Technology Collaboration Programme
by iea

Evaluating technology options to mitigate greenhouse gas emissions

IEAGHG Technical Report
2020-14
December 2020

Carbon Capture and Storage and the Sustainable Development Goals

IEA GREENHOUSE GAS R&D PROGRAMME

International Energy Agency

The International Energy Agency (IEA), an autonomous agency, was established in November 1974. Its primary mandate was – and is – two-fold: to promote energy security amongst its member countries through collective response to physical disruptions in oil supply, and provide authoritative research and analysis on ways to ensure reliable, affordable and clean energy for its 30 member countries and beyond. Within its mandate, the IEA created Technology Collaboration Programmes (TCPs) to further facilitate international collaboration on energy related topics. To date, there are 38 TCPs who carry out a wide range of activities on energy technology and related issues.

ACKNOWLEDGEMENTS AND CITATIONS

This report describes research commissioned by TNO on behalf of IEAGHG.

This report was prepared by:

- Tom Mikunda, TNO
- James Rawlins, TNO
- Logan Brunner, TNO
- Eirini Skylogianni, TNO
- Juliana Monteiro, TNO

Special thanks go to Lydia Rycroft and Filip Neele (both TNO) for their inputs and project oversight.

To ensure the quality and technical integrity of the research undertaken by IEAGHG each study is managed by an appointed IEAGHG manager. The report is also reviewed by a panel of independent technical experts before its release.

The IEAGHG manager for this report was: Jasmin Kemper, with additional oversight by Tim Dixon

The expert reviewers for this report were:

- Arthur Lee, Chevron
- Mick Buffier, Glencore
- Peter Morris, Minerals Council of Australia
- Piera Patrizio, Imperial College London
- Wilfried Maas, Shell

The report should be cited in literature as follows:

'IEAGHG, "Carbon Capture and Storage and the Sustainable Development Goals", 2020-14, December 2020.'

Further information or copies of the report can be obtained by contacting IEAGHG at:

IEAGHG, Pure Offices, Cheltenham Office Park
Hatherley Lane, Cheltenham,
GLOS., GL51 6SH, UK

Tel: +44 (0)1242 802911
E-mail: mail@ieaghg.org Internet: www.ieaghg.org

CCS AND THE SUSTAINABLE DEVELOPMENT GOALS

Key Messages

This study has mapped carbon capture and storage (CCS) against a select number of the 17 sustainable development goals (SDGs, see Figure 1 on the next page) that have a direct interaction for both the power and industrial sectors.

- CCS has a number of positive interactions with the SDGs:
  - The considerable potential for CCS to immediately decarbonize both the power and industrial sector means that the deployment of CCS is considered indivisible with actions needed to combat climate change and its impacts (SDG13).
  - CCS plays an enabling role in the provision of reliable, sustainable and modern energy and can support the decarbonisation of industry both through direct emissions reductions but also indirectly through the supply of low carbon power (SDG7).
  - CCS can promote sustained, inclusive and sustainable economic growth, full and productive employment and decent work for all and contribute to a decoupling of economic growth from environmental degradation, through the reduction of CO_2 emissions (SDG8).
  - CCS can also enable sustainable infrastructure developments as well as inclusive and sustainable industrialization, provide a boost to innovation systems, (SDG9), and reduce the carbon footprint of cities to make them more sustainable (SDG11).
  - Through the reduction of CO_2 in the atmosphere, CCS can enable the stabilisation of ocean acidification (a key target of SDG14, i.e. SDG14.3).
- CCS can also have a number of negative interactions with the SDGs:
  - Lifecycle emissions may result in counteracting or constraining interactions with a number of SDGs (3, 6 and 15).
  - In a demand-driven scenario, the energy penalty of CCS means that it can be seen as a constraint on meeting energy efficiency targets (SDG7) but this is only if the assumption that the additional electricity production due to the energy penalty will be supplied by fossil fuels with CCS. In a modern electricity system based on economic generation dispatch (merit order) this may not be the case (see sections on Approach and Limitations for more context).
- Although CCS obtained a variety of scores across the SDG targets in the assessment, for none of the mapped SGDs CCS was seen as 'cancelling', i.e. making it impossible to reach the related SDG and/or sub target.
- A number of limitations apply when using the results of this study for policy development:
  - Availability and comparability of data.
  - Definition of the counterfactual will impact on the results (e.g. demand-driven vs capacity-driven scenario, in the latter most negative impacts of CCS, i.e. the ones related to the energy penalty and the related fuel consumption, will not materialise).
  - Construction and use of all low-emission technologies will have various environmental, economic and social impacts, i.e. evaluation of trade-offs in isolation will likely have limited value for policy development and selection of pathways.
- Several knowledge gaps were identified and recommendations for further work include:
  - Additional lifecycle assessments (LCAs) of 2nd generation CCS technologies and CCS in industry (especially in terms of water and energy efficiency gains).
  - More studies on the macroeconomic impact of CCS in different regions.
  - Research on the employment aspects of CCS compared to other low-emission technologies.
  - Investigation of the role of certain CCS technologies for carbon dioxide removal (CDR), i.e. bioenergy with CCS (BECCS) and direct air capture with CCS (DACS).

Background to the Study

A few months prior to the Paris Agreement, in September 2015 'Transforming our World: the 2030 Agenda for Sustainable Development' was adopted by the United Nations General Assembly. This resolution, consisting of 17 Sustainable Development Goals (SDGs), covering a wide range of human development areas and broader environmental sustainability issues, is a follow-up to the Millennium Development Goals. Both the Paris Agreement, and the 2030 Agenda, although negotiated under different multilateral processes, are considerably interlinked. The Paris Agreement emphasises the need for sustainable development considerations in low-emissions transitions; at the same time combatting climate change is one of the 17 SDGs.

Figure 1 The 17 Sustainable Development Goals (SDGs)

However, not all climate actions may be compatible with the SDGs, and vice-versa. Policy makers may be faced with strategic choices where insights into climate-development interactions are essential for successful development and implementation of policies and targets that serve both agendas. The IPCC's Special Report on 1.5°C (SR1.5) has made an initial assessment on the synergies and trade-offs between mitigation options and sustainable development, including CCS use in the energy supply and industrial sectors.

The Special Report recognised that CCS plays an important role in all deep decarbonisation scenarios. In terms of synergies with the SDGs, it was stated that CCS can contribute to the provision of advanced and cleaner fossil fuel technology, in line with the targets of SDG7 on 'affordable and clean energy'. The deployment of CCS can also contribute to industrial development, innovation and the provision of resilient infrastructure (SDG9). However a number of trade-offs were highlighted, particularly the potential for increased coal consumption, due to the lower efficiency of CCS-equipped coal-fired power plants (SDG12 'responsible consumption and production'), possible risks of carbon dioxide leakage from geological storage and CO_2 transport infrastructure (SDG3 'good health and well-being'), and the associated price impacts affecting energy access and poverty due to the costs of investing in CCS (SDGs 1 'no poverty', and 7 'affordable and clean energy').

The IPCC assessment represents a useful first insight on the interaction of CCS with the SDGs. The review, however, does appear to place the focus on CCS use with coal-fired power plants, which could mean that SDG interactions of CCS on gas-fired power plants, or in the broad range of other potential industrial applications, have been overlooked. Furthermore, for a number of SDGs no assessment was feasible as no relevant public literature could be identified. Since the adoption of the 2030 Agenda, a number of mapping exercises have been completed to assess the interaction between key energy-related sectors and technologies and the SDGs. However, a dedicated, in-depth assessment can further help to support and complement the findings of the IPCC.

Scope of Work

The overall objective of this assessment was to improve the availability and accessibility of information regarding the relevance of CCS in contributing to the achievement of the Sustainable Development Goals. The primary objective was achieved through the completion of three key goals:

1. Collation of existing information on impacts of CCS on specific targets of the 17 SDGs, using the rating, scoring and information assessment as per IPCC's SR1.5,
2. Articulation of specific gaps in information, and
3. Proposal of a path forward by providing a prioritised lists of gap closures.

There is a growing body of literature orientated towards converting climate action into policies directed towards implementation of SDGs. There is also a trend of material becoming available examining the interaction of technologies and sectors against SDGs. CCS remains a complex technological solution to climate change, and public understanding of the technology remains low. This study can help to substantiate the wider value of CCS, but it can also highlight points of attention/action on potentially negative interactions with specific SDGs.

TNO (Netherlands Organisation for Applied Scientific Research) has been the contractor for this study.

Approach

There is no set approach nor methodology for assessing the interaction of sectors and technologies with the SDGs. It is therefore a significant challenge to link the complex and precise characteristics of CCS with the broad nature of the SDGs, even with consideration given to the 169 associated targets. An approach has been taken to focus this assessment on the interactions of CCS and SDGs where credible and quantifiable evidence is available. Taking this approach has meant a distinction had to be made between SDGs considered to have a direct potential interaction with CCS, and those considered to have indirect or limited interaction. This report captures only the SDGs that have a direct interaction with CCS.

By pre-identifying the potential direct, indirect and limited impacts of CCS, the methodology has been streamlined and the risk of subjectivity in the assessment reduced. An overview of the outcome of this pre-identification process is provided in Table 1.

Table 1 Pre-identification of direct and indirect interactions between CCS and SDGs

Direct interaction	Indirect interaction	Limited interaction foreseen
3. Good health and wellbeing	1. No poverty	2. Zero hunger
6. Clean water and sanitation	4. Quality education	5. Gender equality
7. Affordable and clean energy		10. Reduced inequalities
8. Decent work and economic growth		16. Peace, justice and strong institutions
9. Industry, innovation and infrastructure		17. Partnerships for the goals
11. Sustainable cities and communities		
12. Responsible consumption and production		
13. Climate action		
14. Life below water		
15. Life on land		

The pre-identification process allows each of the three different SDG groupings to be treated differently during the evidence collection stage. Each of the direct interactions are subjected to a thorough literature review. Literature used to identify evidence of potential interactions between CCS and SDGs included:

- Peer-reviewed and non-peer reviewed scientific journal articles
- Official national and international governmental documents
- Other types of grey literature[1]
- Relevant IEAGHG documents
- Use of the Ambition to Action SCAN-tool[2]

As a first step, the International Council for Science has developed a tool, or framework, whereby "interactions between SDGs and targets are classified on a seven-point ordinal scale, indicating the nature of the interaction with other targets, and the extent to which the relationship is positive or negative to help policymakers identify and test development pathways that minimize negative interactions and enhance positive ones"[3]. The seven possible types of interactions (indivisible, reinforcing, enabling, consistent, constraining, counteraction, cancelling – ranging from +3 to -3) can be applied at any level among goals and targets, to individual policies or to actions. Commonly known as 'the Nilsson score' (based on the author, see Table 2), its application allows the generation of comparable and robust outcomes. The Nilsson score is the most developed system for assessing SDG interactions, and it has also been applied for the assessment in Chapter 5 of the IPCC's Special Report on 1.5°C. For these reasons, the Nilsson score has also been adopted for use in this assessment.

[1] Grey literature is materials and research produced by organizations outside of the traditional commercial or academic publishing and distribution channels, i.e. it mainly refers to non-peer-reviewed documents.
[2] The SDG Climate Action Nexus tool (SCAN-tool) is designed to provide high-level guidance on how climate actions can impact achievement of the Sustainable Development Goals (SDGs). https://ambitiontoaction.net/scan_tool/
[3] Griggs, et al. 2017

Table 2 Scoring for the interactions between SDGs as proposed by Nilsson et al.[4]

Interaction Score	Name	Explanation
+3	Indivisible	Inextricably linked to the achievement of another goal.
+2	Reinforcing	Aids the achievement of another goal.
+1	Enabling	Creates conditions that further another goal.
0	Consistent	No significant positive or negative interactions.
-1	Constraining	Limits options on another goal.
-2	Counteracting	Clashes with another goal.
-3	Cancelling	Makes it impossible to reach another goal.

When CCS is integrated into a power plant system, the production of 1 kWh electricity will carry the energy burden of the additional CCS process. The additional energy requirement would need to be satisfied with additional fuel, the supply chain of which is associated with waste and emissions, leading to negative impacts to the environment. Therefore, the production of 1 kWh electricity with CCS will have higher environmental impacts than without CCS. This applies under the premise that the power plants' electricity generation is demand-driven, and not capacity-driven. In a capacity-driven scenario, the addition of CCS does not lead to increased fuel consumption but rather to a decreased electricity output, implying similar environmental impacts as in the case of unabated power production. In a capacity-driven scenario, there is indeed limited and even positive influence on the environmental indicators, while in a demand-driven scenario, which is adopted in this study, there are negative environmental impacts.

It should be noted that defining a suitable counterfactual situation upon which to make this assessment has a major impact on the outcome. Based on the 'with' and 'without' CCS-scenarios, CCS is treated as an additional industrial activity which subsequently compares unfavourably because of the additional energy requirement and the associated emissions, despite considerable CO_2 emission reductions. To further understand the limitations that the chosen framework poses, one could consider also the ancillary services offered by deployment of CCS, such as maintaining system's frequency and reserving capacity for unexpected demand increases and disturbances, which are not available from renewables. This contribution for CCS technologies is not depicted on its scoring against the SDGs.

Nineteen life-cycle assessments were used as reference in this study and all of them considered coal as fuel. In the power sector, half of the LCAs also considered natural gas-fired plants, while three out of the total five studies in industrial sectors assumed use of natural gas for the additional energy requirements of CCS. Only one LCA included another fuel for power generation, i.e. wood. The

[4] Nilsson, Griggs and Visbeck 2016

environmental impacts can vary significantly depending on the fuel and technology used and coal-fired power plants are better represented in this study than the others.

Finally, this study has taken a global perspective regarding the interactions between CCS and SDGs. However, it is important to bear in mind that conducting an LCA requires inputs that are country- and region-dependent, such the material supply chains and CO_2 pipeline distance, and that specific characteristics, for example industrial development, may significantly differ between sectors, regions and countries.

Limitations and Caveats

When using the results of this study, it is important to be aware of a number of limitations and caveats of the assessment, which especially apply to the applicability and transferability of the results in policy development and policy recommendations:

- Findings presented in this overview are highly summarised. For more details and context the reader is advised to check the full report.
- General applicability of the Nilsson score for assessments of technologies against SDGs (it was originally used to assess SDGs against one another).
- Availability and comparability of data, especially LCA studies (The environmental impacts can vary significantly depending on the fuel and technology used and coal-fired power plants are better represented in this study than natural gas fired ones or others due to data availability. In addition, this study has taken a global perspective regarding the interactions between CCS and SDGs. However, LCAs are usually based on inputs that are country-, region- or sector-specific.).
- Definition of the counterfactual will have a major impact on the outcome (Approach used here: CCS is treated as an additional industrial activity which subsequently compares unfavourably because of the additional energy requirement and the associated emissions, despite considerable CO_2 emission reductions. To further understand the limitations that the chosen framework poses, one could consider also the ancillary services offered by deployment of CCS which are not available from renewables. This contribution for CCS technologies is not depicted on its scoring against the SDGs).
- Question regarding the weighting of the SDG scores. It might be acceptable to have impacts on health, economy and environment if it is perceived that they will be outweighed by large reductions in CO_2 emissions.
- Construction and use of all low carbon technologies will have various environmental, economic and social impacts.
- Evaluating trade-offs in isolation is likely to have limited value for policy development.
- Caution is urged in the use of isolated SDG technology assessments for the development of policies which directly influence the selection of carbon abatement pathways.
- Periodic replication of SDG mappings is likely to be warranted, as technologies mature and new technologies emerge.

Findings

This section presents the results of the literature review for the direct interactions between CCS and the SDGs. Each SDG is covered separately in a subsection on a designated page. The tables present the scoring assessment and the estimation of a Nilsson score for each relevant target, including a comment on the confidence of the scoring, based on the amount of literature found, and the extent of agreement between the different literature sources.

<u>Note: A condensed, simplified summary of the information provided in the following assessments can be found in the "Conclusions" section of this paper.</u>

SDG 3 – Good health and wellbeing

Table 3 SDG3 assessment overview

SDG Targets[5]	Summary of literature findings	Score	Confidence	References
3.4 Reduce premature mortality from diseases & 3.9 Reduce deaths from pollution	**Power Sector:** Increased HTP[6] in almost all cases across multiple technologies and fuel types. Large range of increases and some inconsistency over what drives the increase. Oxy-fuel and calcium looping generally perform better for HTP than MEA[7]. For PM[8] formation and POCP[9], results are mixed, with both net increases and decreases, depending on capture technology and fuel source.	-2	High Multiple sources Good agreement	(Cuéllar-Franca & Azapagic, 2015) (Oreggioni, et al., 2017) (Petrescu, Bonalumi, Valenti, Cormos, & Cormos, 2017) (IEAGHG, 2010) (Tzanidakis, Oxley, Cockerill, & ApSimon, 2013)
	Industrial Sector: Increased HTP, PM formation and PCOP are reported for MEA. For calcium looping, increases and decreases are reported for PM and POCP. Also, mixed effects on HTP depending on the fuel. Options with coal worse than other energy sources.	+2 -2	Medium Few sources Limited agreement	(Volkart, Bauer, & Boulet, 2013) (Chisalita, et al., 2019) (Schakel, et al., 2018) (Rolfe, et al., 2018)

[5] For the purpose of readability, the SGD targets in the overview tables have been shortened. The full description of every target as adopted by member states can be found in the main report and on the UN's SDG website: https://sustainabledevelopment.un.org/topics/sustainabledevelopmentgoals

[6] Human toxicity potential

[7] Monoethanolamine

[8] Particulate matter

[9] Photochemical ozone creation potential

SDG6 – Clean water and sanitation

Table 4 SDG6 assessment overview

SDG Target	Summary of literature findings	Score	Confidence	References
6.3 Improve water quality by reducing pollution.	**Power Sector:** The parasitic energy load of CO_2 capture installations reduces plant efficiency and therefore increases upstream environmental impacts due to increased mining/gas extraction. The non-CO_2 emissions, chemical use and waste stream can also impact the freshwater ecotoxicity.	-2	High Multiple literature sources Good agreement	**Power Sector** (Cuéllar-Franca and Azapagic 2015) (Oreggioni, et al., 2017) (Ou et al. 2016); (Singh et al. 2011) (Hylkema and Read 2012) (International CCS Knowledge Centre 2018) **Industrial Sector** (Rubin, Davison and Herzog 2015) (Hayward and Graham 2017) (Brouwer, van den Broek, Zappa, Turkenburg, & Faaij, 2016)
	Industrial Sector: CO_2 capture plants in the industrial sector will lead to additional energy use and potentially greater upstream environmental impacts associated with coal mining. Natural gas and biomass use lead to decreased environmental impacts in systems with waste heat recovery. Some industrial processes in the chemical/refining sector may involve less energy intensive CO_2 capture processes, reducing the environmental impacts.	+2 -2	Low Few sources of literature Good agreement	
6.4 Substantially increase water-use efficiency	**Power Sector:** CO_2 capture installations could considerably increase both total water withdrawal and consumption by fossil-fuel power plants. Water is needed for flue-gas cooling prior to capture, solvent make-up, and compression processes. However, recent designs for post-combustion CCS power plants suggest additional water demand can be met by use of water that has been condensed from the flue gas prior to entering the absorber.	0	High Multiple literature sources Conflicts present	
	Industrial Sector: Water use is expected to increase for industrial applications of CO_2 capture utilising amine-based post-combustion capture systems. Pre-combustion systems using water-gas shift technologies will also lead to greater water use.	-1	Low Few sources of literature Limited agreement	

SDG7 – Affordable and clean energy

Table 5 SDG7 assessment overview

SDG Target	Summary of literature findings	Score	Confidence	References
7.1 Ensure universal access to affordable, reliable and modern energy services.	**Power Sector:** Fossil-fuel power generation sources play an important role in the provision of modern power services in many nations. Adding CCS to coal or gas-fired power plant will increase the LCOE[10], to the detriment of affordability. However, the integration of all low carbon power sources, including IRES[11], will increase the total cost of power supply. A combination of natural gas with CCS and IRES could result in the most cost-efficient decarbonised power system.	+1	High Multiple literature sources Good agreement	**Power Sector** (Rubin, Davison and Herzog 2015) (Hayward and Graham 2017) (Brouwer, van den Broek, Zappa, Turkenburg, & Faaij, 2016) **Industrial Sector** (UNIDO, 2010) (Volkart, Bauer and Boulet 2013)
	Industrial Sector: CCS in the power sector has the potential to indirectly reduce the carbon intensity of industrial production through the provision of low carbon power. CCS in the power sector also enables the provision of dispatchable and reliable power supply for industry.	+1	High Multiple literature sources Good agreement	
7.3 Double the global rate of improvement in energy efficiency.	**Power Sector:** Adding CCS to any power or industrial installation will lead to an inherent energy penalty, which is a direct trade-off with the climate benefits to be achieved. Particularly for post-combustion CO_2 capture, the heat required for the regeneration of amine-based solvents can reduce the overall efficiency of the power plant by as much as 25% for coal-fired power plants, and 20% for gas-fired power plants.	-2	High Multiple literature sources Good agreement	
	Industrial Sector: As in the power sector, particularly post-combustion capture applications in industry can have a negative impact on the energy efficiency of processes. Some industrial processes may be less effected than others.	-1	Medium Limited literature sources Good agreement	

[10] Levelised cost of electricity
[11] Intermittent renewable energy sources

SDG8 – Decent work and economic growth

Table 6 SDG8 assessment overview

SDG Target	Summary of literature findings	Score	Confidence	References
8.1 Sustain per capita economic growth in accordance with national circumstances.	**Power Sector:** CCS deployment will likely have some impact on GDP[12] though (limited) scenario studies have shown this to be relatively small. At the sector level, impacts are more pronounced with fossil fuel related sectors benefitting from CCS, and losses in sectors with displaced activity. Effects also likely to vary between country depending on their economic dependence on fossil fuel use and exports.	+1 -1	Medium Limited studies but general agreement	(Fankhauser, Sehlleier and Stern 2008) (PBL, 2011) (Scottish Enterprise, 2011) (Koelbl, et al., 2015) (Cambridge Econometrics, 2013) (Capros, et al., 2014) (Ou et al. 2016) (Koornneef et al. 2014) (Størset, Tangen, Wolfgang, & Sand, 2018)
	Industrial Sector: No direct literature. Industrial CCS likely to have some impacts on industrial costs, demand, international trade. Hard to predict direction or magnitude of net effect.	Not scored		
8.2 Achieve higher levels of economic productivity through diversification, technological upgrading and innovation.	**Power Sector:** CCS will likely impact economic productivity. On the negative side, the energy penalty will negatively impact productivity; while for some countries there may be substantial commercial opportunities from developing CCS and gaining export market share.	+2 -1	Medium No direct literature about productivity effects, but literature available on energy penalty, commercial opportunities and investment in CCS innovation.	
	Industrial Sector: CCS will likely impact economic productivity. On the negative side, the energy penalty will negatively impact productivity; while for some countries there may be substantial commercial opportunities from developing CCS and gaining export market share.	+1 -1	Low No direct literature on productivity effects. Findings for power CCS seem applicable to industry.	
8.4 Improve global resource efficiency in consumption and production and endeavour to decouple economic growth from environmental degradation.	**Power Sector:** Resource efficiency: negatively affected by CCS energy penalty; potential benefits from optimising use of current fossil fuel infrastructure and avoiding stranded (resource intensive) assets. Decoupling: positive support for decoupling of carbon emissions from economic growth; but negative impact through increased environmental impacts.	+2 -2	Medium confidence Ample evidence and good agreement for energy penalty, GHG[13] reduction and other environmental indicators	
	Industrial Sector: Resource efficiency: negatively affected by CCS energy penalty. Decoupling: positive support for decoupling of carbon emissions from economic growth; but negative impact through increased environmental impacts.	+2 -2	Medium Limited evidence for industry CCS energy penalty, GHG reduction and environmental impacts	
8.5	**Power Sector:** CCS likely to have some impact on employment levels, but (limited) studies suggest these are not large at the net, macro level. As with GDP there will be	+2	Medium	

[12] Gross domestic product
[13] Greenhouse gas

SDG Target	Summary of literature findings	Score	Confidence	References
Achieve full and productive employment and decent work for all.	more pronounced effects between sectors, and the net impact for countries will be influenced by their dependence on fossil fuel extraction and use. For specific countries able to develop and export CCS technology and services, job creation may be far higher.	-1	Limited studies but general agreement	
	Industrial Sector: No direct literature. Industrial CCS likely to have some impacts on industrial costs, demand, international trade, and thus employment. Hard to predict direction or magnitude of net effect. Some (limited) additional jobs to install and run CCS industry.	Not scored		

SDG9 – Industry, innovation and infrastructure

Table 7 SDG9 assessment overview

SDG Target	Summary of literature findings	Score	Confidence	References
9.1 Develop quality, reliable, sustainable and resilient infrastructure	CCS is sustainable from a GHG perspective but leads to worse performance on other environmental indicators and reduces energy efficiency. CCS could support economic growth in fossil fuel dependent countries or countries with competitive advantage in CCS development.	+1 -1	High confidence on 'sustainability findings' Low confidence about impact on economic growth	(Cuéllar-Franca and Azapagic 2015) (Vergragt, Markusson and Karlsson 2011) (Markusson, 2012) (Turner, Race, Alabi, & Low, 2018) (Koelbl, et al., 2015)
9.2 Promote inclusive and sustainable industrialization	CCS is sustainable from a GHG perspective but leads to worse performance on other environmental indicators and reduces energy efficiency. Unclear whether CCS can support increased industrial share of GDP / employment, primary sectors may benefit more.	+1 -1	High confidence on 'sustainability findings' Low confidence on industry share impact	
9.4 Upgrade infrastructure and retrofit industries to make them sustainable	CCS is sustainable from a GHG perspective but leads to worse performance on other environmental indicators and reduces energy efficiency.	+1 -1	High	
9.5 Enhance scientific research and upgrade the technological capabilities of industrial sectors in all countries	CCS development could help enhance research and boost innovation activity (although not realistic for many countries). Deployment of CCS would support aim to upgrade technological capabilities.	+1	Low	

SDG11 – Sustainable cities and communities

Table 8 SDG11 assessment overview

SDG Target	Summary of literature findings	Score	Confidence	References
11.6 Reduce the adverse per capita environmental impact of cities	CCS reduces the GHG emissions from power and industrial products used by cities, but leads to worse performance on other environmental indicators. Municipal solid waste has the potential to become a zero or even negative emissions energy source via waste-to-energy with CCS.	+2 -2	High Multiple sources and good agreement	(Cuéllar-Franca and Azapagic 2015) (Volkart, Bauer and Boulet 2013) (Global CCS Institute, 2019)

SDG12 – Responsible consumption and production

Table 9 SDG12 assessment overview

SDG Target	Summary of literature findings	Score	Confidence	References
12.2 Achieve the sustainable management and efficient use of natural resources.	CCS requires more energy to operate, as well as increasing the material demand to implement the carbon capture system, reducing the efficiency of the plant. For power plants with CCS, the efficiency is about 20-25% less than for power plants without CCS. This efficiency fluctuates depending on the plant type and capture technology. The materials required for a fossil fuel plant with CCS are about double than those required for a fossil fuel plant without CCS. Water usage increases significantly with the implementation of CCS.	-1	High Several LCAs mention the decrease in efficiency, increase in materials, and increase in water usage.	(Rubin, Davison and Herzog 2015) (Pehnt and Henkel 2009) (Hertwich, et al., 2015) (Odeh and Cockerill 2008) (Arasto, Tsupari, Kärki, Pisilä, & Sorsamäki, 2013) (Fan, et al., 2018)
12.4 Achieve the environment ally sound management of chemicals and all wastes.	CCS draws on water resources, as well as increases the waste stream due to the capture system and cooling requirements[14]. Reductions in greenhouse gas emissions would range from about 75 – 90% for fossil fuel plants and 39 – 78% for cement or steel plants[15].	+2 -2	High Well documented water usage and waste increase. Consensus on reduction in CO_2 emissions.	
12.5 Substantially reduce waste generation	The deployment of CCS would increase the generated waste, due to the carbon capture process. This differs depending on the plant type and the capture technology, but includes NO_x, NH_3, ash, sulphur, and spent sorbent residue.	-2	Medium Several studies, but highly variable depending on the system.	
12.6 Encourage companies to adopt sustainable practices.	CCS would make it possible for power and industrial plants to reduce CO_2 emissions to meet emission goals. For industrial CCS, could enable continuing production while reducing greenhouse gases.	+2	Low No specific literature on encouraging companies to implement CCS. Some overlap with subsidy studies.	
12.c Rationalize inefficient fossil-fuel subsidies.	Power CCS: Subsidies would help the deployment of power CCS, since the implementation of a CCS system is not economically profitable. The effect of the subsidy is contingent on the CO_2 price as well.	+1	Medium Few studies on analysis of fossil fuel subsides. The few referenced do support CCS subsidies.	

[14] Under SDG 6, it has already been discussed that the increased water requirements can potentially be managed.
[15]There are no technical barriers to increasing capture rates in power plants beyond 90%, with a modest increase in LCOE and CO_2 avoidance cost (IEAGHG Technical Report 2019-02). Similar findings apply to some industrial processes as well.

SDG 13 – Climate action

Table 10 SDG13 assessment overview

SDG Target	Summary of literature findings	Score	Confidence	References
13.1 Strengthen resilience and adaptive capacity to climate-related hazards and natural disasters	Although CCS does not contribute to resilience or climate adaptation directly, it allows the rapid decarbonisation of power and industrial sectors to reduce the reliance on adaptation measures.	+3	High Multiple literature sources Good agreement	(IPCC, 2018) (IPCC, 2014) (IEA, 2017) (IEA, 2011) (UNIDO, 2010) (Rubin, Davison , & Herzog, 2015) (Kearns, et al., 2016)
13.2 Integrate climate change measures into national policies, strategies and planning	CCS offers policy makers the ability to integrate carbon abatement strategies into industrial development and power sector developments. CCS can be applied to key industrial processes which have few alternatives to reduce emissions and are needed for basic building materials. IPCC analysis indicates that without CCS, the goals of the UNFCCC Paris Agreement will not be reached.	+3	High Multiple literature sources Good agreement	
13.3 Improve education and awareness-raising on climate change mitigation	There is evidence that the majority of large scale CCS demonstration projects involve dedicated local public outreach plans. There is also evidence of CCS educational resources being developed for use in schools.	+2	Medium Some literature sources Good agreement	

SDG 14 – Life below water

Table 11 SDG14 assessment overview

SDG Target	Summary of literature findings	Score	Confidence	References
14.1 Reduce marine pollution	**Power Sector:** The additional cleaning of flue-gases from coal-fired power plants via FGD[16] prior to post-combustion CO_2 capture will also remove other pollutants such as hydrogen fluoride, improving the net environmental performance with regards to marine ecotoxicity.	+1 -1	Medium Few literature sources Some agreement	(Koornneef, van Keulen, Faaij, & Turkenburg, 2008) (Nie, Korre, & Durucan, 2011) (Singh, Stromman, & Hertwich, 2011) (ECO2, 2015) (Rolfe, et al., 2018) (Chisalita, et al., 2019)
14.1 Reduce marine pollution	**Industrial Sector:** Impact on marine ecotoxicity will be dependent on the composition of the flue gas from the industrial source, and the type of capture system.	-2	Low Limited literature Good agreement	
14.2 Sustainably manage and protect marine and coastal ecosystems	**Power and Industrial Sector:** Through international marine treaties, there are regulatory frameworks in place to manage the geological storage of CO_2 in sub-seabed formations. Experience with offshore CO_2 storage sites do not show signs of leakage, despite extensive monitoring. Environmental impacts of CO_2 transport and storage infrastructure development are associated with minimal seabed disturbance and noise.	0	High Significant literature Good agreement	
14.3 Minimize and address the impacts of ocean acidification	**Power Sector:** CCS has the potential to remove large amounts of CO_2 from the atmosphere, storing it in geological traps where it cannot reach the atmosphere or oceans. CCS can therefore contribute to the long-term stability of ocean pH.	+2	High Significant literature Good agreement	
14.3 Minimize and address the impacts of ocean acidification	**Industrial Sector:** CCS can be applied to multiple industrial sectors, with the potential to reduce emissions significantly.	+2	High Significant literature Good agreement	

[16] Flue gas desulphurisation

SDG 15 – Life on land

Table 12 SDG15 assessment overview

SDG Target	Summary of literature findings	Score	Confidence	References
15.1 Sustainable use of terrestrial and inland freshwater ecosystems	LCAs show that the water requirement for power and industrial plants with CCS can be between 32% and 93% higher than the plant without CCS[17]. The indicators that address this target are GWP[18] and POCP, as they affect the conservation of life on land. GWP is reduced significantly for power and industrial plants with CCS, while POCP is generally expected to increase with CCS, though results are mixed for this target (also depending on the capture method). In addition, CCS deployment might reduce the need for other land-intensive low carbon measures (e.g. wind parks, afforestation, hydropower projects).	+2 -2	High Significant literature Moderate agreement	(Cuéllar-Franca and Azapagic 2015) (Corsten, Ramirez, Shen, Koornneef, & Faaij, 2013) (García-Gusano, Garraín, Herrera, Cabal, & Lechón, 2015) (Rolfe, et al., 2018) (Schakel, et al., 2018) (Chisalita, et al., 2019)
15.5 Reduce the degradation of natural habitats	For this target, relevant indicators from the LCAs are EP[19], AP[20], FAETP[21] and TETP[22]. Each of these rose in general in the case of CCS for both power and industrial plants. There were some counterarguments that TETP would be lower with CCS, as some toxins in the air might be removed instead in the water discharge, thus impacting more the FAETP. For oxyfuel combustion capture, an analysis of LCAs found that the AP and EP would be lower since HF and acidic emissions are reduced.	-2	High Significant literature Moderate agreement	

[17] Under SDG 6, it has already been discussed that the increased water requirements can potentially be managed.
[18] Global warming potential
[19] Eutrophication potential
[20] Acidification potential
[21] Freshwater aquatic ecotoxicity potential
[22] Terrestrial ecotoxicity potential

Conclusions

When evaluated against the SDGs, there are a number of areas which appear challenging for CCS as a technology. Capturing CO_2 from the power and industrial processes has to be considered as a significant supplementary industrial activity which can have impacts on a range of environmental media. The use of chemical sorbents in conventional post-combustion capture systems, in particular, tends to score negatively in all life-cycle analyses referenced in this assessment. The majority of life-cycle assessments indicate emissions to air and water and the production of wastes through the use of CCS. These emissions result in the technology having counteracting or constraining interactions with SDGs 3, 6 and 15, which have a strong focus on reduction of any form of discharges to the environment. The technology could also be considered as constraining in meeting energy efficiency targets of SDG 7, due to the inherent energy penalty associated with operating CO_2 capture systems. However, those negative impacts related to the energy penalty only apply in a demand-driven scenario and would not materialise if there is societal consensus that the increased fuel demand will not be made up by fossil energy sources. An important finding of this study is that CCS did not score a -3, indicating a cancelling interaction, against any of the SDGs covered in this assessment.

CCS also has a number of positive interactions with the SDGs. Global modelling assessments from both the IPCC and IEA indicate that the significant deployment of CCS is indivisible in combating climate change (SDG 13), in line with the goals of the UNFCCC Paris Agreement. CCS plays an enabling role in the provision of reliable, sustainable and modern energy and can support the decarbonisation of industry both through direct emissions reductions but also indirectly through the supply of low – emission power (SDG 7). Evidence has been found that CCS can promote sustained, inclusive and sustainable economic growth, full and productive employment and decent work and contribute to a decoupling of economic growth from environmental degradation, through the reduction of CO_2 emissions (SDG 8). CCS can also enable sustainable infrastructure developments, provide a boost to innovation systems (SDG 9), and reduce the carbon footprint of cities to make them more sustainable (SDG 11). Through the reduction of CO_2 in the atmosphere, CCS can enable the stabilisation of ocean acidification, a key target of SDG 14. In contrast to the IPCC Special Report 1.5°C, no evidence of leakage to the marine environment could be found, and CO_2 storage appears to be adequately regulated in many parts of the world through extensive marine treaties.

The divergent nature of many of the individual targets that are encompassed in each of the SDGs, has meant that assigning a single Nilsson score to each SDG is not possible. For example, where CCS can be considered enabling for target 9.2 'Promoting inclusive and sustainable industrialization…', it is at the same time counteracting to target 9.4 which includes 'increased resource-use efficiency', due to the associated energy penalty of the majority of CCS applications. Where possible, the scoring across targets has been aggregated to provide an overall score at SGD level (see Table 13). SDG 14 can be considered an example of this. Table 14 provides a comparison between the scoring outcomes of this study and the IPCC's SR1.5.

Table 13 Summary table of key findings, Nilsson normative scores and confidence rating per SDG. Upper row of each assessment refers to interaction with CCS in the power sector, and lower row the interaction with industry. NB: scores cannot be combined

SDG	Findings from literature	Nilsson score	Confidence	Selected references
3 GOOD HEALTH AND WELL-BEING	Life-cycle assessments (LCA) indicate increase in human toxicity potential (HTP) through the use of amine solvents. Particulate matter (PM) reduction on-site is offset by additional upstream emissions. New capture technologies could help to reduce the environmental impacts of CO_2 capture, however these have yet to be implemented.	-2 Counteracting	High	(Cuéllar-Franca and Azapagic 2015) (Oreggioni, et al. 2017) (Petrescu, et al. 2017) (IEAGHG 2010) (Tzanidakis, et al. 2013)
	Fewer sources available for industrial sector assessments, but those available point towards to both negative and positive human health impacts (HTP, PM, PCOP) depending on capture technology and fuel.	+2 Reinforcing / -2 Counteracting	Medium	(Volkart, Bauer and Boulet 2013) (Chisalita, et al. 2019) (Schakel, et al. 2018) (Rolfe, et al. 2018)
6 CLEAN WATER AND SANITATION	LCA literature indicate that fresh water aquatic ecotoxicity potential (FAETP) and eutrophication potential (EP) will increase due to amine use and reduced efficiency of capture plants. Reclaiming water from flue gases does allows water consumption to be minimised when using CCS.	0 Consistent / -2 Counteracting	High	(Cuéllar-Franca and Azapagic 2015) (Oreggioni, et al. 2017) (Ou et al. 2016); (Singh et al. 2011) (Hylkema and Read 2012) (International CCS Knowledge Centre 2018)
	Industrial application of post-combustion CCS with MEA or calcium looping shows increased FAETP and EP with coal, and decreased EP with natural gas and biomass. Water use is expected to increase for some industrial applications. Literature limited.	+2 Reinforcing / -2 Counteracting	Low	(Bosoaga, Masek and Oakey 2009) (Volkart, Bauer and Boulet 2013) (Schakel, et al. 2018)
7 AFFORDABLE AND CLEAN ENERGY	Modelling scenarios suggest that CCS has an important role to play in delivering the lowest cost decarbonised power systems. Generally speaking, however, CCS plants are associated with a lower energy efficiency.	+1 Enabling / -2 Counteracting	High	(Rubin, Davison and Herzog 2015) (Hayward and Graham 2017) (Brouwer, et al. 2016)
	CCS in the power sector can indirectly reduce emissions from industry through the provision of low carbon power. Direct application of CCS in industry has a negative impact on energy efficiency.	+1 Enabling / -1 Constraining	Medium	(UNIDO 2010) (Volkart, Bauer and Boulet 2013)

8 DECENT WORK AND ECONOMIC GROWTH	The impact of CCS on work and economic growth will vary per sector and country. At sector level, positive impacts are associated with fossil fuel related sectors. CCS can also provide more jobs and allow more jobs to be retained. The net employment effects of CCS vs. alternative energy sectors are unclear. CCS can contribute to decoupling economic growth from environmental degradation, however reduced energy efficiency is observed.	+2 Reinforcing / -1 Constraining	Medium	(Fankhauser, Sehlleier and Stern 2008) (PBL 2011); (Scottish Enterprise 2011) (Koelbl, et al. 2015); (Cambridge Econometrics 2013) (Capros, et al. 2014); (Ou et al. 2016) (Koornneef et al. 2014) (Størset, Tangen en Wolfgang, et al. 2018)
9 INDUSTRY, INNOVATION AND INFRASTRUCTURE	CCS can contribute to creating decarbonised industrial sectors. CCS can prevent the risk of stranded assets through the retrofitting of CO2 capture, and can support innovation in industrial processes and infrastructure. However, CCS may hinder the realisation of resource efficiency targets and its environmental impacts should be reduced.	+1 Enabling / -1 Constraining	Medium	(Cuéllar-Franca and Azapagic 2015) (Vergragt, Markusson and Karlsson 2011) (Markusson, 2012) (Turner, et al. 2018) (Koelbl, et al. 2015)
11 SUSTAINABLE CITIES AND COMMUNITIES	CCS reduces the CO_2 emissions from power and industrial products by between 60-80%, improving the carbon footprint of cities. CCS can improve local air quality around industrial sites. Many capture technologies are associated with negative impacts on other environmental indicators reducing its sustainability score. Municipal solid waste has the potential to become a zero or even negative emissions energy source via waste-to-energy with CCS.	+2 Reinforcing / -2 Counteracting	High	(Cuéllar-Franca and Azapagic 2015) (Volkart, Bauer and Boulet 2013) (Global CCS Institute 2019)
12 RESPONSIBLE CONSUMPTION AND PRODUCTION	CCS is a positive way for companies to adopt responsible practices to maintain industrial production, while reducing CO_2 emissions. The use of CCS does, however, lead to increased energy consumption and there is production of waste from the capture process.	+2 Reinforcing / -2 Counteracting	Medium	(Rubin, Davison and Herzog 2015) (Pehnt and Henkel 2009) (Hertwich, et al. 2015) (Odeh and Cockerill 2008) (Arasto, et al. 2013) (Fan, et al. 2018)

13 CLIMATE ACTION	CO_2 capture can reduce up to 90% of emissions from coal and gas-fired power plants, as well as key industrial processes. Global modelling assessments utilised by the IPCC clearly indicate that the broad deployment of CCS is unavoidable in order to limit human-induced global warming to 2 degrees by 2050. The greater the delay in reducing global GHG emissions, the greater the dependence will be on CCS, and also bio-energy combined with CCS (BECCS). Regional and global assessments indicate that sufficient geological storage capacity is available.	+3 Indivisible	High	(IPCC 2018) (IPCC 2014) (IEA 2017) (IEA 2011) (UNIDO 2010) (Rubin, Davison and Herzog 2015) (Kearns, et al. 2016)
14 LIFE BELOW WATER	The additional cleaning of flue-gases from coal-fired power plants via flue gas desulphurisation (FGD) prior to post-combustion CO_2 capture may also inadvertently remove other pollutants, improving the net environmental performance with regards to marine ecotoxicity. Increased FAETP is reported for both cement and steel sectors, though the literature is very limited. There is no evidence of CO_2 leakage to the marine environment at currently operating CO_2 storage sites. CCS can therefore contribute to the long-term stability of ocean pH.	+2 Reinforcing / -2 Counteracting	High	(Koornneef, van Keulen, et al. 2008) (Nie, Korre and Durucan 2011) (Singh, Stromman and Hertwich 2011) (ECO2 2015) (Rolfe, et al. 2018) (Chisalita, et al. 2019)
15 LIFE ON LAND	The Global Warming Potential is reduced significantly for power and industrial plants with CCS, contributing greatly to the protection of natural habitats and ecosystems. LCA literature indicate that fresh water aquatic ecotoxicity potential (FAETP) and eutrophication potential (EP) will increase due to amine use and reduced efficiency of capture plants. Some studies on oxyfuel indicate reduced EP and Acidification due to the removal of acidic emissions during CO_2 capture.	+2 Reinforcing / -2 Counteracting	Medium	(Cuéllar-Franca and Azapagic 2015) (Corsten, et al. 2013) (García-Gusano, et al. 2015) (Rolfe, et al. 2018) (Schakel, et al. 2018) (Chisalita, et al. 2019)

Table 14 Comparison of findings between IPCC Special Report 1.5°C (IPCC 2018) and this study completed by TNO. NB: the normative scores for individual SDG areas cannot be combined.

		3 Good Health and Well-Being		6 Clean Water and Sanitation		7 Affordable and Clean Energy		8 Decent Work and Economic Growth		9 Industry, Innovation and Infrastructure		11 Sustainable Cities and Communities		12 Responsible Consumption and Production		13 Climate Action		14 Life Below Water		15 Life on Land	
		IPCC	TNO	IPCC	TNO	IPCC	TNO	IPCC	TNO	IPCC	TNO	IPCC	TNO	IPCC	TNO	IPCC	TNO	IPCC	TNO	IPCC	TNO
Theme	**Technology**																				
Industry	Energy efficiency	+2		+2/-1		+2		+1		+1		+2		+1		-		-		-	
	Low carbon fuel switch	+2		+2/-2		+2		+2		+2		+2		+2		-		-		+1/-1	
	CCS/CCU	-1	+2/-2	+1/-1	+2/-2	+2/-2	+1/-1	+2	+2/-1	+2	+1/-1	-	+2/-2	+2	+2/-2	-	+3	-1	+2/-2	-	+2/-2
Replacing coal	Non-biomass renewables	+2		+2/-2		+3		0		0/-1		+2		+2		-		+2/-1		-1	
	Increased biomass	+2		+1/-2		+3		+1		+1		-		+2		-		-		+1/-2	
	(Advanced) Nuclear	-1		+2/-1		+1		+1		-1		-		-		-		-		-1	
	Coal co-fired with biofuels (Bio-CCS)	+2/-1		+1/-2		+2		+1		+1		-		+1		-		-		+1/-2	
	Coal fired plus CCS	-1	-2	+1/-2	0/-2	+2	+1/-2	-1	+2/-1	+1	+1/-1	-	+2/-2	-	+2/-2	-	+3	-	+2/-2	-	+2/-2

Identified Knowledge Gaps

The study identified several knowledge gaps and further research is required in the following areas to increase the confidence of mapping exercises for CCS against the SDGs:

- Conducting additional life-cycle assessments of 'second-generation' CO_2 capture technologies, with particular attention given to novel capture techniques expected to be able to compete with incumbent technologies.
- Conducting life-cycle assessments of CCS applied to key industrial processes, including evaluations of water usage and energy efficiency.
- More consistent and clear reporting of where in the life-cycle particular environmental impacts occur, and clearer sensitivity analysis to show how important certain assumptions are.
- Conducting studies examining the macroeconomic impacts of CCS in different regions, for example between developed and developing nations, and between fossil-fuel exporters and importers.
- Completing employment studies of CCS versus other low carbon alternatives, which could have greater value than studies which look at these impacts in isolation.
- The role of CCS for CDR either through BECCS or DACCS (which were out of the scope for this study) and the specific interactions of these negative emissions technologies (NETs) with the SDGs.

Expert Review Comments

Seven experts from academia, industry, NGOs and IGOs provided comments on the report and/or the overview. As the scoring with colours used in this study could be perceived as oversimplified, more contextualisation was recommended, e.g. through:

- Additional scoring of CCS against SDG 13 – Climate action. CCS was scored as +3 indivisible. Approach and concluding sections have been adjusted to account for SDG 13 inclusion.
- Comparing the scoring of CCS with the scoring of the other mitigation options in SR1.5. Annex 1 was added, including the themes where CCS was covered by the IPCC work and the findings of TNO. A reference to Annex 1 was added to the relevant section in the report
- Benefits of CCS in the energy mix regarding economic growth could be drawn out more in SDG8 – Decent work and economic growth. Two new recent references from employment in Norway, and innovation investments in Norway[23] were included and the overall scoring of SDG 8 has been increased from a +1/-1 to a +2/-1.
- One reviewer queried the description of the findings for SDG7.1 ('Ensure universal access to affordable, reliable and modern energy services'), noting the impact an implicit carbon price would have on the LCOE. The LCOE discussion in the main report presents numbers for coal and gas fired power plants but did not include the external costs of emitting CO_2 (i.e. impact on the environment), or possible regulatory measures such as emission quotas or taxes on emitting CO_2 in this calculation. However, the report acknowledges such measures would increase the LCOE from unabated fossil-fuel, closing the gap between CCS and non-CCS power production. It is also acknowledged that CCS on coal and gas-fired power plants can have comparable LCOE to IRES when accounting for additional infrastructure (e.g. battery storage, gas fired

[23] Storset et al., 2018:2019

peaking plants). Furthermore, the total system costs of reaching a decarbonised power system are expected to be higher in the absence of CCS. The methodology used in this study does not reflect a total system cost approach, similar to the SDG mapping in SR1.5. This approach is not widely used yet, and we acknowledge this as a shortcoming, which will be addressed more in other existing (e.g. 2017-09 and 2020-08) and future IEAGHG reports.

- Two reviewers raised concerns regarding the selection of the counterfactual scenario. We acknowledge the conflict between a demand-driven and a capacity-driven scenario. This study selected a demand-driven scenario, in which the energy penalty of CCS processes results in an environmental burden that is allocated to the generator/producer and is substituted 'like-for-like', i.e. decrease in coal fired electricity is made up by the same electricity source (at point or elsewhere). We are aware that this represents a 'worst-case' scenario and that other scenarios would lead to less negative impacts on certain SDG targets.
- Include a detailed discussion about the advantages and disadvantages of the used methodology and make recommendations for improvement (if applicable). An additional paragraph was added to section 4.3 of the report.
- More detailed and prominent discussion of the limitations and caveats was added both to the report and the overview. This includes more contextualisation regarding the counterfactual scenario chosen for this study.

Energy
Princetonlaan 6
3584 CB Utrecht
P.O. Box 80015
3508 TA Utrecht
The Netherlands

www.tno.nl

T +31 88 866 42 56
F +31 88 866 44 75

TNO report

| 0.1

Carbon Capture and Storage and the Sustainable Development Goals

Date	21st August 2020
Author(s)	Tom Mikunda James Rawlins Logan Brunner Eirini Skylogianni Juliana Monteiro
Copy no	1
No. of copies	1
Number of pages	81 (incl. appendices)
Number of appendices	1
Sponsor	IEA Greenhouse Gas R&D Programme, Pure Offices, Cheltenham Office Park, Hatherley Lane, Cheltenham, Glos. GL51 6SH, UK
Project name	CCS and the Sustainable Development Goals
Project number	060.45741

Summary

The '2030 Agenda for Sustainable Development' was adopted by the United Nations General Assembly in 2015. This resolution, consisting of 17 Sustainable Development Goals (SDGs) covering a wide range of human development areas and broader environmental sustainability issues.

Since the agreement of the SDGs and the Paris Agreement shortly after in 2015, the issue of 'mainstreaming' climate issues into the design of comprehensive sustainable development policies at regional, national and local levels has gained greater importance. However, not all climate actions may be compatible with the SDGs, and vice-versa. Policy makers may be faced with strategic choices where insights into climate-development interactions are key for successful development and implementation of policies and targets that serve both agendas.

In order to inform these discussions, assessments of the compatibility of certain sectors and technologies with the SDGs have recently been completed. This report documents an assessment of the foreseen interactions between carbon capture and storage (CCS) technologies and the SDGs. Since 2007, the Intergovernmental Panel on Climate Change has consistently highlighted CCS as a key mitigation technology for achieving CO_2 reductions in the energy supply and industrial sectors.

The objective of this assessment is to improve the availability and accessibility of information regarding the relevance of CCS in contributing to the SDGs. An approach has been taken to focus on the interactions of CCS and SDGs where credible and quantifiable evidence is available. This assessment uses an existing framework, whereby interactions between SDGs and targets are classified on a seven-point ordinal scale (+3 to -3), indicating the nature of the interaction with other targets. Thus there are seven possible types of interactions (indivisible, reinforcing, enabling, consistent, constraining, counteraction, cancelling – ranging for +3 to -3). The results of this assessment have been achieved by an extensive and systematic literature review of hundreds of scientific and non-scientific documents and reports, where the findings from life-cycle analyses play a primary role.

When evaluated against the SDGs, CCS shows a number of positive interactions. Evidence indicates that the significant deployment of CCS is 'indivisible' (a score of +3) in combating climate change (SDG 13). This is as expected, as CCS technology is developed specifically for this end. CCS plays an enabling role in the provision of affordable and clean energy and can support the decarbonisation of industry both through direct CO_2 emissions reductions but also indirectly through the supply of low carbon power (SDG 7.1). CCS can also support the retention of jobs in certain sectors and contribute to a decoupling of economic growth from environmental degradation, through the reduction of CO_2 emissions (SDG 8). Additionally, CCS can enable sustainable infrastructure developments, provide a boost to innovation systems (SDG 9), and reduce the carbon footprint of cities to make them more sustainable (SDG 10). Through the reduction of CO_2 in the atmosphere, CCS can enable the stabilisation of ocean acidification, a key target of SDG 14.

On the other hand, there are a number of areas which appear challenging for CCS as a technology. Capturing CO_2 from the power and industrial processes has to be

considered as a significant supplementary industrial activity which can have impacts on a range of environmental media. The main impacts associated with CCS are due to the requirement for extra energy per unit of electricity produced. In that sense, the energy source will dictate the impact of CCS: when applying CCS to coal-fired power plants, the impacts of burning extra coal per unit of electricity produced makes CCS compare negatively against the reference case in which the CO_2 is not captured for a number of SDGs. Moreover, the use of chemical solvents in conventional post-combustion capture systems, mainly their production and associated emissions, seems to contribute to the negative environmental impacts. The majority of life-cycle assessments indicate emissions to air and water and the production of wastes through the use of CCS. These emissions result in the technology having counteracting or constraining interactions with a number of SDGs (3, 6 and 15). The inherent energy penalty of operating CCS also means that the technology could be seen as constraining to meeting energy efficiency targets (SDG 7.3). It is important to note however, that CCS did not score a -3 on any SDG item covered in this assessment, which would have indicated a cancelling interaction, against any of the SDGs.

The negative interactions of CCS with various SDGs are a result of the study's framework, meaning that the findings are strongly dependent on the definition of the counterfactual situation chosen for the assessment. In this framework, which is also used in most of the life-cycle analyses, the Global Warming Potential and other environmental impacts are assessed for an industrial plant *with* and *without CCS*. Therefore, CCS is treated as an additional industrial activity which subsequently compares unfavourably because of the additional energy requirement and the associated emissions. Moreover, the fact that the majority of the studies are conducted for coal-fired power plants implies that the environmental impacts of alternative fuels (natural gas, biomass, waste) require further investigation to get a more comprehensive picture of the trade-offs today and in the future.

Overall, this assessment can be considered to be one of the most detailed evaluations completed to date of a specific technology's interaction with the SDGs. In the course of this work, a number of knowledge gaps have been identified, which if addressed, could both strengthen the conclusions of this assessment, and the overall representation of CCS in the framework of sustainable development. Recommendations on addressing these knowledge gaps include:

- Conducting additional life-cycle assessments of 'second-generation' CO_2 capture technologies, with particular attention given to novel capture techniques expected to be able to compete with incumbent technologies.
- Conducting life-cycle assessments of CCS applied to key industrial processes, including evaluations of water usage and energy efficiency.
- Conducting dedicated assessments focused on the compatibility of CCS with specific SDGs.
- More consistent and clear reporting of where in the life-cycle particular environmental impacts occur, and clearer sensitivity analysis to show how important certain assumptions are.
- Conducting life-cycle assessments in a standardised manner considering same boundary conditions, to allow for the direct comparison between the contributions of different processes in the environmental impacts.

- Conducting studies examining the macroeconomic impacts of CCS in different regions, for example between developed and developing nations, and between fossil-fuel exporters and importers.
- Completing employment studies of CCS versus other low carbon alternatives, which could have greater value than studies which look at these impacts in isolation.

In conclusion, the construction and use of all low carbon technologies have various environmental impacts, incurring trade-offs with the targets of the SDGs. Evaluating these trade-offs in isolation is likely to have limited value for policy development, given that the deployment of not one single low carbon technology will allow the achievement of both the SDGs and the Paris Agreement. It is recommended that future assessments of low carbon technology interactions and the SDGs should take a portfolio approach, comparing diverse sets of technologies and actions with various degrees of application, and reflecting country-specific economic, geographic and environmental considerations, in order to minimise the inevitable trade-offs between climate action, energy security, energy efficiency, investment, trade and sustainable development for all.

1 Introduction

This report documents an assessment of the foreseen interactions between carbon capture and storage (CCS) technologies and the Sustainable Development Goals (SDGs). This section of the report provides relevant background information on the adoption of the SDGs, potential synergies between climate change mitigation technologies and the SDGs, and a short description of the current status of CCS.

Section 2 covers the rationale and objectives of this assessment, including the approach taken. Section 3 documents the bulk of the assessment, a detailed review of the technical, societal and economic facets of CCS with direct interfacing with the targets of a number of SDGs considered particularly relevant. For SDGs with targets considered largely isolated to the impacts of CCS technologies, the justification of their exclusion is provided in Section 3.11. The conclusions of the assessment and a description of key knowledge gaps identified are outlined in Section 4.

1.1 The Sustainable Development Goals

A few months prior to the Paris Agreement, in September 2015 'Transforming our World: the 2030 Agenda for Sustainable Development' was adopted by the United Nations General Assembly (United Nations 2015). This resolution, consisting of 17 Sustainable Development Goals (SDGs), covering a wide range of human development areas and broader environmental sustainability issues, is a follow-up to the Millennium Development Goals. Both the Paris Agreement, and the 2030 Agenda, although negotiated under different multilateral processes, are considerably interlinked. The Paris Agreement emphasises the need for sustainable development considerations in low carbon transitions; at the same time avoiding dangerous climate change is one of the 17 Sustainable Development Goals (SDGs).

Figure 1:The 17 Sustainable Development Goals (International Monetary Fund 2019).

This interdependency has been seen as an opportunity to move away from the discourse of two different agendas, that are often perceived to be in competition (Gonzales-Zuñiga, et al. 2018). Indeed, an integrated approach of ‘mainstreaming’ climate issues into the design of comprehensive sustainable development goals at regional, national and local levels is gaining greater importance (Vilariño 2018).

1.1.1 Synergies and Trade-Offs between mitigation options and sustainable development

However, not all climate actions may be compatible with the SDGs, and vice-versa. Policy makers may be faced with strategic choices where insights into climate-development interactions are key for successful development and implementation of policies and targets that serve both agendas. The IPCC’s Special Report on 1.5°C has made an initial assessment on the synergies and trade-offs between mitigation options and sustainable development, including CCS use in the energy supply and industrial sectors (IPCC 2018).

The Special Report recognised that CCS plays an important role in all deep decarbonisation scenarios. In terms of synergies with the SDGs, it was stated that CCS can contribute to the provision of advanced and cleaner fossil fuel technology, in line with the targets of SDG 7 ‘affordable and clean energy’. The deployment of CCS can also contribute to industrial development, innovation and the provision of new infrastructure (SDG 9). However a number of trade-offs were highlighted, particularly the potential for increased coal consumption, due to the lower efficiency of CCS-equipped coal-fired power plants (SDG 12, responsible consumption and production), possible risks of carbon dioxide leakage from geological storage and CO_2 transport infrastructure (SDG 3, good health and well-being), and the associated price impacts affecting energy access and poverty due to the costs of investing in CCS (SDGs 1, no poverty, and 7, affordable and clean energy).

The IPCC assessment represents a useful first insight on the interaction of CCS with the SDGs. The review however does appear to place the focus on CCS use with coal-fired power plants, which could mean that SDG interactions of CCS on gas-fired power plants or in the broad range of potential industrial applications (e.g. in the cement, steel, refining and waste-to-energy sectors) have been overlooked. A dedicated, in-depth assessment can help to support and complement the findings of the IPCC.

1.1.2 Existing assessments of synergies and trade-offs

Since the agreement of the 2030 Agenda, a number of mapping exercises have been completed to assess the interaction between resources as well as key energy-related sectors and technologies and the SDGs. For example, the need for the investigation of interlinkages between resources (water, energy, material, land and food) using suitable tools and models has been highlighted as essential for a well-integrated and efficient implementation of SDGs (Bleischwitz, et al. 2018). The mining and oil and gas sectors completed sector-SDGs assessments in 2016 and 2018, respectively (United Nations Development Programme 2016) (IPIECA 2018). Synergies and trade-offs between technology innovation and SDGs have been studied for 11 economies (Sinha, Sengupta and Alvarado 2020), while technology-specific assessments have been completed for carbon removal and solar geoengineering, (Honegger, et al. 2018) in addition to the assessment for renewable energy, under public consultation as of March 2019 (UNSDSN 2019).

The most inclusive assessment of how climate actions might influence the SDGs is the SDG Climate Action Nexus, or SCAN tool. (Gonzales-Zuñiga, et al. 2018). The SCAN tool is based on a large evidence base (from similar sources to those used by the IPCC for its Assessment Reports) and details how a range of mitigation actions could impact the achievement of the SDGs, at the level of the 169 targets which make up the SDGs.

1.2 Carbon Capture and Storage

1.2.1 CO_2 capture technologies

CO_2 capture, as part of carbon capture and storage projects, refers to the removal of CO_2 from the flue gases of fossil-fuel or biomass power plants, or from the process gases of industrial installations. The removal of CO_2 is commonly achieved through the use of chemical solvents (absorption), solid adsorbents or by synthetic membranes, with the use of chemical solvents, typically amines, the most dominant capture technology. Chemical solvents for CO_2 capture have been used for natural gas processing and in the production process of hydrogen for many decades. The broader application of CO_2 capture technologies for the purposes of climate change mitigation emerged in the early 2000's (IPCC 2001).

The first R&D and demonstration (RD&D) of CO_2 capture, as part of CCS projects, was primarily targeted at the oil and gas industry with Sleipner in Norway being the first large-scale CO_2 capture and storage project (IEA 2016). Later, this was broadened to include reducing emissions from coal-fired and gas-fired power plants. For example, the initial demonstration programme for CCS in the EU under the European Economic Recovery Plan (EERP) in 2009, included six project plans at coal-fired power plants. In 2013, the UK government shortlisted two projects, White Rose coal-fired power plant and Peterhead gas-fired, for CCS. The former was supported by EU NER 300 funding but the latter was placed on a reserve list for EU funding. None of these demonstration projects moved forward to completion for political, economic and regulatory reasons. In 2014, the first large-scale CO_2 capture plant associated with a fossil fuel unit, Boundary Dam, was realised at the Saskpower coal-fired power plant in Saskatchewan, Canada. In 2016, the second large-scale project in coal-fired power plant, Petro Nova (Texas, US), became operational.

Following the 2010 G8 target set in Hokkaido in 2008, the focus on RD&D for CCS has shifted towards application on fossil fuel power plants as well as in industrial processes. This shift has subsequently been driven by political sentiment in a number of European countries to move away from coal as an energy source, and growing interest in reducing emissions from key industrial processes such as steel and cement production and in oil refining (IEA 2011) (ZEP 2015). It is worth mentioning that in many industrial processes such as cement or waste incineration, (part of) the CO_2 emissions are process-related, and are therefore not abatable by e.g. shifting to CO_2-free fuels. In 2016, a unit capturing CO_2 produced as a by-product of the direct reduced iron process at the Emirates Steel Industries factory in Mussafah became operational. The CO_2 capture plant at the AVR waste incineration plant in Duiven, The Netherlands, became operational in 2019. In 2020, capture plants at the North West Redwater Partnership (NWR) Sturgeon Refinery and Nutrien's Redwater Fertilizer Facility started delivering CO_2 to the Alberta Carbon Trunk Line system, in Canada.

1.2.2 CO_2 transport

CO_2 is transported as a commodity for use in various applications by pipeline, ship, air or by truck. For CCS projects, only pipeline or ship transport can accommodate the large volumes expected to require transport from capture sites to storage locations. In the US, there are 36 CO_2 pipelines in operation, transporting the gas from both natural subsurface accumulations and anthropogenic sources (mainly natural gas processing) for use in enhanced oil recovery projects (Global CCS Institute 2017). Whereas pipelines are considered most suitable for CCS projects with large volumes and relatively close storage locations, maritime CO_2 tankers may be more suitable for longer distances and offer greater flexibility than pipelines.

1.2.3 CO_2 storage

CO_2 storage implies the injection of pressurized CO_2, via one or more wells, into permeable porous media in the deep subsurface at depths of 800 metres to several kilometres (Metz, et al. 2005). CO_2 is contained in these geological reservoirs by a thick, impermeable rock on top of the porous reservoir. Numerous trapping mechanisms then occur over time, increasing containment security, as some of the CO_2 dissolves, some will be physically trapped in pores and some of the CO_2 will precipitate to form new minerals. The Sleipner and Snøhvit CO_2 storage projects in Norway, and the Quest CCS Project in Alberta, Canada, are examples of large-scale geological storage projects that are currently in operation (Furre, et al. 2017), (Hansen, et al. 2013) (Rock, et al. 2017). CO_2 Injection and storage is achieved largely through the use of equipment used in oil and gas exploitation.

1.2.4 CCS in global climate mitigation pathways

Since the release of the Fourth Assessment Report of the Intergovernmental Panel on Climate Change in 2007, CCS has been consistently highlighted as a key mitigation technology for achieving CO_2 reductions in the energy supply and industrial sectors (IPCC 2007). In the IPCC's Fifth Assessment Report, the importance of CCS was further reinforced as many of the global climate mitigation models used in the assessment could not constrain greenhouse gas emissions below 450 ppm CO_2eq by 2100[1] without the use of the technology. The same report estimated that in scenarios which excluded CCS from the portfolio of actions to be used in reaching the 450-ppm target, the total mitigation costs were on average 138% higher in 2100 (IPCC 2014). In the most recent IPCC Special Report on Global Warming of 1.5°C, the use of carbon capture and storage, particularly in combination with biomass (BECCS), was again underlined as an unavoidable technology (IPCC 2018). The findings of the IPCC reverberate with those of the International Energy Agency's '2DS' scenario, with CCS contributing to 14% of total global emissions reductions by 2060 (IEA 2017). The discussion around biomass availability is beyond the scope of

[1] The figure synonymous with keeping mean global temperature by 2100 to no more than 2°C above pre-industrial levels

this report. CO_2 used for enhanced oil recovery is also not covered explicitly in this report, although it is recognised as being a key driver of large-scale CCS projects in Europe, North America and China.

2 Assessment of CCS and the SDGs

2.1 Rationale and objective

The overall objective of this assessment is to improve the availability and accessibility of information regarding the relevance of CCS in contributing to the Sustainable Development Goals. The primary objective will be achieved through the completion of three key goals:

1. Inventorise existing information on impacts of CCS on specific targets of the 17 SDGs, using the rating, scoring and information assessment as per IPCC's SR1.5,
2. articulate specific gaps in information, and
3. propose a path forward by providing a prioritised lists of gap closures.

There is a growing body of literature concerning the mainstreaming of climate action into policies directed towards implementation of SDGs. There is also a trend of material becoming available examining the interaction of technologies and sectors against SDGs (see section 1.1.2). CCS remains a complex technological solution to climate change, and public understanding of the technology remains low (Pietzner, et al. 2011). This study can help to substantiate the wider value of CCS, but also to highlight points of attention/action on potentially negative interactions with specific SDGs.

2.2 Approach

There is no set approach nor methodology for assessing the interaction of sectors and technologies with the SDGs. A brief evaluation of existing studies from the mining and oil and gas sectors is useful as reference documents (United Nations Development Programme 2016) (IPIECA 2018), but the approach taken in these assessments is unsuitable as a means of completing the objectives of this CCS assessment. The mining and oil and gas sectors involve wide-ranging activities with almost unquantifiable impacts across all themes of the SDGs. The breadth and scale of this interaction makes it challenging to include empirical evidence in the assessment.

The approach taken in the assessment of Carbon Removal and Solar Geoengineering (Honegger, et al. 2018) is more suited for CCS, given its technological specificity. However, the assessment includes a multitude of sub-technologies and does not provide sufficient detail to allow conclusions beyond either the presence or not of a technology/SDG interaction.

It is therefore a significant challenge to link the complex and precise characteristics of CCS with the broad nature of the SDGs, even with consideration given to the 169 associated targets. An approach has been taken to focus this assessment on the interactions of CCS and SDGs where credible and quantifiable evidence is available. Taking this approach has meant that the authors have had to make a distinction between SDGs considered to have a direct potential interaction with CCS, and those considered to have indirect or limited interaction.

2.2.1 Direct and indirect interactions

A direct interaction, either positive or negative, is present if a direct causal link can be identified between the deployment of CCS and a goal associated with an SDG. A direct interaction would generally be backed up with empirical evidence from literature. An example here would be potential improvements in air quality (SDG Goal 11.6) through the application of post-combustion CO_2 capture, which can result in reduced emissions of sulphur dioxide and particulate matter from coal-fired power plants (EEA 2011). This is because contaminants in the exhaust gas, such SOx and particulate matter, can be reduced to a very low level prior to CO_2 capture process. This is achieved through deployment of additional unit operations to remove the air pollutants prior to CO_2 capture.

An indirect interaction, either positive or negative, is present if no direct causal link can be identified. Generally speaking, no empirical evidence is available in such instances. However, through justified extrapolation and expert judgement, some form of interaction is expected. An example here would be that CCS deployment in industry could promote inclusive and sustainable industrialisation (SDG Goal 9.2), given the versatility of the technology that can be applied in the steel, cement and petrochemical industries (UNIDO 2010), as well as in the waste-to-energy sector.

By pre-identifying the potential direct and indirect impacts of CCS, the methodology has been streamlined and the risk of subjectivity in the assessment reduced. A preliminary overview of the outcome of this pre-identification process is provided in Table 2-1.

Table 2-1: Example of pre-identification of direct and indirect interactions between CCS and SDGs.

Direct interaction	**Indirect interaction**	**Limited interaction foreseen**
3. Good health and wellbeing	1. No poverty	2. Zero hunger
6. Clean water and sanitation	4. Quality education	5. Gender equality
7. Affordable and clean energy		10. Reduced inequalities
8. Decent work and economic growth		16. Peace, justice and strong institutions
9. Industry, innovation and infrastructure		17. Partnerships for the goals
11. Sustainable cities and communities		
12. Responsible production and consumption		
13. Take urgent action to combat climate change and its impacts		
14. Life below water		
15. Life on land		

2.2.2 Use of SDG targets

Each of the 17 SDGs has a number of associated targets, with each contributing to the achievement of the overall goal. There are 169 targets in total. For this assessment, the description of the targets provides an additional level of detail upon which to assess the interaction between CCS and each of the SDGs. Some of the SDGs have quite a diverse range of targets, and many of the targets have no plausible link with CCS, even though the goal itself is relevant. This assessment focusses on individual targets that have possible interactions with CCS. The keywords contained in the target descriptions are used to constrain the inputs to the literature search, described in the following section.

2.2.3 Evidence collection

The pre-identification process allows each of the three different SDGs grouping to be treated differently during the evidence collection stage. Each of the direct interactions are subjected to a thorough literature review. Literature used to identify evidence of potential interactions between CCS and SDGs included:

- Peer-reviewed and non-peer reviewed scientific journal articles
- Official national and international governmental documents
- Other types of grey literature
- Relevant IEAGHG documents, if made available
- Use of the Ambition to Action SCAN-tool

The results of the literature review were recorded in Excel-based literature trackers. A simple scoring matrix was used to assess the credibility and relevance of each piece of literature found. Each piece of information is assigned a score of 1-3 for credibility, and 1-3 for relevance, with the combined score representing the final result. The most credible sources of information can be considered as peer-reviewed literature, whereas least credible information sources would be unreferenced material on websites, for example.

Indirect interactions are assessed via an internal expert review process, which also included literature reviews to confirm the presence or not of direct and/or indirect interactions. For the SDGs identified as having limited interactions with CCS, no further assessment took place.

2.2.4 Assessment of evidence collected

While existing SDG/technology/sector assessments, including the SCAN-tool, help policymakers identify synergies and trade-offs between climate actions and the SDGs, there is a need to move beyond these identified linkages and for policymakers to understand how to act upon knowledge of them. As a first step, the International Council for Science has developed a tool, or framework, whereby "interactions between SDGs and targets are classified on a seven-point ordinal scale, indicating the nature of the interaction with other targets, and the extent to which the relationship is positive or negative to help policymakers identify and test development pathways that minimize negative interactions and enhance positive ones" (Griggs, et al. 2017).

The seven possible types of interactions (indivisible, reinforcing, enabling, consistent, constraining, counteraction, cancelling – ranging for +3 to -3) can be applied at any level among goals and targets, to individual policies or to actions. Commonly known as 'the Nilsson score' (based on the author), its application allows the generation of comparable and robust outcomes. The Nilsson score is the most developed system for assessing SDG interactions, and it has also been applied for the assessment in Chapter 5 of the IPCC's Special Report on 1.5°C, mentioned in paragraph 1.1.1. For these reasons, the Nilsson score has also been adopted for use in this assessment.

The scale for the scoring of interactions, and examples, is provided in Table 2-2.

Table 2-2: Scoring for the interactions between SDGs as proposed by (Nilsson, Griggs and Visbeck 2016)

GOALS SCORING

The influence of one Sustainable Development Goal or target on another can be summarized with this simple scale.

Interaction	Name	Explanation	Example
+3	Indivisible	Inextricably linked to the achievement of another goal.	Ending all forms of discrimination against women and girls is indivisible from ensuring women's full and effective participation and equal opportunities for leadership.
+2	Reinforcing	Aids the achievement of another goal.	Providing access to electricity reinforces water-pumping and irrigation systems. Strengthening the capacity to adapt to climate-related hazards reduces losses caused by disasters.
+1	Enabling	Creates conditions that further another goal.	Providing electricity access in rural homes enables education, because it makes it possible to do homework at night with electric lighting.
0	Consistent	No significant positive or negative interactions.	Ensuring education for all does not interact significantly with infrastructure development or conservation of ocean ecosystems.
–1	Constraining	Limits options on another goal.	Improved water efficiency can constrain agricultural irrigation. Reducing climate change can constrain the options for energy access.
–2	Counteracting	Clashes with another goal.	Boosting consumption for growth can counteract waste reduction and climate mitigation.
–3	Cancelling	Makes it impossible to reach another goal.	Fully ensuring public transparency and democratic accountability cannot be combined with national-security goals. Full protection of natural reserves excludes public access for recreation.

For this assessment, the proposition of 'broad deployment of CCS technologies' is the basis for evaluation against the interaction with each SDG. CCS technologies were interpreted to include applications in the power and industrial sectors, CO_2 shipping by pipe and maritime vessel, and CO_2 storage, both on- and offshore. Many of the interactions around CO_2 capture and storage are fully applicable to bio-energy with CCS (BECCS), as the technologies to capture, transport and store CO_2 from biomass combustion are comparable to those associated with fossil fuels. However, the issue around biomass availability was considered out of scope of this report. CO_2 used for enhanced oil recovery is also not covered explicitly in this report.

For direct interactions, the evaluation will result in a score of between +3 and -3. For indirect interactions, the outcome of the expert review will not be evaluated against the Nilsson score, but will result in a justified conclusion of either a potential positive or negative interaction.

2.2.5 Gaps assessment

The primary knowledge gaps identified during this assessment are outlined in Section 4.2. The gaps assessment identifies for which of the interactions additional scientific research could be completed to strengthen the results of the assessment. There have been no dedicated studies previously completed with regards to synergies and trade-offs between CCS and the SDGs, and as such numerous knowledge gaps can be expected. Further work should be prioritised to issues where additional information can make a significant impact in strengthening the conclusions of this study.

2.3 Framework and limitations

Within this study, the interactions of CCS with the relevant SDGs are divided into two categories, those relevant for the power sector and those relevant to the industrial sector (e.g. cement and steel). They are assessed based on the comparison between a power or industrial plant *with* and *without* CCS. The same framework is used in most of the life-cycle assessments (LCAs), which have played an important role in this study as they quantify the environmental impacts of deploying carbon capture and storage in a plant. The results of the LCAs are mainly reported per unit of electricity produced in power plants (kWh or MWh) and per unit product in industrial plants (kg or ton of cement or of hot rolled coil in the steel industry). This approach is justified since it allows for a comparison between different power generation technologies, fuels and solvents with and without CCS as well as the determination of the suitability of industrial plants for the implementation of CCS.

When CCS is integrated into a power plant system, the production of 1 kWh electricity then also carries the energy burden of the additional carbon capture and storage processes. The additional energy requirement needs to be satisfied with additional fuel, the supply chain of which is associated with waste and emissions, leading to negative impacts to the environment. Therefore, the production of 1 kWh electricity with CCS will have higher environmental impacts than without CCS. This applies under the premise that the power plants' electricity generation is demand-driven, and not capacity-driven. In a capacity-driven scenario, the addition of CCS does not lead to increased fuel consumption but rather to a decreased electricity output, implying similar environmental impacts as in the case of unabated power production. As depicted in **Error! Reference source not found.**, in a capacity-driven scenario, there is indeed limited and even positive influence on the environmental indicators, while in a demand-driven scenario, which is adopted in this study, there are negative environmental impacts. The Health Toxicity Potential (HTP) was chosen as an example indicator to illustrate this discussion.

Table 2-3: Comparison of capacity-driven and demand-driven power plant operation. Data taken from Volkart et al. (2013) for pulverized coal (lignite)-fired power plant with and without CCS. Post-combustion carbon capture technology is employed. HTP: Health Toxicity Potential, RD: Relative deviation.

		Capacity-driven		Demand-driven	
		No CCS	With CCS	No CCS	With CCS
Net MW	MW	989	759	989	759
Demand	MW	989	759	400	400
Full load hours	h y^{-1}	7500	7500	7500	7500
Total production	kWh y^{-1} ($x10^9$)	7.4	5.7	3.0	3.0
Functional unit	kWh	1	1	1	1
HTP	-	0.8	1	0.8	1
	y^{-1} ($x10^9$)	5.9	5.7	2.4	3.0
RD HTP	%	-	-4.1	-	25

It should be noted that defining a suitable counterfactual situation upon which to make this assessment has a major impact on the outcome. Based on the *with* and *without* CCS-scenarios, CCS is treated as an additional industrial activity which subsequently compares unfavourably because of the additional energy requirement and the associated emissions, despite considerable CO_2 emission reductions. To further understand the limitations that the chosen framework poses, one could consider also the ancillary services offered by employment of CCS, such as maintaining system's frequency and reserving capacity for unexpected demand increases and disturbances, which are not available from renewables. This contribution for CCS technologies is not depicted on its scoring against the SDGs, which is based on the *with* and *without* CCS-scenarios.

Nineteen life-cycle assessments were used as reference in this study and all of them considered coal as fuel. In the power sector, half of the LCAs also considered natural gas-fired plants, while three out of the total five studies in industrial sectors assumed use of natural gas for the additional energy requirements of CCS (**Error! Reference source not found.**). Four of the LCAs including natural gas-fired plants reported on the environmental impacts, indicating comparatively smaller impacts on NGCC plants than on coal-fired power plants with post-combustion capture, with similar trends identified in the industrial sector. Only one LCA included another fuel for power generation, i.e. wood, and found varying impacts between the three different cases studied; wood combustion with post-combustion capture, wood IGCC with pre-combustion capture and wood gasification to produce synthetic natural gas with post-combustion capture. It is, therefore, clear that the environmental impacts can vary significantly depending on the fuel and technology used and that coal-fired power plants are better represented in this study.

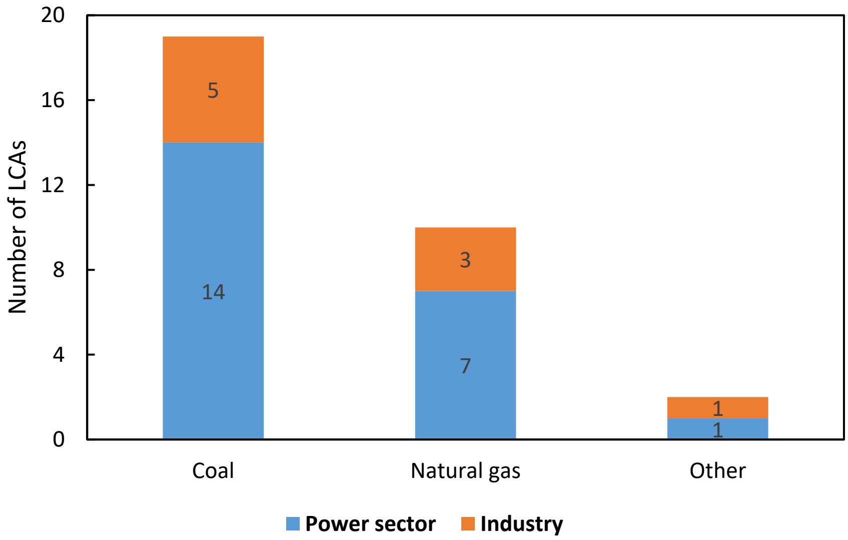

Figure 2: Distribution of life-cycle assessments according to fuel employed in power sector and industry.

This study has taken a global perspective regarding the interactions between CCS and SDGs. Nevertheless, it is important to bear in mind that conducting a LCA requires inputs that are country- and region-dependent, such the material supply chains and CO_2 pipeline distance, and that specific characteristics, for example industrial development, may significantly differ between sectors, regions and countries.

3 Direct interactions between CCS and the SDGs

This section presents the results of the literature review for the direct interactions between CCS and the SDGs. Each SDG is covered separately. The sections begin with a general overview of the objective of the SDG, and the identification of the relevant targets and a justification for their inclusion. The bulk of each section contains the findings of an extensive literature review, which is then followed by the scoring assessment and the provision of a Nilsson score for each relevant target. A comment on the confidence of the scoring is given, based on the amount of literature found, and the extent of agreement between the different literature sources. Where possible, the individual target scores are aggregated to provide an overall score per SDG. The final section of each SDG assessment contains the knowledge gaps or uncertainties found within the analysis.

3.1 SDG 3 – Good health and wellbeing

SDG 3 focusses on human health, addressing a wide range of health and wellbeing issues including maternal mortality, neonatal and child mortality, disease epidemics, hazardous pollution, substance abuse, road traffic deaths and injuries and sexual health. Most of these are not directly affected by deployment of CCS technologies.

Of relevance to CCS are health issues caused by environmental pollution. The World Health Organization highlighted the link between air pollution and non-communicable diseases in a report published in 2017, stating that more than 6 million deaths from non-communicable diseases were caused by ambient and household air pollution (World Health Organization 2017).

3.1.1 Key targets relevant for CCS

SDG 3 is made up of 9 targets (3.1-3.9). The majority of these relates to health issues that will not be influenced by CCS. Two are relevant; they are detailed in the table below. The critical one is 3.9, relating to health impacts caused by environmental pollution; 3.4 relates to non-communicable diseases, which can be caused by environmental pollution, so any impacts linked to CCS would essentially be the same as those for 3.9.

Table 3-1: SDG 3 targets with possible interactions with CCS

SDG Target	Target description	Possible interactions - power CCS	Possible interactions - industry CCS
3.4	By 2030, reduce by one third premature mortality from non-communicable diseases through prevention and treatment and promote mental health and well-being.	Local environmental pollution may increase due to emissions from capture plant, though varies with capture technology. Increased lifecycle pollution in fossil fuel supply chain due to increased fuel requirement to run capture plant.	
3.9	By 2030, substantially reduce the number of deaths and illnesses from hazardous chemicals and air, water and soil pollution and contamination.	Same pollution related impacts as 3.4 (non-communicable diseases caused by pollution).	

3.1.2 Evidence from literature

Findings for power CCS

As for other SDGs, where the main interaction with CCS is through emissions to the local environment and resulting impacts on ecosystems or human health, the main evidence base is comprised of Life-cycle Assessments (LCA). A number of LCA studies have been undertaken over the past decade, comparing a range of CCS capture technologies and fuels across a varying set of commonly used LCA indicators.

Absorption-based carbon dioxide capture with aqueous amines is the most mature technology for post-combustion CO_2 removal. Specifically, aqueous solution of 30 wt% monoethanolamine (MEA) is considered the state-of-the-art solvent, and this is the reason why it is the most studied technology in the LCAs. During this process, the flue gas of a power plant or other CO_2 emitting source is brought into contact with the solvent, which selectively absorbs the CO_2 at low temperatures, inside an absorber. In order to reverse this reaction and release the CO_2 from the amine solution, the ‘rich’ amine solution is introduced into a desorber where it is heated to ca. 120°C. The amine solution can then be recirculated to absorb more CO_2, and the resultant CO_2 stream can be prepared for transport and storage. This is an energy-intensive process due to the heat required for the solvent regeneration, leading to a reduction of the overall efficiency of the plant.

Other capture technologies which have been investigated in the LCAs include absorption-based pre-combustion where physical solvents are used (e.g.. Selexol) and chemical looping. Calcium looping has been proposed in the literature where CO_2 is removed via a continuous carbonation/calcination of CaO at high temperatures. Carbon dioxide reacts with the solid sorbent (CaO) to form calcium carbonate. Then, the carbonate is decomposed into CaO and CO_2 stream which can be sent for storage (Petrescu, et al. 2017). It is understood that increased energy requirements are an integral part of CO_2 capture processes. The extent of the energy demand depends on the chosen technology and solvent/sorbent, as well as the degree of heat integration in the plant.

Health impacts caused by environmental pollution are assessed through various indicators, such as the Human Toxicity Potential (HTP), the photochemical oxidant creation potential (POCP) and the particulate matter (PM) formation. Cuéllar-Franca and Azapagic reviewed and compared the findings of 11 LCA studies on power plants published in the literature, around half of which reported on HTP. The LCA studies generally have a consistent system boundary including fossil fuel extraction and supply, power generation and then CO_2 capture, transport and storage. Of the four studies on pulverised coal plants with chemical absorption with MEA, three found an increase in HTP of 55-183% due to MEA production, and one found that HTP decreases by 29%, because MEA reduces the amount of fly ash and trace metals. One study reported on HTP for oxyfuel combustion plants, finding higher HTP due to conversion of hydrogen fluoride air emissions into effluent that is discharged to water. One study, which considered a combined cycle gas turbine (CCGT) plant with post-combustion CCS, reported an increase in HTP of 140%. The overall conclusion of the review was that human toxicity impacts are higher with CCS than without.

A few studies also reported on photochemical oxidant creation potential (POCP), which has harmful impacts for health. Both higher (9-150%) and lower (28-270%) POCP were reported across the studies for post-combustion plants, when comparing plants with CCS to those without. Higher POCPs are mainly caused by the coal supply chain due to the increased energy demands , while lower findings resulted from removal of NOx and SO_2 by MEA capture plant. For oxyfuel, POCP was found to be lower (53-120%) with CCS, because of the removal of hydrogen fluoride and other acid gases (Cuéllar-Franca and Azapagic 2015).

Several subsequent studies report relevant findings. Oreggioni et al. undertook a comparative LCA study for three different CCS technologies applied to a coal-fired power plant (conventional MEA; blended solvent; oxy-fuel). Helpfully, they separate their findings for on-site emissions and emissions over the whole life-cycle, including from the coal supply chain. They report increases in HTP from all three technologies, ranging from 23% (oxyfuel) to 29% (MEA), which result overwhelmingly from the coal supply chain, in particular the disposal of coal mining waste. The coal supply chain accounts for around 95% of the total life-cycle impact. Oxyfuel performs better for toxicity because its greater efficiency reduces the additional supply chain impact. Their study also reported on particulate matter (PM) formation, finding a reduction in on-site PM emissions of 62% (blended solvent) to 99% (oxyfuel), however this on-site reduction is offset by increases in supply chain related PM emissions from coal transport, caused by the increased fuel demand of the CCS plants. Around 70% of life-cycle PM formation is due to coal transport, and results from combustion of heavy fuel oil when coal is shipped by sea. Overall, increased life-cycle PM emissions were reported for MEA (24%) and blended solvent (20%); for oxy-fuel, life-cycle PM emissions were reduced by around 4% (Oreggioni, et al. 2017). These findings on PM – mixed performance across CCS technology and fuel types due to opposing impacts (increased PM from the increased fuel consumption; and potentially reduced PM emissions caused by the CCS capture plant) were also seen in one other study reviewed (Volkart, Bauer and Boulet 2013).

Petrescu et al. compared three different CCS technologies for a pulverised coal plant (methyl diethanolamine (MDEA), aqueous ammonia and Calcium Looping (CaL)) on a life-cycle assessment basis. They found very substantial increases in HTP for the CCS technologies, especially from MDEA, for which they report a 1500% increase. For aqueous ammonia and CaL, HTP increases by 470-480%, still a very large increase but considerably less than for MDEA. They explain that the large increase for MDEA is caused by ethylene oxide emissions from the MDEA production process; this accounts for 63% of the total life-cycle HTP value for the MDEA technology (Petrescu, et al. 2017). It should be noticed that aqueous MDEA is not a suitable solvent for post-combustion CO_2 capture, due to the low reaction kinetics with CO_2. Thus, it is used in blends with other amines (e.g. in blends with piperazine). Operating a CO_2 capture plant with MDEA would require significantly large quantities of MDEA, which could possibly explain the high impact of its production. It is unclear which values were used in the cited study to calculate the solvent losses, and therefore the demanded MDEA production rate.

It should be highlighted that the studies reviewed in Section 3.1.2 of this report are inconsistent when it comes to the effects on the HTP. Korre and co-workers, who included MEA production in their LCA, reported a decrease in HTP upon addition of CCS due to reduced fly ash and trace metals. Other publications report HTP increase, from which three studies found high contributions from MEA production (Koornneef, van Keulen, et al. 2008) (Nie, Korre and Durucan 2011) (Schreiber, Zapp en Kuckshinrichs 2009). However, Koornneef et al., who reported 51% contribution to HTP from MEA production, underline that the ethylene oxide emission data used have high uncertainty and recent literature suggests that their use can lead to overestimation of the HTP impact by several orders of magnitude. At the same time, more recent works found that the MEA production contribution to HTP is small (3% in the work of (Oreggioni, et al. 2017)).

The production of MEA and associated emissions that can impact the HTP are linked to the solvent consumption in the CO_2 capture process. Solvent consumption depends on the degradation of the solvent and the emissions of the system. Overestimation of solvent consumption might lead to overestimation of HTP impact. Typically, amine consumption of 1.5 kg MEA/ton CO_2 removed is considered in the literature (Chisalita, et al. 2019, Korre, Zhenggang and Durucan 2010, Pehnt and Henkel 2009). This is a justifiable assumption based on the reported values from different pilot plant campaigns, however improved solvent management and/or second-generation solvents can lead to lower chemical consumption (Moser, et al. 2020). Moser and co-workers showed that in the campaign performed with MEA in Niederaussem post-combustion pilot plant in Germany, MEA consumption was kept low and below 1 kg/ton CO_2 even after 8,000 h of operation. Moreover, second-generation solvents can exhibit lower consumptions. A campaign performed also in Niederaussem plant, demonstrated consumption of CESAR-1 (a blend of 2-amino-2-methyl-propanol and piperazine) lower than 0.5 kg/ton CO_2 even after 9,500 h of operation. Another example, is KS-1 solvent (hindered amine), which is presented by Korre et al. as an alternative with high chemical stability and a significantly lower reported consumption of 0.35 kg/ton CO_2 captured. They compared the post-combustion CO_2 capture performance in a coal-fired power plant with different fuels and with three different solvents, i.e. MEA, piperazine-promoted potassium carbonate and KS-1 solvent. At any rate, Korre et al. report decrease in HTP for all solvents, with highest HTP for MEA and lowest for KS-1 (Korre, Zhenggang and Durucan 2010).

The overall conclusion of the papers reviewed is that deployment of CCS technologies leads to increased negative human health impacts from HTP, though there are some important differences between fuels and technology types (with MEA generally performing worse than alternatives). There are also differences in the results regarding the causes of the increased HTP (e.g. whether the driver is the increased coal supply or the MEA production process) which needs to be better understood. This conclusion – of worse human toxicity impacts in CCS cases vs. unabated plant – is consistent with other papers (Tzanidakis, et al. 2013) (Volkart, Bauer and Boulet 2013) (IEAGHG 2010), and with the recent IPCC Special Report (IPCC 2018). The findings regarding PM and POCP are less clear, as they are reported in fewer papers and there are both positive and negative net results depending on the capture technology and power plant fuel.

Findings for Industrial CCS

For CCS in industrial applications, there is considerably less LCA literature available. Four relevant papers were identified considering CCS in the cement sector, and one for the steel sector.

Volkart et al. conducted life-cycle analysis for a cement plant with post-combustion MEA capture technology, modelling varying combinations of energy sources for the steam and power demand of the capture plant (coal, local grid electricity, combined heat and power (CHP), and waste heat), and reporting on both HTP and PM formation. For HTP, increases were found for all the CCS options compared to the unabated plant, however there was a large range. The largest increases were from the option using hard coal for steam production performing worst (350% increase in HTP), and the option with both steam and power from the local grid resulting in a 155% increase. Using waste heat for steam production led to a 25% increase in HTP and using a natural gas CHP plant for both steam and electricity for the capture plant resulted in a small 9% increase. The option involving hard coal led to such an increase because of the direct emissions from the coal furnace and also the life-cycle impact of the disposal of mining waste. Such impacts were also caused by the local grid electricity due to there being some coal-fired generation in the local mix (in Switzerland, where the notional plant was based). For PM formation, the option involving hard coal again performs worst, with an increase in PM of 170% vs. the unabated plant, due to the emissions from the coal furnace. All other options perform much better, with increased PM ranging from 3% (waste heat) to 24% (grid electricity) (Volkart, Bauer and Boulet 2013). Moreover, Garcia-Gusano et al. compared a base scenario in 2030 and a CCS scenario with a coal-fired CHP plant for the Spanish cement production, using the same capture technology (MEA). They reported HTP and PCOP impacts multiple times higher than without CCS highlighting the superior performance when using a natural gas-fired CHP plant and that extra material, such as ammonia and MEA, do not cause significant impact increases.

Post-combustion calcium looping (CaL) has been also investigated in its application to a cement plant. Schakel and co-workers assessed the environmental impact of using different fuels (coal, natural gas, woody biomass and a fuel mix of 50% coal, 25% biomass and 25% animal meal) to drive the calcium looping process. It was found that HTP increases when coal or the fuel mix is used, while with natural gas or biomass it actually decreases. This is mainly due to the replacement of electricity from the grid with heat recovery from the CaL process, which leads to avoided emissions from coal production. No significant impacts were reported for either PM or PCOP compared to the plant without CCS (Schakel, et al. 2018). Similar results were reported by Rolfe et al. who considered coal as fuel and found that HTP increased by 57%, while PM and PCOP decrease. In this study, post-combustion calcium looping was also compared with oxy-fuel combustion and was found superior in terms of HTP and PM, though not for POCP, where oxyfuel technology performs better (Rolfe, et al. 2018).

Chisalita et al. considered the life-cycle impacts of both MEA and CaL capture technologies when applied to an integrated steel plant. Findings for HTP and PCOP are reported, with increases of both in all CCS cases. For HTP, significant increases of 74-81% were found for capture with MEA, caused by the addition of a natural gas combined-cycle plant, which accounts for around 40% of the total HTP value for the two MEA cases studied. For the CaL capture cases, much smaller increases in HTP (8-11%) were found, resulting from CO_2 transportation and storage and the supply chain for the natural gas required in the calciner. For PCOP, the MEA cases showed increases of 166-180%, as with HTP, driven by the addition of the gas plant; for the CaL cases the increases were smaller, at 36-61%, and again driven by the CO_2 transport and storage and gas supply chain. Unsurprisingly, the researchers concluded in this paper that calcium looping is a more environmentally friendly capture technology due to its performance across the range of environmental indicators studied; this appears even more clear for the two most relevant to human health, HTP and PCOP (Chisalita, et al. 2019). However, it is important to note that the assumptions regarding the energy requirements reported for the MEA case are not well understood. It is reported that in the case of capture from two CO_2 emitting sources (use of two absorbers and one stripper), the heat requirement is 3.03 MJ/kg CO_2, while in the case of capture from four emitting sources (use of four absorbers and two strippers), the corresponding value is 6.21 MJ/kg CO_2 (Chisalita, et al. 2019). A typical value in MEA-operated plants is 3.5 MJ/kg CO_2, therefore the process used in the evaluation with demands of 6.21 MJ/ton CO_2 is not realistic. Moreover, seeking higher plant efficiency, the use of one stripper for the regeneration of the solvent used in the four different absorbers would be preferred.

Although the evidence base for health impacts from industrial CCS applications is small, the studies above indicate that CCS leads to worse performance on HTP, mainly due to emissions associated with coal production. The choice of fuel can play a decisive role on the impact with less negative or even decrease in HTP when natural gas or biomass is used. PM and POCP seem to increase with post-combustion MEA-based capture, but they are inconclusive with calcium looping.

3.1.3 Scoring assessment and justification

Table 3-2: Assessment overview for CCS in power sector

SDG Target	Summary of literature findings	Score	Confidence
3.4 3.9	Increased HTP in almost all cases across multiple technologies and fuel types. Large range of increases and some inconsistency over what drives the increase. Oxy-fuel and calcium looping generally perform better for HTP than MEA. For PM formation and PCOP, results are mixed, with both net increases and decreases, depending on capture technology and fuel source.	-2	High Multiple sources Good agreement

Table 3-3: Assessment overview for CCS in industrial sector

SDG Target	Summary of literature findings	Score	Confidence
3.4 3.9	Increased HTP, PM formation and PCOP are reported for MEA. For calcium looping, increases and decreases are reported for PM and PCOP. Also, mixed effects on HTP depending on the fuel. Options with coal worse than other energy sources.	+2/-2	Medium Few sources Limited agreement

Based on the overall conclusion that deployment of CCS leads to both negative and positive human health impacts depending on capture technology and fuel, the interaction is scored as both **+2 (reinforcing)** and **-2 (counteracting)** on the Nilsson scale, because this outcome both aids and clashes with the objective of the relevant

SDG targets which are to reduce negative health impacts through reduced pollution (3.9) and non-communicable diseases (3.4).

3.1.4 Specific knowledge gaps in current literature

The evidence for this interaction could be strengthened by:

- Additional LCA studies focussed purely on human health outcomes (rather than the full set of environmental indicators), or syntheses focussed on human health.
- Greater consistency in the indicators reported (especially coverage of PM, which is increasingly considered to be a major health threat in developed and developing countries and for which the evidence is currently less clear).
- Development of cross-cutting approaches, for instance, studies that incorporate finding from LCA analysis with pollutant models calculating atmospheric dispersion of these emissions, which might help address human exposure levels in a more consistence manner.
- More LCA studies on capture technologies with lower energy demand and investigation of heat integration. Comparison of novel capture technologies (e.g. calcium looping) which seem to have substantially reduced health impacts, with chemical solvents with lower energy demands than MEA.
- Relative assessment of the health impacts from CCS vs. other current or potential contributors, to help with contextual understanding of rather abstract indicators (reporting just a percent increase in HTP remains hard to interpret).
- More consistent and clear reporting of where in the life-cycle the health impacts occur and clearer sensitivity analysis to show how important certain assumptions are (e.g. whether coal is shipped by sea seems to have a big impact).
- More LCA studies on health impacts of CCS in industrial applications (waste-to-energy, steel, cement and refining industry), including assessment of using different fuels.

3.2 SDG 6 – Clean water and sanitation

SDG 6 aims to ensure access to safe water sources and sanitation for all. Water scarcity affects more than 40 percent of people around the world, a figure that is expected to increase with the rise of global temperatures as a result of climate change. Although 2.1 billion people are understood to have gained access to improved sanitation since 1990, dwindling supplies of safe drinking water is still a major problem affecting every continent (UN 2019). Improved water sanitation is linked to achieving the other SDG goals of good health (SDG 3) and gender equality (SDG 5). Sustainable management of water resources is also closely linked with 'Life on land' (SDG 15), particularly the protection of freshwater ecosystems.

3.2.1 Key targets relevant for CCS

SDG 6 includes 6 targets (6.1-6.6). The deployment of CCS could have an interaction in the achievement of 2 of these targets. An overview of the relevant targets and justification for their inclusion in this assessment is provided in Table 3-4.

Table 3-4: SDG 6 targets with possible interactions with CCS

<table>
<tr><th>SDG Target</th><th>Target description</th><th>Possible interactions - power CCS</th><th>Possible interactions - industry CCS</th></tr>
<tr><td>6.3</td><td>By 2030, improve water quality by reducing pollution, eliminating dumping and minimizing release of hazardous chemicals and materials, halving the proportion of untreated wastewater and substantially increasing recycling and safe reuse globally.</td><td colspan="2">Some CO_2 capture systems use chemical solvents. The production and use of these solvents could have an impact on water quality. Increased energy requirements in the CO_2 capture system can increase pollution due to increased coal production.</td></tr>
<tr><td>6.4</td><td>By 2030, substantially increase water-use efficiency across all sectors and ensure sustainable withdrawals and supply of freshwater to address water scarcity and substantially reduce the number of people suffering from water scarcity.</td><td>CO_2 capture at power plants needs additional energy (steam), which may mean that more cooling water is needed at the power plant.</td><td>CO_2 capture at industrial installations will need additional energy which could have an impact on water use.</td></tr>
</table>

3.2.2 Evidence from literature

Impacts of CCS on freshwater quality

The impacts of the deployment of CCS on different environmental media have been addressed in research through environmental life-cycle assessments (LCA). The use of CCS in combination with coal-fired power plants and the associated environmental impacts has received considerable attention (Koornneef, van Keulen, et al. 2008) (Koornneef, Ramírez, et al. 2012) (Cuéllar-Franca and Azapagic 2015) (Petrescu, et al. 2017) (Oreggioni, et al. 2017). There have also been a number of LCA's on gas-fired power plants equipped with CCS (Singh, Stromman and Hertwich 2011) (Corsten, et al. 2013), however LCAs of CCS in industrial applications are lacking.

Of particular relevance for SDG Target 6.3, is the LCA impact category of fresh water aquatic ecotoxicity potential (FAETP), which refers to the impact on fresh water ecosystems, as a result of emissions of toxic substances to air, water and soil. The Eutrophication Potential (EP), is another relevant impact category which includes all impacts due to excessive levels of macro-nutrients in the environment caused by emissions of nutrients to air, water and soil.

Koornneef et al. (2008) asssesed the environmental impacts of applying CCS to a pulverised-coal supercritical power plant. The CO_2 capture system was based on the commonly used chemical absorption processes using the solvent monoethanolamine (MEA). Although the Global Warming Potential of the CCS-equipped power plant was reduced by approximately 70%, the CCS-equipped plant is also expected to have increased environmental impacts on FAETP and EP compared to the non-equipped equivalent by 30% and 40%, respectively. More recent comparative evaluations by (Cuéllar-Franca and Azapagic 2015) and (Oreggioni, et al. 2017) support the findings of earlier work, concluding that there is a clear trade-off with CCS plants between considerable CO_2 reductions to the atmosphere, and increases in other emissions to air, water and soil compared to non-equipped plants. The emissions are dominantly from the coal supply chain; mining and transportation. It is important to note that emissions linked to the transportation of fuel by ship are expected to decrease, given the recent stricter regulations in the marine industry regarding SOx and NOx emissions.

The dominant cause for the increased impacts to FAETP and EP of coal-fired power plants is the increased energy demand. In commercially available amine-based CO_2 capture systems, the heat required for the amine regeneration reduces the overall efficiency of the power plant by as much as 25% for coal-fired power plants, and 20% for gas-fired power plants (Ou, Zhai and Rubin 2016). Other CO_2 capture technologies, such as CaL or membrane separation, will also require energy. The R&D efforts related to CCS applied to the power sector have historically focused on the development of technologies demanding lower energy, to limit the impact to the plant efficiency. However, separating CO_2 from a flue gas will always require energy. Simply speaking, more fuel is needed to produce the same amount of power as opposed to a non-CCS-equipped power plant, regardless of the technology used. It is this 'energy penalty' that is highlighted as one of the causes of increased environmental impacts in power plants equipped with CCS (Koornneef, van Keulen, et al. 2008) (Koornneef, Ramírez, et al. 2012) (Petrescu, et al. 2017). The additional coal mining and emissions from additional coal transportation are associated with impacts across a number of LCA impact categories, including FAETP and EP. As far as the impact from the emissions of the CO_2 capture unit is concerned, Singh and co-workers reported that emissions of MEA, formaldehyde and acetaldehyde during the capture process contribute less than 1% on the fresh water and marine ecotoxicity potential (Singh, Stromman and Hertwich 2011).

As far as the industrial sector is concerned, FAETP and EP have been reported in life-cycle assessments regarding the cement industry (García-Gusano, et al. 2015) (Rolfe, et al. 2018) (Schakel, et al. 2018). Both FAETP and EP are reported to increase in both MEA-based capture and calcium looping. Exceptions are the cases considering natural gas and biomass as fuel to drive the calcium looping process where FEP is reduced compared to the plane without CCS (Schakel, et al. 2018). Chisalita et al. also report increased FAETP and EP in their study of CCS with both MEA and calcium looping in the steel industry (Chisalita, et al. 2019).

Water use efficiency and scarcity

Fossil fuel power plants have considerable water requirements for both cooling purposes and for producing steam. Water use in power plants are measured by two key metrics, water withdrawal and water consumption. Water withdrawal refers to the total amount of water taken from a source by the power plant, and consumption refers to the loss of water due to power plant operation, primarily due to evaporation (Ou, Zhai and Rubin 2016). Although the majority of life-cycle water use for fossil-fuel power generation is associated with plant infrastructure, upstream emissions from coal mining and gas extraction account for approximately 20% and 10% of the total water consumption, respectively (Ou, Zhai and Rubin 2016).

Adding a CO_2 capture system to a power plant will increase water use considerably. CCS requires water for the cooling of equipment used during the separation and compression processes, as well as for the regeneration of chemical and physical solvents/sorbents and related processes. These water requirements are in addition to the already large amount of water typically needed for power generation, which is exacerbated by the parasitic load that CCS operations can place on existing power generation facilities (Klapperich, et al. 2014). Ou et al. (2016) calculate that based on a coal-fired power plant with a CO_2 capture rate of 90%, the figures for water withdrawal and consumption (gal/MWh) would be approximatly 70% higher than the non-CO_2 capture equivalent. For natural gas combined cycle (NGCC) power plants, which use far less water than coal-fired plant, the same two metrics increased by approximately 65% in water usage when compared to the non-CO_2 capture equivalent (Ou, Zhai and Rubin 2016).

However, the amount of additional water and energy required for carbon capture and compression depends greatly on the design and size of the system, and particularly the type of cooling system used. The degree of water stream integration can play an important role on the overall water usage. In some plants, the flue gas is emitted at high temperature, i.e. 130ºC or higher, leading to considerable amount of water vapour losses. In the case of low-temperature streams, i.e. 60ºC or lower, water vapor condenses and can therefore be recovered. In CO_2 capture plants employing MEA, the flue gas is typically cooled to 40ºC, thus, most of the water is recovered and can be used for cooling purposes.

Hylkema and Read state that at a planned CCS demonstration plant at a coal-fired power plant located at the coast in the Netherlands, although the cooling requirements would increase by 63%, freshwater water use could be reduced by 94%. This reduction in freshwater usage is due to the water gained through the water condensation of cooling flue gases prior to CO_2 absorption. Moreover, if seawater is available and can be used, this would have an even lower environmental impact (Hylkema and Read 2012).

A similar approach has also been adopted for the feasibility study of a post-combustion retrofit of a 305-MW coal-fired power plant in Saskatchewan, Canada. Due to tight restrictions on water withdrawal in the region, the Shand (the name of the aforementioned power plant) CCS Feasibility Study proposes the use a hybrid cooling system allowing the capture system to require no additional water (International CCS Knowledge Centre 2018). The study suggests that the total additional water demand of the capture facility could be met by use of water that has been condensed from the flue gas of the power plant. Should the design plans for the Shand site proceed and be realized successfully, these solutions could be broadly applicable to all post-combustion CCS retrofits of thermal power plants.

3.2.3 Scoring assessment and justification

Table 3-5: Assessment overview for CCS in power sector

SDG Target	Summary of literature findings	Score	Confidence
6.3	The parasitic energy load of CO_2 capture installations reduces plant efficiency and therefore increases upstream environmental impacts due to increased mining/gas extraction. The non-CO_2 emissions, chemical use and waste stream can also impact the freshwater ecotoxicity.	-2	High Multiple literature sources Good agreement
6.4	CO_2 capture installations could considerably increase both total water withdrawal and consumption by fossil-fuel power plants. Water is needed for flue-gas cooling prior to capture, solvent make-up, and compression processes. However, recent designs for post-combustion CCS power plants suggest additional water demand can be met by use of water that has been condensed from the flue gas prior to entering the absorber.	0	High Multiple literature sources Conflicts present

Table 3-6: Assessment overview for CCS in industrial sector

SDG Target	Summary of literature findings	Score	Confidence
6.3	CO_2 capture plants in the industrial sector will lead to additional energy use and potentially greater upstream environmental impacts associated with coal mining. Natural gas and biomass use lead to decreased environmental impacts in systems with waste heat recovery. Some industrial processes in the chemical/refining sector may involve less energy intensive CO_2 capture processes, reducing the environmental impacts.	+2/-2	Low Few sources of literature Good agreement
6.4	Water use is expected to increase for industrial applications of CO_2 capture utilising amine-based post-combustion capture systems. Pre-combustion systems using water-gas shift technologies will also lead to greater water use.	-1	Low Few sources of literature Limited agreement

In conclusion, the increased environmental impacts on freshwater ecotoxicology of CO_2 capture systems, and the possible additional water use associated with CO_2 capture would indicate an overall **constraining (-1)** interaction between CCS and SDG 6. The possibility for reduced water consumption in modern plant designs could improve this scoring in the future.

3.2.4 Specific knowledge gaps in current literature

Evidence on the environmental impacts and water-usage of CO_2 capture applications in the industry is limited as is the study of other fuels than coal. Furthermore, second-generation CO_2 capture processes, such as ammonia-based CO_2 capture could be further examined to assess the potential improvements in terms of environmental impacts as compared to conventional amine-based capture systems.

3.3 SDG 7 – Affordable and clean energy

SDG 7 is focused on increasing the provision of affordable and clean energy. Providing universal access to energy, increasing energy efficiency and accelerating the deployment of renewable energy are key objectives. SDG 7 is linked to many of the other SDGs, such as good health and wellbeing (SDG 3), through the provision of clean cooking fuels, climate action (SDG 13), through reduced fossil-fuel use, and work and economic growth (SDG 8) due to new economic and job opportunities brought about by renewable energy technologies as well as by the CCS application in power generation and industry.

3.3.1 Key targets relevant for CCS

SDG 7 includes 3 targets (7.1-7.3). The deployment of CCS could have an interaction in the achievement of 2 of these targets. An overview of the relevant targets and justification for their inclusion in this assessment is provided in Table 3-7.

Table 3-7: SDG 7 targets with possible interactions with CCS

SDG Target	Target description	Possible interactions – power CCS	Possible interactions – industry CCS
7.1	By 2030, ensure universal access to affordable, reliable and modern energy services.	CCS could reduce the climate impact of fossil fuels in the energy sector, however it will also increase the cost of producing power from coal and gas-fired power stations.	CCS could reduce the climate impact of fossil fuels used to provide heat and power to industry.
7.3	By 2030, double the global rate of improvement in energy efficiency.	Capturing CO_2 from power stations needs energy, so this reduces the energy efficiency of power production.	Capturing CO_2 from industry needs energy, so this could reduce the energy efficiency of some industrial production processes.

3.3.2 Evidence from literature

Affordability

The assumed affordability of a particular power generation technology can be informed by an assessment of the levelized cost of electricity (LCOE). The cost is typically given per kilowatt-hour or megawatt-hour. It includes the initial capital, discount rate, as well as the costs of continuous operation, fuel, and maintenance. This type of calculation assists policymakers, researchers and others to guide discussions and decision-making. The LCOE is a measure of a power source that allows comparison of different methods of electricity generation on a consistent basis.

Adding CO_2 capture technology onto a conventional gas or coal-fired power plant will increase the capital and operational costs to the plant, pushing up the LCOE. These increases can be quite considerable. Data in Table 3-8 depicts that adding CO_2 capture to a new coal-fired power plant can increase the LCOE by between 35-40%, and between 27-33% for new natural gas combined cycle power plants (Rubin, Davison and Herzog 2015). These are by no means the only figures available for the levelized cost of CCS, however these can be considered as well representative from literature. Based on this information, it can be concluded that adding CO_2 capture to a fossil-fuel power plant will increase the cost of producing electricity, with these costs presumably passed onto the customer, to the detriment of 'affordability'. It should be made clear that the costs in Table 3-8 do not include the external costs of emitting CO_2 (i.e. impact on the environment), or possible regulatory measures such as emission quotas or taxes on emitting CO_2. Such measures would increase the LCOE from unabated fossil-fuel, closing the gap between CCS and non-CCS power production.

Table 3-8: Levelised cost of electricity production associated with coal and gas fired power plants, with and without CO_2 capture (after (Rubin, Davison and Herzog 2015)).

Power plant type	**Range (USD/MWh) (2013)**	
	Low	High
New bituminous coal power		
LCOE w/o capture	61	79
LCOE w/ capture	94	130
New Natural Gas Combined Cycle		
LCOE w/o capture	42	83
LCOE w/ capture	63	115

The LCOE of power at fossil-fuel power plants equipped with CO_2 capture systems are also higher than the LCOE from certain intermittent renewable energy sources (IRES) such as wind power, large scale solar PV and solar thermal systems (Hayward and Graham 2017). However, LCOE is not a sound measure when comparing baseload power plant with IRE sources. So to fully explore the issue of affordability, it's important to look beyond individual LCOE of CCS at plant level, and to consider the role of the technology as part of a future energy system. For example, in future energy systems with a high proportion of IRES, additional infrastructure such as battery storage and gas-fired peaking plants may be necessary to maintain a stable power system. In this instance, there is evidence to suggest that CCS on coal and gas-fired power plants have comparable LCOE to IRES when accounting for this additional infrastructure. Furthermore, the total system costs of reaching a decarbonised power system are expected to be higher in the absence of CCS (Bui, et al. 2018) (Brouwer, et al. 2016).

Reliability

Reliability in the context of SDG 7, is interpreted to be concerned with power systems being able to meet the demand for power in a consistent manner without the risk of shortages or interruptions. Fossil-fuel powered generation can provide reliable and dependable power generation that can be used to match demand. The addition of CCS to a coal or gas-fired power will not affect the dispatchable nature of these plants. The increased proliferation of intermittent renewable energy sources in the power system has considerable environmental benefits, however this does represent challenges for demand matching given that wind and solar power technologies have capacity factors of approximately 20-40% (Hayward and Graham 2017). Although at times, at least in a political context, renewables and CCS are considered as 'either or' technologies, there is evidence to suggest that a combination of these power generation sources is likely to provide the most robust and cost-efficient power system (Brouwer, et al. 2016).

The provision of all forms of low carbon power, including CCS, can indirectly reduce the emission of industrial production. In the US, for example, roughly a third of the greenhouse gas emissions associated with industrial production (1.5 $GtCO_2$) are caused by indirect emissions (EPA 2018). The emissions are produced by the burning of fossil fuels at a power plant to provide the electricity consumed by industry.

Energy efficiency
As mentioned in SDG 6, adding CCS to any power or industrial installation will lead to an inherent energy penalty, which is a direct trade-off with the climate benefits to be achieved. Particularly for post-combustion CO_2 capture, the heat required for the regeneration of amine-based solvents can reduce the overall efficiency of the power plant by as much as 25% for coal-fired power plants, and 20% for gas-fired power plants (Ou, Zhai and Rubin 2016). Second-generation amine systems such as CESAR-1 (blended 2-Amino-2-Methyl-Propanol and piperazine) have the potential to reduce this impact. CESAR-1 reduces power penalty by 25% for coal fired plant, and by 12% for gas fired plant as compared to standard MEA (Sanchez Fernandez, et al. 2014). Applications of post-combustion capture systems in industry will have similar impacts on energy efficiency as in the power sector. Some industrial processes to produce hydrogen, particularly those based on steam-methane reforming or gasification, already capture CO_2, which is expelled into the atmosphere as a by-product. Under these circumstances, the energy penalty for CCS would be limited to transport and storage of the CO_2 (UNIDO 2010).

3.3.3 Scoring assessment and justification

Table 3-9: Assessment overview for CCS in power sector

SDG Target	Summary of literature findings	Score	Confidence
7.1	Fossil-fuel power generation sources play an important role in the provision of modern power services in many nations. Adding CCS to coal or gas-fired power plant will considerably increase the levelized cost of electricity (LCOE), to the detriment of affordability. However, the integration of all low carbon power sources, including IRES, will increase the total cost of power supply. A combination natural gas with CCS and IRES could result in the most cost-efficient decarbonised power system.	+1	High Multiple literature sources Good agreement
7.3	Adding CCS to any power or industrial installation will lead to an inherent energy penalty, which is a direct trade-off with the climate benefits to be achieved. Particularly for post-combustion CO_2 capture, the heat required for the regeneration of amine-based solvents can reduce the overall efficiency of the power plant by as much as 25% for coal-fired power plants, and 20% for gas-fired power plants.	-2	High Multiple literature sources Good agreement

Table 3-10: Assessment overview for CCS in industrial sector

SDG Target	Summary of literature findings	Score	Confidence
7.1	CCS in the power sector has the potential to indirectly reduce the carbon intensity of industrial production through the provision of low carbon power. CCS in the power sector also enables the provision of dispatchable and reliable power supply for industry.	+1	High Multiple literature sources Good agreement
7.3	As in the power sector, particularly post-combustion capture applications in industry can have a negative impact on the energy efficiency of processes. Some industrial processes may be less effected than others.	-1	Medium Limited literature sources Good agreement

Whereas CCS offers a reliable, and in the long-term, cost-efficient power supply, the energy needed to operate CCS is to the detriment of energy efficiency goals. In conclusion, CCS applications in the power and industrial sectors have both **enabling and counteracting** interactions with SDG 7.

3.3.4 Specific knowledge gaps in current literature

There is currently limited literature focused on the additional energy use of CCS in industrial applications. More focus in this area could provide a clearer picture of conflicts between energy efficiency goals and CO_2 emission reduction efforts.

3.4 SDG 8 – Decent work and economic growth

SDG 8 aims to 'Promote sustained, inclusive and sustainable economic growth, full and productive employment and decent work for all'. It includes 10 actionable targets (8.1-8.10) that cover various aspects of economic growth, improved productivity and resource efficiency, the decoupling of economic growth from environmental degradation, and achieving full employment and decent work.

3.4.1 Key targets relevant for CCS

Because the development and deployment of CCS combines very substantial investment in innovation and infrastructure development, and because it has clear implications for the future role of fossil fuels (and the industries which extract, process, transport and use them) in low GHG energy system scenarios, CCS is likely to interact with SDG 8 in various ways, some more directly than others. While there are some SDG 8 targets that are clearly not so relevant (e.g. those about slavery and child labour, or sustainable tourism), there are several where it is more of a 'judgement call' whether there is an interaction of sufficient directness to include. For example, target 8.3[2] mentions several economic outcomes that seem relevant to CCS (job creation, innovation) but its primary focus is on the promotion of 'development-oriented policies' and deploying CCS does not seem especially closely connected to this. Similarly, target 8.8 is about labour rights and safe working environments, and while CCS is likely to either increase or maintain the amount of coal mining, it seems rather indirect to argue that because some coal mines are unsafe, this constrains or clashes with promoting safe working environments (which can be addressed separately).

The targets assessed to be most relevant and an overview of potential interactions are shown in the table below:

Table 3-11 SDG 8 targets with possible interactions with CCS

SDG Target	Target description	Possible interactions – power CCS	Possible interactions – industry CCS
8.1	Sustain per capita economic growth in accordance with national circumstances and, in particular, at least 7 per cent gross domestic product growth per annum in the least developed countries.	CCS deployment will have some influence on GDP (through investment, energy costs, etc). For fossil fuel exporters CCS would protect key industries.	CCS would increase costs for industrial producers but net macro effects are hard to predict.
8.2	Achieve higher levels of economic productivity through diversification, technological upgrading and innovation, including through a focus on high-value added and labour-intensive sectors.	Deploying a new technology / industry would support innovation and upgrading and may increase productivity. The CCS energy penalty however would reduce energy productivity.	As for power sector.

[2] The full text of target 8.3 is: "Promote development-oriented policies that support productive activities, decent job creation, entrepreneurship, creativity and innovation, and encourage the formalization and growth of micro-, small- and medium-sized enterprises, including through access to financial services"

8.4	Improve progressively, through 2030, global resource efficiency in consumption and production and endeavour to decouple economic growth from environmental degradation, in accordance with the 10-Year Framework of Programmes on Sustainable Consumption and Production, with developed countries taking the lead.	CCS energy penalty negatively affects resource efficiency, but CCS also could allow continued use of existing fossil fuel assets and resources. The large GHG reduction from CCS would help decouple growth from CO_2-related environmental harm, but other environmental pollution exists.	As for power sector.
8.5	By 2030, achieve full and productive employment and decent work for all women and men, including for young people and persons with disabilities, and equal pay for work of equal value.	CCS deployment will have some direct and indirect employment effects across sectors (both positive and negative), depending on employment intensity and investment levels vs. alternative technologies.	CCS would increase costs for industrial producers and likely influence employment levels, but net macro effects hard to predict. There would be some additional employment from manufacturing, installing and running capture plants.

3.4.2 Evidence from literature

The economic impacts of the deployment of power CCS are not well covered in the academic (or other) literature, which limits the evidence base that can be drawn on to support any assessment of the interactions with SDG 8. This lack of evidence is commented on in several of the few papers which touch on the economic aspects of CCS (Koelbl, et al. 2015) (Cambridge Econometrics 2013). Various papers explore the overall mitigation costs of different mitigation scenarios and typically include a no or low CCS scenario, but they do not comment in detail on findings for CCS, nor do they report on broader economic indicators.

The only paper identified that focusses predominantly on the economic impacts of CCS is a 2015 paper by Koelbl et al. which explored the employment, gross value added, and import dependency impacts of a mitigation scenario vs. a scenario without CCS (for Europe). Unfortunately, however, some of the key results of that paper are heavily influenced by the inclusion of bio-energy CCS (which is out of scope for this report) in the modelling, rendering some of the results less applicable. When reviewing the study by Koelbl et al. it should also be noted that 1) trades in materials/technologies are not modelled in the study, and 2) policy mechanism fostering low carbon technologies (e.g. BECCS) are exogenously determined in the model. These assumptions have a large impact on the employment/ gross value added (GVA) figures obtained in the study.

Regarding the US coal sector, one paper has investigated the role CCS could play in creating and retaining employment, but this paper also focuses on bio-energy CCS (Patrizio, Leduc, et al. 2018). An evaluation of the UK CCS investment scenarios, including the impact on identified linked economies, has also been undertaken to determine the potential for Jobs, GVA, and other benefits (). This report concluded there are economic benefits to deploying CCS along the East Coast of the UK through the creation of jobs and from the import and export of CCS related goods and services (Summit Power 2017).

For industrial CCS applications, no specific evidence has been identified about potential economic impacts (there is less evidence about industrial CCS more generally). The following sub-sections discuss the evidence and potential implications for the key SDG 8 targets, principally focussing on power CCS.

8.1 – sustain GDP growth

Various studies have compared the impact on overall mitigation costs of a greater or lesser contribution from specific technology options, for example by running scenarios in which nuclear or CCS are constrained or not available at all. These typically find that constraining or delaying CCS deployment increases overall costs, because a greater contribution is required from higher cost renewables than would optimally be deployed, although this is generally also true if other major low carbon energy sources are constrained (nuclear, solar PV etc) (OECD 2009) (Capros, et al. 2014) (Dessens, Anandarajaha and Gambhir 2016).

In general the consensus on the relationship between energy costs and economic growth is that higher energy costs inhibit economic growth (Berk and Yetkiner 2014), therefore having CCS available as an option should be positive for economic growth, though that may result more from having all major decarbonisation options available for cost-optimised selection than any intrinsic characteristic of CCS itself.

The studies that have explored the GDP impacts of CCS availability have typically found that the GDP differences are rather marginal between the scenarios with constrained vs. unconstrained CCS. For example, in a major study of EU energy scenarios undertaken for the European Commission (using two well-known models, E3ME and GEM-E3), Cambridge Econometrics found very limited differences in GDP growth out to 2050 between their delayed CCS scenario and other scenarios where CCS was unconstrained or where other options (energy efficiency; renewables) were maximised (Cambridge Econometrics 2013). A similar finding was observed in (Capros, et al. 2014).

As noted above, the only identified paper focussing only on the economic impacts of CCS was produced by Koelbl et al. in 2015. Their study modelled the impact of CCS on gross output, gross value added (GVA), employment, and import dependency, using a combination of energy system modelling and input-output modelling, at both economy and sector level. They find that in the CCS scenario, total gross output is slightly lower than in the no-CCS scenario. This is the net result of two opposing effects: firstly, the direct output of the electricity sector is lower in the CCS scenario because investment costs are lower, due to higher marginal cost investments if CCS is not available (a consistent finding with the higher costs of constrained CCS scenarios observed in the other papers referenced above). Secondly, there is higher upstream market expenditure in the CCS scenario, caused by a combination of lower taxes and BECCS-related subsidies, which lead to more money being available for expenditure on electricity and thus fuel. The impact on GVA is more pronounced, with 25% lower total GVA in the CCS scenario, however this is mainly caused by the subsidies available for BECCS, which have the effect of reducing GVA. Unfortunately the paper only models one CCS scenario, which allows bio-energy, so it is not possible to isolate the bio-energy related impacts entirely. The paper does however note that if more natural gas was used with CCS rather than BECCS, then the GVA of the CCS scenario would be higher, and thus closer to the no-CCS scenario (Koelbl, et al. 2015).

Koelbl et al. also present some interesting and relevant findings at the sector level. As might be expected, given the importance of CCS in making a continued role for fossil fuel related industries possible in carbon-constrained scenarios, for some sectors the differences in GVA are substantial between the scenarios. Primary and secondary sectors (i.e. extraction and processing) associated with fossil fuels have much higher output in the CCS scenario, while some tertiary (i.e. services, for example relating to grid integration and transmission and distribution) sectors benefit more in the no-CCS scenario (Koelbl, et al. 2015).

This last finding about the relative impact on fossil fuel related sectors also links to a more general issue relating to economic growth prospects in countries that are heavily dependent upon fossil fuel export revenues or fossil fuel generation (either because of domestic fossil resources or lack of alternatives). Future constraints on the use of fossil fuels could lead to substantial economic (and social) impacts as substantial mining, fuel processing, and power generation industries and assets become unsustainable (IPCC 2018); for these countries the successful development and deployment of CCS locally and globally could have major implications for future prosperity. Countries such as Australia have recognized that reduced coal consumption due to carbon constraints without CCS would have a 'detrimental impact' on their economy (Australian Parliament 2007). The global scale of this issue is explored in a paper on the role of CCS in unlocking 'unburnable carbon', which found that in CCS scenarios, approximately 200EJ per year more fossil fuel is used than in scenarios without CCS[3] (Budinis, et al. 2017). This means that the deployment of CCS allows for 200 EJ per year more low carbon energy to be available for society keeping energy prices in the overall energy system lower than without. This is important with regards to SDG 7, Affordable and Clean Energy.

For industrial applications of CCS, no evidence has been identified which explores the impact on economic growth. Applying capture technology to industrial sites would represent a substantial investment and the energy penalty (and other operation costs of the capture plant) would increase operating costs. However for many energy intensive products (e.g. steel, cement), there are no substitutes available for most applications, so it is not simple to predict how CCS-driven cost increases would influence demand for the products. It is likely that increased cost per tonne of product would drive greater efficiency in use (e.g. through optimized material and process design), but again, the impacts on national or sectoral GDP/GVA is hard to predict. The availability (and cost) of alternative deep decarbonization options for industry, and the speed of deployment of industrial CCS globally (and implications for industrial carbon leakage across borders) would also influence the impact on the relevant sectors within countries.

8.2 – improve economic productivity through diversification, technological upgrading and innovation

---

[3] To put that in context, total world primary energy supply in 2015 was 571 EJ (13,647 MTOE) according to the IEA Key world energy statistics 2017

No literature was found that comments directly on the impacts of CCS on economic productivity, however it seems likely that CCS would have some impact on productivity, in both power sector and industrial applications.

On the negative side, the fact that CCS incurs an energy penalty of 20-25% (Ou, Zhai and Rubin 2016) suggests that its deployment would reduce productivity (because more (energy) inputs are required for the same amount of output (of power, or industrial product).

On the positive side, the innovation and technological upgrading that would be necessary in order to further develop and deploy CCS may have some positive effects on economic productivity, especially in regions which are able to develop particular industrial expertise and manufacturing capability relating to CCS and which may generate substantial export revenues (as is the case with other low carbon technologies – indeed gaining competitive advantage in emerging low carbon markets is a major motivation for their deployment in e.g. the EU and China). Several countries who are well placed to capitalize on the commercial opportunities relating to CCS development (e.g. due to existing strengths in energy industries, oil & gas transmission, precision engineering etc) have already undertaken studies to explore the potential value of CCS (Koornneef, Noothout, et al. 2014) (Scottish Enterprise 2011), and while these studies do provide estimates for GVA (or market turnover) and employment, they are very region specific and based on assumptions about export market share that would not necessarily hold outside these well positioned regions.

One concrete example of the potential benefits of investing in CCS innovation is focused on R&D efforts in Norway (Størset, Tangen en Berstad, et al. 2019) examined 7 innovations in the CCS field, and through interviews with key scientists estimated the potential value creation of such innovations in the market. Although quantitative estimates were only able to made for 3 of the 7 innovations, the report concluded that the potential value creation of the innovations studies by 2050, would far outweigh the initial research and development investment of €100 million.

How these negative and positive potential impacts would net out is likely to depend on the country and sector context, and a country’s relative availability to capture the potential economic benefits.

8.4 – improve resource efficiency and decouple economic growth from environmental degradation

Target 8.4 combines two different objectives – improving resource efficiency; and decoupling economic growth from environmental degradation. CCS could potentially interact with these in various ways.

Resource efficiency, like economic productivity, is likely to be negatively affected by the energy penalty incurred by CCS; to improve resource efficiency in the energy sector would require the production of more usable final energy from a given amount of raw material inputs, however CCS has the opposite effect, and there is therefore a trade-off between resource efficiency and climate mitigation (PBL 2011).

A positive contribution to resource efficiency from CCS may be through the avoidance of stranded assets. The global fossil fuel infrastructure has been established at vast cost over the preceding decades (or longer) and is still being extended with new extraction infrastructure and fossil-powered generation around the world. In carbon constrained scenarios that are consistent with the goals of the Paris Agreement, much of this infrastructure would need to be retired before the end of its economic lifetime; creating stranded assets, investment losses, and inefficient use of embodied resources (i.e. the raw materials used to construct the infrastructure). Clearly, it is not resource efficient to construct resource-intensive infrastructure and then to not use it for its full life. By extending the period over which such assets can be used, CCS could enable the maximum utility to be obtained from the embodied resources. Use of CCS in this way is explored in a paper by (Johnson, et al. 2014) who conclude that CCS is an effective strategy for avoiding stranded capacity under stringent carbon constraints, but only if CCS can be deployed quickly enough. On the industrial side, it may also be more efficient to fit industrial plants with CCS than to develop alternative materials or production techniques that would require completely new manufacturing facilities.

The interaction between CCS and the objective to decouple economic growth from environmental degradation also seems likely to be both positive and negative. The positive interaction comes from the *raison d'être* of CCS – decarbonisation. CCS is being developed in order to reduce the GHG emissions of stationary, large point-source GHG-intensive activities such as power generation and some industrial activities . LCA studies show GHG reductions of 60-80% depending on the capture technology and fuel (Cuéllar-Franca and Azapagic 2015); given the importance of electricity generation and heavy industry to economic growth, CCS surely helps decouple economic growth from environmental degradation, at least from a climate change perspective. However, as detailed elsewhere in this report (i.e. in the chapters relating to SDG 3 (human health), SDG 6 (water), SDG 14 (life below water) and SDG 15 (life on land)), deployment of CCS technologies has significant negative impacts across a range of other environmental indicators (for details and references, see those chapters). Thus, from a broader environmental perspective, reliance on CCS clashes with the objective to decouple growth from environmental degradation. Both these positive and negative interactions would occur for both power and industrial sector CCS applications.

8.5 – full and productive employment and decent work

Target 8.5 aims for "full and productive employment and decent work for all women and men, including for young people and persons with disabilities, and equal pay for work of equal value". Deployment of CCS will impact employment levels because it will have major implications, as noted above, for continued activity in fossil-fuel related sectors. Whether the net effect at the national level is likely to be positive or negative is less clear, and probably depends on the country context, for example the level of dependence on fossil fuels and the employment intensity of alternative energy options (such as renewables). In general, there is consensus in the literature that high renewables scenarios will have higher overall employment than 'business as usual' pathways featuring lower levels of renewables and more fossil fuel capacity (Cameron and Zwaan 2015) (IRENA 2018) (New Climate Economy 2018), however theses sources do not specifically compare CCS against renewable pathways.

The Cambridge Econometrics study referenced above was focussed on employment (but reported GDP results as well), but as noted, it did not focus on CCS other than to include a delayed CCS scenario. They note that ‘it is difficult to estimate the employment effects of widespread implementation of CCS’. All scenarios showed an increase in employment versus the baseline, and they do not report any findings that indicate how CCS impacts employment levels vs. other technology options. Regarding the nature of jobs, they suggest that across the wider economy there will not be major changes in the balance of high and low skill jobs, though they note that CCS would require the updating of existing skills and the introduction of new skills, specialised to CCS. Looking at the sectoral impacts, they report that fossil fuel supply sectors will lose out unless CCS is deployed at scale, in which case fossil fuel and other CCS related sectors will benefit (Cambridge Econometrics 2013).

Koelbl et al. modelled the employment impacts of a CCS scenario vs. a no-CCS scenario. They observe lower direct employment in the power sector in the CCS scenario (due to higher employment intensity of renewable energy sources), but this is more than offset by higher employment in the upstream supply sectors, leading to a net increase in employment in the CCS scenario. However, as noted earlier, this result is heavily influenced by the dominance of BECCS among the CCS technologies in the CCS scenarios. The high employment intensity of the biomass supply chain leads to higher employment in the agriculture and forestry sectors as a result; this might not be seen were more of the CCS plants to be fueled by coal or gas, which would make the scenarios more similar at the macro level (Koelbl, et al. 2015).

An extensive country-specific assessment of job creation has been completed for the country of Norway (Størset, Tangen en Wolfgang, et al. 2018). The assessment concluded that through the development of a full-scale CCS project in the country, capturing and storing 1.4 $MtCO_2$ per year, 5,000 full-time jobs would be created. Furthermore, if Norway would develop its CCS market internationally, for example by exporting CO_2 capture equipment, producing and exporting blue hydrogen, and storing CO_2 from third-party countries in Norwegian storage sites, the total number of people directly employed in the CCS industry could reach up to 200,000 by 2050. These jobs would be created in the process industry, engineering, R&D, offshore and maritime sectors.

The conclusion from this limited set of studies seems to be that the macro level, net employment effects of CCS are likely to be linked heavily to the extent of an existing hydrocarbon production sector. At the sector level there will be important impacts from deployment (or not) of CCS, due to its role in sustaining fossil-fuel activities which would not be possible in carbon-constrained scenarios predominantly relying on other low carbon options. This last conclusion is also made by (Fankhauser, Sehlleier and Stern 2008), who also note the probable creation of a ‘limited number’ of jobs from the manufacture, installation and operation of capture systems. However, the Norwegian case study (Størset, Tangen en Wolfgang, et al. 2018) suggests that for countries looking at the export potential of CCS technologies and services, the potential employment figures can be much higher than when considering national application alone.

No evidence has been identified which considers the employment impacts of industrial CCS. While CCS in the power sector can be considered as an alternative decarbonization option competing with (and potentially displacing) other options, there would be both job gains and job losses across different sectors, as observed in the sources referenced above. However in industrial applications, CCS applied to steel or cement plants (for example) may potentially not displace any activity (because there may be no alternative way to reduce process emissions to sufficiently low levels), but rather represents additional activity in the form of the manufacturing, installation and operation of the capture technology. This of course would add considerable cost to the price of the finished product, and whether this would lead to opposing impacts on employment (e.g. by driving material efficiency in usage which reduces demand and thus employment) is hard to assess.

3.4.3 Scoring assessment and justification

Table 3-12: Assessment overview for CCS in power sector

SDG Target	Summary of literature findings	Score	Confidence
8.1	CCS deployment will likely have some impact on GDP though (limited) scenario studies have shown this to be relatively small. At the sector level, impacts are more pronounced with fossil fuel related sectors benefitting from CCS, and losses in sectors with displaced activity. Effects also likely to vary between country depending on their economic dependence on fossil fuel use and exports.	+1/-1	Medium Limited studies but general agreement
8.2	CCS will likely impact economic productivity. On the negative side, the energy penalty will negatively impact productivity; while for some countries there may be substantial commercial opportunities from developing CCS and gaining export market share.	+2/-1	Medium No direct literature about productivity effects, but literature available on energy penalty. Evidence is available on commercial opportunities of investment in CCS innovation.
8.4	Resource efficiency: negatively affected by CCS energy penalty; potential benefits from optimising use of current fossil fuel infrastructure and avoiding stranded (resource intensive) assets. Decoupling: positive support for decoupling of carbon emissions from economic growth; but negative impact through increased environmental impacts.	+2/-2	Medium confidence Ample evidence and good agreement for energy penalty, GHG reduction and other environmental indicators
8.5	CCS likely to have some impact on employment levels, but (limited) studies suggest these are not large at the net, macro level. As with GDP there will be more pronounced effects between sectors, and the net impact for countries will be influenced by their dependence on fossil fuel extraction and use. For specific countries able to develop and export CCS technology and services, job creation may be far higher.	+2/-1	Medium Limited studies but general agreement

Table 3-13: Assessment overview for CCS in industrial sector

SDG Target	Summary of literature findings	Score	Confidence
8.1	No direct literature. Industrial CCS likely to have some impacts on industrial costs, demand, international trade. Hard to predict direction or magnitude of net effect.	Not scored	
8.2	CCS will likely impact economic productivity. On the negative side, the energy penalty will negatively impact productivity; while for some countries there may be substantial commercial opportunities from developing CCS and gaining export market share.	+1/-1	Low No direct literature on productivity effects. Findings for power CCS seem applicable to industry.
8.4	Resource efficiency: negatively affected by CCS energy penalty. Decoupling: positive support for decoupling of carbon emissions from economic growth; but negative impact through increased environmental impacts.	+2/-2	Medium Limited evidence for industry CCS energy penalty, GHG reduction and environmental impacts
8.5	No direct literature. Industrial CCS likely to have some impacts on industrial costs, demand, international trade, and thus employment. Hard to predict direction or magnitude of net effect. Some (limited) additional jobs to install and run CCS industry,	Not scored	

3.4.4 Specific knowledge gaps in current literature

The evidence for the interactions between CCS and the different aspects of SDG 8 (economic growth, productivity impacts, resource efficiency and decoupling, employment impacts) could be strengthened by:

- More studies exploring economic impacts of CCS (GDP, GVA, employment), at different regional scales, reporting sector level and net impacts, and exploring key influencing factors such as current dependence on fossil fuels
  - Also considering different CCS options in isolation (BECCS / coal / gas)
  - Also including industrial applications
- Lifecycle employment studies of CCS vs. other low carbon alternatives (key renewables, nuclear)
- Studies on impact of CCS on industrial costs and implications for GVA, demand, employment, considering decarbonisation alternatives or product substitutions, and effect of uneven regional deployment of CCS on global trade

3.5 SDG 9 – Industry, innovation and infrastructure

SDG 9 aims to "Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation". Several of its 5 primary targets – for example those relating to sustainable infrastructure development, sustainable industrialisation, upgrading of industry, and research and innovation – seem likely to have synergies with CCS (though potentially trade-offs too). Targets relating to access to financial services and ICT are not relevant.

3.5.1 Key targets relevant for CCS

The key targets and possible interactions are summarised in the table:

Table 3-14 SDG 9 targets with possible interactions with CCS

SDG Target	Target description	Possible interactions – power CCS	Possible interactions – industry CCS
9.1	Develop quality, reliable, sustainable and resilient infrastructure, including regional and transborder infrastructure, to support economic development and human well-being, with a focus on affordable and equitable access for all.	From a GHG reduction perspective, CCS is sustainable infrastructure, and especially for countries dependent on fossil fuels or energy intensive industry, it will support economic development. However, there are some negative environmental impacts and concerns about lock-in to fossil fuels.	
9.2	Promote inclusive and sustainable industrialization and, by 2030, significantly raise industry's share of employment and gross domestic product, in line with national circumstances, and double its share in least developed countries.	CCS reduces GHG emissions from power and industry, supporting sustainable industrialisation (but has other negative environmental impacts). CCS is likely to have some impact on industry's share of employment and GDP but depends on various factors.	
9.4	By 2030, upgrade infrastructure and retrofit industries to make them sustainable, with increased resource-use efficiency and greater adoption of clean and environmentally sound technologies and industrial processes, with all countries taking action in accordance with their respective capabilities.	CCS makes power and industry sectors more sustainable from a GHG perspective but increases other environmental impacts. The energy penalty decreases (energy) resource efficiency, but CCS may allow more optimal use of existing infrastructure and avoid stranding (resource intensive) assets due to carbon constraints.	
9.5	Enhance scientific research, upgrade the technological capabilities of industrial sectors in all countries, in particular developing countries, including, by 2030, encouraging innovation and substantially increasing the number of research and development workers per 1 million people and public and private research and development spending.	Although CCS is a developed technology, it still faces challenges and requires research and innovation for reducing the cost for large-scale deployment and country-specific fuel and/or application. Thus, continued innovation in power and industrial CCS aligns with this target. CCS innovation activity though may be concentrated in a small number of countries (and generally not developing countries).	

3.5.2 Evidence from literature

No literature was identified which specifically explores whether CCS deployment has synergies with the thematic areas of industry, infrastructure and innovation, at least that could be broadly applicable outside specific country (or even sub-national) contexts.

Several of the SDG targets combine a number of sub-themes, for example 9.1 refers to various attributes of infrastructure (sustainability, resilience, reliability, quality), as well as mentioning economic development, human well-being, affordability and equitable access; this makes a range of potential interactions relevant within just one target.

The following sub-sections describe the most relevant and direct interactions for the key targets in some more detail. In the absence of specific evidence directly relevant to the core focal areas of the above targets, evidence and conclusions from other CCS-SDG relationships explored in this report is referenced.

9.1 – Develop quality, reliable, sustainable and resilient infrastructure

Assuming that it is not controversial to state that CCS (in either power or industrial applications) is likely to be (high) quality, reliable and resilient, the key question for the first interaction in target 9.1 is whether it is 'sustainable'. Here, as elsewhere with the SDGs, there is room for interpretation. 'Sustainable' has both environmental and economic connotations.

The environmental sustainability of CCS is discussed elsewhere in this report in relation to its impact in reducing GHGs (with 60-80% reductions possible depending on the capture technology, according to (Cuéllar-Franca and Azapagic 2015)), and in relation to its broader negative environmental impacts, which are discussed in the sections on SDGs 3, 6, 14 and 15, and about which there is consensus in the literature that CCS leads to greater environmental impacts than in unabated plants. In addition, there is the energy penalty, which is taken into account in both the GHG reduction and the broader environmental on a life-cycle basis, but is relevant in and of itself given that most sustainable futures envisage an increase in energy efficiency on both supply and demand sides. So for environmental sustainability the picture for CCS is mixed, with both positive and negative aspects.

Economic sustainability, as distinct from environmental sustainability, refers to whether an economic activity can be continued over the longer-term. For CCS the question of finite resources, and the concept of 'lock-in' becomes potentially relevant. There are concerns that CCS, because it allows continued use of fossil-fuels that would otherwise become unusable under stringent carbon constraints, and because of its high investment cost and long-life associated infrastructure, reinforces lock-in to a fossil-fuel system that is ultimately unsustainable or in some way sub-optimal (because the resources are finite, because of other environmental issues, or because alternatives might be better) (Markusson 2012) (Vergragt, Markusson and Karlsson 2011). It might not be economically sustainable to invest further in a system that relies on finite resources. As Markusson notes, however, some see CCS as the solution to the lock-in problem (because it decarbonises fossil fuel use) while others see it as extending the problem (because it adds further investment and infrastructure). It is far out of scope for this report to take a view on whether a (largely) decarbonised fossil fuel energy system is fundamentally problematic or not, and it is thus not possible here to conclude whether CCS is ‘sustainable’ or not from this economic perspective.

The second part of the target text contains the objective ‘to support economic development’. As discussed in connection with SDG 8.1, for countries that are dependent on fossil fuel extraction and usage, major reductions in coal (or gas) demand due to carbon constraints would represent a challenge to their prosperity. Widespread deployment of CCS would alleviate that and allow fossil fuel producers to continue to benefit economically. To a somewhat lesser scale, this may also be true for countries with major existing investment and activity in GHG intensive industries, whose sustained economic contribution could be enabled by industrial CCS. This ‘sustained contribution’ narrative is identified as the most compelling argument for CCS in the UK in a recent policy brief (Turner, et al. 2018). There are also potential economic opportunities for countries who are able to develop a competitive advantage in CCS technology and related services, as noted in reference to SDG 8.2; these are however unlikely to be realistically available to many developing countries.

9.2 – Promote inclusive and sustainable industrialization

The previous sub-section on target 9.1 discussed the ‘sustainability’ of CCS from various angles; these same issues would all apply in the context of ‘sustainable industrialization’ which is the key focus of target 9.2. CCS would substantially reduce the direct GHG emissions of both the power sector and certain GHG-intensive industries, and indirectly could support increased sustainability across further industrial sectors through the provision of low carbon (fossil-fuelled) electricity. On the other hand, CCS leads to worse performance across a range of other environmental indicators. So here too, the performance is mixed. There is no direct evidence available on whether CCS contributes to the ‘inclusive’ aspect of the target; because it is largely an extension of existing fossil fuel related activities, it is probably not likely to improve (or worsen) current levels of inclusivity.

The second part of the target aims to “significantly raise industry’s share of employment and GDP”. The limited studies on the economic impacts of CCS observe clear differences in impacts between sectors, however whether they show support for increasing industry’s share is not straightforward. Patrizio et al. demonstrated that manufacturing employment might increase with CCS implementation depending on whether the technologies are produced locally or are imported (Patrizio, Wienda Pratama and MacDowell 2020). Koelbl et al. reported largest increases in sectoral GVA in agriculture and forestry (driven by high bio-energy use with CCS in their model) and in mining, and much smaller increases in minerals and refining and basic metals. This result does not seem to support an increased share for industry (but is influenced by the large amount of bio-energy included) (Koelbl, et al. 2015). As noted for target 9.1, for certain well-placed countries, development of CCS may offer an interesting industrial development opportunity which if successfully grasped, could raise industry’s share. However, for the least developed countries referenced in the target text, CCS development is unlikely to be a realistic contributor to doubling industrial share.

9.4 – Upgrade infrastructure and retrofit industries

Target 9.4 focusses on the upgrading of infrastructure and retrofitting of industries "to make them sustainable, with increased resource-use efficiency and greater adoption of clean and environmentally sound technologies and industrial processes". From a GHG perspective, CCS clearly supports this aim in both power sector and industrial applications. However, there are trade-offs, as noted in the previous two targets, in the form of the negative environmental impacts of CCS and the energy penalty which does not help with increased resource efficiency. So for both power and industrial CCS, there are some clear positive and negative interactions with target 9.4. More indirectly, some of the linkages to broader resource efficiency (where CCS allows continued use of infrastructure that was resource intensive to create) and lock-in may apply, depending on how broadly the target text is interpreted.

9.5 – Enhance scientific research and upgrade the technological capabilities of industrial sectors

There are some slightly indirect potential interactions between CCS and target 9.5, which focusses on research and innovation as well as capacity development. CCS still requires considerable further research and development for reducing the cost for large-scale deployment. Activity to commercialise and deploy CCS is clearly consistent with a goal to boost innovation activity, spending and personnel. However, it is not obvious that CCS would achieve this any more than any other new technology at a similar stage, whether low carbon or not. Indeed, there may be smaller scale, more disruptive technologies that would align better with this aim, given the high costs and limited number of actors who can credibly engage in CCS innovation. As noted in previous sub-sections, CCS innovation (and resulting commercial benefits) may really only be accessible to a relatively small number of countries.

The actual deployment of CCS in power stations and industrial sites would support the goal to "upgrade the technological capabilities of industrial sectors", because it would require new equipment, new jobs and new skills, however many other activities (e.g. improving process, material and energy efficiency in industry) could achieve the same and at lower cost.

3.5.3 Scoring assessment and justification

Table 3-15: Assessment overview for CCS in power and industry sector

SDG Target	Summary of literature findings	Score	Confidence
9.1	CCS is sustainable from a GHG perspective but leads to worse performance on other environmental indicators and reduces energy efficiency. CCS could support economic growth in fossil fuel dependent countries or countries with competitive advantage in CCS development.	+1/-1	High confidence on 'sustainability findings' Low confidence about impact on economic growth
9.2	CCS is sustainable from a GHG perspective but leads to worse performance on other environmental indicators and reduces energy efficiency. Unclear whether CCS	+1/-1	High confidence on 'sustainability findings'

	can support increased industrial share of GDP / employment, primary sectors may benefit more.		Low confidence on industry share impact
9.4	CCS is sustainable from a GHG perspective but leads to worse performance on other environmental indicators and reduces energy efficiency.	+1/-1	High
9.5	CCS development could help enhance research and boost innovation activity (although not realistic for many countries). Deployment of CCS would support aim to upgrade technological capabilities.	+1	Low

3.5.4 Specific knowledge gaps in current literature

SDG 9 addresses several broad thematic areas, and interactions between CCS and some of these may be difficult to measure or predict, and perhaps best considered qualitatively. Thus, it is harder to identify specific knowledge or research gaps than for SDGs where the interactions are more direct and quantifiable. Some areas where the evidence base could be strengthened are outlined below:

- Further consideration of whether CCS contributes to lock-in to fossil fuel energy systems, and whether that is problematic or not, for different country contexts
- Studies into how both developed and developing countries could benefit from CCS development and deployment, analysing the CCS value chain and identifying activities where local firms could credibly be active and what sort of countries could credibly develop meaningful domestic CCS industries
- Further modelling studies to explore impact of CCS on GVA and employment of different sectors and how energy or industrial product cost increases would flow through the economy (e.g. input-output modelling)

In addition, filling the research gaps for SDGs 3, 6, 14 and 15 would help strengthen the evidence about the ‘sustainability’ of CCS, while addressing some of the SDG 8 gaps would improve understanding of the economic interactions.

3.6 SDG 11 – Sustainable cities and communities

SDG 11 aims to "Make cities and human settlements inclusive, safe, resilient and sustainable". It recognises that with more than half the world's population already living in cities, and with that proportion expected to reach two-thirds by 2050, it is vital that we build and manage cities in a sustainable way. Through its 10 targets it covers a range of core issues relevant to cities and communities including: access to safe and affordable basic services and transport; disaster resilience; environmental impact; as well as quality of life issues such as access to green spaces and protection for cultural and natural heritage.

3.6.1 Key targets relevant for CCS

The only SDG 11 target with clear direct relevance for CCS is 11.6 which focusses on environmental impact including air quality and waste management. The environmental footprint of a city includes the electricity and industrial products it consumes, whether these are produced near the city or not. The sustainability, or not, of these inputs thus contributes to the sustainability of the city itself.

Targets 11.1 (access to safe and affordable housing and basic services), 11.2 (access to safe and affordable sustainable transport) and 11.3 (sustainable urbanisation) may have some indirect relationship with CCS, because CCS deployment will affect the price of electricity (a basic service), and because low carbon electricity provided by CCS helps enabling sustainable transportation (e.g. rail and electric vehicles) and sustainable urbanisation. There is no direct evidence for these relationships though, and there are other more direct ways to enable sustainable urbanisation and transport. These targets are not discussed any further.

Table 3-16 SDG 11 targets with possible interactions with CCS

SDG Target	Target description	Possible interactions – power CCS	Possible interactions – industry CCS
11.6	By 2030, reduce the adverse per capita environmental impact of cities, including by paying special attention to air quality and municipal and other waste management.	CCS reduces the GHG emissions of electricity and industrial processes, thus can help provide cities with sustainable inputs from a GHG perspective. However some environmental impacts (especially air quality) are worse with CCS, and the energy penalty increases supply chain impacts, including mining wastes.	

3.6.2 Evidence from literature

Reducing the environmental impact of cities

Whether or not power stations or GHG-intensive industrial facilities are located within city limits, a considerable proportion of their outputs (electricity or industrial products such as steel or cement) will be used in cities. A full accounting of the environmental impact of a city should include the life-cycle impacts of these inputs.

As noted in several previous sub-sections, CCS has both positive and negative environmental implications. It can reduce GHG emissions by 60-80% (Cuéllar-Franca and Azapagic 2015), which could clearly make a substantial contribution to reducing the climate change related impacts of both the electricity and industrial products used by cities. However other environmental impacts, such as human toxicity, photo-chemical ozone, particulate matter and water consumption and pollution, are generally agreed to be worsened by CCS application (vs. unabated plant; see sections on SDGs 3, 6, 14 and 15 for details and references), though it strongly depends on chosen fuel and technology. The extra energy required to run the CCS capture plant leads to increased fuel demand, which exacerbates environmental issues along the fuel supply chain. Waste management is highlighted in the target text; in some coal CCS LCA studies, disposal of the coal mining waste has been identified as a particular cause of worse environmental impacts (Volkart, Bauer and Boulet 2013).

Besides the waste associated with power generation and industrial facilities, growth in population signifies the increase of municipal solid waste. Cities and communities could address the issue of increasing waste in a sustainable manner and benefit from waste-to-energy, where electricity and heat are produced from the waste treatment. According to Global CCS Institute, CCS integration with waste-to-energy could make waste a zero or even negative emissions energy source (Global CCS Institute 2019).

3.6.3 Scoring assessment and justification

Table 3-17: Assessment overview for CCS in power and industrial sector

SDG Target	Summary of literature findings	Score	Confidence
11.6	CCS reduces the GHG emissions from power and industrial products used by cities, but leads to worse performance on other environmental indicators. Municipal solid waste has the potential to become a zero or even negative emissions energy source via waste-to-energy with CCS.	+2/-2	High Multiple sources and good agreement

3.6.4 Specific knowledge gaps in current literature

The literature relevant to 11.6 is the same as the literature relevant to SDGs 3, 6, 14 and 15; no additional knowledge gaps are identified that relate only to the interactions with 11.6.

3.7 SDG 12 – Responsible consumption and production

The twelfth sustainable development goal deals with the consumption and production practices of companies. It aims to reduce the strain on natural resources, as well as reduce the waste streams that end up in the environment, be it on the land, air or water. An important characteristic of this goal is the encouragement of sustainable lifestyles and business practices, which has similarities with the tasks within SDG 3 (good health and wellbeing), SDG 7 (affordable and clean energy) and SDG 9 (industry, innovation and infrastructure).

3.7.1 Key targets relevant for CCS

SDG 12 consists of 7 primary targets, 5 of which are relevant when considering the development of CCS for power and industry.

Table 3-18 SDG 12 targets with possible interactions with CCS

SDG Target	Target description	Possible interactions - power CCS	Possible interactions - industry CCS
12.2	By 2030, achieve the sustainable management and efficient use of natural resources.	CCS requires more energy to operate, reducing the efficiency of the industrial plant, and may increase water consumption.	
12.4	By 2020, achieve the environmentally sound management of chemicals and all wastes throughout their life cycle, in accordance with agreed international frameworks, and significantly reduce their release to air, water and soil in order to minimize their adverse impacts on human health and the environment.	Using CCS will positively impact the CO_2 emissions from a power or industrial plant, but the process generates additional waste from the capture process as well as draws on water resources.	
12.5	By 2030, substantially reduce waste generation through prevention, reduction, recycling and reuse.	The operation of CCS generates chemical waste.	
12.6	Encourage companies, especially large and transnational companies, to adopt sustainable practices and to integrate sustainability information into their reporting cycle.	CCS could be a positive way for companies to adopt the sustainable practice of reducing CO_2 emissions.	
12.c	Rationalize inefficient fossil-fuel subsidies that encourage wasteful consumption by removing market distortions, in accordance with national circumstances, including by restructuring taxation and phasing out those harmful subsidies, where they exist, to reflect their environmental impacts, taking fully into account the specific needs and conditions of developing countries and minimizing the possible adverse impacts on their development in a manner that protects the poor and the affected communities.	CCS could be a positive option to reallocate inefficient fossil-fuel subsidies to help offset. their environmental impact.	None.

3.7.2 Evidence from literature

The targets under this goal of ensuring sustainable consumption and production patterns have some overlap in how they relate to CCS, both for power and for consumption. These can be separated into 4 categories:

- Energy and natural resource use
- Water usage and waste
- Sustainable practices
- Fossil-fuel subsidies

The following sections will discuss the relevant targets within the context of these categories.

Energy and natural resource use

The topic of the energy use of the power plant or industry with CCS relates to target 12.2, which aims for the "sustainable management and efficient use of natural resources". Aside from the increased energy to install the carbon capture system, running the carbon capture system itself requires energy. Due to this increased energy draw, as compared to a power plant or industry without CCS, LCA studies often discuss the decreased efficiency of the overall system when CCS is included.

The efficiency for fossil fuel plants varies dependant on the type of capture process as well as what type of fuel is used. For post-combustion, pre-combustion, and oxy-combustion capture of various coal types (SCPC with bituminous coals, IGCC with bituminous coals), the efficiency for the plant without CO_2 capture was around 41%, while that with CO_2 capture was around 31%. When considering post-combustion capture at an NGCC power plant, the efficiencies were higher, with the non-CO_2 capture plant having about 51% efficiency and the CO_2 capture plant having about 44% efficiency (Rubin, Davison and Herzog 2015). A different life-cycle assessment ranks coal-fired power plants around 44% efficient without CO_2 capture, while natural gas power plants around 57% efficient without CO_2 capture. The respective efficiencies with CO_2 capture vary between about 33% and 38% for coal power plants and between 47% and 50% for gas-fired power plants (Singh, Stromman and Hertwich 2011). Similarly, one life-cycle assessment placed efficiency of a conventional power plant without CCS at about 46%, which decreased to about 28% with CCS. For an integration gasification combined cycle plant without CCS, the efficiency was listed at 48% while that with CCS is about 39%. The efficiency of an oxyfuel power plant with CCS was provided as about 33% (Pehnt and Henkel 2009). Other than the energy use, the materials requirement (which includes iron, cement, copper, and aluminium) for a fossil fuel plant with CCS is about double that of a fossil fuel plant without, when considering post-combustion and pre-combustion CCS (Hertwich, et al. 2015).

The situation for efficiency for industry and CCS is a bit more nuanced, since the output of an industrial plant is not energy, but a product, as well as the fact that there are limited studies performed for industrial CCS. Regardless, it is noted that the efficiency would decrease for cement and steel plants. For one LCA that considers cement production, the energy requirement is given per kg CO_2 captured for both the heat requirement for MEA regeneration and for electricity requirement for the capture and compression, though these are not converted into efficiencies (Volkart, Bauer and Boulet 2013). In another report, the alternative technique of calcium looping for

CO_2 capture within the cement industry is stated to have an expected efficiency penalty of less than 6%, remarking that this would be very low compared to oxy-combustion and amine scrubbing, though no details are given for the assessment of the three technologies (Bosoaga, Masek and Oakey 2009). On the contrary, an extensive study from Voldsund and co-workers within the cement industry reports that among MEA-based absorption, oxyfuel process, chilled ammonia process, membrane-assisted CO_2 liquefaction and calcium looping, the best energy performance is achieved by oxyfuel process (Voldsund, et al. 2019). In one study on a steel mill, 3 scenarios fluctuated the amount of thermal power used for both the carbon capture solvent regeneration and the district heating network. They found that the potential electricity production goes from 1,200 GWh/a with no CCS to 730 GWh/a when the heat production in excess of the district heating is used for CCS. This results in a reduction of electricity production by 40% (Arasto, et al. 2013).

Target 12.2 brings up the efficient use of resources, and both power and industrial CCS interact with this in that it decreases the efficiency of the plants.

Water usage and waste

Targets 12.2 and 12.4 deal with water usage, since they aim to achieve sustainable management of natural resources and the wastes that are released to water, among other environments. This applies for both power and industrial uses, since the water use is used for the capture process, and often released back into the source potentially carrying remnants of the chemical processes.

It is noted in several studies and LCAs that the water requirement increases with the use of CCS as compared to with a power or industrial plant without CCS (Volkart, Bauer and Boulet 2013) (Tsupari, et al. 2013) (Koornneef, Ramírez, et al. 2012) (Cuéllar-Franca and Azapagic 2015). Under SDG 6, it has already been discussed that the increased water requirements can potentially be managed by proper water stream integration in the process, while a study conducted for a post-combustion retrofit of a 305-MW coal-fired power plant in Saskatchewan, Canada, suggests that that the total additional water demand of the capture facility could be met by use of water that has been condensed from the flue gas of the power plant.

The generation of waste from CCS relates to targets 12.4 and 12.5 which address the responsible management of chemicals and wastes throughout their life cycles and the reduction of waste. CCS integration implies additional waste from the desulphurization unit as well as the CO_2 capture plant (spent sorbent, reclaiming waste, atmospheric emissions). SOx emissions to the atmosphere are generally decreased since high degree of desulphurization is required. The sulphur that is not emitted to the atmosphere is produced as a solid waste, i.e. FDG residues or elemental sulphur(Rubin, Chen and Rao 2007). without. Another assessment also reported an increase in waste and by-product in a power plant with CCS, though the extend of the increase varies depending on the type of plant, fuels and technology used (Koornneef, Ramírez, et al. 2012).

Sustainable practices

Adopting sustainable practices such as reducing emissions released to the atmosphere can be found within the targets 12.4 and 12.6. This serves as the primary goal for CCS and is widely described in literature.

For fossil fuel power plants with CCS, several studies and life cycle assessments have found significant decreases in greenhouse gas emissions when compared to fossil fuel plants without CCS, often citing emission reductions between 50% (which was for gas cycle and natural gas combined cycle plants with oxyfuel capture) and 100% (Koornneef, Ramírez, et al. 2012) (Giannoulakis, Volkart and Bauer 2014) (Cuéllar-Franca and Azapagic 2015) (Volkart, Bauer and Boulet 2013). One report compared the CO_2 emission reduction for fuel and capture type, showing that between natural gas combined cycle with post-combustion capture, supercritical pulverized coal with post-combustion or oxy-combustion capture, and integrated gasification combined cycle plants with pre-combustion capture, the CO_2 avoided is around 82-97% (Rubin, Davison and Herzog 2015). Another life cycle assessment found that with a 90% capture efficiency, the greenhouse gas emissions are decreased by 75-84% with CCS deployed (Odeh and Cockerill 2008).

Similarly for industrial applications, there are also large emissions reductions possible with the addition of carbon capture. A life cycle assessment of cement production found that the reduction of CO_2 emissions is between 39% and 78% depending on whether the energy source was from hard coal electricity or from waste heat or electricity (Volkart, Bauer and Boulet 2013). For the application of CO_2 capture with steel plants, the reduction in CO_2 emissions can be between 50-75% (Arasto, et al. 2013).

Fossil-fuel subsidies

The final target, target 12.c, deals with reallocating inefficient fossil fuel subsidies to better uses, to better represent the real cost of the environmental impacts. This could interact with CCS in that subsidies could be provided to fossil fuel plants if they were to implement carbon capture to reduce their emissions. This topic is scarcely discussed in literature, though there are reports on the overall economics of CCS. Other economic studies show it is often not profitable to implement carbon capture (Tsupari, et al. 2013), which could be remedied by the support from subsidies.

Two studies examined the effects of a subsidy on CCS in China and came up with several conclusions. The first is that since the NPV of retrofitting a coal-fired power plant with a carbon capture is negative, subsidies would encourage this deployment in an otherwise unprofitable venture. Another point the study makes is that there is an increase in CCS investment returns when there is a government subsidy, but not much change in CCS investment decision, concluding that the subsidy wouldn't entirely fund the CCS system, but would help to promote it (Fan, et al. 2018). An uncertainty analysis reported that by subsidizing CCS from $0.01 to $0.05/kWh, the investment potential would rise between 9 and 39%, while return on investment could be shortened by between about 4 months to 2 years. This could then result in carbon abatement potential between 0.1 to 1.89 Gt of CO_2 in 2030 (Chen, Wang and Ye 2016). This information is quite market-dependant, but it provides an idea of the potential of CCS subsidies on fossil fuel power plants. One last study looks into funding research and development for CCS and the deployment of CCS in general. It reports that with high CO_2 prices, the subsidies to R&D and new CCS plants make a little difference to the overall deployment of CCS, while lower CO_2 prices will lead to the subsidies resulting in better CCS deployment (Lohwasser and Madlener 2013).

3.7.3 Scoring assessment and justification

Table 3-19: Assessment overview for CCS in power and industrial sector

SDG Target	Summary of literature findings	Score	Confidence
12.2	CCS requires more energy to operate, as well as increasing the material demand to implement the carbon capture system, reducing the efficiency of the plant. For power plants with CCS, the efficiency is about 20-25% less than for power plants without CCS. This efficiency fluctuates depending on the plant type and capture technology. The materials required for a fossil fuel plant with CCS are about double than those required for a fossil fuel plant without CCS. Water usage increases significantly with the implementation of CCS.	-1	High Several LCAs mention the decrease in efficiency, increase in materials, and increase in water usage.
12.4	CCS draws on water resources, as well as increases the waste stream due to the capture system and cooling requirements. Reductions in greenhouse gas emissions would range from about 75 – 90% for fossil fuel plants and 39 – 78% for cement or steel plants.	+2/-2	High Well documented water usage and waste increase. Consensus on reduction in CO_2 emissions.
12.5	The deployment of CCS would increase the generated waste, due to the carbon capture process. This differs depending on the plant type and the capture technology, but includes NO_x, NH_3, ash, sulphur, and spent sorbent residue.	-2	Medium Several studies, but highly variable depending on the system.
12.6	CCS would make it possible for power and industrial plants to reduce CO_2 emissions to meet emission goals. For industrial CCS, could enable continuing production while reducing greenhouse gases.	+2	Low No specific literature on encouraging companies to implement CCS. Some overlap with subsidy studies.
12.c	Power CCS: Subsidies would help the deployment of power CCS, since the implementation of a CCS system is not economically profitable. The effect of the subsidy is contingent on the CO_2 price as well.	+1	Medium Few studies on analysis of fossil fuel subsides. The few referenced do support CCS subsidies.

SDG 12 is relatively broad, and CCS has constraining (-1), counteracting (-2), but also enabling (+1) and reinforcing (+2) interactions across the relevant targets. It is therefore not possible to provide an overall Nilsson score for this SDG.

3.7.4 Specific knowledge gaps in current literature

Particular literature is lacking over the potential effects of subsidies for CCS as well as the uptake of plants to introduce CCS, as brought up by target 12.6. Some inconsistencies have been observed regarding the comparison of results between alternative CO_2 capture processes in the cement industry, thus additional technical assessments would be beneficial. On the topic of alternative processes to MEA-based absorption CO_2 removal, there is limited information regarding water use and waste streams associated with novel capture types such as calcium looping.

3.8 SDG 13 – Take urgent action to combat climate change and its impacts

Although SDG 13 encourages action to address climate change and its impacts, it does not include quantitative targets for the reduction of GHG emissions. SDG 13 includes a clear caveat acknowledging that the United Nations Framework Convention on Climate Change (UNFCCC) is the primary international, intergovernmental forum for negotiating the global response to climate change. In order not to encroach on the remit of the UNFCCC, SDG 13 focuses on broad policy related targets.

3.8.1 Key targets relevant for CCS

The table below outlines the three primary targets of SDG 13, and possible interactions with CCS. It is clear from this table that there are few direct interactions between CCS and the targets of SDG 13, given that it excludes any qualitative or quantitative targets for emissions reductions. As the primary rationale for CCS is the reduction of CO_2 emissions, in order to combat climate change, it is considered appropriate that this emission reduction potential is included as part of this assessment. From this perspective therefore, it has been chosen to broaden this assessment to include the potential of CCS to reduce CO_2 emissions for the purpose of combatting climate change, consistent with the overall goal of SDG 13.

Table 3-20: SDG 13 targets with possible interactions with CCS

SDG Target	Target description	Possible interactions - power CCS	Possible interactions - industry CCS
13.1	Strengthen resilience and adaptive capacity to climate-related hazards and natural disasters in all countries	CCS is not focused on adaptation to climate change or natural disasters, but is a climate change mitigation technology. Implementing CCS can reduce the necessity for climate adaptation.	
13.2	Integrate climate change measures into national policies, strategies and planning	CCS offers policy makers different technical options for integrating climate change actions into national policies for industrial and power sector developments.	
13.3	Improve education, awareness-raising and human and institutional capacity on climate change mitigation, adaptation, impact reduction and early warning	As a technology, CCS does not contribute to this goal directly. As part of demonstration and industrial CCS projects, considerable efforts have been made to boost awareness and educate the public on the characteristics of the technology.	

3.8.2 Evidence from literature

Emission reduction potential of CCS

Applying post-combustion CO_2 capture to coal and gas-fired power plants can achieve emission reductions per MWh of close to 90% (Rubin, Davison and Herzog 2015). In theory, CO_2 capture rates as high as 99.7% can be achieved at low additional marginal cost in coal and gas-fired power plants equipped with CCUS (IEAGHG 2019). Capture rates of 90% are technically feasible for post-combustion CO_2 capture in blast furnaces and cement kilns, as well as for steam-methane reforming and ethylene oxide production processes (IEA 2011). Slightly lower capture rates can be expected for oil refineries given the presence of multiple distributed point sources and site space restrictions for CO_2 capture equipment. For many key industrial production processes, CCS represents the only technology able to achieve significant emissions reductions in the foreseeable future (UNIDO 2010).

Of course in order for CCS to be effective, there must be sufficient geological storage capacity available. There have been several regional storage capacity assessments conducted for China (Wei, et al. 2013), Europe (Geological Survey of Denmark and Greenland 2009) and North America (U.S. Department of Energy 2015), which all provide evidence for storage availability far in excess of expected CO_2 capture amounts. Globally, it has been estimated that there is between 8,000 and 55,000 gigatonnes (Gt) of practically accessible geologic storage capacity, and that for most regions storage capacity will not be the limiting factor for CCS deployment (Kearns, et al. 2016). To put these figures into perspective, the IEA calculates that the most cost-effective mitigation portfolio to reach a 2 degree scenario, would require approximately 7 Gt of CO_2 to be captured and stored globally (IEA 2017).

CCS in global mitigation assessments

Since the release of the Fourth Assessment Report of the IPCC in 2007, CCS has been consistently highlighted as a key mitigation technology for achieving CO_2 reductions in the energy supply and industrial sectors (IPCC 2007). In the IPCC's Fifth Assessment Report, the importance of CCS was further reinforced as many of the global climate mitigation models used in the assessment could not constrain greenhouse gas emissions below 450 ppm CO_2eq by 2100[4] without the use of the technology. The same report estimated that in scenarios which excluded CCS from the portfolio of actions to be used in reaching the 450-ppm target, the total mitigation costs were on average 138% higher in 2100 (IPCC 2014).

In the most recent IPCC Special Report on Global Warming of 1.5°C, a target of the UNFCCC Paris Agreement, the use of carbon capture and storage, particularly in combination with biomass (BECCS), was again underlined as an unavoidable technology (IPCC 2018). The modelling assessments detailed within the Special Report suggest that unless global final energy demand is reduced by 15% by 2030, and by 32% by 2050, and the share of renewable energy is increase from 14% today to 60% in 2030, and 77% by 2050, significant deployment of CCS will be needed to meet the goals of the Paris Agreement. Global energy demand is expected to continue to rise by 1.3% per year until 2040 (IEA 2017). The findings of the IPCC reverberate with those of the International Energy Agency's '2 degree scenario' (2DS)

---

[4] The figure synonymous with keeping mean global temperature by 2100 to no more than 2°C above pre-industrial levels

scenario, with CCS contributing to 14% of total global emissions reductions by 2060 (IEA 2017).

Awareness raising and education

There have been considerable efforts to communicate CCS as part of the development of demonstration projects (Lockwood 2017). The general low awareness of the technology has encouraged project developers to make considerable investments in public outreach and education activities (Shell 2016). In the UK, educational resources have also been developed to communicate CCS and it's potential role in climate change mitigation to 11-14 years, written in accordance with the UK national academic curriculum (CO2degrees 2019).

3.8.3 Scoring assessment and justification

Table 3-21: Assessment overview for CCS in power and industrial sector

SDG Target	Summary of literature findings	Score	Confidence
13.1	Although CCS does not contribute to resilience or climate adaptation directly, it allows the rapid decarbonisation of power and industrial sectors to reduce the reliance on adaptation measures.	+3	High Multiple literature sources Good agreement
13.2	CCS offers policy makers the ability to integrate carbon abatement strategies into industrial development and power sector developments. CCS can be applied to key industrial processes which have few alternatives to reduce emissions and are needed for basic building materials. IPCC analysis indicates that without CCS, the goals of the UNFCCC Paris Agreement will not be reached.	+3	High Multiple literature sources Good agreement
13.3	There is evidence that the majority of large scale CCS demonstration projects involve dedicated local public outreach plans. There is also evidence of CCS educational resources being developed for use in schools.	+2	Medium Some literature sources Good agreement

The considerable potential for CCS to immediately decarbonize both power and industrial sector, and the clear expectation that growth in global energy demand will continue to be met by fossil fuels, means that the deployment of CCS is considered **indivisible (+3)** with the SDG combatting climate change, in line with the targets of the Paris Agreement.

3.9 SDG 14 – Life below water

Introduction to goal SDG 14 is focused on the protection of the marine environment through the protection of the seas and oceans from pollution and overfishing. This goal also aims to minimize and address the impacts of ocean acidification.

3.9.1 Key targets relevant for CCS

Of the goal's 7 targets, 3 of them could have direct interactions with CCS.

Table 3-22: SDG 13 targets with possible interactions with CCS

SDG Target	Target description	Possible interactions - power CCS	Possible interactions - industry CCS
14.1	By 2025, prevent and significantly reduce marine pollution of all kinds, in particular from land-based activities, including marine debris and nutrient pollution.	There may be emissions, or waste products from the CO_2 capture system, that could cause marine pollution if not managed. CO_2 may leak from transport and infrastructure in the case of an accident.	
14.2	By 2020, sustainably manage and protect marine and coastal ecosystems to avoid significant adverse impacts.	The construction of offshore CO_2 transport and storage infrastructure could temporarily disrupt marine ecosystems.	
14.3	Minimize and address the impacts of ocean acidification.	In the long term, CCS will reduce atmospheric concentrations of CO_2 and can there contribute to a reduction in ocean acidification.	

3.9.2 Evidence from literature

Marine pollution

Post-combustion CO_2 capture systems using amine solvents need low levels of sulphur dioxide (SO_2) in the flue gas entering the system. To achieve this, flue gas desulphurisation (FGD) systems are used, which involve spraying limestone fines into the flue gas which reacts with the SO_2 to produce gypsum. In addition to the removal of SO_2, FGD systems can also inadvertently (partially) remove other substances in the flue gas. The addition of CCS leads to a deeper reduction of direct emissions of sulphur oxides, particulate matter, hydrogen chloride and hydrogen fluoride (HF) per kWh. The reduction of hydrogen fluoride results in an improvement of the score for the marine aquatic ecotoxicity potential (MAETP) impact category as part of life cycle assessment studies of post-combustion capture systems (Koornneef, van Keulen, et al. 2008). These findings are also supported by (Nie, Korre and Durucan 2011), who noted a reduction in the MAETP of 93% for the full life-cycle assessment of post-combustion CCS systems in power generation as compared to non-CCS equivalent. It is noted that Koornneef et al. (2008) points towards a possible overestimation of the potential environmental impact of HF emissions, and to a dominance of these emissions in the contribution to the total MAETP score. On the other hand, Singh et al. report MAETP increase in both coal-fired power plants and in natural gas combined cycle power plants (NGCCs) (Singh, Stromman and Hertwich 2011). This increase was associated with the production and waste disposal of monoethanolamine (MEA). Petrescu and co-workers also reported higher FAETP for all three technologies studied in a power plant (MDEA, ammonia and CaL), the largest of which is for MDEA and associated with the chemical's production and transportation (Petrescu, et al. 2017).

Two LCAs have been found reporting MAETP for the industrial sector, one for the cement (Rolfe, et al. 2018) and one for the steel industry (Chisalita, et al. 2019). They both report increased impact on marine aquatic ecotoxicity for all technologies studied, i.e oxy-fuel combustion and CaL for the cement industry and post-combustion MEA and CaL for the steel industry. In the first source, Rolfe et al. discuss the better performance of CaL compared to oxy-fuel combustion due to integrated waste hear recovery for CaL thus reduced electricity need and due to increased electricity need for oxy-fuel for the air separation unit (ASU) to provide pure oxygen. In the second source, main contributors in MAETP are the carbon dioxide transport and storage as well as the operation of NGCC.

Management and protection of marine and coastal ecosystems

Regarding the protection of the marine environment, there are several regulatory frameworks in place to manage any possible risks of the development and operation of offshore CO_2 storage sites. In 2007, the Convention for the Protection of the Marine Environment of the North East Atlantic (OSPAR Convention - 1992), recognised that the geological storage of anthropogenic CO_2 could help reduce ocean acidification brought about by human-induced climate change. In response, amendments were made to allow CO_2 storage under the marine environment to take place, but only in accordance with a risk management framework agreed upon by the 16 parties to the convention (OSPAR Commission 2007). Another broader treaty for the protection of the marine environment, the London Protocol (1996), also made amendments to allow CO_2 storage to be stored in geological formations under the sea-bed. Akin to the OSPAR Convention, the parties to the London Protocol agreed on a risk assessment and management framework (IMO 2006), as well as a set of specific guidelines for the disposal of CO_2 in sub-seabed geological formations (IMO 2012).

As with any industrial activity, there may be risks to human health and the environment. There are, however, two CO_2 storage sites in sub-seabed geological structures that have been in operation for multiple years. The Sleipner and Snøhvit sites in Norway, where CO_2 has been injected since 1996 and 2008, respectively, have been extensively monitored throughout their operational lifetime. Perhaps one of the most extensive monitoring programs could be considered the one completed within the large EU funded research project 'ECO2', which combined detailed seismic analyses of the storage sites and overburden (the layers of rock above the CO_2 storage layer), with state-of-the-art hydro-acoustic imaging of the seabed and chemical analysis of gas bubbles above the storage site. In short, the project did not find any evidence of leakage at the test sites (ECO2 2015).

The impact on the marine environment of developing CO_2 transport infrastructure is likely to be highly site specific. There is no literature available on this topic, however an environmental impact assessment of an offshore CO_2 pipeline and platform modification in the North Sea has been completed as part of the cancelled 'ROAD CCS Project'. The environmental impacts were identified as the displacement of seabed material for the shallow pipeline trench, additional noise and disturbance by ships involved in realising the project, and noise produced during the drilling of the CO_2 injection well. The environmental impacts of this activity were concluded as being negligible, with only unplanned catastrophic releases of CO_2 having possible consequences for seabirds (van Ginkel and Speets 2011).

Minimize and address the impacts of ocean acidification.
Increased anthropogenic CO_2 emissions are blamed for the increase uptake of CO_2 by oceans, causing the seawater to become more acidic, having a detrimental impact on marine life. CCS has the potential to remove large amounts of CO_2 from the atmosphere, storing it in geological traps where it cannot reach the atmosphere or oceans. CCS is recognized by international marine protection treaties the OSPAR convention and London Protocol as an important technology to prevent ocean acidification. CCS could mitigate the economic impacts due to reduced fishing as a result of ocean acidification (van der Zwaan and Gerlagh 2016).

3.9.3 Scoring assessment and justification

Table 3-23: Assessment overview for CCS in power sector

SDG Target	Summary of literature findings	Score	Confidence
14.1	The additional cleaning of flue-gases from coal-fired power plants via flue gas desulphurisation (FGD) prior to post-combustion CO_2 capture will also remove other pollutants such as hydrogen fluoride, improving the net environmental performance with regards to marine ecotoxicity.	+1/-1	Medium Few literature sources Some agreement
14.2	Through international marine treaties, there are regulatory frameworks in place to manage the geological storage of CO_2 in sub-seabed formations. Experience with offshore CO_2 storage sites do not show signs of leakage, despite extensive monitoring. Environmental impacts of CO_2 transport and storage infrastructure development are associated with minimal seabed disturbance and noise.	0	High Significant literature Good agreement
14.3	CCS has the potential to remove large amounts of CO_2 from the atmosphere, storing it in geological traps where it cannot reach the atmosphere or oceans. CCS can therefore contribute to the long-term stability of ocean pH.	+2	High Significant literature Good agreement

Table 3-24: Assessment overview for CCS in industrial sector

SDG Target	Summary of literature findings	Score	Confidence
14.1	Impact on marine ecotoxicity will be dependent on the composition of the flue gas from the industrial source, and the type of capture system.	-2	Low Limited literature Good agreement.
14.2	The transport and storage infrastructure for industrial CO_2 will be the same as in the power sector	0	High Significant literature Good agreement
14.3	CCS can a be applied to multiple industrial sectors, with the potential to reduce emissions significantly	+2	High Significant literature Good agreement

There is conflicting evidence regarding the impact of CCS on marine ecotoxicity, with literature suggesting improved performance due to the use of FGD on capture systems, and on the other hand the use of potentially harmful chemicals such as MEA in the power sector. The impact in the industry is also reported negative, though only two sources have been used. Regarding CO_2 storage, there are a number of marine treaties in place to manage the activity and ensure that it can be implemented in an environmentally benign manner. Furthermore, there is no literature to suggest that either closed nor currently operational CO_2 storage sites are leaking. This could warrant a re-examination of the IPCC’s findings when highlighted a counteracting interaction between CCS and SDG 14 due to the risk of CO_2 leakage to the marine environment. Finally, CCS can contribute greatly to the stabilisation and reversal of ocean acidity.

It is shown that CCS has both reinforcing and counteracting interaction with the targets of SDG 14 for the power sector and for the industry, therefore no overall scoring can be assigned.

3.9.4 Specific knowledge gaps in current literature

The impact characterisation score of hydrogen fluoride reduction through flue gas desulphurisation needs to be substantiated as it has the ability to greatly influence the net marine toxicity impact of CCS on coal-fired power plants. As with many of the other SDG assessment outcomes, there is a considerable lack of LCAs focused on the application of CCS in the industrial sector.

3.10 SDG 15 – Life on land

The fifteenth sustainable development goal relates to life on land. It covers both the reduction of wastes as well as the sustainable management of resources such as soil, forests and wetlands to help maintain good biodiversity and healthy ecosystems. The goal is targeted towards protecting both terrestrial and freshwater environments, with heavy overlap with SDG 6 about clean water.

3.10.1 Key targets relevant for CCS

Of the nine primary goals, two goals are relevant for CCS.

Table 3-25 SDG 15 targets with possible interactions with CCS

SDG Target	Target description	Possible interactions - power CCS	Possible interactions - industry CCS
15.1	By 2020, ensure the conservation, restoration and sustainable use of terrestrial and inland freshwater ecosystems and their services, in particular forests, wetlands, mountains and drylands, in line with obligations under international agreements.	Power or industrial CCS could interact with the freshwater ecosystems due to the water that is used for CCS and then released. Also, the atmospheric emissions other than CO_2 could impact the surrounding environment. In addition, CCS deployment might reduce the need for other land-intensive low carbon measures (e.g. wind parks, afforestation, hydropower projects).	
15.5	Take urgent and significant action to reduce the degradation of natural habitats, halt the loss of biodiversity and, by 2020, protect and prevent the extinction of threatened species.	By-products and emissions from the CCS systems could negatively interact with the surrounding habitats. Reducing CO_2 emissions would reduce damaging climate effects on biodiversity.	

3.10.2 Evidence from literature

The two targets of interest deal with the conservation of terrestrial and freshwater land and ecosystems and the reduction of habitat degradation. These targets interact with power and industrial CCS in two main ways: 1. emissions from the systems and life cycle and 2. water usage.

Emissions

The relevant indicators, as described by Korre et al. (2010), for life on land include

- Global Warming Potential (GWP) – impact of anthropogenic emissions on earth's climate
- Eutrophication Potential (EP) – impacts from high levels of macronutrients on both terrestrial and aquatic ecosystems
- Acidification Potential (AP) – impacts from acidity in soil, water, and organisms
- Freshwater Aquatic Ecotoxicity Potential (FAETP) – impact of toxic substances on the freshwater ecosystem
- Photochemical Ozone Creation Potential (POCP) – interaction of chemicals with sunlight to form certain air pollution, potentially interacting with plants
- Terrestrial Ecotoxicity Potential (TETP) – impact of toxic substances on the terrestrial ecosystem

Several LCAs address the effect of implementing CCS on these indicators (Volkart, Bauer and Boulet 2013) (Koornneef, Ramírez, et al. 2012) (Singh, Stromman and Hertwich 2011) (Pehnt and Henkel 2009). Cuéllar-Franca and Azapagic examined many of such LCAs and gathered the results. The main indicator CCS tries to reduce is the GWP, which can have reductions between 63% (with post-combustion capture in combined cycle gas turbine plants) and 82% (using oxy-fuel combustion in pulverized coal and integrated gasification combined cycle plants) (Cuéllar-Franca and Azapagic 2015).

Looking at pulverized coal power plants with post-conversion capture, Cuéllar-Franca and Azapagic state that EP has a wide range from 1% higher to 173% higher due to the use of MEA sorbent, which could result in ammonia emissions. FAETP ranged from 9% to 135% with the explanation that the removal of trace metals from MEA capture could be transferred to the wastewater stream. Contrasting this, the TETP was 36% reduced with CCS potentially because the trace metals ended up in the wastewater in the plant. There were varying opinions on the acidification potential, as some literature found that more coal was needed to supply extra energy to the capture facility, while others found that SO_2 and NOx emissions were removed at higher efficiencies. Similarly, increased fuel demand from a CCS capture system will raise the POCP, yet removing SO_2 and NOx in the MEA capture plant will decrease the POCP. For oxyfuel combustion capture, FAETP is expected to rise, but HF emissions and other acidic gases are reduced, lowering AP, EP and POCP. Fewer trace metals in the emissions also lowers the impact on TETP by about 20%. In a combined cycle gas turbine plant with post- and pre-conversion capture, the EP, TETP, AP and FAETP are all much higher with CCS. This can be attributed primarily to the MEA and ammonia emissions. Higher emissions are expected from the CCS supply chain for an integrated gasification combined cycle plant with post- and pre-conversion capture, where AP is 17% more, EP is 20% more, and POCP is 50% more than the power plant without CCS (Cuéllar-Franca and Azapagic 2015).

Another report which collected LCA results from power plants with various fuels concluded that the main contributor for GWP and acidification are indirect CCS emissions, while eutrophication mainly comes from a rise in direct emissions. Results were mixed for POCP, since indirect emissions were said to both increase and decrease (Corsten, et al. 2013).

Regarding the waste from industrial CCS, information was found for both the cement industry and the steel industry. For the cement plant, Garcia-Gusano et al. compared the results between a base scenario in 2030 and a CCS scenario which included a coal-fired CHP plant. As with the power CCS, GWP was reduced by 15%. POCP became worse with CCS by 5 times as much as without CCS. Acidification potential and freshwater aquatic ecotoxicity potential both increased 300% with CCS. Eutrophication on terrestrial life was 600% worse, and for the freshwater ecosystem, eutrophication rose by 14% when CCS was deployed. Introduction of a natural gas-fired CHP plant does not alter the overall trends observed with coal, with the exception of a significant decrease in GWP (García-Gusano, et al. 2015). Two more literature sources confirmed the reduction of the Global Warming Potential (Rolfe, et al. 2018) (Schakel, et al. 2018). Rolfe et al. reported that by deployment of either CaL or oxy-fuel combustion technology, EP and FAETP increased while PCOP was reduced. In the same direction, Schankel et al. stated that the PCOP deviation was insignificant while the net eutrophication impact increased for coal and decreased for natural gas and biomass-driven calcium looping in a cement plant.

An LCA for a steel mill compared post-combustion capture with MEA solvents and calcium looping. The GWP was reduced by between 48% and 58% when the MEA solvent was used and between 65% and 76% when the calcium looping process was used. There were increases in AP (14% - 58%), EP (8% - 46%), FAETP (6% - 21%), POCP (6% - 10%), and TETP (17% - 23%) when CCS was included, where for the most part calcium looping was less impactful than using MEA (Chisalita, et al. 2019).

Water usage

Out of the indicators above, eutrophication potential, acidification potential and freshwater aquatic ecotoxicity potential are those that interact with freshwater life, which is also included in life on land. These indicators primarily affect water discharged from the power or industrial plant, and their impact from LCAs can be seen in the analysis above.

Other studies have examined the requirement of water with CCS systems, as well as the wastewater that is then released with potential trace metals and substances. One study on a coal-fired power plant found that the use of carbon capture increases water withdrawal by more than half of the demand without capture (Sharma and Mahapatra 2018). Koornneef et al. (2012) found the increase in water usage for power plants to be between 32% and 93% (Koornneef, Ramírez, et al. 2012). A more recent study assessed water usage from a coal-fired power plant with CCS and a natural gas combined-cycle power plant, which was 72% more and 65% more, respectively, than the plants without CCS (Ou, Zhai and Rubin 2016). For a steel-making plant, the water usage for CCS was about 108 kg/ton of captured CO_2 (Tsupari, et al. 2013). This topic overlaps with SDG 12 and responsible consumption of water, which also describes the aspect of water usage and CCS and the possibility to provide the required water through water stream integration in the plant and water recovery from the flue gas during cooling before the absorber.

3.10.3 Scoring assessment and justification

Table 3-26: Assessment overview for CCS in power and industrial sector

SDG Target	Summary of literature findings	Score	Confidence
15.1	LCAs show that the water requirement for power and industrial plants with CCS can be between 32% and 93% higher than the plant without CCS. The indicators that address this target are Global Warming Potential and Photochemical Ozone Creation Potential, as they affect the conservation of life on land. GWP is reduced significantly for power and industrial plants with CCS, while POCP is generally expected to increase with CCS, though results are mixed for this target (also depending on the capture method).	+2/-2	High Significant literature Moderate agreement
15.5	For this target, relevant indicators from the LCAs are Eutrophication Potential, Acidification Potential, Freshwater Aquatic Ecotoxicity Potential and Terrestrial Ecotoxicity Potential. Each of these rose in general in	-2	High Significant literature Moderate agreement

	the case of CCS for both power and industrial plants. There were some counterarguments that TETP would be lower with CCS, as some toxins in the air might be removed instead in the water discharge, thus impacting more the FAETP. For oxyfuel combustion capture, an analysis of LCAs found that the AP and EP would be lower since HF and acidic emissions are reduced.		

Overall, LCAs show that for both power plants and industrial plants, adding CCS will significantly reduce the Global Warming Potential, yet this is accompanied by a general rise in emissions from the plant, impacting terrestrial ecosystems and freshwater ecosystems. The water usage also is significant for CCS, which could similarly impact habitats. Given this evidence, it is concluded that CCS can have both a **counteracting (-2)** bit also some **reinforcing (+2)** interaction with the targets of SDG 15.

3.10.4 Specific knowledge gaps in current literature

One gap found when examining the literature is the connection between the impact indicators and the degradation of the terrestrial or freshwater ecosystems, making it difficult to have a physical understanding of what the potential impacts are. Also, the specific interactions of some emissions are still ambiguous, and this can be seen by the variation in results from the LCAs. One review study mentioned that there are fewer LCAs on combined cycle gas turbine plants and integrated gasification combined cycle (Cuéllar-Franca and Azapagic 2015), while another study found few LCAs on the oxyfuel capture method (Corsten, et al. 2013).

3.11 Indirect or limited interactions

This assessment also identified a number of SDGs that could possibly interact with CCS, however no direct causal link was expected.

3.11.1 SDG 1 – No poverty

This SDG was included as having a potential indirect interaction with CCS. It is assumed that application of CCS could have a role to play in the provision of clean and affordable energy, which could have a knock-on effect on poverty levels. SDG 7 suggests that CCS can contribute to the provision of the most cost-efficient decarbonised energy system. However, no literature could be found specifically focused on the cost to the consumer of power produced from CCS-equipped power stations, and no literature is available which refers directly to CCS and poverty eradication. SDG 1 is also not assessed against CCS in the IPCC Special Report 1.5°C (IPCC 2018).

3.11.2 SDG 4 – Quality education

This SDG was included as having a potential indirect interaction with CCS, due to the possibility of providing clean and affordable power to schools and educational facilities. However, although power from CCS-equipped installations can be considered low carbon, the provision of power to schools is more of an issue of energy access, which can be met by any form of power generation. No literature could be found focused on CCS and education. SDG 4 is also not assessed against CCS in the IPCC Special Report 1.5°C (IPCC 2018).

4 Concluding remarks

4.1 Assessment outcomes

This assessment can be considered to be one of the most detailed evaluations to date of a specific technology's interaction with the Sustainable Development Goals. An approach has been taken to focus this assessment on the interactions of CCS and SDGs where credible and quantifiable evidence is available. The results of this assessment have been achieved by an extensive and systematic literature review of hundreds of scientific and non-scientific documents and reports. An overview of this assessment's key findings, with associated Nilsson scores, is presented in Table 4-1. Given the Nilsson score involves a normative approach, it is noted that it is not possible to add up the scores to assess the impact of CCS overall.

CCS has a number of **positive interactions** with the SDGs. Global modelling assessments from both the IPCC and IEA indicate that the significant deployment of CCS is indivisible in combating climate change (SDG 13), in line with the goals of the UNFCCC Paris Agreement. CCS plays an enabling role in the provision of affordable and clean energy and can support the decarbonisation of industry both through direct emissions reductions but also indirectly through the supply of low carbon power (SDG 7). Evidence has been found that CCS can support the retention of jobs in certain sectors and contribute to a decoupling of economic growth from environmental degradation, through the reduction of CO_2 emissions (SDG 8). Furthermore, CCS can enable sustainable infrastructure developments, provide a boost to innovation systems (SDG 9), and reduce the carbon footprint of cities to make them more sustainable (SDG 10). Through the reduction of CO_2 emissions to the atmosphere, and the subsequent lowering of the CO_2 concentration in the atmosphere, CCS can enable the stabilisation of ocean acidification, a key target of SDG 14. In contrast to the IPCC Special Report 1.5°C (IPCC 2018), no evidence of leakage to the marine environment could be found, and CO_2 storage appears to be adequately regulated in many parts of the world through extensive marine treaties.

When evaluated against the SDGs, there are also a number of areas which appear **challenging** for CCS as a technology. Capturing CO_2 from the power and industrial processes has to be considered as a significant supplementary industrial activity which can have impacts on a range of environmental media. Primary cause of these negative environmental impacts are the waste and emissions in coal supply chain, while the use of chemical solvents in conventional post-combustion capture systems, mainly their production and associated emissions, seem to also contribute. The majority of life-cycle assessments indicate emissions to air and water and the production of wastes through the use of CCS. These emissions result in the technology having counteracting or constraining interactions with SDGs 3, 6 and 15, which have a strong focus on reduction of any form of discharges to the environment. It is noted that natural gas and biomass show overall significantly lower impacts than coal. CCS technology could also be considered as constraining in meeting energy efficiency targets of SDG 7, due to the inherent energy penalty associated with operating CO_2 capture systems. It is important to note however, that the CCS did not score a -3, indicating a cancelling interaction, against any of the SDGs covered in this assessment.

The divergent nature of many of the individual targets that are encompassed in each of the SDGs, has meant that assigning a single Nilsson score to each SDG is not possible. For example, where CCS can be considered enabling for target 9.2 ‘Promoting inclusive and sustainable industrialization…’, it is at the same time counteracting to target 9.4 which includes ‘increased resource-use efficiency’, due to the associated energy penalty of the additional CCS processes. Where possible, the scoring across targets has been aggregated to provide an overall score at SDG level in the summary Table 4-1. SDG 14 can be considered an example of this.

A full comparison of the findings of this report with the scoring of CCS in the IPCC Special Report can be found in Annex I: Comparison of findings between IPCC Special Report 1.5°C and this study completed by TNO.

Table 4-1: Summary table of key findings, Nilsson normative scores and confidence rating per SDG. Upper row of each assessment refers to interaction with CCS in the power sector, and lower row the interaction with industry. NB: scores cannot be combined

SDG	Findings from literature	Nilsson score	Confidence	Selected refences
3 GOOD HEALTH AND WELL-BEING	Life-cycle assessments (LCA) indicate increase in human toxicity potential (HTP) through the use of amine solvents. Particulate matter (PM) reduction on-site is offset by additional upstream emissions. New capture technologies could help to reduce the environmental impacts of CO_2 capture, however these have yet to be implemented.	-2 Counteracting	High	(Cuéllar-Franca and Azapagic 2015) (Oreggioni, et al. 2017) (Petrescu, et al. 2017) (IEAGHG 2010) (Tzanidakis, et al. 2013)
	Fewer sources available for industrial sector assessments, but those available point towards to both negative and positive human health impacts (HTP, PM, PCOP) depending on capture technology and fuel.	+2 Reinforcing / -2 Counteracting	Medium	(Volkart, Bauer and Boulet 2013) (Chisalita, et al. 2019) (Schakel, et al. 2018) (Rolfe, et al. 2018)
6 CLEAN WATER AND SANITATION	LCA literature indicate that fresh water aquatic ecotoxicity potential (FAETP) and eutrophication potential (EP) will increase due to amine use and reduced efficiency of capture plants. Reclaiming water from flue gases does allows water consumption to be minimised when using CCS.	0 Consistent / -2 Counteracting	High	(Cuéllar-Franca and Azapagic 2015) (Oreggioni, et al. 2017) (Ou et al. 2016); (Singh et al. 2011) (Hylkema and Read 2012) (International CCS Knowledge Centre 2018)
	Industrial application of post-combustion CCS with MEA or calcium looping shows increased FAETP and EP with coal, and decreased EP with natural gas and biomass. Water use is expected to increase for some industrial applications. Literature limited.	+2 Reinforcing / -2 Counteracting	Low	(Bosoaga, Masek and Oakey 2009) (Volkart, Bauer and Boulet 2013) (Schakel, et al. 2018)
	Modelling scenarios suggest that CCS has an important role to play in delivering the lowest cost decarbonised power systems. Generally speaking, however, CCS plants are associated with a lower energy efficiency.	+1 Enabling / -2 Counteracting	High	(Rubin, Davison and Herzog 2015) (Hayward and Graham 2017) (Brouwer, et al. 2016)

7 AFFORDABLE AND CLEAN ENERGY	CCS in the power sector can indirectly reduce emissions from industry through the provision of low carbon power. Direct application of CCS in industry has a negative impact on energy efficiency.	+1 Enabling / -1 Constraining	Medium	(UNIDO 2010) (Volkart, Bauer and Boulet 2013)
8 DECENT WORK AND ECONOMIC GROWTH	The impact of CCS on work and economic growth will vary per sector and country. At sector level, positive impacts are associated with fossil fuel related sectors. CCS can also provide more jobs and allow more jobs to be retained. The net employment effects of CCS vs. alternative energy sectors are unclear. CCS can contribute to decoupling economic growth from environmental degradation, however reduced energy efficiency is observed.	+2 Reinforcing / -1 Constraining	Medium	(Fankhauser, Sehlleier and Stern 2008) (PBL 2011); (Scottish Enterprise 2011) (Koelbl, et al. 2015); (Cambridge Econometrics 2013) (Capros, et al. 2014); (Ou et al. 2016) (Koornneef et al. 2014) (Størset, Tangen en Wolfgang, et al. 2018)
9 INDUSTRY, INNOVATION AND INFRASTRUCTURE	CCS can contribute to creating decarbonised industrial sectors. CCS can prevent the risk of stranded assets through the retrofitting of CO2 capture, and can support innovation in industrial processes and infrastructure. However, CCS may hinder the realisation of resource efficiency targets and its environmental impacts should be reduced.	+1 Enabling / -1 Constraining	Medium	(Cuéllar-Franca and Azapagic 2015) (Vergragt, Markusson and Karlsson 2011) (Markusson, 2012) (Turner, et al. 2018) (Koelbl, et al. 2015)
11 SUSTAINABLE CITIES AND COMMUNITIES	CCS reduces the CO_2 emissions from power and industrial products by between 60-80%, improving the carbon footprint of cities. CCS can improve local air quality around industrial sites. Many capture technologies are associated with negative impacts on other environmental indicators reducing its sustainability score. Municipal solid waste has the potential to become a zero or even negative emissions energy source via waste-to-energy with CCS.	+2 Reinforcing / -2 Counteracting	High	(Cuéllar-Franca and Azapagic 2015) (Volkart, Bauer and Boulet 2013) (Global CCS Institute 2019)
12 RESPONSIBLE CONSUMPTION AND PRODUCTION	CCS is a positive way for companies to adopt responsible practices to maintain industrial production, while reducing CO_2 emissions. The use of CCS does, however, lead to increased energy consumption and there is production of waste from the capture process.	+2 Reinforcing / -2 Counteracting	Medium	(Rubin, Davison and Herzog 2015) (Pehnt and Henkel 2009) (Hertwich, et al. 2015) (Odeh and Cockerill 2008) (Arasto, et al. 2013) (Fan, et al. 2018)

13 CLIMATE ACTION	CO_2 capture can reduce up to 90% of emissions from coal and gas-fired power plants, as well as key industrial processes. Global modelling assessments utilised by the IPCC clearly indicate that the broad deployment of CCS is unavoidable in order to limit human-induced global warming to 2 degrees by 2050. The greater the delay in reducing global GHG emissions, the greater the dependence will be on CCS, and also bio-energy combined with CCS (BECCS). Regional and global assessments indicate that sufficient geological storage capacity is available.	+3 Indivisible	High	(IPCC 2018) (IPCC 2014) (IEA 2017) (IEA 2011) (UNIDO 2010) (Rubin, Davison and Herzog 2015) (Kearns, et al. 2016)
14 LIFE BELOW WATER	The additional cleaning of flue-gases from coal-fired power plants via flue gas desulphurisation (FGD) prior to post-combustion CO_2 capture may also inadvertently remove other pollutants, improving the net environmental performance with regards to marine ecotoxicity. Increased FAETP is reported for both cement and steel sectors, though the literature is very limited. There is no evidence of CO_2 leakage to the marine environment at currently operating CO_2 storage sites. CCS can therefore contribute to the long-term stability of ocean pH.	+2 Reinforcing / -2 Counteracting	High	(Koornneef, van Keulen, et al. 2008) (Nie, Korre and Durucan 2011) (Singh, Stromman and Hertwich 2011) (ECO2 2015) (Rolfe, et al. 2018) (Chisalita, et al. 2019)
15 LIFE ON LAND	The Global Warming Potential is reduced significantly for power and industrial plants with CCS, contributing greatly to the protection of natural habitats and ecosystems. LCA literature indicate that fresh water aquatic ecotoxicity potential (FAETP) and eutrophication potential (EP) will increase due to amine use and reduced efficiency of capture plants. Some studies on oxyfuel indicate reduced EP and Acidification due to the removal of acidic emissions during CO_2 capture.	+2 Reinforcing / -2 Counteracting	Medium	(Cuéllar-Franca and Azapagic 2015) (Corsten, et al. 2013) (García-Gusano, et al. 2015) (Rolfe, et al. 2018) (Schakel, et al. 2018) (Chisalita, et al. 2019)

4.2 Knowledge gaps identified

The findings of life-cycle analyses play an important role in defining the outcomes of this assessment. The counteracting and constraining interactions between CCS and SDGs are generally informed by the negative scoring of CCS in LCAs found in literature. However, the bulk of these LCAs are focussed on the capture of CO_2 from coal-fired power plants using conventional chemical sorbents such as monoethanolamine (MEA). This combination of capture technology and CO_2 source leads to pronounced environmental impacts both upstream (additional coal mining), and also from the capture system (emissions to air, water, MEA production and waste disposal). Far fewer LCAs are available for natural gas power plants (which could have less pronounced upstream emissions) or the application of CCS in other industries (see Figure 2).

Furthermore, few literature sources could be found which examine the life-cycle impacts of alternative CO_2 capture systems, such as calcium looping or aqueous ammonia. These literature sources, (Petrescu, et al. 2017), (Chisalita, et al. 2019) and (Bosoaga, Masek and Oakey 2009), indicated that such systems have reduced environmental impacts as compared to those based on MEA. Additional LCAs examining these systems are therefore needed, with particular attention given to novel capture technologies expected to be able to compete with incumbent technologies. Particular attention should be given to so-called second-generation solvents, which are representative of commercially available technologies, and thus are likely to be the first technologies to be adopted when implementing CCS commercially. Attention to water usage and the energy efficiency of alternative CO_2 capture systems would be equally as valuable.

LCA material on the application of CCS in industry is extremely limited. Many of the conclusions in this assessment regarding the application of CCS in industry and the potential environmental impacts of doing so, have been based on expert judgement based on assumptions of industrial processes. For example, post-combustion capture is considered as feasible for blast furnaces and cement kilns, and thus may have similar environmental impacts applications of the same system in the power sector. However, there is a wide range of industrial processes, each with different CO_2 capture possibilities and process configurations (ZEP 2015). Specific LCA work completed on CCS applications in industrial sectors could be greatly beneficial to support the conclusions of this assessment, and to boost understanding of this topic in general.

Generally speaking, more consistent and clear reporting of where in the life-cycle particular environmental impacts occur, and clearer sensitivity analysis to show how important certain assumptions would be beneficial to this assessment. With regards to impacts on human health (measured using the indicator HTP), a relative assessment of the health impacts from CCS *vs.* other current or potential contributors, would help with contextual understanding of rather abstract indicators. Frequently in LCA studies, a description of the connection between the impact indicators and the degradation of the terrestrial or freshwater ecosystems is lacking, making it difficult to have a physical understanding of what the potential impacts are. Also, the specific interactions of some emissions are still ambiguous, and this can be seen by the variation in results from the LCAs, even for comparable activities. In addition, different technologies emit multiple gases during their life cycles, hence new metrics would be beneficial for the comparison of their climate impacts on a single scale.

This assessment has approached the issue of interaction between CCS and SDGs on a global level. But, as the outcomes of the evaluations concerning employment, economic growth and industrial development highlight (particularly SDGs 8 and 9), the economic impacts of CCS may differ between region, sector and a country's dependence on fossil fuels. Studies examining the macroeconomic impacts of CCS between developed and developing nations, and between fossil-fuel exporters and importers could allow a more meaningful and balanced assessment of these issues. In addition, employment studies of CCS versus other low carbon alternatives could have greater value than studies which look at these impacts in isolation.

4.3 Notes and recommendations for future work

During the execution of this assessment, a number of limitations to the applicability of these findings in policy development have become apparent. Defining a suitable counterfactual situation upon which to make this assessment will have a major impact on the outcome. As CCS is considered an additional industrial activity, this actually leads to a default situation where we see more non-CO_2 emissions to the environment, and greater resource use, despite considerable CO_2 emission reductions. This can lead to a rather negative portrayal of the technology against many SDGs, with the exception of SDG 13 on climate action, the *raison d'être* of CCS. As described in Section 3.8, it should also be noted that SDG 13 on climate action focusses on broad policy related targets and is a global modelling assessment exercise, but other SDGs, e.g. SDG 3, are based on plant level LCA assessments. Given that SDG 13 therefore excludes any qualitative or quantitative targets for emissions reductions, it means there are few direct interactions between CCS and the targets of SDG 13. This assessment has therefore been broadened to include the potential of CCS to reduce CO_2 emissions for the purpose of combatting climate change, which is very much consistent with the overall goal of SDG 13.

The construction and use of all low carbon technologies will have various environmental impacts. Like CCS, photovoltaic solar cells, lithium batteries, wind turbines and biomass plants will also incur trade-offs between the targets of the SDGs. Evaluating these trade-offs in isolation is likely to have limited value for policy development, given that the deployment of not one single low carbon technology will allow the achievement of both the SDGs and the Paris Agreement. It's recommended that future assessments of low carbon technology interactions and the SDGs should take a portfolio approach, comparing diverse sets of technologies and actions, with various degrees of application, in order to minimise the inevitable trade-offs between climate action and sustainable development for all.

Therefore, caution is urged in the use of isolated SDG technology assessments for the development of national and international policies which directly influence the selection of carbon abatement pathways. Studies such as these, are useful to broadly describe the interactions between a technology and the SDGs, highlighting specific opportunities and challenges which provide a basis for further detailed investigations regarding suitability and acceptable trade-offs. However, the optimum portfolio of mitigation actions must be based on a far more nuanced assessment, reflecting country-specific economic, geographic and environmental considerations. Finally, it is hoped that the outcomes of this study could help direct research and development efforts to improve the performance of CCS against certain SDGs. Periodic replication of such assessments over a numbers of years could thus be warranted.

5 Bibliography

Arasto, Antti, Eemeli Tsupari, Janne Kärki, Erkki Pisilä, and Lotta Sorsamäki. 2013. "Post-combustion capture of CO2 at an integrated steel mill - Part I: Technical concept analysis." *International Journal of Greenhouse Gas Control* 271-277.

Australian Parliament. 2007. "Between a rock and a hard place - The science of geosequestration. A report from the House of Representatives Standing Committee on Science and Innovation." Canberra.

Berk, Istemi, and Hakan Yetkiner. 2014. "Energy prices and economic growth in the long run: Theory and evidence." *Renewable and Sustainable Energy Reviews* 228-235.

Bleischwitz, Raimund, Catalina Spataru, Stacy D. VanDeveer, Michael Obersteiner, Ester van der Voet, Corey Johnson, Philip Andrews-Speed, Tim Boersma, Holger Hoff, and Detlef P. van Vuuren. 2018. “Resource nexus perspectives towards the United Nations Sustainable Development Goals.” *Nature Sustainability.*

Bosoaga, Adina, Ondrej Masek, and John E. Oakey. 2009. "CO2 Capture Technologies for Cement Industry." *Energy Procedia* 133-140.

Brouwer, Anne Sjoerd, Machteld van den Broek, William Zappa, Wim C Turkenburg, and Andre Faaij. 2016. "Least-cost options for integrating intermittent renewables in low-carbon power systems." *Applied Energy* 48-74.

Budinis, Sara, Niall Mac Dowell, Samuel Krevor, Tim Dixon, Jasmin Kemper, and Adam Hawkes. 2017. "Can carbon capture and storage unlock ‘unburnable carbon’?" *Energy Procedia* 7504-7515.

Bui, Mai, Claire S Adijman, Andre Bardow, Edward J Anthony, Andy Boston, Solomon Brown, Paul S Fennell, et al. 2018. "Carbon capture and storage: The way forward." *Energy and Environmental Science* (Royal Society of Chemistry). doi:DOI:10.1039/c7ee02342.

Cambridge Econometrics. 2013. "Employment Effects of selected scenarios from the Energy roadmap 2050. Final report for the European Commission."

Cameron, Lachlan, and Bob van der Zwaan. 2015. "Employment factors for wind and solar energy technologies: A literature review." *Renewable and Sustainable Energy Reviews* 160-172.

Capros, Pantelis, Leonidas Paroussos, Panagiotis Fragkos, Stella Tsani, Baptiste Boitier, Fabian Wagner, Sebastian Busch, Gustav Resch, Markus Blesl, and Johannes Bollen. 2014. "European decarbonisation pathways under alternative technological and policy choices: A multi-model analysis." *Energy Strategy Reviews* 231-245.

Chen, Huadong, Can Wang, and Minhua Ye. 2016. "An uncertainty analysis of subsidy for carbon capture and storage (CCS) retrofitting investment in China's coal power plants using a real-options approach." *Journal of Cleaner Production* 200-212.

Chisalita, D-A, L Petrescu, P Cobdenb, H van Dijk, A-M Cormos, and C-C Cormos. 2019. "Assessing the environmental impact of an integrated steel mill with post-combustion CO2 capture and storage using the LCA methodology." *Journal of Cleaner Production* 1015-1025.

CO2degrees. 2019. *CO2degrees.com.* 12 12. Accessed 12 12, 2019. https://co2degrees.com/content/crown-estate-and-geobus-education-resources%20.

Corsten, Marielle, Andrea Ramirez, Li Shen, Joris Koornneef, and Andre Faaij. 2013. "Environmental impact assessment of CCS chains – Lessons learned and limitations from LCA literature." *International Journal of Greenhouse Gas Control* 59-71.

Cuéllar-Franca, Rosa, and Adisa Azapagic. 2015. "Carbon capture, storage and utilisation technologies: A critical analysis and comparison of their life cycle environmental impacts." *Journal of CO2 Utilization* 82-102.

Dessens, Olivier, Gabrial Anandarajaha, and Ajay Gambhir. 2016. "Limiting global warming to 2 °C: What do the latest mitigation studies tell us about costs, technologies and other impacts?" *Energy Strategy Reviews* 67-79.

ECO2. 2015. *ECO2 Final Publishable Summary Report.* Kiel: ECO2. Accessed February 3, 2019. www.eco2-project.eu/.

EEA. 2011. *Air pollution impacts from carbon capture and storage (CCS). EEA Technical Report.* Copenhagen: European Environment Agency.

EPA. 2018. *Inventory of U.S. Greenhouse Gas Emissons and Sinks.* United States Environmental Protection Agency.

Fan, Jing-Li, Mao Xu, Shi-Jie Wei, Ping Zhong, Xian Zhang, and Yang Yang. 2018. "Evaluating the effect of a subsidy policy on carbon capture and storage (CCS) investment decision-making in China - A perspective based on the 45Q tax credit." *Energy Procedia* 22-28.

Fankhauser, Sam, Friedel Sehlleier, and Nicholas Stern. 2008. "Climate change, innovation and jobs." *Climate Policy* 421-429.

Furre, Anne-Kari, Ola Eiken, Havard Alnes, Jonas Nesland Vevantne, and Anders Fredrik Kiaer. 2017. "20 Years of Monitoring CO2-injection at Sleipner." *Energy Procedia* 114: 3916-3926.

García-Gusano, Diego, Daniel Garraín, Israel Herrera, Helena Cabal, and Yolanda Lechón. 2015. "Life Cycle Assessment of applying CO2 post-combustion capture to the Spanish cement production." *Journal of Cleaner Production* 328-338.

Geological Survey of Denmark and Greenland. 2009. *EU Geocapacity: Assessing European Capacity for Geological Storage of Carbon Dioxide - Storage Capacity.* EU Geocapacity.

Giannoulakis, Stylianos, Kathrin Volkart, and Christian Bauer. 2014. "Life cycle and cost assessment of mineral carbonation for carbon." *International Journal of Greenhouse Gas Control* 140-157.

Global CCS Institute. 2019. *2019 Perspective. Waste-to-Energy with CCS: A pathway to carbon-negative power generation.* Global CCS Institute.

Global CCS Institute. 2017. *Transport of CO2.* Canberra: Global CCS Institute.

Gonzales-Zuñiga, Sofia, Frauke Roeser, James Rawlins, Jonna Luijten, and Jessie Granadillos. 2018. *SDG Climate Action Nexus tool (SCAN-tool).* Cologne: NewClimate Institute.

Griggs, D, M Nilsson, A Stevance, and D McCollum. 2017. *A guide to SDG interactions: from science to implementation.* Paris: International Council for Science (ICSU).

Hansen, Olav, Douglas Gilding, Bamshad Nazarian, Bard Osdal, Philip Ringrose, Jan-Boye Kristoffersen, Ola Eiken, and Hilde Hansen. 2013. "Snøhvit: The History of Injecting and Storing 1 Mt CO2 in the Fluvial Tubåen Fm." *Energy Procedia* 37: 3565-3573.

Hayward, A Jenny, and Paul W Graham. 2017. *Electricity generation technology cost projections: 2017-2050.* Australia: CSIRO.

Hertwich, Edgar G., Thomas Gibon, Evert A. Bouman, Anders Arvesen, Sangwon Suh, Garvin A. Heath, Joseph D. Bergesen, Andrea Ramirez, Mabel I. Vega, and Lei Shi. 2015. "Integrated life-cycle assessment of electricity-supply scenarios confirms global environmental benefit of low-carbon technologies." *Proceedings of the National Academy of Sciences* 6277-6282.

Honegger, M, H Derwent, N Harrison, A Michaelowa, and S Schäfer. 2018. *Carbon removal and solar geoengineering: Potential implications for delivery of the Sustainable Development Goals.* New York, US: Carnegie Climate Geoengineering Governance Initiative.

Hylkema, Hette, and Andy Read. 2012. "Reduction of freshwater usage of a coal fired power plant with CCS by applying a high level of integration of all water streams." *Energy Procedia* 7187–7197.

IEA. 2016. *20 Years of Carbon Capture and Storage - Accelerating Future Deployment.* IEA.

IEA. 2018. *Electricity information: Overview 2018.* Paris: International Energy Agency.

IEA. 2017. *Energy technology perspectives.* Paris: OECD/IEA.

IEA. 2011. *Technology roadmap - carbon capture and storage in industrial applications.* Paris: Internation Energy Agency, OECD.

IEAGHG. 2010. *Environmental evaluation of CCS using life cycle assessment (LCA).* IEAGHG.

IEAGHG. 2019. *Towards Zero Emission CCS in Power Plants Using Higher Capture Rates or Biomass. IEAGHG Technical Report 2019-02.* IEAGHG.

IMO. 2012. *2012 Specific Guidelines for the Assessment of Carbon Dioxide for Disposal into Sub-Seabed Geological Formations.* London: International Martime Organisation.

IMO. 2006. *Risk Assessment and Management Framework for CO2 Sequestration in Sub-Seabed Geological Structures.* London: International Maritime Organization.

International CCS Knowledge Centre. 2018. *The Shand CCS Feasibility Study - Public Report.* Regina: International CCS Knowledge Centre.

International Monetary Fund. 2019. *Sustainable Development Goals.* March 26. https://www.imf.org/en/Topics/SDG.

IPCC. 2001. *Climate Change 2001 - The Third Assessment Report of the Intergovernmental Panel on Climate Change.* Cambridge: Cambridge University Press.

IPCC. 2007. *Climate Change 2007: Synthesis Report. Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, Pachauri, R.K and Reisinger, A. (eds.)].* Geneva, Switzerland: IPCC.

IPCC. 2014. *Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, R.K. Pachauri and L.A. Meyer (eds.)].* Geneva, Switzerland: IPCC.

IPCC. 2018. *Global warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change,.* Geneva, Switzerland: World Meteorological Organization.

IPIECA. 2018. *Mapping the oil and gas sector industry to the sustainable development goals: An Atlas.* London: The global oil and gas industry association for environmental and social issues.

IRENA. 2018. "Global Energy Transformation: A roadmap to 2050." Abu Dhabi.

Johnson, Nils, Volker Krey, David L. McCollum, Shilpa Rao, Keywan Riahi, and Joeri Rogelj. 2014. "Stranded on a low-carbon planet: Implications of climate policy for the phase-out of coal-based power plants." *Technological Forecasting & Social Change.*

Kearns, Jordan, Gary Teletzkeb, Jeffrey Palmer, Hans Thomann, Haroon Keshgi, Henry Chena Yen-Heng, Sergey Paltseva, and Howard Herzog. 2016. “Developing a consistent database for regional geological CO2 storage capacity worldwide .” *Energy Procedia* 4697-4709.

Klapperich, Ryan, Daniel Stepan, Melanie Jensen, Charlie Gorecki, Edward Teadman, John Harjua, David Nakles, and Andrea McNemar. 2014. "The Nexus of Water and CCS: A Regional Carbon Sequestration Partnership Perspective." *Energy Procedia* 7162-7172.

Koelbl, Barbara Sophia, Richard Wood, Machteld A. van den Broek, Mark W.J.L.Sanders, André P.C.Faaij, and Detlef P.van Vuuren. 2015. "Socio-economic impacts of future electricity generation scenarios in Europe: Potential costs and benefits of using CO2 Capture and Storage (CCS)." *International Journal of Greenhouse Gas Control* 471-484.

Koornneef, Joris, Andrea Ramírez, Wim Turkenburg, and André Faaij. 2012. "The environmental impact and risk assessment of CO2 capture, transport and storage – An evaluation of the knowledge base." *Progress in Energy and Combustion Science* 62-86.

Koornneef, Joris, Paul Noothout, Matthew Smith, and Chris Hendriks. 2014. "Steering CCS research and development to optimise benefits of implementing CCS in the Netherlands." *Energy Procedia* 7585-7597.

Koornneef, Joris, Tim van Keulen, Andre Faaij, and Wim Turkenburg. 2008. "Life cycle assessment of a pulverized coal power plant with post-combustion capture, transport and storage of CO2." *International Journal of Greenhouse Gas Control* 448-467.

Korre, Anna, Nie Zhenggang, and Sevket Durucan. 2010. "Life cycle modelling of fossil fuel power generation with post-combustion CO2 capture." *International Journal of Greenhouse Gas Control* 289-300.

Lockwood, T. 2017. *Public outreach approaches for carbon capture and storage project.* London: IEA Clean Coal Centre.

Lohwasser, Richard, and Reinhard Madlener. 2013. "Relating R&D and investment policies to CCS market diffusion through two-factor learning." *Energy Policy* 439-452.

Markusson, Nils. 2012. "Born Again: The Debate on Lock-in and CCS." *Energy & Environment* 389-394.

Metz, B., O. Davidson, H. C. de Coninck, M. Loos, L. A. Meyer, and (eds.). 2005. *IPCC Special Report on Carbon Dioxide Capture and Storage. Prepared by Working Group III of the Intergovernmental Panel on Climate Change.* Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press, 442.

Moser, Peter, Georg Wiechers, Sandra Schmidt, Juliana Garcia Moretz-Sohn Monteiro, Charithea Charalambous, Susana Garcia, and Eva Sanchez Fernandez. 2020. “Results of the 18-month test with MEA at the post-combustion capture pilot." *International Journal of Greenhouse Gas Control* 102945.

New Climate Economy. 2018. "Unlocking the Inclusive Growth Story of the 21st Century: Accelerating Climate Action in Urgent Times." Washington.

Nie, Zhenggang, Anna Korre, and Sevket Durucan. 2011. "Life cycle modelling and comparative assessment of the environmental impacts of oxy-fuel and post-combustion CO2 capture, transport and injection processes." *Energy Procedia* (Energy Procedia) 4 (2510-2517): 2510-2517.

Nilsson, Måns, Dave Griggs, and Martin Visbeck. 2016. "Map the interactions between Sustainable Development Goals." *Nature* 534.

Odeh, Naser A., and Timothy T. Cockerill. 2008. "Life cycle GHG assessment of fossil fuel power plants with carbon capture and storage." *Energy Policy* 367-380.

OECD. 2009. "The role of R&D and technology diffusion in climate change mitigation: new perspectives using the WITCH Model." Paris.

Oreggioni, Gabriel, Bhawna Singh, Christine Hung, Mijndert van der Spek, Ragnhild Skagestad, Nils Henrik Eldrup, Andrea Ramirez, and Anders Hammer Stromman. 2017. "Comparative Environmental Life Cycle Assessment of Oxyfuel and Post-combustion Capture with MEA and AMP/PZ - Case Studies from the EDDiCCUT Project." *Energy Procedia* 6604-6611.

OSPAR Commission. 2007. *OSPAR Guidelines for risk assessment and management of storage of CO2 streams in geological formations.* London: OSPAR Commission.

Ou, Yang, Haibo Zhai, and Edward Rubin. 2016. "Life cycle water use of coal- and natural-gas-fired power plants with and without carbon capture and storage." *International Journal of Greenhouse Gas Control* 249-261.

Patrizio, Piera, Sylvain Leduc, Florian Kraxner, Sabine Fuss, Georg Kindermann, Sennai Mesfun, Kasparas Spokas, et al. 2018. "Reducing US Coal Emissions Can Boost Employment." *Joule* 2633-2648.

Patrizio, Piera, Yoga Wienda Pratama, and Niall MacDowell. 2020. "Socially Equitable Energy System Transitions." *Joule* 1700-1713.

PBL. 2011. "EU Resource Efficiency Perspectives in a Global Context."

Pehnt, Martin, and Johannes Henkel. 2009. "Life cycle assessment of carbon dioxide capture and storage from lignite power plants." *International Journal of Greenhouse Gas Control* 49-66.

Petrescu, Letitia, Davide Bonalumi, Gianluca Valenti, Ana-Maria Cormos, and Calin-Christian Cormos. 2017. "Life Cycle Assessment for supercritical pulverized coal power plants with post-combustion carbon capture and storage." *Journal of Cleaner Production* 10-21.

Pietzner, Katja, Diana Schumann, Sturle D Tvedt, Hans Torvatn, Robert Naess, David Reiner, Sorin Anghel, et al. 2011. "Public awareness and perceptions of carbon dioxide capture and storage (CCS): Insights from surveys adminstered to representative samples in six European countries." *Energy Procedia* (Energy Procedia) 4: 6300-6306.

Rock, Luc, Simon O'Brien, Stephen Tessarolo, Jeff Duer, Vicente Oropeza, Bill Hirst, David Randell, et al. 2017. "The Quest CCS Project: 1st Year Review Post Start of Injection." *Energy Procedia* 114: 5320-5328.

Rolfe, A., Y. Huang, M. Haaf, A. Pita, S. Rezvani, A. Dave, and N. J. Hewitt. 2018. "Technical and environmental study of calcium carbonate looping versus oxy-fuel options for low CO2 emission cement plants." *International Journal of Greenhouse Gas Control* 85-97.

Rubin, Edward S, E John Davison , and Howard J Herzog. 2015. "The cost of CO2 capture and storage." *International Journal of Greenhouse Gas Control* 378-400.

Rubin, Edward S., Chao Chen, and Anand B. Rao. 2007. "Cost and performance of fossil fuel power plants with CO2 capture and storage." *Energy Policy* 4444-4454.

Sanchez Fernandez, E., E.L.V. Goetheer, G. Manzolini, E. Macchi, S. Rezvani, and T.J.H. Vlugt. 2014. “Thermodynamic assessment of amine based CO2 capture technologies in power plants based on European Benchmarking Task Force methodology.” *Fuel* 318-329.

Schakel, Wouter, Christine Roxanne Hung, Lars-Andre Tokheim, Anders Hammer Strømman, Ernst Worrell, and Andrea Ramírez. 2018. “Impact of fuel selection on the environmental performance of post- combustion calcium looping applied to a cement plant.” *Applied Energy* 75-87.

Schneider, M., M. Romer, M. Tschudin, and H. Bolio. 2011. "Sustainable cement production - present and future." *Cement and Concrete Research* 642-650.

Schreiber, Andrea, Petra Zapp, and Wilhelm Kuckshinrichs. 2009. “Environmental assessment of German electricity generation from coal-fired power plants with amine-based carbon capture.” *International Journal of Life Cycle Assessment* 547-559.

Scottish Enterprise. 2011. "Economic Impact Assessments of the proposed Carbon Capture and Storage demonstration Projects in Scotland – a Summary report."

Sharma, Naushita, and Siba Sankar Mahapatra. 2018. "A preliminary analysis of increase in water use with carbon capture and storage for Indian coal-fired power plants." *Environmental Technology & Innovation* 51-62.

Shell. 2016. *Peterhead CCS project - Stakeholder and public engagement and communications plan.* London: Shell UK Ltd.

Singh, Bhawna, Anders Stromman, and Edgar Hertwich. 2011. "Life cycle assessment of natural gas combined cycle power plant with post-combustion carbon capture, transport and storage." *Internation Journal of Greenhouse Gas Control* 5 (3): 457-466.

Sinha, Avik, Tuhin Sengupta, and Rafael Alvarado. 2020. “Interplay between technological innovation and environmental quality: Formulating the SDG policies for next 11 economies.” *Journal of Cleaner Production* 118549.

Størset, S, G Tangen, D Berstad, P Eliasson, K Anders Hoff, S Munkejord, S Roussanaly, and Malin Torsaeter. 2019. “Profiting from CCS innovations: A study to measure potential value creation from CCS research and development.” *International Journal of Greenhouse Gas Control* 208-215.

Størset, S, G Tangen, O Wolfgang, and Gunnar Sand. 2018. *Industrial opportunities and employment prospects in large-scale CO2 management in Norway.* SINTEF. https://www.nho.no/contentassets/e41282b08ceb49f18b63d0f4cc9c5270/industrial-opportunities-ccs_english.pdf.

Summit Power. 2017. “Clean Air – Clean Industry – Clean Growth. How Carbon Capture Will Boost the UK Economy.”

Tanzer, Samantha Eleanor, Kornelis Blok, and Andrea Ramírez. 2020. “Can bioenergy with carbon capture and storage result in carbon negative steel?” *International Journal of Greenhouse Gas Control* 103104.

Tsupari, Eemeli, Janne Kärki, Antti Arasto, and Erkki Pisilä. 2013. "Post-combustion capture of CO2 at an integrated steel mill - Part II: Economic feasibility." *International Journal of Greenhouse Gas Control* 278-286.

Turner, Karen, Julia Race, Oluwafisayo Alabi, and Ragne Low. 2018. "Making the macroeconomic case for near term action on CCS in the UK? The current state of economy-wide modelling evidence. Policy brief from the Centre for Energy Policy, University of Strathclyde International Public Policy Institute."

Tzanidakis, K, T Oxley, T Cockerill, and H ApSimon. 2013. "Illustrative national scale scenarios of environmental and human health impacts of carbon capture and storage." *Environment International* 48-64.

U.S. Department of Energy. 2015. *Carbon Storage Atlas 5th ed.* Washington DC: U.S. Department of Energy, Office of Fossil Energy .

UN. 2019. *Goal 6: Clean water and sanitation.* March 28. https://www.undp.org/content/undp/en/home/sustainable-development-goals/goal-6-clean-water-and-sanitation.html.

UN. 2017. *Progress towards the Sustainable Development Goals. United Nations Economic and Social Council.* United Nations.

UNIDO. 2010. *Carbon capture and storage in Industrial Applications.* Vienna: United Nations Industrial Development Organization.

United Nations Development Programme. 2016. *Mapping Mining to the Sustainable Development Goals: At Atlas.* UNDP.

United Nations. 2015. *Transforming our World: The 2030 Agenda for Sustainable Development.* New York: United Nations.

UNSDSN. 2019. *Mapping the renewable energy sector to the SDGs: An Atlas – Draft for public consultation.* Paris/New York: United Nations Sustainable Development Solutions Network.

van der Zwaan, Bob, and Reyer Gerlagh. 2016. "Offshore CCS and ocean acidification: a global long-term probabilistic cost-benefit analysis of climate change mitigation." *Climate Change* 137 (1-2): 157-170.

van Ginkel, Marloes, and Rob Speets. 2011. *Milieueffectrapportage CCS Maasvlakte (ROAD-Project).* Rotterdam: Royal Haskoning. Accessed February 4, 2019. http://www.commissiemer.nl/docs/mer/p24/p2479/2479-068mer.pdf.

Vergragt, Philip, Nils Markusson, and Henrik Karlsson. 2011. "Carbon capture and storage, bio-energy with carbon capture and storage, and the escape from the fossil-fuel lock-in." *Global Environmental Change* 282-292.

Vilariño, M. 2018. "Adaptation and mitigation in relation to sustainable development, poverty eradication and food security. Proceedings of the scoping meeting for Special Report on the impacts of global warming of 1.5ºC above pre-industrial levels and related global greenh." Accessed March 26, 2019. https://www.ipcc.ch/report/sr15/sr15_scoping_meeting.shtml.

Voldsund, Mari, Stefania Osk Gardarsdottir, Edoardo De Lena, José-Francisco Pérez-Calvo, Armin Jamali, David Berstad, Chao Fu, et al. 2019. “Comparison of Technologies for CO2 Capture from Cement Production—Part 1: Technical Evaluation.” *Energies* 559.

Volkart, K, C Bauer, and C Boulet. 2013. "Life cycle assessment of carbon capture and storage in power generation and industry in Europe." *International Journal of Greenhouse Gas Control* 91-106.

Wei, N, L Xiaochun, R.T Dahowski, C.L Davidson, and G.S Bromhal. 2013. “A preliminary sub-basin scale evaluation framework of site suitability for onshore aquifer based CO2 storage in China." *Int. J. Greenh. Gas Control, 12* 231-46.

World Health Organization. 2017. "Preventing noncommunicable diseases (NCDs) by reducing environmental risk factors." Geneva.

ZEP. 2015. *CCS in industry - Modelling the lowest-cost route to decarbonising Europe.* Brussels: European Technology Platform for Zero Emission Power Plants.

Annex I: Comparison of findings between IPCC Special Report 1.5°C (IPCC 2018) and this study completed by TNO. NB: the normative scores for individual SDG areas cannot be combined.

		3 GOOD HEALTH AND WELL-BEING		6 CLEAN WATER AND SANITATION		7 AFFORDABLE AND CLEAN ENERGY		8 DECENT WORK AND ECONOMIC GROWTH		9 INDUSTRY, INNOVATION AND INFRASTRUCTURE		11 SUSTAINABLE CITIES AND COMMUNITIES		12 RESPONSIBLE CONSUMPTION AND PRODUCTION		13 CLIMATE ACTION		14 LIFE BELOW WATER		15 LIFE ON LAND	
		IPCC	**TNO**	**IPCC**	**TNO**	**IPCC**	**TNO**	**IPCC**	**TNO**	**IPCC**	**TNO**	**IPCC**	**TNO**	**IPCC**	**TNO**	**IPCC**	**TNO**	**IPCC**	**TNO**	**IPCC**	**TNO**
Theme	**Technology**																				
Industry	Energy efficiency	+2		+2/-1		+2		+1		+1		+2		+1		-		-		-	
	Low carbon fuel switch	+2		+2/-2		+2		+2		+2		+2		+2		-		-		+1/-1	
	CCS/CCU	-1	+2/-2	+1/-1	+2/-2	+2/-2	+1/-1	+2	+2/-1	+2	+1/-1	-	+2/-2	+2	+2/-2	-	+3	-1	+2/-2	-	+2/-2
Replacing coal	Non-biomass renewables	+2		+2/-2		+3		0		0/-1		+2		+2		-		+2/-1		-1	
	Increased biomass	+2		+1/-2		+3		+1		+1		-		+2		-		-		+1/-2	
	(Advanced) Nuclear	-1		+2/-1		+1		+1		-1		-		-		-		-		-1	
	Coal co-fired with biofuels (Bio-CCS)	+2/-1		+1/-2		+2		+1		+1		-		+1		-		-		+1/-2	
	Coal fired plus CCS	-1	-2	+1/-2	0/-2	+2	+1/-2	-1	+2/-1	+1	+1/-1	-	+2/-2	-	+2/-2	-	+3	-	+2/-2	-	+2/-2

Evaluating technology options to mitigate greenhouse gas emissions

IEA Greenhouse Gas R&D Programme

Pure Offices, Cheltenham Office Park, Hatherley Lane,
Cheltenham, Glos. GL51 6SH, UK

Tel: +44 1242 802911

mail@ieaghg.org
www.ieaghg.org