Technology Collaboration Programme
by iea

Evaluating technology options to mitigate greenhouse gas emissions

IEAGHG Technical Report
2021-04
December 2021

Assessing the Techno-Economic Performance, Opportunities and Challenges of Mature and Nearly-mature Negative Emissions Technologies (NETs)

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.

DISCLAIMER

The GHG TCP, also known as the IEAGHG, is organised under the auspices of the International Energy Agency (IEA) but is functionally and legally autonomous. Views, findings and publications of the IEAGHG do not necessarily represent the views or policies of the IEA Secretariat or its individual member countries.

This report was prepared as an account of the work sponsored by IEAGHG. The views and opinions of the authors expressed herein do not necessarily reflect those of the IEAGHG, its members, the organisations listed below, nor any employee or persons acting on behalf of any of them. In addition, none of these make any warranty, express or implied, assumes any liability or responsibility for the accuracy, completeness or usefulness of any information, apparatus, product of process disclosed or represents that its use would not infringe privately owned rights, including any parties intellectual property rights. Reference herein to any commercial product, process, service or trade name, trade mark or manufacturer does not necessarily constitute or imply any endorsement, recommendation or any favouring of such products.

COPYRIGHT

ACKNOWLEDGEMENTS AND CITATIONS

This report describes work undertaken by Imperial College London on behalf of IEAGHG. The principal researchers were:

- Piera Patrizio
- Niall MacDowell

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

The expert reviewers for this report were:

- Aïcha ElKhamlichi, ADEME
- Alessandro Peluzzi, Politecnico di Milano
- Kristian Melin, LUT University
- Mathilde Fajardy, University of Cambridge
- Peter Morris, CIAB
- Sara Budinis, IEA

The report should be cited in literature as follows: 'IEAGHG, "Assessing the Techno-Economic Performance, Opportunities and Challenges of Mature and Nearly-mature Negative Emissions Technologies (NETs)", 2021-04, December 2021.'
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

ASSESSING THE TECHNO-ECONOMIC PERFORMANCE, OPPORTUNITIES AND CHALLENGES OF MATURE AND NEARLY-MATURE NEGATIVE EMISSIONS TECHNOLOGIES (NETs)

The aim of this study is to provide a transparent framework to evaluate the potential (in terms of sequestered and displaced carbon), and economics (in terms of cost of carbon avoided and removed) of a non-exhaustive selection of NETs pathways. Ecosystem and socio-economic impacts associated with their deployment is also quantified.

The study sets out to help the carbon capture and storage (CCS) community in trying to gain a better understanding of the costs and value of NETs. It also helps the modelling community in being able to better model the role of NETs; and policy/decision makers in having more information on costs, value and scalability of NETs.

Key Messages

- 11 key performance indicators (KPIs) have been defined and assessed for a select number of NET pathways, including direct air capture (DAC), biochar and bioenergy with CCS (BECCS) for power, fuel, hydrogen, steel and cement production.
- The highest CO_2 removals are achieved in NET pathways that maximize the capture of CO_2, have low energy conversion efficiencies, or have access to low-carbon energy. This is especially important when quantifying the net removal potential of DAC: if the energy is supplied by fossil sources, the amount of negative emissions generated lowers significantly.
- Except for corn-based ethanol, all BECCS to bioenergy pathways achieve net negative emissions in the range of 0.08 - 0.35 t_{CO2}/GJ. Whilst hydrogen production pathways exhibit high capture rates, the energy conversion efficiency for these processes is also high, so less biogenic emissions are being sequestered in the process compared to other biofuel pathways. The production of biochar via slow pyrolysis leads to a net removal of 0.47-0.89 t_{CO2} per tonne of dry mass of feedstock (2.6-3.3 t_{CO2}/t_{char}).
- For pathways involving the production of bioenergy, the amount of CO_2 emissions that can be avoided depends on the carbon intensity and on the products/fuel's substitution factor. In low-carbon power grids, biomass provides a much greater value in decarbonizing the transport sector by substituting gasoline than in the power sector.
- Configurations that maximize the CO_2 capture perform better in terms of certain ecosystem impacts. Due to the lower permanence of carbon in soil compared to geological storage, the production of biochar results in the largest water and land footprints among all routes investigated. These trade-offs might be lower when accounting for the potential long-term agricultural benefits of biochar in soil, which have not been included in the present analysis.
- Recommendations:
    - Demonstration of NETs at scale to improve and validate the existing data.
    - NETs should be included in new and existing emission trading schemes.

Background to the Study

According to the Intergovernmental Panel for Climate Change (IPCC), limiting global warming to 1.5°C will require large scale deployment of negative emissions technologies (NETs) to remove CO_2 from the atmosphere, which enables the offset of residual emissions in hard-to-abate sectors, and also the recovery of emission overshoot. NETs cover a wide range of technologies with diverse development levels, economics, and scale; with mitigation potentials varying across time and geographical scale.

Top-down decarbonisation scenarios typically do not consider where NETs could feasibly be incorporated. Decarbonisation scenario reports allocate BECCS use to the power sector, or an unspecified combination of power and industry. Since NETs are characterized by different technology readiness levels (TRLs), scalability and cost, a transparent characterization of each individual option is needed to perform a high-quality integrated assessment.

A number of prior studies (Minx et al. 2018[1]; Fuss et al. 2018[2]; Nemet et al. 2018[3]) have recently assessed the potential for NETs deployment based on an exhaustive number of academic papers and techno-economic assessments. In their analysis, the authors have observed how the heterogeneous nature of the results presented in the literature, with large regional variations owing to different biophysical factors, for example, biomass characteristics, time scale, process characterisation (capture efficiency and counterfactual) among others. Hence, providing detailed cost estimates of a comprehensive set of NETs is essential, given that their technical performances have a large impact on integrated assessment modelling (IAM) scenario outcomes.

Moreover, global mitigation pathways descending from IAMs, currently rely on few carbon dioxide removal (CDR) technologies (i.e. bioenergy with carbon capture and storage (BECCS) and more recently afforestation) to achieve the mitigation targets. Literature evidence (Heck et al. 2018[4]; Smith et al. 2015[5]) has warned that to avoid irreversible negative impacts on natural ecosystems, the inclusion and evaluation of a larger range of NETs is crucial. Transparent techno-economic analysis (TEA) of the different CDR technologies would, therefore, allow for a wider representation of these options in IAMs.

---

[1] Minx, J. C. *et al.* (2018) 'Negative emissions - Part 1: Research landscape and synthesis', *Environmental Research Letters*, 13(6). doi: 10.1088/1748-9326/aabf9b.

[2] Fuss, S. *et al.* (2018) 'Negative emissions - Part 2: Costs, potentials and side effects', *Environmental Research Letters*. Institute of Physics Publishing. doi: 10.1088/1748-9326/aabf9f.

[3] Nemet, G. F. *et al.* (2018) 'Negative emissions - Part 3: Innovation and upscaling', *Environmental Research Letters*. Institute of Physics Publishing. doi: 10.1088/1748-9326/aabff4.

[4] Heck, V. *et al.* (2018) 'Biomass-based negative emissions difficult to reconcile with planetary boundaries', *Nature Climate Change*, 8(2), pp. 151–155. doi: 10.1038/s41558-017-0064-y.

[5] Smith, P. *et al.* (2015) 'Biophysical and economic limits to negative CO2 emissions', *Nature Climate Change*, 6(1), pp. 42–50. doi: 10.1038/nclimate2870.

Scope of Work

IEAGHG commissioned Imperial College London, UK, to evaluate the potential (in terms of sequestered and displaced carbon), and economics (in terms of cost of carbon avoided and removed) of a non-exhaustive selection of NETs pathways.

The scope of work consisted of the following tasks:

1. Identify key criteria for the equitable comparative analysis of NETs.
2. Identify a number of pathways describing NETs that could be included in IAMs.
3. Quantify the techno-economic performances of the selected options and provide an outlook for their large-scale deployment in the long term.
4. Provide a transparent assessment of the potential for negative CO_2 emission across different sectors (including power, transport, and industrial sectors).
5. Identify and discuss socio-economic opportunities and ecosystems trade-offs for the assessed options.

Findings of the Study

Methods and approach

This work relies on a combination of optimization models and techno-economic tools to provide detailed cost estimates of the selected NETs pathways in the short and long term. The carbon accounting was complemented with the Modelling and Optimisation of Negative Emissions Technologies (MONET) framework presented in **Figure 1**. MONET informed the analysis on the ecosystems impacts (in terms of water and land use) associated with deployment of these technologies in different EU countries. The Jobs and Economic Development Impact (JEDI) modelling tool (see Figure 2) was adopted to complement the analysis with the quantification of the societal impacts for each NETs pathway.

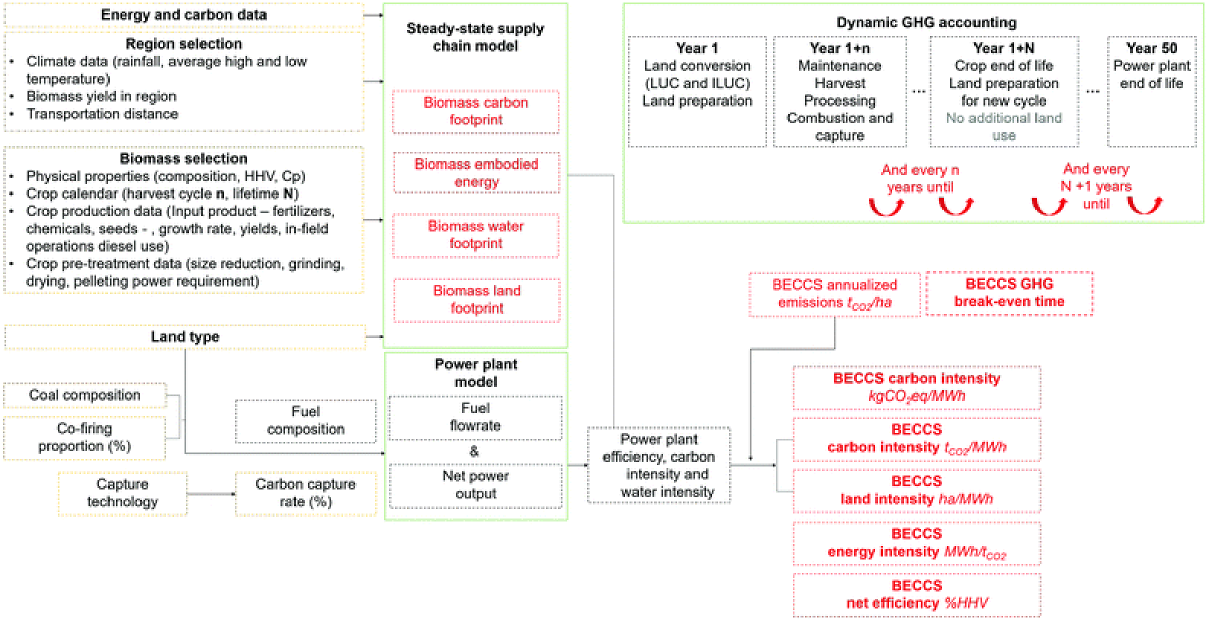


Figure 1 Overview of the MONET model (taken from Fajardy and Mac Dowell, 2017)

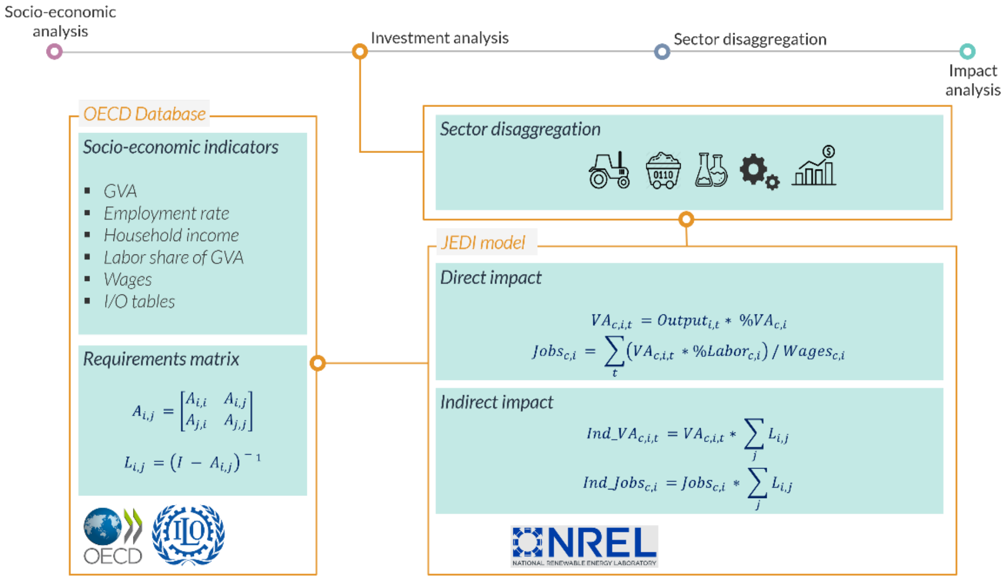


Figure 2 JEDI framework adopted in this study

Key performance indicators

The analysis of the selected NETs pathways is based on eleven key performance indicators (KPIs). These KPIs have been defined to compare the technical, socio-economic and environmental performances of the NETs pathways against a baseline scenario: a reference cement kiln or an integrated still mill for BECCS in industrial sectors, or fossil energy counterparts in the case of pathways associated with the production of biofuel or bioelectricity. Table 1 summarises the selected KPIs for this study.

Table 1 KPIs adopted in this study

		Description	Unit
KPI 1	**Levelized cost of production**	Annual capital and operating expenses associated with the annual production of bioenergy or bioproduct	• \$ per GJ of bioenergy produced • \$ per tonne of final product (pr), for BECCS in the iron and steel and cement industries (crude steel and clinker respectively)
KPI 2	**Sequestered emissions**	Physical amount of biogenic CO_2 fixed in geological or natural storage. Considers potential CO_2 leakages occurring during biomass processing as well in CO_2 transport and storage activities	• t_{co2}/t of biomass consumed
KPI 3	**Removed emissions**	Net CO_2 removed from the atmosphere. Accounts for upstream emissions associated with agricultural activities and biomass transport emissions. ***Removed = Sequestered – Upstream***	
KPI 4	**Lifecycle emissions**	Considers direct and indirect CO_2 emissions associated with the production of bioenergy or bioproduct, as well as emissions of upstream and downstream supply chains	• t_{co2} per GJ of bioenergy produced • t_{co2} per tonne of final product (pr) for BECCS in the iron and steel and cement industries (crude steel and clinker respectively)
KPI 5	**Avoided emissions**	Emission avoided by one unit of bioenergy or bioproduct produced. Depends on the emission intensity of the product or energy vector being displaced, e.g. crude steel or diesel.	
KPI 6	**Removal cost**	Cost of removing one tonne of CO_2 from the atmosphere, can be expressed as the ratio of KPI 1 to KPI 3	• \$/t_{co2} removed
KPI 7	**Avoidance cost**	Cost of avoiding one tonne of CO_2 from the atmosphere, can be expressed as the ratio of KPI 1 to KPI 5	• \$/t_{co2} avoided
KPI 8	**Land footprint**	Land footprint associated with crop cultivation and use within each conversion pathway. Here Miscanthus has been selected as reference crop.	• Hectare of land per GJ of bioenergy produced • Hectare of land per tonne of final product (pr), for BECCS in the iron and steel and cement industries (crude steel and clinker respectively)
KPI 9	**Water footprint**	Blue and grey water footprint associated with crop cultivation and use within each conversion pathway. Here Miscanthus has been selected as reference crop.	• m^3 of water per GJ of bioenergy produced • m^3 of water per tonne of final product (pr) for BECCS in the iron and steel and cement industries (crude steel and clinker respectively)
KPI 10	**Removal value**	CO_2 emissions removed with each \$ of Gross Value Added (GVA) created in the domestic economy	• t_{co2} removed per \$ of GVA created
KPI 11	**Avoidance value**	CO_2 emissions avoided with each \$ of Gross Value Added (GVA) created in the domestic economy	• t_{co2} avoided per \$ of GVA created

NET pathways

These following NET pathways are assessed in this study:

1) BECCS in the iron and steel and cement industries
2) BECCS to fuel pathways (bioethanol, Fischer-Tropsch (FT) diesel and hydrogen)
3) Direct Air Capture (DAC)
4) Biochar production via slow-pyrolysis processes
5) BECCS for power production

Techno-economic performance of NETs

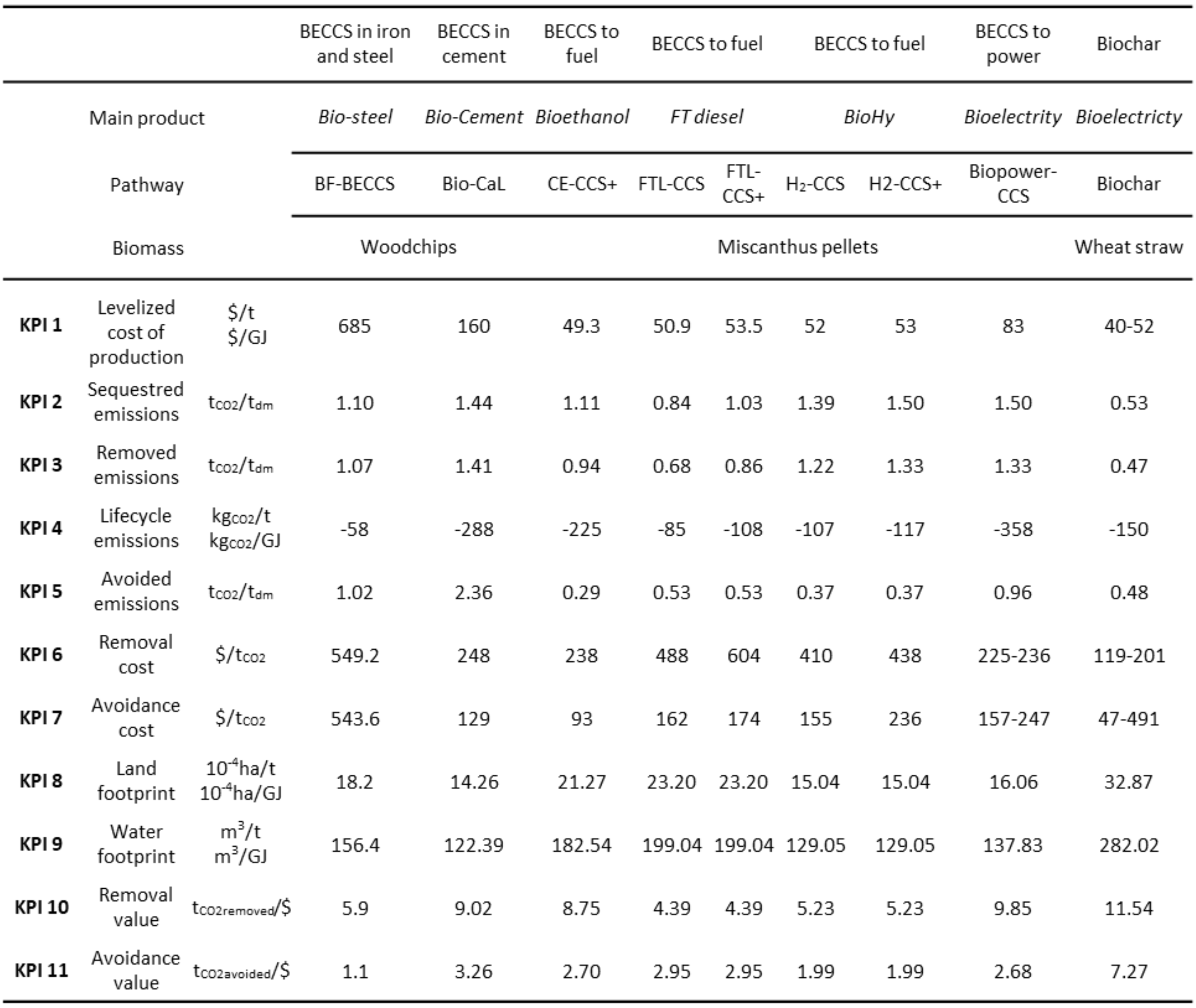
A key finding of this study is that the highest CO_2 removals are achieved in NET pathways that maximize the capture of CO_2, have low energy conversion efficiencies, or have access to low-carbon energy for their continuous operation. This latter point is particularly important when quantifying for the net removal potential of DAC: since DAC facilities require 4.3 GJ of extra energy per ton of CO_2 sequestered, if the energy is supplied by fossil sources, the amount of negative emissions generated lowers significantly.

As shown in Table 2, except for corn-based ethanol, all BECCS to bioenergy pathways achieve net negative emissions in the range of 0.08 - 0.35 t_{CO2} /GJ. Whilst hydrogen production pathways exhibit capture rates between 90-96%, the energy conversion efficiency for these processes is also high. Since less biomass is required to produce the same amount of biofuel, less biogenic emissions are being sequestered in the process compared to other biofuel pathways. The production of biochar via slow pyrolysis leads to a net removal of 0.47-0.89 t_{CO2} per tonne of dry mass of feedstock (2.6-3.3 t_{CO2} /t_{char}) with upper bound values associated with the use of forest residues as feedstock, having low CO_2 upstream emissions. These values are lower when compared to the removal potential of BECCS for bioelectricity production since slow-pyrolysis processes are characterized by a lower CO_2 capture efficiency, while only a fraction of the carbon in the fresh biochar remains stabilized in the long term.

Some NETs pathways involve the production of low carbon energy or material that may be substituted to fossil energy/material. Hence, for pathways involving the production of bioenergy, the amount of CO_2 emissions that can be avoided depends on the carbon intensity and on the products/fuel's substitution factor. In low-carbon power grids, such as those in the Nordic countries, biomass provides a much greater value in decarbonizing the transport sector by substituting gasoline than in the power sector. For instance, the substitution of gasoline with FT diesel avoids 0.59 t_{CO2} per tonne of dry biomass (tdm) around the same as the CO_2 avoided by BECCS in an average European power grid. Similarly, because electric vehicles (EVs) have a higher energy conversion efficiency than conventional diesel cars, NETs-derived fuels exhibit an energy substitution factor as low as 26% when substituting EVs. Hence, in countries where EVs are available, biofuels would provide greater value in hard to abate sectors, such as aviation, rather than in the mobility sector. Since the mitigation value of low carbon energy or material, is dependent on the incumbent energy system, it also reduces if low carbon alternatives become available.

The availability of low carbon and low-cost energy is also a necessary prerequisite for the overall feasibility of energy-intensive DAC processes. Because of the low CO_2 concentration of the air compared to the flue gases of a conventional coal fired power plant, DAC facilities require about three times the energy needed to achieve a 90% capture rate with CCS. In particular, the current energy requirements for Climeworks' DAC process are 500 kWh/t_{CO2} electric energy and 2,000 kWh/t_{CO2} thermal energy. When accounting for the indirect emission deriving from energy use within the DAC process, the net CO_2 removal can be as little as 0.4 t_{CO2} for each tonne of CO_2 sequestered. This fact has also important cost implications. Whilst Climeworks has proposed costs in the range of 600–700 \$/t_{CO2} depending on site-specific conditions, these cost estimates are on a "gross CO_2 removed", i.e. they are at captured, basis and they also do not include compression and storage costs. Computing these costs in terms of net CO_2 removed, i.e. by accounting for indirect emissions from energy use, would lead to an overall cost of 1100-1500 \$/t_{CO2} removed.

Table 2 Summary of results obtained for the selected NETs pathways (results for DAC not included, as several KPIs do not apply – please refer to the text for results and conclusions on DAC)



			BECCS in iron and steel	BECCS in cement	BECCS to fuel	BECCS to fuel		BECCS to fuel		BECCS to power	Biochar
	Main product		*Bio-steel*	*Bio-Cement*	*Bioethanol*	*FT diesel*		*BioHy*		*Bioelectrity*	*Bioelectricty*
	Pathway		BF-BECCS	Bio-CaL	CE-CCS+	FTL-CCS	FTL-CCS+	H_2-CCS	H2-CCS+	Biopower-CCS	Biochar
	Biomass		Woodchips		Miscanthus pellets						Wheat straw
KPI 1	Levelized cost of production	\$/t \$/GJ	685	160	49.3	50.9	53.5	52	53	83	40-52
KPI 2	Sequestred emissions	t_{CO2}/t_{dm}	1.10	1.44	1.11	0.84	1.03	1.39	1.50	1.50	0.53
KPI 3	Removed emissions	t_{CO2}/t_{dm}	1.07	1.41	0.94	0.68	0.86	1.22	1.33	1.33	0.47
KPI 4	Lifecycle emissions	kg_{CO2}/t kg_{CO2}/GJ	-58	-288	-225	-85	-108	-107	-117	-358	-150
KPI 5	Avoided emissions	t_{CO2}/t_{dm}	1.02	2.36	0.29	0.53	0.53	0.37	0.37	0.96	0.48
KPI 6	Removal cost	$\$/t_{CO2}$	549.2	248	238	488	604	410	438	225-236	119-201
KPI 7	Avoidance cost	$\$/t_{CO2}$	543.6	129	93	162	174	155	236	157-247	47-491
KPI 8	Land footprint	10^{-4}ha/t 10^{-4}ha/GJ	18.2	14.26	21.27	23.20	23.20	15.04	15.04	16.06	32.87
KPI 9	Water footprint	m^3/t m^3/GJ	156.4	122.39	182.54	199.04	199.04	129.05	129.05	137.83	282.02
KPI 10	Removal value	$t_{CO2removed}/\$$	5.9	9.02	8.75	4.39	4.39	5.23	5.23	9.85	11.54
KPI 11	Avoidance value	$t_{CO2avoided}/\$$	1.1	3.26	2.70	2.95	2.95	1.99	1.99	2.68	7.27

Selected ecosystem and macroeconomic impacts

This report also discusses selected ecosystem's impacts, i.e. water and land footprint associated with biomass cultivation, and use in NET pathways. To compute KPIs 8-11, miscanthus has been adopted as the reference energy crop for all conversion pathways, which allowed comparison of the land and water footprint of one tonne of product on a consistent basis, i.e. crude steel or cement in the case of BECCS in industrial processes, or one GJ of bioelectricity and biofuel, for bioenergy routes.

A summary of the land and water footprint associated with biomass based NETs pathways is proposed in the upper part of Figure 3. It shows that configurations that maximize CO_2 capture perform better: BECCS to power has the lowest water footprint (37-232 m^3/t_{CO2} removed), followed by BECCS in cement configurations (39-247 m^3/t_{CO2} removed). Since slow pyrolysis is both energy and carbon removal inefficient, due to the lower permanence of carbon in soil compared to geological storage, it results in the largest ecosystems impacts among all routes investigated (91-570 m^3/t_{CO2} removed). An important caveat to this conclusion is that this analysis excludes potential agricultural benefits associated with biochar application to soil, i.e. crop yield increase and change in soil organic carbon (SOC), as the agronomic value of biochar remains highly debated in the literature.

The water requirements of DAC systems are much smaller compared to biomass-based solutions, whilst varying between technologies. A DAC facility capturing 3 Mt_{CO2}/year using Climework's process, consumes 0.67 m^3/t_{CO2} captured, equal to 1.6 m^3/t_{CO2} removed.

The analysis also provides an indication of the economic value of CO_2 mitigation and removal associated with the deployment of NETs value chains within a certain economic region. This is done by combining the techno-economic and carbon accounting analysis with the quantification of the socio-economic impacts of deploying NETs in the UK. With this aim, the JEDI tool, an Input/Output model that quantifies the economic impacts associated with low carbon technology investments, has been extended to accommodate the techno-economic features of the selected portfolio of NETs. Subsequently, the tool has been populated with macroeconomic data on the main industrial sectors of the UK to derive the gross value added (GVA) associated with the deployment and operation of NETs within each sector of the UK economy. Hence, the removal and mitigation values presented in Figure 3 (expressed as kg_{CO2} removed and avoided per \$ of GVA created), provide an indication of the removal and avoidance efficiency of government spending, since each unit of GVA generated within the NETs supply chains (and corresponding industrial sectors) will result in the avoidance and removal of a certain amount of carbon.

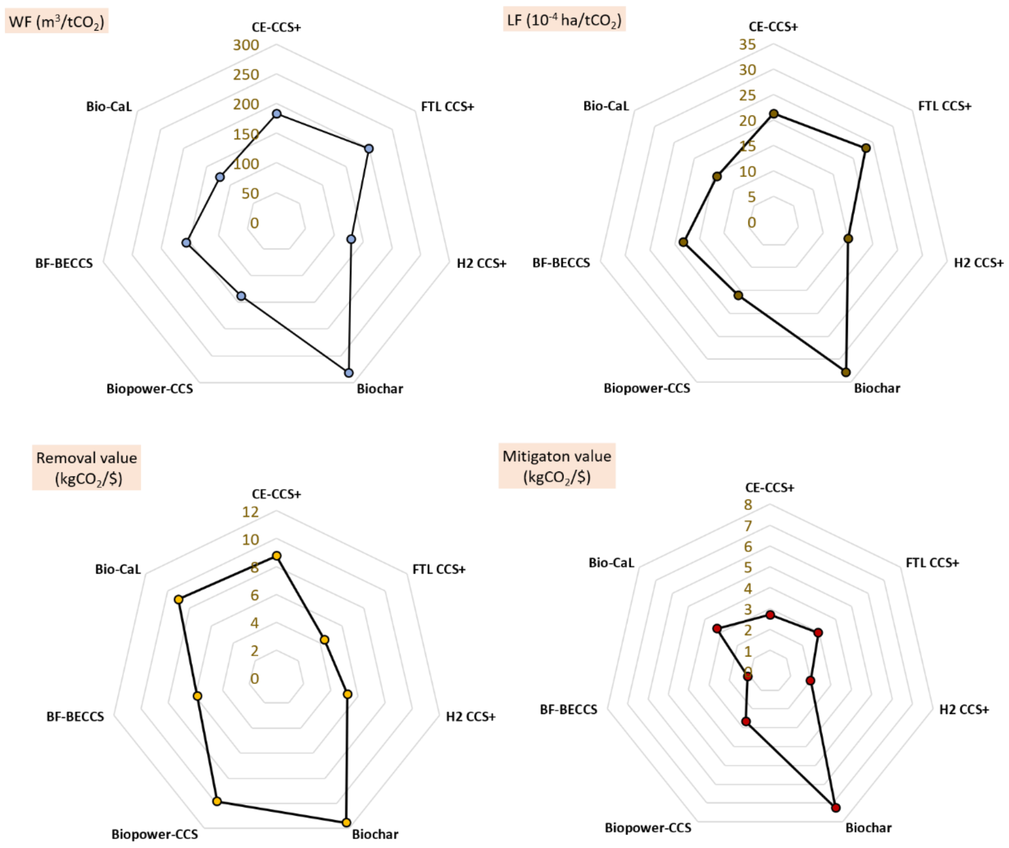


Figure 3 Summary of selected ecosystems and macroeconomic impacts of bio-based NETs deployment

Expert Review Comments

Six reviewers from academia, NGOs and other organisations provided comments on the draft report. Most of the comments have been addressed by the contractor, including but not limited to:

- Font size and captions of figures have been improved. In addition, one figure was modified to address suggestion from a reviewer.
- Several comments were received on how to improve the methodology section. The following changes were made to accommodate them:
  - Included a table describing the indexes and coefficients adopted for characterizing the KPIs at the beginning of Section 2.
  - Extended the description of KPIs where needed.
  - Added a subsection entitled “conclusions and recommendations” in the summary to better guide the reader through the conclusions regarding the KPIs.
  - One reviewer suggested to merge KPI 3 and KPI 4, i.e., removed and life cycle emissions respectively. It is important to keep these indicators separated though, as they can provide important insights on the overall value of these pathways. Whilst KPI 3 measures the net CO_2 removal that NETs can achieve, KPI 4 also accounts for the direct and indirect emissions arising from the production of energy or product within NET pathways. This distinction is particularly important for BECCS in industry. However, a more detailed explanation of these KPIs was needed, particularly regarding the boundaries of the analysis, and thus added where relevant.
- Some of the KPIs do not relate to DAC processes, i.e. emissions avoided, avoidance cost and mitigation value. To avoid confusion, DAC has been excluded from the relevant comparative tables. Instead, a description of the results obtained for this technology is provided in the text.

Conclusions

This study provides a comparative assessment of the value of a range of bio-based CO_2 removal pathways in terms of CO_2 emission avoidance and CO_2 removal, it also highlights the role of the counterfactual scenario when assessing the mitigation potential of a technology. Overall, a large-scale biomass combustion plant with CCS, though one of the lowest ranking pathways in terms of energy efficiency, provides the greatest CO_2 mitigation potential in a carbon intensive grid such as Poland. When considering the same counterfactual scenario, the production of bioelectricity in pyrolytic processes avoids around half of the emissions avoided in BECCS to power routes, since slow-pyrolysis processes tend to maximize the biochar to electricity output ratio.

In addition, since the mitigation value of low carbon energy or material is dependent on the incumbent energy system, it also reduces if low carbon alternatives become available. Hence, pathways maximizing the production of bioelectricity or biofuels are preferred when the energy systems are yet to be decarbonized, while in the longer term, when high CO_2 removal rates are to be realized by removing carbon from the atmosphere, the service provided by biomass as a CDR option is vital.

The results of the carbon accounting analysis also highlighted that access to low carbon energy is a necessary requirement for pathways requiring extra energy for continuous process operation, such as DAC and integrated steel mills equipped with BECCS. Whilst the iron and steel industry is currently considering the adoption of alternative steel production technologies, such as the use of hydrogen in the direct reduction of iron, the future cost trajectory of low carbon electricity will have a significant impact on the financial viability of these options.

Finally, most of the pathways presented in this report, rely on NETs which are yet to be demonstrated at scale. Long-term deployment opportunities for these technologies will be closely linked to robust CO_2 pricing mechanisms and accounting frameworks that recognize and value the negative emissions associated with storing CO_2 captured from the atmosphere. This could, for example, be achieved by including NETs in an emissions trading scheme such as the EU or UK ETS.

Recommendations

The following recommendations were identified during the study:

- Demonstration of NETs at scale is necessary to improve and validate the existing data.
- CO_2 pricing mechanisms and accounting frameworks that recognize and value the negative emissions associated with storing CO_2 captured from the atmosphere are needed. NETs, like other low carbon technologies, could benefit from being included in existing emissions trading schemes such as the EU ETS and the UK ETS where they provide such a value to the carbon emissions reduced by such technologies.

Techno-economic performance, opportunities, and challenges of Negative Emissions Technologies (NETs)

Report for IEAGHG

March 2021

Piera Patrizio and Niall Mac Dowell

Imperial College London

Contents

1 Executive summary

A recent IPCC report[1] indicates that immediate and rapid reductions in greenhouse gas (GHG) emissions are required to limit global warming to 1.5°C and calls for global efforts across all sectors. The report also assigns a crucial role for Negative emission technologies (NETs), which have the potential to offset emissions from the heat, power, and hard to abate sectors such as cement and steel industries and aviation, by removing CO_2 from the atmosphere. However, Integrated Assessment Models (IAMs) extensively rely on bioenergy and carbon capture and storage (BECCS) and afforestation as potential carbon dioxide removal (CDR) options, with few exceptions featuring other technologies such as Direct Air Capture (DAC). Whilst the role of advanced technologies like CCS to achieve deep decarbonization in energy intensive sectors has received increasing attention from the IAM community (Van Ruijven *et al.*, 2016; Napp *et al.*, 2019), the level of detail in the industry modules of many IAMs is often not detailed enough to allow for sector specific technology representation (Edelenbosch *et al.*, 2017; Kermeli *et al.*, 2019).

The reliance on single or restricted portfolio of NETs to reach global mitigation targets not only triggers potential irreversible ecosystems impacts but also hinders the simultaneous implementation of other carbon mitigation strategies. In addition, since NETs are characterized by different technology readiness levels (TRLs), scalability and cost, a transparent characterization of each option is needed to perform a high-quality integrated assessment.

Method and approach

This report presents a comprehensive framework to evaluate the techno-economic potential, ecosystems, and socio-economic impacts of a non-exhaustive selection of NETs pathways, based on eleven key performance indicators (KPIs). These pathways are:

1) BECCS in the iron and steel and cement industries
2) BECCS to fuel pathways to produce bioethanol, Fischer-Tropsch (FT) diesel, and hydrogen
3) Biochar production via slow-pyrolysis processes
4) BECCS for power production
5) Direct Air Capture (DAC)

Table 1 describes the KPIs adopted in the study, these indicators cover the techno-economic performances (KPI 1), removal and avoidance efficiency and costs (KPIs 2-7), ecosystems impacts (KPIs 8-9), and socio-economic value (KPIs 10-11) associated with the deployment of NETs at regional level. Note that, in the case of DAC processes, the computation of some of these indicators was not possible since these processes typically remove CO_2 from the atmosphere without producing any low carbon energy product.

To compute the KPIs presented in Table 1, the work relies on a combination of optimization models and techno-economic tools to provide detailed cost estimates of the selected NETs pathways in the short and long term. Carbon accounting is complemented with the Modelling and Optimisation of Negative Emissions Technologies (MONET) framework, which informs the analysis on water and land use associated with deployment of technologies

---

[1] Intergovernmental Panel on Climate Change (IPCC), 2018. Global warming of 1.5°C, https://www.ipcc.ch/sr15/.

in different countries. The Jobs and Economic Development Impact (JEDI) modelling tool is adopted to complement the analysis with the quantification of the societal impacts for each NETs pathway.

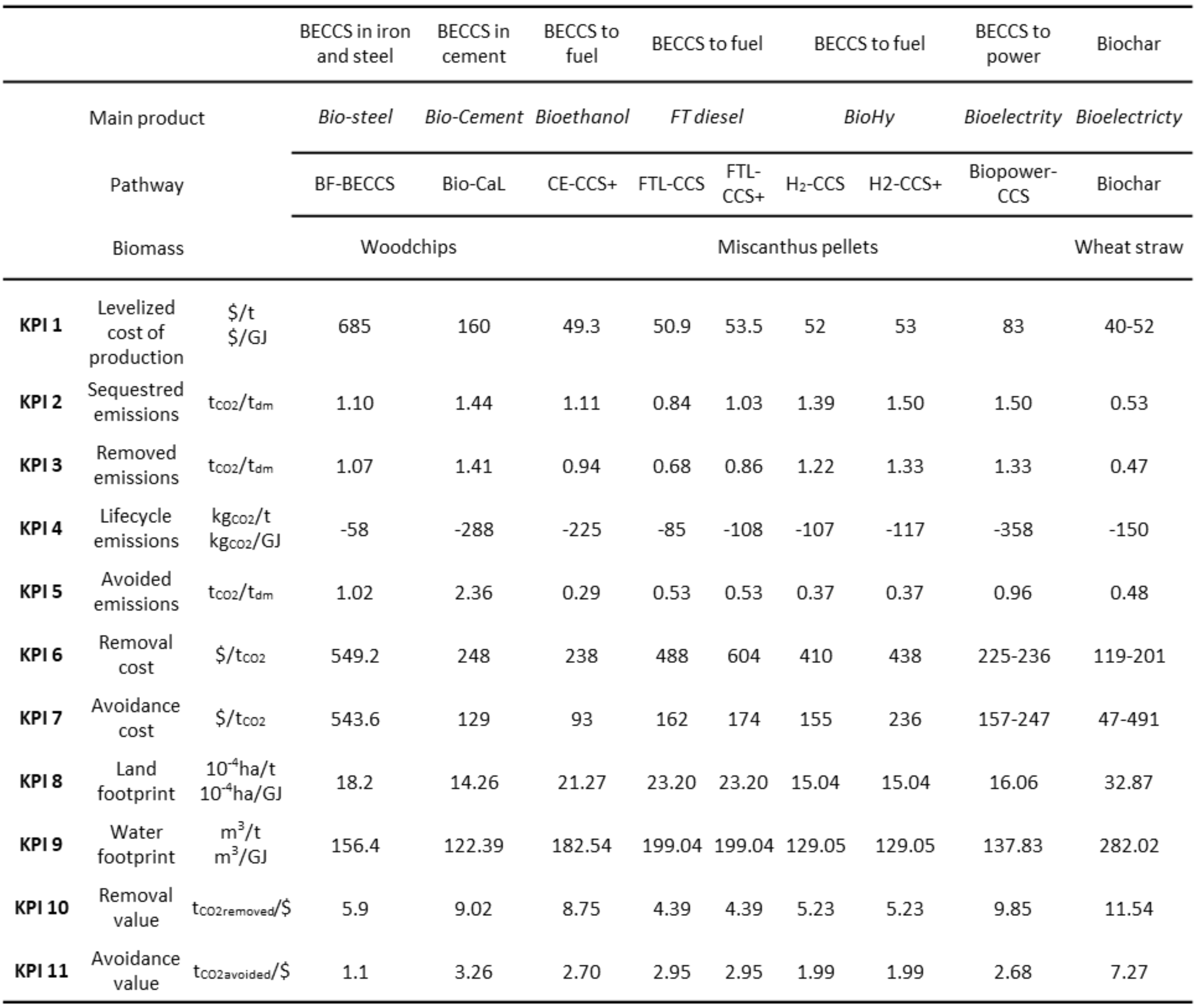
		Description	Unit
KPI 1	**Levelized cost of production**	Annual capital and operating expenses associated with the annual production of bioenergy or bioproduct	• \$ per GJ of bioenergy produced • \$ per tonne of final product (pr), for BECCS in the iron and steel and cement industries (crude steel and clinker respectively)
KPI 2	**Sequestered emissions**	Physical amount of biogenic CO_2 fixed in geological or natural storage. Considers potential CO_2 leakages occurring during biomass processing as well in CO_2 transport and storage activities	• t_{co2}/t of biomass consumed
KPI 3	**Removed emissions**	Net CO_2 removed from the atmosphere. Accounts for upstream emissions associated with agricultural activities and biomass transport emissions. ***Removed = Sequestered – Upstream***	
KPI 4	**Lifecycle emissions**	Considers direct and indirect CO_2 emissions associated with the production of bioenergy or bioproduct, as well as emissions of upstream and downstream supply chains	• t_{co2} per GJ of bioenergy produced • t_{co2} per tonne of final product (pr) for BECCS in the iron and steel and cement industries (crude steel and clinker respectively)
KPI 5	**Avoided emissions**	Emission avoided by one unit of bioenergy or bioproduct produced. Depends on the emission intensity of the product or energy vector being displaced, e.g. crude steel or diesel.	
KPI 6	**Removal cost**	Cost of removing one tonne of CO_2 from the atmosphere, can be expressed as the ratio of KPI 1 to KPI 3	• \$/t_{co2} removed
KPI 7	**Avoidance cost**	Cost of avoiding one tonne of CO_2 from the atmosphere, can be expressed as the ratio of KPI 1 to KPI 5	• \$/t_{co2} avoided
KPI 8	**Land footprint**	Land footprint associated with crop cultivation and use within each conversion pathway. Here Miscanthus has been selected as reference crop.	• Hectare of land per GJ of bioenergy produced • Hectare of land per tonne of final product (pr), for BECCS in the iron and steel and cement industries (crude steel and clinker respectively)
KPI 9	**Water footprint**	Blue and grey water footprint associated with crop cultivation and use within each conversion pathway. Here Miscanthus has been selected as reference crop.	• m^3 of water per GJ of bioenergy produced • m^3 of water per tonne of final product (pr) for BECCS in the iron and steel and cement industries (crude steel and clinker respectively)
KPI 10	**Removal value**	CO_2 emissions removed with each \$ of Gross Value Added (GVA) created in the domestic economy	• t_{co2} removed per \$ of GVA created
KPI 11	**Avoidance value**	CO_2 emissions avoided with each \$ of Gross Value Added (GVA) created in the domestic economy	• t_{co2} avoided per \$ of GVA created

Table 1: KPIs adopted in this study to describe the cost, removal, and mitigation value of biomass-based NETs removal pathways.

Findings

A key finding of the study is that the highest CO_2 removal is achieved in NET pathways that maximize the capture of CO_2, have low energy conversion efficiencies, and, importantly, have access to low-carbon energy for their continuous operation.

As shown in Figure 1, all BECCS to bioenergy pathways achieve net negative emissions in the range of 0.08 - 0.35 t_{CO2} /GJ of bioenergy (KPI 4). Whilst hydrogen production pathways exhibit capture rates between 90-96%, the energy conversion efficiency for these processes is also high. Since less biomass is required to produce the same amount of biofuel, less biogenic emissions are being sequestered in the process per energy generated compared to other biofuel pathways. The production of biochar *via* slow pyrolysis leads to a net removal of 0.47-0.89 t_{CO2} per tonne of dry mass of feedstock (2.6-3.3 t_{CO2} per tonne of biochar ,t_{char}) with upper bound values associated with the use of forest residues as feedstock, having low CO_2 upstream emissions. These values are lower when compared to the removal potential of BECCS for bioelectricity production since slow-pyrolysis processes are characterized by a lower CO_2 capture efficiency[2] , while only a fraction of the carbon in the fresh biochar remains stabilized in the long term.



			BECCS in iron and steel	BECCS in cement	BECCS to fuel	BECCS to fuel		BECCS to fuel		BECCS to power	Biochar
Main product			*Bio-steel*	*Bio-Cement*	*Bioethanol*	*FT diesel*		*BioHy*		*Bioelectrity*	*Bioelectricty*
Pathway			BF-BECCS	Bio-CaL	CE-CCS+	FTL-CCS	FTL-CCS+	H_2-CCS	H2-CCS+	Biopower-CCS	Biochar
Biomass			Woodchips		Miscanthus pellets						Wheat straw
KPI 1	Levelized cost of production	\$/t \$/GJ	685	160	49.3	50.9	53.5	52	53	83	40-52
KPI 2	Sequestred emissions	t_{CO2}/t_{dm}	1.10	1.44	1.11	0.84	1.03	1.39	1.50	1.50	0.53
KPI 3	Removed emissions	t_{CO2}/t_{dm}	1.07	1.41	0.94	0.68	0.86	1.22	1.33	1.33	0.47
KPI 4	Lifecycle emissions	kg_{CO2}/t kg_{CO2}/GJ	-58	-288	-225	-85	-108	-107	-117	-358	-150
KPI 5	Avoided emissions	t_{CO2}/t_{dm}	1.02	2.36	0.29	0.53	0.53	0.37	0.37	0.96	0.48
KPI 6	Removal cost	$\$/t_{CO2}$	549.2	248	238	488	604	410	438	225-236	119-201
KPI 7	Avoidance cost	$\$/t_{CO2}$	543.6	129	93	162	174	155	236	157-247	47-491
KPI 8	Land footprint	10^{-4}ha/t 10^{-4}ha/GJ	18.2	14.26	21.27	23.20	23.20	15.04	15.04	16.06	32.87
KPI 9	Water footprint	m^3/t m^3/GJ	156.4	122.39	182.54	199.04	199.04	129.05	129.05	137.83	282.02
KPI 10	Removal value	$t_{CO2removed}/\$$	5.9	9.02	8.75	4.39	4.39	5.23	5.23	9.85	11.54
KPI 11	Avoidance value	$t_{CO2avoided}/\$$	1.1	3.26	2.70	2.95	2.95	1.99	1.99	2.68	7.27

Figure 1: Summary of results obtained for the selected NETs pathways. For BECCS to fuel pathways the CCS+ configuration considers potential process modifications that enable higher CO_2 capture rates. KPIs 5 and 7 presented here assume the replacement of diesel fuel (BECCS to fuel pathways) and electricity (BECCS to power and biochar pathways) with an average carbon intensity of EU28.

Some NETs pathways involve the production of low carbon energy or material that may be substituted to fossil energy/material. Hence, for pathways involving the production of bioenergy, the amount of CO_2 emissions that can be avoided depends on the carbon intensity and on the products/fuel's substitution factor. In low-carbon power grids, such as those in the

---

[2] The capture efficiency of slow pyrolysis processes can also be defined as pyrolysis carbon yield, i.e. the mass of C in the solid biochar residue divided by the mass of C in the initial dry biomass feedstock

Nordic countries, biomass provides a much greater value in decarbonizing the transport sector by substituting gasoline than in the power sector. For instance, the substitution of gasoline with FT diesel avoids 0.59 tCO_2 per tonne of dry biomass (t_{dm}) around the same as the CO_2 avoided by BECCS in an average European power grid. Similarly, because electric vehicles (EVs) have a higher energy conversion efficiency than conventional diesel cars, NETs-derived fuels exhibit an energy substitution factor as low as 26% when substituting EVs. Hence, in countries where EVs are available, biofuels would provide greater value in hard to abate sectors, such as aviation, rather than in the mobility sector. Since the mitigation value of low carbon energy or material, is dependent on the incumbent energy system, it also reduces if low carbon alternatives become available.

The availability of low carbon and low-cost energy is also a necessary prerequisite for the overall feasibility of energy-intensive DAC processes[3]. In fact, because of the low CO_2 concentration of the air compared to the flue gases of a conventional coal faired plant, DAC facilities require about three times the energy needed to achieve a 90% capture rate with CCS. In particular, the current energy requirements for Climework's DAC process are 500 kWh/tCO_2 electric energy and 2000 kWh/tCO_2 thermal energy. As detailed in section 4.5.2, when accounting for the indirect emission deriving from energy use within the DAC process, the net CO_2 removal can be as little as 0.4 t_{CO2} for each tonne of CO_2 sequestered. This fact has also important cost implications. Whilst Climeworks has proposed costs in the range of 600–700 \$/t_{CO2} depending on site-specific conditions, these cost estimates are on a "gross CO_2 removed", i.e. they are at captured basis and they also do not include compression and storage costs. Computing these costs in terms of net CO_2 removed, i.e. by accounting for indirect emissions from energy use, would lead to an overall cost of 1100-1500 \$ per tonne of CO_2 removed.

Selected ecosystem and macroeconomic impacts

This report also discusses the ecosystem's impacts, in terms of water and land footprint associated with biomass cultivation and use in NET pathways. To compute KPIs 8-11, miscanthus has been adopted as the reference energy crop for all conversion pathways, which allowed to compare the land and water footprint of one tonne of product on a consistent basis, i.e. crude steel or cement in the case of BECCS in industrial processes, or one GJ of bioelectricity and biofuel, for bioenergy routes.

A summary of the land and water footprint associated with biomass based NETs pathways is proposed in the upper part of Figure 2. It shows that configurations that maximize CO_2 capture perform better: BECCS to power has the lowest water footprint (37-232 m^3/t_{CO2} removed), followed by BECCS in cement configurations (39-247 m^3/t_{CO2} removed). Since slow pyrolysis is both energy and carbon removal inefficient, due to the lower permanence of carbon in soil compared to geological storage, it results in the largest ecosystems impacts among all routes investigated (91-570 m^3/t_{CO2} removed). An important caveat to this conclusion is that our analysis excludes potential agricultural benefits associated with biochar application to soil, *i.e.* crop yield increase and change in soil carbon (SOC), as the agronomic value of biochar remains highly debated in the literature.

The water requirements of DAC systems are quite smaller compared to biomass-based solutions, whilst varying between technologies. In particular, a DAC facility capturing 3 Mt_{CO2}/year using Climework process, consumes 0.67 m^3 per tonne of CO_2 captured, equal to 1.6 m^3 per tonne of CO_2 removed.

---

[3] Whilst 15 DAC plants are currently operational globally, these are mostly small-scale facilities that sell the captured CO2 for use. Hence, to describe this pathway we adopted the Carbon Engineering process as reference DAC archetype, as this is the only large-scale DAC project available today.

Finally, the report provides an indication of the economic value of CO_2 mitigation and removal associated with the deployment of NETs value chains within a certain economic region. This is done by combining the techno-economic and carbon accounting analysis presented in sections 4 and 5 with the quantification of the socio-economic impacts of deploying NETs in the UK. With this aim, the Jobs and Economic Development Impact (JEDI) tool, an Input/Output model that quantifies the economic impacts associated with low carbon technology investments (Patrizio, Pratama and Dowell, 2020), has been extended to accommodate the techno-economic features of the selected portfolio of NETs. Subsequently, the tool has been populated with macroeconomic data on the main industrial sectors of the UK, so to derive the gross value added (GVA) associated with the deployment and operation of NETs within each sector of the UK economy. Hence, the removal and mitigation values presented in Figure 2 (expressed as kg of CO_2 removed and avoided per $ of GVA created), provide an indication of the removal and avoidance efficiency of government spending, since each unit of GVA generated within the NETs supply chains (and corresponding industrial sectors) will result in the avoidance and removal of a certain amount of carbon.

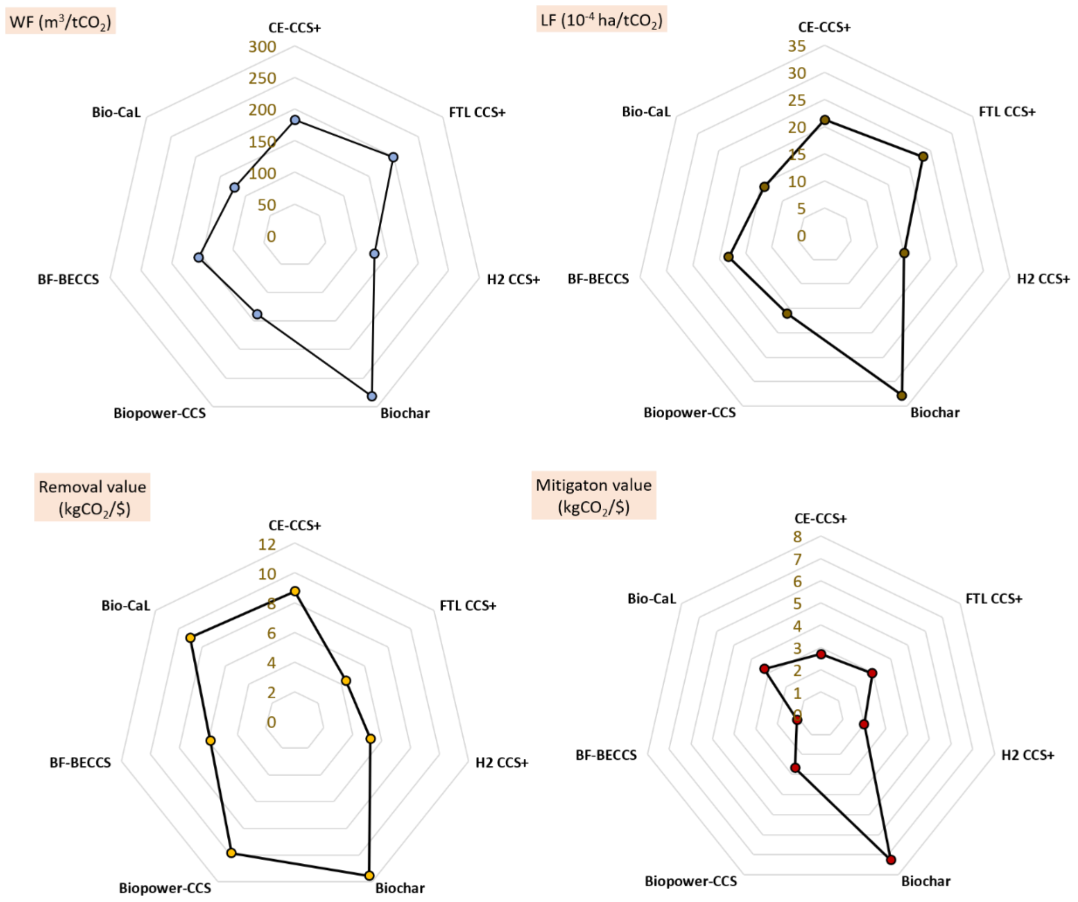


Figure 2: Summary of selected ecosystems and macroeconomic impacts associated with the avoidance and removal of one tonne of CO_2 within selected bio-based NETs. In the analysis, miscanthus has been selected as reference energy crops for all pathways. Water footprint (WF) accounts only for freshwater use and pollution associated with farming activities. Land footprint (LF) associated with miscanthus cultivation is based on an average crop yield in EU 28. Removal and avoidance values indicate the gross value added (GVA) created within the domestic economy from removal and mitigation activities.

Conclusions and recommendations

This study provides a comparative assessment of the value of a range of bio-based CO_2 removal pathways in terms of CO_2 emission avoidance and CO_2 removal, it also highlights the role of the counterfactual scenario when assessing the mitigation potential of a technology. Overall, a large-scale biomass combustion plant with CCS, though one of the lowest ranking pathways in terms of energy efficiency, provides the greatest CO_2 mitigation potential in a carbon intensive grid such as Poland. When considering the same counterfactual scenario, the production of bioelectricity in pyrolytic processes avoids around half of the emissions avoided in BECCS to power routes, since slow-pyrolysis processes tend to maximize the biochar to electricity output ratio.

In addition, since the mitigation value of low carbon energy or material is dependent on the incumbent energy system, it also reduces if low carbon alternatives become available. Hence, pathways maximizing the production of bioelectricity or biofuels are preferred when the energy systems are yet to be decarbonized, while in the longer term, when high CO_2 removal rates are to be realized by removing carbon from the atmosphere, the service provided by biomass as a CDRs option is vital.

The results of the carbon accounting analysis also highlighted that access to low carbon energy is a necessary requirement for pathways requiring extra energy for continuous process operation, such as DAC and integrated steel mills equipped with BECCS. Whilst the iron and steel industry is currently considering the adoption of alternative steel production technologies, such as the use of hydrogen in the direct reduction of iron, the future cost trajectory of low carbon electricity will have a significant impact on the financial viability of these options.

Finally, most of the pathways presented in this report, rely on NETs which are yet to be demonstrated at scale. Long-term deployment opportunities for these technologies will be closely linked to robust CO_2 pricing mechanisms and accounting frameworks that recognize and value the negative emissions associated with storing CO_2 captured from the atmosphere. This could, for example, be achieved by including NETs in an emissions trading scheme such as the EU or UK ETS.

2 Introduction and motivation

According to the International Panel for Climate Change (IPCC), limiting global warming to 1.5°C will require large scale deployment of negative emissions technologies (NETs) to remove CO_2 from the atmosphere, which enables the offset of residual emissions from hard-to-abate sectors, and also the recovery of emission overshoot. NETs cover a wide range of technologies with diverse development levels, economics, and scale; with mitigation potentials varying across time and geographical scale.

Top-down decarbonization scenarios typically do not consider *where* NETs could feasibly be incorporated. Decarbonization scenario reports allocate BECCS use to the power sector, fuel production, or an unspecified combination of power and industry. Since NETs are characterized by different technology readiness levels (TRLs), scalability, and cost, a transparent characterization of each individual option is needed to perform a high-quality integrated assessment.

A number of prior studies (Fuss *et al.*, 2018; Minx *et al.*, 2018; Nemet *et al.*, 2018) have recently assessed the potential for NETs deployment based on an exhaustive number of academic papers and techno-economic assessments. In their analysis, the authors have observed how the heterogeneous nature of the results presented in the literature, with large regional variations owing to different biophysical factors, *e.g.,* biomass characteristics, time scale, process characterization, *e.g.,* capture efficiency and counterfactual, among others. Hence, providing detailed cost estimates of a comprehensive set of NETs is essential, given that their technical performances potentially have a large impact on integrated assessment modelling (IAM) scenario outcomes.

Moreover, global mitigation pathways descending from IAMs, currently rely on few (BECCS and more recently afforestation) CDR technologies to achieve the mitigation targets. Literature evidence (Smith *et al.*, 2015; Heck *et al.*, 2018) has warned that to avoid irreversible negative impacts on natural ecosystems, including a larger range of NETs, as well as accounting for their wider environmental impacts, is crucial. Transparent techno-economic analysis of the different CDR technologies would, therefore, allow for a wider representation of these options in IAMs.

This project provides a transparent framework to evaluate the potential (in terms of sequestered and avoided carbon), and economics (in terms of cost of carbon avoided and removed) of a non-exhaustive selection of NETs pathways. Ecosystems and socio-economic impacts associated with their deployment are also quantified, *via* the adoption of optimization and socio-economic models. Specifically, the carbon accounting will be complemented with the Modelling and Optimisation of Negative Emissions Technologies (MONET) framework presented in Section 3 of this report. MONET will inform the analysis on the biomass carbon footprint and on the ecosystems impacts (in terms of water and land use) associated with deployment of these technologies in different EU countries. The Jobs and Economic Development Impact (JEDI) modelling tool will be adopted to complement the analysis with the quantification of the societal impacts for each NETs pathway.

To this end, this project is structured around the following objectives:

1. To identify key criteria for the equitable comparative analysis of NETs
2. To identify a number of pathways describing NETs, that could be included in IAMs

3. To quantify the techno-economic performances of the selected option and provide an outlook for their large-scale deployment in the long term
4. To provide a transparent assessment of the potential for negative CO_2 emissions across different sectors (including power, transport, and industrial sectors)
5. To identify and discuss socio-economic opportunities and ecosystems trade-offs for the assessed options.

2.1 Structure of the report

Based on the objectives proposed above, this report is structured as follows. First, the KPIs for the comparative analysis of NETs are identified in section 3.2, these indicators cover the techno-economic performances (KPI 1), removal and avoidance efficiency and costs (KPIs 2-7), ecosystems impacts (KPIs 8-9), and socio-economic value (KPIs 10-11) associated with the deployment of NETs at regional level.

Following an extensive literature review, promising pathways relying on nearly technologically mature NETs are discussed in section 4, together with their techno-economic performance. Potential technological improvement, as well as emerging technologies that can become available in the long-term, are also proposed in this section. Future improvement potentials of each technology, especially in terms of costs and efficiencies, will be based on existing cost studies and expert judgments.

The emission balance as well as CO_2 avoidance and removal of biomass-based pathways are proposed in the carbon accounting section 5, where the cost of CO_2 avoided and removed associated with each NETs product is also discussed.

Finally, section 6 quantifies the ecosystems impacts, *i.e.,* water and land use, and the socio-economic value, *i.e.,* mitigation and removal value, generated along the NETs supply chains.

3 Methodology

3.1 Modelling framework

This work relies on a combination of optimization models and techno-economic tools to provide detailed financial, carbon and resource cost estimates of the selected NETs pathways in the short and long term. The carbon accounting will be complemented with the Modelling and Optimisation of Negative Emissions Technologies (MONET) framework presented below. MONET will inform the analysis on the biomass carbon footprint and on the ecosystems impacts (in terms of water and land use) associated with deployment of these technologies in different EU countries. The Jobs and Economic Development Impact (JEDI) modelling tool will be adopted to complement the analysis with the quantification of the societal impacts for each NETs pathway.

3.1.1 The MONET framework

The Modelling and Optimisation of Negative Emissions Technologies (MONET) framework (Fajardy and Mac Dowell, 2017, 2020; Fajardy, Chiquier and Mac Dowell, 2018) evaluates the technical and environmental performance of NETs throughout their value chain, which includes biomass supply chain, conversion to energy, and post-combustion CO_2 capture. The model identifies the region-specific least cost supply chain configuration for meeting regional carbon removal targets, while minimizing sustainability contraindications, with land and water use, and carbon efficiencies acting as key performance indicators (KPIs). The MONET framework is presented in Figure 3.

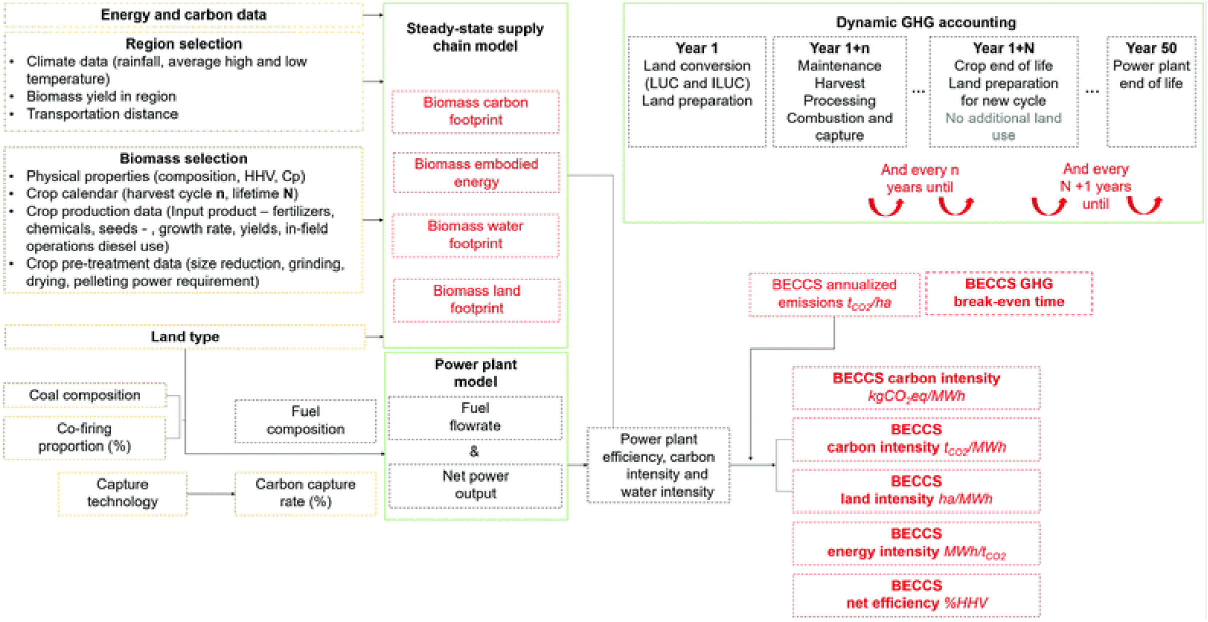


Figure 3: Overview of the MONET model, taken from Fajardy and Mac Dowell, 2017

In this work, we adopted the MONET database to derive the biophysical proprieties, *e.g.,* carbon content and heating values (HHV) of a range of biomass feedstock as well as the carbon, land and water footprint associated with their cultivation and transport in the EU. In this way we could quantify the regional ecosystems impacts associated with biomass use within each NETs pathway.

3.1.2 The JEDI model

The Jobs and Economic Development Impacts (JEDI) model is an economic tool initially developed by the National Renewable Energy Laboratories (NREL), that estimates socio-economic impacts from a portfolio of energy supply chains and technology projects. A schematic representation of the model is provided in Figure 4. The overall approach is to combine cost data of a specific energy project with country level socio-economic indicators from the database for structural analysis (STAN). The STAN database is a comprehensive tool for analysing industrial performance at a relatively detailed level of activity across countries. It includes annual measures of output, gross value added (GVA) and its components, labour input, investment, and capital stock, which are used to evaluate a wide range of indicators, focusing on areas such as productivity growth, competitiveness, and general structural change. STAN is primarily based on member countries' annual national accounts, while data from the International Labour Organization (ILO) are adopted to estimate annual wages per sector and industrial activities.

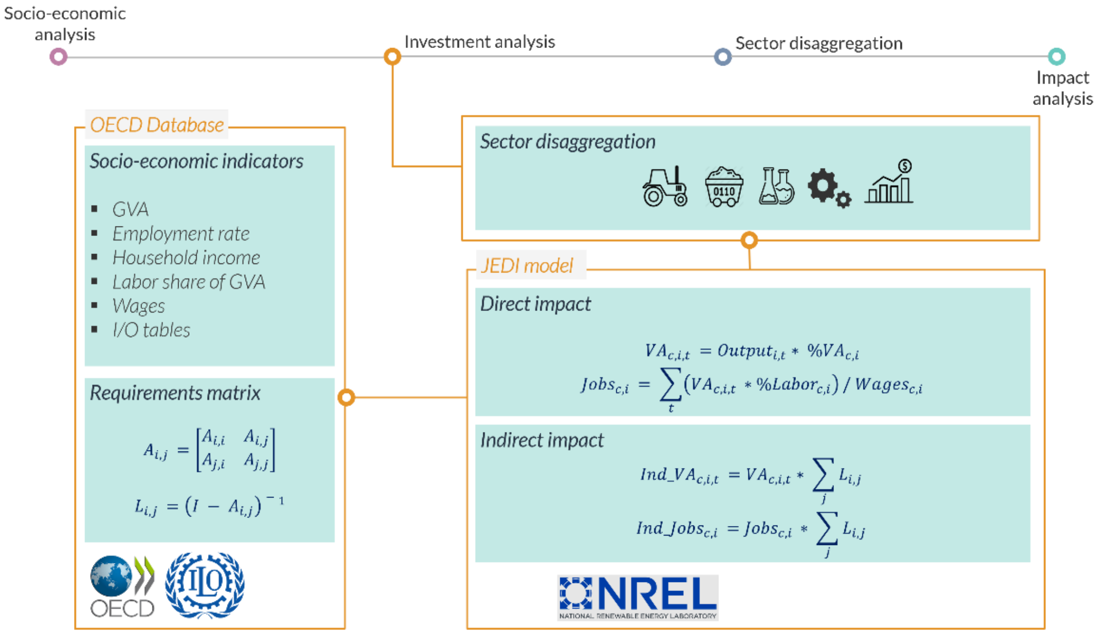


Figure 4: JEDI framework adopted in this study

For this study, we further extended the JEDI portfolios of energy technologies to include the NETs under investigation, *i.e.,* BECCS for integrated steel mills and cement kilns, biofuels production technologies with CCS, slow-pyrolysis, and BECCS for bioelectricity production. To do so, capital investments and operational activities associated with these technologies have been allocated to their corresponding industrial sectors. A detailed description of the tool and its application for assessing the socio-economic impacts of low carbon technology deployment can be found in the literature (Patrizio *et al.*, 2018; Patrizio, Pratama and Dowell, 2020) .

3.2 Key performance indicators (KPIs)

The analysis of the selected NETs pathways is based on eleven key performance indicators (KPIs) enumerated in this section. These KPIs have been defined to compare the technical, socio-economic and environmental performances of the NETs pathways against a baseline scenario: a reference cement kiln or an integrated still mill for BECCS in industrial sectors, or fossil energy counterparts in the case of pathways associated with the production of biofuel or bioelectricity. Table 2 lists the main indexes adopted in the equations presented in this section, while the following indexes are used to characterize the formulation of each KPI:

- p : pathway investigated, comprising the agricultural, transport, conversion and CO_2 transport and storage (T&S) activities associated with each NETs
- pr : bioenergy, *i.e.,* GJ of bioelectricity or biofuel, or product, i.e., a tonne of clinker or crude steel, generated within each pathway.
- b : biomass feedstock considered, i.e., forest and agricultural residues, first and second-generation biomass and wood chips
- c : counterfactual scenario representing the fossil energy that is being displaced by bioelectricity and biofuels, i.e., grid electricity, diesel or electric vehicles (EV), or by the direct use of biomass in industrial processes.

Index	Description	Formula	Note	KPI
$C_{bio}(b)$	Biomass carbon content	tC/t_{dm}	Feedstock specific	2
$SR(b)$	Supply chain dry mass recovery	%	Accounts for losses during biomass transporting and processing	2
$\eta_C(p)$	Process capture efficiency	%	Refers to the overall CO_2 capture efficiency of the process	2
$\eta_{PC}(p)$	Post capture efficiency	%	Accounts for losses during CO_2 transport and storage	2
$\eta_S(p)$	Storage efficiency	%	Refers to the permanence of CO_2 storage (in % of CO_2 initially stored)	2
$\eta_E(p)$	Process energy efficiency	%	Refers to the biomass conversion efficiency of each production process	4
$HHV_{bio}(b)$	Biomass heating value	GJ/ t_{dm}	Based on higher heating value of the feedstocks	4,5
$Ebio(pr,b)$	Bioenergy production	GJ/t_{dm}	Amount of bioenergy *produced within* each pathway	4
$Prbio\ (pr,b)$	Bioenergy use	GJ/t_{pr}	Amount of biomass *used* in BECCS to industry pathways	4
$Sub_E(c)$	Fossil energy substitution factor	%	Share of fossil energy that can be substituted with bioenergy in the counterfactual scenario	5
$EF_E(c)$	Carbon intensity	t_{CO2}/GJ	Carbon footprint of the fossil energy that is being substituted	5
$GVA(pr,p)$	Domestic value	\$/GJ or \$/t_{pr}	Value created in the domestic economy with the biomass products	10,11

Table 2: Summary of mathematical indexes adopted for characterizing the KPIs in this section, dm= dry mass, pr= product

KPI 1 – Levelized cost production (\$/GJ or \$/t_{pr})

This indicator considers the annual capital and operating expenses associated with the annual production of product pr in the reference plant $Prod\ (pr,p)$

$$LC(pr,p) = \frac{CapEx\ (pr,p) + FixOpex(pr,p) + VarOpex(pr,p)}{Prod\ (pr,p)}$$

KPI 2 – Sequestered CO_2 emissions (t_{CO2}/t)

This indicator refers to the physical amount of biogenic CO_2 fixed in geological or natural storage. The amount of CO_2 that can be sequestered within each bio-based NETs pathway is associated with the carbon content of the biomass feedstock used $C_{bio}(b)$ and the process capture efficiency $\eta_C(p)$, which characterizes the amount of CO_2 captured from the biomass conversion process. In the equation below the carbon content of the feedstock is multiplied by the ratio of molecular weight of CO_2 (44) and of Carbon (12), to obtain the amount of biogenic CO_2 sequestered in the biomass. It is also assumed that some fraction of feedstock dry mass is lost during transport and processing $SR(b)$, at the rate of 5% for residues (drying, local transport), and 10% for timber (drying, >100km transport) and pellets (pelletizing, >100km transport).

After the capture process potential CO_2 leakage might occur in downstream activities such as CO_2 transport and injection for BECCS pathways or biochar spreading. Such losses, which correspond to around 4% and 6% of the total amount of CO_2 captured in biochar production and BECCS processes respectively, are reflected in the storage efficiency parameters $\eta_C(p)$.

$$CO_2\ sequestred\ (b,p) = \ C_{bio}(b) * \frac{44}{12} * SR(b) * \eta_C(p) * \eta_{PC}(p) * \eta_S(p)$$

KPI 3 – Net CO_2 emissions removed (t_{CO2}/t)

Following the quantification of the CO_2 sequestered, the net CO_2 removal is calculated by accounting for the carbon footprint associated with each biomass feedstock. The carbon footprint of biomass pellets is an European average calculated in the MONET framework and includes biomass production (seed, fuel for land preparation and harvest, fertiliser direct and indirect CO_2 equivalent emissions), pelletising, average distance transport (50 km), and pellet grinding. The carbon footprint of agricultural residues is taken to be a European average calculated using MONET and includes straw collection, additional fertiliser application to compensate for straw removal, drying, chopping, and 50km transport.

$$CO_2\ removed\ (p,b) = \ CO_2\ sequestred\ (b,p) - \ CO_2\ upstream(b,p)$$

KPI 4 – Life cycle CO_2 emissions (LCE) (t_{CO2}/GJ OR t_{CO2}/t_{pr})

This indicator considers direct $CO_2\ direct\ (pr,p)$ and indirect $Indirect\ (br,p)$ emissions associated with the NETs pathways as well as emissions of upstream and downstream supply chains. In industrial pathways, direct emissions refer to the CO_2 content of the exhaust gases of the cement kiln or the various CO_2 streams generated in the integrated steel mill. Indirect emissions are associated with the consumption of fossil electricity for biofuel production or to compensate for additional energy required by the process after the capture technology integration. Removals of CO_2 from the atmosphere are also accounted in the life cycle analysis by combining the emissions removed by each tonne of biomass adopted in the conversion processes $CO_2\ removed\ (p,b)$, with the total amount of bioenergy that is being produced within the pathway $Ebio(pr,b)$

$$LCE\ (pr,p) = CO_2\ direct\ (pr,p) + Indirect\ (br,p) - \left(CO_2\ removed\ (p,b) * Ebio(pr,b)\right)$$

Where $Ebio(pr,b)$ depends on the process energy conversion efficiency $\eta_E(p)$ and on the biomass higher heating value $HHV_{bio}(b)$

$$Ebio(pr,b) = SR(b) * HHV_{bio}(b) * \eta_E(p)$$

Note that, in the case of BECCS to industry pathways, LCE refer to the amount of emission associated with the final product, a tonne of clinker (t_{clk}) or a tonne of crude steel (t_{cs}). Thus, it is important to consider the share of bioenergy that can be used in these production processes $Prbio(pr,b)$

$$\begin{aligned} LCE\ (pr,p) = CO_2\ direct\ (pr,p) + Indirect\ (br,p) \\ - (CO_2\ removed\ (p,b) * Ebio(pr,b) *\ Prbio\ (pr,b)) \end{aligned}$$

KPI 5 – Avoided CO_2 emissions (t_{CO2}/t_{pr} or t_{CO2}/GJ)

The amount of CO_2 avoided is somewhat more complex to quantify as it is entirely dependent on the counterfactual, c, chosen for each scenario. In this study, high, average, and low carbon intensity counterfactuals were chosen to determine a CO_2 avoidance range. The net emission avoided within a NETs pathway are generally calculated by accounting for the entire life cycle CO_2 emissions. However, since the LCE depends purely on the pathway considered, *e.g.* the production of H_2 via biomass gasification, regardless of the emission intensity of energy or product displaced, *e.g.* diesel fuel in the case of $BioH_2$, a separate indicator has been adopted in the computation of the CO_2 avoided. Note also that the amount of CO_2 avoided in DAC processes is essentially zero since these technologies do not produce any product or energy vector. This KPI considers:

- the amount of energy that is being produced within the biomass pathway, $Ebio(pr,b)$ the fossil energy substitution factor which depends on the counterfactual scenario considered $Sub_E(c)$
- the carbon intensity of fossil energy that is being displaced $EF_E(c)$

$$CO_2\ avoided(b,p,c) = Ebio(pr,b) * Sub(c) * EF_E(c))$$

KPI 6 – Removal cost ($/$t_{CO2}$)

Based on the indicators presented above, the removal cost can be calculated by dividing the production cost of the biomass-based product with the amount of CO_2 removed

$$Cost\ of\ CO_2\ removal\ \ (pr,p) = \frac{LC(pr,p)}{CO_2\ removed\ (p,b) * Ebio(pr,b)}$$

In the case of BECCS to industry pathways, the total share of bioenergy used within the production process $Prbio\ (pr,b)$ needs to be included in the calculation of the removal cost. Since, for instance, only a share of coal can be substituted with biomass in the production of steel.

$$Cost\ of\ CO_2\ removal\ \ (pr,p) = \frac{LC(pr,p)}{CO_2\ removed\ (p,b) * Ebio(pr,b) * Prbio\ (pr,b)}$$

KPI 7 – Avoidance cost ($/$t_{CO2}$)

The same rationale adopted in the computation of removal cost is used to quantify the avoidance cost associated with each pathway. In this case the market price of the fossil counterfactual $LC(pr,c)$, *e.g.* unabated clinker or gasoline, is subtracted from the low-carbon production cost.

$$Cost\ of\ CO_2\ avoided\ \ (pr,p,c) = \frac{LC(pr,p) - \ LC(pr,c)}{CO_2\ avoided(b,p,c) * Ebio(pr,b)}$$

And in the case of BECCS to industry:

$$Cost\ of\ CO_2\ avoided\ \ (pr,p,c) = \frac{LC(pr,p) - \ LC(pr,c)}{CO_2\ avoided(b,p,c) * Ebio(pr,b) * Prbio\ (pr,b)}$$

KPIs 8 and 9 – Land and water footprint

These indicators account for the land and water use associated with the cultivation of biomass, b, in the European regions, r. To derive the cumulative ecosystems impacts of NETs, land and water footprints of agricultural residues and bioenergy crops obtained from the MONET database have been multiplied by the amount of biomass required to produce bioenergy or bioproducts within each pathway. Given the low TRL levels of some technologies, such as slow-pyrolysis, data related to the water consumption at the process level are scarce in the literature. Hence these KPIs consider only the ecosystems impacts generated during the cultivation and harvest of biomass.

$$LF\ \ (r,pr,p) = \ Land\ footprint\ (r,b) * Ebio(pr,b)$$

$$WF\ \ (r,pr,p) = \ Water\ footprint\ (r,b) * Ebio(pr,b)$$

KPI 10 – Value of CO_2 removal

The Gross Value Added (GVA) is a widely recognized macroeconomic variable that measures the contribution to the Gross Domestic Product (GDP) made by individual producers, industries, or sectors in a country. The expression is profound as it consists of measuring the *value* that each industrial activity adds to the domestic economy. Here, the value of CO_2 removal is obtained by relating the CO_2 removed with the production of each product pr to the total amount of GVA created in the domestic economy $GVA(pr,p)$, descending from the JEDI tool

$$Removal\ value\ \ (pr,p) = \frac{CO_2\ removed\ (p,b) * Ebio(pr,b)}{GVA(pr,p)}$$

KPI 11 – Value of CO_2 avoidance

Similar to KPI 10, this indicator relates the amount of CO_2 emission avoided with the substitution of fossil energy counterfactuals c, to the total amount of GVA created in the domestic economy $GVA(pr,p)$

$$Avoidance\ \ value\ \ (pr,p) = \frac{CO_2\ avoided(b,p,c) * Qbio(pr,b)}{GVA\ (pr,p)}$$

4 Techno-economic performances of NETs pathways

4.1 BECCS in the iron and steel industries

The iron and steel industry accounts for around 23% of the global industry final energy demand and 28% of the industrial sector's total direct emissions in 2018, resulting primarily from the combustion of coal in ironmaking processes. Currently, around 60% of the global steel production is made from pig iron in integrated steel mills, comprising an ironmaking blast furnace (BF) and a steelmaking basic oxygen furnace (BOF).

The dominant BF-BOF steelmaking route relies on the use of coking coal and its metallurgical properties to produce hot metal. The best available technology (BAT) benchmark in Europe is emitting 1.4 tCO_2 per tonne of crude steel (t_{CS}). Whilst a portion of metallurgical coal in the blast furnace can be substituted with alternative fuels such as charcoal to provide heat to the process, substantial emission reductions can only be achieved through the implementation of CCS.

There is little knowledge available on the use of BECCS in iron and steel, separately, bioenergy and CCS use are established concepts in the context of steel production. The partial replacement of some coal with charcoal is an established procedure in Brazilian steelmaking (Sonter et al. 2015). The use of carbon capture at steel mills is in early commercialization, with approximately 1.0 Mt of fossil CO_2 per year captured in steel or Direct Reduced Iron (DRI) plants in the United Arab Emirates, Belgium, and China. Reuse of captured CO_2, also called CO_2 utilization or carbon capture and utilization (CCU) can reduce CO_2 emissions by displacing fossil carbon typically used to make fuels or materials, but unless reuse results in long-term storage, CO_2 reuse will result in net positive CO_2 emissions.

A recent study (Mandova *et al.*, 2019) considered cost-optimized BECCS scenarios for European blast furnace steel plants, concluding that BECCS could be used to achieve carbon neutrality with avoidance costs ranging between 140 - 280 $\$/t_{CO2}$ depending on site specific factors. Tanzer, Blok, and Ramirez (2020) also explored several options of BECCS for different commercial and emerging steelmaking technologies, to assess whether negative emissions are theoretically possible in steelmaking (Tanzer, Blok and Ramírez, 2020)One of the main conclusions of the study is that carbon neutral iron and steel making is only possible with high levels of biomass substitution and CCS integration, with net CO_2 being highly sensitive to a number of factors, including carbon intensity of electricity and biomass carbon debt.

4.1.1 Systems boundaries and main assumptions

The production of steel based on the integrated BF-BOF route involves various processes, shown in Figure 5, including raw material preparation (sinter, coke, and lime production), iron making processes (hot metal production & desulphurisation), steel making process, finishing and rolling. The three main raw materials used to make pig iron (the raw material needed to make steel) for primary steel production in a blast furnace are iron ore, coke (residue left after heating coal in the absence of air, generally containing up to 90% carbon supplemented by other coking coal and/or pulverised coal injection (PCI)) and limestone. The sinter iron, resulting from the agglomeration of iron ore fines in the sinter plant are fed into the blast furnace together with coke and PCI to produce pig iron and blast furnace gas (BFG). In the BOF, steel is produced by using high purity oxygen which removes carbon and other impurities from the pig iron. Output from BOF include liquid steel and off-gases (BOFG). To support the iron and steel production processes, power plant and air separation units are generally included as part of the integrated mill. The electricity required is mainly provided by BFG and BOFG. A smaller amount of power demand (~5%) is imported from the grid or produced via natural gas combustion.

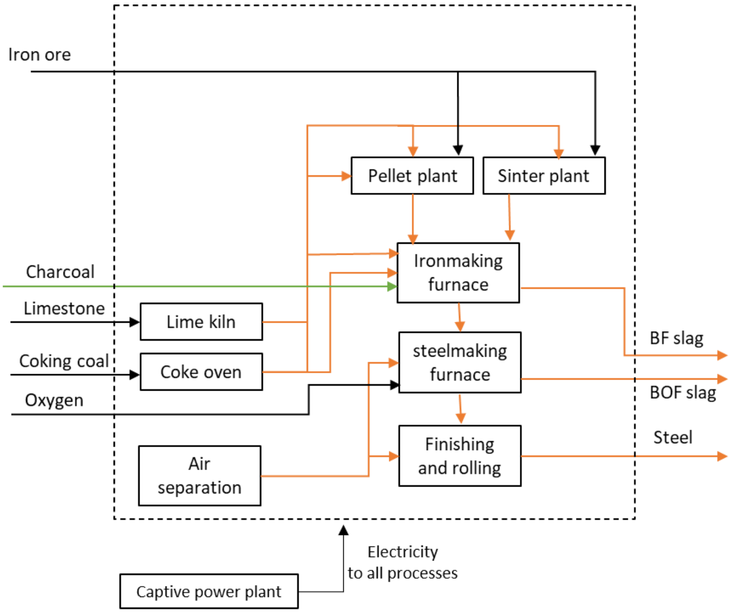


Figure 5: Simplified process flow diagram of a reference integrated steel mill

The clinker production characteristics used in this study were based on a reference integrated steel mill producing 5.5 Mt/year of crude steel. The IEAGHG (2013a) study on CCS integration in the iron and steel mill has been adopted as a reference to derive detailed process gas flows for the integrated still mill plant without capture (Table 7. 1) and to derive main techno-economic process parameters resulting from the integration of a monoethanolamine (MEA)[4] capture technology. To investigate the feasibility of BECCS deployment in the existing still mill, the study also explores the substitution of PCI in the blast furnace with charcoal, which would potentially lead to negative emissions. Main technical parameters and raw material consumptions are reported in Table 7. 2

---

[4] According to different sources MEA represents the most promising and commercially mature capture technology for the iron and steel industry (IEAGHG, 2013b; Tanzer and Ramirez, 2019), chemical absorption with amine represents the most promising and commercially mature capture technology for the iron and steel industry and is hence the focus here.

4.1.2 Techno-economic analysis

One major challenge associated with implementing carbon capture on integrated steel mills is the presence of different CO_2 sources, mainly from the flue gases of the hot stoves, power plant, sinter plant, coke oven underfired heaters and limestone calcination. This accounts for ~ 90% of the total direct CO_2 emissions. The most investigated CCS configuration in integrated steel mills captures the CO_2 emitted for the BF gases, which accounts for ~60% of the whole process emissions. To achieve further emission reductions additional CO_2 streams originating from the coke oven, sinter, and lime plants need to be captured. Hence, this study assumes the retrofit of the reference still mill with two different CCS configurations, presented in Figure 6, capturing the CO_2 emission from the blast furnace (CCS min) as well as from coke and lime production, and from the sinter plant (CCS max).

When the still mill is retrofitted with CCS, BF and BOF flue gases which are normally used to provide electricity to the plant, are being redirected to the steam generation plant, which provides heat to the capture process. The total heat required for solvent regeneration is ~ 3 MJ/Kg_{CO2} captured. The electricity required for the continuous operation of the steel plant can then be supplied by the electric grid or by natural gas combustion. Since access to low-carbon electricity is a necessary requirement to achieve substantial emission reduction in BF-CCS, countries relying on fossil-based electricity might import natural gas instead of relying on grid electricity.

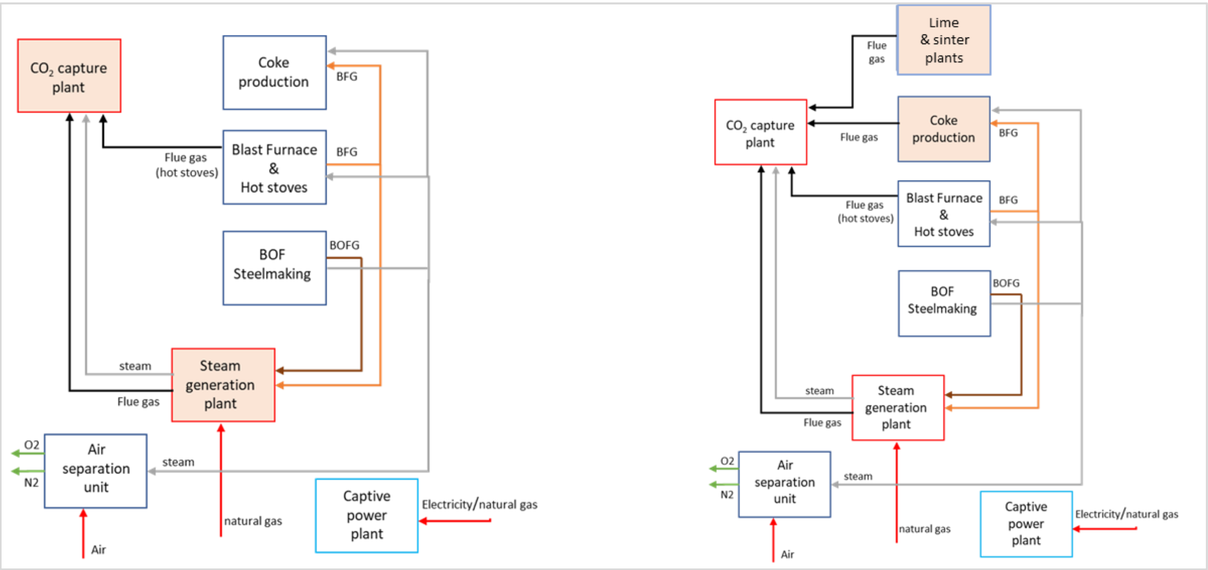


Figure 6: CCS configurations and main gas flows for the reference BF-BOF plant

To achieve further emission reductions, wood-based charcoal can be injected into the blast furnace, providing the heat required to the ironmaking process and substituting PCI. This option is therefore investigated in two additional scenarios, *i.e.* BECCS min and BECCS max, depending on the level of CO_2 capture assumed. The reference plant consumes 210 kg/tcs of PCI, equal to 5.8 GJ/tcs of thermal energy. Providing this energy with the injection of charcoal requires 0.33 t/tcs of wood chips, which is converted into charcoal in pyrolysis units.

KPI 1 – Crude steel cost

The results of economic assessment for the reference BF-BOF plant with different levels of CCS and biomass integration are presented in Figure 7, electricity and natural gas prices are reported in the technical annex, while the costs of iron ore derive from a confidential source. The price of crude steel produced from the reference plant was estimated at 510 $/tcs. The addition of CCS increases the production costs by 110 and 150 $/tcs for CCS min and CCS max respectively, of which ~30% are CAPEX (Capital Expenditure) associated with the capture plant. In BECCS configurations additional cost for charcoal production results in steel production prices of 650-685 $/tcs, with biomass (wood chips) costs being 60 $/tcs.

With the still mill having limited access to the power grid, the additional energy for the continuous operation of the plant can be provided by natural gas. Hence, additional investment in natural gas combined cycle plants (NGCC) is required (~600 k$/MW). In this case steel production cost are 620 $/tcs (CCS min) and 655 $/tcs (CCS max), while BECCS configurations leads to a steel production costs of 640 and 690 $/tcs.

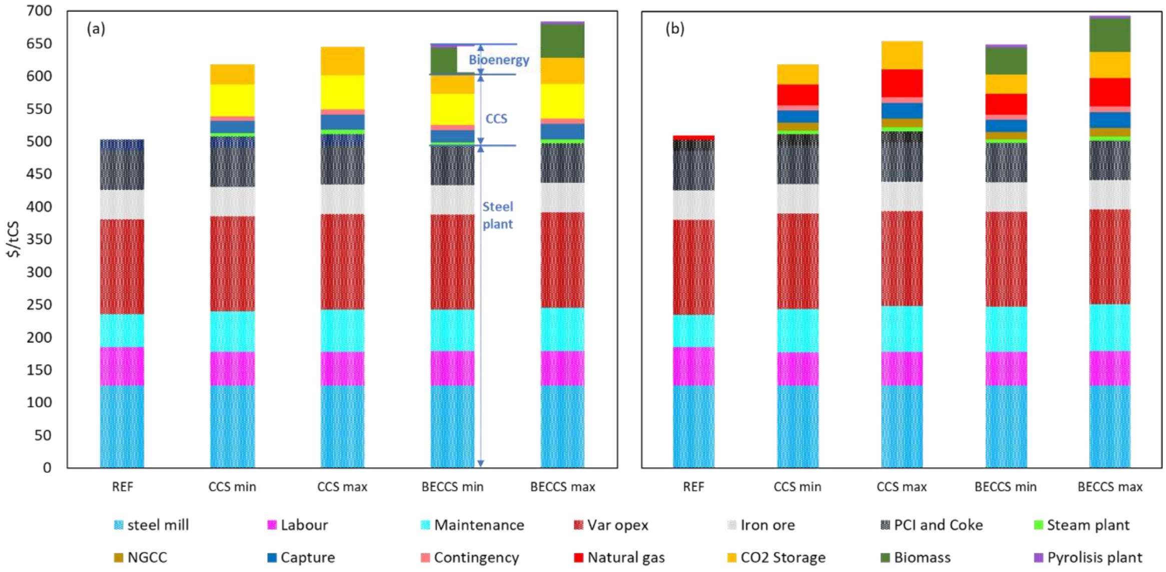


Figure 7: Levelized cost of steel production associated with different BECCS and CCS integration, assuming (a) access and (b) no access to grid electricity

For the remainder of this study, only the CCS max configurations will be considered in the remaining part of the analysis, *i.e.,* BF-CCS and BF-BECCS, assuming the possibility of exploiting electricity from the grid, as this is the case in most of the integrated steel plants in the EU.

4.1.3 Long term technological improvements and scalability

Over the past decades, Research and Development initiatives under the ‘CO_2 Breakthrough Programme’ have been investigating the potential for developing breakthrough technologies that hold the promise of large reductions in CO_2 emission in the iron and steel industry. Among various initiatives, the ULCOS program[5], convening a consortium of 48 European companies and organisations, represented a cooperative research and development initiative to enable drastic reduction in CO_2 emissions from steel production. Key areas of research identified are Carbon Capture and Storage (CCS) in combination with hydrogen as innovative reducing agents for the reduction process. Technologies with the highest long-term potential in the iron and steel industry are carbon capture and storage (CCS) in combination with a top gas recycling for the blast furnace (TGR-BF), direct reduction of hydrogen (DR) with electric arc furnace (EAF), and a rather immature technology with high future potential, the iron ore electrolysis also called electrowinning (EW) (Fischedick *et al.*, 2014). Note that, since steel plant lifetimes are long, and investments are very high, technological breakthroughs are considered a long-term option.

Direct reduction is a solid-state reduction process for iron ore with natural gas, already in operation since the 1970s. The replacement of natural gas with hydrogen as a reducing agent in the DR shaft, represents a promising option to achieve low-carbon steel in direct reduction routes. Because hydrogen is converted to H_2O and condensed in the shaft top gas scrubber, no CO_2 removal system is necessary and the process results in 80% lower emissions than a conventional BF-BOF plant. After the reduction of ore in the shaft, the solid hot briquetted iron is fed into the EAF together with steel scrap for steel production.

One drawback of this process is the high electricity requirements particularly to produce a sufficient amount of hydrogen: recent techno-economic assessments (Fischedick *et al.*, 2014; Vogl, Åhman and Nilsson, 2018) calculated a hydrogen demand of 800 Nm^3 per unit of crude steel. Assuming an average annual production of 1 Mt_{cs} , this would correspond to a cumulative electrolysis capacity of ~ 170 MW.

In addition, since the process is almost entirely electrified, the process emissions for the H_2-DR route are affected by two main factors:

I. Power grid emission intensity: Electricity correspond to ~ 87% of process emissions in H_2-DR routes, hence access to low-carbon power is a necessary requirement.

II. Share of scrap use in EAF: recycling scrap reduces the power requirement for ore heating and the H_2 demand per unit of crude steel, resulting in 40% less CO_2 emissions when 50% scrap is used compared to pure hot briquetted iron (HBI) (Figure 7. 1)

As a result, to achieve the same level of emissions of a BF-BOF plant equipped with CCS and BECCS, *i.e.* ~ 500 and 54 kg_{CO2}/t_{cs} as the emission balance in the section 5 will show, access to low-carbon electricity is required. In addition, today's low TRL of polymer electrolyte membrane (PEM) electrolysers results in high capital and fixed costs for hydrogen production. Hence, for H_2-DRI routes to be competitive with BECCS, low operating costs need to be achieved, which is only possible if abundant, and cheap electricity is available. This notwithstanding, ongoing initiatives such as the Hydrogen Breakthrough Ironmaking Technology (HYBRIT) project[6], are currently investigating the potential for bringing steel produced by hydrogen reduction to the market in the future.

---

[5] More information about ULCOS are available at: https://cordis.europa.eu/project/id/515960

[6] More information on the HYBRID initiative are available at: https://www.lkab.com/en/about-lkab/technological-and-process-development/research-collaborations/hybrit--for-fossil-free-steel/

4.2 BECCS in the cement industry

Cement kilns are less complex than integrated still mills, with the calciner representing the largest CO_2 point source. Post-combustion and oxyfuel combustion are the preferred technologies for CO_2 capture in clinker production, as pre-combustion cannot capture the CO_2 from the calcination process, which accounts for 50-60% of total emissions (Schakel *et al.*, 2018).

A study commissioned by IEAGHG in 2013 (IEAGHG, 2013a), compared the economics of integrating Monoethanolamine (MEA) and oxy-fuel capture in a reference integrated cement kiln. The study showed that, due to the scarcity of low-grade heat for solvent regeneration, post-combustion capture using amine scrubbing is nearly three times more expensive than oxyfuel. Similar conclusions have been reported by the CEMCAP project[7], a recent comparative study that investigated five CO_2 capture technologies for cement kilns and compared them against a reference MEA capture technology. The study found that compared to MEA, all other capture options performed better in terms of primary energy consumption, with the oxyfuel technology achieving the lowest CO_2 avoidance cost, followed by the calcium looping technologies.

Calcium looping is considered an especially favourable CO_2 capture technology for the cement industry, as cement plants already have limestone handling infrastructure in place, and can potentially utilize the resulting spent solids in the cement production process. Calcium looping can be integrated with the calcination process or at the tail-end of the clinker production process. Whilst the integration of the calcium looping process with clinker production is more energy efficient (Schakel *et al.*, 2018), this configuration might affect the operation of the existing cement kiln equipment, *i.e.* the process performance in the preheating tower, making it a more suitable option for greenfield cement plants. The operation of the CaL process in tail-end configuration has been already demonstrated in two different facilities, at 30 kW_{th} and 200 kW_{th} scale (Arias, Alonso and Abanades, 2017; Hornberger *et al.*, 2020). It is hence a sufficiently mature technology and a promising decarbonization option for the cement industry in the near term.

The economic, process performance and technology readiness of adopting calcium looping in the cement industry have been extensively investigated in literature (Ozcan, Ahn and Brandani, 2013; Hills *et al.*, 2016; De Lena *et al.*, 2017; Schakel *et al.*, 2018). Coal is generally selected as the fuel to cover the heat demand of the calcium looping CO_2 capture processes, as this is the most dominant fuel used in cement production. The opportunity for using fuels with low carbon intensity, *i.e.* natural gas, woody biomass and a fuel mix to maximize the mitigation potential of this technology has been investigated in a recent life cycle assessment (LCA) (Schakel *et al.*, 2018). The study found that the use of woody biomass to provide the heat for the capture process might lead to carbon neutral or even negative cement production.

4.2.1 System boundaries and main assumptions

Considering these literature findings and building on previous study conducted by IEAGHG on the economics of CCS in the cement industry (IEAGHG, 2013a), this study adopts

---

[7] Objectives, methodology and main outputs of the project can be found at: https://cordis.europa.eu/project/id/641185

calcium looping tail-end capture technology (CaL) as a CCS retrofitting option for existing cement plants. To explore the potential for achieving negative emissions from cement production, different fuels have been considered in the calcium looping process. Beside a scenario using coal (Coal-CaL), which is the most used fuel in clinker production, a scenario using wood pellets (Bio-CaL) for the calcium looping process is investigated.

Clinker production characteristics used in this study were based on a reference (REF) cement plant with an annual production of 1 Mt clinker (clk). Key performance indicators of the reference plant can be found in the technical annex. Process characterization and main techno-economic parameters for the calcium looping process are taken from De Lena et al. (2018), and process modification associated with the replacement of coal with wood chips in the calcium looping are adopted from Schakel et al. 2018. (De Lena *et al.*, 2017; Schakel *et al.*, 2018).

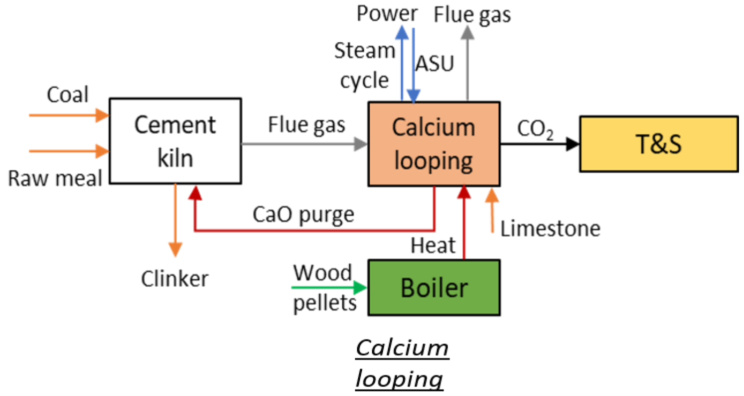


Figure 8: Conceptual scheme of the cement kiln with tail-end CaL process.

A schematic representation of the process is provided in Figure 8. The calcium looping process includes a carbonator and a calciner. In the calciner either coal or biomass is burned with oxygen while limestone is calcined into CaO. The cement kiln exhaust gases are fed into the carbonator and the solid CaO is used to capture the CO_2. Part of the spent CaO sorbent purge of the calcium looping system is extracted from the loop and mixed with the raw meal to the cement kiln, where it replaces limestone in the clinker production process.

Because the calciner and carbonator operate at high temperatures, a substantial amount of waste heat is available from the carbonator and the streams exiting the reactors. This heat can then be utilized for electricity production in a heat recovery steam cycle. In this way, it is possible to generate electricity to compensate the auxiliary consumption of the cement kiln and of the CO_2 capture section and in some cases exporting the excess electric power to the grid. As a result, the cement plant equipped with CaL capture technology becomes a net electricity producer.

One drawback of the process is that the limestone sorbent activity degrades with time as repeated cycles pollute the sorbent with ash and $CaSO_4$ originating from fuel combustion in the calciner. To compensate the purge of solid from the CaL loop, a periodic make-up of fresh limestone is required, resulting in total consumption of ~ 250 $Kg_{limestone}$ / t_{clk}. Since the levels of sulphur and ash produced are lower when using biomass instead of coal as fuel in the calciner (Schakel *et al.*, 2018), lower levels of limestone consumption are expected in the Bio-CaL scenario, as will be shown in the next session.

4.2.2 Techno-economic analysis

In a CaL process, integration level is defined as the ratio of limestone fed for the CaL process to the total limestone fed to the cement plant with the CaL capture unit. This parameter decides the extent to which the CaL unit is integrated into the cement plant, in a tail-end scenario. Based on the assumption from De Lena et al. (2018), which form the basis of this analysis, integration level of 20% has been considered. This means that, 80% of the $CaCO_3$ in the raw meal is fed to the raw mill while the rest is fed to the new calciner unit which is part of the retrofitted capture plant.

Figure 9 presents the energy balance for the cement kiln with and without calcium looping. Total thermal fuel input in the reference plant is 3.2 GJ/ t_{clk}, with the precalciner consuming the largest share (62%). Total fuel consumption increases by 240–270% when including the CaL into the cement plant, due to the double calcination needed for the CO_2 originating from limestone decomposition (De Lena *et al.*, 2017). Fuel consumption in the rotary kiln remains basically constant, while fuel consumption in the pre-calciner reduces by 13% with respect to the reference cement kiln, owing to the replacement of limestone in the raw meal with CaO from the CaL solid purge. The rate of fuel supplied to the CaL calciner is mainly driven by the quantity of limestone calcined and the heating value of the fuel used. The reduction in limestone consumption from 250 kg/t to 90 kg/t associated with the switch from coal to biomass to provide the energy required to the CaL process, lowers the calciner duty, and consequently the fuel use, which is 15% less in the biomass case.

In addition, the higher the total fuel consumption in the CaL system, the higher the thermal power that can be recovered in the steam cycle: a net surplus of electricity of 0.39 GJ/ t_{clk} and 0.35 is available in the Coal-CaL and Bio-CaL systems, respectively.

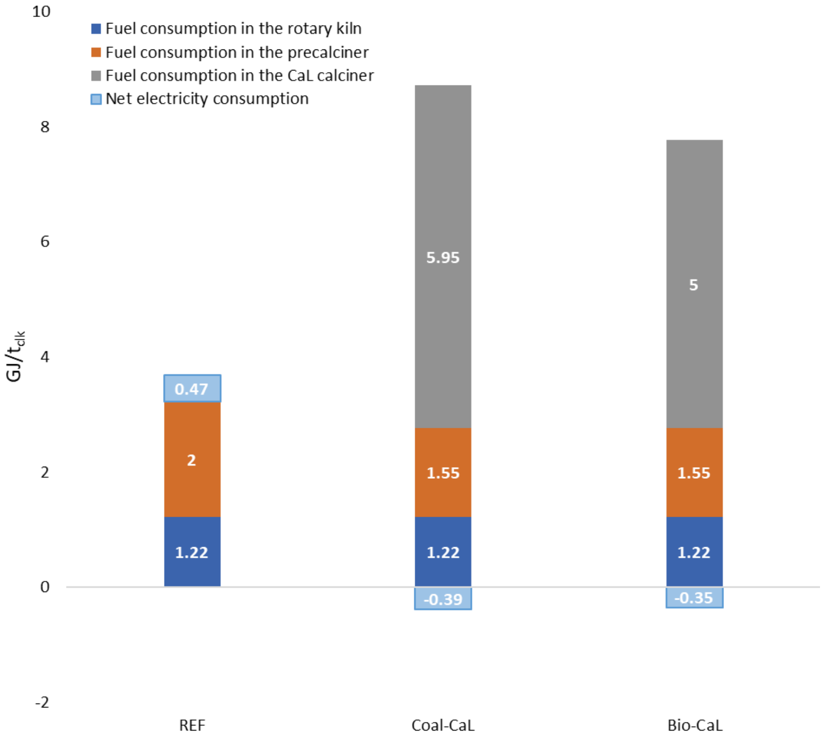


Figure 9: Energy balance for the cement kiln with and without CaL tail-end (Coal-CaL) and with the use of wood pellets for the calcium looping process (Bio-CaL)

KPI 1 – Cost of cement

The results of the economic assessment for CaL-based CO_2 capture are presented in Figure 10. The production cost for the reference plant without capture is 77 $\$/t_{clk}$, which is 16% higher than the value reported in the CEMCAP's report and is mainly associated with the different electricity prices assumed. Integrating the CaL technology in the reference kiln increases clinker production costs by 90%-110%. In both CaL configurations the highest contribution to the cost of clinker derives from the capital expenditures which are roughly doubled compared to the reference case. CO_2 transport costs are also significant and variates between 32-38 $\$/t_{clk}$ with higher value associated with the Coal-CaL configuration since more CO_2 is being captured in this scenario. As a result the levelized costs of Clinker production resulting from the integration of calcium looping are 145 $\$/t_{clk}$ and 160 $\$/t_{clk}$ for Coal-CaL and Bio-CaL respectively, with the highest cost in the Bio-CaL scenario being associated with higher biomass cost compared to coal.

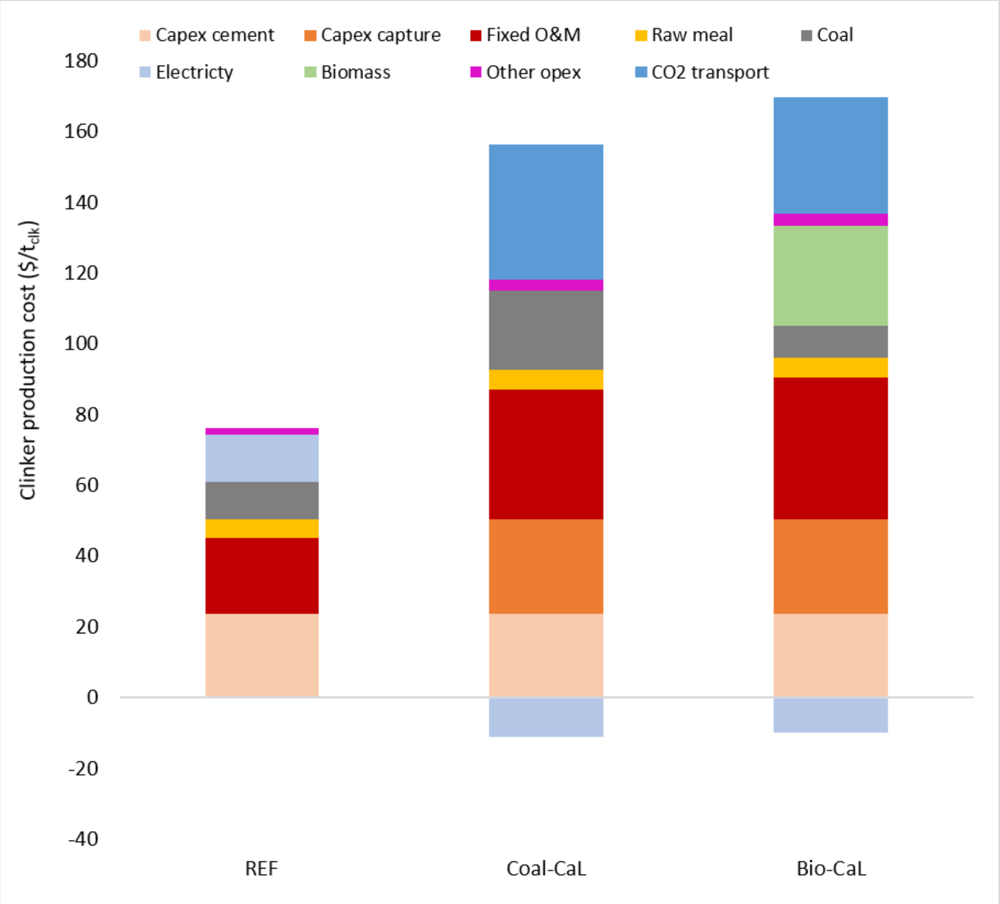


Figure 10: Breakdown of clinker costs for the cement kilns with and without CaL tail-end

4.2.3 Long term technological improvements and scalability

The key challenge of implementing CCS in cement kilns is to produce cement with consistently high product quality. From this perspective, the preferred scenario would be easy retrofit of CO_2 capture at a low cost, with lower modification to the kiln operation and low downtime for installing the CO_2 capture equipment.

In an investigation carried out within the CELCAT project, oxyfuel technology represents the most promising CCS technology for the cement industry. The study has found that oxyfuel technology led to lower energy consumption and CO2 avoidance costs than calcium looping, membrane-assisted liquefaction and chilled ammonia processes.

In the oxyfuel process, combustion is performed with an oxidizer consisting of oxygen mixed with recycled flue gases to produce rich flue gas. This allow the concentration of CO_2 to reach about 80 vol% and a relatively easy downstream purification with a CO_2 purification unit (CPU). Additional power is required compared to the reference kiln without capture, mainly to provide electricity to the air separation unit (ASU) and the CO_2 purification unit. However, some of this power demand can be covered by an organic Rankine cycle (ORC) generating power from waste heat.

Unlike other CCS technologies, the integration of oxyfuel combustion will affect the whole plant configuration and require a significant amount of land for the ASU and the recirculation loop (Hills *et al.*, 2016). As clarified by Hills et al, the design of virtually every unit is different from a traditional cement kiln to take account of different gas properties and to minimize gas ingress or egress from the units. This is likely to be technically achievable but not for existing cement kilns, which would be more reasonably opt for technologies involving fewer process modifications, such as calcium looping in a tail-end configuration (Hills *et al.*, 2016). Hence, oxy-fuel can be regarded as the best technology for new-build low-carbon cement manufacture. Considering that the cement kiln lifetime is around 50 years, and oxyfuel are currently at TRL 4, a good estimate of its commercial availability, i.e. TRL 8, would be after 2040.

4.3 BECCS in fuel and power production

An inherent advantage of BECCS relies on its potential integration within different conversion processes, such as combustion, gasification and fermentation-based routes, thereby providing a wide range of low carbon energy vectors, including electricity, liquid fuel, heat and hydrogen, while providing long-term removal of CO_2 emissions. In integrated assessment models (IAMs), the main BECCS pathways represented are typically biomass conversion to electricity in large scale combustion plants as well as for the production of biofuels. There are few low carbon alternatives available for the transport sector. The production of liquid fuels via BECCS (*i.e.*, biofuels) can provide a substantial contribution to transport decarbonisation in the mid-century stabilisation scenarios (Muratori *et al.*, 2017; Muri, 2018). Hydrogen can be used to decarbonise multiple sectors at a national level, *e.g.*, industry, transport and heating. Assuming high capture rates of CO_2 (*i.e.*, greater than 90%), biomass for hydrogen production is presented as an energy efficient biomass utilisation route to CO_2 removal (Energy Systems Catapult, 2020; Lawrence Livermore National Laboratory, 2020). However, CO_2 removal costs of biohydrogen are generally high due to the high capital cost associated with its production (Bui *et al.*, 2020).

The BECCS pathways predominant in IAMs involve biomass combustion such as a pulverised combustion boiler (PC), or fluidised bed reactor (FBR), and gasification such as integrated gas combined cycle (IGCC) to produce electricity. Co-production of heat is also possible when using a combined heat and power plant (CHP). Numerous modelling studies have investigated the techno-economic potential of BECCS deployment in the power sector. The most recent review of CDRs in terms of scale and economics (Fuss *et al.*, 2018) indicates costs for combustion BECCS in the range of 88-288 \$/tCO_2, with wide variations can be attributed to differences in modelling assumptions and boundaries conditions. The CO_2 capture technology varies as a function of the conversion process: post-combustion capture of CO_2 (absorption or adsorption), oxy-combustion, and pre-combustion capture (with biomass gasification). The efficiency of BECCS power generation can be as low as 17% in small-scale plants (Hetland *et al.*, 2016) and as high as 37% (Koornneef *et al.*, 2011). Depending on the efficiency of the base plant, process design improvements could potentially increase efficiency up to 38-42% (Koornneef *et al.*, 2011; Bui, Fajardy and Mac Dowell, 2017). Compared to pulverised combustion plants, the efficiency of IGCC plants is typically higher at around 43% with potential improvement to 50% (Koornneef *et al.*, 2011). However, uncertainties remain around the commercialisation potential of biomass IGCC, which remains at the pilot scale.

Out of the five “BECCS” projects in operation today, four are bioethanol plants integrating CO_2 capture. The Decatur plant in Illinois permanently stores CO_2 geologically (Gollakota and McDonald 2014), whereas three utilise the CO_2 for enhanced oil recovery (EOR) – Bonanza and Arkalon plants in Kansas, Husky Energy plant in Canada (Christopher Consoli, 2019). Fermentation produces a high-purity (99%) gaseous stream consisting only of CO_2, H_2O, and small amounts of organic and sulphur compounds. Therefore, purification, dehydration, and compression of fermentation streams can be accomplished at a cost lower than \$25 $tCO_2{}^{-1}$ avoided (Sanchez *et al.*, 2015). Cellulosic ethanol production costs range between \$22-30 GJ^{-1} in literature, where cost variations are mainly associated with the level of revenues from co-electricity production and feedstock costs. (Hamelinck, Van Hooijdonk and Faaij, 2005; Viikari, Vehmaanperä and Koivula, 2012).

Fischer-Tropsch (FT) is considered the most developed and mature technology for synthesis of liquid transportation fuels. Large-scale FT plants worldwide employ either gasification of coal or reforming of natural gas to generate syngas. The adoption of biomass in the process has been explored in various demonstration plants worldwide (Sikarwar *et al.*, 2017) while the inclusion of CCS in the production route has been widely assessed in literature. Liu et al, investigated the techno-economic performance of alternative FT-CCS designs, and found a FT production cost of around 28 \$ GJ^{-1}, when using switchgrass as a feedstock (Liu *et al.*, 2011). The study also compared the economics of FT production against bioethanol and found that for carbon prices higher than 120 \$ $tCO_2{}^{-1}$, producing FT diesel becomes cheaper than ethanol due to the much higher CO_2 capture rate that can be achieved within this biofuel production pathway.

For hydrogen generation, biomass processing pathways include gasification, pyrolysis, liquefaction and hydrolysis. Gasification has one of the highest stoichiometric yields of hydrogen and is often presented as a promising option based on economic and environmental considerations and is the focus here (Balat and Kırtay, 2010). Biomass gasification is closely related to coal gasification, consisting of steam gasification, gas cleaning (removal of ash and contaminants), water-gas-shift and hydrogen separation *via* pressure swing adsorption.

Gasification with steam reforming of the syngas and water-gas-shift can reach hydrogen yields of 37-50% on an energy basis (Koroneos, Dompros and Roumbas, 2008; IEAGHG, 2014; Parthasarathy and Narayanan, 2014). Although biomass gasification for hydrogen production as a whole process is not commercialised for BECCS applications, individual components of the technology are technically mature. Gasification, gas clean up tech, water-gas-shift reactors, CO_2 absorption, ASUs *etc.,* are commercially available as individual units and used in fossil fuel applications**.** Like coal gasification, the cost of hydrogen production from biomass are most sensitive to the high cost of capital. Capital costs of solid fuel gasification facilities are expected to reduce with the development of projects at larger scale. Hydrogen production costs are estimated to be \$1.82–2.11 kg^{-1} for an output capacity of 139.7 t H_2 day^{-1} with biomass costs of \$47.4–82.5 dry ton^{-1} (Parkinson *et al.*, 2019).

4.3.1 System boundaries and main assumptions

Based on the literature finding presented above, five BECCS to biofuel and biopower pathways, which are expected to become available at commercial scale in the medium term, have been selected (Figure 11):

- 1st generation ethanol via fermentation of corn stover,
- 2nd generation ethanol via biochemical conversion of lignocellulosic feedstock,
- Fisher-Tropsch liquids (FTL) via thermal gasification,
- Hydrogen via thermal gasification
- Bioelectricity production via ultracritical pulverised combustion

These pathways are characterized by two alternative CCS configurations, as detailed in Table 3. Beside a base case approach where CO_2 is captured only from the high concentration stream and an alternative configuration (CCS+) considers process modifications that enable higher CO_2 capture rates. Process capture efficiencies for each CCS configuration are presented in the techno-economic analysis, values obtained for CCS+ process configurations can be regarded as the feasible upper bounds.

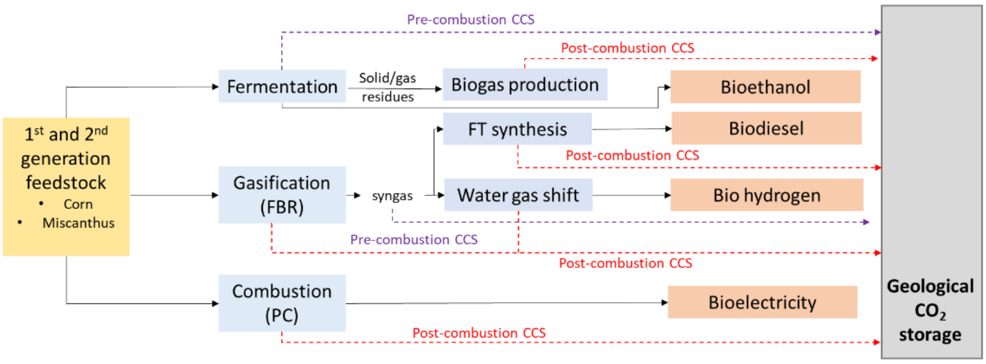
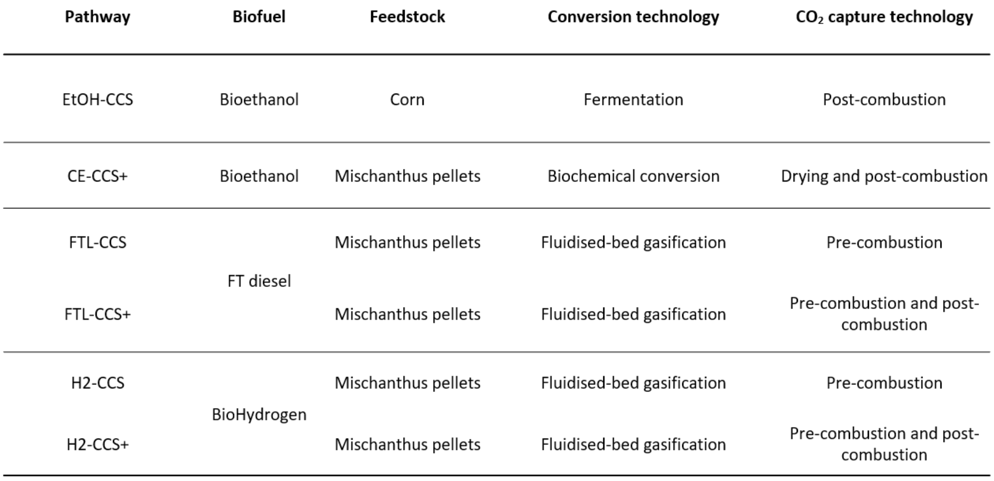


Figure 11: Selected BECCS to fuel and power pathways

For pathways involving the production of biofuels, this study adopts the process cost and parameters from the latest IEAGHG study on biorefineries with CCS (IEAGHG, 2021) which facilitates the evaluation of different biofuel pathways on a consistent basis. Note that the IEAGHG study assumes First-of-a-kind (FOAK) plants with necessarily high investment cost assumptions. This might influence the economic performances of biofuel production pathways compared to the other biomass conversion plants investigated in this study. For BECCS to bioelectricity, we adopted the MONET database (Fajardy, Chiquier and Mac Dowell, 2018) to derive the capital and operational costs associated with the deployment and operation of a large scale (500 MW) BECCS combustion plant in Europe.



Pathway	Biofuel	Feedstock	Conversion technology	CO_2 capture technology
EtOH-CCS	Bioethanol	Corn	Fermentation	Post-combustion
CE-CCS+	Bioethanol	Mischanthus pellets	Biochemical conversion	Drying and post-combustion
FTL-CCS	FT diesel	Mischanthus pellets	Fluidised-bed gasification	Pre-combustion
FTL-CCS+		Mischanthus pellets	Fluidised-bed gasification	Pre-combustion and post-combustion
H2-CCS	BioHydrogen	Mischanthus pellets	Fluidised-bed gasification	Pre-combustion
H2-CCS+		Mischanthus pellets	Fluidised-bed gasification	Pre-combustion and post-combustion

Table 3: BECCS to bioenergy scenarios investigated in this study

4.3.2 Techno-economic analysis

As Figure 12 shows, the integration of CCS in these biomass conversion processes leads to different levels of CO_2 capture. Ethanol configurations with CCS design have the smallest CO_2 capture efficiency (21%) as most of the biomass carbon ends up in the distiller's dried grain solids. However, when CO_2 from the by-product ((lignin and biogas) biomass is also captured, a substantial increase in CO_2 captured (74%) can be achieved. Compared to bioethanol production routes, a larger quantity of CO_2 can be sequestered in FTL pathways, with capture efficiencies ranging from 53 to 66%, while 30% of the biomass carbon is found in the FT fuels. For thermochemical configurations, base case CCS designs already capture most of the available CO_2 from the process and the maximal design will only contribute a small addition to the total capture. The highest capture rates are achieved with hydrogen configurations as all carbon from the process is in the form of CO_2 that can be captured.

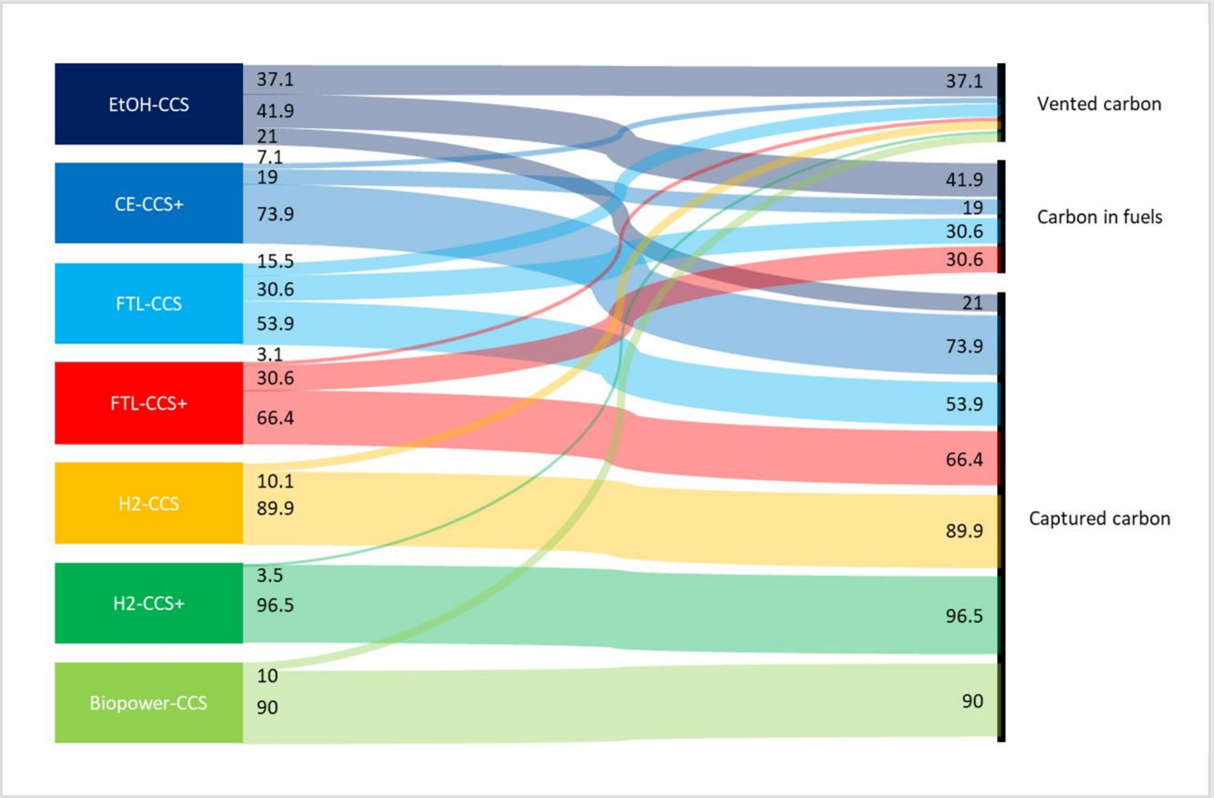


Figure 12: Carbon balance of selected biofuel pathways assuming 100C of biomass feed. The biopower-CCS and H_2-CCS configurations capture the highest share of input carbon to a concentrated stream of CO_2 (90%-97%), followed by CE-CCS+ (74%), FTLs (54%-66%), and EtOH-CCS (21%).

KPI 1 – Bioenergy (biofuel and bioelectricity) cost

Figure 13 shows the cost breakdown obtained for the different BECCS configurations. The levelized cost of biofuel production ranges between 20.8 to 53 $\$/GJ_{fuel}$ while the production of electricity in the reference BECCS plant reaches 82 $\$/GJ_{fuel}$. Corn based ethanol shows the lowest production cost, mainly thanks to the marginal capital costs required within this configuration: since the separation of CO_2 is only performed at the fermentation stage, the capture costs only comprise the cost of compression. The cost of transport CO_2 is also minimized since only 50 kg CO_2/GJ are been captured within the process. Despite lower capital costs compared to the other biofuel route, the CE-CCS+ shows significant variable costs, mainly due to the biomass pre-treatment processes required to separate the lignin content of the biomass before the fermentation stage. Similar levelized costs are achieved for FT and Hydrogen fuels in the CCS configuration, *i.e.* 50-53 $\$/GJ_{fuel}$ while cost increases are mild when the CO_2 capture is maximized (FTL-CCS+ and H2-CCS+) since only a small part of CO_2 is captured using post-combustion capture. As for the Biopower-CCS route, CO_2 transport costs equal to 13 \$/GJ, thanks to the high amount of CO_2 that can be sequestered within the process.

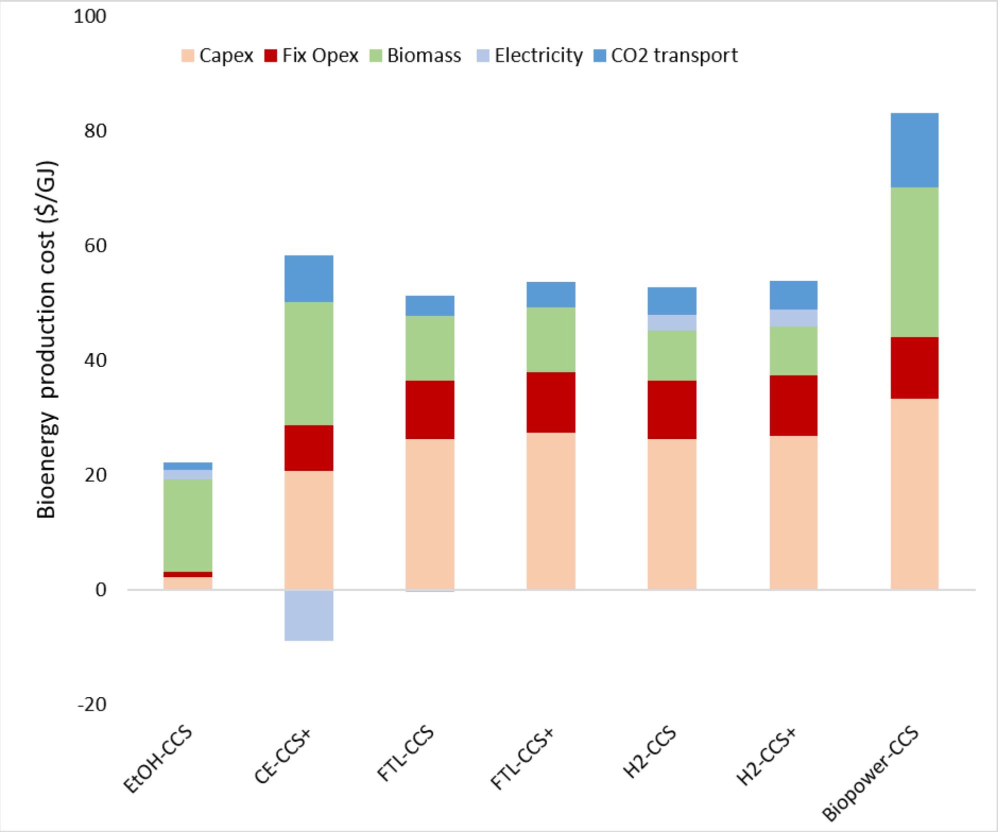


Figure 13: Biofuel and biopower production cost in selected CCS configurations

4.3.3 Long term technological improvements and scalability

Given the need to achieve zero-emission target in national energy systems, both pre-combustion and post-combustion capture technologies will likely be applied within the biofuel conversion routes by 2050. Hence, this section presents an outlook for the commercialization of biofuel production, based on main literature findings. The resulting cost reductions for the conversion technologies are presented in Figure 14, reflecting the following long term assumptions:

- Large scale deployment of post combustion capture technologies by 2050, with cost reductions consistent with the World Energy Outlook (IEA, 2016)
- Improvement in syngas clean-up and large-scale commercialization of biomass gasification technologies for hydrogen production[8]

In bioethanol production routes, lignocellulosic feedstocks require several steps such as pre-treatment and enzymatic hydrolysis processes to allow the breakdown of sugars during fermentation. These processes make up around 60% of the production cost and represent the greatest barrier for the commercialization of cellulosic bioethanol. It should be noted that enzymes producers such as Dyadic, Novozymes and DuPont have made significant progress

---

[8] Dodds and McDowall (2012) A review of hydrogen production technologies for energy system models. UKSHEC Working Paper 6. UCL Energy Institute.

to reduce the production cost of enzymes, which has been reducing by almost 70% in the past five years. At the same time, there is currently not one single process that is suitable and optimised for all biomass type, which challenges the deployment of this technology at large scale. Hence, only marginal cost reduction (~4%) are expected to be achieved for second generation ethanol, as CCS only contributes to 20% of the levelized cost of its production.

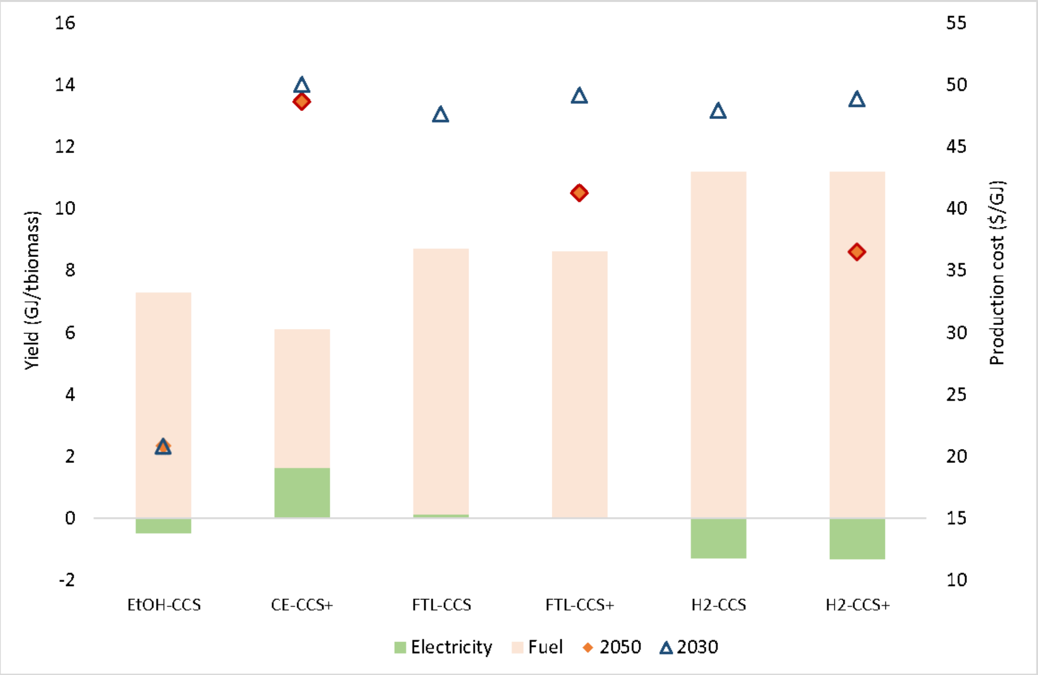


Figure 14: Biofuels production cost in the medium and long term associated with expected process improvements

Whilst FT synthesis is a mature technology, novel technologies for the production of sustainable synthetic fuels are currently being developed at the EU level. The successful commercialization and scale up of existing pilot projects, is expected to lower the production cost of biofuels. Finally, a reduction in biohydrogen production costs can be expected in the long term, as coal gasification developments might offer a potential development route for biomass gasification, provided that the challenges associated with the presence of impurities from the gasification of biomass can be overcome. According to different sources, the cost of biomass gasification with CCS is expected to reach 3.2 £ / $MW_{H2,\ HHV}$ following commercialization. This would lead to a 25% reduction in production cost compared to current levels.

4.4 Biochar from slow pyrolysis

Biochar is a carbon rich material produced through the pyrolysis of biomass. Biogenic waste materials suitable for biochar production include crop residues, food and forestry wastes, and animal manure. Biochar's climate-mitigation potential stems primarily from its highly recalcitrant nature (Woolf *et al.*, 2010), which slows the rate at which photosynthetically fixed carbon (C) is returned to the atmosphere. A study using 128 observations of soil carbon sequestration (Wang, Xiong and Kuzyakov, 2016), found biochar-to-soil had a mean residence time (MRT) of 107 years, confirming its ability to store carbon over a long period of time. Studies also suggest that biochar application in soil can improve soil quality (Gaunt and Lehmann, 2008; Biederman and Stanley Harpole, 2013; Hagemann *et al.*, 2017), potentially increasing net primary productivity and thereby reducing economic pressure to convert native lands to agricultural production, or land use change.

A growing number of LCA studies have estimated the climate change impacts of biochar production, showing emissions reduction from 1.8 to -0.7t CO_2/t_{bio} with negative values indicating increasing emissions from biochar application due to land use. The wide variation in results obtained arises from different biochar scenarios, *e.g.* feedstocks types, design and scale of pyrolysis plants and application rates as well as system boundaries, *e.g.* changes in Soil Organic Carbon (SOC), counterfactual scenarios and differences in calculation methodology. Variability is particularly high for the assumed agronomic effects of biochar when applied to soil: metanalysis of the impacts of biochar on crop yields (Verheijen *et al.*, 2010; Crane-Droesch *et al.*, 2013) have shown an average from all studies of a +10% response to biochar; however, the studies are heavily skewed towards (sub-) tropical conditions on degraded soils. Field trial results from more temperate regions tend to show smaller (or no) yield increases when compared with sub-tropical field trials. This is because, systems responses over biochar addition are strongly affected by soil properties such as SOC, rather than biochar characteristics (Crane-Droesch *et al.*, 2013).

Hence, the most certain environmental benefit of biochar relates to its ability to permanently store organic carbon and good estimates can be given of the persistence of biochar as a function of biomass feedstock types, the process heating temperature and duration. The C fraction of biochar can fluctuate between 25% to 70% mainly depending on feedstock ash content (and, to a lesser extent, H and O content), with waste wood and animal manure on the upper and lower bound of this range, respectively. Biochar produced from residues of crops and grasses is generally more degradable than that from wood, which is attributed to inert properties of various feedstocks, such as high lignin content.

Biochar also yields several potential co-benefits including the production of bioelectricity from syngas, thus generating avoided emissions as a function of the carbon intensity of the displaced electricity. Various pyrolysis technologies yield different proportions of biochar and syngas, the latter typically used to generate electricity. In general, pyrolysis maximizes biochar production at temperatures between 300-700 °C (slow pyrolysis) and maximizes condensable vapours production, *i.e.* bio-oil, at higher process temperature (fast pyrolysis). Technological development of fast pyrolysis is more advanced than slow pyrolysis, with several medium scale facilities having been constructed over the last decade to produce bio-oils (Brown *et al.*, 2015). Finally, soil biochar application may also directly reduce GHG emissions from soil, by reducing both the need for nitrogen fertiliser, and the subsequent N_2O emissions from the soil by unit of applied fertiliser (Woolf et al. 2010).

4.4.1 System boundaries and main assumptions

The boundaries of the biochar production system adopted in this study are illustrated in Figure 15 and include biomass collection and transport, biochar production process and its application into the field. For the reasons outlined above, the potential agricultural benefits of biochar application to soil have not been included in the analysis.

Accurate capital and operational cost estimates of slow pyrolysis facilities are scarce, given the commercial immaturity of this technology. Shackley et al. provided a detailed cost benefit analysis of biochar production in the UK, considering three potential unit sizes and potential economic benefits such as avoided gate fees, sales of electricity and the revenues from renewables obligation certificates (Shackley *et al.*, 2011). The work adopted data from one of the few demonstration units for slow pyrolysis to derive operational costs and estimate the value of electricity generated; this data was used to form the basis of the economic analysis in this study. Data from gasification plants were used to inform the calculation of capital expenditure, ranging between 0.9-41.25 M$ for the selected plant scale (Shackley *et al.*, 2011).

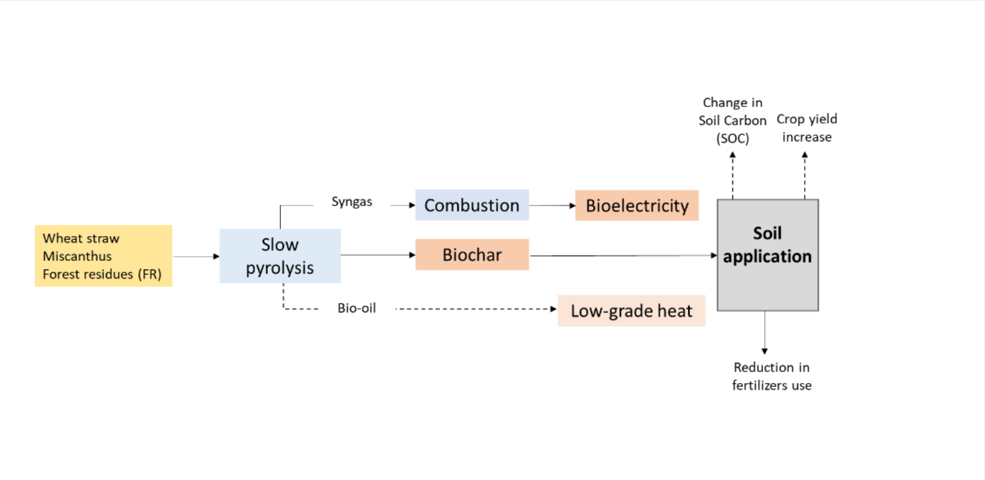


Figure 15: Scheme of the biochar production pathway under analysis. Dashed lines correspond to processes that have not been included in the study. These are the potential adoption of bio-oil for low-grade heat applications, and agricultural benefits, i.e. SOC and crop yield increase,

The carbon abatement of biochar relates to the amount of recalcitrant carbon resulting from the production process as a function of feedstock types and pyrolysis process conditions. Based on the review of existing literature, we investigate the use of three different biomass feedstock, *i.e.* wheat straw, miscanthus and forest residues, representing promising feedstock for biochar production. Similar to other NETs pathways, biophysical proprieties as well as carbon and water footprint of the biomass feedstocks are derived from the MONET database (Fajardy and Mac Dowell, 2017), complemented with data available from the literature (Hammond *et al.*, 2011; Shackley *et al.*, 2011). Moreover, in this study we assumed that the application of 5 t_C/ha of biochar, which is the most common application rate assumed in the literature, would lead to a 10% reduction in fertilizers use, *i.e.* 55 kg N/ha compared to 62 kg N/ha in a reference scenario.

4.4.2 Techno-economic analysis

Slow pyrolysis typically yields up to 20-50% char, 40-75% syngas and 0-15% bio-oil, depending on the feedstock and operating conditions. Here we have assumed a biochar pyrolysis yield of 49%, which represents the mean of values obtained by slow pyrolysis in Wolf et al, (Woolf *et al.*, 2010). The reference plant is a large-scale pyrolysis facility processing 184,800 t of biomass per year. Accordingly, around 38 kt of biochar are being produced per year while it is assumed that electricity is generated from the syngas produced during pyrolysis at 35% efficiency of conversion.

KPI 1 – Biochar production cost

Figure 16 present the breakdown of biochar production cost for a large-scale pyrolysis unit, processing 184,800 t of biomass per year. Depending on the feedstock adopted, biochar production and application cost between 220-530 $/t. The capital expenditures, which include cost of biomass pre-treatment equipment and pyrolysis facility correspond to 52 M$, in line the range of 40-60 M$ adopted for large scale facilities in literature (Shackley *et al.*, 2011; Brown *et al.*, 2015; Thornley *et al.*, 2015). Revenues for around 60 $/t are generated through the sales of electricity to the grid, based on the assumption presented above.

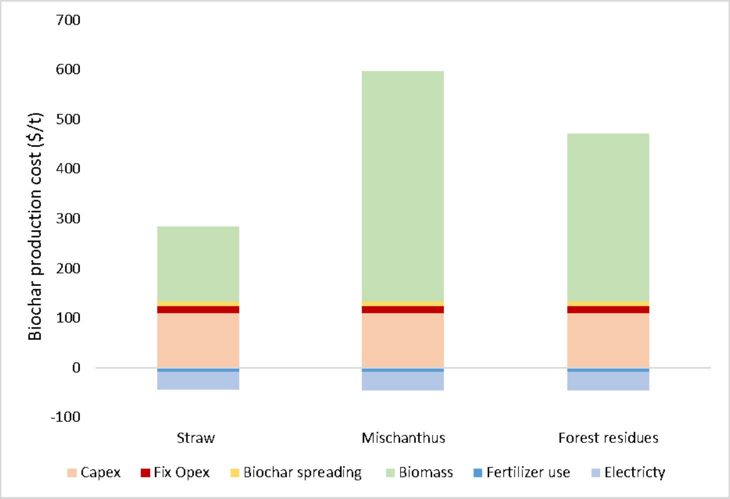


Figure 16: Breakdown of biochar production cost for a large scale slow-pyrolysis plant

Biochar from Miscanthus is the most expensive type, which is in line with the main findings from Shackley et al. 2011. It should be noted that costs obtained here are ~30% higher than the values obtained from that study, mainly because of other potential revenue streams such as Renewables Obligation Certificates (ROCs) that could be obtained from the sale of electricity into the market have not been accounted here.

4.4.3 Long term technological improvements and scalability

Several techno-economic and institutional barriers currently hinder the development of slow-pyrolysis conversion processes. Whilst the number of biochar facilities has increased over the past decade, these generally represent small-scale projects and are mostly concentrated in rural regions. For these reasons, there is a lack of publicly available guidelines on how to produce standardize biochar with reproducible characteristics and how to align them with market demand.

Studies on the prospects of biochar production facilities in the long term are also scarce in the literature. Several techno-economic assessments suggest a potential decrease of biochar production costs in the range of 10-20% compared to current levels, mainly associated with its deployment at scale.

Besides the overall techno-economic performances of this technology, important social and institutional barriers need to be overcome for its large-scale adoption. In particular, the agronomic value of biochar is highly debated in the literature and the potential for predicting its long-term ecosystems impact is very low. Before farmers are likely to take up the use of biochar, it is probably necessary for the positive (and any negative) effects of biochar addition to being properly understood and more reproducible and predictable (Shackley *et al.*, 2011).

4.5 Direct Air Capture (DAC)

4.5.1 System boundaries and main assumptions

Direct Air Capture (DAC) technologies involve a chemical process that removes CO_2 from air, concentrates it and injects it into geological storage. CO_2 in the air can be captured using contact with basic liquids, and solids and later released at different operating conditions. This latter desorption step is an endothermic process and very energy-intensive, requiring clean fuel inputs to maximise carbon removal.

As Figure 17 shows, there are two types of DAC technologies that are commonly discussed in literature - CO_2 separation using liquid solvents and solid sorbents. The former system relies on using a weak base as the sorbent, usually a type of amine, while the latter system uses a strong base, usually a hydroxide. In these systems, CO_2 is removed from the air by chemically binding with the base.

The total costs of DAC are reported to range between 100 - 1,000 $\$/t_{CO2}$ captured (Ishimoto *et al.*, 2017), with the upper range estimated using the minimum thermodynamic separation energy. Cost estimates for solvent-based capture vary between 300 – 820 $\$/t_{CO2}$ captured with the lower estimate attainable through process optimisation (Socolow *et al.*, 2011; Mazzotti *et al.*, 2013). However, alternative flow configurations have been proposed involving a combination of crossflow gas-liquid with a cost estimate of 336 – 389 $\$/t_{CO2}$ captured. Keith et al. proposed a novel process in which CO_2 is captured from air in combination with oxy-fired regeneration in a carbonate-based capture system with cost estimates reported to range between 93 – 220 \$/ tCO_2 captured (Keith et al., 2018). In all cases, it is necessary to clearly distinguish between the cost of CO_2 captured and the cost of CO_2 removed.

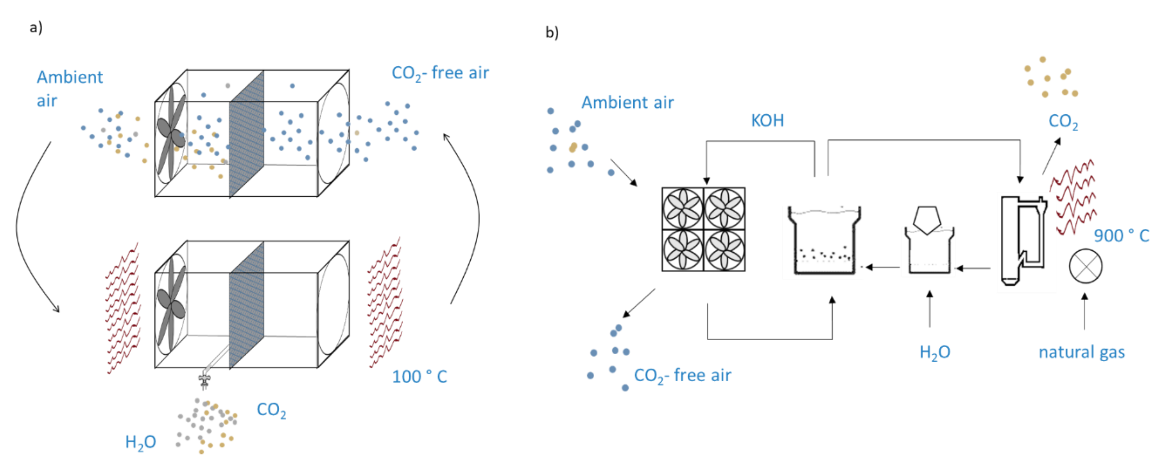


Figure 17: Schematic representation of DAC technologies based on a) solid adsorption and b) liquid absorption

4.5.2 Techno-economic analysis

A major difference between DAC compared to CCS processes at power plants or industrial facilities is the concentration of CO_2 in the feed stream. CO_2 concentration in air is about 410 parts per million (ppm) or 0.041%. In comparison, typical CO_2 concentrations range from 3–5% in gas turbine exhausts, 10–15% in coal-fired boiler flue gases, and 15–30% in cement plant exhausts. The low concentration of CO_2 in air has important implications on the techno-economic feasibility of DAC plants. To be able to capture one tonne of CO_2, large volumes of air, *i.e.* around 1.80 million m^3, must be processed and hence large “capturing” areas need to be installed. This results in capital intensive DAC facilities, with land requirements in the range of 1-7 m^2 (National Academy of Science, 2018). This notwithstanding the area requirements differ between DAC technologies and, overall, land use is recognised to be orders of magnitude lower than land-based NETs such as afforestation and BECCS.

Moreover, because of the low CO_2 concentration of the air compared to the flue gases of coal faired plants, DAC facilities require about three times the energy needed to achieve a 90% capture rate with CCS. The current energy requirements for Climework’s DAC process are 500 kWh/tCO_2 electric energy and 2000 kWh/tCO_2 thermal energy. The primary purpose of the electric energy is to operate the fans and the vacuum pumps, while thermal energy is used primarily to heat up the sorbent beds during regeneration. Such heat requirements translate into 580 kWh/tCO_2 of energy when assuming a coefficient of performance (COP)[9] of 3.5 for the heat pump. Hence, as demonstrated by a recent analysis (Herzog, in press), when accounting also for the energy required for compression (120 kWh/tCO_2)the total energy required for capturing 1 tonne of CO_2 in DAC plants currently amounts to 1200 kWh (4.3 GJ)[10] . This fact has important implications on the overall CO_2 removal that can be achieved within the process. As the process is highly energy intensive, the carbon intensity of the energy

---

[9] The heat is provided via a thermodynamic cycle, commonly called "heat pump". Work is herein used to transfer heat of a lower temperature to heat of a higher temperature. The heat pump is defined by its Coefficient of Performance (COP), which indicates the ratio of useful heating to the work required.

[10] This is because: 500 kWh/tCO_2 of electric energy + (2000/3.5 kWh/tCO_2) of thermal energy + 120 kWh/tCO_2 for compression = 1200 kWh/tCO_2

supplied to DAC for its operation as a great impact on the life-cycle emissions of this technology.

Figure 18 shows, when the indirect emission deriving from energy use[11] are accounted for, the net amount of CO_2 that is removed from the atmosphere with each unit of energy, reduces from 280 to 90 kg_{co2}/GJ. Consequently, the net negative emissions from the process are also reduced: since 4.3 GJ are required for each tonne of CO_2 captured, the net amount of CO_2 removal is as little as 0.4 t_{CO2} for each tonne of CO_2 sequestered.

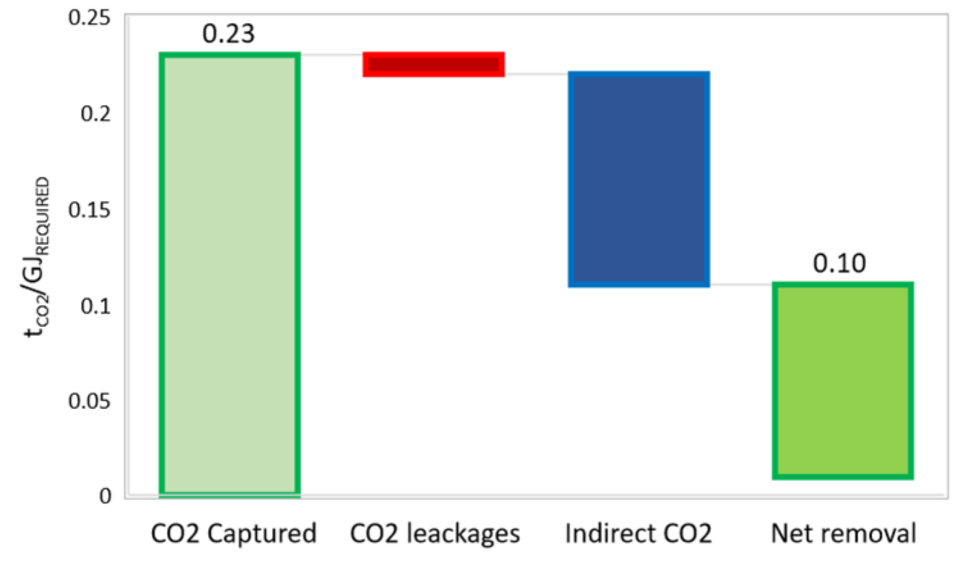


Figure 18: Lifecycle emissions of DAC processes, assuming that the energy required for the process is provided by a natural gas-fired plant having a carbon intensity of 0.41 tCO_2/MWh. In the figure, we accounted for CO_2 leakages occurring in downstream activities such as CO_2 transport and storage, assumed to be equal to 6% of CO_2 captured, consistent with the value used for BECCS pathways. Indirect emissions are those associated with energy use.

This fact has important implications on the overall economics of DAC plants: Climeworks, the only DAC installation plant available today, has proposed costs in the range of 600–700 $/$t_{CO2}$ depending on site specific conditions. It must also be recognised that Climeworks is currently offering the removal of CO_2 for a price between $1,000 – 1,200 $/$t_{CO2}$. However, these cost estimates are on a "gross CO_2 removed" basis and do not include compression and storage costs. Accounting for the plant lifecycle emissions presented above would lead to an overall cost of 1100-1500 $ per tonne of CO_2 removed. These values are also higher than those reported in the literature, ranging between 600–1000 $/$tCO_2$ (Fuss *et al.*, 2018).

4.5.3 Long term technological improvements and scalability

As explained in the previous section, the supply of low-carbon energy is a necessary requirement for the techno-economic feasibility of DAC systems. To this end, renewable

---

[11] Here we assumed that the energy is provided by a natural gas fired plant having a carbon intensity of 0.41 t_{CO2}/MWh, in line with the analysis from Herzog (in press) which form the basis of our assessment

energy sources could be used for the operation of these facilities. However, this clashes with the requirement of DAC plants of running at high utilization rates, which is a necessary pre-condition for balancing the significant upfront capital costs. One potential solution could be to combine the use of renewable energy sources with a storage facility, but this would, in turn, significantly raise the cost of energy supply. In addition, providing significant amounts of low-carbon energy to DAC systems will be a major challenge as the size and number of DAC installations grow. In this sense, the future trajectory of carbon-free energy costs will have a significant impact on DAC costs.

Another important barrier to the large-scale deployment of DAC, descends from the high volumes of air that need to be processed to achieve significant amounts of CO_2 removal. To be able to operate at a gigatonne scale, which is the scale required for DAC to be effective as a climate mitigation option, considerable amount of land is required. In addition, issues like access to low-carbon energy and sufficient amount of water, permitting issues, and acceptable meteorological conditions, place further constraints on the siting of DAC plants.

In the near term, large-scale demonstration of direct air capture technologies will require targeted government support, including through grants, tax credits and public procurement of CO_2 offsets. Longer-term deployment opportunities will be closely linked to robust CO_2 pricing mechanisms and accounting frameworks that recognise and value the negative emissions associated with storing CO_2 captured from the atmosphere.

5 Carbon accounting

In this section, we present the results of the NETs carbon balance based on the KPIs identified in section 3.2. Key process parameters for the computation of the KPIs are summarized in

Table *4*, together with main parameters assumptions. The amount of CO_2 sequestered (KPI 2) and CO_2 removed (KPI 3) are expressed per tonne of raw biomass adopted in the conversion process, while the lifecycle emissions (KPI 4) associated with the NETs pathways have been allocated to their main product:

- tonne of clinker (t_{clk}) or tonne of crude steel (t_{cs}) for BECCS in industries
- GJ of fuel or bioelectricity for BECCS to bioenergy pathways
- GJ of bioelectricity for slow-pyrolysis processes.

The rationale for considering bioelectricity rather than biochar as the main product of slow pyrolysis is that this facilitated the computation of the emission avoided on a consistent basis. In fact, for the reasons highlighted in previous sections, potential agricultural benefits associated with the application of biochar in the field have been excluded from the analysis. Notwithstanding this, the emission mitigation potential of slow pyrolysis process, i.e. the CO_2 avoided, refers to the amount of bio electricity generated within the process which replaces conventional fossil power.

KPI 2 – Sequestered CO_2 emissions

Figure 19 shows the amount of biogenic CO_2 emissions that is fixed in geological or natural storage within the selected NETs pathways. It can be noticed that pathways where the efficiency of the capture technology is higher result in higher biogenic CO_2 being sequestered. This is true for pathways involving the combustion of biomass for bioelectricity production (Biopower-CCS: 1.5 t_{CO2}/t_{dm}) or for pathways where the biomass is used as a fuel for the capture process (Bio-CaL: 1.44 t_{CO2}/t_{dm}). Conversely, lower quantities of CO_2 can be sequestered when BECCS is applied in integrated steel mills, since the biomass needs to be converted into charcoal before it is used in the blast furnace. In biofuel pathways, higher amounts of CO_2 can be sequestered when biomass is adopted for hydrogen production, as all carbon from the process is in the form of CO_2 that can be captured. Conversely, the production of bioethanol from corn has the smallest CO_2 capture efficiency (21%) as CO_2 is captured only at the fermentation stage while most of the biomass carbon ends up in the distiller's dried grain solids.

The low value obtained in biochar production pathways (Biochar: 0.53 t_{CO2}/t_{dm}) is associated with the issue of CO_2 storage permanence in natural sink since only 68% of the biochar carbon is generally assumed to be permanently fixed in the soil (Gaunt and Lehmann, 2008; Shackley *et al.*, 2011).

Pathway	Main product	Biomass	Biomass HHV (GJ/t_{odt})^a	Biomass Carbon Content ^{a} (%$_{odt}$)	Biomass carbon footprint^b (kgCO$_2$/t_{odt})	Supply chain dry mass recovery^c	Process capture efficiency (%$_{CO2}$)^d	Post capture efficiency (%$_{CO2}$)	Storage efficiency^f (%$_{CO2}$)	Process energy efficiency^g (%$_{LHV}$)
			HHV_{bio}	C_{bio}	CF_{bio}	SR	η_C	η_{PC}	η_S	η_E
BF-BECCS	Bio-steel	Wood chips	19.5	51.5	37.8	65%	90%	94%	100%	66%
Bio-CaL	Bio-cement	Wood chips	19.5	51.5	37.8	90%	90%	94%	100%	66%
EtOH-CCS	Bioethanol	Corn	16.6	44	273	95%	21%	94%	100%	44%
CE-CCS/CCS+	Bioethanol	Miscanthus pellets	19.2	47.7	176	95%	14%/71%	94%	100%	23%
FT-CCS/ CCS+	FT diesel		19.2	47.7	176	95%	54/66%	94%	100%	43%
H2-CCS/ CCS+	Biohydrogen		19.2	47.7	176	95%	89%/96%	94%	100%	55%
Biopower CCS	Bio-electricity		19.2	47.7	176	90%	95%	94%	100%	26%
Slow pyrolysis	Biochar/ electricity	wheat straw	18	45.9	67	95%	49%	96%	68%	13%

(a) Biomass carbon content are from Vassilev et al. (2010) and higher heating values from Nhuchhen and Abdul Salam (2012).

(b) The carbon footprint of biomass pellets is an European average calculated in the MONET framework (Fajardy, Chiquier, and Mac Dowell 2018) and includes biomass production (seed, fuel for land preparation and harvest, fertiliser direct and indirect $CO_{2,eq}$ emissions), pelletising, average distance transport (100-200km), and pellet grinding. The carbon footprint of agricultural residues is also an European average calculated in MONET and include straw collection, additional fertiliser application to compensate for straw removal, drying, chopping and 50k transport.

c) It is assumed biomass dry mass is lost during transport and processing, at the rate of 5% for residues (drying, local transport), and 10% for timber (drying, >100km transport) and pellets (pelletising, >100km transport).

(d) It is assumed that biomass initial carbon content is captured at 100% in timber, 49% in biochar (Woolf et al. 2010), 14% from the biomass fermentation to ethanol (Humbird et al. 2011), 56% from biomass gasification for biodiesel (Liu et al. 2011), 90% for biomass gasification to hydrogen (Antonini et al. 2018; IEAGHG 2014), 95% for biomass combustion to electricity (IEAGHG 2011). For biomass in iron and steel industry, 63% of initial biomass carbon is captured in BF-BOF route and 34% in the case of DRI-EAF ((Tanzer, Blok, and Ramírez 2020)

(e) This parameter captures any post conversion process emissions associated with energy use including 4% CO_2 emissions tilling and spreading for biochar (Gaunt and Lehmann 2008), 6% emissions associated with CO_2 transport and storage (L. J. Smith and Torn 2013).

(f) Out of the CO_2 sequestered in timber and geological storage, 100% of the CO_2 is considered fixed and stored. For the biochar process, it is assumed that 68% of the biochar carbon is fixed in the soil (Gaunt and Lehmann 2008).

(g) Process efficiency of biomass conversion (in electricity or fuel LHV/biomass HHV) is considered to be 13% for biomass to bioelectricity via pyrolysis (Gaunt and Lehmann 2008), 44% for biomass to bioethanol (Humbird et al. 2011) 43% for biomass to biodiesel (Liu et al. 2011), 55% for biomass to hydrogen Bui et al. (2020), and 26% for biomass to electricity (simulation in IECM see Berkenpas et al. 2001).

Table 4: Summary of key parameters and assumptions adopted in the carbon balance of each biomass pathways

KPI 3 – Net CO_2 removed

Net CO_2 removed accounts for biomass carbon footprint, *i.e.* the CO_2 emissions associated with biomass production preparation, and transport of feedstocks to the plant. These upstream emissions are significantly high for first generation feedstock such as corn grains, compared to Miscanthus and agricultural residues. This, and the fact that in EtOH CCS configurations CO_2 is captured only at the fermentation stage, explain the little CO_2 removal (EtOH CCS: 0.30 t_{CO2}/t_{dm}) that can be achieved within this pathway.

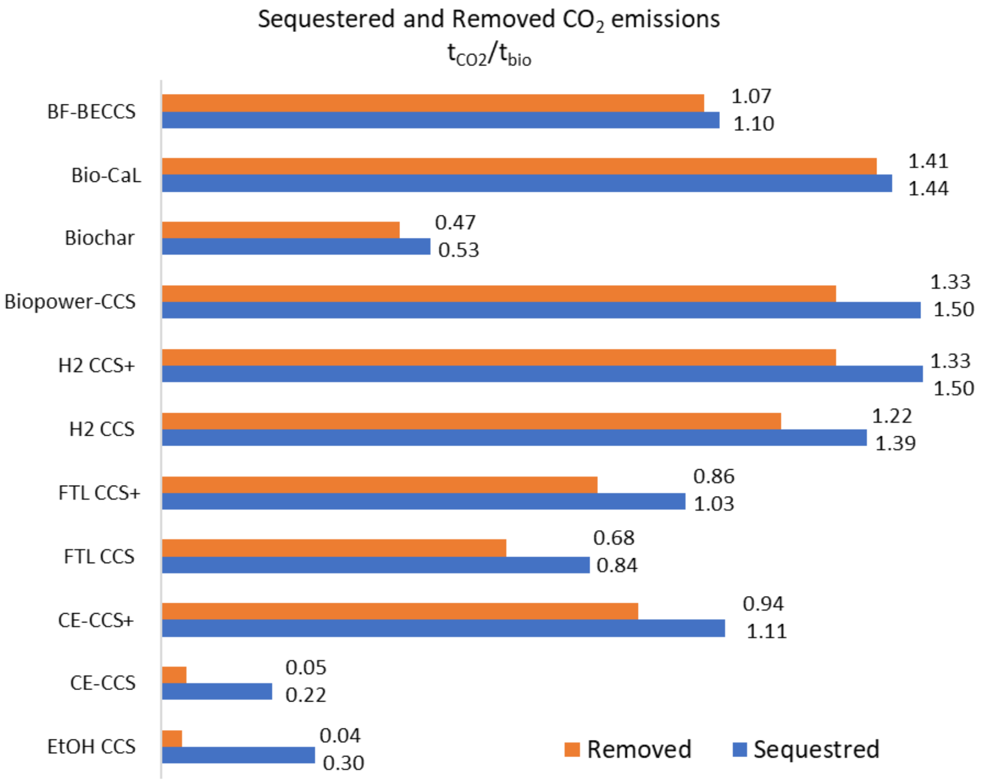


Figure 19: Sequestered and removed CO_2 emissions within each NETs pathway, calculated by accounting for the biomass upstream emissions as described in Section 3.2

KPI 4 – Lifecycle CO_2 emissions (LCE)[12]

As explained in detail in section 3.2, this indicator accounts for the gate-to-gate emissions, *i.e.* the direct and indirect emissions associated with the production processes, as well as the downstream and upstream emissions along the supply chains. Note that the downstream emissions represent the Net CO_2 removed from the atmosphere, that is KPI 3, since this indicator also considers the CO_2 losses during CO_2 transport and, in the case of biochar, the carbon that is realised back in the atmosphere after its application into the fields.

As shown in Figure 20, the carbon intensity of steel approaches carbon neutrality when the reference still mill is retrofitted with BECCS: compared to the unabated BF-BOF plants, producing 1.9 t_{CO2}/t_{cs} , the BECCS-BF configuration results in 0.54 t_{CO2}/t_{cs} life cycle emissions. Of these, the greatest share is associated with the residual direct emissions of secondary

---

[12] The LCE are associated with the output of each NETs pathway, i.e. bioenergy, bio-steel and bio-cement, hence they account for the amount of biomass that is used for the production of each unit of product.

steelmaking processes, while 0.34 t_{CO2}/t_{cs} are indirect emissions associated with the extra power required after the integration of the capture plant. On the other hand, 0.28 t_{CO2}/t_{clk} negative emissions are generated in the cement kiln using the calcium looping technology and biomass as fuel (Bio-CaL), confirming the efficiency of CaL to achieve low-carbon cement production.

Except for corn-based ethanol, all BECCS to bioenergy pathways achieve net negative emissions in the range of 0.08 - 0.35 t_{CO2}/GJ. The greatest emission benefits are achieved in configurations that maximize the capture of CO_2 and use large amounts of biomass in the conversion process (CE-CCS+: -0.22 t_{CO2}/GJ and Biopower-CCS: -0.35 t_{CO2}/GJ). Whilst hydrogen production pathways exhibit capture rates between 90-96%, the energy conversion efficiency for these processes is also high (37% for H_2-CCS versus 23% for CE-CCS). Since less biomass is required to produce the same amount of biofuel, fewer biogenic emissions are being sequestered in the process.

Finally, the production of biochar *via* slow pyrolysis leads to a net removal of 0.15-0.22 t_{CO2}/GJ (2.6-3.3 t_{CO2}/t_{char}) with upper bound values associated with the use of forest residues as feedstock, having low CO_2 upstream emissions (a biomass carbon footprint of 31 kg_{CO2}/t_{dm} has been assumed in this case).

KPI 5 – Avoided CO_2 emissions

The amount of CO_2 emissions that can be avoided within each pathway depends on the carbon intensity[13] and on the products/fuel's substitution factor. Hence, Figure 21 shows the total emission avoided in NETs bioenergy pathways as a function of the carbon intensity of the power grid. It can be noticed that adopting bioelectricity-CCS routes in Poland, offers a mitigation potential of 0.96 tCO_2/t_{dm} and 0.54 tCO_2/t_{dm} in Germany. As expected, the cumulative avoided emissions for BECCS to electricity are essentially zero when the carbon intensity of the electricity mix is also zero. Hence, in low-carbon power grids, such as those in the Nordic countries, biomass provides a much greater value in decarbonizing the transport sector. For instance, the substitution of gasoline with FT diesel avoids 0.59 tCO_2/t_{dm} around the same as the CO_2 avoided by BECCS in an average European power grid.

---

[13] The carbon intensity is defined as the mass of carbon emitted per unit of total energy produced, in the case of electricity, this depend on the power generation mix of individual countries

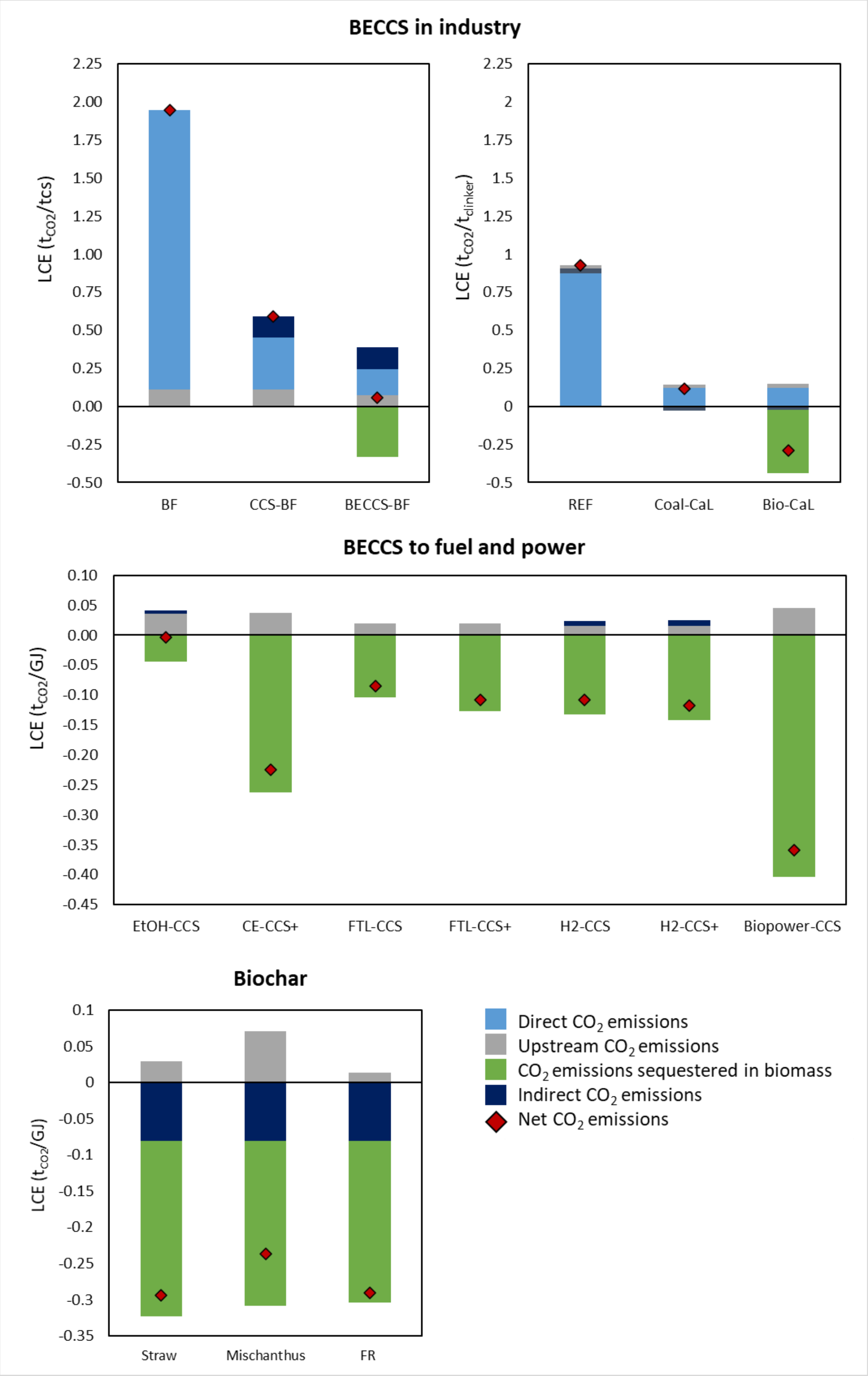


Figure 20: Lifecycle emission associated with different NETs and CCS configurations

Moreover, because electric vehicles (EVs) have a higher energy conversion efficiency than conventional gasoline and diesel cars, biomass-derived fuels exhibit an energy substitution factor as low as 26% when EVs are considered as the counterfactual scenario. Hence, in countries where EVs are available, adopting BECCS for biofuel production has little mitigation value, even when considering a highly carbon intensive energy generation mix.

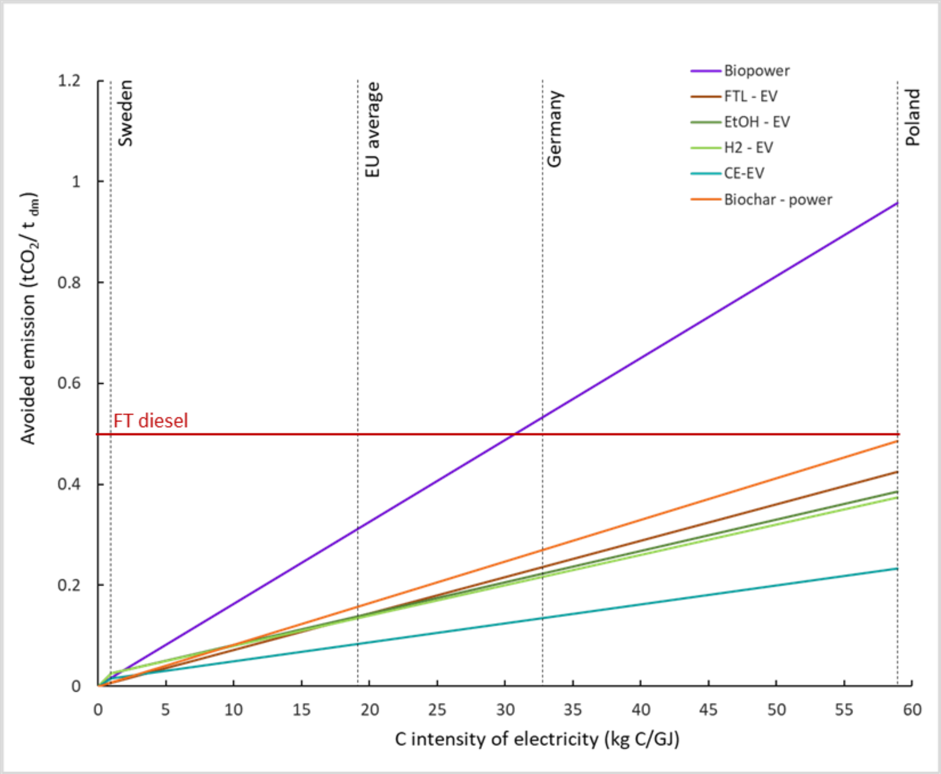


Figure 21: Mitigation potential of selected biomass pathways as a function of the carbon intensity of the power grid. The vertical dashed lines at 1, 18.8, 33.3 and 59 kg C GJ^{-1} denote the carbon intensity of Sweden, EU28, Germany and Poland electricity generation mix in 2016, according to the European Environmental Agency (EEA) database.

The amount of CO_2 avoided by adopting biomass with the different NETs pathways are summarized in Table 5, Min and Max values for biopower-CCS and biochar refer to the replacement of fossil electricity in Sweden and Poland respectively. In the case of biofuels, the substitution of petrol cars or electric vehicles (EVs) powered by low-carbon electricity have been assumed.

Pathway	BF-BECCS	Bio-CaL	EtOH CCS	CE-CCS+	FTL CCS/CCS+	H_2 CCS/CCS+	Biopower-CCS	Biochar
	CO_2 emission avoided (t_{CO2}/t_{dm})							
Product	*Bio-steel*	*Bio-cement*	*Ethanol*		*FT diesel*	*Hydrogen*	*Bio-electricity*	
Min	1.0257	2.367	0.007	0.004	0.007	0.047	0.017	0.008
Max	1.0257	2.367	0.481	0.29	0.53	0.371	0.963	0.486

Table 5: Upper and lower values of avoided CO_2 emissions for NETs pathways

KPI 6 and KPI 7 – Cost of removal and avoidance

Figure 22 combines the findings obtained from KPI 2 and 4 (CO_2 emissions avoided and removed) with the techno-economic analysis in section 4 to derive ranges of avoidance and removal costs for the NETs. Note that variations in avoidance costs within the same pathway reflect the use the different counterfactuals of Table 3, while variation in removal costs depend on the CCS configuration assumed.

High removal costs are associated with capital-intensive technologies or relatively low CO_2 capture rates. This is the case of FT production pathways, sequestering less CO_2 than other biofuel routes, and biohydrogen via biomass gasification, which is capital intensive. At the same time, the high removal and avoidance costs of BF-BECCS, is mainly due to low levels of biogenic fraction of CO_2 that can be sequestered, combined with the fact that retrofitting the steel mill with CCS significantly increase the production costs compared to other routes. Corn based ethanol and bio-cement production pathways achieve lower removal and avoidance costs, between 225-248 $/$t_{CO2}$ and 129-247 $/$t_{CO2}$, thanks to their CO_2 sequestration potentials.

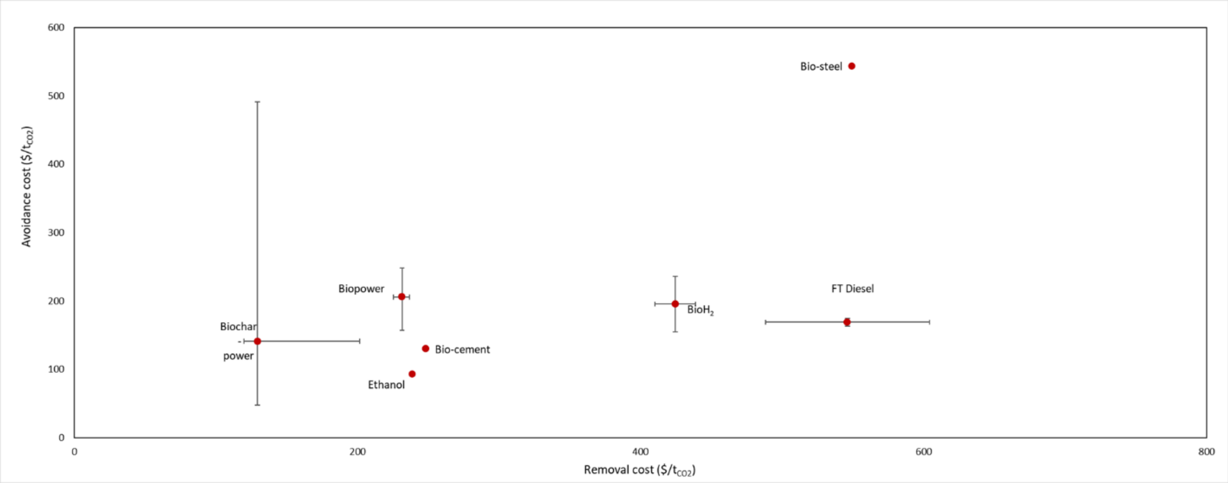


Figure 22: Ranges of removal and avoidance costs achieved with each pathway

Finally, the differences in removal and avoidance costs achieved when bioelectricity is produced either with BECCS or slow pyrolysis reveals an important feature of biochar production pathways. Because slow-pyrolysis processes are less efficient in converting biomass to useful electricity as the process is designed to maximize the production of char, the avoidance cost is particularly high in low-carbon power grids. This notwithstanding, bioelectricity can be produced at a lower cost in pyrolysis plants compared to large-scale biomass combustion plants with CCS, hence a removal cost that equals 119 $/$t_{CO2}$ and 223 $/$t_{CO2}$ in slow-pyrolysis and BECCS to power plants respectively.

6 Selected ecosystems and macroeconomic impacts

6.1 Land and water footprint of biomass

This section considers the land and water footprint associated with crop cultivation and use within each conversion pathway. Table 3 summarizes the water and land use of different crops in the EU, descending from the MONET database, country level values are available in the technical annex.

The water footprint of a crop in each region can be interpreted as the summation of three contributions: the green, blue and grey water. Detailed methodologies are available in Mekonnen and Hoekstra (Mekonnen and Hoekstra, 2011). As a simplification, the green water footprint can be quantified as the amount of effective rainfall and can hence be assumed to be a function of the region considered. The blue water can be approximated to the amount of freshwater required in addition to the green water to compensate for the crop evapotranspiration. The last contribution accounts for water pollution resulting from farming. The main cause of water pollution is associated with nitrogen leaching from nitrogen-based fertilizer use. Hence, grey water footprint can be calculated as a direct function of nitrogen-based fertilizers application rate. Although water footprint methodologies typically present green, blue and grey water footprint values, in this comparative assessment only the blue and grey water footprints have been considered, hence the water footprint presented here accounts only for freshwater use and pollution. Since straw is a by-product of wheat production, land conversion and farming contributions were not attributed to the residue. However, as straw would have normally been left on the field to provide the crop with nutrients, additional fertilizers need to be applied to compensate for its removal, which explains the non-zero water footprint associated to wheat straw in Table 6.

	Miscanthus	Switchgrass	Wheat	Willow
Blue + grey water footprint (m3/tonne DM)	55.6-348	205-5451	54.1	188-7479
Land footprint (10-4ha/tonne DM)	8.2-20	19.8-270	44-296	17.7-231

Table 6: Ranges of water and land footprints of four crops in the EU, taken from the MONET database

KPI 8 and KPI 9 – Land and water footprint

The land and water footprint associated with each NET are shown in Figure 23. There, miscanthus has been adopted as the reference energy crop for all conversion pathways, which allowed to compare the land and water footprint of one tonne of product, *i.e.* crude steel or cement in the case of BECCS in industrial processes, or one GJ of bioelectricity and biofuel, for bioenergy routes.

As illustrated in Figure 23, the land and water footprint associated with these pathways is a direct function of the energy efficiency of each biomass conversion process. Among biofuels, the production of hydrogen via biomass gasification has the lowest water and land use requirements, i.e. 5 m^3/GJ and 0.73 ha/MJ respectively, followed by FT diesel. The production of second-generation bioethanol leads to higher ecosystems impacts than other biofuels, mainly because of the high lignin content of miscanthus feedstock. This because most of the lignin in Miscanthus is acid-insoluble lignin, which leads to lower biofuels yields compared to gasification pathways (Lee and Kuan, 2015).

The production of bioelectricity in slow-pyrolysis process requires 0.4 t_{dm}/GJ since biomass is firstly converted into charcoal, bio-oil and gas and subsequently electricity is produced via the combustion of bio-syngas. This results in a water footprint of 23 m^3/GJ for slow-pyrolysis processes, 50% higher than when biomass is combusted in BECCS power plants. Among industrial processes, the use of charcoal in blast furnaces leads to higher land and water use than in cement production processes, since the amount of biomass used to sustain the heat required for the ironmaking processes is higher than for biomass based calcium looping.

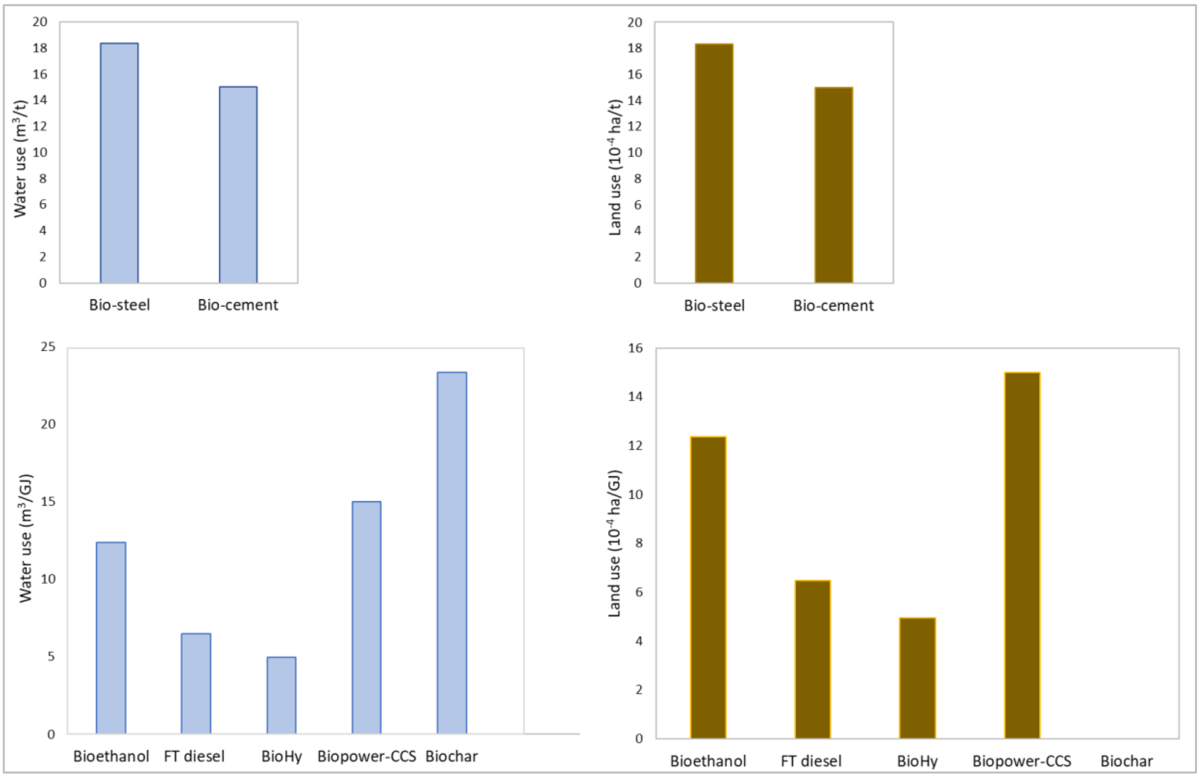


Figure 23: Land and water footprints associated with the production of one tonne of the final product (NETs for the industrial sector) or GJ of useful energy (NETs for the energy sector) in Europe (average values)

Different results are obtained when the land and water footprint of bio based NETs are allocated to the CO_2 removed rather than to the final product of each conversion process (Figure 24). In this case the performance of the different NETs configurations depends on both, biomass conversion, and CO_2 capture efficiencies. As shown in Figure 24, configurations that maximize CO_2 capture perform better: BECCS to power and cement have the lowest water footprint (37-247 m^3/t_{CO2} removed). Interestingly, despite bioethanol showing higher ecosystems impacts than FT diesel in Figure 23, net CO_2 removal is higher within CE-CCS+ configuration compare to FT-CCS+, which results in a water footprint that is 10% lower than for FT production processes. Finally, since slow pyrolysis is both energy and carbon removal inefficient, due to the lower permanence of carbon in soil compared to geological storage, it results in the largest ecosystems impacts among all routes investigated (91-570 m^3/t_{CO2} removed).

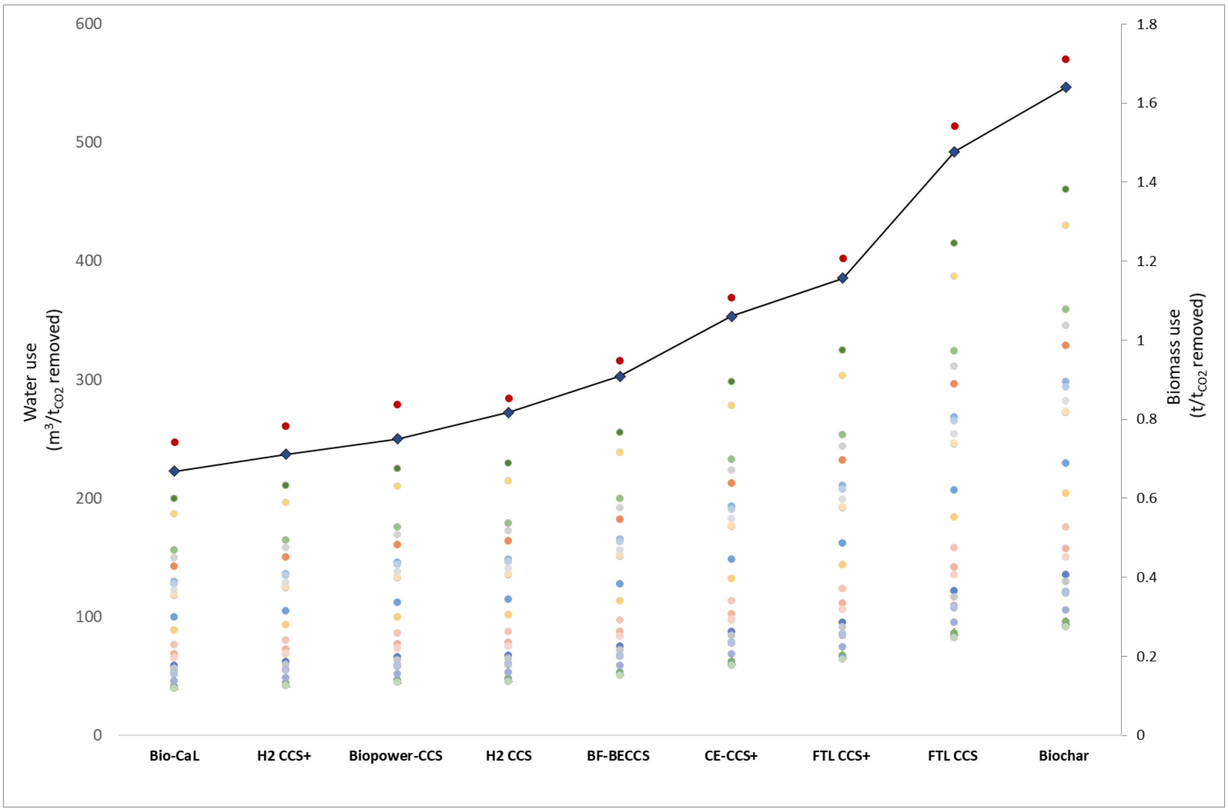


Figure 24: Water footprint associated with the removal of one tonne of CO_2 within the NETs pathways and for each EU country: upper and lower bound values are associated with agricultural activities in Cyprus and Slovenia, respectively (country level results are reported in the annex)

6.2 Water and land use of DAC technologies

The water requirements of DAC systems vary between technologies: Climeworks' process produces a stream of wastewater, as it simultaneously removes moisture from the air. The process itself, however, does not require any additional water streams. The water consumption of the whole system is therefore only based on the water required for the cleaning of solar panels. A recent study comparing the water and land use of BECCS and DAC archetypes (Joanna Sitarz, 2019), found that a reference Climeworks' process capturing 3 Mt_{CO2}/year, consumes around 2 Mm^3/year of water[14] , hence 0.67 m^3 per tonne of CO_2 captured, equal to 1.6 m^3 per tonne of CO_2 removed, based on the analysis presented in section 4.5.

The Carbon Engineering process requires a constant supply of water of around 4.8 m^3/t_{CO2} removed from air, this value might be larger when accounting for the cooling water needed for the heat exchangers. However, the amount of water needed within the process may decrease if no natural gas is used, as the output stream of CO_2 decreases in the latter

---

[14] The BECCS archetype adopted in this study, a 500 MW miscanthus fired power plant, consumes 4.47 m^3/t_{CO2} removed

case. Hence, as noted in the previous sections, the pace of decarbonisation of national energy systems will have a significant impact on the overall water footprint of DAC systems.

The land footprint of both Climeworks and Carbon Engineering DAC archetypes capturing dimensioned to capture 3 Mt_{CO2} per year is estimated at around 126- 253 km^2. In the case of Climeworks' technology, the land required for the batteries and the DAC device is negligible, as it represents less than 0.5 % of the total area needed.

6.3 Socio-economic impacts

The following section presents the macroeconomic impact resulting from the deployment of NETs and their associated value chains in the UK. This has been done by integrating the results of the techno-economic analysis and the carbon accounting presented in Sections 4 and 5 into the JEDI model. Besides the quantification of the GVA created within each industrial sector of the economy presented in Figure 25, the removal and avoidance value of each NET is also provided through KPIs 10 and 11 respectively.

As Figure 25 shows, the GVA created *via* the deployment of BECCS in industry amounts to 68 $\$/t_{cs}$ for the iron and steel and 47 $\$/t_{clk}$ in the cement sectors. In BF-BECCS pathways, around 23% of this value is allocated to the utility sector, such as natural gas and electricity providers, and is associated with the supply of additional energy to the steel mill after the CCS retrofit. In Bio-CaL configurations the agroforestry industry benefits for 20 $\$/t_{clk}$, corresponding to 20 M$/year for the reference cement kiln. Among biofuels, the GVA is between 20-23 $/GJ, with high shares being generated in agriculture in the case of second-generation bioethanol, given the lower biofuel yields associated with this pathway. Since this configuration allows for greater CO_2 removal compared to other biofuel routes (see the carbon accounting section), a larger economic value is also being allocated to the CO_2 transport and storage activities compared to the FT and biohydrogen options.

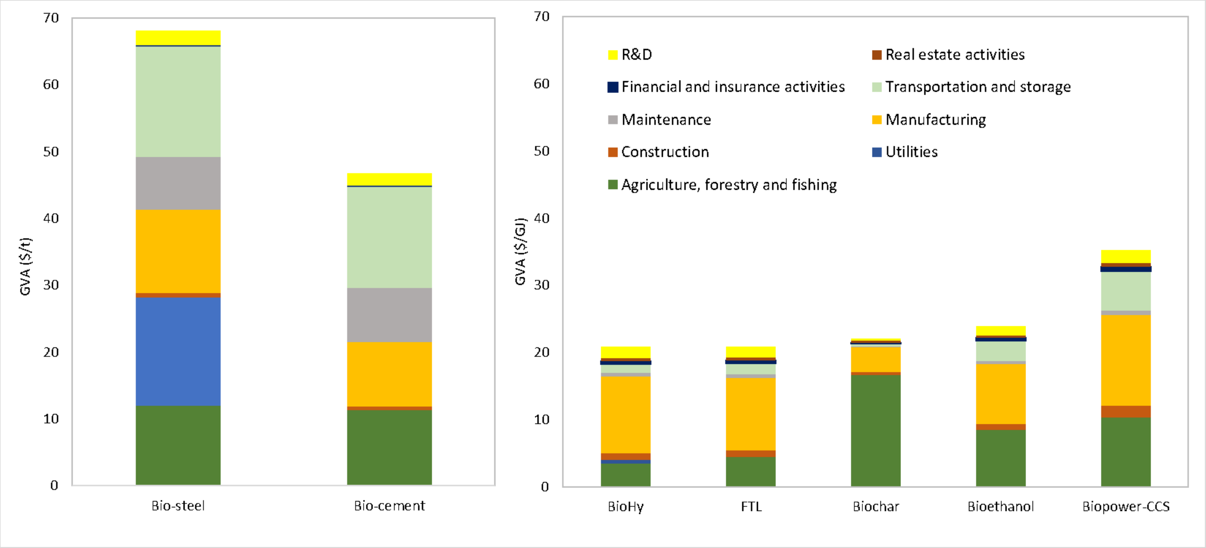


Figure 25: Economic impacts of NETs deployment within the UK industrial sectors

In general, the distribution of GVA created in the agroforestry and transport sectors respectively is a reliable proxy of the CO_2 removal efficiency achieved within each NET: while in BECCS to power around 30% and 17% of the GVA is associated with CO_2 T&S and agriculture activities respectively, almost 85% of the economic value created with biochar production is in biomass supply. Similarly, for BF-BECCS plants the GVA associated with CO_2 storage is even higher than for the forestry sector, since this CCS configuration maximizes the CO_2 capture from the different steel mill off-gases.

KPI 10 and KPI 11 – Removal and mitigation value

Combining these findings with the carbon accounting analysis, it is possible to quantify the amount of CO_2 emissions that can be avoided and removed by deploying NETs within the UK economy. Hence, KPIs 10 and 11 provide an indication of the removal and avoidance efficiency of government spending, since each unit of value created within the NETs supply chains will result in the avoidance and removal of a certain amount of carbon.

As shown in Figure 26, each NETs product has a distinctive removal and avoidance value for the UK economy. Among biofuels, the production of FT diesel plus CCS has the highest avoidance value, since higher biofuels yields are achievable compared to bioethanol production, hence higher amounts of fossil gasoline are being displaced. The cost of one GJ of FT diesel is also lower than 1 GJ of biohydrogen, hence higher amounts of CO_2 can be avoided with the same level of investment for their production. However, when it comes to the value of carbon removal, producing bioethanol represents the most efficient investment since 9 $KgCO_2$ are being removed from the atmosphere for each $ spent in the UK economy.

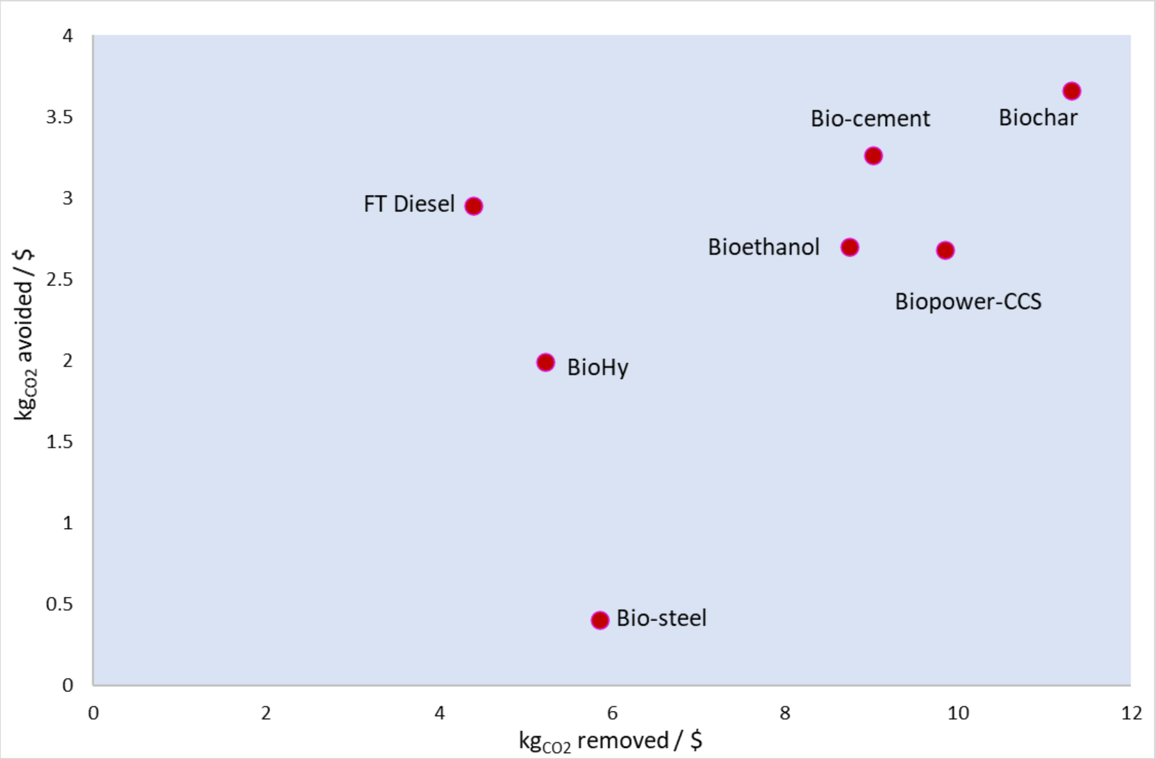


Figure 26: Amount of CO_2 emissions that can be avoided and removed by creating value for the UK economy

Large combustion BECCS power plants represent a valid investment both in terms of mitigation and removal services provided since each unit of GVA created within the economy removes 10 Kg and avoids 3 Kg of CO_2 emissions otherwise emitted by fossil electricity. At the end of the spectrum, we find biochar, representing the best investment for mitigation: this is mainly because of the small investment associated with slow-pyrolysis plants compared to large BECCS to power projects, which allow achieving higher CO_2 removal with the same amount of GVA. However, as already observed from the GVA breakdown in Figure *25*, these benefits are disproportionally concentrated in the agricultural sectors, while the value created in other industries, such as manufacturing and construction, is minimal. In addition, as shown, when considering the water footprint associated with biochar production compared to other manufacturing intensive NETs, it becomes clear that the socio-economic benefits of removing carbon via slow-pyrolysis pathways might also induce large ecosystems trade-offs.

7 Conclusions

This report has compared the techno-economic potential, ecosystems, and socio-economic impacts of a non-exhaustive selection of NETs pathways, based on eleven key performance indicators (KPIs).

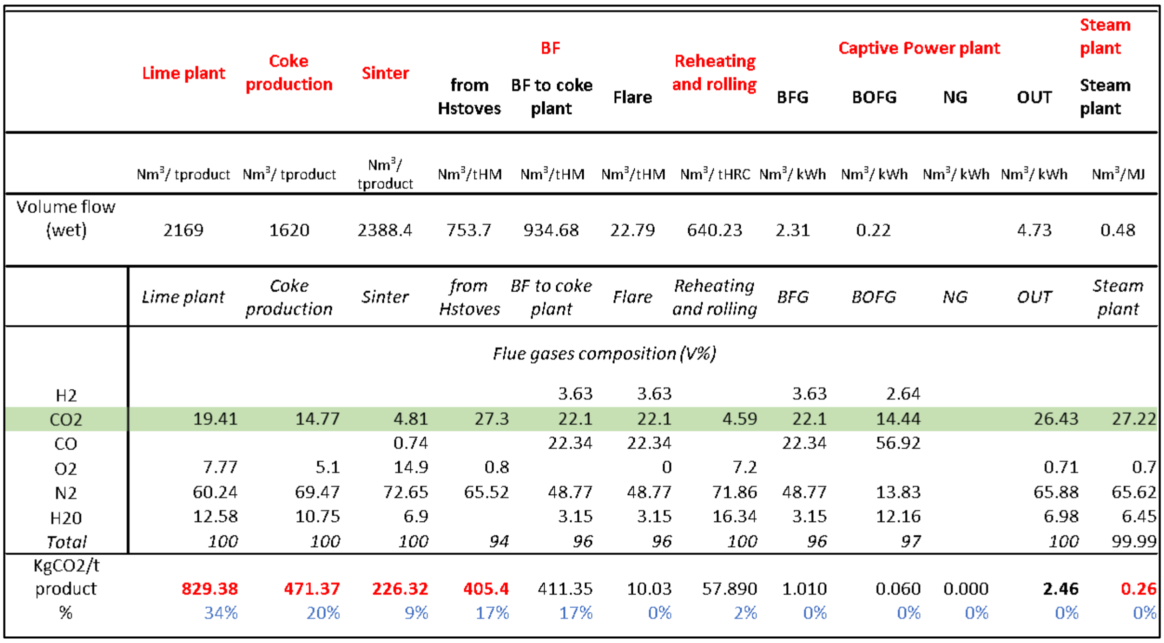
A key finding of the study is that the highest CO_2 removal per energy generated is achieved in NET pathways that maximize CO_2 capture, have low energy conversion efficiencies, or have access to low-carbon energy for their continuous operation. This latter point is particularly important when quantifying the *net* removal potential of DAC: since DAC facilities require 4.3 GJ of energy (heat and electricity) per tonne of CO_2 sequestered, if the energy is supplied by fossil sources, the amount of negative emissions generated lowers significantly.

Except for corn-based ethanol, all BECCS to bioenergy pathways achieve net negative emissions in the range of 0.08 - 0.35 t_{CO2} /GJ of secondary energy produced (e.g., biofuels, bioelectricity, or hydrogen). Whilst hydrogen production pathways exhibit capture rates between 90-96%, the energy conversion efficiency for these processes is also high. Since less biomass is required to produce the same amount of biofuel, less biogenic emissions are being sequestered in the process compared to other biofuel pathways. The production of biochar *via* slow pyrolysis leads to a net removal of 0.15-0.22 t_{CO2} /GJ (2.6-3.3 t_{CO2} /t_{char}) with upper bound values associated with the use of forest residues as feedstock, having low CO_2 upstream emissions. However, the production of electricity in BECCS plants achieves higher CO_2 removal compared to slow-pyrolysis process. This because in the latter pathway biomass is firstly converted into charcoal, bio-oil, and gas and subsequently electricity is produced via the combustion of bio-syngas.

In terms of mitigation cost, the amount of CO_2 emissions that can be avoided within each pathway depends on the carbon intensity and on the products/fuel's substitution factor. This means that the avoidance cost of NETs dedicated to the production of electricity is a direct function of the fossil electricity they are substituting. Hence, in low-carbon power grids, such as those in the Nordic countries, biomass provides a much greater value in decarbonizing the transport sector. For instance, the substitution of gasoline with FT diesel avoids 0.59 tCO_2 /t_{dm} around the same as the CO_2 avoided by BECCS in an average European power grid. Similarly, because electric vehicles (EVs) have a higher energy conversion efficiency than conventional gasoline and diesel cars NETs-derived fuels exhibit an energy substitution factor as low as 26% when substituting EVs. Hence, in countries where EVs are available, adopting BECCS for biofuel production has little mitigation value, even when considering a high carbon intensive energy generation mix.

We also presented the ecosystem's impacts, in terms of water and land footprint associated with biomass cultivation and adoption within the NET pathways. The results of section 6 showed that configurations that maximize the CO_2 capture perform better. Hence, due to the lower permanence of carbon in soil compared to geological storage, the production of biochar results in the largest ecosystems impacts among all routes investigated (91-570 m^3/t_{CO2} removed). These trade-offs might be lower when accounting for the potential long-term agricultural benefits of biochar in soil, which have not been included in the present analysis.

8 Technical annex

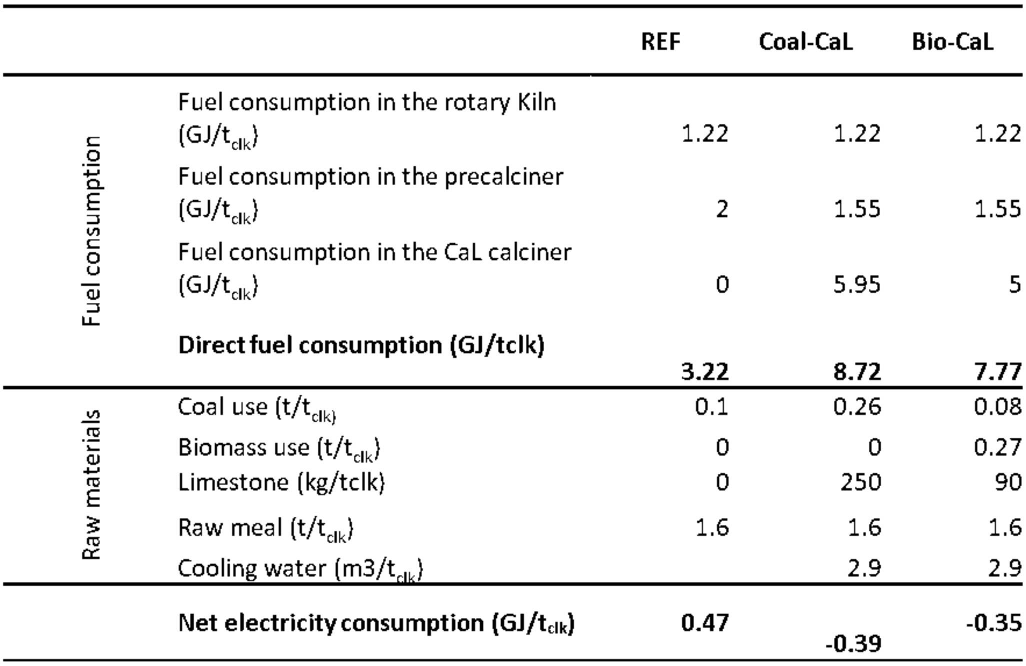


	Lime plant	**Coke production**	**Sinter**	**BF**		**Flare**	**Reheating and rolling**	**Captive Power plant**				**Steam plant**
				from Hstoves	**BF to coke plant**			**BFG**	**BOFG**	**NG**	**OUT**	**Steam plant**
	Nm^3/ tproduct	Nm^3/ tproduct	Nm^3/ tproduct	Nm^3/tHM	Nm^3/tHM	Nm^3/tHM	Nm^3/ tHRC	Nm^3/ kWh	Nm^3/ kWh	Nm^3/ kWh	Nm^3/ kWh	Nm^3/MJ
Volume flow (wet)	2169	1620	2388.4	753.7	934.68	22.79	640.23	2.31	0.22		4.73	0.48
	Lime plant	*Coke production*	*Sinter*	*from Hstoves*	*BF to coke plant*	*Flare*	*Reheating and rolling*	*BFG*	*BOFG*	*NG*	*OUT*	*Steam plant*
	Flue gases composition (V%)											
H2					3.63	3.63		3.63	2.64			
CO2	19.41	14.77	4.81	27.3	22.1	22.1	4.59	22.1	14.44		26.43	27.22
CO			0.74		22.34	22.34		22.34	56.92			
O2	7.77	5.1	14.9	0.8		0	7.2				0.71	0.7
N2	60.24	69.47	72.65	65.52	48.77	48.77	71.86	48.77	13.83		65.88	65.62
H20	12.58	10.75	6.9		3.15	3.15	16.34	3.15	12.16		6.98	6.45
Total	*100*	*100*	*100*	*94*	*96*	*96*	*100*	*96*	*97*		*100*	*99.99*
KgCO2/t product	**829.38**	**471.37**	**226.32**	**405.4**	411.35	10.03	57.890	1.010	0.060	0.000	**2.46**	**0.26**
%	34%	20%	9%	17%	17%	0%	2%	0%	0%	0%	0%	0%

Table 7. 1 Process gas flows for the reference BF-BOF steel mill. Values in red refer to the CO2 volumes that can be captured with CCS within each process

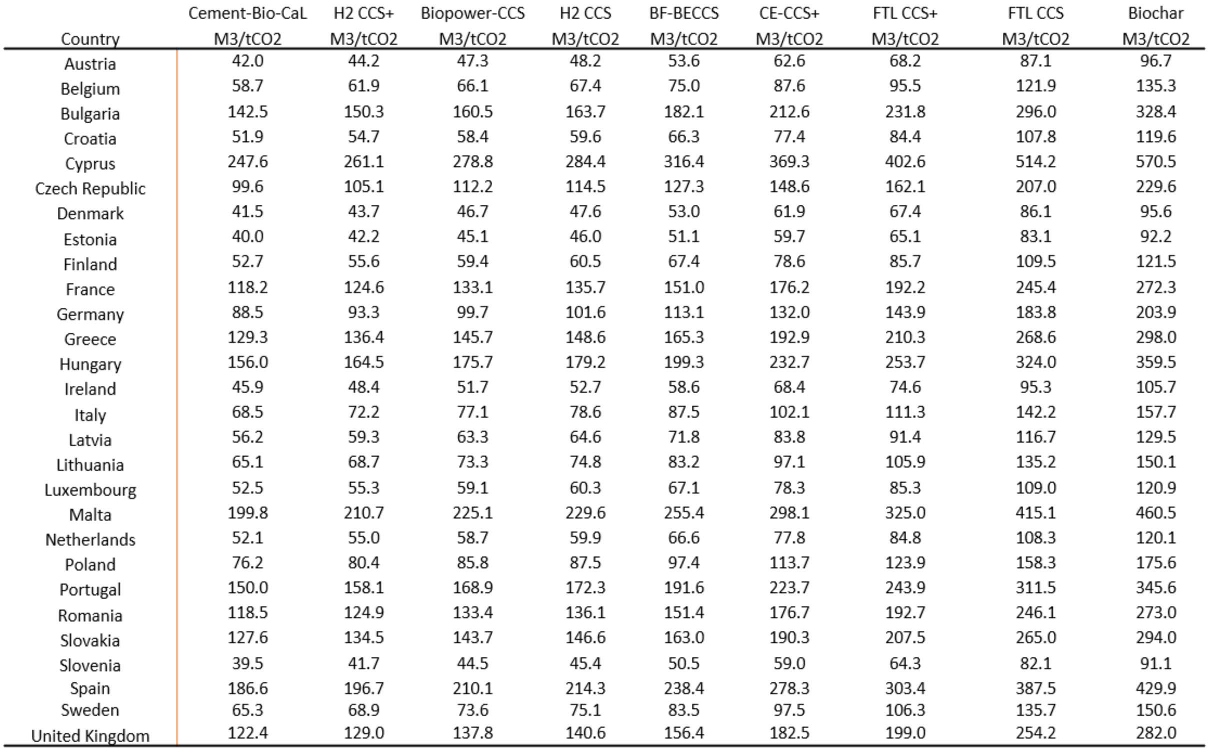
Annual production	Mtcs/yr	5.59
Emission BF	tCO_2/tcs	0.69
Coke	kg/tcs	263
PCI	kg/tcs	210
Sinter	kg/tcs	917
Natural Gas	$/GJ	9.1
Grid Electricity	$/kWh	0.117

Table 7. 2 Techno-economic assumptions adopted in the BF-BOF route



		REF	Coal-CaL	Bio-CaL
Fuel consumption	Fuel consumption in the rotary Kiln (GJ/t_{clk})	1.22	1.22	1.22
	Fuel consumption in the precalciner (GJ/t_{clk})	2	1.55	1.55
	Fuel consumption in the CaL calciner (GJ/t_{clk})	0	5.95	5
	Direct fuel consumption (GJ/tclk)	**3.22**	**8.72**	**7.77**
Raw materials	Coal use (t/t_{clk})	0.1	0.26	0.08
	Biomass use (t/t_{clk})	0	0	0.27
	Limestone (kg/tclk)	0	250	90
	Raw meal (t/t_{clk})	1.6	1.6	1.6
	Cooling water ($m3/t_{clk}$)		2.9	2.9
	Net electricity consumption (GJ/t_{clk})	**0.47**	**-0.39**	**-0.35**

Table 7. 3 Main technical assumptions adopted for tail-end calcium looping processes



Country	Cement-Bio-CaL M3/tCO2	H2 CCS+ M3/tCO2	Biopower-CCS M3/tCO2	H2 CCS M3/tCO2	BF-BECCS M3/tCO2	CE-CCS+ M3/tCO2	FTL CCS+ M3/tCO2	FTL CCS M3/tCO2	Biochar M3/tCO2
Austria	42.0	44.2	47.3	48.2	53.6	62.6	68.2	87.1	96.7
Belgium	58.7	61.9	66.1	67.4	75.0	87.6	95.5	121.9	135.3
Bulgaria	142.5	150.3	160.5	163.7	182.1	212.6	231.8	296.0	328.4
Croatia	51.9	54.7	58.4	59.6	66.3	77.4	84.4	107.8	119.6
Cyprus	247.6	261.1	278.8	284.4	316.4	369.3	402.6	514.2	570.5
Czech Republic	99.6	105.1	112.2	114.5	127.3	148.6	162.1	207.0	229.6
Denmark	41.5	43.7	46.7	47.6	53.0	61.9	67.4	86.1	95.6
Estonia	40.0	42.2	45.1	46.0	51.1	59.7	65.1	83.1	92.2
Finland	52.7	55.6	59.4	60.5	67.4	78.6	85.7	109.5	121.5
France	118.2	124.6	133.1	135.7	151.0	176.2	192.2	245.4	272.3
Germany	88.5	93.3	99.7	101.6	113.1	132.0	143.9	183.8	203.9
Greece	129.3	136.4	145.7	148.6	165.3	192.9	210.3	268.6	298.0
Hungary	156.0	164.5	175.7	179.2	199.3	232.7	253.7	324.0	359.5
Ireland	45.9	48.4	51.7	52.7	58.6	68.4	74.6	95.3	105.7
Italy	68.5	72.2	77.1	78.6	87.5	102.1	111.3	142.2	157.7
Latvia	56.2	59.3	63.3	64.6	71.8	83.8	91.4	116.7	129.5
Lithuania	65.1	68.7	73.3	74.8	83.2	97.1	105.9	135.2	150.1
Luxembourg	52.5	55.3	59.1	60.3	67.1	78.3	85.3	109.0	120.9
Malta	199.8	210.7	225.1	229.6	255.4	298.1	325.0	415.1	460.5
Netherlands	52.1	55.0	58.7	59.9	66.6	77.8	84.8	108.3	120.1
Poland	76.2	80.4	85.8	87.5	97.4	113.7	123.9	158.3	175.6
Portugal	150.0	158.1	168.9	172.3	191.6	223.7	243.9	311.5	345.6
Romania	118.5	124.9	133.4	136.1	151.4	176.7	192.7	246.1	273.0
Slovakia	127.6	134.5	143.7	146.6	163.0	190.3	207.5	265.0	294.0
Slovenia	39.5	41.7	44.5	45.4	50.5	59.0	64.3	82.1	91.1
Spain	186.6	196.7	210.1	214.3	238.4	278.3	303.4	387.5	429.9
Sweden	65.3	68.9	73.6	75.1	83.5	97.5	106.3	135.7	150.6
United Kingdom	122.4	129.0	137.8	140.6	156.4	182.5	199.0	254.2	282.0

Country	Cement-bioCaL M3/tCO2	H M

Austria	42.0
Belgium	58.7
Bulgaria	142.5
Croatia	51.9
Cyprus	247.6
Czech Republic	99.6
Denmark	41.5
Estonia	40.0
Finland	52.7
France	118.2
Germany	88.5
Greece	129.3
Hungary	156.0
Ireland	45.9
Italy	68.5
Latvia	56.2
Lithuania	65.1
Luxembourg	52.5
Malta	199.8
Netherlands	52.1
Poland	76.2
Portugal	150.0
Romania	118.5
Slovakia	127.6
Slovenia	39.5
Spain	186.6
Sweden	65.3
United Kingdom	122.4

Table 7.4 Regional water footprint (blue + grey) associated with feedstock cultivation and use per tonne of CO_2 removed in the different NETs pathways. Regional data are extracted from the MONET database.

Country	Biopower-CCS M3/TCO2	Cement-bioCaL M3/TCO2	H2 CCS+ M3/TCO2	H2 CCS M3/TCO2	BF-BECCS M3/TCO2	CE-CCS+ M3/TCO2	FTL CCS+ M3/TCO2	FTL CCS M3/TCO2	Biochar M3/TCO2
Austria	10.60	9.41	9.92	10.81	53.61	14.04	15.31	19.55	21.69
Belgium	12.86	11.42	12.04	13.12	14.59	17.03	18.57	23.72	26.31
Bulgaria	14.36	12.75	13.44	14.64	16.29	19.01	20.73	26.47	29.37
Croatia	11.43	10.15	10.70	11.66	12.97	15.14	16.51	21.08	23.39
Cyprus	10.35	9.19	9.69	10.56	11.74	13.71	14.94	19.09	21.18
Czech Republic	10.83	9.62	10.14	11.05	12.29	14.34	15.64	19.97	22.16
Denmark	15.53	13.79	14.54	15.84	17.62	20.57	22.42	28.64	31.77
Estonia	14.42	12.80	13.50	14.71	16.36	19.10	20.82	26.59	29.51
Finland	12.24	10.87	11.46	12.49	13.89	16.21	17.68	22.58	25.05
France	13.72	12.18	12.84	13.99	15.56	18.17	19.81	25.30	28.07
Germany	14.29	12.69	13.38	14.57	16.21	18.92	20.63	26.35	29.24
Greece	6.60	5.86	6.17	6.73	7.48	8.73	9.52	12.16	13.49
Hungary	14.36	12.75	13.44	14.64	16.29	19.01	20.73	26.47	29.37
Ireland	14.41	12.79	13.49	14.70	16.35	19.08	20.81	26.57	29.48
Italy	8.02	7.12	7.51	8.18	9.10	10.62	11.58	14.78	16.40
Latvia	14.36	12.75	13.44	14.64	16.29	19.01	20.73	26.47	29.37
Lithuania	14.36	12.75	13.44	14.64	16.29	19.01	20.73	26.47	29.37
Luxembourg	11.48	10.20	10.75	11.71	13.03	15.21	16.58	21.18	23.50
Malta	10.35	9.19	9.69	10.56	11.74	13.71	14.94	19.09	21.18
Netherlands	13.72	12.18	12.84	13.99	15.56	18.17	19.81	25.30	28.07
Poland	13.72	12.18	12.84	13.99	15.56	18.17	19.81	25.30	28.07
Portugal	10.33	9.18	9.68	10.54	11.73	13.69	14.92	19.06	21.15
Romania	12.86	11.42	12.04	13.12	14.59	17.03	18.57	23.72	26.31
Slovakia	12.86	11.42	12.04	13.12	14.59	17.03	18.57	23.72	26.31
Slovenia	12.86	11.42	12.04	13.12	14.59	17.03	18.57	23.72	26.31
Spain	8.57	7.61	8.03	8.74	9.73	11.35	12.38	15.81	17.54
Sweden	12.79	11.36	11.98	13.05	14.52	16.94	18.47	23.59	26.18
United Kingdom	16.06	14.26	15.04	16.38	18.23	21.27	23.20	29.62	32.87

Table 7.5 Regional land footprint associated with feedstock cultivation and use. Regional data are extracted from the MONET database.

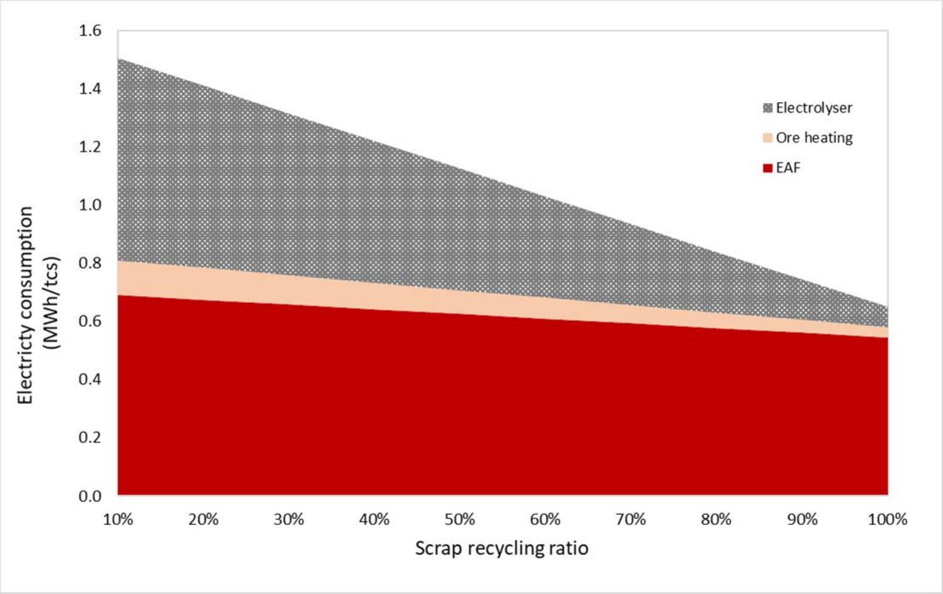


Figure 7. 1 Specific electricity consumption of H_2-DR route, from (Vogl, Åhman and Nilsson, 2018)

References

Arias, B., Alonso, M. and Abanades, C. (2017) ‘CO2 Capture by Calcium Looping at Relevant Conditions for Cement Plants: Experimental Testing in a 30 kWth Pilot Plant’, *Industrial and Engineering Chemistry Research*. doi: 10.1021/acs.iecr.6b04617.

Balat, H. and Kırtay, E. (2010) ‘Hydrogen from biomass – Present scenario and future prospects’, *International Journal of Hydrogen Energy*, 35(14), pp. 7416–7426. doi: https://doi.org/10.1016/j.ijhydene.2010.04.137.

Biederman, L. A. and Stanley Harpole, W. (2013) ‘Biochar and its effects on plant productivity and nutrient cycling: A meta-analysis’, *GCB Bioenergy*. Blackwell Publishing Ltd, 5(2), pp. 202–214. doi: 10.1111/gcbb.12037.

Brown, R. C. *et al.* (2015) ‘Fundamentals of Biochar Production’, in *Biochar for Environmental Management: Science, Technology and Implementation, 2nd Edition (Hardback) - Routledge*.

Bui *et al.* (2020) *Delivering negative emissions from biomass derived hydrogen*. Available at: http://www.h2fcsupergen.com/delivering-negative-emissions-from-biomass-derived-hydrogen.

Bui, M., Fajardy, M. and Mac Dowell, N. (2017) ‘Bio-Energy with CCS (BECCS) performance evaluation: Efficiency enhancement and emissions reduction’, *Applied Energy*. Elsevier Ltd, 195(June), pp. 289–302. doi: 10.1016/j.apenergy.2017.03.063.

Christopher Consoli (2019) *Bioenergy and carbon capture and storage*, *Global CCS Institute*. Available at: https://www.globalccsinstitute.com/resources/publications-reports-research/bioenergy-and-carbon-capture-and-storage/.

Crane-Droesch, A. *et al.* (2013) ‘Heterogeneous global crop yield response to biochar: A meta-regression analysis’, *Environmental Research Letters*. doi: 10.1088/1748-9326/8/4/044049.

Energy Systems Catapult (2020) ‘Innovating to net zero’, pp. 45–50. Available at: https://es.catapult.org.uk/.

Fajardy and Mac Dowell (2017) ‘Can BECCS deliver sustainable and resource efficient negative emissions?’, *Energy & Environmental Science*. Royal Society of Chemistry, 10(6), pp. 1389–1426. doi: 10.1039/C7EE00465F.

Fajardy, M., Chiquier, S. and Mac Dowell, N. (2018) ‘Investigating the BECCS resource nexus: Delivering sustainable negative emissions’, *Energy and Environmental Science*. Royal Society of Chemistry, 11(12), pp. 3408–3430. doi: 10.1039/c8ee01676c.

Fajardy, M. and Mac Dowell, N. (2020) ‘Recognizing the Value of Collaboration in Delivering Carbon Dioxide Removal’, *One Earth*. Cell Press, 3(2), pp. 214–225. doi: 10.1016/j.oneear.2020.07.014.

Fischedick, M. *et al.* (2014) ‘Techno-economic evaluation of innovative steel production technologies’, *Journal of Cleaner Production*. Elsevier Ltd, 84(1), pp. 563–580. doi: 10.1016/j.jclepro.2014.05.063.

Fuss, S. *et al.* (2018) ‘Negative emissions - Part 2: Costs, potentials and side effects’, *Environmental Research Letters*. Institute of Physics Publishing. doi: 10.1088/1748-9326/aabf9f.

Gaunt, J. L. and Lehmann, J. (2008) ‘Energy balance and emissions associated with biochar sequestration and pyrolysis bioenergy production’, *Environmental Science and Technology*, 42(11), pp. 4152–4158. doi: 10.1021/es071361i.

Gollakota, S. and McDonald, S. (2014) ‘Commercial-scale CCS project in Decatur, Illinois - Construction status and operational plans for demonstration’, *Energy Procedia*. Elsevier B.V., 63, pp. 5986–5993. doi: 10.1016/j.egypro.2014.11.633.

Hagemann, N. *et al.* (2017) ‘Organic coating on biochar explains its nutrient retention and stimulation of soil fertility’, *Nature Communications*. Nature Publishing Group, 8(1). doi: 10.1038/s41467-017-01123-0.

Hamelinck, C. N., Van Hooijdonk, G. and Faaij, A. P. C. (2005) ‘Ethanol from lignocellulosic biomass: Techno-economic performance in short-, middle- and long-term’, *Biomass and Bioenergy*. Elsevier Ltd, 28(4), pp. 384–410. doi: 10.1016/j.biombioe.2004.09.002.

Hammond, J. *et al.* (2011) 'Prospective life cycle carbon abatement for pyrolysis biochar systems in the UK', *Energy Policy*, 39(5), pp. 2646–2655. doi: 10.1016/j.enpol.2011.02.033.

Heck, V. *et al.* (2018) 'Biomass-based negative emissions difficult to reconcile with planetary boundaries', *Nature Climate Change*, 8(2), pp. 151–155. doi: 10.1038/s41558-017-0064-y.

Hetland, J. *et al.* (2016) 'Carbon-negative emissions: Systemic impacts of biomass conversion. A case study on CO2 capture and storage options', *International Journal of Greenhouse Gas Control*. Elsevier Ltd, 49, pp. 330–342. doi: 10.1016/j.ijggc.2016.03.017.

Hills, T. *et al.* (2016) 'Carbon Capture in the Cement Industry: Technologies, Progress, and Retrofitting', *Environmental Science and Technology*. doi: 10.1021/acs.est.5b03508.

Hornberger, M. *et al.* (2020) 'Experimental investigation of the carbonation reactor in a tail-end Calcium Looping configuration for CO2 capture from cement plants', *Fuel Processing Technology*. doi: 10.1016/j.fuproc.2020.106557.

IEA (2016) 'World Energy Outlook 2016', *International Energy Agency: Paris, France*, p. 28. doi: http://www.iea.org/publications/freepublications/publication/WEB_WorldEnergyOutlook2015ExecutiveSummaryEnglishFinal.pdf.

IEAGHG (2013a) 'Deployment of CCS in the Cement Industry', *Ieaghg*.

IEAGHG (2013b) 'Iron and Steel CCS study (Techno-economics integrated steel mill)'. Available at: https://ieaghg.org/docs/General_Docs/Reports/2013-04.pdf.

IEAGHG (2014) 'CO2 Capture at Coal Based Power and Hydrogen Plants'. Available at: https://ieaghg.org/docs/General_Docs/Reports/2014-03.pdf.

IEAGHG (2021) *Biorefineris with CCS*.

Ishimoto, Y. *et al.* (2017) 'Putting Costs of Direct Air Capture in Context', *SSRN Electronic Journal*. doi: 10.2139/ssrn.2982422.

Joanna Sitarz (2019) *Economic and Environmental Assessment of a Solar-Driven Direct Air Capture System*. RWTH Acheen University.

Koornneef, J. *et al.* (2011) 'Potential for Biomass and Carbon Dioxide Capture and Storage Why Biomass and CCS - the net carbon balance', (May).

Koroneos, C., Dompros, A. and Roumbas, G. (2008) 'Hydrogen production via biomass gasification—A life cycle assessment approach', *Chemical Engineering and Processing: Process Intensification*, 47(8), pp. 1261–1268. doi: https://doi.org/10.1016/j.cep.2007.04.003.

Lawrence Livermore National Laboratory (2020) *Getting to Neutral: Options for negative carbon emissions in California*. Available at: https://www-gs.llnl.gov/content/assets/docs/energy/Getting_to_Neutral.pdf.

Lee, W. C. and Kuan, W. C. (2015) 'Miscanthus as cellulosic biomass for bioethanol production', *Biotechnology Journal*. doi: 10.1002/biot.201400704.

De Lena, E. *et al.* (2017) 'Process integration study of tail-end Ca-Looping process for CO2 capture in cement plants', *International Journal of Greenhouse Gas Control*. doi: 10.1016/j.ijggc.2017.10.005.

Liu, G. *et al.* (2011) 'Making Fischer−Tropsch Fuels and Electricity from Coal and Biomass: Performance and Cost Analysis', *Energy & Fuels*. American Chemical Society, 25(1), pp. 415–437. doi: 10.1021/ef101184e.

Mandova, H. *et al.* (2019) 'Achieving carbon-neutral iron and steelmaking in Europe through the deployment of bioenergy with carbon capture and storage', *Journal of Cleaner Production*. doi: 10.1016/j.jclepro.2019.01.247.

Mazzotti, M. *et al.* (2013) 'Direct air capture of CO2 with chemicals: Optimization of a two-loop hydroxide carbonate system using a countercurrent air-liquid contactor', *Climatic Change*. doi: 10.1007/s10584-

012-0679-y.

Mekonnen, M. M. and Hoekstra, A. Y. (2011) ‘The green, blue and grey water footprint of crops and derived crop products’, *Hydrology and Earth System Sciences*. doi: 10.5194/hess-15-1577-2011.

Minx, J. C. *et al.* (2018) ‘Negative emissions - Part 1: Research landscape and synthesis’, *Environmental Research Letters*, 13(6). doi: 10.1088/1748-9326/aabf9b.

Muratori, M. *et al.* (2017) ‘Carbon capture and storage across fuels and sectors in energy system transformation pathways’, *International Journal of Greenhouse Gas Control*. Elsevier Ltd, 57, pp. 34–41. doi: 10.1016/j.ijggc.2016.11.026.

Muri, H. (2018) ‘The role of large - Scale BECCS in the pursuit of the 1.5°C target: An Earth system model perspective’, *Environmental Research Letters*. Institute of Physics Publishing, 13(4). doi: 10.1088/1748-9326/aab324.

National Academy of Science (2018) ‘Negative Emissions Technologies and Reliable Sequestration: a Research Agenda’, *National Academies Press*.

Nemet, G. F. *et al.* (2018) ‘Negative emissions - Part 3: Innovation and upscaling’, *Environmental Research Letters*. Institute of Physics Publishing. doi: 10.1088/1748-9326/aabff4.

Ozcan, D. C., Ahn, H. and Brandani, S. (2013) ‘Process integration of a Ca-looping carbon capture process in a cement plant’, *International Journal of Greenhouse Gas Control*. doi: 10.1016/j.ijggc.2013.10.009.

Parkinson, B. *et al.* (2019) ‘Levelized cost of CO 2 mitigation from hydrogen production routes’, *Energy and Environmental Science*. Royal Society of Chemistry, 12(1), pp. 19–40. doi: 10.1039/c8ee02079e.

Parthasarathy, P. and Narayanan, K. S. (2014) ‘Hydrogen production from steam gasification of biomass: Influence of process parameters on hydrogen yield – A review’, *Renewable Energy*, 66, pp. 570–579. doi: https://doi.org/10.1016/j.renene.2013.12.025.

Patrizio, P. *et al.* (2018) ‘Reducing US Coal Emissions Can Boost Employment’, *Joule*. Elsevier Inc., 2(12), pp. 2633–2648. doi: 10.1016/j.joule.2018.10.004.

Patrizio, P., Pratama, Y. W. and Dowell, N. Mac (2020) ‘Socially Equitable Energy System Transitions’, *Joule*. Cell Press, 4(8), pp. 1700–1713. doi: 10.1016/j.joule.2020.07.010.

Sanchez, D. L. *et al.* (2015) ‘Biomass enables the transition to a carbon-negative power system across western North America’, *Nature Climate Change*, 5(3), pp. 230–234. doi: 10.1038/nclimate2488.

Schakel, W. *et al.* (2018) ‘Impact of fuel selection on the environmental performance of post-combustion calcium looping applied to a cement plant’, *Applied Energy*. doi: 10.1016/j.apenergy.2017.10.123.

Shackley, S. *et al.* (2011) ‘The feasibility and costs of biochar deployment in the UK’, *Carbon Management*, pp. 335–356. doi: 10.4155/cmt.11.22.

Sikarwar, V. S. *et al.* (2017) ‘Progress in biofuel production from gasification’, *Progress in Energy and Combustion Science*. Elsevier Ltd, pp. 189–248. doi: 10.1016/j.pecs.2017.04.001.

Smith, P. *et al.* (2015) ‘Biophysical and economic limits to negative CO2 emissions’, *Nature Climate Change*, 6(1), pp. 42–50. doi: 10.1038/nclimate2870.

Socolow, R. *et al.* (2011) *Direct Air Capture of CO2 with Chemicals A Technology Assessment for the APS Panel on Public Affairs*, *Technology*.

Tanzer, S. E., Blok, K. and Ramírez, A. (2020) ‘Can bioenergy with carbon capture and storage result in carbon negative steel?’, *International Journal of Greenhouse Gas Control*, 100. doi: 10.1016/j.ijggc.2020.103104.

Tanzer, S. E. and Ramirez, A. (2019) ‘When are negative emissions negative emissions?’, *Energy & Environmental Science*, 12, pp. 1210–1218. doi: 10.1039/C8EE03338B.

Thornley, P. *et al.* (2015) ‘Maximizing the greenhouse gas reductions from biomass: The role of life cycle assessment’, *Biomass and Bioenergy*. Elsevier Ltd, 81(0), pp. 35–43. doi:

10.1016/j.biombioe.2015.05.002.

Verheijen, F. *et al.* (2010) *Biochar Application to Soils: A Critical Scientific Review of Effects on Soil Properties, Processes and Functions*, *Environment*. doi: 10.2788/472.

Viikari, L., Vehmaanperä, J. and Koivula, A. (2012) ‘Lignocellulosic ethanol: From science to industry’, *Biomass and Bioenergy*, 46, pp. 13–24. doi: 10.1016/j.biombioe.2012.05.008.

Vogl, V., Åhman, M. and Nilsson, L. J. (2018) ‘Assessment of hydrogen direct reduction for fossil-free steelmaking’, *Journal of Cleaner Production*. doi: 10.1016/j.jclepro.2018.08.279.

Wang, J., Xiong, Z. and Kuzyakov, Y. (2016) ‘Biochar stability in soil: Meta-analysis of decomposition and priming effects’, *GCB Bioenergy*. Blackwell Publishing Ltd, pp. 512–523. doi: 10.1111/gcbb.12266.

Woolf, D. *et al.* (2010) ‘Sustainable biochar to mitigate global climate change’, *Nature Communications*. Nature Publishing Group, 1(5). doi: 10.1038/ncomms1053.

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