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Working Group III – Mitigation of Climate Change

Annex III:

Technology-specific cost and performance parameters

Chapter:	A.III	
Title:	Annex III – Technology-specific cost and performance parameters	
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Annex III. Technology-specific cost and performance parameters

Contents

III.1 Introduction

Annex III contains data on technologies and practices that have been collected to produce a summary assessment of the potentials and costs of selected mitigation options in various sectors as displayed in figure 7.7, table 8.3, figures 10.7, 10.8, 10.9, 10.10, 10.19, 10.21, figure 11.16 as well as in corresponding figures in the Technical Summary.

The nature and quantity of mitigation options as well as data availability and quality of the available data vary significantly across sectors. Even for largely similar mitigation options, a large variety of context-specific metrics is used to express their cost and potentials that involve conversions of input data into particular output formats. For the purpose of the AR5, a limited but still diverse set of sector-specific metrics is used to strike a balance between harmonization of approaches across sectors and adequate consideration of the complexities involved.

Mitigation potentials are approached via product-specific or service-specific emission intensities, i.e. emissions per unit of useful outputs, which are as diverse as electricity, steel and cattle meat. Mitigation potentials on a product/service level can be understood as the potential reduction in specific emissions that can result from actions such as switching to production processes that cause lower emissions for otherwise comparable products[1] and reducing production/consumption of emission-intensive products.

Mitigation costs are approached via different levelized cost metrics, which share a common methodological basis but need to be interpreted in very different ways. A detailed introduction to the metrics used can be found in the Metrics and Methodology Annex (Section A.II.3.1). All of these cost metrics are derived under specific conditions that vary in practice and, hence, need to be set by assumption. These assumptions are not always clear from the literature, where such metrics are presented. Hence, comparison of the same metric taken from different studies is not always possible. For this reasons, in the AR5 these metrics are generally re-calculated under specified conditions, e.g. with respect to weighted average cost of capital, based on underlying input parameters that are less sensitive to assumptions. Sensitivities to assumptions made in the AR5 are made explicit. In several cases, however, the availability of data on the parameters needed to re-calculate the relevant cost metric is very limited. In such cases, expert judgment was used to assess information on costs taken directly from the literature.

More detail on sector-specific metrics, the respective input data and assumptions used as well as the conversions required is presented in the sector-specific sections below.

References for data, justifications for assumptions and additional context is provided in footnotes to the data tables. Footnotes are inserted at the most general level possible, i.e. footnotes are inserted at table headings where they apply to the majority of data, at column/row headings where they apply to the majority of data in the respective column/row and at individual cells where they apply only to data points or ranges given in individual cells. Cells of input data are light blue, cells of output data resulting from data conversions shown in figures and tables mentioned above are coloured in green, cells showing intermediate outputs are coloured light red.

[1] Note that comparability of products is not always given even for seemingly similar ones. For instance, in the case of electricity the timing of production is crucial for the value of the product and reduces the insights that can be derived from simple comparisons of the metrics used here.

III.2 Energy Supply

III.2.1 Approach

The emission intensity of electricity production (measured in kg CO_2eq/MWh) can be used as a measure to compare the specific GHG emissions of suggested emission mitigation options and those of conventional power supply technologies. With respect to costs, the levelized cost of energy (LCOE, measured in USD_{2010}/MWh) serves the same purpose.[2]

The calculation of LCOE of a technology requires data on all cash flows that occur during its lifetime (cf. formula in M&M Annex) as well as on the amount of energy that is provided by the respective technology. Cash flows are usually reported in some aggregate form based on widely deployed monetary accounting principles combining cash flows into different categories of expenditures and revenues that occur at varying points during the lifetime of the investment.

The applied method presents LCOE that include all relevant costs associated with the construction and operation of the investigated power plant in line with the approach in IEA (2010). Taxes and subsidies are excluded, and it is assumed that grids are available to transport the electricity. Additional costs associated with the integration of variable sources are neglected as well (see Section 7.8.2 for an assessment of these costs).

The input data used to calculate LCOE are summarized in table 1 below. The conversion of input data into LCOE requires the steps outlined in the following:

Levelised cost (LCOE) in USD_{2010}/MWh_e

$$LCOE = \frac{\alpha \cdot I + OM + F}{E} \qquad \text{(Eq. 1)}$$

$$\alpha = \frac{r}{1-(1+r)^{-L_T}} \qquad \text{(Eq. 2)}$$

$$I = \frac{C}{L_B} \cdot \sum_{t=1}^{L_B} (1+i)^t \cdot \left(1+\frac{d}{(1+r)^{L_T}}\right) \qquad \text{(Eq. 3)}$$

$$OM = FOM + (VOM - REV + d_\upsilon) \cdot E \qquad \text{(Eq. 4)}$$

$$E = P \cdot FLH \qquad \text{(Eq. 5)}$$

$$F = FC \cdot \frac{E}{\eta} \qquad \text{(Eq. 6)}$$

Where:

- LCOE is the levelized cost of electricity.
- *α* is the capital recovery Factor (CRF).
- *r* is the weighted average cost of capital (WACC - taken as either 5% or 10%).
- *I* is the investment costs, including finance cost for construction at interest *i.*

[2] The merits and shortcomings of this method are discussed in detail in the Methodical Annex of the AR5 (Annex II).

- *C* is the capital costs, excluding finance cost for construction ('overnight cost').
  In order to calculate the cost for construction, the overnight costs are equally distributed over the construction period.
- *d* represent the decommissioning cost. Depending on the data in the literature, this is incorporated as an extra capital cost at the end of the project duration which is discounted to t=0 (using a decommissioning factor *d*, as in (3)), or as a corresponding variable cost (d_v in (4)). d = 0.15 for nuclear energy, and zero for all other technologies (given the low impact on LCOE).
- *OM* are the net annual operation and maintenance costs; summarizing fixed OM (FOM), variable OM (VOM), and variable by-product revenues (REV). As a default and if not stated explicitly otherwise, carbon costs (e.g. due to carbon taxes or emission trading schemes) are not taken into account in calculating the LCOE values.
- *E* is the energy (electricity) produced annually, which is calculated by multiplying the capacity (P) with the number of (equivalent) full load hours (FLH).
- *F* are the annual fuel costs,
  - FC are the fuel costs per unit of energy input, and
  - η is the conversion efficiency (in lower heating value – LHV).
- *i* is the interest rate over the construction loan (taken as 5%).
- L_T is the project duration (in operation), as defined in IEA (2010).
- L_B is the construction period.

Emission Intensities:

For data, see table 2 below. For methodological issues and literature sources, see Annex II, Section A.II.10.

III.2.2 Data

Table 1. Cost and performance parameters of selected electricity supply technologies[i, ii]

Options	*C*	L_B	*FOM*	*VOM*	*REV*	*F*
	Overnight capital expenditure (excl. construction interest) (USD_{2010}/kW)	Construction time (yr)	Fixed annual O&M cost (USD_{2010}/kW)[iii]	Variable O&M cost (USD_{2010}/MWh)[iii]	Variable by-product revenue (USD_{2010}/MWh)	Average fuel price of fuel j (USD_{2010}/GJ)
	Min / Median / Max	Avg	Min / Median / Max	Min / Median / Max	Min / Median / Max	Min / Max
Currently Commercially Available Technologies						
Coal – PC[iv]	380 / 2200 / 3900	5	0 / 23 / 75	0 / 3.4 / 9.0		2.9 / 5.3
Gas - Combined Cycle[v]	550 / 1100 / 2100	4	0 / 7 / 39	0 / 3.2 / 4.9		3.8 / 14
Biomass – CHP[vi]	2000 / 5600 / 11000	4.5	0 / 101 / 400	0 / 0 / 56	4 / 26 / 93[vii]	3.3 / 9.3
Biomass - cofiring[vi,viii]	350 / 900 / 1800	1	13 / 20 / 20	0 / 0 / 2		3.3 / 9.3
Biomass - dedicated[vi]	1900 / 3600 / 6500	4.5	42 / 99 / 500	0 / 3.8 / 34		3.3 / 9.3
Geothermal[ix, x]	1000 / 5000 / 10000	3	0 / 0 / 150	0 / 11 / 31		
Hydropower[xi, xii]	500 / 1900 / 8500	5	5 / 35 / 250	0 / 0 / 15		
Nuclear[xiii, xiv]	1600 / 4300 / 6400	9	0 / 0 / 110	1.7 / 13 / 30		0.74 / 0.87
Concentrated Solar Power[xv, xvi]	3700 / 5100 / 11000	2	0 / 50 / 66	0 / 0 / 35		
Solar PV - rooftop[xvii, xviii]	2200 / 4400 / 5300	0	17 / 37 / 44	0 / 0 / 0		
Solar PV - utility[xvii, xviii]	1700 / 3200 / 4300	0	12 / 20 / 30	0 / 0 / 0		
Wind onshore[xix, xx]	1200 / 2100 / 3700	1.5	0 / 0 / 60	0 / 14 / 26		
Wind offshore[xix, xxi]	2900 / 4400 / 6500	3.5	0 / 40 / 130	0 / 16 / 63		
Pre-commercial Technologies						
CCS - Coal - Oxyfuel[xxii]	2800 / 4000 / 5600	5	0 / 58 / 140	9.1 / 10 / 12[xxiii]		2.9 / 5.3
CCS - Coal - PC[xxii]	1700 / 3300 / 6600	5	0 / 45 / 290	11 / 15 / 28[xxiii]		2.9 / 5.3
CCS - Coal - IGCC,[xxii]	1700 / 3700 / 6600	5	0 / 23 / 110	12 / 13 / 23[xxiii]		2.9 / 5.3
CCS - Gas - Combined Cycle[xxii]	1100 / 2000 / 3800	4	5 / 13 / 73	4.8 / 8.3 / 15[xxiii]		3.8 / 14
Ocean[xxiv, xxv]	2900 / 5400 / 12000	2	0 / 78 / 360	0 / 0.16 / 20		

Table 1 (continued). Cost and performance parameters of selected electricity supply technologies[i, ii]

Options	*η*	*FLH*	*LT*		*LCOE*			
	Plant efficiency for fuel j (%)	Capacity utilization /FLH (hr)	Plant lifetime (yr)	Decommissioning cost[xxvi]	Levelized cost of electricity[i] (USD_{2010}/MWh) 10% WACC, high FLH, 0 $USD_{2010}/tCO_{2,\ direct}$	5% WACC, high FLH, 0 $USD_{2010}/tCO_{2,\ direct}$	10% WACC, low FLH, 0 $USD_{2010}/tCO_{2,\ direct}$	10% WACC, high FLH, 100 $USD_{2010}/tCO_{2,\ direct}$
	Min / Median / Max	Min / Max	Avg		Min / Median / Max	Min / Median / Max	Min / Median / Max	Min / Median / Max
Currently Commercially Available Technologies								
Coal – PC[iv]	33 / 39 / 48	3700 / 7400	40	See endnote xxvi	30 / 78 / 120	27 / 61 / 95	36 / 120 / 190	97 / 150 / 210
Gas - Combined Cycle[v]	41 / 55 / 60	3700 / 7400	30		34 / 79 / 150	31 / 71 / 140	43 / 100 / 170	69 / 120 / 200
Biomass – CHP[vi]	14 / 29 / 36	3500 / 7000	30		85 / 180 / 400	71 / 150 / 330	130 / 310 / 610	-[xxvii]
Biomass – cofiring[vi]	38 / 41 / 48	3700 / 7400	40		65 / 89 / 110	49 / 67 / 88	100 / 140 / 170	160 / 200 / 260[xxviii]
Biomass – dedicated[vi]	20 / 31 / 48	3500 / 7000	40		77 / 150 / 320	63 / 130 / 270	120 / 230 / 440	-[xxvii]
Geothermal[ix, x]		5300 / 7900	30		18 / 89 / 190	12 / 60 / 130	25 / 130 / 260	18 / 89 / 190
Hydropower[xi, xii]		1800 / 7900	50		9 / 35 / 150	6 / 22 / 95	40 / 160 / 630	9 / 35 / 150
Nuclear[xiii, xiv]	33 / 33 / 34	3700 / 7400	60		45 / 99 / 150	32 / 65 / 94	72 / 180 / 260	45 / 99 / 150
Concentrated Solar Power[xv, xvi]		2200 / 3500	20		150 / 200 / 310	110 / 150 / 220	220 / 320 / 480	150 / 200 / 310
Solar PV – rooftop[xvii, xviii]		1100 / 2400	25		110 / 220 / 270	74 / 150 / 180	250 / 490 / 600	110 / 220 / 270
Solar PV – utility[xvii, xviii]		1200 / 2400	25		84 / 160 / 210	56 / 110 / 130	170 / 310 / 400	84 / 160 / 210
Wind onshore[xx, xx]		1800 / 3500	25		51 / 84 / 160	35 / 59 / 120	92 / 160 / 300	51 / 84 / 160
Wind offshore[xxi, xx]		2600 / 3900	25		110 / 170 / 250	80 / 120 / 180	160 / 240 / 350	110 / 170 / 250
Pre-commercial Technologies								
CCS - Coal – Oxyfuel[xxii]	32 / 35 / 41	3700 / 7400	40		90 / 120 / 170	71 / 100 / 130	140 / 180 / 270	92 / 130 / 180
CCS - Coal – PC[xxii]	28 / 30 / 43	3700 / 7400	40		69 / 130 / 200	57 / 110 / 150	97 / 210 / 310	78 / 150 / 210
CCS - Coal – IGCC[xxii]	30 / 32 / 35	3700 / 7400	40		75 / 120 / 200	63 / 100 / 150	100 / 180 / 310	85 / 140 / 210
CCS - Gas - Combined Cycle[xxii]	37 / 47 / 54	3700 / 7400	30		52 / 100 / 210	45 / 86 / 190	70 / 140 / 270	55 / 110 / 220
Ocean[xxiv, xxv]		2000 / 5300	20		82 / 150 / 300	60 / 110 / 210	200 / 390 / 780	82 / 150 / 300

[i] General: Note that many input parameters (C, FOM, VOM, and η) are not independent from each other; they come in parameter sets. Parameters that are systematically varied to obtain output values include fuel prices, WACC, and full load hours (FLH). Lifetimes and construction times are set to standard values. The range in levelized cost of electricity (LCOE) results from calculating two LCOE values per individual parameter set, one at a low and one at a high fuel price, for the number of individual parameter sets available per technology. Variation with WACC and with FLHs is shown in separate output columns. This approach is different from the SRREN (IPCC, 2011), where input parameters were considered as independent from each other and the lowest (highest) LCOE value resulted from taking all best-case (worst-case) parameter values,

[ii] General: Comparison of data on capital expenditures with values presented in SRREN (IPCC, 2011) are only possible to limited degrees, since the datasets used in the AR5 reflect a larger sample of projects (including those with more extreme costs) than in the SRREN.

[iii] General: Some literature references only report on fixed OM costs (FOM), some only on variable OM costs (VOM), some on both, and some none. The data in the FOM and VOM columns show the range found in literature. Hence note that these FOM and VOM values cannot be combined to derive total OM costs. The range of levelized costs of electricity shown in the table is the result of calculations for the individual combinations of parameters found in the literature.

[iv] Coal PC (Pulverized Coal): Black and Veatch (2012), DEA (2012), IEA/NEA (2010), IEA (2013a), IEA-RETD (2013), Schmidt et al. (2012), US EIA (2013).

[v] Gas Combined Cycle: Black and Veatch (2012), DEA (2012), IEA/NEA (2010), IEA (2011),IEA (2013a), IEA-RETD (2013), Schmidt et al. (2012), US EIA (2013).

[vi] Biomass: Black and Veatch (2012), DEA (2012), IPCC-SRREN (2011), IRENA (2012), NREL (2012), US EIA (2013).

[vii] Biomass CHP (Combined Heat and Power): Revenues from heat from CHP are assumed to be the natural gas price divided by 90% (this is the assumed reference boiler efficiency). It is assumed that 1/3 of the heat production is marketable, caused by losses and seasonal demand changes. This income is subtracted from the variable O&M costs (proportional to the amount of heat produced per unit of power), where applicable. Only heat production from biomass-CHP is treated in this manner.

[viii] Biomass Co-firing: Capital costs for co-firing as reported in literature (and the summary table) represent an investment to upgrade a dedicated coal power plant to a co-firing installation. The LCOEs shown in the summary table are those of the total upgraded plant. For the calculation of the LCOEs the capital costs of the co-firing upgrade are added to the median coal PC capital costs. Fuel costs are obtained by weighting coal and biomass costs with their share in the fuel mix (with biomass shares ranging between 5% and 20%). To calculate specific emissions, the dedicated biomass emissions and (pulverized) coal emissions were added, taking into account biomass shares ranging between 5% and 20%. In the direct emissions coal-related emissions are shown, while the biomass related emissions are shown in column n (Biogenic, geogenic CO2 and albedo), indicating indirect emissions. We applied an efficiency of 35% to the coal part of the combustion.

[ix] Geothermal: This category includes both flash steam and binary cycle power plants. Data on costs show wide ranges, depending on specific conditions. Geothermal (binary plant) LCOE averages have increased by 39% since the SRREN (BNEF, and Frankfurt and School-UNEP Centre, 2013). Low-end estimate is from NREL (2012) for a flash plant at higher temperatures; the high-end estimate is from Black and Veatch and based on enhanced geothermal systems, which are not fully commercialised. IRENA (2013) reports values down to 1400 USD_{2011}/kW.

[x] Geothermal: Black and Veatch (2012), IEA (2013a), NREL (2012), Schmidt et al. (2012), UK CCC (2011), US EIA (2013).

[xi] Hydropower: This includes both run-of-the-river and reservoir hydropower, over a wide range of capacities. Project data from recent IRENA inventories are incorporated, showing a wider range than reported in IPCC SRREN. High-end of capital expenditures refers to Japan, but other sources also report these higher values.

[xii] Hydropower: Black and Veatch (2012), IEA (2013a), IEA-RETD (2013), IRENA (2012), Schmidt et al. (2012), UK CCC (2011), US EIA (2013).

[xiii] Nuclear: Limited recent data and/or original data are available in the published literature. More recent, (grey literature) sources provide investment cost and LCOE estimates that are considerably higher than the ones shown here (Brandão et al., 2012). Nuclear fuel prices (per GJ input) are based on fuel cycle costs (usually expressed per MWh generated), assuming a conversion efficiency of 33%. They include the front-end (Uranium mining and milling, conversion, enrichment and fuel fabrication) and back-end (spent fuel transport, storage, reprocessing and disposal) costs of the nuclear fuel cycle (see IEA and NEA, 2010).

[xiv] Nuclear: IAEA (2012), EPRI (2011), IEA/NEA (2010), Rangel and Lévêque (2012), UK CCC (2011), US EIA (2013).

[xv] Concentrated Solar Power: This includes both CSP with storage as well as CSP without storage. To prevent an overestimation of the LCOE for CSP with storage, full load hours were used that are directly linked to the design of the system (in- or excluding storage). Project data from recent IRENA inventories are incorporated, showing a wider range than reported in IPCC SRREN. High-end value comes from IRENA (solar tower, 6-15 hours of storage). Low-end comes from IEA and is supported by IRENA data.

[xvi] Concentrated Solar Power: Black and Veatch (2012), IEA (2013a), IRENA (2012), US EIA (2013).

[xvii] Solar Photovoltaic: IEA (2013a), IRENA (2013), JRC (2012), LBNL (2013), UK CCC (2011), US EIA (2013).

[xviii] Solar Photovoltaic: Solar PV module prices have declined substantially since the SRREN (IPCC, 2011), accounting for much of the decline in capital costs shown here relative to those used in SRREN. The LCOE of (crystalline silicon) photovoltaic systems fell by 57% since 2009 (BNEF, and Frankfurt and School-UNEP Centre, 2013).

[xix] Wind: Black and Veatch (2012), DEA (2012), IEA (2013a), IEA-RETD (2013), IRENA (2012), JRC (2012), UK CCC (2011), US DoE (2013), US EIA (2013).

[xx] Wind onshore: High-end of capital expenditures is taken from IEA-RETD study (Mostajo Veiga et al., 2013) for Japan. The capital costs presented here show a higher upper end than in the SRREN, and reflect generally smaller wind projects or projects located in remote or otherwise-costly locations. Data from IRENA for Other Asia and Latin America show cost ranges well beyond SRREN. In some regions of the world, wind projects have been increasingly located in lower-quality wind resource sites since the publication of the SRREN (due in part to scarcity of developable higher-quality sites). The FLHs on wind projects, however, have not necessarily decreased -- and in many cases have increased -- due to a simultaneous trend towards longer rotors and higher hub heights. Wind onshore average LCOE have decreased by 15% (BNEF, and Frankfurt and School-UNEP Centre, 2013).

[xxi] Wind offshore: Offshore wind costs have generally increased since the SRREN, partially explaining the higher upper-end of the cost range shown here. Average LCOE of offshore wind have increased by 44% (BNEF, and Frankfurt and School-UNEP Centre, 2013). Higher capital expenditures reported here are in line with market experiences, i.e. a tendency to more remote areas, deeper seas, higher construction costs and higher steel prices.

[xxii] Carbon Capture and Storage (CCS): Black and Veatch (2012), DEA (2012), Herzog (2011), IPCC-SRCCS (2005), Klara and Plunkett (2010), US EIA (2013), Versteeg and Rubin (2011), IEA (2011).

[xxiii] Carbon Capture and Storage: Includes transport and storage costs of \$10/tCO_2.

[xxiv] Ocean: Ocean includes both tidal and wave energy conversion technologies. The high-end of capital expenditures is for wave energy DEA (2012). Since the SRREN, marine wave and tidal average LCOE have increased by 36 and 49% respectively (BNEF, and Frankfurt and School-UNEP Centre, 2013).

[xxv] Ocean: Black and Veatch (2012), DEA (2012), UK CCC (2011).

[xxvi] General: Some literature references report decommissioning costs under VOM. If decommissioning costs are not given, default assumptions are made (see 'Definition of additional parameters').

[xxvii] Biomass: Due to the complexities involved in estimating GHG emissions from biomass, no estimates for LCOE at a positive carbon price are given here.

[xxviii] Biomass co-firing: Only direct emissions of coal share in fuel consumption is considered to calculate LCOE at a carbon price of 100 USD_{2010}/tCO_2.

1 **Table 2.** Emissions of selected electricity supply technologies (gCO_2eq/kWh)[i]

Options	Direct emissions	Infrastructure & supply chain emissions	Biogenic CO_2 emissions and albedo effect	Methane emissions	Lifecycle emissions (incl. albedo effect)
	Min / Median / Max	Typical values			Min / Median / Max
Currently Commercially Available Technologies					
Coal – PC	670 / 760 / 870	9.6	0	47	740 / 820 / 910
Gas - Combined Cycle	350 / 370 / 490	1.6	0	91	410 / 490 / 650
Biomass – CHP	n.a. [ii]	210	27	0	130 / 230 / 420[iii]
Biomass - cofiring	n.a.[ii]	-	-	-	620 / 740 / 890[iv]
Biomass - dedicated	n.a. [ii]	210	27	0	130 / 230 / 420[iii]
Geothermal	0	45	0	0	6.0 / 38 / 79
Hydropower	0	19	0	88	1.0 / 24 / 2200
Nuclear	0	18	0	0	3.7 / 12 / 110
Concentrated Solar Power	0	29	0	0	8.8 / 27 / 63
Solar PV - rooftop	0	42	0	0	26 / 41 / 60
Solar PV - utility	0	66	0	0	18 / 48 / 180
Wind onshore	0	15	0	0	7.0 / 11 / 56
Wind offshore	0	17	0	0	8.0 / 12 / 35
Pre-commercial Technologies					
CCS - Coal - Oxyfuel	14 / 76 / 110	17	0	67	100 / 160 / 200
CCS - Coal - PC	95 / 120 / 140	28	0	68	190 / 220 / 250
CCS - Coal - IGCC	100 / 120 / 150	9.9	0	62	170 / 200 / 230
CCS - Gas - Combined Cycle	30 / 57 / 98	8.9	0	110	94 / 170 / 340
Ocean	0	17	0	0	5.6 / 17 / 28

[i] For a comprehensive discussion of methodological issues and underlying literature sources see Annex II, Section A.II.10.
[ii] Direct emissions from biomass combustion at the power plant are positive and significant, but should be seen in connection with the CO_2 absorbed by growing plants. They can be derived from the chemical carbon content of biomass and the power plant efficiency. For a comprehensive discussion see Bioenergy Appendix to Chapter 11. For co-firing, carbon content of coal and relative fuel shares need to be considered.
[iii] Life cycle emissions from biomass are for dedicated energy crops and crop residues. Lifecycle emissions of electricity based on other types of biomass are given in Chapter 7, figure 7.6. For a comprehensive discussion see Bioenergy Appendix to Chapter 11 (11.A.4). For a description of methodological issues see Annex II of this report.
[iv] Indirect emissions for co-firing are based on relative fuel shares of biomass from dedicated energy crops and residues (5-20%) and coal (80-95%).

III.3 Transport

III.3.1 Approach

The following tables provide a limited number of examples of transport modes and technologies in terms of their typical potential CO_2 emissions per passenger kilometre (p-km) and freight tonne kilometre (t-km), now and in the 2030 time frame. Estimates of mitigation cost ranges (USD/t CO_2eq avoided) are also provided for the limited set of comparisons where data was available. Mitigation cost ranges for HDVs, shipping and air travel were taken directly from the literature. For SUVs and LDVs, specific mitigation costs were re-calculated for well-defined conditions based on basic input parameter sets (see equations and data provided below). The methodology to calculate specific mitigation costs, also called levelized cost of conserved carbon, is discussed in Annex II. Future estimates of both emission intensities and specific mitigation costs are highly uncertain and depend on a range of assumptions.

The variation in emission intensities reflects variation in vehicle efficiencies together with narrow ranges for vehicle occupancy rates, or reflects estimates extracted directly from the literature . No cost uncertainty analysis was conducted. As mentioned above, mitigation cost ranges for HDVs, shipping and air travel were taken directly from the literature. A standardized uncertainty range of +/- 100 USD_{2010}/t CO_2 was used for SUVs and LDVs. Some parameters such as CO_2 emitted from electricity generation systems and well-to-wheel CO_2 emission levels from advanced biofuels should be considered as specific examples only.

This approach was necessitated due to a lack of comprehensive studies that provide estimates across the full range of vehicle and technology types. Therefore, possible inconsistencies in assumptions and results mean that the output ranges provided here should be treated with caution. The output ranges shown are more indicative than absolute, as suggested by the fairly wide bands for most emission intensity and mitigation cost results.

The meta-analysis of mitigation cost for alternative road transport options was conducted using a 5% discount rate and an approximate vehicle equipment life of 15 years. No fuel or vehicle taxes were included. Assumptions were based on the literature review provided throughout Chapter 8 and the estimates shown in Tables 8.3.1 and 8.6.1. Changes in assumptions could result in quite different results.

Some of the key assumptions are included in footnotes below the tables. Further information is available upon request from authors of chapter 8.

Where emission intensities and LCCC were re-calculated based on specific input data, those inputs are summarized in table 1 below. The conversion of input data into emission intensities and LCCC requires the steps outlined in the following:

Emission per useful distance travelled (tCO_2/p-km and tCO_2/t-km)

$$EI = \frac{VEff_i \cdot FCI_i}{OC_i} * \beta \qquad \text{(Eq. 7)}$$

Where:

- *EI* is the emission intensity
- *VEff* is the typical vehicle efficiency
- *FCI* is the fuel carbon intensity
- *OC* is the vehicle occupancy
- *ß* is a unit conversion factor

Levelized Cost of Conserved Carbon ($USD_{2010}/tCO_{2\ conserved}$)

$$LCCC_r = \frac{\Delta E}{\Delta C} \quad \text{(Eq. 8)}$$

$$\Delta E = \alpha \Delta I + \Delta F \quad \text{(Eq. 9)}$$

$$\alpha = \frac{r}{1-(1+r)^{-L}} \quad \text{(Eq. 10)}$$

$$\Delta F = (VEff_i \cdot AD_i \cdot FC_i - VEff_j \cdot AD_j \cdot FC_j) \cdot \gamma \quad \text{(Eq. 11)}$$

$$\Delta C = (VEff_j \cdot FCI_j \cdot AD_j - VEff_i \cdot FCI_i \cdot AD_i) * \eta \quad \text{(Eq. 12)}$$

Where:

- ΔE is the annualized travel cost increment
- ΔC is the difference in annual CO_2 emissions of alternative *i* and baseline vehicle *j*, i.e. the amount of CO_2 saved
- α is the capital recovery Factor (CRF).
- ΔI is the difference in purchase cost of baseline and the alternative vehicle
- ΔF is the difference in annualized fuel expenditures of alternative *i* and baseline vehicle *j*
- *r* is the weighted average cost of capital (WACC)
- *L* is the vehicle lifetime
- *VEff* is the typical vehicle efficiency as above, but in calculations for ΔFC and ΔC average typical vehicle efficiency is used.
- AD is the average annual distance travelled
- FC_i is average unit fuel purchase cost (taxes or subsidies excluded) of fuel used in vehicle *i*
- γ and η are unit conversion factors

Remarks:

Since annual distance travelled is assumed constant for baseline and replacement, it cancels out and doesn't affect the LCCC.

Variation in output *EI* derives from variation of vehicle fuel consumption *VEff* and vehicle occupancy *OC*.

III.3.2 Data

Table 3. Passenger transport - currently commercially available technologies

	VEff	FCI	OC	ΔI	L	AD
Option	Vehicle fuel consumption (l/100km for fossil fuel; kWh/km for electricity)[i]	CO_2 intensity of fuel[ii]	Vehicle occupancy (capita)[iii]	Vehicle price markup on baseline car (Incremental capital expenditure) (USD_{2010})[iv]	Vehicle lifetime (yrs)[v]	Annual distance travelled (km/yr)[vi]
Aviation (commercial, medium to long haul)						
2010 Stock Average	-	73 g/MJ	-	-	-	-
Narrow and Wide Body	-	73 g/MJ	-	baseline	-	-
Rail (Light Rail Car)						
Electric, 600 g CO_2/kWh_{el}	1.3-2.0	600 g/kWh	60-80	-	-	-
Electric, 200 g CO_2/kWh_{el}	1.3-2.0	200 g/kWh	60-80	-	-	-
Road						
New Busses, Large Size						
Diesel	36-42	3.2 kg/litre	40-50	-	-	-
Hybrid Diesel	25-29	3.2 kg/litre	40-50	-	-	-
New Sport Utility Vehicles (SUV), Mid-Size						
2010 Stock average SUV	10-14	2.8 kg/litre	1.5-1.7	-	15	15,000
Gasoline	9.6-12	2.8 kg/litre	1.5-1.7	baseline	15	15,000
Hybrid Gasoline (25% better)	7.2-9	2.8 kg/litre	1.5-1.7	5000	15	15,000
New Light Duty Vehicles (LDV), Mid-Size						
2010 Stock average LDV	8-11	2.8 kg/litre	1.5-1.7	-	15	15,000
Gasoline	7.8-9	2.8 kg/litre	1.5-1.7	baseline	15	15,000
Hybrid Gasoline (28% better)	5.6-6.5	2.8 kg/litre	1.5-1.7	3000	15	15,000
Diesel	5.9-6.7	3.2 kg/litre	1.5-1.7	2500	15	15,000
CNG	7.8-9	2.1 kg/litre	1.5-1.7	2000	15	15,000
Electric, 600 g CO_2/kWh_{el}	0.24-0.3	600 g/kWh	1.5-1.7	16000	15	15,000
Electric, 200 g CO_2/kWh_{el}	0.24-0.3	200 g/kWh	1.5-1.7	16000	15	15,000
New 2 Wheelers (Scooter up to 200 cm² cylinder capacity)						
2010 Stock Average	1.5-2.5	2.8 kg/litre	1.1-1.3	-	-	-
Gasoline	1.1-1.9	2.8 kg/litre	1.1-1.3	-	-	-

Table 3 (continued). Passenger transport - currently commercially available technologies

	FC	EI	ΔE	ΔC	$LCCC_{5\%}$
Option	Average annual fuel purchase cost (USD_{2010}/litre for fossil fuel; $UScents_{2010}$/kWh)[vii]	Emissions per useful distance travelled (g CO_2/p-km)	Annualized travel cost increment (USD_{2010}/yr)	Annual CO_2 savings from vehicle switch (tCO2/yr)	Levelized cost of conserved carbon at 5% WACC (USD_{2010} /t CO_2)
Aviation (commercial, medium to long haul)					
2010 Stock Average	-	80-218[viii]	-	-	-
Narrow and Wide Body	-	66-95[ix]	-	-	-200[x]
Rail (Light Rail Car)					
Electric, 600 g CO_2/kWh_{el}	-	10-20	-	-	-
Electric, 200 g CO_2/kWh_{el}	-	3.3-6.7	-	-	-
Road					
New Busses, Large Size					
Diesel	-	23-34	-	-	-
Hybrid Diesel	-	16-24	-	-	-
New Sport Utility Vehicles (SUV), Mid-Size					
2010 Stock average SUV	0.81	160-260	-	-	-
Gasoline	0.81	160-220	baseline	baseline	baseline
Hybrid Gasoline (25% better)	0.81	120-170	150	1.1	140
New Light Duty Vehicles (LDV), Mid-Size					
2010 Stock average LDV	0.81	130-200	-	-	-
Gasoline	0.81	130-170	baseline	baseline	Baseline
Hybrid Gasoline (28% better)	0.81	92-120	2.5	1.0	2.6
Diesel	0.81	110-150	-15	0.43	-35
CNG	0.35	97-130	-390	0.83	-470
Electric, 600 g CO_2/kWh_{el}	0.12	85-120	1000	1.1	950
Electric, 200 g CO_2/kWh_{el}	0.12	28-40	1000	2.7	370
New 2 Wheelers (Scooter up to 200 cm^2 cylinder capacity)					
2010 Stock Average	-	32-63	-	-	-
Gasoline	-	24-47	-	-	-

[i] Vehicle fuel economy estimates for road vehicles based on IEA (2012a) and IEA Mobility Model (MoMo) data values, using averages for stock and new vehicles around the world to establish ranges. For rail, water and air these estimates are based on a range of studies, see Chapter 8 Section 8.3.Rail estimates were based on expert judgment.
[ii] CO_2 fuel intensities are based on IPCC (2006). CO_2 intensities of electricity based on generic low and high carbon power systems. Well-to-wheel estimates from a range of sources, and specific examples as indicated in tables.

[iii] Occupancy rates for trains, buses, SUVs, LDVs, 2 wheelers based on IEA Mobility Model averages from around the world. Bus and rail represent relatively high intensity usage; average loadings in some countries and regions will be lower.
[iv] Vehicle purchase price increments for LDVs based primarily on NRC (2013), IEA (2012a).
[v] For LDVs, vehicle lifetime-kilometres set to 156,000 kms based on discounting 15 years and 15,000 km per year. Other vehicle type assumptions depend on literature. No normalization was attempted.
[vi] Annual distance travelled as described above.
[vii] Fuel prices are point estimates based on current and projected future prices in IEA (2012b). Variation in relative fuel prices can have significant impacts on transport costs and LCCC. Though no cost uncertainty analysis was performed, cost ranges were used where available and a standardized $100/t CO2 uncertainty range was added around all final point estimates.
[viii] Current energy consumption per passenger kilometre is 1.1 – 3 MJ/p-km (IEA, 2009a).
[ix] Based on TOSCA (2011, Table S-1). Slightly wider range for new/very new to account for range of load factors and distances.
[x] Based on IEA and TOSCA analysis, IEA based on 30 years, 10% discount rate.

Table 4. Passenger transport – future (2030) expected technologies[i]

	VEff	FCI	OC	ΔI	L	AD
Option	Vehicle fuel consumption (l/100km)	CO_2 intensity of fuel[ii]	Vehicle occupancy (capita)[iii]	Vehicle price markup on baseline car (Incremental capital expenditure) (USD_{2010})[iv]	Vehicle lifetime (yrs)[v]	Annual distance travelled (km/yr)[vi]
Aviation						
Narrow Body (20% better)	-	-	-[vii]	-	15	-
Narrow Body, Open Rotor Engine (33% better)	-	-	-[vii]	-	15	-
Road						
Optimized Sport Utility Vehicles (SUV), Mid-Size						
Gasoline (40% better)	5.8-7.2	2.8 kg/litre	1.5-1.7	3500[viii], future baseline	15	15,000
Hybrid Gasoline (50% better)	4.8-6[ix]	2.8 kg/litre	1.5-1.7	1200	15	15,000
Optimized Light Duty Vehicles (LDV), Mid-Size						
Gasoline (40% better)	4.7-5.4[x]	2.8 kg/litre	1.5-1.7	2500[viii], future baseline	15	15,000
Hybrid Gasoline (50% better)	3.9-4.5[xi]	2.8 kg/litre	1.5-1.7	1000	15	15,000
Hybrid Gasoline/Biofuel (50/50 share) (Assuming 70% less CO2/MJ biofuel than /MJ gasoline)	3.9-4.5[xi]	2.8 kg/litre	1.5-1.7	1000	15	15,000
Diesel Hybrid	3.3-3.8[xii]	3.2 kg/litre	1.5-1.7	1700	15	15,000
CNG Hybrid	3.9-4.5[xi]	2.1 kg/litre	1.5-1.7	1200	15	15,000
Electric, 200 g CO_2/kWh_{el}	0.19-0.26[xiii]	200 g/kWh	1.5-1.7	3600	15	15,000

Table 4 (continued). Passenger transport – future (2030) expected technologies

	FC	EI	ΔE	ΔC	$LCCC_{5\%}$
Option	Average annual fuel purchase cost (USD_{2010}/litre for fossil fuel; $UScents_{2010}$/kWh)[xiv]	Emissions per useful distance travelled (g CO_2/p-km)	Annualized travel cost increment (USD_{2010}/yr)	Annual CO_2 savings from vehicle switch (tCO2/yr)	Levelized cost of conserved carbon at 5% WACC (USD_{2010}/t CO_2)
Aviation					
Narrow Body (20% better)	-	-	-	-	0 – 150
Narrow Body, Open Rotor Engine (33% better)	-	44-63[xv]	-	-	0 – 350
Road					
Optimized Sport Utility Vehicles (SUV), Mid-Size					
Gasoline (40% better)	0.93	94-130	-190[xvi]	1.8[xvi]	-110[xvi]
Hybrid Gasoline (50% better)	0.93	78-110	-440	2.2	-200
Optimized Light Duty Vehicles (LDV), Mid-Size					
Gasoline (40% better)	0.93	76-100	-230[xvii]	1.4[xvii]	-160[xvii]
Hybrid Gasoline (50% better)	0.93	64-83	-21	0.35	- 61
Hybrid Gasoline/Biofuel (50/50 share) (Assuming 70% less CO2/MJ biofuel than /MJ gasoline)	0.93	41-54	38	1.0	39
Diesel Hybrid	0.93	63-83	-15	0.36	-43
CNG Hybrid	0.44	48-63	-310	0.77	-410
Electric, 200 g CO_2/kWh_{el}	0.13	23-35	86	1.4	61

[i] Only those options, where data was available and where significant advances are expected are listed. Other transport options, such as trains, buses and 2 wheelers will remain relevant means of transport in the future but are not covered due to data limitations.
[ii] CO_2 fuel intensities are based on IPCC (2006). CO_2 intensities of electricity based on generic low and high carbon power systems. Well-to-wheel estimates from a range of sources, and specific examples as indicated in tables.
[iii] Occupancy rates for trains, buses, SUVs, LDVs, 2 wheelers based on IEA Mobility Model averages from around the world. Bus and rail represent relatively high intensity usage; average loadings in some countries and regions will be lower.
[iv] Future vehicle purchase price mark ups based primarily on NRC (2013) and NRC (2010), also IEA (2009a), TIAX (2011), TOSCA (2011), Horton G. (2010) and other sources.
[v] For LDVs, vehicle lifetime-kilometres set to 156,000 kms based on discounting 15 years and 15,000 km per year. Other vehicle type assumptions depend on literature. No normalization was attempted.
[vi] Annual distance travelled as described above.
[vii] Horton G. (2010) gives ranges from 100 to 150 for Boeing 737-800 and 350 to 500 for Airbus A380.
[viii] Relative to 2010 baseline.

[ix] Based on NRC (2013) and other studies, see Section 8.3.
[x] Based on NRC (2013) and other studies, see Section 8.3.
[xi] Fuel consumption of future hybrid gasoline, hybrid gasoline/biofuel and hybrid CNG based on NRC (2013) and other studies, see Section 8.3.
[xii] Fuel consumption of future diesel based on NRC (2013) and other studies, see Section 8.3.
[xiii] Fuel consumption of future electric based on NRC (2013) and other studies, see Section 8.3.
[xiv] Future fuel prices based on IEA (2012b). These are point estimates - variation in relative fuel prices can have significant impacts on transport costs and LCCC.
[xv] Value results from assumption of 33% improvement relative to current new narrow and medium body aircrafts based on TOSCA (2011) and Horton G. (2010).
[xvi] Relative to 2010 gasoline SUV at 2010 fuel price of 0.81 USD_{2010}/litre.
[xvii] Relative to 2010 gasoline LDV at 2010 fuel price of 0.81 USD_{2010}/litre.

Table 5. Freight transport – currently commercially available technologies

	VEff	FCI	OC	ΔI	L	AD
Option	Vehicle fuel consumption (l/100km)	CO_2 intensity of fuel (kg/litre for fossil fuel; g CO_2/kWh_{el} for electricity)	Vehicle load (t)	Vehicle price markup on baseline car (Incremental capital expenditure) (USD_{2010})	Vehicle lifetime	Annual distance travelled (km/yr)
Aviation (commercial, long haul) [i]						
2010 Stock Average	-	-	-	-	-	-
Dedicated Aircraft	-	-	-	-	-	-
Belly-hold	-	-	-	-	-	-
Rail (freight train) [ii]						
Diesel, light goods	-	-	-	-	-	-
Diesel, heavy goods	-	-	-	-	-	-
Electric , 200g CO2/kWhel	-	-	-	-	-	-
Maritime[iii]						
Current Average International Shipping	-	-	-	-	-	-
New Large International Container Vessel[iv]	-	-	-	-	-	-
Large Bulk Carrier/Tanker[v]	-	-	-	-	-	-
LNG Bulk Carrier[vi]	-	-	-	-	-	-
Road[vii]						
New Medium Duty Trucks						
2010 Stock Average	16-24	3.2 kg/litre	1.6-1.9	-	-	-
Diesel	14-18	3.2 kg/litre	1.6-1.9	-	-	-
Diesel Hybrid	11-14	3.2 kg/litre	1.6-1.9	-	-	-
CNG	18-23	2.1 kg/litre	1.6-1.9	-	-	-
New Heavy Duty, Long-Haul Trucks						
2010 Stock Average	28-44	3.2 kg/litre	8-12	-	-	-
Diesel	25-32	3.2 kg/litre	8-12	-	-	-
CNG	31-40	2.1 kg/litre	8-12	-	-	-

Table 5 (continued). Freight transport – currently commercially available technologies

	FC	EI	ΔE	ΔC	$LCCC_{5\%}$
Option	Average annual fuel purchase cost (USD_{2010}/litre for fossil fuel; $UScents_{2010}$/kWh)	Emissions per useful distance travelled (g CO_2/t-km)	Annualized travel cost increment (USD_{2010}/yr)	Annual CO_2 savings from vehicle switch (tCO2/yr)	Levelized cost of conserved carbon at 5% WACC (USD_{2010} /t CO_2)
Aviation (commercial, long haul) [i]					
2010 Stock Average	-	550-740	-	-	-
Dedicated Aircraft	-	500-820	-	-	-200[viii]
Belly-hold	-	520-700[ix]	-	-	-
Rail (freight train) [ii]					
Diesel, light goods	-	26-33	-	-	-
Diesel, heavy goods	-	18-25	-	-	-
Electric , 200g CO2/kWhel	-	6-12	-	-	-
Maritime[iii]					
Current Average International Shipping	-	10-40	-	-	-
New Large International Container Vessel[iv]	-	10-20	-	-	-
Large Bulk Carrier/Tanker[v]	-	3-6	-	-	-
LNG Bulk Carrier[vi]	-	9-13	-	-	-
Road[vii]					
New Medium Duty Trucks					
2010 Stock Average	-	270-490	-	-	-
Diesel	-	240-370	-	-	-
Diesel Hybrid	-	180-270	-	-	-
CNG	-	200-300	-	-	-
New Heavy Duty, Long-Haul Trucks					
2010 Stock Average	-	76-180	-	-	-
Diesel	-	70-130	-	-	-
CNG	-	60-110	-	-	-

[i] These baseline carbon intensity values for long haul airfreight are based on mean estimates from DEFRA (2013). They relate to Boeing 747 and 757 airfreight with an average carrying capacity of 84 tonnes and load factor of 69%. High and low estimates set at 15% above and below the means to reflect differences in the energy efficiency of different aircraft types operating with differing load factors.
[ii] The carbon intensity values for railfreight are based mainly on analyses by DEFRA (2013) and EcoTransit (2011). Expert judgment has been exercised to allow for international differences in the age, capacity and efficiency of railway rolling stock and railway operating practices.
[iii] Estimates are derived mainly from DEFRA (2012). This source presents mean carbon intensity values for particular types and size ranges of vessels. The ranges around these means allow for differences in actual vessel size, loading and energy efficiency on the basis of expert judgment.

[iv] Carrying more than 8000 twenty-foot equivalent units (TEU).
[v] 100-200,000 dead weight tonnes.
[vi] 100-200,000 cubic metres.
[vii] Truck CO2/tonne-km ranges estimated from NRC (2010) and IEA Mobility Model data for averages for truck load factors around the world; vehicle efficiency estimates primarily from NRC (2010), IEA (2009a) and TIAX (2011). Baseline estimates derived from DEFRA (2013), EcoTransit (2011) and IEA (2009a). High and low estimates allow for variations in vehicle size, weight, age, operation and loading in different parts of the world.
[viii] Aviation freight cost estimates assumptions similar to passenger. Based on IEA and TOSCA analysis, IEA based on 30 years, 10% discount rate.
[ix] The allocation of emissions between passenger and freight traffic on belly-hold services conforms to a standard 'freight weighting' method.

Table 6. Freight transport – future (2030) expected technologies

Options[i]	VEff	FCI	OC	ΔI	L	AD
	Vehicle fuel consumption (l/100km)	CO_2 intensity of fuel (kg/litre for fossil fuel; g CO_2/kWh_{el} for electricity)	Vehicle load (t)	Vehicle price markup on baseline car (Incremental capital expenditure) (USD_{2010})	Vehicle lifetime	Annual distance travelled (km/yr)
Aviation (commercial, long haul)						
Improved Aircraft (25% better)	-	-	-	-	-	-
Improved, Open Rotor Engine (33% better)	-	-	-	-	-	-
Maritime						
Optimized Container Vessel	-	-	-	-	-	-
Optimized Bulk Carrier	-	-	-	-	-	-
Road[ii]						
Optimized Medium Duty Trucks						
Diesel	8-13	3.2 kg/litre	1.6-1.9	-	-	-
Optimized Heavy Duty, Long-Haul Trucks						
Diesel	15-22	3.2 kg/litre	8-12	-	-	-
Diesel/Biofuel (50/50 share) (Assuming 70% less CO2/MJ biofuel than /MJ diesel)	15-22	2.1 kg/litre	8-12	-	-	-

1 **Table 6 (continued).** Freight transport – future (2030) expected technologies

	FC	EI	ΔE	ΔC	$LCCC_{5\%}$
Option	Average annual fuel purchase cost (USD_{2010}/litre for fossil fuel; $UScents_{2010}$/kWh)	Emissions per useful distance travelled (g CO_2/t-km)	Annualized travel cost increment (USD_{2010}/yr)	Annual CO_2 savings from vehicle switch (tCO2/yr)	Levelized cost of conserved carbon at 5% WACC (USD_{2010} /t CO_2)
Aviation (commercial, long haul)					
Improved Aircraft (25% better)	-	300-450[iii]	-	-	150[iv]
Improved, Open Rotor Engine (33% better)	-	270-400[iii]	-	-	350[iv]
Maritime					
Optimized Container Vessel	-	7-13[v]	-	-	-100[vi]
Optimized Bulk Carrier	-	2-4[v]	-	-	-100[vi]
Road[ii]					
Optimized Medium Duty Trucks					
Diesel	-	140-260	-	-	-100
Optimized Heavy Duty, Long-Haul Trucks					
Diesel	-	41-91	-	-	-250
Diesel/Biofuel (50/50 share) (Assuming 70% less CO2/MJ biofuel than /MJ diesel)	-	26-59	-	-	-

[i] No future rail CO2 or cost estimates were included due to lack of information.
[ii] Future truck efficiencies and costs primarily from NRC (2010), Zhao et al (2013).
[iii] These baseline carbon intensity values for long haul airfreight are based on mean estimates from DEFRA (2013). They relate to Boeing 747 and 757 airfreight with an average carrying capacity of 84 tonnes and load factor of 69%. High and low estimates set at 15% above and below the means to reflect differences in the energy efficiency of different aircraft types operating with differing load factors.
[iv] Projections of the carbon mitigation costs of future aircraft development are based mainly on Tosca. Mitigation costs for future technologies assumed similar to passenger aircraft since the specific large commercial type aircraft are mostly the same configuration.
[v] Estimates are derived mainly from DEFRA (2012). This source presents mean carbon intensity values for particular types and size ranges of vessels. The ranges around these means allow for differences in actual vessel size, loading and energy efficiency on the basis of expert judgment.
[vi] Shipping cost estimates based primarily on Buhaug (2009), Lloyds Register/DNV (2011) and IEA (2009a) (review of literature).

III.4 Industry

III.4.1 Introduction

The data presented below has been used to assess typical product-specific CO_2-eq emissions (i.e. emission per unit of product) [3] for different production practices, which are commercially available today or may become so in the future, and for selected industrial sectors. Both direct and indirect specific emissions are assessed. Specific emissions could be reduced by switching to production processes that cause lower emissions for otherwise comparable products[4] and by reducing production/consumption of emission-intensive products. Some production practices are mutually exclusive; others can be combined to yield deeper reductions in specific emissions. The impact of decarbonizing electricity supplied for industrial processes has been assessed, too, for well-defined exemplary conditions.

For all input parameters and specific CO_2eq emissions global average values are given as a benchmark. Parameters of individual production practices are generally estimates of typical values based on limited studies and expert judgment. Comparisons of input parameters across different individual production practices and with global averages (cf. tables below) yields insights into the intermediate effect via which changes in final specific CO_2eq emissions occur for certain production practices.

Estimates of future global averages in specific CO_2eq emissions are derived for long-term scenarios that stabilized GHG concentrations at about 450ppm CO_2eq and provide data at the necessary level of detail. These can be considered as another rough benchmark for emission intensities that can be achieved with currently available and potential future production practices. Generally, scenarios that provide sufficient detail at the level of industrial subsectors/products are very scarce (2-3 models) and are in many cases derived from the same data source as data for individual production practices (mostly International Energy Agency)[5]. Comparisons of emission intensities in future 450ppm stabilization scenarios with available production practices can yield rough insights into future trends for production practices with different specific emissions, but need to be considered with caution.

Specific mitigation costs have been assessed for all production practices except for the decarbonization of electricity supply, the cost of which are dealt with in chapter 7 (Section 7.8). Specific mitigation costs are expressed in USD_{2010}/tCO_2 or USD_{2010}/tCO_2eq and take into account total incremental operational and capital costs. Generally, costs of the abatement options shown vary widely between individual regions and from plant to plant. Factors influencing the costs include typical capital stock turnover rates (some measures can only be applied when plants are replaced), relative energy costs, etc. No meta-analysis of such individual cost components has been attempted, however, due to limited data availability. Estimates are based on expert judgment of the limited data

[3] Emissions cannot always be expressed in product-specific terms. In the case of chemicals, products are too heterogeneous to express emissions per unit of product. Hence, global emissions of different production practices/technologies have been assessed for total global chemicals production.

[4] Note that the extent to which certain production processes can be replaced by others is often constrained by various conditions that need to be considered on a case by case basis. The replacement of blast oxygen steel furnaces by electric arc furnaces, for instance, is limited by availability of scrap.

[5] Further literature sources are assessed in chapter 10 (Section 10.7). The data sources assessed in 10.7 could, however, often not be used in the summary assessment mainly due to non-comparability of methodological approaches. Chapter 6 presents more comprehensive scenario assessments including all sectors of the economy, which often comes, however, at the expense of sectoral detail. Chapter 10 (Section 10.10) discusses these scenarios from an industry perspective.

that is available. Hence, the estimates of specific mitigation costs should be considered with care and as indicative only.

Information on specific emissions of different production practices and associated specific mitigation cost is presented in figures 10.7 – 10.10 and in figure 10.19 and 10.20.

III.4.2 Approaches and Data by Industry Sector

III.4.2.1 Cement

Direct specific emissions of cement (tCO_2/t cement) are derived from technical parameters via the following equation:

$$EI_{direct} = (1-\lambda)\cdot clc \cdot (e_{n-el} \cdot FCI_{n-el} + CI_{calc}) \qquad \text{(Eq. 13)}$$

Where

- λ is the percentage of emissions captured and stored via CCS
- clc is the clinker to cement ratio
- e_{n-el} is the specific non-electric energy use, i.e. the non-electric energy use per unit of cement
- FCI_{n-el} is the carbon intensity of the non-electric fuel used
- CI_{calc} is the carbon intensity of the calcination process

Indirect specific emissions of cement (tCO_2/t cement) are derived from specific electricity use and the carbon intensity of electricity:

$$EI_{indirect} = e_{el} \cdot FCI_{el} \qquad \text{(Eq. 14)}$$

Where

- e_{el} is the specific electric energy use, i.e. the electricity use per unit of cement
- FCI_{el} is the carbon intensity of the electricity used

Total specific emissions of cement (tCO_2/t cement) are the sum of both direct and indirect specific emissions:

$$EI_{total} = EI_{direct} + EI_{indirect} \qquad \text{(Eq. 15)}$$

Remarks:

Variation in emission intensity derives from variation in selected input parameters. Individual input parameters are varied systematically, i.e. in accordance with the definition of each production practice, while all other input parameters are kept at global average values.

Data on technical input parameters is also very limited. Sources are specified in footnotes to data entries.

Specific mitigation costs (cost of conserved carbon) are estimated based on expert assessment of limited selected studies. See footnote i for details.

Table 7. Technical parameters and estimates for cost of conserved carbon of cement production processes

	clc	$e_{n\text{-}el}$	$FCI_{n\text{-}el}$	CI_{calc}	e_{el}	FCI_{el}	λ	EI_{direct}	$EI_{indirect}$	EI_{total}	*LCCC*
Options	Clinker to cement ratio (%)	Non-electric fuel intensity (GJ/t clinker)	CO_2 intensity of non-electric fuel (tCO_2/GJ)	CO_2 intensity of calcination process (t CO_2/t clinker)	Electricity intensity (kWh/t cement)	CO_2 intensity of electricity ($kgCO_2/kWh$)	CO_2 capture rate (%)	Direct emission intensity w/ CCS (tCO_2/t cement)	Indirect emission intensity (tCO_2/t cement)	Total emission intensity (tCO_2/t cement)	Levelized cost of conserved carbon ($USD_{2010}/tCO_{2\ saved}$)[i]
Historical Global Average Data and Future Data for 450ppm Scenarios from Integrated Assessment Models											
Global average (2030)[ii]	-	-	-	-	-	-	-	-	-	0.38 – 0.59	
Global average (2050) [ii]	-	-	-	-	-	-	-	-	-	0.24 – 0.39	
Global average (2010)	0.8	3.9	0.1	0.51	109	0.46[iii]	0	0.72	0.05	0,77	
Currently Commercially Available Technologies											
Best practice energy intensity	0.8	2.9 – 3.1[iv]	0.1	0.51	80 – 90[v]	0.46[iii]	0	0.64 – 0.66	0.037 – 0.041	0.68 – 0.70	<0 - 150
Best practice clinker to cement ratio	0.6 – 0.7[vi]	3.9	0.1	0.51	109	0.46[iii]	0	0.54 – 0.63	0.05	0.59 – 0.68	<0 - 50[vii]
Best practice energy intensity and clinker to cement ratio combined	0.6 – 0.7[vi]	2.9 – 3.1[iv]	0.1	0.51	80 – 90[v]	0.46[iii]	0	0.48 – 0.57	0.037 – 0.041	0.52 – 0.62	<0 - 150[vii]
Improvements in non-electric fuel mix[viii]	0.8	3.9	0.056[ix]	0.51	109	0.46[iii]	0	0.58	0.05	0.63	<0 - 150[vii]
Decarbonization of electricity supply	0.8	3.9	0.1	0.51	109	0 – 0.39[x]	0	0.72	0 – 0.043	0,72 – 0.76	
Pre-commercial Technologies											
CCS[xi]	0.8	3.9	0.1	0.51	109	0.46[iii]	75 – 90	0.072 – 0.18	0.05	0.12 – 0.23	50 – 150[xii]
CCS and fully decarbonized electricity[xiii]	0.8	3.9	0.1	0.51	109	0	75 – 90	0.072 – 0.18	0	0.072 – 0.18	

[i] Expert judgment based on McKinsey (2009), 2012, IEA (2009b, 2012a), BEE (2012) and others. The costs of the abatement options shown vary widely between individual regions and from plant to plant. Factors influencing the costs include typical capital stock turnover rates (some measures can only be applied when plants are replaced), relative energy costs, etc.
[ii] Data range is taken from the following models: AIM Enduse model (Akashi et al., 2013), IEA 2DS low demand (IEA, 2012a)
[iii] Based on global industry-wide average CO_2eq intensity of primary energy used in electricity and heat supply in 2010 (cf. Chapter 10. Table 10.2)
[iv] This range is based on best practice operation of 4 to 6 stage pre-heater + pre-calciner kiln technology based on IEA (2009b). Actual operation performance does depend on issues such as moisture content and raw material quality and can be above this range.
[v] Best practice electricity consumption is based on IEA (2007).
[vi] Minimum clinker to cement ratio is for Portland cement according to IEA (2007) is a globally achievable value taking availability of substitutes into account IEA (2009b). Further reductions in the clinker to cement ratio are possible for other types of cement (e.g. fly ash or blast furnace slag cement).
[vii] For clinker substitution and fuel mix changes, costs depend on the regional availability and price of clinker substitutes and alternative fuels.
[viii] This is assuming that only natural gas is used as non-electric fuel. Further reduction in non-electric fuel emission intensity are technically possible, e.g. by increased use of biomass.
[ix] Natural gas fuel emission factor (IPCC, 2006)
[x] The upper end of the range is based on natural gas combined cycle (IGCC) with an efficiency of 55% and fuel emission factors from IPCC (2006).
[xi] CCS: Carbon capture and storage. This option assumes no improvements in fuel mix. Feasibility of CCS depends on global CCS developments. CCS is currently not yet applied in the cement sector.
[xii] IEA GHG (2008) estimates CCS abatement cost at 63 to 170 USD / t CO_2 avoided.
[xiii] This option assumes no improvements in non-electric fuel mix.

III.4.2.2 Iron and Steel

Direct specific CO_2 emissions of crude steel (tCO_2/t steel) are derived from technical parameters via the following equation:

$$EI_{direct} = (1-\lambda) \cdot EI_{direct,noCCS} \quad \text{(Eq. 16)}$$

Where

- λ is the percentage of emissions captured and stored via CCS
- $EI_{direct,noCCS}$ is the direct emission intensity without CCS

Indirect specific CO_2 emissions of crude steel (tCO_2/t steel) are derived from specific electricity use and the carbon intensity of electricity:

$$EI_{indirect} = e_{el} \cdot FCI_{el} \quad \text{(Eq. 17)}$$

Where

- e_{el} is the specific electric energy use, i.e. the electricity use per unit of crude steel
- FCI_{el} is the carbon intensity of the electricity used

Total specific CO_2 emissions of crude steel (tCO_2/t steel) are the sum of both direct and indirect specific emissions:

$$EI_{total} = EI_{direct} + EI_{indirect} \quad \text{(Eq. 18)}$$

Remarks:

Data on technical input parameters is limited and almost exclusively based on IEA (2007). Emission intensities of the advanced blast furnace route, the natural gas DRI route, and the scrap-based electric arc furnace route are point estimates of global best practice based on IEA (2007). Since no variation in input parameters could be derived from the literature, output ranges have been constructed as an interval around the mean value based on +/-10% of the respective savings. Where input parameters are set by assumption, they are varied within typical ranges and become the sole source of variation in output values, while all other input parameters are kept at global average values.

Specific mitigation costs (cost of conserved carbon) are estimated based on expert assessment of limited selected studies. See footnote i for details.

Table 8. Technical parameters and estimates for cost of conserved carbon of iron and steel production processes

	$EI_{direct,noCCS}$	e_{el}	FCI_{el}	λ	EI_{direct}	$EI_{indirect}$	EI_{total}	$LCCC$
Options[i]	Specific direct CO_2 emissions w/o CCS[ii] (tCO_2/t steel)	Specific electricity consumption (kWh/t steel)	CO_2 intensity of electricity ($kgCO_2$/kWh)	CO_2 capture rate[iii] (%)	Specific direct CO_2 emissions w/ CCS[iv] (tCO_2/t steel)	Indirect emission intensity (tCO_2/t steel)	Total emission intensity (tCO_2/t steel)	Levelized cost of conserved carbon ($USD_{2010}/tCO_{2\ saved}$)[v]
Historical Global Average Data and Future Data for 450ppm Scenarios from Integrated Assessment Models								
Global average (2030)[vi]	-	-	-	-	-	-	0.92 – 1.36	
Global average (2050)[vi]	-	-	-	-	-	-	0.47 – 0.84	
Global average (2010)	1.8[vii]	820[viii]	0.46[ix]	0	1.8	0.38	2.2	
Currently Commercially Available Technologies								
Advanced blast furnace route[x]	1.3[xi]	350[xii]	0.46[ix]	0	1.3	0.16	1.5	<0 – 150
Natural gas DRI route[xiii, x]	0.7[xi]	590[xii]	0.46[ix]	0	0.7	0.27	0.97	50 – 150
Scrap based EAF[xiv, x]	0.25[xi]	350[xii]	0.46[ix]	0	0.25	0.16	0.41	<0 – 50[xv]
Decarbonization of electricity supply	1.8[vii]	820[viii]	0 – 0.39[xvi]	0	1.8	0 – 0.32	1.8 – 2.1	
Pre-commercial Technologies								
CCS[xvii]	1.8[vii]	820[viii]	0.46[ix]	75 – 90	0.18 – 0.45	0.38	0.56 – 0.82	50 – 150
CCS and fully decarbonized electricity[xviii]	1.8[vii]	-	0	75 – 90	0.18 – 0.45	0	0.18 – 0.45	

[i] Non-electric fuel mix improvements are not listed as an abatement option, because a large share of the coal use in the iron and steel industry, via the intermediate production of coke, is an inherent feature of the blast furnace technology. The coke is used to reduce iron ore to iron and for structural reasons in the furnace. The limited data availability did not allow assessing the limited potential related to the part of the fuel use that can be substituted.
[ii] Direct CO_2 emissions contain all emissions from steel production that are unrelated to electricity consumption.
[iii] As percentage of specific direct CO_2 emissions in steel production
[iv] Direct CO_2 emissions contain all emissions from steel production that are unrelated to electricity consumption.
[v] Expert judgment based on McKinsey (2009; 2010), IEA (2009b, 2012a), BEE (2012) and others. The costs of the abatement options shown vary widely between individual regions and from plant to plant. Factors influencing the costs include typical capital stock turnover rates (some measures can only be applied when plants are replaced), relative energy costs, etc.
[vi] Data range is provided by AIM Enduse model (Akashi et al., 2013) DNE21+ (Sano, Akimoto, et al., 2013; Sano, Wada, et al., 2013) and IEA 2DS low demand (IEA, 2012a).
[vii] IEA (2012a)
[viii] Derived from IEA (2012a, 2013b)
[ix] Based on global industry-wide average CO_2eq intensity of primary energy used in electricity and heat supply in 2010 (cf. Chapter 10, Table 10.2). This is a simplified calculation in line with the method used for other sectors ignoring the practice in many iron and steel plants to use process derived gases (blast furnace gas and basic oxygen furnace gas) for electricity production. The emissions from these derived gases are already included in the direct emissions.
[x] Excluding rolling and finishing
[xi] Value equals lower bound of total emission intensity in IEA (2007, p. 108, table 5.4) as that is for zero-carbon electricity.
[xii] Derived from spread in total emission intensity in IEA (2007, p. 108, table 5.4)and using a typical coal emission factor of 0.85.
[xiii] DRI: direct reduced iron
[xiv] EAF: Electric arc furnace
[xv] Costs depend heavily on the regional availability and price of scrap.
[xvi] The upper end of the range is based on natural gas combined cycle (IGCC) with an efficiency of 55% and fuel emission factors from IPCC (2006). The approach taken here is a simplified calculation, consistent with the approach for other sectors and does not explicitly take into account the share of the electricity consumed that is produced with process derived gases (see also footnote ix).
[xvii] CCS: Carbon capture and storage. This option assumes no improvements in fuel mix.
[xviii] This option assumes no improvements in non-electric fuel mix

III.4.2.3 Chemicals

Global direct CO_2 emissions ($GtCO_2$) of global chemicals production in 2010 are derived from technical parameters via the following equation:

$$CO2_{direct} = (1-\lambda)\cdot CO2_{direct,noCCS} \quad \text{(Eq. 19)}$$

Where

- λ is the percentage of emissions captured and stored via CCS
- $CO2_{direct,noCCS}$ are global direct CO_2 emissions in chemicals production in 2010 without CCS

Global indirect CO_2 emissions ($GtCO_2$) of global chemicals production in 2010 are derived from global electricity use in chemicals production and the carbon intensity of electricity:

$$CO2_{indirect} = Elec \cdot FCI_{el} \cdot \gamma \quad \text{(Eq. 20)}$$

Where

- *Elec* is the global electric energy use in the chemicals sector in 2010
- FCI_{el} is the carbon intensity of the electricity used
- γ is a unit conversion factor of 1/1000

Total global CO_2eq emissions ($GtCO_2eq$) of chemicals production in 2010 are the sum of direct and indirect CO_2 emissions and CO_2-equivalents of non-CO_2 emissions:

$$CO2e_{total} = CO2_{direct} + CO2_{indirect} + CO2e_{acid} + CO2e_{HFC-22} \quad \text{(Eq. 21)}$$

Where

- $CO2e_{acid}$ are global direct N_2O emissions from global nitric and adipic acid production expressed in CO_2 equivalents
- $CO2e_{HFC-22}$ are global direct HFC-23 emissions from HFC-22 production expressed in CO_2 equivalents

Remarks:

For most production practices, only central estimates for technical input parameters could be derived from the available literature. Where input parameters are set by assumption, they are varied within typical ranges and become a source of variation in output values. Where no variation in input parameters could be derived from the literature, output ranges have been constructed as an interval around the mean value based on +/-10% of the respective savings.

Specific mitigation costs (cost of conserved carbon) are estimated based on expert assessment of limited selected studies. See footnote iii for details.

Table 9. Technical parameters and estimates for cost of conserved carbon of chemicals production processes

Options	$CO2_{direct,noCCS}$ Global direct CO_2 emissions w/o CCS ($GtCO_2$)	$CO2e_{acid}$ Global non-CO_2 emissions from HFC-22 production ($GtCO_2$-eq)[i]	$CO2e_{HFC\text{-}22}$ Global non-CO_2 emissions from adipic and nitric acid production ($GtCO_2$-eq)[i]	*Elec* Global electricity use (TWh)	FCI_{el} CO_2 intensity of electricity ($kgCO_2$/kWh)	*λ* CO_2 capture rate[ii] (%)	$CO2_{direct}$ Global direct CO_2 emissions w/ CCS ($GtCO_2$)	$CO2_{indirect}$ Global indirect CO_2 emissions ($GtCO_2$)	$CO2_{total}$ Global total emissions ($GtCO_2$-eq)	*LCCC* Cost of conserved carbon (USD_{2010}/tCO_2 saved)[iii]
Historical Data and Future Data from IEA ETP 2DS Scenario										
Global total (2030)[iv]	-	-	-	1400	-	-	1.5 – 1.6	-	-	
Global total (2050)[iv]	-	-	-	1400	-	-	1.3	-	-	
Global total (2010)	1.6[v]	0.13	0.12	1100[vi]	0.46[vii]	0	1.6	0.51	2.4	
Currently Commercially Available Technologies										
Best practice energy intensity	1.0[viii]	0.13	0.12	860[ix]	0.46[vii]	0	1.0	0.39	1.7	<0 – 150
Enhanced recycling, cogeneration and process intensification	1.3[x]	0.13	0.12	1100[vi]	0.46[vii]	0	1.3	0.51	2.1	20 – 150
Abatement of N2O from nitric and adipic acid	1.6[v]	0.13	0.01[xi]	1100[vi]	0.46[vii]	0	1.6	0.51	2.3	0 – 50
Abatement of HFC-23 emissions from HFC-22 production	1.6[v]	0[xii]	0.12	1100[vi]	0.46[vii]	0	1.6	0.51	2.2	0 – 20
Improvements in non-electric fuel mix[xiii]	1.2[xiv]	0.13	0.12	1100[vi]	0.46[vii]	0	1.2	0.51	2.0	<0 – 150
Decarbonization of electricity supply	1.6[v]	0.13	0.12	1100[vi]	0 – 0.39[xv]	0	1.6	0 – 0.44	1.8 – 2.3	
Pre-commercial Technologies										
CCS for ammonia production[xvi]	1.6[v]	0.13	0.12	1100[vi]	0.46[vii]	3.5[xvii]	1.5	0.51	2,3	50 – 150
CCS[xviii]	1.6[v]	0.13	0.12	1100[vi]	0.46[vii]	75 – 90	0.16 – 0.4	0.51	0.92 – 1.16	50 – 150
CCS and fully decarbonized electricity[xix]	1.6[v]	0.13	0.12	1100[vi]	0	75 – 90	0.16 – 0.4	0	0.41 – 0.65	

[i] Based on EPA (2012) unless specified otherwise.
[ii] As percentage of global direct CO_2 emissions in chemicals production
[iii] Expert judgment based on McKinsey (2009; 2010), IEA (2009c, 2012a), BEE (2012) and others. The costs of the abatement options shown vary widely between individual regions and from plant to plant. Factors influencing the costs include typical capital stock turnover rates (some measures can only be applied when plants are replaced), relative energy costs, etc.
[iv] Based on IEA ETP 2DS scenarios with high and low global energy demand (IEA, 2012a).
[v] Based on IEA (2012a).
[vi] Based on IEA (IEA, 2013b). IEA (2012a) provided higher values of 1340 TWh.
[vii] Based on global industry-wide average CO_2eq intensity of primary energy used in electricity and heat supply in 2010 (cf. Chapter 10. Table 10.2)
[viii] Based on global potential for savings of 35% in direct emissions in chemicals production as estimated for 2006 (IEA, 2009c)applied to direct emissions in 2010.
[ix] Based on potential for electricity savings of 0,91 EJ (IEA, 2012a).
[x] Based on global technical potential for saving in primary energy consumption of 4.74 EJ (IEA, 2012a) and assuming that conserved primary energy supply is based on natural gas with an emission factor of 56.2 kg CO_2-eq/GJ (IPCC, 2006). This translates into savings in global direct CO_2 emissions of 0.27 GtCO2-eq.
[xi] Based on a global technical potential to save 85% of non-CO_2 emissions from HFC-22 production (EPA, 2012)
[xii] Based on a global technical potential to save 100% of non-CO_2 emissions from production of adipic and nitric acid (Miller and Kuijpers, 2011)
[xiii] This includes a switch to a zero carbon non-electric fuel, e.g. some types of biomass, or to natural gas.
[xiv] Based on the assumption that 23% of direct CO2 emissions can be saved from a switch to natural gas (IEA, 2009c).
[xv] The upper end of the range is based on natural gas combined cycle (IGCC) with an efficiency of 55% and fuel emission factors from IPCC (2006).
[xvi] Ammonia production was 159 Mt in 2010 (IEA, 2012a). According to Neelis et al. (2005), a best practice gas-based ammonia facility produces 1.6 t CO_2/t ammonia, of which 70% are pure CO_2 emissions (1.1 t CO_2/t ammonia). 50% of that pure CO2 stream is assumed to be used in urea production (0.55 t CO_2/t ammonia). 90% of the remaining 0.55 t CO_2/t ammonia is assumed to be captured. This results in an effective CO_2 capture rate of 3.5% of total emissions in chemicals by application of CCS in ammonia production.
[xvii] This is the effective rate of CO_2 emissions captured in ammonia production relative to global direct CO2 emissions in chemicals. See also endnote xvi.
[xviii] This option assumes no improvements in fuel mix.
[xix] This option assumes no improvements in non-electric fuel mix.

III.4.2.4 Pulp and Paper

Specific direct CO_2 emissions of paper (tCO_2/t paper) are derived from technical parameters via the following equation:

$$EI_{direct} = (1-\lambda) \cdot EI_{direct,noCCS} \qquad \text{(Eq. 22)}$$

Where

- λ is the percentage of emissions captured and stored via CCS
- $EI_{direct,noCCS}$ is the direct emission intensity without CCS

Indirect specific CO_2 emissions of paper (tCO_2/t paper) are derived from specific electricity use and the carbon intensity of electricity:

$$EI_{indirect} = e_{el} \cdot FCI_{el} \qquad \text{(Eq. 23)}$$

Where

- e_{el} is the specific electric energy use, i.e. the electricity use per tonne of paper
- FCI_{el} is the carbon intensity of the electricity used

Total specific CO_2 emissions of paper (tCO_2/t paper) are the sum of both direct and indirect specific emissions:

$$EI_{total} = EI_{direct} + EI_{indirect} \qquad \text{(Eq. 24)}$$

Remarks:

For most production practices, only central estimates for technical input parameters could be derived from the available literature. Where input parameters are set by assumption, they are varied within typical ranges and become a source of variation in output values. Where no variation in input parameters could be derived from the literature, output ranges have been constructed as an interval around the mean value based on +/-10% of the respective savings.

Specific mitigation costs (cost of conserved carbon) are estimated based on expert assessment of limited selected studies. See footnote iii for details.

Table 10. Technical parameters and estimates for cost of conserved carbon of pulp and paper production processes

Options	$EI_{direct,noCCS}$ Specific direct CO_2 emissions w/o CCS[i] (tCO_2/t paper)	e_{el} Specific electricity consumption (kWh/t paper)	FCI_{el} CO_2 intensity of electricity ($kgCO_2$/kWh)	λ CO_2 capture rate[ii] (%)	EI_{direct} Specific direct CO_2 emissions w/ CCS[iii] (tCO_2/t paper)	$EI_{indirect}$ Indirect emission intensity (tCO_2/t paper)	EI_{total} Total emission intensity (tCO_2/t paper)	$LCCC$ Cost of conserved carbon ($USD_{2010}/tCO_{2\ saved}$)[iv]
Historical Data and Future Data from IEA ETP 2DS Scenario								
Global average (2030)[v]	-	990 – 1100[vi]	-	-	0.26 – 0.30[vi]	-	-	
Global average (2050)[v]	-	920 – 950[vi]	-	-	0.16 – 0.20[vi]	-	-	
Global average (2010)	0.56[vii]	1,200[viii]	0.46[ix]	0	0.56	0.55	1,1	
Currently Commercially Available Technologies								
Best practice energy intensity	0.48[x]	1,000[xi]	0.46[ix]	0	0.48	0.46	0.94	<0 - 150
Co-generation	0.53[xii]	1,200[viii]	0.46[ix]	0	0.53	0.55	1,1	20 – 50
Decarbonization of electricity supply	0.56[vii]	1,200[viii]	0 – 0.39[xiii]	0	0.56	0 – 0.47	0.56 – 1,0	
Pre-commercial Technologies								
CCS[xiv]	0.56[vii]	1,200[viii]	0.46[ix]	75 – 90	0.056 – 0.14	0.55	0,61 – 0,69	50 – 150
CCS and fully decarbonized electricity[xv]	0.56[vii]	1,200[viii]	0 – 0.39	75 – 90	0.056 – 0.14	0 – 0.47	0,056 – 0,14	

[i] Direct CO_2 emissions w/o CCS contain all emissions from paper production that are unrelated to electricity consumption, including those that could be captured and stored.
[ii] As percentage of specific direct CO_2 emissions in steel production
[iii] Direct CO_2 emissions w/ CCS contain all non-captured emissions from paper production that are unrelated to electricity consumption.
[iv] Expert judgment based on McKinsey (2009; 2010), IEA (2009b, 2012a), BEE (2012) and others. The costs of the abatement options shown vary widely between individual regions and from plant to plant. Factors influencing the costs include typical capital stock turnover rates (some measures can only be applied when plants are replaced), relative energy costs, etc.
[v] Based on IEA ETP 2DS scenarios with high and low global energy demand (IEA, 2012a).
[vi] Derived from IEA (2012a).
[vii] Based on global direct emissions of 0.22 Gt CO2 and global paper production of 395 Mt (IEA, 2012a)
[viii] Based on global electricity consumption in pulp and paper production of 1.7 EJ (IEA, 2013b) and global paper production of 395 Mt (IEA, 2012a)
[ix] Based on global industry-wide average CO_2eq intensity of primary energy used in electricity and heat supply in 2010 (cf. Chapter 10. Table 10.2)
[x] Based on technical potential for savings in non-electric fuel input of 1.5 GJ/t paper (IEA, 2012a).and assuming no change in the non-electric fuel emission factor of 51 kg CO_2/GJ (derived from IEA, 2012a). This translates into savings in specific direct CO_2 emissions of 77 kg CO_2/t paper.
[xi] Based on technical potential for saving electricity of 200 kWh/t paper (IEA, 2012a)
[xii] Based on technical potential for savings in non-electric fuel input of 0.6 GJ/t paper (derived from IEA, 2012a) and assuming that conserved fuel is natural gas with an emission factor of 56.2 kg CO_2-eq/GJ (IPCC, 2006). This translates into savings in specific direct CO_2 emissions of 34 kg CO_2/t paper.
[xiii] The upper end of the range is based on natural gas combined cycle (IGCC) with an efficiency of 55% and fuel emission factors from IPCC (2006).
[xiv] This option assumes no improvements in fuel mix.
[xv] This option assumes no improvements in non-electric fuel mix.

III.4.2.5 Municipal Solid Waste (MSW)

For waste treatment practices that reduce landfill, specific methane emission (gCH_4/kg MSW) and specific nitrous oxide emissions (gN_2O/ kg MSW) are taken directly from the literature. Methane emission intensities (gCH_4/kg MSW) of conventional and improved landfill options are derived from technical parameters given below. CO_2eq emission intensities (tCO_2eq/t MSW) are calculated using global warming potentials (GWP) of methane and nitrous oxide of 21 and 310, respectively.

$$EI_{CH4} = MCF \cdot DOC \cdot DOCf \cdot F \cdot (1 - OX) \cdot (1 - R) \cdot \gamma \cdot \eta \qquad \text{(Eq. 25)}$$

Where

- *MCF* is the methane correction factor, $Min(MCF) = 0.6$, $Max(MCF) = 1$
- *DOC* is degradable organic carbon (gC/kg MSW)
- *DOCf* is the fraction of DOC dissimilated, $DOCf = 0.5$
- *F* is the fraction of methane in landfill gas, $F = 0.5$
- OX is oxidation factor (fraction)
- *R* is the fraction of recovered methane
- *γ* is the unit conversion factor of C into CH_4, $\gamma = 16/12$
- *η* is a unit conversion factor of 1/1000

Values given above are based on *IPCC (2001; and 2006),* default values.

Variation in specific emissions is from maximum to minimum assuming all input parameters are independently distributed.

Cost are taken from EPA (2012) and based on a 10% WACC.

Table 11. Technical parameters and estimates for cost of conserved carbon of waste treatment practices

Options	DOC	OX	R	EI_{CH4}	EI_{N2O}	EI_{CO2eq}	LCCC
	Degradable organic carbon (g C/kg MSW)[i, ii]	Oxidation factor (fraction)	Fraction of recovered CH_4	CH_4 emission intensity of MSW (gCH_4/kg MSW)[i, iii]	N_2O emission intensity of MSW (g N_2O/ kg MSW)[i, iii]	CO_2-eq emission intensity of MSW (tCO_2eq/t MSW)[i]	Levelized cost of conserved carbon at 10% WACC (USD_{2010}/tCO_2 saved)[iv]
	min /max			min /max	min /max	min /max	min /max
Reference: Landfill at MSW disposal site	140 /210	0	0	42 /110	~0	0.58 /1.5	
Reducing MSW landfill							
Composting	-	-	-	0.0 /8	0.06 /0.6	0.019 / 0.35	- 140 / 470
Anaerobic digestion	-	-	-	0 /1 /8	~0	0 / 0.17	150 / 590
Improving MSW landfill practices							
Biocover	140 /210	0.8[v]	0	8.5 / 21	~0	0.12 / 0.19	99 / 100
In-situ aeration	140 /210	0.9	0	4.2 / 11	~0	0.058 / 0.10	99 / 130
Flaring	140 /210	0	0.6 / 0.85	6.4 / 43	~0	0.087 / 0.35	5.0 / 58
CH_4 capture for power generation	140 /210	0	0.6 / 0.9	4.2 / 43	~0	0.058 / 0.35	-37 / 66
CH_4 capture for heat generation	140 /210	0	0.6 / 0.9	4.2 / 43	~0	0.058 / 0.35	-70 / 89

[i] On wet weight basis.
[ii] Total DOC derived from estimates for regional composition of wastes and fraction of DOC in each type of waste (Pipatti et al., 2006, tables 2.3 and 2.4)
[iii] Methane emissions intensity of reference and improved landfill practices is based on IPCC (2001, table 3) and approach above, which is based on equation 1 of aforementioned source. Methane emission intensity and nitrous oxide emissions intensity of reduced landfill options is based on IPCC (IPCC, 2006, table 4.1)
[iv] Based on EPA (2012)
[v] Based on EPA (2006)

III.4.2.6 Domestic Wastewater

Specific CO_2eq emissions of wastewater (t CO_2/t BOD5) are based on IPCC (2006) using the following equation to convert methane emissions.

$$EI_{CO2e} = MAX_{CH4} \cdot MCF \cdot GWP_{CH4} \quad \text{(Eq. 26)}$$

Where

- *MAX_{CH4}* is the maximum CH_4 production
- *MCF* is the methane correction factor
- *GWP_{CH4}* is the global warming potential of methane, $GWP_{CH4} = 21$

The levelized cost of conserved carbon is taken directly from EPA (2013). The discount rate used by EPA (2013) to derive these values was 10%.

Table 12. Technical parameters and estimates for cost of conserved carbon of waste water treatment practices

Options	MAX_{CH4}	MCF	EI_{CO2e}	$LCCC$
	Maximum CH_4 production (kg CH_4/kg BOD_5)[i,ii]	Methane Correction Factor (fraction)[ii]	CO_2-eq emission intensity (t CO_2/t BOD_5)	Levelized cost of conserved carbon (USD_{2010}/t CO_2eq)[iii]
Untreated system: Stagnant sewer (open and warm)[iv]	0.6	0.4 – 0.8	5 - 10	-
Aerobic wastewater plant (WWTP)[v]	0.6	0.2 – 0.4	2.5 – 5	0 - 530
Centralized wastewater collection and WWTP[vi]	0.6	0 – 0.1	0 – 1.3	0 - 530
Aerobic biomass digester with CH_4 collection[vii]	0.6	0 – 0.1	0 – 1.3	0 - 530

[i] BOD: Biochemical Oxygen Demand. The amount of dissolved oxygen that biological organisms need in order to break down organic material into CH_4. For domestic wastewater this value is in the range of 110 – 400 mg/ l.
[ii] Based on IPCC (2006). N_2O emission are neglected, since they do not play a significant role in emissions from domestic wastewater.
[iii] These values are directly taken from EPA (2013). They are relative to regional baselines.
[iv] Untreated wastewater that is stored in a stagnant sewer under open and warm conditions.
[v] Aerobic wastewater treatment refers to the removal of organic pollutants in wastewater by bacteria that require oxygen to work. Water and carbon dioxide are the end products of the aerobic wastewater treatment process.
[vi] Centralised waste water collection improves the reduction efficiency. Processes are the same as for the aerobic treatment plant. Centralised collection of wastewater assumes that in general an infrastructure was established that ensures local wastewater storage in closed tanks and secures (emission impermeable) transport from production site to treatment plant.
[vii] Anaerobic wastewater treatment is a process whereby bacteria digest bio-solids in the absence of oxygen.

III.5 AFOLU

III.5.1 Introduction

Figure 11.16 shows ranges for baseline emission intensities of selected agricultural and forestry commodities, emission intensities after application of mitigation options and specific mitigation costs.

III.5.2 Approach

Commodity definitions are taken from FAOSTAT (2013) database where “cereals” is the aggregation of 16 cereal crops, “rice” is paddy rice, “milk” is whole, fresh milk from dairy cows, “meat” is meat from cattle only, and wood is “roundwood”.

III.5.2.1 Baseline Emission Intensities

Baseline emission intensities represent the minimum and maximum of regional averages for five world regions. For agricultural commodities (rice, cereals, milk and meat), they are calculated based on 11-year averages (2000 – 2010) of total annual CO_2-eq emissions and total annual production volumes per region taken from (FAOSTAT, 2013). The following emission categories are considered for the calculation of baseline emission intensities: “synthetic fertilizer” for cereals, “rice cultivation” for paddy rice, and “enteric fermentation” and “manure management” for milk and meat.

For production of roundwood only afforestation and reforestation of idle land is considered. Hence, baseline emission intensities are set to zero.

III.5.2.2 Improved emission intensities

Improved emission intensities are derived by deducing product-specific mitigation potentials from baseline emission intensities.

Mitigation options considered in the derivation of product-specific mitigation potentials include “improved agronomic practices”, “nutrient management”, “tillage and residue management” and “agroforestry” for cereals; “rice land management” for rice; “feeding” and “dietary additives” for milk and meat production; and “afforestation and reforestation” for roundwood production.

For cereals and paddy rice, data on mitigation potentials is provided by Smith et al. (2008) as average amount of CO_2-eq sequestered per land area for four climate zones. These values are converted into amounts of CO_2-eq sequestered per product by multiplication with global average product yields per land area based on FAOSTAT (2013).

For meat and milk, mitigation potentials are provided by Smith et al. (2008) as percentage reductions in emissions per mitigation option (see above) and region for five geographical regions. Minimum, average and maximum of five regional values per mitigation option are taken and converted into amounts of CO_2-eq sequestered per product by multiplication with an unweighted average of regional averages of emissions from enteric fermentation per product derived from FAOSTAT (2013). The derivation of the latter is done by dividing the 11-year (2000-2010) regional averages of emissions from enteric fermentation per commodity by the corresponding 11-year regional averages of the total number of producing animals for five geographical regions and by subsequently taking the unweighted average of those five regional averages. For roundwood, the carbon sequestration potential is calculated for representative tree species (based on FAO 2006 and IPCC; 2006) which match the rotation periods for short-term rotations given by Sathaye et al. (2005, 2006) for ten geographical regions. Regional and country averages are calculated based on the highest and lowest values for the ten geographical regions.

III.5.2.3 Levelized Cost of Conserved/Sequestered Carbon

Mitigation costs for agricultural mitigation options are taken from Smith et al. (2008) for cereals and paddy rice, and from US-EPA (2013) for milk and meat. For the livestock mitigation options, only the low end of the given cost range is considered. Costs for afforestation and reforestation are based on Sathaye et al. (2005, 2006).

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