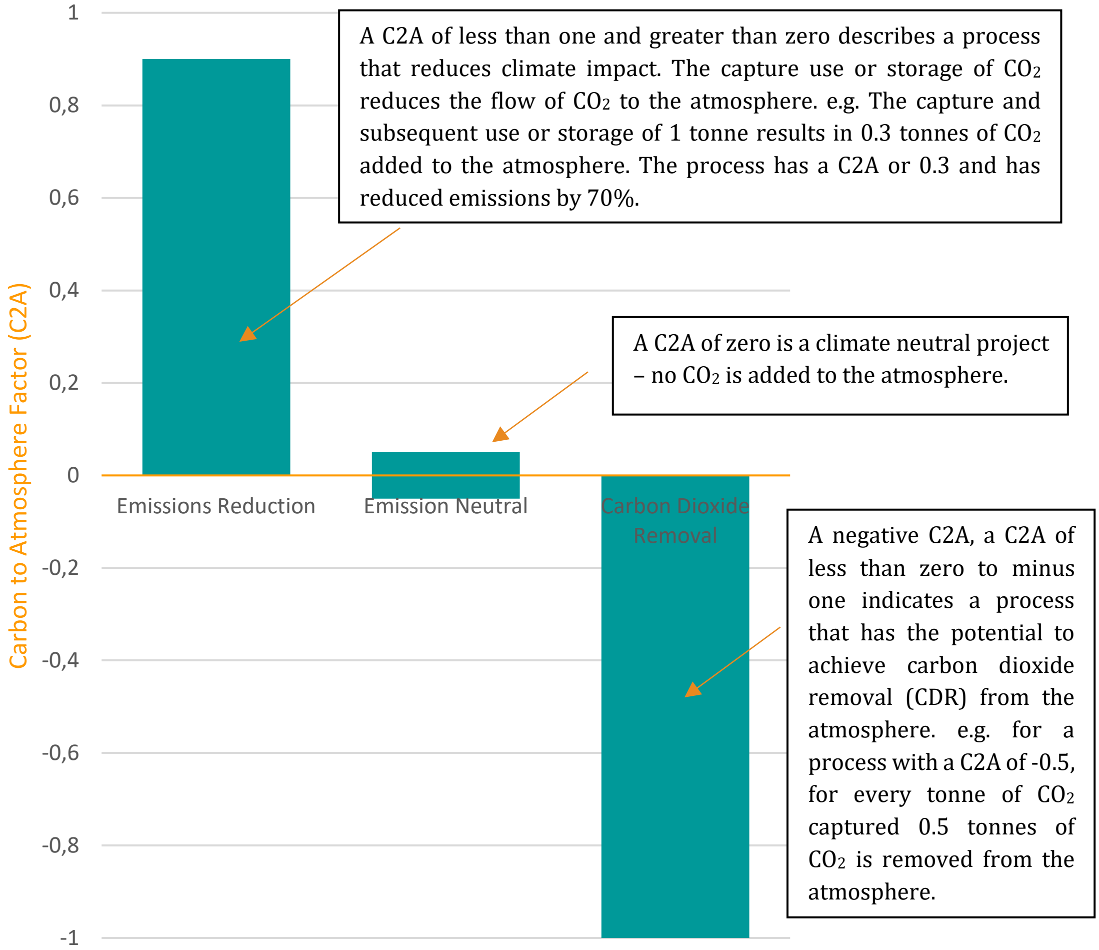
Table 3 – C2A values and graphical illustrations

The simple examples deliver four major categories for the best-case outcomes for the C2A.

C2A categories	Outcome
C2A ≥ 1	• No mitigation or even an increase in emissions
1 < C2A < 0	• Potential for emissions reduction • Traditional energy-intensive process with 100% reuse of the captured CO_2 for new products (e.g. synthetic-fuels)
C2A = 0	• Potential to be carbon neutral • Traditional energy-intensive process with 100% capture and permanent storage of the CO_2 or similar process with net zero carbon emissions to the atmosphere
-1 ≥ C2A < 0	• Potential for Carbon Dioxide Removal (CDR) • Direct Air Capture followed by permanent storage or use of biogenetic based fuels followed by capture and permanent storage • Process with positive climate mitigation effect due to mineralisation and/or geological storage of part of the carbon used • See also the ZEP paper on carbon negative emissions

Table 4 – C2A categories

Figure 1 – C2A categories



In the calculation of the mitigation effect via the C2A, the emissions from energy supply for the process of CCS / CCU assessed are to be taken into account. Also, the emissions to the atmosphere for the production of biogenetic based fuels or materials need to be taken into account.[2]

[2] The C2A methodology is accurate for emissions mitigation and carbon dioxide removal. The methodology can also identify when emissions will increase, that is CO_2 capture and use will result in increased overall CO_2 emissions. However, the C2A methodology should not be used to accurately calculate the magnitude of emission increases.

4. KPI 2: Energy needed expressed as Net Energy Factor

The application of CCU and CCS technologies will normally need additional energy, especially electrical energy. But some of the sources of GHGs can contribute with part of the energy needed.

The net energy needed should be part of the assessment of CCU and CCS technologies. The Net Energy Factor reflects how much extra electrical energy is needed for the CCU and CCS technologies per tonne of CO_2 abated. Energy converted and exported in a useful way, such as energy in synthetic CCU fuel, may be deducted from the overall CCU/CCS energy consumption. The lower the NEF_{CCUS} the greater CO_2 mitigation that can be achieved per unit of electrical energy consumed.

$$NEF_{CCUS} = \frac{ECCUS_{total-}ECCUS_{Exported}}{1-C2A}$$

5. KPI 3: Implementation period in three clusters

The last element of the methodology is the implementation period of technologies. Some of the technologies can be implemented now, while others will need a development time of 20 years (or more) before commercial application is possible. This time implementation period will indicate which “solutions” can already help now (or in a few years’ time) to achieve significant progress, while the implementation of longer-term “solutions” might face some challenges. A technology is considered to be ready for implementation when the Technical Readiness Level of 9 is achieved.

The idea is to have four implementation periods:

A. Before 2030
B. 2030 – 2040
C. 2040 – 2050
D. Beyond 2050

6. Examples, using the KPIs

The examples indicated below in table 5 are more or less theoretical examples based on public available information, which has been one of the conditions for listing in this table. The purpose of the examples is to illustrate the applicability of the concept for the assessment of CCS and CCU technologies, not to compare the results.

		Emissions intensity of electricity (tCO_2/kWh)	C2A (Carbon to Atmosphere)	Emissions Reduction %	NEF_{CCUS} (kWh electrical per tCO_2 mitigated)	TP (Time Period)	Comment
1	Cement CO_2 Capture (without biomass) + permanent CO_2 storage	EU Grid average (0.0003)	**+0.15**	85%	117.43	Now	Emissions reduction
2	Municipal Waste incineration CO_2 Capture + permanent CO_2 storage	EU Grid average (0.0003)	**-0.35**	135%	73.99	Now	CO_2 removed from atmosphere (CDR)
3	Direct Air Capture + CO_2 Use to Synthetic Aviation Fuel (Power to Liquid)	Swedish Grid average (0.0000135)	**+0.42 Swedish grid** **+3.03 EU average grid**	Sweden: 58%	Sweden: 4,942	2030 / 2040	Sweden: Emissions reduction Average Europe: Overall increase in emissions due to CO_2 emissions from electricity use.
4	Direct Air Capture + CO_2 Mineralisation for construction material	EU Grid average (0.0003)	**-0.41**	141%	365.65	2030 / 2040	Carbon Dioxide Removal
5	Cement CO2 Capture + CO_2 to chemicals (methanol)	Swedish Grid average (0.0000135)	**+0.61 Swedish grid** **+1.74 EU average grid**	Sweden: 39%	Sweden: 6,081	2030 / 2040	Sweden: Emissions reduction Average Europe: Overall increase in emissions due to CO_2 emissions from electricity use.

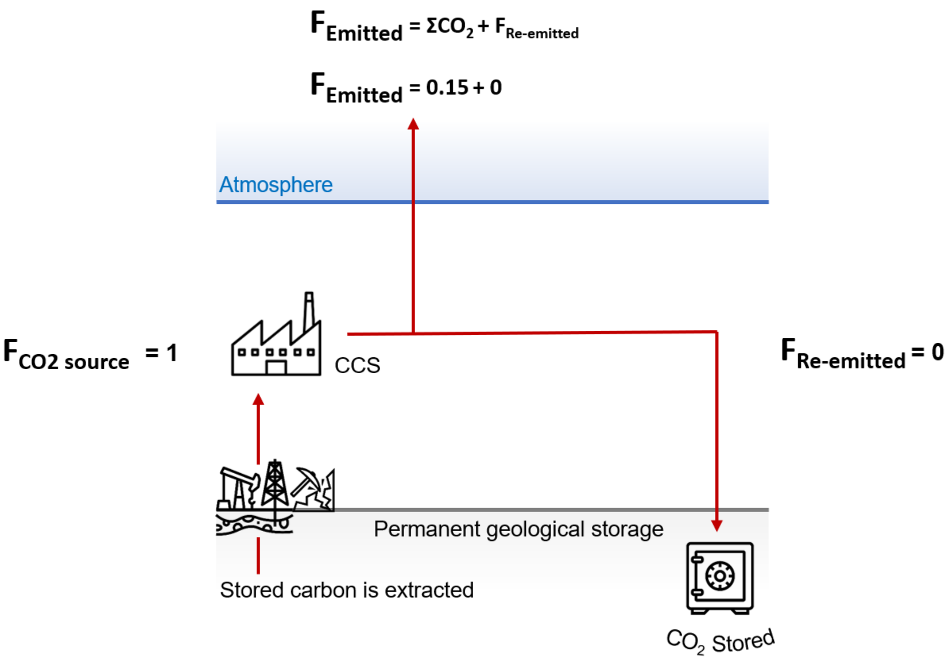
Table 5 – Example of C2A from different CO_2 capture use or storage operations

The positive effects on climate change resulting from the application of any CCS or CCU technology (including Direct Air Capture) are for a major part dependent on the emissions coming from the supply of (electrical) energy. In many countries that supply is far yet from carbon neutrality with the result that application in the short-term of highly (electrical) energy intensive technologies might lead to a net emission increase, rather than decrease, of CO_2 to the atmosphere.

1. Cement CO_2 Capture + permanent CO_2 storage

Capturing all geological emissions from a traditional cement plant and permanently storing them has the potential to be carbon neutral. However, CO_2 capture plants are generally not intended to capture all CO_2 emissions. In addition, energy use and emissions will result from the compression of CO_2 for injection and storage in geological formations.

- This illustrative example of industrial CO_2 capture and storage results in the emission of 0.15t CO_2 to the atmosphere for every tonne of CO_2 intended to be captured from the industrial facility.
- Carbon to Atmosphere **C2A = + 0.15**
- Emissions reduction over no CO_2 capture and storage is 85%.



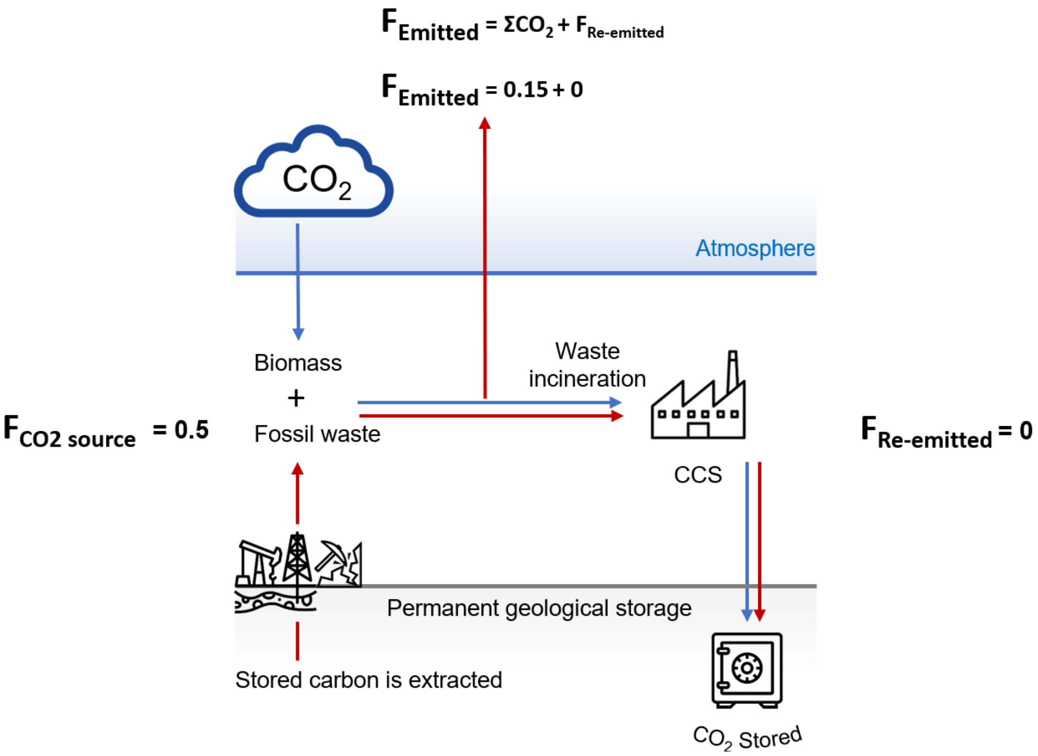
Post Combustion CO_2 Capture + permanent CO_2 storage				**Emitted CO_2 resulting from CO_2 capture & CO_2 storage**	Reference
CO_2 Capture	Capture Rate	0.9		A typical post combustion CO_2 capture unit separates 90% of the CO_2. For every tonne of CO_2 intended to be captured **0.1 tCO_2** is emitted to the atmosphere.	
	Capture Energy (GJ/tCO_2)	3.36	MEA 30wt %	The post combustion CO_2 capture unit requires thermal energy. In this example the heat it is provided by natural gas, resulting in CO_2. 90% of the resulting CO_2 is captured in the CO_2 capture plant. For every tonne of CO_2 intended to be captures ≈ **0.02 tCO_2** is emitted	(Dubois & Thomas, 2018)
	Emissions intensity of energy (tCO_2/GJ)	0.0549	Natural Gas		(VROM, 2005)
CO_2 Compression	Compression Energy ($kWhe/tCO_2$)	100		CO_2 must be compressed to be transported and injected into the geological storage reservoir. Electrical energy is required to power the CO_2 compressor. In this example the use of EU grid average electricity results in ≈ **0.03 tCO_2** emitted.	(Jackson & Brodal, 2019)
	Emissions intensity of electricity (tCO_2/kWh)	0.0003	Electricity EU Average		(EEA, 2018)
Σ CO_2 resulting from CO_2 capture & CO_2 storage				**0.15**	

Cement CO_2 Capture + permanent CO_2 storage				**Comment**
Is the carbon to be captured Geological origin Y/N?				
YES=1	NO=0	**$F_{CO2\ source}$**	**1**	CO_2 from cement kiln. All CO_2 from geological source
Will the carbon be Re-emitted Y/N?				
YES=1	NO=0	**$F_{Re\text{-}emitted}$**	**0**	No CO_2 will be re-emitted. Permanent geological storage
$F_{Emitted} = F_{Re\text{-}Emitted}$ + Σ CO_2 resulting from capture, conversion or storage		**$F_{Emitted}$**	**0.15**	Emissions from CO_2 capture and injection
$C2A = F_{CO2\ source} - (1 - F_{Emitted}) - \left(\frac{F_{Emitted} * F_{CO2\ source} * F_{Re-emitted}}{2}\right)$				
CO_2 added to the atmosphere per tonne of carbon to be captured		**C2A**	**+ 0.15**	Emissions reduction = 85%
KWh electrical consumed per tCO_2 mitigated		NEF_{CCUS}	**117**	
Time period		**TP**	**Now**	

2. Municipal waste incineration CO_2 Capture + permanent CO_2 storage

Municipal solid waste incinerators combust a mix of biogenic and fossil waste resulting in a mixed CO_2 stream. For this illustrative example, we assume 50% of the CO_2 is derived from biogenic and thus atmospheric carbon. This atmospheric CO_2 is a result of degradable organic content such as food, mixed paper and garden waste being combusted in the waste incinerator. The remaining 50% of the CO_2 originates from fossil derived plastics and textiles among other waste. CO_2 is captured and stored from the waste incinerator.

- This example of CO_2 capture and storage from a mixed geological and atmosphere derived CO_2 stream results in carbon dioxide removal from the atmosphere; 0.35 tCO_2 is removed from the atmosphere for every tonne of CO_2 intended to be captured from the waste incineration facility.
- Carbon to Atmosphere **C2A = - 0.35**
- Emissions reduction over no CO_2 capture and storage is 135%.



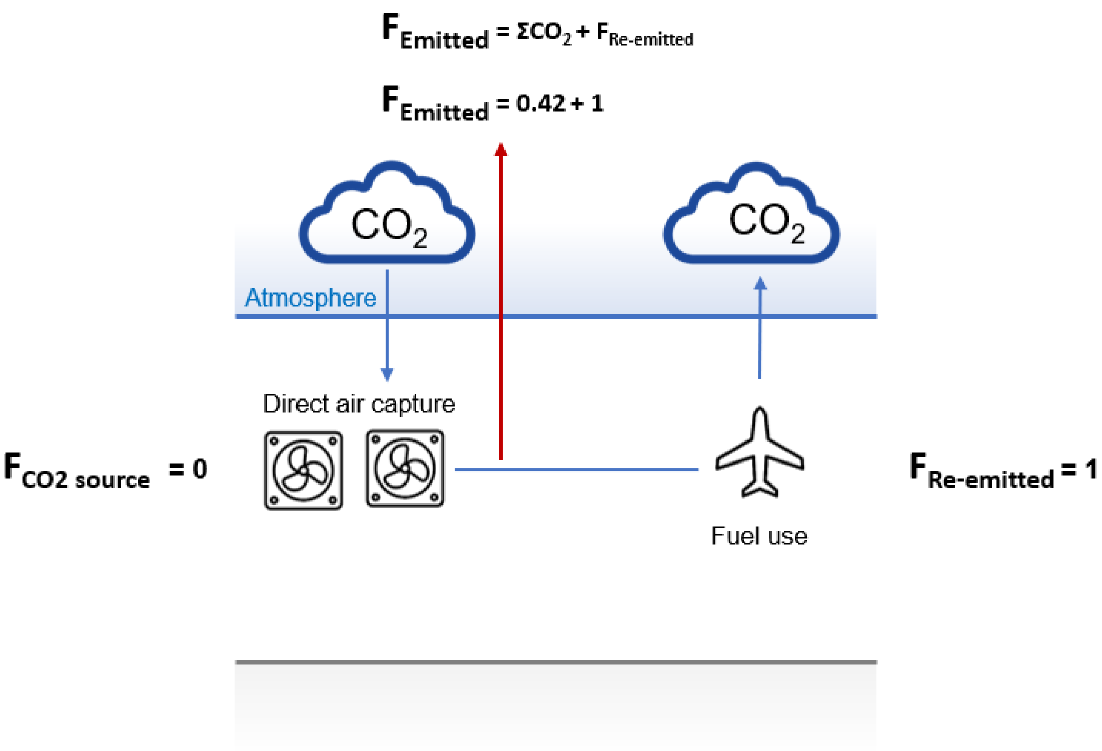
Post Combustion CO_2 Capture + permanent CO_2 storage				**Emitted CO_2 resulting from CO_2 capture & CO_2 storage**	Reference
CO_2 Capture	Capture Rate	0.9		CO_2 not captured is **0.1 tCO_2**	
	Capture Energy (GJ/tCO_2)	3.36	MEA 30wt %	CO_2 not captured from energy use at CO_2 capture plant is ≈ **0.02 tCO_2**	(Dubois & Thomas, 2018)
	Emissions intensity of energy (tCO_2/GJ)	0.0549	Natural Gas		(VROM, 2005)
CO_2 Compression	Compression Energy ($kWhe/tCO_2$)	100		Electricity use for CO_2 compression results in ≈ **0.03 tCO_2** emitted at EU grid average.	(Jackson & Brodal, 2019)
	Emissions intensity of electricity (tCO_2/kWh)	0.0003	Electricity EU Average		(EEA, 2018)
Σ CO2 resulting from CO_2 capture & CO_2 storage				**0.15**	

Municipal waste incineration CO_2 Capture + permanent CO_2 storage				**Comment**
Is the carbon to be captured Geological origin Y/N?				
YES=1	NO=0	$F_{CO2\ source}$	**0.5**	50% of the CO_2 flow is from a geological source (e.g. fossil derived plastics and others)
Will the carbon be Re-emitted Y/N?				
YES=1	NO=0	$F_{Re\text{-}emitted}$	**0**	No CO_2 will be re-emitted. Permanent geological storage of captured CO_2
$F_{Emitted} = F_{Re\text{-}Emitted} + \Sigma\ CO_2$ resulting from capture, conversion or storage		$F_{Emitted}$	**0.15**	Emissions from CO_2 capture and injection
$C2A = F_{CO2\ source} - (1 - F_{Emitted}) - \left(\frac{F_{Emitted} *\ F_{CO2\ source} * F_{Re-emitted}}{2}\right)$				
CO_2 added to the atmosphere per tonne of carbon to be captured		**C2A**	**- 0.35**	Emissions reduction = 135%
KWh electrical consumed per tCO_2 mitigated		NEF_{CCUS}	**74**	
Time period		**TP**	**Now**	

3. Direct Air Capture + CO_2 Use to Synthetic Aviation Fuel (Power to Liquid)

Capturing CO_2 from the atmosphere and using it to produce a synthetic fuel has the potential to be carbon neutral – the same amount of CO_2 removed from the atmosphere will be added when the fuel is combusted. Energy required to capture and convert the atmospheric CO_2 into a fuel will add CO_2 emissions to the process making it less than carbon neutral.

- Both capturing CO_2 from the air and the conversion of CO_2 to a fuel is energy intensive. In this example, the very low carbon electrical energy is used. This results in emissions of 0.42 tCO_2 for every tonne of CO_2 captured from the atmosphere and converted into a fuel.
- Carbon to Atmosphere **C2A = +0.42**
- Emissions reduction is 58%.



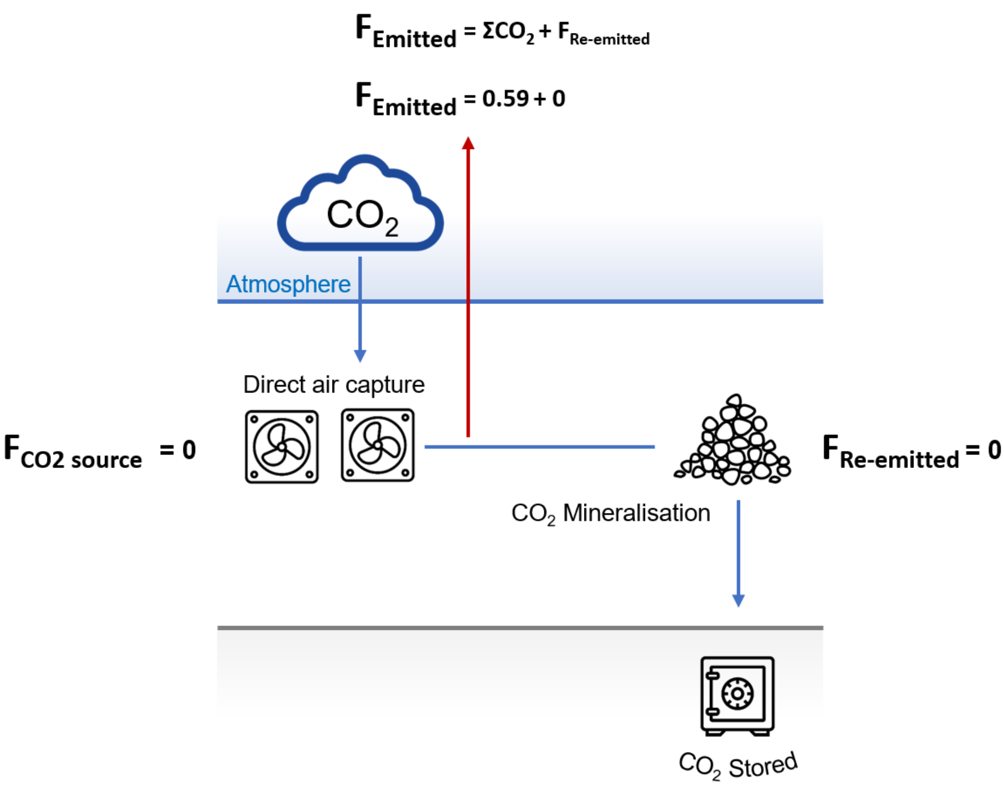
Direct Air Capture + CO_2 Use to Synthetic Aviation Fuel (Zero Carbon Electricity)				Emitted CO_2 resulting from CO_2 capture & CO_2 storage	Reference
Air-Capture	*Capture Energy (thermal)(GJ/tCO₂)*	5.4	Climeworks	Capturing CO_2 from the atmosphere is energy intensive, as the CO_2 is dilute. In this example thermal energy is required to power the direct air capture unit. When this thermal energy is provided by natural gas the capture of 1 tCO_2 results in 0.3 tCO_2 emitted ≈ **0.30 tCO_2**	(Fasihi, Efimova, & Breyer, 2019)
	Emissions intensity of energy (tCO_2/GJ)	0.0549	Natural Gas		(VROM, 2005)
	Capture Energy electrical (kWhe/tCO_2)	200	Climeworks		(Fasihi, Efimova, & Breyer, 2019)
	Emissions intensity of electricity (tCO_2/kWhe)	0.0000135	Electricity Sweden		(EEA, 2018)
Power 2 Liquid	*CO2 to Fuel energy (kWhe/tCO_2)*	8900	Power to Liquid Fuel	The conversion of CO_2 to a synthetic fuel requires electricity. This example uses near zero carbon electricity which results in **≈0.12 tCO2** emitted per tCO_2 converted. Using current EU grid average electricity would increase emissions to approximately 1.59 tCO_2 per tCO_2 converted.	(Shell, 2018)
	Emissions intensity of electricity (tCO_2/kWhe)	0.0000135	Electricity Sweden		(EEA, 2018)
Σ CO_2 resulting from CO_2 air capture & CO_2 conversion to aviation fuel				**0.42**	

Direct Air Capture + CO_2 Use to Synthetic Aviation Fuel				**Comment**
Is the carbon to be captured Geological origin Y/N?				
YES=1	NO=0	**$F_{CO2\ source}$**	**0**	Direct air capture, No CO_2 from geological source
Will the carbon be Re-emitted Y/N?				
YES=1	NO=0	**$F_{Re\text{-}emitted}$**	**1**	All CO_2 will be reemitted on combustion of synthetic fuel
$V_{Emitted} = V_{Re\text{-}Emitted}$ + Σ CO_2 resulting from capture, conversion or storage		**$F_{Emitted}$**	**1.42**	Emissions from CO_2 air-capture and P2L (Power to Liquid) with near zero carbon electricity.
$C2A = V_{CO2\ source} - (1 - V_{Emitted}) - \left(\frac{V_{Emitted} * V_{CO2\ source} * V_{Re-emitted}}{2}\right)$				
CO_2 added to the atmosphere per tonne of carbon to be captured		**C2A**	**0.42**	Emissions reduction = 63%
KWh electrical consumed per tCO_2 mitigated		NEF_{CCUS}	**4,942**	
Time Period		**TP**	**2030-2040**	

4. Direct Air Capture + CO_2 Mineralisation for construction material

Capturing CO_2 from the atmosphere and using it to produce stable construction material (carbonated blocks in this example) through mineralisation (of stainless steel slag in this example) is a carbon dioxide removal (CDR) process – the amount of CO_2 removed from the atmosphere is permanently stored into a product. Energy required to capture and convert the atmospheric CO_2 into the material will add CO_2 emissions to the process.

- This example of direct air capture of CO_2 with permanent storage through mineral carbonation in alkaline materials results in carbon dioxide removal from the atmosphere. 0.41 tCO_2 is removed from the atmosphere for every tonne of CO_2 intended to be captured, mineralised and permanently stored.
- Carbon to Atmosphere **C2A = - 0.41**
- Emissions reduction is 141%.



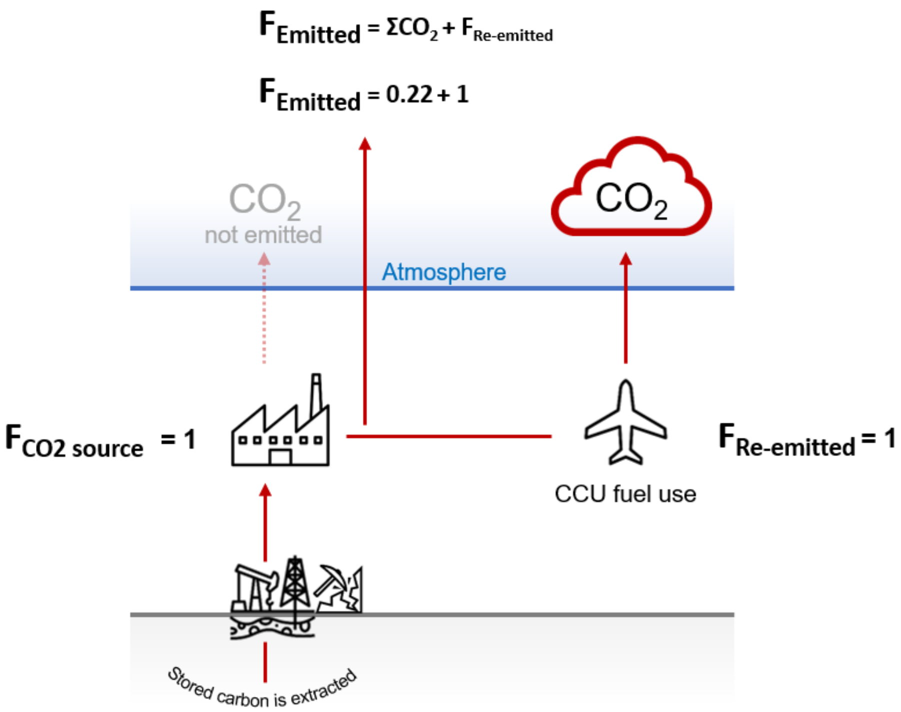
				CO_2 resulting from CO_2 air capture & CO_2 mineralisation	Reference
Air-Capture	*Capture Energy (thermal)(GJ/tCO_2)*	5.4	Climeworks		(Fasihi, Efimova, & Breyer, 2019)
	Emissions intensity of energy (tCO_2/GJ)	0.0549	Natural Gas		(VROM, 2005)
	Capture Energy electrical (kWhe/tCO_2)	200	Climeworks		(Fasihi, Efimova, & Breyer, 2019)
	Emissions intensity of electricity (tCO_2/kWhe)	0.0003	Electricity EU Average		(EEA, 2018)
Mineralisation	*CO2 to carbonated block (thermal) (GJ/tCO_2)*	2.45	From steel slag	Thermal energy is required in the mineralisation of CO_2 with stainless steel slag. Providing this heat via natural gas results in 0.13 t CO_2 emitted per tonne of CO_2 mineralised.	(Maria, Snellings, & Alaerts, 2020)
	Emissions intensity of energy (tCO_2/GJ)	0.0549	Natural Gas		(VROM, 2005)
	CO_2 to carbonated block (electrical) (kWhe/tCO_2)	317	From steel slag	At the current EU grid average electrical energy in CO_2 mineralisation in stainless steel slag emits 0.09 tCO_2 per tonne of CO_2 mineralised.	(Maria, Snellings, & Alaerts, 2020)
	Emissions intensity of electricity (tCO_2/kWhe)	0.0003	Electricity EU Average		(EEA, 2018)
Σ CO_2 resulting from CO_2 air capture & CO_2 mineralisation				**0.59**	

Direct Air Capture + CO_2 Mineralisation				**Comment**
Is the carbon to be captured Geological origin Y/N?				
YES=1	NO=0	$\mathbf{F_{CO2\ source}}$	**0**	Direct air capture, No CO_2 from geological source
Will the carbon be Re-emitted Y/N?				
YES=1	NO=0	$\mathbf{F_{Re\text{-}emitted}}$	**0**	No CO_2 will be re-emitted. Permanent storage into a mineral product
$F_{Emitted} = F_{Re\text{-}Emitted} + \Sigma CO_2$ resulting from capture, conversion or storage		$\mathbf{F_{Emitted}}$	**0.59**	Emissions from CO_2 air-capture and mineralisation
$C2A = F_{CO2\ source} - (1 - F_{Emitted}) - \left(\frac{F_{Emitted} * F_{CO2\ source} * F_{Re-emitted}}{2}\right)$				
CO_2 added to the atmosphere per tonne of carbon to be captured		**C2A**	**-0.41**	Emissions reduction = 141%
KWh electrical consumed per tCO_2 mitigated		NEF_{CCUS}	**365**	
Time Period		**TP**	**2030 – 2040**	

5. Cement CO_2 Capture + CO_2 to chemicals (methanol)

Capturing geological emissions from a traditional cement plant and converting them to methanol has the potential to reduce emission from conventional methanol production and additionally avoids the use of fossil resources for the same amount of product. The C2A methodology automatic accounts for emissions reduction when geological CO_2 is recycled and converted into a fuel or chemical. Energy use and emissions will result from the capture and conversion of the CO_2.

- The conversion of CO_2 to methanol is energy intensive. In this example the very low carbon electrical energy is used.
- Accounting for the reuse of CO_2 and subsequent emission 0.61 tCO_2 are emitted to the atmosphere for every tonne of CO_2 captured.
- Carbon to Atmosphere **C2A = +0.61**
- The overall emissions reduction is 39%[3].



[3] The emissions reduction is shared between the industrial source (e.g. cement plant) capturing emissions and the synthetic methanol product. Allocation of all the emissions to a single party can concentrate the emissions reduction. For example, allocation of all emissions reduction to the methanol product would mean a methanol with 78% reduction. In this no emissions reduction has taken place at the the industrial source (e.g. cement plant).

				CO_2 resulting from CO_2 air capture & CO_2 to methanol	Reference
CO_2 capture	Capture Rate	0.9		CO_2 not captured is **0.1 tCO_2**	
	Capture Energy (GJ/tCO_2)	3.36	MEA 30wt %	CO_2 not captured from energy use at CO_2 capture plant is ≈ **0.02 tCO_2**	(Dubois & Thomas, 2018)
	Emissions intensity of energy (tCO_2/GJ)	0.0549	Natural Gas		(VROM, 2005)
CO_2 to methanol	*CO2 to methanol (electrical, including electrolysis) (kWhe/tCO_2)*	7860	CO_2 to methanol (including hydrogen production)	The conversion of CO_2 to a synthetic methanol requires electricity. This example uses near zero carbon electricity which results in **≈0.11 tCO_2** emitted per tCO_2 converted	(Meunier, Chauvy, Mouhoubi, & Thomas, 2020)
	Emissions intensity of electricity (tCO_2/kWhe)	0.0000135	Electricity Sweden		(EEA, 2018)
Σ CO_2 resulting from CO_2 air capture & CO_2 to methanol				**0.22**	

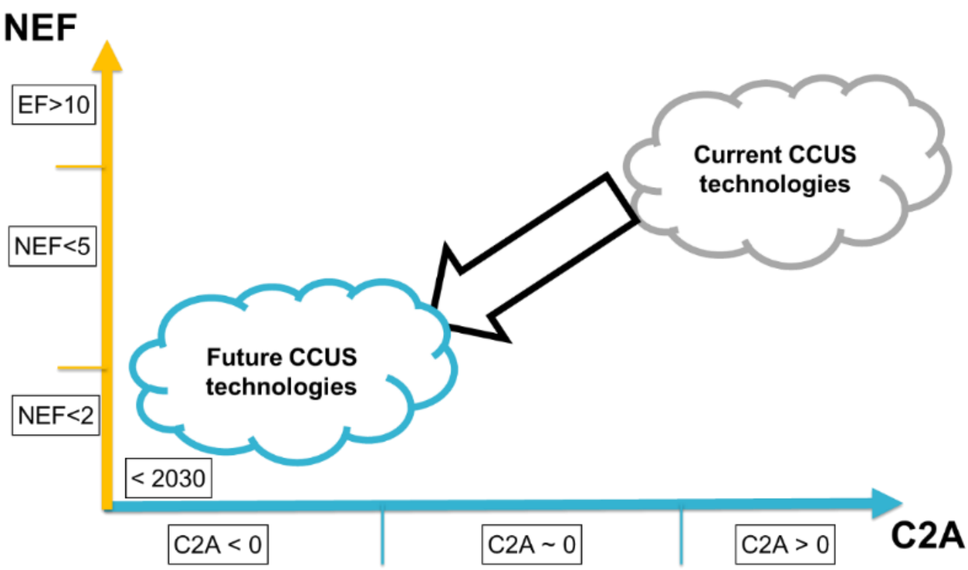
Cement CO_2 capture + CO_2 to methanol				**Comment**
Is the carbon to be captured Geological origin Y/N?				
YES=1	NO=0	**$F_{CO2\ source}$**	**1**	CO_2 from cement kiln. All CO_2 from geological source
Will the carbon be Re-emitted Y/N?				
YES=1	NO=0	**$F_{Re\text{-}emitted}$**	**1**	All CO_2 will be reemitted on combustion of product
$F_{Emitted} = F_{Re\text{-}Emitted} + \Sigma\ CO_2$ resulting from capture, conversion or storage		**$F_{Emitted}$**	**1.22**	Emissions from cement CO_2 capture and CO_2 to methanol synthesis
$C2A = F_{CO2\ source} - (1 - F_{Emitted}) - \left(\frac{F_{Emitted} * F_{CO2\ source} * F_{Re-emitted}}{2}\right)$				
CO_2 added to the atmosphere per tonne of carbon to be captured		**C2A**	**0.61**	
KWh electrical consumed per tCO_2 mitigated		NEF_{CCUS}	**6,080**	
Time Period		**TP**	**2030 – 2040**	

7. Taxonomy

The combination of the two technical KPIs (C2A and EF) plus the time period in which the technology is to be ready for commercial implementation, indicates a development in time of technologies. In the first period, only a few technologies will be commercially available – and this has a high energy penalty. In the later periods many new technologies with better performance and at the same lower Net Energy Factor will appear and take the lead in carbon capture application. In the last period, even the modern technologies will be outdated, and new technologies will appear with even higher performances and NEF. In combination with a continuous reduction of the emissions factor, also for the electricity need, a development will be seen.

What is considered "green" will develop over time

Today, technologies with a C2A even below -50% and a relatively high NEF (> 200%) should be seen as "green". Over time, the C2A factor needed for green projects should increase at the same time as the EF will decrease.



Around 2040, a C2A of -25% in combination with a NEF of 150% could be quite positive for climate change mitigation.

And finally, what will happen after 2050 could be seen as… Science Fiction.

The key message is that from a sustainability perspective, an upward trend over time of the combination of C2A and NEF will be seen and should be recognised in the European Taxonomy for Sustainable Finance.

8. Conclusions

A simple and fast assessment of the positive effects on climate change of CCU and CCS technologies has been developed on the basis of three key performance indicators. The CO_2 to Atmosphere factor indicates for technologies the positive contribution to climate change mitigation in units of CO_2 emissions prevented, reduced or (permanently) sequestered. The Net Energy Factor indicates the additional energy needed for the use of each technology. And the Time Period indicates the timeframe when commercial use is feasible.

The combination of the three factors puts each technology and its implementation in a perspective of others. Each technology will have its own merits, advantages, and disadvantages. The three KPIs combined do not indicate which technology is to be used or not to be used, but creates an overview of all possibilities within a certain timeframe. For example, a high Net Energy Factor might be an advantage when renewable energy supplies are available at irregular times, or a higher CO_2 to Atmosphere factor is currently acceptable as other and better technologies are not available.

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Reference 2 = Indicative Sink Factor paper ZEP 2017
Reference 3 = Carbon negative paper ZEP 2020
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Reference 6 = IEA Energy Technology Perspective
Reference 7 = BDI Klimapfade 2019

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