Supplementary Material

SM Cross-sectoral perspectives

Supplementary Material 12.A: Detailed explanation of the data on costs and potentials in Section 12.2

SM 12.A.1. Introduction

In this Supplementary Material, background information is provided on the way the data on costs and potentials has been synthesised. Section SM 12.A.2 provides information on how the extended Table 12.3 on costs and potentials of mitigation options was constructed using the input of the sectoral chapters and other information. Section SM 12.A.3 provides information on the construction of Figure SPM.9 in the Summary for Policy Makers.

SM 12.A.2. Data on emission scenarios and mitigation potentials (Table 12.3)

Energy sector

For the energy sector, the starting point for determining the mitigation potential was UNEP (2017), which was also published as Blok et al. (2020) This assessment was checked for key updates that substantially influence the ranges as reported in these literature sources.

The reference emissions scenario in the World Energy Outlook 2016 report (IEA 2016) was compared to the preferred reference scenario for this assessment, World Energy Outlook 2019 (IEA 2019). There is limited change in the overall parameters between the World Energy Outlooks of 2019 and 2016. Total electricity production in 2030 was marginally higher (0.6%) and the average fossil fuel emission factor 2.4% lower in WEO2019 as compared to WEO2016. A substantially higher contribution of wind and solar energy was seen in the reference scenario (Current Policies), leading to a reduction of the remaining potential by 0.50 and 0.95 $GtCO_2$ for wind and solar respectively. In contrast, the contribution of nuclear energy in the reference scenario has become smaller. For all other low-carbon sources the differences are small.

Estimating the potential deployment of low-carbon electricity sources by 2030 is difficult. The technical potentials are significant, and for all technologies are higher or much higher than the potentials identified by UNEP (2017). In many cases, the technical potential of electricity generating technologies is even much higher than the anticipated electricity demand projected for 2030, see for example recent assessments for solar energy (Creutzig et al. 2017; Dupont et al. 2020), onshore wind energy (Bosch et al. 2017), offshore wind energy (Bosch et al. 2018) and hydropower (Hoes et al. 2017).

There are few studies that explicitly explore the limits of deployment of technologies by 2030. For solar energy a group of solar energy experts (Haegel et al. 2019) showed the feasibility of achieving 10 TW of installed photovoltaic energy capacity in 2030, which is higher than the highest end of the 8.2 TW estimate in the UNEP (2017) report. Bogdanov et al. (2019) provide a somewhat lower contribution of solar energy in 2030 (installed power 7 TW), but a somewhat higher contribution from wind energy than assumed before, i.e., 3.3 TW. Combined with a substantially higher full-load equivalent hours of wind turbines (3200 h y^{-1} versus 2600 h y^{-1}), this leads to a higher production and associated avoided emissions compared to UNEP (2017). Combined with the higher reference levels for solar and wind energy, this brings the achievable mitigation potential range for 2030 for solar energy to 2 to 7 $GtCO_2$ (from 3 to 6 $GtCO_2$) and for wind energy to 2.1 to 5.6 $GtCO_2$-eq (from 2.6 to 4.1 $GtCO_2$).

Regarding nuclear energy, (IEA 2019a) explores the role of lifetime extensions of nuclear power plants. The report shows that an extra 80 GW can stay online by 2030, which would be equivalent to about 0.4 $GtCO_2$ of avoided emissions. This is well below the potential estimate in UNEP (2017) and could be part of the realisation of that potential, compensating for the fact that the potential for new-built power plants in the timeframe until 2030 will gradually decrease given the long lead times required to get nuclear power plants online (IEA 2019b). Based on these considerations, the potential for nuclear energy is not updated from the figures presented in UNEP (2017).

For other low-carbon electricity sources, no studies were found that led to a downward or upward revision of the potentials identified in UNEP (2017).

The mitigation cost data per electricity generation technology were provided by Chapter 6. The starting point was electricity production cost data for 2019 and 2030 provided by IEA for four marker regions: Asia (China), Asia (India), Europe, and North America. For these regions, mitigation costs were calculated for two scenarios, the first in which coal-fired power plants are replaced, and the second in which natural-gas fired power plants are replaced, leading to a total of eight cases. Although these cases cannot be used to determine an accurate global distribution of mitigation costs, they are considered sufficiently representative for the *range* of mitigation costs for each technology

For onshore wind and utility solar energy the mitigation costs end up in the negative cost bins, if we compare full LCOE of these technologies with the full LCOE of conventional power production. However, if solar and wind energy develop rapidly, they will not necessarily replace existing capacity, but rather just avoid the fuel and other operational costs of existing power plants. Taking that into account, the mitigation costs will become higher. In many cases still negative costs occur, but also costs in the ranges of 0 to 50 USD tCO_2-eq^{-1} (for wind) and 0 to 100 USD tCO_2-eq^{-1} (for solar) occur. This full range of cost bins is used, noting that the majority of the potential will be in the negative cost bin. The latter is also confirmed by the analysis of the historic development of electricity production costs in Chapter 6 (Figure SPM.5). Offshore wind currently is more expensive, but also here negative costs are expected by 2030. For nuclear energy, costs can vary widely, largely region-dependent, the cases end up in the cost bins ranging from negative to over 100 USD tCO_2eq^{-1}. For bio-energy, carbon capture and storage and bio-energy combined with carbon capture and storage (BECCS), mitigation costs virtually all end up in the range of 50 to 200 USD tCO_2eq^{-1}. For hydropower and geothermal energy costs in the range of 0 to 100 USD tCO_2eq^{-1} are assumed. It should be stressed that costs vary widely depending on local and regional conditions (see also Section 6.4.7), but the cost ranges presented here are considered to represent how the various technologies compare in mitigation costs, along with the variability per technology.

Methane emission reductions (excluding AFOLU)

Data for CH_4 emission reductions from coal, oil and natural gas operations, solid waste and waste water were provided by three organisations: IIASA, Netherlands Environmental Assessment Agency PBL and US-EPA. For oil and gas, data from the IEA were also used. In this analysis, as far as possible global warming potentials (GWPs) as established in the 6th Assessment Report are used: 27 for biogenic methane and 28.9 for fossil methane (Cross-Chapter Box 2 in Chapter 2).

The analysis by IIASA is reported in Höglund-Isaksson et al. (2020). Data were provided by Mrs. Lena Höglund-Isaksson (most recent version on 27 Oct. 2021). The data were reported in EUR tCO_2^{-1} and allocated to USD tCO_2^{-1} cost bins using a USD to EUR ratio of 0.86.

The analysis by the Netherlands Environmental Assessment Agency PBL is reported in (Harmsen et al. 2019a). Data were provided by Mr. Mathijs Harmsen in Excel format (1 Feb. 2021), see also (Harmsen et al. 2019b). Cumulative relative emission reduction potentials were provided. The relative emission reductions were applied to the SSP2-baseline provided with the PBL dataset and subsequently organised in cost bins.

The analysis by the United States Environmental Protection Agency is reported in US EPA (2019). Data were downloaded via the Non-CO_2 Greenhouse Gas Data Tool (US EPA 2021), which provides cumulative cost data, and organized in cost bins. The mitigation potentials were corrected for the GWPs used in AR6. However, as EPA originally uses a GWP of 25, there may still be a small mismatch over the cost bins.

Data from the IEA for oil and gas were downloaded from the Methane Tracker Database (IEA 2021). Costs are given in USD BTU^{-1}, these were converted using a conversion factor of 21.5 kg methane per million BTU.

The results are shown in Table SM 12.A.1. There are notable differences between the sources in mitigation potentials. There is however a fair agreement between the data sources as to whether mitigation potentials typically appear in lower or higher cost ranges. In the table, a ‘best estimate’ per cost bin is also presented, based on an average of the estimates. For coal and oil/gas, PBL and IIASA are each allocated half of the weight of the other sources, based on the observation that PBL relies heavily on IIASA for these sources. For the ‘less than zero’ cost bin, data from PBL were not taken into account as these potentials are already included in the baseline. The uncertainty ranges are determined by the lowest and highest value per cost bin. Cumulative uncertainty ranges are based on cumulative values and are in relative terms substantially smaller.

Table SM 12.A.1: Methane mitigation potentials for the year 2030 for coal mining, oil and gas operations, waste and waste water from four different sources. For comparison, the reference emissions are also given. A 'best estimate' per source is given in italics. Sources: see text.

Sector / data source	Cost ranges (USD tCO_2-eq^{-1})						Total mitigation potential ($GtCO_2$-eq)	Reference 2030 emissions ($GtCO_2$-eq)
	<0	0–20	20–50	50–100	100–200	>200		
Coal								
IIASA	0.06	0.22	0.05	0.02	0.00	0.00	0.36	1.21
EPA	0.01	0.64	0.02	0.01	0.00	0.00	0.68	0.91
PBL		0.15	0.02	0.03	0.00	0.00	0.20	1.28
Best estimate	*0.04*	*0.41*	*0.03*	*0.02*	*0.00*	*0.00*	*0.50*	
Oil and gas								
IIASA	0.56	0.19	0.20	0.05	0.00	0.00	1.01	2.88
EPA	0.12	0.23	0.03	0.01	0.29	0.00	0.67	1.78
PBL		0.41	0.04	0.29	0.00	0.00	0.74	3.28
IEA	0.26	1.30	0.06	0.00	0.00	0.00	1.61	2.15
Best estimate	*0.31*	*0.61*	*0.07*	*0.06*	*0.10*	*0.00*	*1.15*	
Solid waste								
IIASA	0.43	0.03	0.03	0.03	0.02	0.02	0.56	1.49
EPA	0.24	0.15	0.07	0.10	0.12	0.00	0.68	1.19
PBL		0.14	0.08	0.01	0.10	0.15	0.48	1.04
Best estimate	*0.33*	*0.11*	*0.06*	*0.04*	*0.08*	*0.06*	*0.69**	
Wastewater								
IIASA	0.05	0.05	0.07	0.04	0.01	0.00	0.21	0.61
EPA	0.00	0.04	0.03	0.03	0.16	0.00	0.27	0.68
PBL		0.01	0.01	0.02	0.03	0.07	0.14	0.84
Best estimate	*0.02*	*0.03*	*0.04*	*0.03*	*0.07*	*0.02*	*0.22*	

*) This number is the summation over the cost bins and can be higher than all the values per institute because PBL is not taken into account for the negative-bin.

Agriculture, forestry and land-use change (AFOLU)

The data for agriculture, forestry and land-use change were obtained from Chapter 7 (Table 7.3), where potentials below a certain cost level are provided. These values were converted into cost bins in Table 12.3 by calculating the additional potential when going from one cost level to the next. The uncertainty ranges of the cost bin were scaled down proportionally from the cumulative values.

Buildings

The data for Buildings were obtained from Chapter 9. A more extended overview than in Table 12.3, with a breakdown for developing and developed countries, can be found in Tables SM9.2 and SM9.3.

Transport

For the transport sector, an assessment was made by Chapter 12, partly based on information from Chapter 10.

Data for the technical options for passenger cars were taken from ICCT[1] (2019). The authors explore the potential of rapid further fuel economy technologies (50% reduction in new passenger vehicle per kilometre CO_2 emissions in 2030 compared to 2005) and fast adoption of electric vehicles (35% of sales in 2030). This share in new vehicle sales is comparable with what is assumed in Chapter 10 (30%) and estimated in BNEF (2021). For heavy duty trucks the reduction in new per kilometre CO_2 emissions is 35% in 2035 compared to 2005, and the share of electric vehicles sales is 19% in 2030. The emission reduction in freight transport is comparable to the potential calculated in IEA (2020b). According to ICCT (2019) the fuel economy measures are cost-effective, i.e. negative costs per tonne of CO_2 avoided. For electric vehicles, it is expected that price-parity with conventional vehicles is reached in the late-2020s(BNEF, 2021), meaning that life-cycle benefits will already exceed costs prior to that date.

Data for the impact of modal shifts in passenger transport are taken from ITDP and UC Davis[2] (2015). They calculate that costs, both for the shift to public transport and the shift to cycling, are lower than for transport by passenger cars.

For aviation, limited estimates are available. Emission reduction potentials (excluding biofuels) in the range of 0.12 to 0.32 $GtCO_2$ are reported (ICAO 2019; ICCT 2020; IEA 2020), but underlying assumptions are not very well documented.

For shipping, in Chapter 10 an emission reduction potential of 39% (range 30 to 56%) compared to business-as-usual is quoted (Section 10.6.4), which translates to 0.7 $GtCO_2$, using an average business-as-usual emissions of approximately 1.8 $GtCO_2$ (Bouman et al. 2017). It is assumed that one-third of the potential is for biofuels, which are excluded here, as this is a separate category in this overview. The review study by Bouman et al. (2017) quotes earlier studies “that it is possible to improve energy efficiency and reduce emissions in a cost effective manner, either with zero costs or with net cost savings” and so it is assumed that the potential will mostly be in the below-zero cost bin.

IRENA (2016) estimates that 10% of the fuels for the transport sector can be in the form of biofuels in 2030. For the calculation of avoided CO_2 emissions, the approach in UNEP (2017) is used. Mitigation costs for transportation biofuels are uncertain. Transportation biofuels are currently mostly more expensive than regular fuels, but they could move closer to parity with regular fuels, especially if next generation biofuels are applied (Junqueira et al. 2017; IEA Bioenergy 2020). Given this uncertainty, it can be expected that costs will end up in the range of 0 to 100 USD tCO_2eq^{-1}, although the distribution over the cost bins is uncertain.

Industry

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[1] FOOTNOTE: Data were kindly provided by Zifei Yang, ICCT, Washington DC, USA.

[2] FOOTNOTE: Data were kindly provided by Taylor Reich, Institute for Transportation and Development Policy, New York, USA.

The data for industry were obtained from Chapter 11 (Sections 11.4.1, 11.4.2, Figure 11.13). The reference shows an increase in CO_2 emissions from 2017 to 2030 of 28%. For comparison, industrial final energy use increases by 24% in the Current Policies scenario of the World Energy Outlook 2019 (IEA 2019b) (no data on CO_2 emissions is available for the World Energy Outlook scenario). This suggests that the Chapter 11 reference emissions are slightly higher than in the World Energy Outlook (assuming no major fuel shifts in the Current Policies scenario).

Fluorinated gases

Data for fluorinated gas emission reductions were taken from three sources. Data from IIASA are taken directly from Purohit and Höglund-Isaksson (2017). The analysis by the United States Environmental Protection Agency is reported in US EPA (2019). Data were downloaded via the Non-CO_2 Greenhouse Gas Data Tool (US EPA 2021), which provides cumulative cost data, which were subsequently organized in cost bins. The analysis by the Netherlands Environmental Assessment Agency PBL is reported in (Harmsen et al. 2019a), Data were provided by Mr. Mathijs Harmsen in Excel format (1 Feb. 2021), see also (Harmsen et al. 2019b). Cumulative relative emission reductions were provided. The emission reduction potentials for the various gases were summed together and subsequently organised in cost bins.

The results are presented in Table SM 12.A.2. There are notable differences between the sources in mitigation potentials. There is, however, a fair agreement that most of the potential appears in the lower cost ranges. In the table, a 'best estimate' per cost bin is also presented, using an average value per cost bin. For the 'less than zero' cost bin, data from PBL were not taken into account as these potentials are already included in the baseline. The uncertainty ranges are determined by the lowest and highest value per cost bin. Cumulative uncertainty ranges are based on cumulative values and are, in relative terms, substantially smaller.

Table SM 12.A.2: Methane mit gation potentials for fluorinated gases for 2030 from three different sources. For comparison the reference emissions are also given. A 'best estimate' per source is given in italics. Sources: see text.

Data source	Cost ranges (USD tCO_2-eq^{-1})						Total emission reduction potential ($GtCO_2$-eq)
	<0	0–20	20–50	50–100	100–200	>200	
IIASA	0.50	0.90	0.10	0.00	0.00	0.00	1.50
EPA	0.01	0.55	0.01	0.07	0.05	0.00	0.70
PBL		0.58	0.42	0.20	0.05	0.00	1.25
Best estimate	*0.26*	*0.68*	*0.18*	*0.09*	*0.03*	*0.00*	*1.24*

Carbon dioxide removal options not treated previously in this Supplementary Material

The information for direct air carbon capture and storage and enhanced weathering is that reported in Section 12.3.

SM 12.A.3. Construction of Figure SPM.9 for the Summary for Policymakers

Figure SPM.9 is directly derived from Table 12.3, considering the following:

- The mid-range numbers were used. If no mid-range was provided, the average of the low and high extremes was selected.
- For the demand-side options in AFOLU the so-called feasible potential was used.
- Options for which no potential was estimated were excluded from Figure SPM.9, to avoid the impression that the potential is zero.
- For options stretching over more than one cost range, without an indication of the share of each cost range, a smooth transition between the colours was applied (this was done for the energy sector and the buildings sector, and for the option biofuels in transportation).
- For solar energy and wind energy, the notion that ‘the majority of the potential is in the negative cost bin’ is translated in the picture by putting 60% of the potential in that cost bin. The rest is evenly distributed over the other cost bins. As raised in the previous point, the transition between the cost bins was smoothed to avoid the impression of high precision over the cost bins.
- Uncertainty ranges were indicated with error bars. The error bars represent the uncertainty in the total potential per option. In most cases, the uncertainty range can be derived directly from Table 12.3. For AFOLU, the ranges presented in Table 7.3 for the options with costs less than 100 USD tCO_2-eq^{-1} were used. For the emission reduction of methane (excluding in AFOLU) and fluorinated gases the lowest and highest potential cumulative potential found for the various estimates were used as the lowest and highest bound of the error bars presented.

Supplementary Material 12.B: Feasibility assessment of DACCS, EW, ocean fertilisation and “blue carbon” as presented in Section 12.3.1.4

The following tables include the line of sight on which the feasibility assessment of the carbon dioxide removal methods (direct air carbon capture and storage (DACCS), enhanced weathering (EW), ocean fertilisation and “blue carbon”) was based, presented in Section 12.3.1.4, Figure 12.4. The identification of barriers and enablers of the deployment of these carbon dioxide methods is organised according to six dimensions of feasibility, each comprised of a number of indicators (Annex II.12): geophysical feasibility (Supplementary Material 12.B Table 1), environmental-ecological feasibility (Supplementary Material 12.B Table 2), technological feasibility (Supplementary Material 12.B Table 3), economic feasibility (Supplementary Material 12.B Table 4), socio-cultural feasibility (Supplementary Material 12.B Table 5) and institutional feasibility (Supplementary Material 12.B Table 6). The tables also provide an overview of the factors affecting the feasibility of of DACCS, EW, ocean fertilisation and “blue carbon” and how they differ across context (e.g., region), time (e.g , 2030 versus 2050), and scale (e.g., small versus large). See Section 6.4, Annex II.11 and Annex II 12 for the full methodology adopted for assessing the feasibility of mitigation response options, including the descriptions of the indicators.

Supplementary Material 12.B Table 1: Line of sight and role of context for indicators in the geophysical feasibility dimension for the assessment of DACCS, EW, ocean fertilisation and "blue carbon".

	Geophysical feasibility dimension					
	Indicator: Physical potential		**Indicator: Geophysical recourses**		**Indicator: Land use**	
	Line of sight	**Role of context**	**Line of sight**	**Role of context**	**Line of sight**	**Role of context**
DACCS	(Fuss et al. 2018; Breyer et al. 2020)	Depends on where DAC is employed; Locational flexibility of DACCS can help identify a suitable region	(Dooley 2013; Kearns et al. 2017)	Depends on where DAC is employed; Locational flexibility of DACCS can help identify a suitable region	(Socolow et al. 2011; Smith et al. 2016; Fuss et al. 2018)	
EW	(Lackner et al. 1995; Renforth 2012; Taylor et al. 2016; Kelemen et al. 2019; Renforth 2019; Beerling et al. 2020)		(Hartmann et al. 2013; Beerling et al. 2018; Strefler et al. 2018; Renforth 2019; Amann et al. 2020; Beerling et al. 2020)	Silicate rock formations, silicate rock dust stockpiles, C&D waste	(Beerling et al 2020), LE	Existing croplands, co-deployable with afforestation/reforestation/BECCS/biochar
Ocean Fertilisation	(Bopp et al. 2013; Siegel et al. 2014; Trull et al. 2015; Boyd et al. 2019; GESAMP 2019)	Potential is high but 90% of removed carbon is released back into the atmosphere within a year	(Bopp et al. 2013; Siegel et al. 2014; Trull et al. 2015; Boyd et al. 2019; GESAMP 2019)		NA	
Blue carbon	(Sondak et al. 2017; Wilcox et al. 2017; NASEM 2019; Gattuso et al. 2021)	Depends on ecosystem's type and areas covered	NA		(Gattuso et al. 2021)	(-) Coastal area is used, could be applicable for other purposes; (+) could be alternative for land-based CDR

Supplementary Material 12.B Table 2: Line of sight and role of context for indicators in the environmental-ecological feasibility dimension for the assessment of DACCS, EW, ocean fertilisation and "blue carbon".

	Environmental-ecological feasibility dimension							
	Indicator: Air pollution		**Indicator: Toxic waste, ecotoxicity and eutrophication**		**Indicator: Water quantity and quality**		**Indicator: Biodiversity**	
	Line of sight	**Role of context**	**Line of sight**	**Role of context**	**Line of sight**	**Role of context**	**Line of sight**	**Role of context**
DACCS	(Jacobson 2019; Deutz and Bardow 2021; Terlouw et al. 2021)		(Deutz and Bardow 2021; Terlouw et al. 2021)		(Fasihi et al. 2019; Fuhrman et al. 2020; Smith et al. 2016)	Depends on the technology; some technologies consume water while others generate it	NE	
EW	LE	Air-blown rock dust, reduction in NOx emissions	NE		NE		NE	
Ocean Fertilisation	NA		(Fuhrman and Capone 1991; DFO 2010; Oschlies et al. 2010; Silver et al. 2010; Trick et al. 2010; Williamson et al. 2012)		(Fuhrman and Capone 1991; DFO 2010; Oschlies et al. 2010; Williamson et al. 2012; Minx et al. 2018)		(Fuhrman and Capone 1991; DFO 2010; Oschlies et al. 2010; Williamson et al. 2012; Minx et al. 2018)	
Blue carbon	(Howard et al. 2017; Hamilton and Friess 2018)		(N'Yeurt et al. 2012; Howard et al. 2017; Hamilton and Friess 2018)		NE		(Sondak et al. 2017; NASEM 2019; Gattuso et al. 2021)	

Supplementary Material 12.B Table 3: Line of sight and role of context for indicators in the technological feasibility dimension for the assessment of DACCS, EW, ocean fertilisation and "blue carbon".

	Technological feasibility dimension					
	Indicator: Simplicity		**Indicator: Technological scalability**		**Indicator: Maturity and technology readiness**	
	Line of sight	**Role of context**	**Line of sight**	**Role of context**	**Line of sight**	**Role of context**
DACCS	(Nemet 2019)		(Nemet 2019; Realmonte et al. 2019; Fasihi et al. 2019)		(Royal Society and Royal Academy of Engineering 2018; NASEM 2019; Larsen et al. 2019; IEA 2020)	
EW	(Renforth 2012; Strefler et al. 2018)	Straight forward, utilises existing technology	(Beerling et al. 2020)	Upscaling is potentially straight forward, infrastructure (e.g. road rail) already in place for handling harvests of equivalent mass	(Royal Society and Royal Academy of Engineering 2018)	Components of technology are mature, including the application of minerals to land, however commercially operating supply chains for CO_2 removal are immature, longitudinal field scale demonstrations are required
Ocean Fertilisation	(Blain et al. 2008; Williamson et al. 2012; Trull et al. 2015; GESAMP 2019)		(Blain et al. 2008; Williamson et al. 2012; Trull et al. 2015; GESAMP 2019)		(Williamson and Bodle 2016; GESAMP 2019)	
Blue carbon	(Sondak et al. 2017; NASEM 2019; Gattuso et al. 2021)	Depends on ecosystem's type and areas covered	(Sondak et al. 2017; NASEM 2019; Gattuso et al. 2021)	Depends on ecosystem's type and areas covered	(Sondak et al. 2017; NASEM 2019; Gattuso et al. 2021)	Depends on ecosystem's type and areas covered

Supplementary Material 12.B Table 4: Line of sight and role of context for indicators in the economic feasibility dimension for the assessment of DACCS, EW, ocean fertilisation and "blue carbon".

	Economic feasibility dimension			
	Indicator: Costs in 2030 and long term		**Indicator: Employment effects and economic growth**	
	Line of sight	**Role of context**	**Line of sight**	**Role of context**
DACCS	(Sinha et al. 2017; Fuss et al. 2018; Keith et al. 2018; NASEM 2019; McQueen et al. 2021; Shayegh et al. 2021)	Learning could bring down the costs substantially, which depends on the deployment scenario	(Larsen et al. 2019)	
EW	Most accurate costs so far from (Beerling et al. 2020).	Developed countries: 160-190 USD tCO_2^{-1} removed; developing countries cheaper: 55-120 USD tCO_2^{-1}	NE	Potential to increase employment in mining, transport sectors
Ocean Fertilisation	(Boyd 2008; Denman 2008; Harrison 2013; Jones 2014; Minx et al. 2018; Gattuso et al. 2021)	Depends on nutrient production and its delivery to the application area, but currently OF cost is very uncertain and could be expensive	NE	
Blue carbon	(Siikamäki et al. 2012; Nelson 2013; Bayraktarov et al. 2016; Narayan et al 2016; Gattuso et al. 2021)	Climate mitigation cost is very high, but cost effectiveness considering other ecosystem services could be very high	LE	Potential to increase employment

Supplementary Material 12.B Table 5: Line of sight and role of context for indicators in the socio-cultural feasibility dimension for the assessment of DACCS, EW, ocean fertilisation and "blue carbon".

	Socio-cultural feasibility dimension					
	Indicator: Public acceptance		**Indicator: Effects on health & wellbeing**		**Indicator: Distributional effects**	
	Line of sight	**Role of context**	**Line of sight**	**Role of context**	**Line of sight**	**Role of context**
DACCS	(Bellamy et al. 2013; Cox et al. 2020)	Very few countries examined	NE		NE	
EW	(Pidgeon and Spence 2017; Cox et al. 2020)	US and UK Public support for limited trials with careful monitoring, public concern if it involved opening new mines	NE	Respirable dust means caution required during application, not a barrier to implementation	(Beerling et al 2018)	
Ocean Fertilisation	(Minx et al. 2018; GESAMP 2019)		NA		(Blain et al. 2008; Williamson et al. 2012; Trull et al. 2015; GESAMP 2019)	
Blue carbon	(Howard et al 2017; Hamilton and Friess 2018)		(Howard et al. 2017; Hamilton and Friess 2018)		(Sondak et al. 2017; Bindoff et al. 2019)	Depends on available areas and suitable ecosystems

Supplementary Material 12.B Table 6: Line of sight and role of context for indicators in the institutional feasibility dimension for the assessment of DACCS, EW, ocean fertilisation and "blue carbon".

	Institutional feasibility dimension					
	Indicator: Political acceptance		**Indicator: Institutional capacity & governance, cross-sectoral coordination**		**Indicator: Legal and administrative feasibility**	
	Line of sight	**Role of context**	**Line of sight**	**Role of context**	**Line of sight**	**Role of context**
DACCS	(Meckling and Biber 2021)		NE		NE	
EW	(Cox and Edwards 2019)	But on-climate co-benefits may be valuable in terms of the policy 'demand pull' for CDR	LE		NA - All components of the supply chain are already practiced commercially	May not be limiting for natural silicate rock given existing protocols for fertiliser, potentially limiting for alkaline wastes/by-products
Ocean Fertilisation	(Minx et al. 2018; GESAMP 2019)		(Minx et al 2018; GESAMP 2019)		(Minx et al. 2018; GESAMP 2019)	
Blue carbon	(Kuwae and Hori 2019)		(Nelson 2013; Kuwae and Hori 2019)		(Nelson 2013; Kuwae and Hori 2019)	

Supplementary Material 12.C: The link between co-benefits and adverse side effects of mitigation actions and the SDGs

The following tables (SM 12.C Table 1 and SM 12.C Table 2) present examples of the information used in the construction of SM 12.C Table 1provides examples of mitigation actions that fall into the groups of actions shown SM 12.C Table 2 in the different sectors. Note that the mapping is intended to be illustrative and is not intended to be exhaustive.

SM 12.C Table 1 Examples of mitigation actions in the different sectors

Types of mitigation actions	Examples of sector application
A. Energy efficiency	**Energy:** Reducing the auxiliary load of fossil and renewable power stations **Transport:** Advances in vehicle technologies to make them more fuel efficient such as vehicle light weighting, accessory load management, powertrain systems optimisations, and aerodynamics (Kammen and Sunter 2016) **Industry:** Efficient motors and pumps, increased heat integration. **Buildings:** Thermal insulation and efficient HVAC systems (Cao et al. 2016; Kammen and Sunter 2016) **Urban systems:** (Amado et al. 2016) **AFOLU:** Increased efficiency in pumping
B. Fuel changes	**Transport:** Shift from liquid fossil fuels to biofuels, synthetic fuels produced from renewables and CO_2 recycling **Industry:** Shift to natural gas and bioenergy as sources of energy in industrial processes (Åhman et al. 2017)
C. Planning	**Transport:** Improved public transport systems **Urban systems:** Including GHG considerations in decisions surrounding urban development intensity (Wang et al. 2015)
D. AFOLU actions	**AFOLU:** Wetland restoration, biochar and BECCCS (Smith et al. 2019)
E. Renewable energy	**Energy:** Shift from fossil fuels to the various renewable alternatives such as wind, solar, geothermal, wave and bioenergy options **Transport:** Electric vehicles, biofuels in land and aviation transport (Mathiesen et al. 2015) **Industry:** Use of bioenergy and other renewable sources for heating and cooling (Fais et al. 2016), producing hydrocarbons in processes based on renewable electricity (e.g. methane from power-to-gas conversion)(Åhman et al. 2017). **Buildings:** Distributed/embedded renewable energy technologies coupled with smart grids (Cao et al. 2016) **Urban systems:** Urban solar thermal energy, for space and domestic water heating (Kammen and Sunter 2016) **AFOLU:** Solar PV for pumping, solar energy in greenhouses (Hassanien et al. 2016)
F. Feedstock change	**Industry:** Replacing fossil feedstock with biomass in the petrochemicals industry (Åhman et al. 2017)

G. Process change	**Industry:** Producing virgin steel without process-related emissions through the introduction of new concepts such as process-integrated CCS and electrification (electrowinning) or bio- methane/hydrogen direct reduction (DRI) (Åhman et al. 2017).

SM 12.C Table 2 Examples of co-benefits and adverse side effects, linked to different mitigation actions. The letters A-G link to the groups of mitigation actions shown in Table SM 12C Table 1.

Types of Co-benefits	**Examples**	**Examples of adverse side effects**
I. Climate resilience	Improved insulation to reduce building energy demand also provides resilience to increasing temperatures (A) Integrated planning of urban systems and infrastructure to mitigate emissions can incorporate climate resilience (C) Afforestation and reforestation in the AFOLU sector can help biodiversity, reduce erosion and increase land productivity, thereby increasing climate resilience (D) Distributed renewable energy infrastructure is less vulnerable to climate impacts than large centralised infrastructure (E)	
II. Energy security	Energy efficiency results in a lower primary energy demand to achieve the same productive energy and hence increases energy security (A). Renewable energy reduces requirements for fossil inputs which may be in finite supply, imported, and/or vulnerable to policy legislation and penalties on fossil fuels. This can contribute to greater energy security for a country or region (B).	
III. Investment, growth	More efficient energy use, switching to more efficient and locally sourced fuels and renewable energy options can be linked to greater resource efficiency and lower productive energy costs, and thus can have positive economic growth outcomes (A, B, E).	Depending on the application, switching to alternative fuels, alternative feedstocks and new processes may require significant technology development, high capital inputs and be more expensive, resulting in negative impacts on investment and growth (B, F, G).
IV. Employment	Job opportunities can be created in energy efficiency, AFOLU and renewable energy actions (A, D, E)	Job losses can be experienced during the transition to increased efficiency, alternative fuels and processing routes (A, B, D, E, G). The growing literature on “just transitions” describes this concern in the energy sector. Reducing deforestation could lead to reduced employment opportunities to those dependent on firewood for sale (D)

V. Biodiversity, ecosystem services, soil	Many alternative fuels, various actions in the AFOLU sector and renewable energy options require lower inputs of primary resources and thus have a lower impact on biodiversity, ecosystem services and soil (B, D, E)	
VI. Water pollution	Alternative fuels, feedstocks and processes, actions in the AFOLU sector and renewable energy options may require lower water inputs and give rise to lower pollutant loads than the options they are replacing (B, E, D, F, G)	Although alternative feedstocks and processes may be less GHG intensive than current options, some could have potential for negative water pollution impacts (F, G).
VII. Air pollution	Alternative fuels, feedstocks and processes, and renewable energy options may give rise to lower air pollutant loads than the options they are replacing, which are often based on fossil fuels (B, E, F, G)	Although alternative feedstocks and processes may be less GHG intensive than current options, there is potential for greater local air pollutant impacts. An example here is diesel vehicles which have lower GHGs but higher local air pollutants than petroleum ones (F, G)
VIII. Energy access	Energy efficiency, alternative fuels and renewable options can provide affordable and reliable energy supply to areas that are both currently served and unserved with electricity and other energy carriers (ABE) Sustainable harvesting of forestry resources can contribute to energy access in communities reliant on these sources for supply (E).	Reducing deforestation could lead to reduced energy access for those dependent on collecting firewood from forests for use (D)
IX. Poverty alleviation	Energy efficient technologies can contribute to lower costs of energy, thereby increasing access and reducing poverty (A) Afforestation can provide increased access to firewood and protection of diversity which can lead to positive economic outcomes (D) (Smith et al. 2019). Renewable energy can help increased energy access which can contribute to poverty alleviation through access to lighting, pumping for agriculture etc (E)	Reducing deforestation could lead to reduced incomes and increased hardship for those dependent on firewood for use and sale (D)
X. Food & water security	Climate mitigation interventions in the AFOLU sector can help increase land productivity, reduce erosion, and protect biodiversity, which can all contribute to enhanced food and water security (D) (Smith et al. 2019) Renewable energy technologies typically require lower water inputs than fossil fuel options, thereby increasing water	

	availability for other uses and hence increasing water security (E).	
XI. Health	Energy efficiency, alternative fuels and renewable energies can result in lower indoor and outdoor air pollution impacts, thereby contributing to positive health outcomes (A, B, E). Agriculture mitigation options can include lower pesticide and fertiliser application rates, thereby reducing negative impacts on health of surrounding communities (D)	
XII. Noise, congestion etc	Alternative fuel vehicles and integrated urban planning approaches can help reduce noise and congestion (B, C).	
XIII. Political stability, democracy	Integrated planning approaches which include climate mitigation considerations can support political stability and democracy in decision making (C)	

Sources include: (Buonocore et al. 2016; Ürge-Vorsatz et al 2014; Kerr et al. 2017 Karlsson et al. 2020; Cohen et al. 2019; Forouli et al. 2019; Van de Ven et al. 2019; Åhman et al. 2017; Smith et al. 2019)

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