Coalition for Negative Emissions

Technical Appendix

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Disclaimer

Methodology was developed by McKinsey and McKinsey & Company's Nature Analytics solution , which builds on peer-reviewed methodologies and existing data points or spatial data layers. Although geospatial analytics can provide useful directional guidance at global scale, drawing any local conclusions will require additional detailed, local studies, notably to include precise local geographic contexts or recent local developments (political or otherwise). In particular, analysis of costs of CO2 abatement are country-level estimates primarily based on expert interviews aiming at providing directional information on costs. Any project-specific assessment should require additional, site-specific research.

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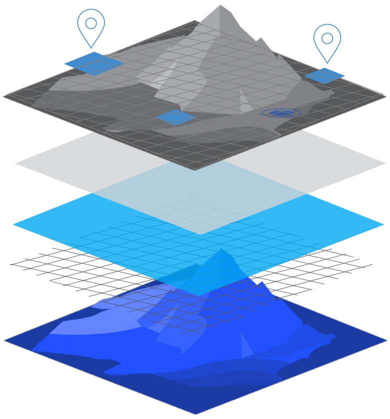
Overview

In this report we estimate the potential of five Natural Climate Solutions (NCS): reforestation, coastal restoration, natural forest management, trees in cropland and cover crops. We did this by combining geospatial data layers, advanced algorithms and expert insights (see Figure 1).

Figure 1:
Geospatial modelling approach
We combined multiple geospatial data layers, advanced algorithms and expert insights to assess the technical abatement potential of NCS and BECCS



For each NCS, we assessed the solution potential via NCS-specific modelling, the granularity of which depends on the available data. Where available, geospatial data on the extent of targeted ecosystems (such as forests and wetlands) and their degradation status allowed us to assess in which location each NCS can be implemented. This is then combined with an estimate (geospatial or not) of the CO_2 sequestration potential of the NCS. For some NCS, the technical potential is further reduced into a practical potential, taking biophysical exclusion filters (such as water stress) into account.

For each NCS, we further differentiate the abatement potential into a short-term (2030) and long-term (2050) potential using economic feasibility as a proxy, effectively assuming that what is more economically feasible is more likely to be deployed first. The economic feasibility is based on the agricultural rent, the economic return from agricultural land. The agricultural rent represents a key decision factor in land-use choices relevant to NCS and it is accounted for in most studies on NCS costs. We defined the short-term abatement potential as areas with low (less than or equal to $10 per hectare) to medium (greater than $10 per hectare and less than or equal to $45 per hectare) agricultural rent, characterized by a high to medium feasibility. Accordingly, we defined the long-term abatement potential as areas with high agricultural rent (greater than $45 per hectare), characterized by a low economic feasibility[1].

1 We used statistical thresholds of $10 and $45 per hectare per year to differentiate between high and medium, and medium and low feasibility, corresponding roughly to the 33rd and 66th percentiles of median values of all ecoregions. These thresholds were found to match well the current distribution of carbon credit projects globally. We geo-localized 143 projects of the Verra standard registry (https://registry.verra.org/) under the Forestry and Land Use category, and sub-categories Agroforestry, ARR (Afforestation/Reforestation), Conservation (REDD+) and IFM (Improved Forest Management), and extracted the agricultural rent at each location. We found that 53% of projects total area fell in the high feasibility, 33% in the medium feasibility, and the rest (14%) in the low feasibility category.

Following Naidoo and Iwamura[2], we calculated the agricultural rent as follows:

- We took granular crop yield and distribution for more than 40 main crops[3] and livestock weight and density for eight major livestock categories[4].
- We derived granular gross agricultural revenue by matching yields with farm-gate prices of these crops and livestock[5].
- We used the ecoregion[6] gross agricultural revenue median as the relevant ecoregion agricultural rent, to filter out extreme values and fill areas where no cropland is currently present, effectively assigning a hypothetical agricultural rent to land uses that are not (yet) converted to agriculture such as forests.
- We assumed 30 years of agricultural revenues discounted at 10 percent annually; a rate that is typically used by development banks for evaluating public investments in developing countries.
- We applied revenue to each area selected for NCS based on highest-revenue yielding crop in that area.

Figure 2 summarizes the overall approach and filtering of land use potential for NCS.

Figure 2:
NCS land use potential

Land-use potential

For each NCS, the theoretical land use potential is based on the total land area/extent that could be attributed to a specific land use:

- For reforestation, the predicted natural forest occurrence less the area covered by existing forests
- For Natural Forest Management, the global extent of naturally regenerating forests
- For soil carbon, the global extent of existing cropland

Environmentally sustainable land-use

For each NCS, the technical solution potential is assessed via a NCS-specific geospatial modelling effort

For selected NCS, the potential is further constrained using biophysical exclusion filters, such as e.g.,:

- Biomes
- Water stress
- Human footprint

Economical, sustainable land-use

The economic feasibility of each NCS is assessed at the country level by modelling the economic return from agricultural land on a granular scale (~870 areas)

Areas with higher agricultural returns receive a lower economic feasibility score. The 2030 potential excludes all low feasibility areas. This potential is assumed to become economically feasible in 2050, when higher carbon prices will increase the returns from NCS

2 Naidoo, R. et al. Biological Conservation 140, 40–49 (2007)
3 International Food Policy Research Institute, 2019, "Global Spatially-Disaggregated Crop Production Statistics Data for 2010 Version 2.0", https://doi.org/10.7910/DVN/PRFF8V, Harvard Dataverse, V4
4 Gilbert, M. et al. Scientific Data 5, 180227 (2018)
5 FAOSTAT, Producer Price
6 Olson, D. M., et al. Bioscience 51(11):933-938. (2001)

Costs

Short-term cost projections (2030)

Country-level cost curves were built for each NCS focusing on high potential countries. NCS project costs were determined via expert interview and literature review. To account for the different time horizons of expenses, present value costs were computed using a 10 percent discount rate on 30-year projects (in line with the academic literature). These costs were divided by the projects lifetime carbon credit issuances to derive a per tonne of CO_2 cost estimate. Finally, the weighted average cost of each NCS was computed, by combining all the available country cost points.

Four types of cost are considered in our assessment:

- **Land costs:** The cost of acquiring or renting the area of land on which the NCS is developed plus any other land-related cost (such as land taxes)[7]. For each country assessed, two cost estimates were provided: one for high feasibility (low cost) areas and one for medium feasibility (medium cost) areas. We assumed that cost differences in these areas were driven by land cost difference, which is highly correlated with the agricultural rent. For high feasibility areas, we therefore used the land cost provided by local expert (triangulated with local/official data sources) assuming that existing projects (on which experts base their information) were implemented in such high feasibility areas. For medium feasibility areas, we derived estimates of land value from a World Bank analysis[8]. One simplifying assumption taken was that project developers would be leasing land directly and paying land costs in full, rather than with the help of governments and non-profits, meaning at low to no cost.
- **Initial project costs:** The initial costs and investments needed to start a NCS project, including project and site preparation, site set-up, administration, and legal costs.
- **Recurring project costs:** The payments for labor, materials and overhead necessary to operate a NCS-project throughout its duration, such as maintenance, administration, security, and community payment.[9]
- **Carbon credit monetization costs:** The cost of converting realized NCS impact into actual carbon credits. Detailed cost components included are: initial validation costs, annual verification costs,[10] and issuance fees. This does not include marketing costs.

7 Land ownership structures (e.g., communal land) mean that land used for an NCS might not be effectively acquired or rented at a market price. We still include the land value in our costs in those cases, as a proxy for the land opportunity costs.
8 *"The changing wealth of nations 2018: Building a sustainable future,"* World Bank, 2018. When World Bank values were either below or one order of magnitude larger than the prices for high-feasibility locations, we replaced them using a price correlation equation.
9 Using a standardized $ per hectare rate for countries outside Europe, North America and Australia, based on expert inputs and a review of the academic literature.
10 This can be every other year or up to every 5-years depending on the certification organism.

Long-term cost projections (2050)

Given high levels of uncertainty, we did not compute detailed cost estimates for each individual NCS in 2050, but provided an aggregate perspective on cost trends over 2030-2050 for each category:

- **Land costs:** the 50-200% increase in land costs over 2030-2050 for NCS projects is based on an extrapolation of historical trends in agricultural land prices in the EU, the US, Canada and Australia[11]. Historical prices of agricultural land in those countries/regions[12], covering 1997-2019, were combined into a weighted average index of real prices of agricultural land. The trend increase in prices (3.7 percent per year) was then extrapolated out to 2050 in our baseline scenario, with a 50% faster increase (5.5 percent per year) used for the aggressive price scenario (higher range of price increases).
- **One-time costs:** A 10%-20% decline is assumed based on expert insights, in particular around tree plantings and the potential to reduce costs through new technologies, including drone-planting.
- **Recurring project costs:** Our stable cost assumption is based on expert insights and in particular the perception that potential small efficiency improvements could be offset by rising labor costs.
- **Carbon monetization costs:** The 30-70% decline in costs is based on experts' inputs on the potential for technology, especially remote sensing, to significantly lower the costs associated with Monitoring, Reporting and Verification of carbon projects, especially around soil carbon.

Project level business cases

We computed the estimated cash flows of three type of specific NCS projects in 3 different locations: reforestation in Colombia, Trees in croplands in the UK and Soil carbon in croplands (through cover crops) in the EU To ensure comparability with BECCS and DACS business cases, assumptions were adjusted from the baseline NCS cost curve methodology for a number of variables:

- Project duration was increased from the standard 30 year-period where relevant (e.g., 50 years for reforestation in Colombia and 60 years for trees in cropland in the UK).
- Discount rates were lowered from 10% to 4% (for the UK and EU cropland cases) and 5% for the Colombia forestry case.
- Land costs in the Colombian reforestation case was adjusted from outright purchase to an annual rental fee of 4% of land value.[13]
- Non-carbon revenues were added for Reforestation in Colombia (timber revenue and co-benefit revenue) and Trees in croplands in the UK (co-benefit revenue). All revenues (carbon and non-carbon) were then discounted at the project discount rate.

11 The choice of countries to be included in this sample was restricted by data availability and we acknowledge it has a bias towards industrialized economies. Based on anecdotal evidence of price trends in emerging market economies this bias is likely to be conservative.
12 Using data from Statistics Canada, Eurostat, USDA, and for Australia ABARES and the Rural Bank.
13 Extrapolating from USDA data on the ratio of agricultural land purchase price to rental fee

Technical potential and sustainable potential

Reforestation

We started by creating a map of global reforestation potential, following Bastin et al.[14] To do so, we first predicted tree coverage globally under natural conditions, independently of land-use. Based on Bastin et al. data set on observed tree coverage within protected areas (78,774 photo-interpreted measurements), we trained a Random Forest model[15] using a set of spatial predictors at a resolution of one square kilometre grouped in four categories:

- Climate[16]: Mean annual temperature, mean temperature in the wettest quarter, annual precipitation, precipitation seasonality, and precipitation in the driest quarter
- Topographic[17]: Slope, elevation, and hill shade
- Soil[18]: Bedrock depth, sand content, and World Reference Base soil classes
- Biogeographic[19]: Biomes and continent

Hyperparameter tuning was made using R's caret package[20] and repeated cross-validation with 40 folds and setting the number of trees at 500.

After transforming tree cover to forest cover,[21] we calculated the technical reforestation potential as the difference between the predicted forest cover and the current forest cover.[22]

The practical reforestation potential is then calculated by filtering the technical abatement potential using three biophysical exclusion filters:

- **Biome:** we excluded biomes where reforestation is non-natural or could have negative effects on ecosystems and climate, i.e. boreal forests/taiga; grasslands, tropical savannas, and shrublands; and deserts and xeric shrublands biomes.[23]
- **Peatland:** similarly to the biome filter, considering uncertainties on the GHG balance[24], we excluded reforestation of temperate peatlands based on a global map of peatlands[25], excluding tropical and sub-tropical regions[26]
- **Water stress:** based on data from the World Resource Institute[27], we excluded areas where water stress is projected to be extremely high (greater than 80 percent) or to be arid in 2040, based on the RCP 8.5 scenario.
- **Urban:** we excluded urban and impervious areas[28], as well as areas where urban expansion is projected with a probability greater than 50 percent by 2050.[29]
- **Cropland:** we excluded cropland areas[30], to avoid competition with food production.

14 Jean-Francois Bastin et al., "The global tree restoration potential," Science, 2019, Volume 365, Issue 6448, pp. 76–79.
15 Leo Breiman, "Random forests," *Machine Learning,* October 2001, Volume 45, pp. 5–32.
16 Stephen E. Fick and Robert J. Hijmans, "WorldClim 2: New 1-kilometre spatial resolution climate surfaces for global land areas," *International Journal of Climatology*, May 15, 2017, Volume 37, Issue 12, pp. 4302–15.
17 Derived from Shuttle Radar Topography Mission (SRTM) 1 Arc-Second Global, US Geological Survey, usgs.gov.
18 T. Hengl et al., "SoilGrids250m: Global gridded soil information based on machine learning," *PLoS ONE*, 2017, Volume 12.
19 D. M. Olson et al., "Terrestrial ecoregions of the world: A new map of life on Earth," *BioScience*, 2001, Volume 51, pp. 933–38.
20 M. Kuhn, "Building predictive models in R using the caret package," *Journal of Statistical Software*, Volume 28, Number 5, pp. 1–26.
21 Defined here as the transition from less than 25% tree cover to more than 25% tree cover in areas, following Cook-Patton et al. 2020
22 Derived from Marcel Buchhorn et al, "Fractional forest cover layer," 2019, Copernicus Global Land Service, Land Cover 100M: Epoch 2015, Globe (version 2.0.2).
23 Following J. W. Veldman et al., "Comment on 'The global tree restoration potential,'" Science, October 18, 2019, Vol. 10, we excluded trees planted in boreal forests, tundra, and montane grasslands and shrublands, which can have a negative net warming effect due to a decrease of albedo. Similarly, we excluded savannas and grasslands biomes, as tree planting in these regions will likely threaten biodiversity, through habitat replacement and increased fire risk, and reduce food security for locals relying on them for livestock forage, hunting, or water supply.
24 Sloan, T. et al. Mires and Peat 23, (2018)
25 Xu, J. et al. CATENA 160, 134–140 (2018)
26 Defined here as the area between 30 degrees of latitude north and south of the equator
27 WRI Aqueduct, accessed on 01-12-2020 (aqueduct.wri.org)
28 Land cover classes 190, 201, 210, 220, from Marcel Buchhorn, Bruno Smets, Luc Bertels, Myroslava Lesiv, Nandin-Erdene Tsendbazar, Martin Herold, & Steffen Fritz. (2019). Copernicus Global Land Service: Land Cover 100m: collection 2: epoch 2015: Globe (Version V2.0.2) [Data set]. Zenodo. http://doi.org/10.5281/zenodo.3243509
29 Chen, G. et al. Nature Communications 11, 537 (2020)
30 Land cover classes 10 to 40 from Marcel Buchhorn, Bruno Smets, Luc Bertels, Myroslava Lesiv, Nandin-Erdene Tsendbazar, Martin Herold, & Steffen Fritz. (2019). Copernicus Global Land Service: Land Cover 100m: collection 2: epoch 2015: Globe (Version V2.0.2) [Data set]. Zenodo. http://doi.org/10.5281/zenodo.3243509.

- **Grassland/rangeland:** the remaining reforestation potential is located on grazing and rangelands. To avoid double counting with improved grazing management NCS ("Grazing-Optimal Intensity" and "Grazing – Legumes")[31], we reduced the reforestation potential by the corresponding percentage of the total grassland and rangeland area with positive net mitigation by region, to account for areas where improved grazing management would potentially co-occur with reforestation.[32]

To compute the total potential CO_2 abated through reforestation for the next 30 years, we combined the reforestation map with state-of-the art geospatial data on CO_2 sequestration rates following natural regrowth[33]. Our underlying assumption here is that reforestation follows a "plant and leave it" approach, rather than a plantation approach. As such, our sequestration rates and costs assume that any hectare of land will only be planted once.

Finally, considering that land could be exploited for other uses than forests such as grazing land or bioenergy, we split spatially the reforestation potential in regions where reforestation under natural regrowth conditions is more likely to take place and regions where it is less likely, accounting for a set of environmental and economic factors. We defined the later category as:

- Areas within current protected areas and key biodiversity areas.[34]
- Areas within future protected areas under a scenario where 30% of the planet would be protected in 2030.[35]
- Areas with low accessibility, defined as regions with low road density network.[36]
- Areas with low competition from other productive land uses, using bioenergy crop yields as a proxy for productivity.[37]

If an area does not fall in at least one of the regions defined above, it is classified under the category "bioenergy and other uses". We further split this latter category into two separate groups based on the bioenergy crop with the highest yield in a given area[38]: "grassy" if the crop is a perennial grass (switchgrass or Miscanthus), "woody" if the crop is fast-growing tree (poplar, willow or eucalypt).

To calculate reforestation project costs, we assumed reforestation projects aimed at replicating natural forests rather than purely commercial plantations. As such, all forestry management costs[39] (and revenues) typically associated with commercial plantations are excluded. This simplifying assumption was made to: (i) build a cost estimate of on higher quality reforestation carbon credits, meaning those with the most co-benefits in terms of biodiversity; (ii) be consistent across countries by having one archetype of reforestation approach; and (iii) step away from the ongoing debate on whether commercial plantations are less legitimate as a result of commercial uses. For simplification, we assumed all planting takes place in year one.

Natural Forest Management

Following Griscom et al.[40], Natural Forest Management (NFM) NCS is defined as the additional carbon sequestration in above- and below-ground carbon following reduced timber harvests in natural forests. Natural, productive forests were mapped based on a global dataset of forest management patterns[41], combining different forest classes and uses[42]. Totalling 1,881 Mha[43], the available area for NFM would span 668 Mha in tropical and sub-tropical regions[44] and 1210 Mha in non-tropical regions.

31 Griscom, B. W. et al. PNAS 114, 11645–11650 (2017).
32 See Table 2-3 in Henderson, B. B. et al. Agriculture, Ecosystems & Environment 207, 91–100 (2015).
33 Cook-Patton, S. C. et al. Nature 585, 545–550 (2020). This includes above- and below-ground carbon, but excludes additional carbon sequestration in soil, due to large uncertainties on soil carbon sequestration rates.
34 UNEP-WCMC and IUCN (2020), Protected Planet: The World Database on Protected Areas (WDPA), 01/2020, Cambridge, UK: UNEP-WCMC and IUCN. BirdLife International (2020). World Database of Key Biodiversity Areas. Available at: www.protectedplanet.net. Commercial license through IBAT (https://ibat-alliance.org/).
35 We used a global, spatially explicit prioritization layer identifying future protected areas accounting for current protection level, biodiversity and carbon in ecosystels, setting the 30% conservation target at the ecoregion level (see https://www.mckinsey.com/business-functions/sustainability/our-insights/valuing-nature-conservation).
36 Road density up to the tertiary network, of less than 10 km/km2, based on Meijer, J. R. et al. Environ. Res. Lett. 13, 064006 (2018).
37 Crop yields below 15 ton of dry matter per year, corresponding to the median lignocellulosic bioenergy crop yield globally, based on Li, W. et al. Earth System Science Data 12, 789–804 (2020). We note that this dataset is based on field trials, i.e. not on demonstrated commercial yields, which would be typically lower.
38 Li, W. et al. Earth System Science Data 12, 789–804 (2020).
39 E.g., fertilization, pruning and thinning of trees, etc.
40 e Griscom, B. W. et al. PNAS 114, 11645–11650 (2017).
41 Schulze, K. et al. Forest Ecology and Management 432, 776–785 (2019).
42 "Naturally regrown forests" and "Primary forests" classes with either "Multiple uses", "Primarily used for production" and "Unclassified use"
43 We note that this is close to the 1,914 Mha potential area identified by Griscom et al.
44 Defined here based on the following biomes: "Tropical & Subtropical Moist Broadleaf Forests", "Tropical & Subtropical Dry Broadleaf Forests", "Tropical & Subtropical Coniferous Forests", Tropical & Subtropical Grasslands, Savannas & Shrublands", "Mangroves" (Olson, D. M. et al. BioScience 51, 933–938 (2001)).

We further constrained the total area, focusing on area with high biodiversity potential, assuming these areas are more likely to be converted under non-intensive management in the future. Similar to the approach taken for reforestation, we identified these areas as areas within current protected areas and key biodiversity areas, as well as areas within future protected areas under a scenario where 30% of the planet would be protected in 2030. We obtained a final potential of 726 Mha, of which 287 Mha occurs in tropical and sub-tropical regions and 439 Mha in non-tropical regions.

Finally, to obtain the NCS sequestration potential, we multiplied the suitable area with carbon sequestration rates specific to tropical (1.43 tCO_2 per hectare per year) and non-tropical regions (0.51 tCO_2 per hectare per year), following Griscom et al.

Converting these productive forests into less intensive managed forests would decrease timber production, an amount that, to maintain current timber production levels, could be compensated through new plantations and intensification in other forested land. Conservatively focusing on new plantations only, we further limited the NFM potential based on the amount of wood production that could be generated in areas that we identified as suitable for both reforestation and woody bioenergy crops (18 Mha in 2030 and 59 Mha in 2050). Assuming an average yield of 20 m3 per hectare in those areas[45], we estimated the maximum timber output that can be 'lost' to Natural Forest Management at 0.4 Gm3 in 2030 and 1.2 Gm3 in 2050. Converting back to CO_2[46], this implies that Natural Forest Management can sequester an estimated 0.4 $GtCO_2$ in 2030 and 1.2 $GtCO_2$ in 2050 without hindering global wood supply. Accordingly, we constrained our 2030 NFM potential to 0.4$GtCO_2$ per year and left the 2050 at 0.6$GtCO_2$ per year.

In line with our assumption the NFM consists mainly of extending logging rotations, NFM costs are driven mainly by (i) the opportunity cost of timber and (ii) carbon credit monetization costs. To compute NFM costs, we thus assume no land costs and no initial project costs. We calculate annual timber revenue foregone in different countries and use this to feed into our recuring project costs. We then use our standard methodology to compute carbon monetization costs.

Coastal restoration

We calculated the carbon abatement potential associated with the restoration of coastal wetlands (focusing on mangroves and seagrass, which jointly represent at least 70 percent of global coastal wetlands[47]) by comparing a baseline cover to a current cover - the difference allowing to define a restoration potential. Extent mangrove data were obtained from Global Mangrove Watch (1996-2016) while those of seagrass habitats were obtained from Ocean Health Index[48] showing the global distribution of seagrass meadows in 2012 (annual loss rates were obtained from literature review). The restoration extent was then multiplied by published carbon sequestration rates. For mangroves, we applied a constant carbon sequestration rate of 6.4 tCO_2 per hectare per year[49] across the globe for restoration. For seagrasses, we applied a constant carbon storage value of 3.4 tCO_2 per hectare per year for seagrass restoration[50].

Following Jakovac et al.[51], we used the agricultural rent to assess the feasibility of coastal restoration. However, contrary to the generic approach outlined above, we used the agricultural rent from cropland only as livestock farming is probably less representative of the feasibility of coastal NCS.

To calculate avoided coastal impact project costs, only costs for mangrove restoration/avoided degradation were investigated (seagrass restoration/avoided degradation projects are less widespread and hence less data is available for them), making the simplifying assumption (in line with expert recommendations) that the cost of restoration was equal to the cost of protection plus the cost of planting trees.[52]

45 Paquette, A. et al. Frontiers in Ecology and the Environment 8, (2010).
46 Assuming 50% C content of wood, and wood density of 0.58 dry ton / m3 wet (Smeets, E. M. W. et al. Climatic Change 81, 353–390 (2007)).
47 Hopkinson et al., "Chapter 1 - Coastal Wetlands: A Synthesis", Coastal Wetlands, pp. 1-75, 2019.
48 http://www.oceanhealthindex.org/methodology/components/seagrass-area.
49 Griscom, B. W. et al. Philosophical Transactions of the Royal Society B: Biological Sciences 375, 20190126 (2020).
50 Griscom, B. W. et al. PNAS 114, 11645–11650 (2017).
51 Jakovac, C. C. et al. Ecological Economics 176, 106758 (2020)
52 Note: Land cost provided by experts for avoided coastal impact sometimes differ than those use for reforestation/avoided deforestation projects

Trees in cropland

We used the results of Chapman et al.[53] to estimate the potential that can be achieved by adding trees to crop systems. First, they estimated current carbon stocks in cropland based on a global map of above- and below-ground biomass. Furthermore, using a threshold of five tCO_2 per hectare to distinguish croplands lacking woody biomass (less than or equal to five tCO_2 per hectare) from those containing woody biomass (greater than five tCO_2 per hectare), they calculated the median carbon stocks in the latter category for each land unit (biome or country) and assigned this value as the sequestration potential that can be achieved by planting trees in cropland in a given unit. Finally, they multiplied the cropland area with the sequestration rate, assuming an adoption rate between one and ten percent. We retained the scenario of a five percent adoption rate (i.e., five percent of cropland area currently below five tCO_2 per hectare is planted with trees).

To calculate trees in cropland project costs, we assumed similar costs structures as for reforestation, with 2 main differences: (i) site set up costs (especially the planting of trees) were factored down as planting density will be much lower and (ii) recurring maintenance costs were also considered as lower as these tasks cannot easily be differentiated from other cropland maintenance tasks carried out by the main land-user. Land costs were not included since the implementation of this NCS has no opportunity cost given full overlap with cropland.

Cover crops

To estimate the theoretical extent of cover crops, we started from a global cropland area of 1571 Mha[54] from which we removed cropland already planted with a perennial or winter crop[55] or where climatic factors and cropping systems require a fallow period. To do this at the granular level, we first computed the Crop Duration ratio (CD), representing the percentage of the year a field is cropped. Following Sieberth et al.[56], CD was calculated at five minute degree pixel resolution as the mean growing area[57] divided by the cropland extent[58]. Conservatively, we considered that areas with CD less than or equal to 60 percent (corresponding to roughly five months of off-season) to be suitable for cover cropping. We further filtered out areas under high water stress[59]. Finally, we computed the percentage of cropland suitable for cover crop per country and applied this number to the current cropland area[60] to estimate the total current cropland area suitable for cover cropping.

In most countries, we assumed an adoption rate of 50 percent by 2050[61], but based on expert insights we adjusted this to 60 percent or 80 percent in some geographies. We also excluded three percent of the remaining surface to accommodate the surface area required to produce the necessary seeds[62], as well as croplands on which cover crops are already being used. We applied a carbon sequestration rate of 1.17 tCO_2 per hectare per year based on a global meta-analysis on the impact of cover crops on soil organic carbon[63].

Our cost calculations for cover crop differ from those of other NCS as we included an estimate of the direct economic benefits accruing to farm operators of using cover crops. As such, we present both gross and net costs of CO_2 with cover crops. Key cost components are: (i) seeds, (ii) planting and (iii) terminating the cover crops, which recur every year. We include three types of economic benefits: (i) reduced input costs, starting in the second year after adopting cover crops, (ii) increased revenue from higher yield of the main crop (starting in year three) and, in some countries, (iii) revenue from the sale of the cover crop harvest (starting in year one). Land costs were not included since the implementation of this NCS has no opportunity cost. Contrary to other NCS, we assume annual carbon certification costs to be fixed per project and equal across countries.

53 Chapman, M. et al. Glob Change Biol 26, 4357–4365 (2020)
54 FAOSTAT, Land Use 2018
55 Poeplau, C. & Don, A.. Agriculture, Ecosystems & Environment 200, 33–41 (2015)
56 Siebert, S. et al. Remote Sensing 2, 1625–1643 (2010)
57 Average of the 12 monthly growing areas per grid cell. Data from MIRCA2000, Portmann, F. T. et al. Global Biogeochemical Cycles 24, (2010)
58 Ramankutty, N. et al. Global Biogeochemical Cycles 22, (2008)
59 We excluded areas where water stress is projected to be extremely high (greater than 80 percent) or to be arid in 2040, based on scenario RCP 8.5 (WRI Aqueduct, accessed on 01-12-2020, aqueduct.wri.org)
60 FAOSTAT, Land Use 2018
61 Poeplau, C. & Don, A. Agriculture, Ecosystems & Environment 200, 33–41 (2015)
62 Runck, B. C. et al. Communications Biology 3, 1–4 (2020)
63 Poeplau, C. & Don, A. Agriculture, Ecosystems & Environment 200, 33–41 (2015)

Engineered removals

Technical potential and sustainable potential of BECCS

Agricultural residues

We started by selecting five crops: maize, rice, sugar cane, sugar beet, soybeans, and a group of cereals (wheat, barley), due to their high residue yields and global footprint. We then used SPAM, a global spatially disaggregated crop production statistic dataset to estimate yearly crop production of the targeted crops at a resolution of 10x10 km, for the year 2010[64]. To update production statistics to more recent years, we computed the contribution of each pixel to the total production of each country and multiplied this percentage by the average production during the 2015-2019 for the given crop and country based on FAOSTAT[65].

To estimate crop residue production, we multiplied production statistics with Residue-to-Product Ratio (RPR)[66] split into primary and secondary residues, gathered from various publications. Primary residues are the biomass left on the field after harvest, such as straws, stover, tops and leaves. Secondary residues are bi-products of the processing of the crops, such as rice husks, sugarcane bagasse and soy beans pods. Since RPR can vary greatly depending on various factors such as crop variety, processing and climate, we used, where possible, a range of RPR values from low, medium to high for each crop, and potentially varying across regions[67].

We further constrained this technical potential to account for (i) sustainability concerns and (ii) competing uses. First, we filtered out area with low organic carbon content[68] and high soil erosion loss[69] to maintain sufficient carbon input in these vulnerable soils. For the same reason, we also ensured at least 2.5 ton of residues per hectare of cultivated land would be left on the ground[70]. Finally, we applied region-specific haircuts to the total residue potential known as Recoverable Fraction (RF)[71]. Based on literature values, these RF range from about 5% to 70% and indicate how much of the residue is available for bioenergy after competitive uses, logistics, legal, sustainability and economic constraints are taken into account. Similar to RPR, RF take a range of low, medium and high values to account for the large uncertainty in these parameters.

Finally, we converted the mass of residue (tons) to energy density (GJ) by multiplying the mass with the dry-matter content and energy content (Higher Heating Value, GJ per tons) of residues. These crop-specific parameters were derived from various sources[72]. We converted to CO_2 abatement using a conversion factor of 0.9 tCO_2/MWh of energy produced (assuming a plant efficiency of 39%, 90% carbon capture rate and supply chain emissions equivalent to 0.14 tCO_2/MWh of energy produced and crop-specific energy density)

64 International Food Policy Research Institute, 2019, "Global Spatially-Disaggregated Crop Production Statistics Data for 2010 Version 2.0", https://doi.org/10.7910/DVN/PRFF8V, Harvard Dataverse, V4.
65 FAOSTAT, Crops Production 2020
66 The RPR is the ratio between the mass of residue and the mass of
67 Deng, Y. Y. et al. Biomass and Bioenergy 74, 253–267 (2015); BioTrade2020plus; Bioenergy and Food Security Rapid Appraisal Tool; LOCOMOTION, Module of energy resources availability H2020-LC-CLA-2018-2
68 Defined here as cropland areas with soil organic carbon content in the 0-30 cm below 2 % C , based on SoilGrid dataset (Hengl, T. et al. PLOS ONE 12, e0169748 (2017))
69 Defined here as cropland areas with erosion loss above 10 tons per hectare, based on GloSEM dataset (Borrelli, P. et al. Nature Communications 8, 2013 (2017)) resampled at 25 km resolution (European Soil Data Centre (ESDAC), esdac.jrc.ec.europa.eu, European Commission, Joint Research Centre)
70 Daioglou, V. et al. GCB Bioenergy 8, 456–470 (2016) ; Gallagher, P. W. et al. Environ Resource Econ 24, 335–358 (2003)
71 Deng, Y. Y. et al. Biomass and Bioenergy 74, 253–267 (2015)
72 Phyllis database ; Karan, S. K. et al. Resources, Conservation and Recycling 164, 105211 (2021) ; Valk, MsC Thesis: Availability and cost of agricultural residues for bioenergy generation , Utrtecht University (2014)

Figure 3 summarizes our approach for agricultural residues.

Figure 3:
Technical potential and sustainable potential for agricultural residues

Technical potential sized by:

1. Sizing the total **global agricultural production each year –** to a resolution of 100 km^2 for maize, rice, sugar cane, sugar beet and a group of cereals
2. Applying ratios to work out the **amount of primary and secondary residues** generated by the crop – at a level of country-level, crop-specific detail
3. **Converting for energy density of dried agricultural residues** – crop-specific[2]

Then filtered potential by:

4. **Excluding areas** that do not meet certain sustainability criteria (e.g., soil loss and soil carbon content)
5. **Reducing the amount of residues** that can be taken, allowing for residues to be left on the land to maintain soil quality[1]

Then filtered by:

6. **Conducting economic analysis to consider:**
   – Competitive uses, as per today
   – Logistics
   – Legal constraints
   – Difficult terrain

1. To obtain a minimum of 250t/km2 primary residues left on the soil after harvest
2. Using Phyllis2 database

Source: McKinsey Nature Analytics

3

Forestry residues

We used FAOSTAT[73] to size the total volume of wood each year by country which we converted into mass equivalent using a constant factor of 0.58 dry ton per cubic meter of green wood[74].

To estimate the potential of primary woody residues[75], we selected the categories "Wood fuel" and "Industrial Roundwood" in FAOSTAT and multiplied country statistics by biome-specific RPR[76]. We followed by applying haircuts, ranging from around 30% to 50% to reduce this technical potential, to ensure that at least 10 tons of residues per hectare of forest are left after the final harvest[77].

For secondary residues[78], we selected the category "Sawnwood" in FAOSTAT to get the technical residue potential. Effectively, this assumes the same quantity of secondary residues is produced as the quantity of processed wood (i.e., residue fraction of roundwood is equal to 0.5).[79]

Similar to agricultural residues, we then applied region-specific RF[80], ranging from about 5 % to 90%, to the primary and secondary residues potential, to factor in competing uses, sustainability concerns and accessibility. Finally, to convert dry wood mass to energy, we used a higher heating value of 19 GJ/ton.

We converted to CO_2 abatement using a conversion factor of 0.9 tCO_2/MWh of energy produced (assuming a plant efficiency of 39%, 90% carbon capture rate and supply chain emissions equivalent to 0.14 tCO_2/MWh of energy produced and crop-specific energy density).

73 FAOSTAT, Forestry Products and Trade 2020
74 Smeets, E. M. W. et al. Climatic Change 81, 353–390 (2007)
75 Defined here as wood left over after the cleaning, thinning, or felling of forest stands. This leftover wood includes small felled trees, branches and tops
76 Based on Daioglou, V. et al. GCB Bioenergy 8, 456–470 (2016), we took wood plantation RPR to be representative of the category "Roundwood" and clear-cut RPR to be representative of the category "Woodfuel", characterized by higher rates of felling than industrial roundwood (smaller branches and tops can be used for wood fuel)
77 Table 15, Buck, MSc Thesis : Sustainable forestry residue parameters, Utrecht University (2013)
78 Defined here as wood derived from roundwood processing in saw mills, including sawdust and wood chips
79 Smeets, E. et al. Progress in Energy and Combustion Science 33, 56–106 (2007)
80 Deng, Y. Y. et al. Biomass and Bioenergy 74, 253–267 (2015)

Figure 4 summarizes our approach for forestry residues.

Figure 4:
Technical potential and sustainable potential for forestry residues

Technical potential sized by:

1. Sizing the total **volume wood and forest products output each year –** at the country level[1]
2. **Applying fractions** to work out the amount of primary and secondary residues associated with this production - using biome-specific fractions
3. **Converting for energy density of dried wood pellet** – using a constant conversion factor of 580 kg of dry wood per m3 of green wood, with a higher heating value of 19 MJ/kg

Then filtered potential by:

4. **Reducing the amount of wood that can be taken** to allow for maintaining soil quality[2]

Then filtered by:

5. **Applying a sustainable recovery ratio** (region-specific) to factor in competing uses, sustainability and accessibility

1. Based on FAO data
2. Obtain a minimum of 1000t/km2 left on the ground

Source: Deng et al., 2015; global forestry (e.g., FAO) and agricultural databases (e.g., Phyllis2, ASA); Wu et al. (2017), Newbold et al (2016); CCI land cover data; Global Soil Erosion, JRC; SoilGrid.com; MapSpam; Bai et al. (2008);).; Xue et al. (2015);. Gibbs and Salmon (2015); Smeets and Faaij, 2007; Diaoglou et al., 2016; Bunting et al., 2018; Potatov et al., 2017; Sandeman et al., 2017; Mai-Moulin et al., 2018;

Low-grade roundwood

Low-Grade Roundwood (LGR) is defined here as pulpwood resulting from thinning operations. We estimated the potential of LGR for bioenergy from two distinct components:

- **Current pellet production:** we multiplied the current pellet production in 2018, estimated at ~55 Mt[81], with various estimates of the share of roundwood in pellets. These estimates ranged from less than 10% in EU[82], 19% in Canada[83], 66 % in UK[84], to 70% in USA[85]
- **Available wood surplus** arising from the difference in sustainable wood supply and wood harvest: we gathered data on wood supply (NAI: net annual increment) and harvest for the major wood producing geographies (Europe[86], Canada[87], USA[88], Russia[89]), assuming no available surplus in the rest of the world[90]. We set the sustainable harvest to be at 90% of the NAI, considering logistic and economic constraints to the full harvesting of the NAI as well as under-reporting of wood production. We considered that the surplus would be available to increase the production of LGR[91] (proportional to its current share to total wood production) and that this increase would be fully captured for bioenergy, assuming no increase in demand of LGR for other uses. Effectively, we computed the production potential according to:

$$\mathrm{LGR} = \sum_{i=0}^{n} max\left(0, \mathrm{LGR}_i \times \left(\frac{H_i}{S_i} - 0.9\right)\right)$$

where LGRi is the current LGR production of country i, (H/S-1) is the surplus, Hi is the harvest rate, Si sustainable harvest. We note that this potential is based on increasing the exploitation of forests, which the relative under-exploitation is a major driver of the current global land carbon sink. Hence, increasing the felling rate is likely to decrease the land sink in the near term (< 30 years), a process that we do not factor in in our analyses. On the other hand, an increased demand for bioenergy can result in net carbon benefits, due to economic incentives for afforestation and more intensive management[92]. Such practices, however, should not be carried out without assessing their potential impacts on biodiversity[93] or nutrient balance[94].

81 EU Pellet council, 2020
82 EU Pellet council, 2020
83 O'Kelly Acumen, pers. comm.
84 ForestReseach.org.uk
85 IEA Bioenergy Task 40: 5/2019
86 State of the European Forests, 2020
87 Canada National Resource Database
88 Mai-Moulin, T. et al. Biofuels, Bioproducts and Biorefining 13, 293–324 (2019)
89 O'Kelly Acumen, pers. comm.
90 Increasing felling rate is only relevant for managed natural forests, common in the Northern Hemisphere. In regions that rely mainly on plantations for wood supply, like Latin America, Indonesia, South Africa, Oceania, increasing wood supply could be achieved by increasing plantation area
91 Defined as the category "pulpwood, round and split" in FAOSTAT, Forestry Production and Trade
92 Favero, A. et al. Science Advances 6, eaay6792 (2020)
93 Duden, A. S. et al. GCB Bioenergy 10, 841–860 (2018)
94 Garcia, W. de O. et al. Scientific Reports 8, 5280 (2018)

Dedicated bioenergy crops

The potential of dedicated bioenergy crops was evaluated using two simplifying assumptions:

- Energy crops are sufficiently similar that we can model many different varieties with one proxy. We selected *Miscanthus Gigantus*, the highest yielding of comparable energy crops and some short rotation woody crops. It is also relatively tolerant in different climates. To account for reduced productivity on degraded land, we assumed yield ranging from 3 to 6 dry ton per hectare per year[95].
- Energy crops would grow on degraded soils[96] only, to minimise competition from other land uses. Furthermore, only a small fraction of these lands (1% to 2.5%) would be dedicated to bioenergy, corresponding to 27-68 Mha. This potential area could partly overlap with the reforestation NCS and do not account for biophysical limits such as water availability, that might further constrain the identified potential.

To estimate the energy content of bioenergy crops, we multiplied miscanthus yields with available degraded land and energy content of miscanthus[97]. Finally, we converted to CO_2 abatement potential using the same conversion factor as the one used for forestry residues (see Figure 5 for an overview of the approach for bioenergy crops).

Figure 5:
Technical and sustainable potential for bioenergy crops

Energy crops are sufficiently similar that it is possible to **model many different varieties with one proxy**

For this proxy we have chosen **miscanthus** (specifically miscanthus x giganteus), the highest yielding of comparable energy crops and some short rotation forestry and is relatively tolerant in different climates. Miscanthus is also in use today in power generation

Technical potential is modelled on the **growth of miscanthus on degraded lands only**. Land degradation is defined as "long-term loss of ecosystem function and productivity caused by disturbances from which land cannot recover unaided." The normalized difference vegetation index (NDVI), derived from remotely sensed imagery, was used as a proxy to assess land degradation

Then filtered potential by:

1. **Applying fractions** to work out the miscanthus yields on degraded land
2. **Converting for energy density** of dried miscanthus

It is assumed that land that is not degraded could be theoretically used for agriculture or other uses, but this is unlikely to happen as they are not prime agricultural lands

It is assumed energy crops have no competing uses as they are a net increment on biomass today

1. Alexopoulou 2018; 2. Statistik Austria; Lewandowski et al., 2016; Furtlehner, 2017; Heaton, 2017.

5

95 Gerwin, W. et al. SOIL 4, 267–290 (2018); Searle, S. et al. GCB Bioenergy 7, 328–336 (2015); Jezowski, S. et al. Frontiers in Plant Science 8, (2017)
96 Country-specific estimates based on Bai, Z. G. et al. Soil Use and Management 24, 223–234 (2008). Land degradation is defined as "long- term loss of ecosystem function and productivity caused by disturbances from which land cannot recover unaided."
97 We assumed an energy content of 19 GJ per ton (Phyllis2 database)

Costs of BECCS and DACS

Overview

This report contains detailed information on the per tonne sequestration cost of both BECCS and DACS projects. It also includes detailed information on how these costs can evolve through increased deployment of each solution. All costs for BECCS and DACS used throughout this report are a blend of publicly available sources, proprietary insight from Coalition members, and outside-in triangulation from comparable analogies in other technologies' markets (see Figure A). This results in the maximum number of data points and balances the ability to trace and appreciate the assumptions in certain sources with having the latest data sets from those actively scaling technologies in the field.

BECCS and DACS costs follow the same methodology. To identify the present-day costs for both BECCS and DACS, two sources of input have been combined: existing data points from publicly available sources, such as academic research and published numbers from suppliers (1A below); and proprietary insight from Coalition members (1B below). To estimate the potential cost evolution of these technologies, these same sources are also used where they include a cost evolution through time or through increased deployment. This view is then triangulated with a third source applying observed cost reductions in other comparable technologies to specific drivers of cost in BECCS and DACS projects (2 below) – e.g., the cost of operations and maintenance in capital-intensive engineering projects like oil and gas has been observed to decline as the deployed capacity scales due to improved and more standardised processes.

Figure A:
Approach to developing present day costs and cost evolution for BECCS and DACS

Approach	Action	Action to be used for cost: Today	2030	2050	Rationale for action
1 Gather existing data points	1A Pull together cost numbers from publicly available sources	✓	✓	✓	Build an initial view based on existing expertise across academic
	1B Pull together data points from Coalition members	✓	✓	✓	Ground this initial view with unique insights from Coalition members who have tangible experience with projects
2 Take outside-in view on what needs to be true for costs to come down over time	Leverage analogies from other technologies across the maturity curve		✓	✓	Demonstrate the viability of cost reductions with objective 'thought experiments'

In terms of sources consulted as part of Approach 1A, for both present-day and future costs, the full set is show below. Given the pace of change in the technology, reflected in available literature, only sources from the last 10 years were included:

1A

BECCS publicly-available sources

- Is Carbon Capture Too Expensive? – (2021, International Energy Agency)
- Potential for Reduced Costs for Carbon Capture, Transport and Storage Value Chains (CCS) – (2020, Gassnova)
- Estimating the Cost of Capital for Renewable Energy Projects – (2020, Steffen et al.)
- CCS Needs to Start With a Bang not a Whimper – (2018, DNV)
- Global Costs of Carbon Capture and Storage – (2017, Global CCS institute)
- The Cost of CO_2 Capture and Storage – (2015, Rubin et al.)

DACS publicly-available sources

- Technoeconomic Assessment Tool for Direct Air Capture – (2020, McQueen et al.)
- Negative Emissions Technologies and Reliable Sequestration – (2019, A Research Agenda)
- Techno-economic assessment of CO2 direct air capture plants (2019, Fasihi et al.)
- A Process for Capturing CO2 from the Atmosphere (2018, Keith et al.)
- Techno-economic assessment of CO2 direct air capture plants (2018, Climeworks)
- Direct air capture of CO2 with chemicals - optimization of a two loop hydroxide (2013, Mazottie et al)
- An air–liquid contactor for large-scale capture of CO2 from air (2012, Holmes & Keith)

CCS publicly-available sources: Department for Business Energy and Industrial Strategy (2020), Potential for reduced costs for carbon capture, transport and storage value chains (CCS) – (2020, Gassnova), Cost of CO_2 transportation infrastructures – (2013, Mallon et al.)

Approach 1B, as mentioned, includes the proprietary insights from Coalition members, and is factored into the blended costs.

To triangulate these future costs, a third data set was considered. Comparable analogies where capacity increases and costs changed were analysed and incorporated. The full table showing these analogies (i.e., approach 2) for cost drivers of BECCS and DACS, and their sources, is shown in each solution deep dive.

BECCS: Economics

Comparable analogies where capacity increases and costs changed

2

Example for BECCS power plant, brownfield

Stage	Sub-stage	Rationale for cost evolution	Example sources
Bio-mass	Processed feedstock	Cost evolution is uncertain due to opposing trends, but is likely to remain constant in coming years as supply scales to meet any new demand (as seen in historic demand increases) . Increased uptake will bring economies of scale, cheaper feedstock sources and technological improvements. However, there will also be increased demand for biomass, opposing these trends.	**Hawkins Wright Wood Pellets Outlook Q2 2020** – projects wood pellet prices stabilising from 2022 onwards, and falling in the late 2020s
Bio-mass	Fuel transport	Scaling the BECCS industry will mean that larger volumes of fuel are being transported, allowing economies at scale. Future plants could also benefit from closer proximity to transport hubs if purpose built.	**Rubin et al (2019)** – highlights a cost reduction of 10-20% across key low carbon technologies with every doubling of deployed capacity
Plant proces sing	Generation	Generation using biomass is a mature technology, but is likely to decrease in cost as operational excellence improves over time, as seen in other mature technologies that have continued to scale.	**McKinsey and Lazard analysis**, showing even mature technologies have demonstrated learning curves as they continue to scale over short-term Gas peakers and gas (combined cycle) cost per unit of output reduced by 30-35% during the 2010s, i.e., when already mature. If extrapolated over a time horizon starting from a lower technology maturity, and augmented by the likely lower cost of capital, the O&M cost is expected to decrease meaningfully
Carbon cap-ture and sto-rage	CO_2 capture	CO_2 capture costs will decrease for four reasons; moderate technological improvements in amine technology; larger scale deployment; process improvement and operational excellence through learning-by-doing; and research into alternative forms of capture at lower levels of technological readiness.	**Gassnova report 2020** – Value chain analysis indicates that cost of CCS decreases by 45% as volume scales from 1mtpa to 10mtpa, and then by a further 55% as volume scales from 10mtpa to ~320 mtpa
Carbon cap-ture and sto-rage	CO_2 compres-sion	CO_2 compression is relatively a mature technology, but is likely to decrease in cost as operational excellence improves over time, as seen in other mature technologies that have continued to scale.	**McKinsey and Lazard analysis** – see above
Carbon cap-ture and sto-rage	CO_2 Transport	CO_2 transport will decrease in cost due to the shift towards permanent transport infrastructure (pipelines) and cost benefits of transporting larger volumes of CO2. The larger the volume of CO2 transported in pipelines the cheaper the cost per ton.	**IPCC Special report on carbon capture and storage 2005** – CO2 transport shown to decrease in cost by more than 75% as mass flow rate increases from 2.5 MtCO2 pa to 25 MtCO2 pa
Carbon cap-ture and sto-rage	CO_2 Storage	CO_2 storage will decrease in cost for four principle reasons; economies of scale; technology and process improvements in MMV; decreased costs of liability as understanding of storage improves; and decreased costs of capital (see below).	**Gassnova report 2020** – Costs of storage will decrease as cheaper storage reservoirs are found and utilised
Financing costs		Technologies become cheaper when they become commercially viable due to reducing debt costs. As technologies grow into a more developed market with stable and consistent sources of revenue, and perceived risks are lower, financiers offer better rates on debt and equity. As the negative emissions market matures, cost of capital is expected to come down to ~5% (from 8-10% today), similar to observed reductions in e.g., UK offshore & onshore wind	**ScienceDirect.com; IEA; Renewable Energy Foundation; Eclareon** – WACC available to onshore and offshore wind energy providers in the UK, Europe, and the USA decreased during the 2010s by 2-4 percentage points Cost of capital is highlighted as a key area of focus in the **CCC's Sixth Carbon Budget**. With strong policy signals it can fall significantly over time.
Total costs		Overall cost expected to come down due to drivers detailed above – overall cost reduction calculated by the above is also triangulated by industry expertise and publicly available sources that provide overall cost reduction figures without comparable breakdowns	**IEA 2021** – top down analysis indicates that the cost of BECCS will come down by approximately 40% by late 2020s as deployment is scaled

1

DACS: Economics

Comparable analogies where capacity increases and costs changed

2

Stage	Sub-stage	Rationale for cost evolution	Example sources
CapEx	Levelised capital	As deployed capacity increases, components are expected to become more standardised, and use more commodified materials with fewer parts – so components such as air contactors are expected to cost meaningfully less.	**Schmidt et al 2017** – details decrease in price for battery components as cumulative installed capacity increases, including lithium-ion batteries, sodium batteries, and nickel batteries **BNEF at EMEA energy summit, expert interviews** – this is also true in emerging techs, such as the levelized cost of capital for renewable wind tech Northern Europe
CapEx	Financing	Technologies become cheaper when they become commercially viable due to reducing debt costs. As technologies grow into a more developed market with stable and consistent sources of revenue, and perceived risks are lower, financiers offer better rates on debt and equity. As the negative emissions market matures, cost of capital is expected to come down to ~5% (from 8-10% today), similar to observed reductions in e.g., UK offshore & onshore wind	**ScienceDirect.com; IEA; Renewable Energy Foundation; Eclareon** – WACC available to onshore and offshore wind energy providers in the UK, Europe, and the USA decreased during the 2010s by 2-4 percentage points Cost of capital is highlighted as a key area of focus in the **CCC's Sixth Carbon Budget**. With strong policy signals it can fall significantly over time.
OpEx	Energy	Cost expected to decrease for two reasons: proportion of energy inputs to shift increasingly towards renewable energy; and cost of renewable energy to decease over time	**BEIS, 2020: Electricity Generation Costs** – Central Case for offshore wind, onshore wind, and solar, showing up to a 70% cost decrease by ~2040
OpEx	Capture solvent / sorbent	Main cost decline is expected for solid sorbent capture chemicals. Main drivers are expected to be increased efficiency of chemicals used, thus requiring less frequent replacement, and lower starting cost from more mature supply chains of the raw materials. Smaller decrease expected for liquid chemicals & input consumables.	Learning curve based on **expert interviews**, extrapolating an efficiency improvement of extending capture chemical replacement cycles from ~2 years to ~4-6 years
OpEx	Operating and main-tenance	Cost expected to decrease, as has been observed in capital-intensive engineering projects like oil and gas – this is due mainly to improved and more standardised processes. This is likely augmented by the reduced number of overall components required through time, and triangulated by most O&M costs being considered as percentages of up front capital component cost	**McKinsey and Lazard analysis**, showing even mature technologies have demonstrated learning curves as they continue to scale over short-term Gas peakers and gas (combined cycle) cost per unit of output reduced by 30-35% during the 2010s, i.e., when already mature. If extrapolated over a time horizon starting from a lower technology maturity, and augmented by the likely lower cost of capital, the O&M cost is expected to decrease meaningfully
OpEx	CO_2 com-pression	CO2 compression is relatively a mature technology, but is likely to decrease in cost as operational excellence improves over time, as seen in other mature technologies that have continued to scale.	**McKinsey and Lazard analysis** – see above
OpEx	CO2 transport	CO2 transport will decrease in cost due to the shift towards permanent transport infrastructure (pipelines) and cost benefits of transporting larger volumes of CO2. In general, the larger the volume of CO2 transported in pipelines the cheaper the cost per ton.	**IPCC Special report on carbon capture and storage 2005** – CO2 transport shown to decrease in cost by more than 75% as mass flow rate increases from 2.5 MtCO2 pa to 25 MtCO2 pa
OpEx	CO_2 storage	CO2 storage will decrease in cost for four principle reasons; economies of scale; technology and process improvements in MMV; decreased costs of liability as understanding of storage improves; and decreased costs of capital	**Gassnova report 2020** – Costs of storage will decrease as cheaper storage reservoirs are found and utilised
Overall cost			**Rubin et al (2019)** – highlights a cost reduction of 10-20% with every doubling of deployed capacity, especially for specific drivers such as CapEx.

2

Job analysis

Overview

The estimation of job creation uses a traditional employment multiplier approach. Total jobs refers to the combination of direct jobs, indirect jobs and induced jobs.

Direct jobs were estimated by calculating the jobs off two approaches and triangulating. The first approach was to use specific volumetric job multipliers – i.e., jobs created per unit of production – as specifically seen in NCS and engineered removals. Different multipliers were used to differentiate between different types of jobs, e.g., building/planting and maintaining/operating. These multipliers were sourced from a range of academic and analyst sources[98]. In addition, a second approach used economic multipliers from the OECD, matched to the economic activities of the negative emissions on a best-fit basis. For simplicity economic multipliers were chosen for the UK, although in practice negative emissions will be deployed in many countries with lower labour productivity, which may make the job estimates conservative. These multipliers were used against the estimated spend over time, allowing for expected cost reductions. Combining these approaches allows for a balance between being specific to the activity in question (approach 1), and allowing for changes in spend over time (approach 2).

Indirect and induced jobs were estimated by considering the spend profile of negative emission technology, and deducing the corresponding ratio of direct to indirect and direct to induced jobs as implied in approach 2, economic multipliers from the OECD.

Due to the limited data availability of job creation for emergent technologies regional variation in job creation and potential productivity changes as industries scale and mature, this should be considered an order of magnitude estimate of the jobs involved in a global scale-up of negative emissions. Any project aiming to estimate the economic impact of negative emissions should go through a detail job analysis

98 Including Vivid Economics, the Rhodium Group, and O'Kelly Acumen.


Coalition for
Negative Emissions