Appendix B: Methodology used in Chapter 4

In section 4.2 and 4.3 of Chapter 4, we present the bottom-up assessment of emission reduction potentials in 2030. Our assessment follows five steps:

1. Select the baseline emissions for each sector in 2030.
2. Identify the abatement measures per sector that can be implemented by 2030 with a maximum cost of US$100/t$CO_2$e.
3. Investigate the emission reduction potentials for each measure in 2030 and correct the estimates to adjust to the baseline.
4. Estimate the overlap between measures and the uncertainty level of the potential of individual measures, and deduct these from the estimates.
5. Aggregate the abatement potentials of measures into sector emission reduction potentials.

We applied these five steps to every sector individually and subsequently, we aggregated the sector potentials into an estimated global emission reduction potential in 2030. To reflect uncertainties in both the sector potentials and the global potential, we provide the estimates in ranges.

Selecting the baseline (step 1)

For energy-related carbon dioxide emissions (CO_2), we used the Current Policy Scenario (CPS) of the International Energy Agency's World Energy Outlook (IEA, 2016). The CPS assumes no changes in policies from mid-2016, and it provides a level from which the impact of new policies and technologies can be measured against.

For non-CO_2 greenhouse gases, we used baselines from various sources. For example, for the agriculture sector, we used the baseline trajectories estimated by the United States Environmental Protection Agency (USEPA, 2012), which include emissions from agricultural soils, livestock management (enteric fermentation and manure management), rice cultivation and other agricultural sources such as the burning of savannahs, forest clearing and agricultural residues. Non-CO_2 energy sector emissions were taken from personal communications with IIASA (Klimont and Höglund-Isaksson, 2017). Emissions originating from fluorinated gases (HFCs, PFCs and SF_6) were taken from Purohit and Höglund-Isaksson (2017), whereas other industrial non-CO_2 emissions and emissions from stationary and mobile combustion were drawn from USEPA (2012).

For non-energy related CO_2 emissions from the calcination process in cement manufacturing we used data from the IEA (2017). For other non-energy related CO_2 emissions, such as from peatland degradation and peat fires we used the Global Peatland Database, various scientific papers and insights from personal communications with Dr. Hans Joosten, from Greifswald University. For forestry and other land use emissions, we used the baseline projections of the IMAGE-LPJmL model.

Estimating the sectoral emission reduction potentials (steps 2 to 5)

We used the most recent available literature to find estimates of emission reduction potentials in 2030. We constrained the sample of abatement measures to those that could be realised through technologies that are available by 2030 at a cost of maximum US$100/t$CO_2$e. This ensured that potentials from abatement measures that are feasible from a technological and cost perspective were chosen. The following chart shows the measures we considered in this study.

When the estimates from literature were based on baselines that differ from the ones used in this study, we made a correction to adjust to our baseline.

We estimated overlaps between abatement measures and applied a correction factor to subtract double-counting. This was done specifically in four sectors: agriculture, buildings, energy and industry sector.

- Agriculture: overlap between shifting dietary patterns and decreasing food loss and waste.

- Buildings: overlap between the construction of new buildings, retrofit of existing buildings, the implementation of energy efficient lighting and energy efficient appliances.
- Energy: overlap between solar, wind, hydropower, nuclear, bioenergy, geothermal and bioenergy with carbon capture and storage (BECCS); and overlap between carbon capture and storage (CCS) and BECCS.
- Industry: overlap between indirect energy efficiency measures and the energy supply sector.

After correcting for overlap, we calculated the uncertainty of the size of the emission reduction potentials. In some cases, the estimates we found in the literature were single point potentials, in other cases, the estimates were given in ranges. To ensure consistency and reflect the uncertainty of the size of the potentials, we applied a general ±25 percent uncertainty factor to individual abatement measures. For measures with higher uncertainty, we applied a ±50 percent uncertainty factor. We applied the latter to seven abatement measures out of 39 in total: peatland degradation and peat fires, biochar, shifting dietary patterns, decreasing food loss and waste, energy efficiency (direct and indirect), and enhanced weathering measures.

By applying these uncertainty factors, we were able to calculate the aggregated margin of error for each sector. We did this in three steps:

1. Squaring (raising to the power of two) the margin of error of each measure.
2. Calculating the total sum of the squared margins of error for each sector.
3. Applying the square root to the sectoral margins of error.

Finally, to calculate the ranges of emission reduction potentials for each sector, we applied the sectoral margins of error to each sector aggregate.

Estimating the total emission reduction potential

In addition to the ranges of emission reduction potentials for each sector, we calculated the range of the total emission reduction potential. This was done by applying a margin of error to the total emission reduction potentials. The margin of error was calculated in three steps:

1. Squaring (raising to the power of two) the margin of error of each measure.
2. Calculating the total sum of the squared margins of error of all measures.
3. Applying the square root to the sum calculated in step 2.

Current policy projections in 2030

This section of the appendix describes the current policy projections as a reference level in 2030 against which the greenhouse gas emission reductions could be achieved. This reference level is used in the bottom-up analysis (section 4.2 and 4.3 of Chapter 4).

The analysis includes the following gases: carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), perfluorocarbons (PFCs), hydrofluorocarbons (HFCs) and sulphur hexafluoride (SF_6). Black carbon is not included in the analysis. For an overview of the baseline emissions in all sectors, see Table B.1.

Energy-related carbon dioxide emissions

Energy-related CO_2 emissions are produced directly by the combustion of fossil fuels and indirectly through the use of electricity; therefore, emissions under this category cover the buildings, industry, transport and energy supply sector. The Current Policy Scenario (CPS) of the International Energy Agency's (IEA's) World Energy Outlook is taken as the reference for the assessment presented in this report (IEA, 2016). The CPS includes only those policies firmly enacted as of mid-2016. This default setting for the energy system is a benchmark from which the impact of new policies and technologies can be measured. In this scenario, energy-related CO_2 emissions increase from 32.2 gigatonnes (Gt) in 2014 to 38.6 Gt in 2030.

Agriculture

The agriculture sector is a large emitter of non-CO_2 greenhouse gases. Based on baseline trajectories developed by the U.S. Environmental Protection Agency (USEPA, 2012), agricultural soils emitting N_2O contribute significantly to the total, with about 2.48 $GtCO_2e$. Livestock management is responsible for 2.73 $GtCO_2e$ emissions in 2030, which can be subdivided into emissions originating from enteric fermentation (2.35 $GtCO_2e$) and manure management (0.38 $GtCO_2e$). Other sources of emissions are rice cultivation (0.51 $GtCO_2e$) and other agricultural sources such as the burning of savannah and burning of agricultural residues, which makes up 1.18 $GtCO_2e$ of the total, mostly emitting CH_4 and to a lesser extent N_2O (USEPA, 2012). Furthermore, CO_2 fluxes from agricultural lands are significant, though net emissions are negligible on a global scale at around 40 $MtCO_2$ (USEPA, 2013).

An important aspect to consider is that emissions from peat degradation and peat fires are often not included in climate models. Data from the Global Peatland Database maintained by the Greifswald Mire Centre shows that microbial oxidation of drained peatlands is currently responsible for 1.6 $GtCO_2e$ emissions worldwide (Tanneberger and Appulo, 2016). Regarding peat fires, Miettinen *et al*. (2017) estimate emissions of 1.2 GtC for the period 1997 to 2015 for the insular South-East Asia region. If this is all converted to CO_2, average annual emissions would be 0.23 $GtCO_2$/year. Peat fires in insular South-East Asia are expected to contribute to about half of the global emissions from peat fires. When taking into account that a substantial amount of the carbon is not oxidised to CO_2 but to more potent greenhouse gases such as CH_4 (Rossi, *et al*., 2016), global emissions are likely in the order of 0.6 $GtCO_2e$/year[1]. Combining peat degradation and peat fires results in peat global emissions of 2.2 $GtCO_2e$/year. However, given that awareness on peat degradation and peat fires is growing strongly in the insular SE Asia region, we come to a reduction under current policies of 0.3 $GtCO_2$/year by 2030, leading to total emissions of 1.9 $GtCO_2e$/year (Joosten, Couwenberg, and Von Unger, 2016; Wilson, *et al*., 2016).

Adding up the emissions originating from the agricultural sectors discussed in this section results in total emissions of 8.8 $GtCO_2e$ in 2030; this includes emissions from peatland degradation and peat fires. Excluding this category yields 6.9 $GtCO_2e$.

[1] It is important to note that there is a large degree of variability in year-to-year emissions from peat fires. In 1997, 2006 and 2015, emissions from peat fires were estimated to have exceeded those of peat oxidation (Miettinen, Hooijer, Vernimmen, Chin Liew, and Page, 2017).

Forestry and other land-use

Few recent baseline projections for the global forestry sector are published. These come with a considerable amount of uncertainty since forests are vulnerable to climate change, even under low-warming scenarios (Settele, *et al*., 2014), and are also affected by natural disturbances not linked to climate change. Currently, deforestation produces emissions of approximately 3.22 GtCO_2. This is calculated by linking IMAGE with the Dynamic Global Vegetation Model LPJmL, starting in 1970 with observed climate, and followed by climate simulations from 2005 onwards (Stehfest, Van Vuuren, Kram, and Bouwman, 2014). Baseline projections by IMAGE-LPJmL expect a slight increase to 3.44 GtCO_2e by 2030. Net deforestation emissions are projected to increase more, due to decreased uptake of CO_2e from afforestation and forest management activities, which will together absorb 0.88 GtCO_2e in 2030 under the baseline (PBL, 2017). Other land-use change emissions that decay back to the atmosphere through microbial decomposition amount to 0.93 GtCO_2e in 2030. Hence, total emissions from the forestry sector are expected to rise from 3.15 GtCO_2e in 2015 to 3.49 GtCO_2e in 2030.

Other emissions

This category groups emissions from the following sources: waste, coal mining and oil and gas systems, emissions from stationary and mobile combustion, substitutes for ozone-depleting substances, calcination processes in the cement industry and other industrial sources.

Total emissions originating from the waste sector are estimated to be 1.7 GtCO_2e in 2030 (USEPA, 2012) and are predominantly made of methane emissions. About 10 percent of the emissions are N_2O.

Energy sector methane emissions are taken from Höglund-Isaksson (2012), who recently updated these to reflect IEA data from 2016 (Klimont and Höglund-Isaksson, 2017). This study focuses specifically on the development of methane emissions up to 2030. Emissions from coal mining and oil and gas systems are the most significant and add up to 3.1 GtCO_2.

Emissions originating from fluorinated gases (HFCs, PFCs and SF_6) were taken from Purohit and Höglund-Isaksson (2017), who estimate that emissions from substitutes for ozone-depleting substances in the current policy scenario are 1.6 GtCO_2e in 2030, and that emissions from HCFC-22 production are 0.2 GtCO_2e in 2030[2]. Other industrial non-CO_2 emissions, such as N_2O from the production of adipic acid and nitric acid, are taken from (USEPA, 2012). Methane and nitrous oxide emissions from stationary and mobile combustion, e.g. from airplanes and automobiles, are estimated to be 0.77 GtCO_2e in 2030 (USEPA, 2012).

Emissions from the calcination process in the cement industry are based on the expected cement production of 4,595 Mt in 2030 (IEA, 2017) and the emission factor for process emissions in cement (Van Ruijven, Vuuren, Boskaljon, Neelis, and D. Sasygin, 2016). The cement process emissions in the baseline are estimated at 2.3 GtCO_2e.

Current policy projections in 2030

For a detailed sectoral breakdown in the current policy projection, see Table B.1. The total emissions projected for 2030 amount to 61.1 GtCO_2e. If we exclude emissions from peat degradation and peat fires we arrive at 59.2 GtCO_2e.

[2] The same study estimates that if the Kigali Amendment is in place, this will reduce emissions from substitutes for ozone-depleting substances to 1.0 Gt CO_2e in 2030.

Table B.1: Emissions by sector in the current policy scenario ($GtCO_2e$). The emissions related to electricity production are also allocated to the end-use sectors, so these are listed twice in this table. These allocated emissions are given in grey italics and not counted in the total figure (USEPA, 2012, IEA, 2016; IEA, 2017; Klimont, 2017).

Sector	Category	Gas	2030 emissions ($GtCO_2e$)	Sector aggregates ($GtCO_2e$)
Agriculture	Agricultural soils	N_2O	2.48	8.8
	Enteric fermentation	CH_4	2.35	
	Manure	CH_4, N_2O	0.38	
	Rice cultivation	CH_4, N_2O	0.51	
	Other agricultural sources (incl. burning of savannahs and from forest clearing, agricultural residues)	CH_4, N_2O	1.18	
	Peat degradation and peat fires[3]	CO_2, CH_4	1.9	
Buildings	Direct energy use	CO_2	3.7	3.7
	Electricity use-related	*CO_2*	*8.89*	
Energy	Electricity production	CO_2	16.31	21.3
	Other energy conversion	CO_2	1.85	
	Natural gas and oil systems	CH_4	2.38	
	Coal mining	CH_4	0.73	
Forestry	Deforestation	CO_2	3.44	3.5
	Afforestation and forest management	CO_2	-0.88	
	Other land-use change	CO_2	0.93	
Industry	Industry direct energy-related emissions	CO_2	7.31	12.7
	Electricity use-related emissions	*CO_2*	*6.58*	
	Process emissions for cement production	CO_2	2.3	
	Emissions from stationary and mobile combustion	CH_4, N_2O	0.77	
	Substitutes for Ozone-Depleting Substances	HFCs	1.6	
	HCFC-22 production	HFC-23	0.2	
	Other industrial sources	All non-CO_2	0.5	
Other	*Other electricity use-related*	*CO_2*	*0.56*	1.7
	Landfilling of solid waste	CH_4	0.96	
	Other waste sources	CH_4, N_2O	0.03	
	Wastewater	CH_4, N_2O	0.71	
Transport	Direct energy use	CO_2	9.42	9.4
	Transport electricity use-related	*CO_2*	*0.28*	
Total including peatland emissions		**CO_2e**	**61.1**	
Total excluding peatland emissions		**CO_2e**	**59.2**	

[3] This emission category is often not included in climate models.

Baseline scenario used in the Integrated Assessment Models analysis

In section 4.4 of Chapter 4, we made a comparison of the bottom-up analysis with the results from Integrated Assessment Models. For this comparison, we used the SSP2 baseline results scenario as developed by six IAMs (Riahi *et al*., 2017). The SSP2 is the 'middle-of-the-road' scenario of the Shared Socioeconomic Pathways, a new scenario framework facilitating the integrated analysis of future climate policy and impacts. Subsequently, we compared the derived mitigation scenarios aiming for a likely (>66 percent) probability of staying below $2^{o}C$, with the bottom-up assessment of mitigation potential. It should be noted that the SSP2 baseline scenarios range from 62 – 69 $GtCO_2e$, which is higher than the baseline emissions used in Table B.1, i.e. 59 $GtCO_2e$. The reason is that SSP2 shows emission development in the absence climate policies, whereas the baseline of the sector-by-sector analysis is a current policies scenario. Estimates of current policies scenarios in IAM models (e.g. Tavoni *et al*., 2016) show a similar emission range as included in table B.1.

At the sector level, the model-based projections show that baseline emissions can grow rapidly in industry and transport sectors. Direct emissions from the buildings sector, in contrast, are projected to grow only slowly or even stabilize due to an increase in electrification rates (Edelenbosch, forthcoming).

Figure B.1 also shows that a similar sectoral pattern emerges in the SSP2 set as in the sector-by-sector analysis implying that it is possible to also compare the mitigation potential. While in the electricity and agriculture sector, the sector-by-sector baseline emissions are significantly below the average of the IAMs, they are in most sectors within or close to the total range reported by the IAMs.

The results of the comparative analysis are presented in figure 4.2 of chapter 4. To facilitate the reading of this figure, Table B.1 below, illustrates the equivalence between the sector categories used in the bottom-up analysis and those used in the IAM assessment.

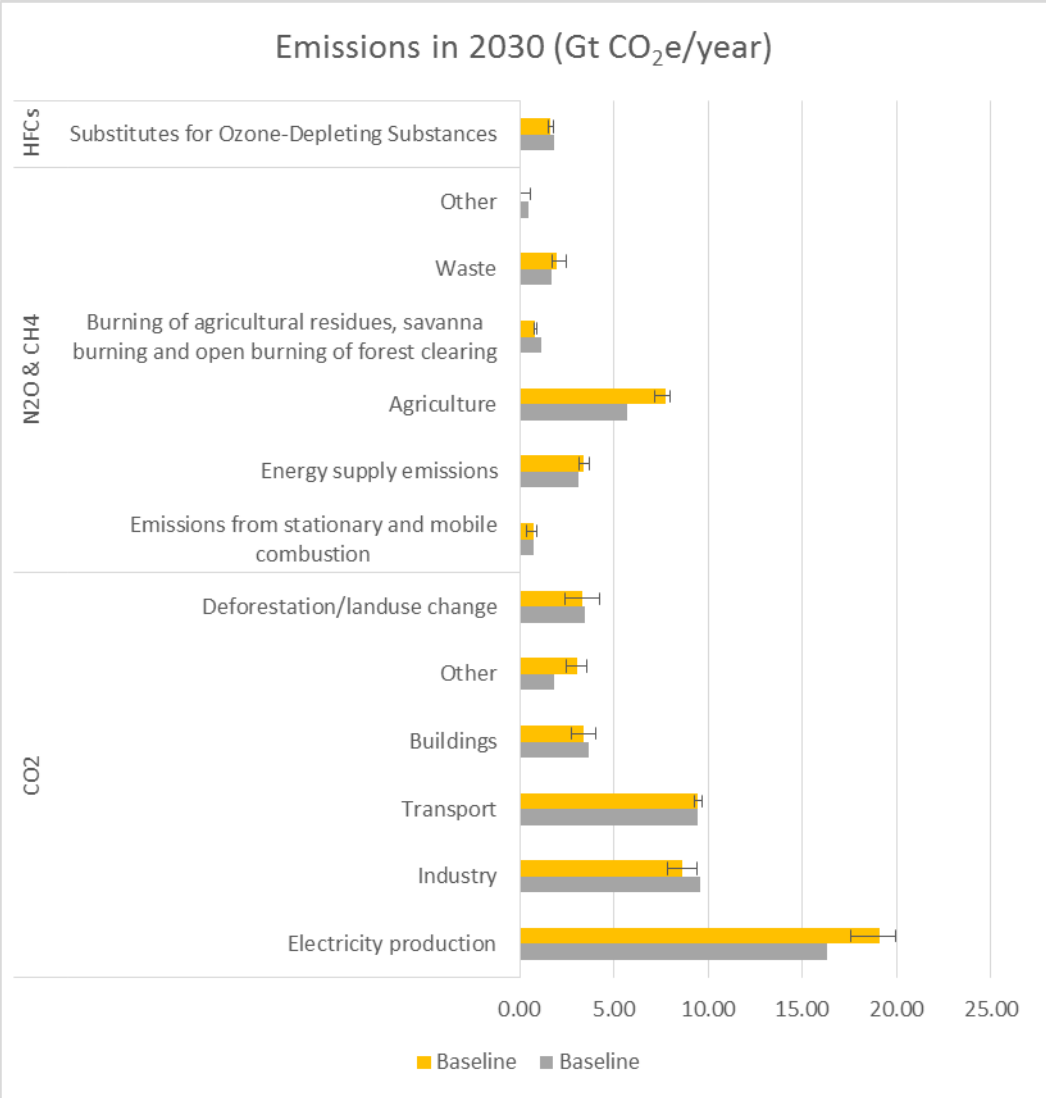

Figure B.1: Comparison of the 2030 baseline emissions in the sector-by-sector analysis with the baselines assumed in the six integrated assessment models. **The IAM results show the mean and the 15-85% percentile range. For the latter, the average, highest and lowest values are given**.

Table B.1. The bottom-up analysis sector categories equivalent to those used in the IAM analysis

Sector	Categories used in the bottom-up analysis	Categories used in the IAM analysis
Energy	Electricity production	Electricity production
	Natural gas and oil systems	Energy supply emissions
	Other energy conversion	Energy supply emissions
	Coal mining	Energy supply emissions
Industry	Industry direct energy emissions	Industry
	Process emissions for cement production	Industry
	Emissions from stationary and mobile combustion	Emissions from stationary and mobile combustion
	Substitutes for Ozone-Depleting Substances	Substitutes for Ozone-Depleting Substances
	HCFC-22 production	Substitutes for Ozone-Depleting Substances
	Wastewater	Waste
	Other waste sources	Waste
	Other industrial sources	Other
Other	Landfilling of solid waste	Waste
Buildings	Buildings direct energy	Buildings
Transport	Transport	Transport
Forestry	Deforestation	Deforestation/land use change
	Afforestation and forest management	Deforestation/land use change
	Other land-use change	Deforestation/land use change
Agriculture	Agricultural soils	Agriculture
	Enteric fermentation	Agriculture
	Rice cultivation	Agriculture
	Manure management	Agriculture
	Other agricultural sources (incl. burning of savannahs and from forest clearing, agricultural residues)	Burning of agricultural residues, savanna burning and open burning of forest clearing

References

IEA. (2016). *World Energy Outlook 2016.* Paris: International Energy Agency.

Joosten, H., Couwenberg, J., and Von Unger, M. (2016). International carbon policies as a new driver for peatland restoration. In A. Bonn, T. Allott, M. Evans, H. Joosten, and R. Stoneman, *Peatland restoration and ecosystem services: Science, policy and practice* (S. 291-313). Cambridge: Cambridge University Press/British Ecological Society.

Klimont, Z., and Höglund-Isaksson, L. (2017). *Personal communication.* IIASA.

Miettinen, J., Hooijer, A., Vernimmen, R., Chin Liew, S., and Page, S. (2017). From carbon sink to carbon source: extensive peat oxidation in insular Southeast Asia since 1990. *Environmental Research Letters*.

PBL. (2017). *IMAGE baseline - land-use emissions.* (Unpublished).

Purohit, P., and Höglund-Isaksson, L. (2017). Global emissions of fluorinated greenhouse gases 2005–2050 with abatement potentials and costs. *Atmos. Chem. Phys., 17*, 2795–2816. doi:10.5194/acp-17-2795-2017

Rossi, S., Tubiello, F., Prosperi, P., Salvatore, M., Jacobs, H., Biancalani, R., Boschetti, L. (2016). FAOSTAT estimates of greenhouse gas emissions from biomass and peat fires. *Climatic Change*, 699-711.

Settele, J., Scholes, R., Betts, R., Bunn, S., Leadley, P., Nepstad, D., Taboada, M. (2014). *Terrestrial and inland water systems. In: Climate Change 2014: Impacts, Adaptation, and Vulnerability.* Cambridge and New York: Cambridge University Press.

Stehfest, E., Van Vuuren, D., Kram, T., and Bouwman, L. (2014). *Integrated Assessment of Global Environmental Change with IMAGE 3.0 - Model description and policy applications.*

Tanneberger, F., and Appulo, L. (2016). Peat for speed. *UNFCCC COP22 Marrakech.* Wetlands International and Greifswald Mire Centre.

USEPA. (2012). *Global Anthropogenic Non-CO2 Greenhouse Gas Emissions: 1990 - 2030.*

USEPA. (2013). *Global Mitigation of Non-CO2 Greenhouse Gases: 2010-2030.*

Van Ruijven, B., Vuuren, D. v., Boskaljon, W., Neelis, M., and D. Sasygin, M. P. (2016). Long-term model-based projections of energy use and CO2 emissions from the global steel and cement industries. *Resources, Conservation and Recycling, 112*, 15-36. Von https://doi.org/10.1016/j.resconrec.2016.04.016 abgerufen

Wilson, D., Blain, D., Couwenberg, J., Evans, C., Murdiyarso, D., Page, S., Tuittila, E.-S. (2016). Greenhouse gas emission factors associated with rewetting of organic soils. *Mires and Peat*, 1-28.