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Annex II

Metrics and Methodology

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Annex II: Methods and Metrics

Contents

A.II.1 Standard units and unit conversion

The following section A.II.1.1 introduces standard units of measurement that are used throughout this report. This includes Système International (SI) units, SI-derived units and other non-SI units as well the standard prefixes for basic physical units. It builds upon similar material from previous IPCC reports.

In addition to establishing a consistent set of units for reporting throughout the report, harmonized conventions for converting units as reported in the scientific literature have been established and are summarized in Section A.II.1.2 (physical unit conversion) and Section A.II.1.3 (monetary unit conversion).

A.II.1.1 Standard units

Table A.II.1. Système International (SI) units

Physical Quantity	**Unit**	**Symbol**
Length	meter	m
Mass	kilogram	kg
Time	second	s
Thermodynamic temperature	kelvin	K
Amount of substance	mole	mol

Table A.II.2. Special names and symbols for certain SI-derived units

Physical Quantity	**Unit**	**Symbol**	**Definition**
Force	Newton	N	kg m s^2
Pressure	Pascal	Pa	kg m^–1 s^–2 (= N m^–2)
Energy	Joule	J	kg m^2 s^–2
Power	Watt	W	kg m^2 s^–3 (= J s^–1)
Frequency	Hertz	Hz	s^–1 (cycles per second)

Table A.II.3. Non-SI standard units

Monetary units	**Unit**	**Symbol**
Currency (Market Exchange Rate)	constant US Dollar 2010	USD_{2010}
Emission- and Climate-related units	**Unit**	**Symbol**
Emissions	Metric Tonnes	T
CO2 Emissions	Metric Tonnes CO2	tCO2
CO2-equivalent Emissions	Metric Tonnes CO2-equivalent	tCO2-e
Abatement Costs and Emissions Prices/Taxes	constant US Dollar 2010 per metric tonne	USD_{2010}/t
CO2 concentration or mixing ratio (µmol mol–1)	Parts per million (10^6)	ppm
CH4 concentration or mixing ratio (µmol mol–1)	Parts per billion (10^9)	ppb
N2O concentration or mixing ratio (µmol mol–1)	Parts per billion (10^9)	ppb
Energy-related units	**Unit**	**Symbol**
Energy	Joule	J
Electricity and Heat generation	Watt Hours	Wh
Power (peak capacity)	Watt (Watt thermal, Watt electric)	W
Capacity Factor	Percent	%

Technical and Economic Lifetime	Years	yr
Specific Energy Investment Costs	USD2010/kW (peak capacity)	USD$_{2010}$/kW
Energy Costs (e.g. LCOE) and Prices	constant US Dollar 2010 per GJ or US Cents 2010 per kWh	USD$_{2010}$/GJ and USct$_{2010}$/kWh
Land-related units	**Unit**	**Symbol**
Area	Hectare	ha

Table A.II.4. Prefixes for basic physical units

Multiple	Prefix	Symbol	Fraction	Prefix	Symbol
1E+21	zeta	Z	1E-01	deci	d
1E+18	exa	E	1E-02	centi	c
1E+15	peta	P	1E-03	milli	m
1E+12	tera	T	1E-06	micro	µ
1E+09	giga	G	1E-09	nano	n
1E+06	mega	M	1E-12	pico	p
1E+03	kilo	k	1E-15	femto	f
1E+02	hecto	h	1E-18	atto	a
1E+01	deca	da	1E-21	zepto	z

A.II.1.2 Physical unit conversion

Table A.II.5. Conversion table for common mass units (IPCC, 2001)

To:		kg	t	lt	St	lb
From:	multiply by:					
kilogram	kg	1	1.00E-03	9.84E-04	1.10E-03	2.20E+00
tonne	t	1.00E+03	1	9.84E-01	1.10E+00	2.20E+03
long ton	lt	1.02E+03	1.02E+00	1	1.12E+00	2.24E+03
short ton	st	9.07E+02	9.07E-01	8.93E-01	1	2.00E+03
Pound	lb	4.54E-01	4.54E-04	4.46E-04	5.00E-04	1

Table A.II.6. Conversion table for common volumetric units (IPCC, 2001)

To:		gal US	gal UK	bbl	ft3	l	m3
From:	multiply by:						
US Gallon	gal US	1	8.33E-01	2.38E-02	1.34E-01	3.79E+00	3.80E-03
UK/Imperial Gallon	gal UK	1.20E+00	1	2.86E-02	1.61E-01	4.55E+00	4.50E-03
Barrel	bbl	4.20E+01	3.50E+01	1	5.62E+00	1.59E+02	1.59E-01
Cubic foot	ft3	7.48E+00	6.23E+00	1.78E-01	1	2.83E+01	2.83E-02
Liter	l	2.64E-01	2.20E-01	6.30E-03	3.53E-02	1	1.00E-03
Cubic meter	m3	2.64E+02	2.20E+02	6.29E+00	3.53E+01	1.00E+03	1

Table A.II.7. Conversion table for common energy units (NAS, 2007; IEA, 2012a)

To:		TJ	Gcal	Mtoe	Mtce	MBtu	GWh
From:	multiply by:						
Tera Joule	TJ	1	2.39E+02	2.39E-05	3.41E-05	9.48E+02	2.78E-01
Giga Calorie	Gcal	4.19E-03	1	1.00E-07	1.43E-07	3.97E+00	1.16E-03
Mega Tonne Oil Equivalent	Mtoe	4.19E+04	1.00E+07	1	1.43E+00	3.97E+07	1.16E+04
Mega Tonne Coal Equivalent	Mtce	2.93E+04	7.00E+06	7.00E-01	1	2.78E+07	8.14E+03
Million British Thermal Units	MBtu	1.06E-03	2.52E-01	2.52E-08	3.60E-08	1	2.93E-04
Giga Watt Hours	GWh	3.60E+00	8.60E+02	8.60E-05	0.000123	3.41E+03	1

A.II.1.3 Monetary unit conversion

To achieve comparability across cost und price information from different regions, where possible all monetary quantities reported in the WGIII AR5 have been converted to constant US Dollars 2010 (USD$_{2010}$). To facilitate a consistent monetary unit conversion process, a simple and transparent procedure to convert different monetary units from the literature to USD$_{2010}$ was established which is described below [Author note to reviewers: this may not have been fully implemented in the SOD].

It is important to note that there is no single agreed upon method of dealing with monetary unit conversion, and thus data availability, transparency and – for practical reasons – simplicity were the most important criteria for choosing a method to be used throughout this report.

To convert from year X local currency unit (LCU$_X$) to 2010 US Dollars (USD$_{2010}$) two steps are necessary:

1. in-/deflating from year X to 2010, and
2. converting from LCU to USD.

In practice, the order of applying these two steps will lead to different results. In this report, the conversion route LCU$_X$ -> LCU$_{2010}$ -> USD$_{2010}$ is adopted, i.e. national/regional deflators are used to measure country- or region-specific inflation between year X and 2010 in local currency and current (2010) exchange rates are then used to convert to USD$_{2010}$.

To reflect the change in prices of all goods and services that an economy produces, and to keep the procedure simple, the economy's GDP deflator is chosen to convert to a common base year. Finally, when converting from LCU$_{2010}$ to USD$_{2010}$, official 2010 exchange rates which are readily available, but on the downside often fluctuate significantly in the short term, are adopted for currency conversion in the report.

Consistent with the choice of the World Bank databases as the primary source for GDP and other financial data throughout the report, deflators and exchange rates from the World Bank's World Development Indicators (WDI) database (World Bank, 2013) is used.

To summarize, the following procedure has been adopted to convert monetary quantities reported in LCU$_X$ to USD$_{2010}$:

1. Use the country-/region-specific deflator and multiply with the deflator value to convert from LCU$_X$ to LCU$_{2010}$.
   In case national/regional data are reported in non-LCU units (e.g., USD$_X$ or Euro$_X$) which is often the case in multi-national or global studies, apply the corresponding currency deflator to convert to 2010 currency (i.e. the US deflator and the Eurozone deflator in the examples above).

2. Use the appropriate 2010 exchange rate to convert from LCU_{2010} to USD_{2010}.

A.II.2 Costs Metrics

Across this report, a number of different metrics to characterize cost of climate mitigation are employed. These cost metrics reflect the different levels of detail and system boundaries at which mitigation analysis is conducted. For example, in response to mitigation policies, different technologies are deployed across different sectors. To facilitate a meaningful comparison of economics across diverse options at the technology level, the metric of "levelised costs" is used throughout several chapters (7, 8, 9, 10) of this report in various forms (Section A.II.2.1). In holistic approaches to climate mitigation, such as the ones used in Chapter 6 on transformation pathways, different mitigation cost metrics are used, the differences among which are discussed in Section A.II.2.2.

A.II.2.1 Levelised costs

The general concept of levelised costs is described in Section A.II.2.1.1 using the example of the most commonly used application of levelised cost of energy (LCOE) which mostly applies to the supply side of the energy system (Chapter 7). Another application of the levelised cost concept that is used predominantly on the demand side is levelised costs of conserved energy, alternatively referred to as cost of conserved energy, applications of which are introduced in Sections A.II.2.1.2.

A.II.2.1.1 Concept, methodology and levelised costs of energy

In order to compare energy supply technologies from an economic point of view, the concept of "levelised costs of energy" (LCOE, also called levelised unit costs or levelised generation costs) frequently is applied (IEA and NEA, 2005; Edenhofer et al., 2011; Larson et al., 2012; Turkenburg et al., 2012; UNEP, 2012). Simply put, "levelised" cost of energy is a measure which is equal to the long-run "average" cost of a unit of energy provided by the considered technology (albeit, calculated correctly in an economic sense by taking into account the time value of money). Strictly speaking, the levelised cost of energy is "the cost per unit of energy that, if held constant through the analysis period, would provide the same net present revenue value as the net present value cost of the system." (Short et al., 1995, p. 93). The calculation of the respective "average" cost (expressed, for instance in US cent/kWh or USD/GJ) palpably facilitates the comparison of projects, which differ in terms of plant size and/or plant lifetime.

According to the definition given above "the levelised cost is the unique break-even cost price where discounted revenues (price x quantities) are equal to the discounted net expenses" (Moomaw et al., 2011):

$$\sum_{t=0}^{n} \frac{E_t \cdot LCOE}{(1+i)^t} := \sum_{t=0}^{n} \frac{Expenses_t}{(1+i)^t}$$

(Eq. 1)

where LCOE are the levelised cost of energy, E_t is the energy delivered in year *t* (which might vary from year to year), $Expense_t$ cover all (net) expenses in the year t, *i* is the discount rate and *n* the lifetime of the project.

After solving for LCOE this gives:

$$LCOE := \frac{\sum_{t=0}^{n} \frac{Expenses_t}{(1+i)^t}}{\sum_{t=0}^{n} \frac{E_t}{(1+i)^t}}$$

(Eq. 2)

Note that while it appears as if energy amounts were discounted in Eq. 2, this is just an arithmetic result of rearranging Eq. (1) (Branker et al., 2011). In fact, originally, revenues are discounted and not energy amounts per se (see Eq. 1).

Considering energy conversion technologies, the lifetime expenses comprise investment costs *I*, operation and maintenance cost *O&M* (including waste management costs), fuel costs *F*, carbon costs *C*, and decommissioning costs *D.* In this case, levelised cost can be determined by (IEA and NEA, 2005, p. 34):

$$LCOE := \frac{\sum_{t=0}^{n} \frac{I_t + O\&M_t + F_t + C_t + D_t}{(1+i)^t}}{\sum_{t=0}^{n} \frac{E_t}{(1+i)^t}}$$

(Eq. 3)

In simply cases, where the provided energy is constant during the lifetime of the project, this translates to:

$$LCOE := \frac{CRF \cdot NPV(Lifetime\ Expenses)}{E} = \frac{Annuity\ (Lifetime\ Expenses)}{E}$$

(Eq. 4)

where $CRF := \frac{i(1+i)^n}{(1+i)^n - 1}$ is the capital recovery factor and NPV the net present value of all lifetime expenditures (Suerkemper et al., 2012).

The LCOE of a technology is not the sole determinant of its value or economic competitiveness. In addition, integration and transmission costs, relative environmental impacts must be considered (e.g., by using external costs), as well as the contribution of a technology to meeting specific energy services, for example, peak electricity demands (Heptonstall, 2007). Joskow (2011) for instance, pointed out that LCOE comparisons of intermittent generating technologies (such as solar energy converters and wind turbines) with dispatchable power plants (e.g., coal or gas power plants) may be misleading as theses comparisons fail to take into account the different production schedule and the associated differences in the market value of the electricity that is provided.

Taking these shortcomings into account, there seems to be a clear understanding that LCOE are not intended to be a definitive guide to actual electricity generation investment decisions e.g. (IEA and NEA, 2005; DTI, 2006). Some studies suggest that the role of levelised costs is to give a ‘first order assessment’ (EERE, 2004) of project viability. In order to capture the existing uncertainty, sensitivity analyses, which are sometimes based on Monte Carlo methods, are frequently carried out in numerical studies. Darling et al. (2011), for instance, suggest that transparency could be improved by calculating LCOE as a distribution, constructed using input parameter distributions, rather than a single number. Studies based on empirical data, in contrast, may suffer from using samples that do not cover all cases. Summarizing country studies in an effort to provide a global assessment, for instance, might have a bias as data for developing countries often are not available (IEA, 2012b).

As Section 7.8.2 shows, typical LCOE ranges are broad as values vary across the globe depending on the site-specific renewable energy resource base, on local fuel and feedstock prices as well as on country specific projected costs of investment, financing, and operation and maintenance. While noting that system and installation costs vary widely, Branker et al. (2011) document significant variations in the underlying assumptions that go into calculating LCOE for PV, with many analysts not taking into account recent cost reductions or the associated technological advancements. In summary, a comparison between different technologies should not be based on LCOE data solely; instead, site-, project- and investor specific conditions should be considered.

A.II.2.1.2 Levelised costs of conserved energy

The concept of “levelised costs of conserved energy” (LCCE), or more frequently referred to as "cost of conserved energy (CCE)", is very similar to the LCOE concept, primarily intended to be used for comparing the cost of a unit of energy saved to the price/cost of providing energy. In essence the concept, similarly to LCOE, also annualises the investment and operation and maintenance cost differences between a baseline technology and the energy-efficiency alternative, and divides this quantity by the annual energy savings (Brown et al., 2008). Similarly to LCOE, it also bridges the time lag between the initial additional investment and the future energy savings through the application of the capital recovery factor (Meier, 1983). Its conceptual formula is essentially the same as Eq. 4 above, with "E" meaning in this context the amount of energy saved annually (Hansen, 2012):

$$CCE = \frac{CRF \cdot \Delta I}{\Delta E_t}$$

(Eq. 5)

Where ΔI is the difference in investment costs of an energy saving measure (e.g. in USD) as compared to a baseline investment; ΔEt is the annual energy conserved by the measure (e.g. in kWh) as compared to the usage of the baseline technology; and CRF is the capital recovery factor depending on the discount rate i and the lifetime of the measure n in years as defined above.

The key difference in the concept with LCOE is the usage of a reference/baseline technology. LCCE can only be interpreted in context of a reference, and is thus very sensitive to how this reference is chosen. For instance, the replacement of a very inefficient refrigerator can be very cost-effective, but if we consider an already relatively efficient product as the reference technology, the CCE value can be many times higher.

The main strength of the CCE concept is that it provides a metric of energy saving investments that are independent of the energy price, and can thus be compared to different energy cost/price values for determining the profitability of the investment.

For the calculation of CCE, a few challenges should be pinpointed. First of all, the lifetimes of the efficient and the reference technology may be different. In this case the investment cost difference needs to be used that incurs throughout the lifetime of the longer-living technology. For instance, a compact fluorescent lamp (CFL) lasts as much as 10 times as long as an incandescent lamp, and thus in the calculation of the CCE for a CFL replacing an incandescent lamp the cost difference of the CFL and 10 incandescent lamps need to be used (Ürge-Vorsatz, 1996). In such a case, as in some other cases, too, the difference can be negative, leading the CCE values to be negative. Negative CCE values mean that the investment is already profitable at the investment level, without the need for the energy savings to recover the extra investment costs.

In case there are operation and maintenance costs (OM) differences between the baseline and efficient technology, these also enter the CCE calculation, similarly to Eq. 3 above:

$$CCE = \frac{CRF \cdot \Delta I + \Delta OM}{\Delta E_t}$$

(Eq. 6)

These can be important for applications where there are significant OM costs, for instance, the lamp replacement on streetlamps, bridges. In such cases a longer-lifetime product, as it typically applies to efficient lighting technologies, is already associated with negative costs at the investment level (less frequent needs for labour to replace the lamps), and thus can result in significantly negative CCEs or cost savings (Ürge-Vorsatz, 1996).

A.II.2.2 Mitigation cost metrics

There is no single metric for reporting the costs of mitigation, and the metrics that are available are not directly comparable (see Section 3.10.2 for a more general discussion; see Section 6.3.6 for an overview of costs used in model analysis). In economic theory the most direct cost measure is a change in welfare due to changes in the amount and composition of consumption of goods and services by individuals. Important measures of welfare change include "equivalent variation" and "compensating variation" which attempt to discern how much individual income would need to change to keep consumers just as well off after the imposition of a policy as before. However, these are quite difficult to calculate, so a more common welfare measurement is change in consumption, which captures the total amount of money consumers are able to spend on goods and services. Another common metric is the change in gross domestic product (GDP). However, GDP is a less satisfactory indicator of overall cost than those focused on individual income and consumption, because it is a measure of output, which includes not only consumption, but also investment, imports and exports, and government spending. A final common measure is the "deadweight loss" or "area on the marginal abatement cost function", which suffers from similar limitations as GDP.

From a practical perspective, different modelling frameworks applied in climate mitigation analysis are capable of producing different cost estimates (Section 6.2). Therefore, when comparing cost estimates across climate mitigation scenarios from different models, some degree of incomparability must necessarily result. In representing costs across transformation pathways in this report and more specifically Chapter 6, consumption losses are used preferentially when available from general equilibrium models, and costs represented by the area under the marginal abatement cost function or additional energy system costs are used for partial equilibrium measures.

One popular measure used in different studies to evaluate the economic implications of mitigation actions is the emissions price, often presented in per metric ton of CO_2 or, in case of multiple gases, per metric ton of CO_2-equivalent. However, it is important to emphasize that emissions prices are not cost measures. There are two important reasons why emissions prices are not a meaningful representation of costs. First, emissions prices measure marginal cost; that is, the cost of an additional unit of emissions reduction. In contrast, total costs represent the costs of all mitigation that took place at lower cost than the emissions price. Without explicitly accounting for these "inframarginal" costs, it is impossible to know how the carbon price relates to total mitigation costs. Second, emissions prices can interact with other policies and measures, either regulatory policies directed at greenhouse gas reduction (for example, renewable portfolio standards or subsidies to carbon-free technologies) or other taxes on energy, labour, or capital. If mitigation is achieved partly by these other measures, the emissions price will not take into account the full costs of an additional unit of emissions reductions, and will indicate a lower marginal cost than is actually warranted.

It is often important to calculate the total cost of mitigation borne over the life of the policy. To compare costs over time, conventional economic practices apply a discount rate to future costs on the basis that money today would earn a return over time. The discount rate, which represents how much less society values the future payments in comparison to the present payments of the same size, is a key parameter, and there are different views on what the appropriate rate is for climate policy (see Section 3.6, (Portney and Weyant, 1999; Nordhaus, 2006; Stern, 2007)). Transformation pathways in the literature have been derived under a range of assumptions about discount rates.

A.II.3 Primary energy accounting

Following the standard set by the IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation (SRREN), this report adopts the direct-equivalent accounting method for the reporting of primary energy from non-combustible energy sources. The following section largely draws from Annex II of the SRREN (Moomaw et al., 2011) and summarizes the most relevant points.

Different energy analyses use a variety of accounting methods that lead to different quantitative outcomes for both reporting of current primary energy use and energy use in scenarios that explore future energy transitions. Multiple definitions, methodologies and metrics are applied. Energy accounting systems are utilized in the literature often without a clear statement as to which system is being used (Lightfoot, 2007; Martinot et al., 2007). An overview of differences in primary energy accounting from different statistics has been described by Macknick (2011) and the implications of applying different accounting systems in long-term scenario analysis were illustrated by Nakicenovic *et al.*, (1998), Moomaw et al. (2011) and Grubler et al. (2012).

Three alternative methods are predominantly used to report primary energy. While the accounting of combustible sources, including all fossil energy forms and biomass, is identical across the different methods, they feature different conventions on how to calculate primary energy supplied by non-combustible energy sources, i.e. nuclear energy and all renewable energy sources except biomass. These methods are:

- *the physical energy content method* adopted, for example, by the OECD, the International Energy Agency (IEA) and Eurostat (IEA/OECD/Eurostat, 2005),
- *the substitution method* which is used in slightly different variants by BP (2012) and the US Energy Information Administration (EIA, 2012a, b, Table A6), both of which publish international energy statistics, and
- *the direct equivalent method* that is used by UN Statistics (2010) and in multiple IPCC reports that deal with long-term energy and emission scenarios (Nakicenovic and Swart, 2000; Morita et al., 2001; Fisher et al., 2007; Fischedick et al., 2011).

For non-combustible energy sources, the *physical energy content method* adopts the principle that the primary energy form should be the first energy form used down-stream in the production process for which multiple energy uses are practical (IEA/OECD/Eurostat, 2005). This leads to the choice of the following *primary* energy forms:

- heat for nuclear, geothermal and solar thermal, and
- electricity for hydro, wind, tide/wave/ocean and solar PV.

Using this method, the primary energy equivalent of hydro energy and solar PV, for example, assumes a 100% conversion efficiency to “primary electricity”, so that the gross energy input for the source is 3.6 MJ of primary energy = 1 kWh electricity. Nuclear energy is calculated from the gross generation by assuming a 33% thermal conversion efficiency[1], i.e. 1 kWh = (3.6 ÷ 0.33) = 10.9 MJ. For geothermal, if no country-specific information is available, the primary energy equivalent is calculated using 10% conversion efficiency for geothermal electricity (so 1 kWh = (3.6 ÷ 0.1) = 36 MJ), and 50% for geothermal heat.

The *substitution method* reports primary energy from non-combustible sources in such a way as if they had been substituted for combustible energy. Note, however, that different variants of the substitution method use somewhat different conversion factors. For example, BP applies 38% conversion efficiency to electricity generated from nuclear and hydro whereas the World Energy Council used 38.6% for nuclear and non-combustible renewables (WEC, 1993; Grübler et al., 1996; Nakicenovic et al., 1998), and EIA uses still different values. For useful heat generated from non-combustible energy sources, other conversion efficiencies are used. Macknick (2011) provides a more complete overview.

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[1] As the amount of heat produced in nuclear reactors is not always known, the IEA estimates the primary energy equivalent from the electricity generation by assuming an efficiency of 33%, which is the average of nuclear power plants in Europe (IEA, 2012b).

The *direct equivalent method* counts one unit of secondary energy provided from non-combustible sources as one unit of primary energy, i.e. 1 kWh of electricity or heat is accounted for as 1 kWh = 3.6 MJ of primary energy. This method is mostly used in the long-term scenarios literature, including multiple IPCC reports (Watson et al., 1995; Nakicenovic and Swart, 2000; Morita et al., 2001; Fisher et al., 2007; Fischedick et al., 2011), because it deals with fundamental transitions of energy systems that rely to a large extent on low-carbon, non-combustible energy sources.

The accounting of combustible sources, including all fossil energy forms and biomass, includes some ambiguities related to the definition of the heating value of combustible fuels. The higher heating value (HHV), also known as gross calorific value (GCV) or higher calorific value (HCV), includes the latent heat of vaporisation of the water produced during combustion of the fuel. In contrast, the lower heating value (LHV) (also: net calorific value (NCV) or lower calorific value (LCV)) excludes this latent heat of vaporization. For coal and oil, the LHV is about 5% less than the HHV, for most forms of natural and manufactured gas the difference is 9-10%, while for electricity and heat there is no difference as the concept has no meaning in this case (IEA, 2012a).

In the Working Group III Fifth Assessment Report, IEA data are utilized, but energy supply is reported using the *direct equivalent method*. In addition, the reporting of combustible energy quantities, including primary energy, should use the LHV which is consistent with the IEA energy balances (IEA, 2012a; b). Table A.II.8 compares the amounts of global primary energy by source and percentages using the *physical energy content, the direct equivalent* and a variant of the *substitution method* for the year 2010 based on IEA data (IEA, 2012b). In current statistical energy data, the main differences in absolute terms appear when comparing nuclear and hydro power. As they both produced comparable amounts of electricity in 2008, under both *direct equivalent* and *substitution methods*, their share of meeting total final consumption is similar, whereas under the *physical energy content method,* nuclear is reported at about three times the primary energy of hydro.

Table A.II.8. Comparison of global total primary energy supply in 2010 using different primary energy accounting methods (data from IEA (2012b)).

	Physical content method		**Direct equivalent method**		**Substitution method**[2]	
	EJ	**%**	**EJ**	**%**	**EJ**	**%**
Fossil fuels	432.99	81.32	432.99	84.88	432.99	78.83
Nuclear	30.10	5.65	9.95	1.95	26.14	4.76
Renewables	69.28	13.01	67.12	13.16	90.08	16.40
Bioenergy	52.21	9.81	52.21	10.24	52.21	9.51
Solar	0.75	0.14	0.73	0.14	1.03	0.19
Geothermal	2.71	0.51	0.57	0.11	1.02	0.19
Hydro	12.38	2.32	12.38	2.43	32.57	5.93
Ocean	0.002	0.0004	0.002	0.0004	0.005	0.001
Wind	1.23	0.23	1.23	0.24	3.24	0.59
Other	0.07	0.01	0.07	0.01	0.07	0.01
Total	532.44	100.00	510.13	100.00	549.29	100.00

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[2] For the substitution method conversion efficiencies of 38% for electricity and 85% for heat from non-combustible sources were used. The value of 38% is used by BP for electricity generated from hydro and nuclear. BP does not report solar, wind and geothermal in its statistics for which, here, also 38% is used for electricity and 85% for heat.

The alternative methods outlined above emphasize different aspects of primary energy supply. Therefore, depending on the application, one method may be more appropriate than another. However, none of them is superior to the others in all facets. In addition, it is important to realize that total primary energy supply does not fully describe an energy system, but is merely one indicator amongst many. Energy balances as published by IEA (2012a; b) offer a much wider set of indicators which allows tracing the flow of energy from the resource to final energy use. For instance, complementing total primary energy consumption by other indicators, such as total final energy consumption (TFC) and secondary energy production (e.g., electricity, heat), using different sources helps link the conversion processes with the final use of energy.

A.II.4 Carbon footprinting, lifecycle assessment, material flow analysis

In AR5, findings from carbon footprinting, life cycle assessment and material flow analysis are used in Chapters 4, 5, 7, 8, 9, 11, and 12. The following section briefly sketches the intellectual background of these methods and discusses their usefulness for climate mitigation research, and some relevant assumptions, limitations and methodological discussions.

The anthropogenic contributions to climate change, caused by fossil fuel combustion, land conversion for agriculture, commercial forestry and infrastructure, and numerous agricultural and industrial processes, result from the use of natural resources, i.e. the manipulation of material and energy flows by humans for human purposes. Climate mitigation research has a long tradition of addressing the energy flows and associated emissions, however, the sectors involved in energy supply and use are coupled with each other through material stocks and flows, which leads to feedbacks and delays. These linkages between energy and material stocks and flows have, despite their considerable relevance for GHG emissions, so far gained little attention in climate change mitigation (and adaptation). The research agendas of industrial ecology and ecological economics with their focus on the socioeconomic metabolism (Wolman, 1965; Baccini and Brunner, 1991; Ayres and Simonis, 1994; Fischer-Kowalski and Haberl, 1997) a.k.a. biophysical economy (Cleveland et al., 1984), can complement energy assessments in important manners and support the development of a broader framing of climate mitigation research as part of sustainability science. Socioeconomic metabolism consists of the physical stocks and flows with which a society maintains and reproduces itself (Fischer-Kowalski and Haberl, 2007). These research traditions are relevant for sustainability because they comprehensively account for resource flows and hence allow to address the dynamics, efficiency and emissions of production systems that convert or utilize resources to provide goods and services to final consumers. Central to the socio-metabolic research methods are material and energy balance principles applied at various scales ranging from individual production processes to companies, regions, value chains, economic sectors, and nations.

A.II.4.1 Material flow analysis

Material flow analysis (MFA) – including substance flow analysis (SFA) – is a method for describing, modeling (using socio-economic and technological drivers), simulating (scenario development), and visualizing the socioeconomic stocks and flows of matter and energy in systems defined in space and time to inform policies on resource and waste management and pollution control. Mass- and energy balance consistency is enforced at the level of goods and/or individual substances. As a result of the application of consistency criteria they are useful to analyze feedbacks within complex systems, e.g. the interrelations between diets, food production in cropland and livestock systems, and availability of area for bioenergy production (e.g., (Erb et al., 2012), see chapter 11, section 11.4).

The concept of socioeconomic metabolism (Ayres and Kneese, 1969; Boulding, 1972; Martinez-Alier, 1987; Baccini and Brunner, 1991; Ayres and Simonis, 1994; Fischer-Kowalski and Haberl, 1997) has been developed as an approach to study the extraction of materials or energy from the environment, their conversion in production and consumption processes, and the resulting outputs to the environment. Accordingly, the unit of analysis is the socioeconomic system (or some of its components), treated as a systemic entity, in analogy to an organism or a sophisticated machine that requires material and energy inputs from the natural environment in order to carry out certain defined functions and that results in outputs such as wastes and emissions.

Some MFAs trace the stocks and flows of aggregated groups of materials (fossil fuels, biomass, ores and industrial minerals, construction materials) through societies and can be performed on the global scale (Krausmann et al., 2009), for national economies and groups of countries (Weisz et al., 2006), urban systems (Wolman, 1965) or other socioeconomic subsystems. Similarly comprehensive methods that apply the same system boundaries have been developed to account for energy flows (Haberl, 2001a), (Haberl, 2001b), (Haberl et al., 2006), carbon flows (Erb et al., 2008) and biomass flows (Krausmann et al., 2008) and are often subsumed in the Material and Energy Flow Accounting (MEFA) framework (Haberl et al., 2004). Other MFAs have been conducted for analyzing the cycles of individual substances (e.g., carbon, nitrogen, or phosphorus cycles (Erb et al., 2008)) or metals (e.g., copper, iron, or cadmium cycles; (Graedel and Cao, 2010)) within socio-economic systems. A third group of MFAs have a focus on individual processes with an aim to balance a wide variety of goods and substances (e.g., waste incineration, a shredder plant, or a city).

The MFA approach has also been extended towards the analysis of socio-ecological systems, i.e. coupled human-environment systems. One example for this research strand is the ‘human appropriation of net primary production’ or HANPP which assesses human-induced changes in biomass flows in terrestrial ecosystems (Vitousek et al., 1986)(Wright, 1990)(Imhoff et al., 2004)(Haberl et al., 2007). The socio-ecological metabolism approach is particularly useful for assessing feedbacks in the global land system, e.g. interrelations between production and consumption of food, agricultural intensity, livestock feeding efficiency and bioenergy potentials, both residue potentials and area availability for energy crops (Erb et al., 2012)(Haberl et al., 2011).

Anthropogenic stocks (built environment) play a crucial role in socio-metabolic systems: (i) they provide services to the inhabitants, (ii) their operation often requires energy and releases emissions, (iii) increase or renewal/maintenance of these stocks requires materials, and (iv) the stocks embody materials (often accumulated over the past decades or centuries) that may be recovered at the end of the stocks’ service lives (“urban mining”) and, when recycled or reused, substitute primary resources and save energy and emissions in materials production (Müller et al., 2006). In contrast to flow variables, which tend to fluctuate much more, stock variables usually behave more robustly and are therefore often suitable as drivers for developing long-term scenarios (Müller, 2006). The exploration of built environment stocks (secondary resources), including their composition, performance, and dynamics, is therefore a crucial pre-requisite for examining long-term transformation pathways (Liu et al., 2012). Anthropogenic stocks have therefore been described as the engines of socio-metabolic systems. Moreover, socioeconomic stocks sequester carbon (Lauk et al., 2012); hence policies to increase the C content of long-lived infrastructures may contribute to climate-change mitigation (Gustavsson et al., 2006).

So far, MFAs have been used mainly to inform policies for resource and waste management. Studies with an explicit focus on climate change mitigation are less frequent, but rapidly growing. Examples involve the exploration of long-term mitigation pathways for the iron/steel industry (Pauliuk et al 2012, Milford et al 2012), the aluminium industry (Liu et al., 2011)(Liu et al., 2012), the vehicle stock (Melaina and Webster, 2011), (Pauliuk et al., 2011) or the building stock (Pauliuk et al., 2012).

A.II.4.2 Carbon footprinting and input-output analysis

Input-output analysis is an approach to trace the production process of products by economic sectors, and their use as intermediate demand by producing sectors (industries) and final demand including that by households and the public sector (Miller and Blair, 1985). Input-output tables describe the structure of the economy, i.e. the interdependence of different producing sectors and their role in final demand. Input-output tables are produced as part of national economic accounts (Leontief, 1936). Through the assumption of fixed input coefficients, input-output models can be formed, determining, e.g., the economic activity in all sectors required to produce a unit of final demand. The mathematics of input-output analysis can be used with flows denoted in physical or monetary units and has been applied also outside economics, e.g. to describe energy and nutrient flows in ecosystems (Hannon et al., 1986).

Environmental applications of input-output analysis include analyzing the economic role of abatement sectors (Leontief, 1971), quantifying embodied energy (Bullard and Herendeen, 1975) and the employment benefits of energy efficiency measures (Hannon et al., 1978), describing the benefits of pre-consumer scrap recycling (Nakamura and Kondo, 2001), tracing the material composition of vehicles (Nakamura et al., 2007), and identifying the environmentally global division of labor (Stromman et al., 2009). Important for climate mitigation research, input-output analysis has been used to estimate the greenhouse gas emissions associated with the production and delivery of goods for final consumption, the "carbon footprint" (Wiedmann and Minx, 2008). This type of analysis basically redistributes the emissions occurring in producing sectors to final consumption. It can be used to quantify GHG emissions associated with import and export (Wyckoff and Roop, 1994), with national consumption (Hertwich and Peters, 2009), or the consumption of specific groups of society (Lenzen and Schaeffer, 2004), regions (Turner et al., 2007) or institutions (Berners-Lee et al., 2011)(Larsen and Hertwich, 2009)(Minx et al., 2009)(Peters, 2010).[3]

Global, multiregional input-output models are currently seen as the state-of-the-art tool to quantify "consumer responsibility" (Ch.5)(Wiedmann et al., 2011)(Hertwich, 2011). Multiregional tables are necessary to adequately represent national production patterns and technologies in the increasing number of globally sourced products. Important insights provided to climate mitigation research is the quantification of the total CO2 emissions embodied in global trade (Peters and Hertwich, 2008) and the South->North directionality of trade (Peters, Minx, et al., 2011), to show that the UK (Druckman et al., 2008)(Wiedmann et al., 2010) and other Annex B countries have increasing carbon footprints while their territorial emissions are decreasing, to identify the contribution of different commodity exports to the rapid growth in China's greenhouse gas emissions (Xu et al., 2009), and to quantify the income elasticity of the carbon footprint of different consumption categories like food, mobility, and clothing (Hertwich and Peters, 2009).

Input-output models have an increasingly important instrumental role in climate mitigation. They are used as a backbone for consumer carbon calculators, to provide sometimes spatially explicit regional analysis (Lenzen et al., 2004), to help companies and public institutions target climate mitigation efforts , and to provide initial estimates of emissions associated with different alternatives (Minx et al., 2009).

Input-output calculations are usually based on industry-average production patterns and emissions intensities and do not provide an insight into marginal emissions caused by additional purchases. However, efforts to estimate future and marginal production patterns and emissions intensities exist (Lan et al., 2012). At the same time, economic sector classifications in many countries are not very fine, so that IO tables provide carbon footprint averages of broad product groups rather than specific products. Many models use monetary units and are not good at addressing waste management and recycling opportunities, although hybrid models with a physical representation of end-of-life processes do exist (Nakamura and Kondo, 2001). At the time of publication, national input-output tables describe the economy several years ago. Multiregional input-output tables are produced as part of research efforts and need to reconcile different national conventions for the construction of the tables and conflicting international trade data (Tukker et al., 2013). Efforts to provide a higher level of detail of environmentally relevant sectors and to now-cast tables are currently under development (Lenzen et al., 2012).

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[3] So far, only GHG emissions related to fossil fuel combustion and cement production are included in the „carbon footprint"; more data work is needed to address GHG emissions related to land-use change.

A.II.4.3 Life cycle assessment

Product life cycle assessment (LCA) was developed as a method to determine the embodied energy use (Boustead and Hancock, 1979) and environmental pressures associated with specific product systems (Finnveden et al., 2009). A product system describes the production, distribution, operation, maintenance, and disposal of the product. From the beginning, the assessment of energy technologies has been important, addressing questions such as how many years of use would be required to recover the energy expended in producing a photovoltaic cell (Kato et al., 1998). Applications in the consumer products industry addressing questions of whether cloth or paper nappies (diapers) are more environmentally friendly (Vizcarra et al., 1994), or what type of washing powder, prompted the development of a wider range of impact assessment methods addressing issues such as aquatic toxicity (Gandhi et al., 2010), eutrophication and acidification (Huijbregts et al., 2000). By now, a wide range of methods has been developed addressing either the contribution to specific environmental problems (midpoint methods) or the damage caused to ecosystem or human health (endpoint methods). At the same time, commonly used databases have collected life cycle inventory information for materials, energy products, transportation services, chemicals and other widely used products. Together, these methods form the backbone for the wide application of LCA in industry and for environmental product declarations, as well as in policy.

LCA plays an increasingly important role in climate mitigation research (SRREN Annex II, Moomaw et al. (2011)). In AR5, life cycle assessment has been used to quantify the greenhouse gas emissions associated with technologies used for GHG mitigation, e.g., wind power, heat recovery ventilation systems or carbon capture and storage. LCA is thus used to estimate the technical emissions reductions offered by these technologies.

LCA has also been used to quantify co-benefits and detrimental side effects of mitigation technologies and measures, including other environmental problems and the use of resources such as water, land, and metals. LCA traditionally focuses only on GHG emissions, often evaluated over a 100 year time horizon. Radiation-based climate metrics (Peters, Aamaas, et al., 2011) and geophysical effects such as albedo changes or indirect climate effects (Bright et al., 2012) have only recently been addressed.

Life-cycle inventories are normally derived from empirical information on actual processes or modeled based on engineering calculations. A key aspect of life cycle inventories for energy technologies is that they contribute to understanding the thermodynamics of the wider product system; combined with appropriate engineering insight, they can provide some upper bound for possible technological improvements. These process LCAs provide detail and specificity, but do usually not cover all input requirements as this would be too demanding. The cut-off error is the part of the inventory that is not covered by conventional process analysis; it is commonly between 20-50% of the total impact (Lenzen, 2001). Hybrid life cycle assessment utilizes input-output models to cover inputs of services or items that are used in small quantities (Treloar, 1996)(Suh et al., 2004)(Williams et al., 2009). Through their better coverage of the entire product system, hybrid LCAs tend to more accurately represent all inputs to production (Majeau-Bettez et al., 2011). They have also been used to estimate the cut-off error of process LCAs (Norris, 2002)(Deng et al., 2011).

It must be emphasized that LCA is a research method that answers specific research questions. To understand how to interpret and use the results of an LCA case study, it is important to understand what the research question is. The research questions “what are the environmental impacts of product x” or “… of technology y” needs to be specified with respect to timing, regional context, operational mode, background system etc. Modeling choices and assumption thus become part of an LCA. This implies that LCA studies are not always comparable because they do not address the same research question. Further, most LCAs are interpreted strictly on a functional unit basis; expressing the impact of a unit of the product system in a described production system, without either up-scaling the impacts to total impacts in the entire economy or saying something about the scale-dependency of the activity. For example, an LCA may identify the use of recycled material as beneficial, but the supply of recycled material is limited by the availability of suitable waste, so that an up-scaling of recycling is not feasible. Hence, an LCA that shows that recycling is beneficial is not sufficient to document the availability of further opportunities to reduce emissions. LCA, however, coupled with an appropriate system models (using material flow data) is suitable to model the emission gains from the expansion of further recycling activities.

LCA was developed with the intention to quantify resource use and emissions associated with existing or prospective product systems, where the association reflects physical causality within economic systems. Depending on the research question, it can be sensible to investigate average or marginal inputs to production. Departing from this descriptive approach, it has been proposed to model a wider socioeconomic causality describing the consequences of actions (Ekvall and Weidema, 2004). While established methods and a common practice exist for descriptive or “attributional” LCA, such methods and standard practice are not yet established in “consequential” LCA (Zamagni et al., 2012). Consequential LCAs are dependent on the decision context. It is increasingly acknowledged in LCA that for investigating larger sustainability questions, the product focus is not sufficient and larger system changes need to be modeled as such (Guinée et al., 2010).

For climate mitigation analysis, it is useful to put LCA in a wider scenario context (Arvesen and Hertwich, 2011; Viebahn et al., 2011). The purpose is to better understand the contribution a technology can make to climate mitigation and to quantify the magnitude of its resource requirements, co-benefits and side effects. For mitigation technologies on both the demand and supply side, important contributors to the total impact are usually energy, materials and transport. Understanding these contributions is already valuable for mitigation analysis. As all of these sectors will change as part of the scenario, LCA-based scenarios show how much impacts per unit are likely to change as part of the scenario.

Some LCAs take into account behavioral responses to different technologies (Takase et al., 2005; Girod et al., 2011). Here, two issues must be distinguished. One is the use of the technology. For example, it has been found that better insulated houses consistently are heated or cooled to higher/lower average temperature (Haas and Schipper, 1998)(Greening et al., 2001). Not all of the theoretically possible technical gain in energy efficiency results in reduced energy use (Sorrell and Dimitropoulos, 2008). Such direct rebound effects can be taken into account through an appropriate definition of the energy services compared, which do not necessarily need to be identical in terms of the temperature or comfort levels. Another issue are larger market-related effects and spill-over effects. A better insulated house leads to energy savings. Both questions of (1) whether the saved energy would then be used elsewhere in the economy rather than not produced, and (2) what the consumer does with the money saved, are not part of the product system and hence of product life cycle assessment. They are sometimes taken up in LCA studies, quantified and compared. However, for climate mitigation analysis, these mechanisms need to be addressed by scenario models on a macro level. (See also section 11.4 for a discussion of such systemic effects).

A.II.5 Fat Tailed Distributions

If we have observed N independent loss events from a given loss distribution, the probability that the next loss event will be worse than all the others is 1/(N+1). How much worse it will be depends on the tail of the loss distribution. Many loss distributions including losses due to hurricanes are very fat tailed. The notion of a "fat tailed distribution" may be given a precise mathematical meaning in several ways, each capturing different intuitions. Older definitions refer to “fat tails” as “leptokurtic” meaning that the tails are fatter than the normal distribution. Nowadays, mathematical definitions are most commonly framed in terms of regular variation or subexponentiality (Embrechts et al., 1997).

A positive random variable X has regular variation with tail index $\alpha > 0$ if the probability $P(X > x)$ of exceeding a value x decreases at a polynomial rate $x\text{-}\alpha$ as x gets large. For any $r > \alpha$, the r-th moment of X is infinite, the α-th moment may be finite or infinite depending on the distribution. If the first moment is infinite, then running averages of independent realizations of X increase to infinity. If the second moment is infinite, then running averages have an infinite variance and do not converge to a finite value. In either case, historical averages have little predictive value. The gamma, exponential, and Weibull distributions all have finite r-th moment for all positive r.

A positive random variable X is subexponential if for any n independent copies X1,…Xn, the probability that the sum X1+...+Xn exceeds a value x becomes identical to the probability that the maximum of X1,…Xn exceeds x, as x gets large. In other words, 'the sum of X1,…Xn is driven by the largest of the X1,…Xn.' Every regularly varying distribution is subexponential, but the converse does not hold. The Weibull distribution with shape parameter less than one is subexponential but not regularly varying. All its moments are finite, but the sum of n independent realizations tends to be dominated by the single largest value.

For X with finite first moment, the mean excess curve is a useful diagnostic. The mean excess curve of X at point x is the expected value of X given that X exceeds x. If X is regularly varying with tail index α > 1, the mean excess curve of X is asymptotically linear with slope 1/(α-1). If X is subexponential its mean excess curve increases to infinity, but is not necessarily asymptotically linear. Thus, the mean excess curve for a subexponential distribution may be 'worse' than a regularly varying distribution, even though the former has finite moments. The mean excess curve for the exponential distribution is constant, that for the normal distribution is decreasing. The following figures show mean excess curves for flood insurance claims in the US, per county per year per dollar income (hereby correcting for growth in exposure, Figure A.II.1) and insurance indemnities for crop loss per county per year in the US (Figure A.II.2). Note that flood claims' mean excess curve lies well above the line with unit slope, whereas that for crop losses lie below (Kousky and Cooke, 2009).

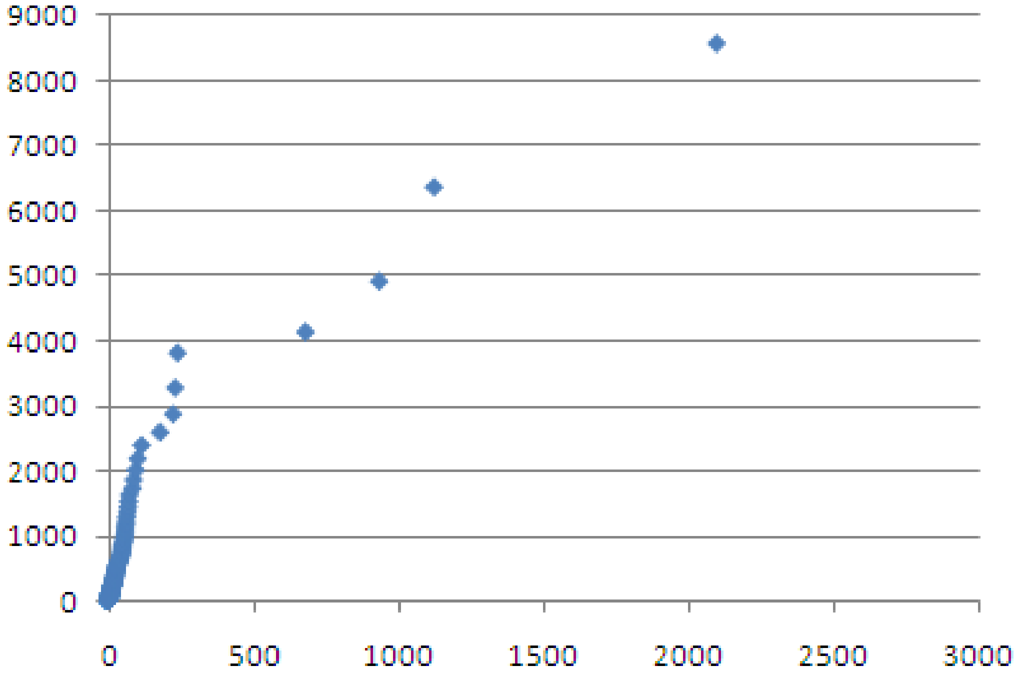

Figure A.II.1. Mean excess curve for US flood insurance claims from the National Flood Insurance Program, 1980 to 2008 in 2000 dollars, per dollar income per county per year. Considering dollar claims per dollar income in each county corrects for increasing exposure.

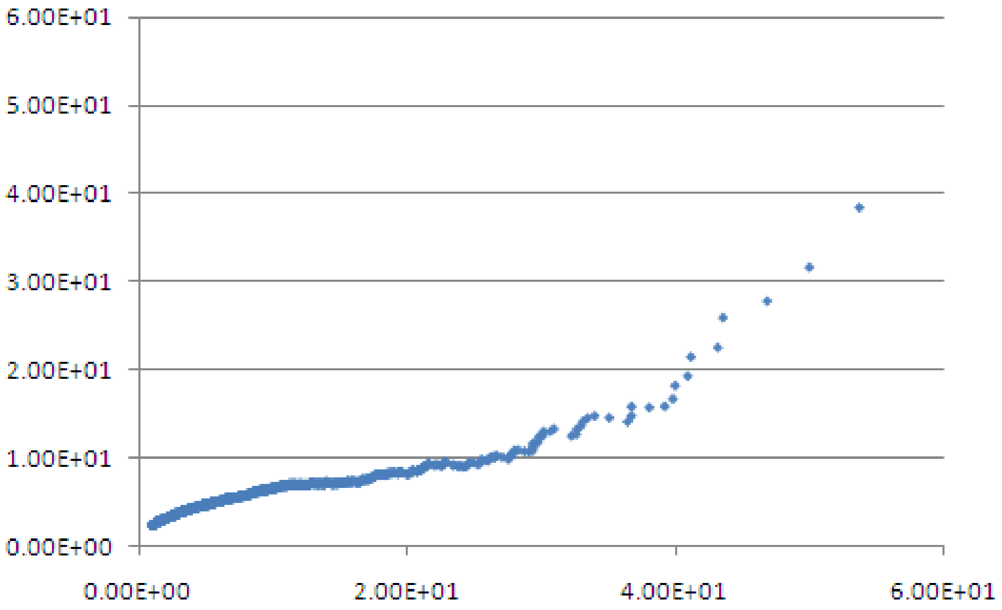

Figure A.II.2. Mean excess curve of US crop insurance indemnities paid from the US Department of Agriculture's Risk Management Agency, aggregated by county and year for the years 1980 to 2008 in 2000 US dollars.

A.II.6 Region Definitions

In this report a number of different sets of regions are used to present results of analysis. These region sets are referred to as RCP5, ECON5 (5 global regions and international transport) and RCP (10 global regions and international transport). The RCP5 and RCP10 sets form a hierarchical set, i.e. the RCP10 regions can be unambiguously aggregated to the RCP 5 regions as shown in Table A.II.9. Note that not in all cases presented in this report is a perfect match to the definitions listed in Sections A.II.6.1-A.II.6.3 possible and therefore minor deviations may apply.

Table A.II.9. Regions in the RCP5 and RCP10 region sets.

Suggested mapping of RCP10 to RCP 5			
RCP5		**RCP10**	
OECD1990	OECD 1990 countries	**NAM**	North America
		WEU	Western Europe
		JPAUNZ	Japan, Australia, New Zealand
EIT	Reforming Economies	**EIT**	Economies in Transition (Eastern Europe and part of former Soviet Union)
LAM	Latin America and Caribbean	**LAM**	Latin America and Caribbean
MAF	Middle East and Africa	**SSA**	Sub Saharan Africa
		MNA	Middle East and North Africa
ASIA	Asia	**EAS**	East Asia
		SAS	South Asia
		PAS	South-East Asia and Pacific
INT TRA	International transport	**INT TRA**	International transport

Table A.II.10. Regions in the ECON5 region set.

ECON5 (Economy-based Aggregation)	
IC-G20	Industrialized Countries - G20 and other EU-27
IC-OTHER	Industrialized Countries
DC-G20	Developing Countries - G20
DC-OTHER	Developing Countries
LDC	Leased Developed Countries
INT TRA	International transport

A.II.6.1 RCP5

OECD1990 (OECD1990 countries): Aland Islands, Andorra, Australia, Austria, Belgium, Canada, Channel Islands, Denmark, Faroe Islands, Finland, France, Germany, Gibraltar, Greece, Greenland, Guam, Guernsey, Holy See (Vatican City State), Iceland, Ireland, Isle of Man, Italy, Japan, Jersey, Liechtenstein, Luxembourg, Monaco, Netherlands, New Zealand, Norway, Portugal, Saint Pierre and Miquelon, San Marino, Spain, Svalbard and Jan Mayen, Sweden, Switzerland, Turkey, United Kingdom, United States

EIT (Reforming Economies): Albania, Armenia, Azerbaijan, Belarus, Bosnia and Herzegovina, Bulgaria, Croatia, Cyprus, Czech Republic, Estonia, Georgia, Hungary, Kazakhstan, Kyrgyzstan, Latvia, Lithuania, Macedonia, Malta, Moldova (Republic of), Montenegro, Poland, Romania, Russian Federation, Serbia, Serbia and Montenegro, Slovakia, Slovenia, Tajikistan, Turkmenistan, Ukraine, Uzbekistan

LAM (Latin America and Caribbean): Anguilla, Antarctica, Antigua and Barbuda, Argentina, Aruba, Bahamas, Barbados, Belize, Bermuda, Bolivia, Bouvet Island, Brazil, British Virgin Islands, Cayman Islands, Chile, Colombia, Costa Rica, Cuba, Dominica, Dominican Republic, Ecuador, El Salvador, Falkland Islands (Malvinas), French Guiana, French Southern Territories, Grenada, Guadeloupe, Guatemala, Guyana, Haiti, Honduras, Jamaica, Martinique, Mexico, Montserrat, Netherlands Antilles, Nicaragua, Panama, Paraguay, Peru, Puerto Rico, Saint Kitts and Nevis, Saint Lucia, Saint Vincent and the Grenadines, South Georgia and the South Sandwich Islands, Suriname, Trinidad and Tobago, Turks and Caicos Islands, Uruguay, US Virgin Islands, Venezuela

MAF (Middle East and Africa): Algeria, Angola, Bahrain, Benin, Botswana, Burkina Faso, Burundi, Cameroon, Cape Verde, Central African Republic, Chad, Comoros, Congo, Congo (The Democratic Republic of the), Cote d'Ivoire, Djibouti, Egypt, Equatorial Guinea, Eritrea, Ethiopia, Gabon, Gambia, Ghana, Guinea, Guinea-Bissau, Iran, Iraq, Israel, Jordan, Kenya, Kuwait, Lebanon, Lesotho, Liberia, Libya, Madagascar, Malawi, Mali, Mauritania, Mauritius, Mayotte, Morocco, Mozambique, Namibia, Niger, Nigeria, Oman, Palestinian Territory, Qatar, Reunion, Rwanda, Saint Helena, Sao Tome and Principe, Saudi Arabia, Senegal, Seychelles, Sierra Leone, Somalia, South Africa, Sudan, Swaziland, Syrian Arab Republic, Tanzania, Togo, Tunisia, Uganda, United Arab Emirates, Western Sahara, Yemen, Zambia, Zimbabwe

ASIA (Asia): Afghanistan, American Samoa, Bangladesh, Bhutan, British Indian Ocean Territory, Brunei Darussalam, Cambodia, China, Christmas Island, Cocos (Keeling) Islands, Cook Islands, Fiji, French Polynesia, Heard Island and McDonald Islands, Hong Kong, India, Indonesia, Kiribati, Korea (Democratic People's Republic of), Lao People's Democratic Republic, Macao, Malaysia, Maldives, Marshall Islands, Micronesia (Federated States of), Mongolia, Myanmar, Nauru, Nepal, New Caledonia, Niue, Norfolk Island, Northern Mariana Islands, Pakistan, Palau, Papua New Guinea, Philippines, Pitcairn, Samoa, Singapore, Solomon Islands, South Korea, Sri Lanka, Taiwan, Thailand, Timor-Leste, Tokelau, Tonga, Tuvalu, US Minor Outlying Islands, Vanuatu, Viet Nam, Wallis and Futuna

INT TRA (International transport): Int. Aviation, Int. Shipping

A.II.6.2 RCP10

NAM (North America): Canada, Guam, Saint Pierre and Miquelon, United States

WEU (Western Europe): Aland Islands, Andorra, Austria, Belgium, Channel Islands, Denmark, Faroe Islands, Finland, France, Germany, Gibraltar, Greece, Greenland, Guernsey, Holy See (Vatican City State), Iceland, Ireland, Isle of Man, Italy, Jersey, Liechtenstein, Luxembourg, Monaco, Netherlands, Norway, Portugal, San Marino, Spain, Svalbard and Jan Mayen, Sweden, Switzerland, Turkey, United Kingdom

JPAUNZ (Japan, Aus, NZ): Australia, Japan, New Zealand

EIT (Economies in Transition (Eastern Europe and part of former Soviet Union)): Albania, Armenia, Azerbaijan, Belarus, Bosnia and Herzegovina, Bulgaria, Croatia, Cyprus, Czech Republic, Estonia, Georgia, Hungary, Kazakhstan, Kyrgyzstan, Latvia, Lithuania, Macedonia, Malta, Moldova (Republic of), Montenegro, Poland, Romania, Russian Federation, Serbia, Serbia and Montenegro, Slovakia, Slovenia, Tajikistan, Turkmenistan, Ukraine, Uzbekistan

LAM (Latin America and Caribbean): Anguilla, Antarctica, Antigua and Barbuda, Argentina, Aruba, Bahamas, Barbados, Belize, Bermuda, Bolivia, Bouvet Island, Brazil, British Virgin Islands, Cayman Islands, Chile, Colombia, Costa Rica, Cuba, Dominica, Dominican Republic, Ecuador, El Salvador, Falkland Islands (Malvinas), French Guiana, French Southern Territories, Grenada, Guadeloupe, Guatemala, Guyana, Haiti, Honduras, Jamaica, Martinique, Mexico, Montserrat, Netherlands Antilles, Nicaragua, Panama, Paraguay, Peru, Puerto Rico, Saint Kitts and Nevis, Saint Lucia, Saint Vincent and the Grenadines, South Georgia and the South Sandwich Islands, Suriname, Trinidad and Tobago, Turks and Caicos Islands, Uruguay, US Virgin Islands, Venezuela

SSA (Sub Saharan Africa): Angola, Benin, Botswana, Burkina Faso, Burundi, Cameroon, Cape Verde, Central African Republic, Chad, Comoros, Congo, Congo (The Democratic Republic of the), Cote d'Ivoire, Djibouti, Equatorial Guinea, Eritrea, Ethiopia, Gabon, Gambia, Ghana, Guinea, Guinea-Bissau, Kenya, Lesotho, Liberia, Madagascar, Malawi, Mali, Mauritania, Mauritius, Mayotte, Mozambique, Namibia, Niger, Nigeria, Reunion, Rwanda, Saint Helena, Sao Tome and Principe, Senegal, Seychelles, Sierra Leone, Somalia, South Africa, Swaziland, Tanzania, Togo, Uganda, Zambia, Zimbabwe

MNA (Middle East and North Africa): Algeria, Bahrain, Egypt, Iran, Iraq, Israel, Jordan, Kuwait, Lebanon, Libya, Morocco, Oman, Palestinian Territory, Qatar, Saudi Arabia, Sudan, Syrian Arab Republic, Tunisia, United Arab Emirates, Western Sahara, Yemen

EAS (East Asia): China, Hong Kong, Korea (Democratic People's Republic of), Macao, Mongolia, South Korea, Taiwan

SAS (South Asia): Afghanistan, Bangladesh, Bhutan, British Indian Ocean Territory, India, Maldives, Nepal, Pakistan, Sri Lanka

PAS (South-East Asia and Pacific): American Samoa, Brunei Darussalam, Cambodia, Christmas Island, Cocos (Keeling) Islands, Cook Islands, Fiji, French Polynesia, Heard Island and McDonald Islands, Indonesia, Kiribati, Lao People's Democratic Republic, Malaysia, Marshall Islands, Micronesia (Federated States of), Myanmar, Nauru, New Caledonia, Niue, Norfolk Island, Northern Mariana Islands, Palau, Papua New Guinea, Philippines, Pitcairn, Samoa, Singapore, Solomon Islands, Thailand, Timor-Leste, Tokelau, Tonga, Tuvalu, US Minor Outlying Islands, Vanuatu, Viet Nam, Wallis and Futuna

INT TRA (International transport): Int. Aviation, Int. Shipping

A.II.6.3 ECON5 (Economy-based Aggregation)

IC-G20 (Industrialized Countries - G20 and other EU-27): Bulgaria, Cyprus, Czech Republic, Estonia, Hungary, Latvia, Lithuania, Malta, Poland, Romania, Russian Federation, Slovakia, Slovenia, US Virgin

Islands, Australia, Austria, Belgium, Canada, Denmark, Finland, France, Germany, Greece, Ireland, Italy, Japan, Luxembourg, Netherlands, Portugal, Spain, Sweden, United Kingdom, United States

IC-OTHER (Industrialized Countries): Singapore, US Minor Outlying Islands, Belarus, Croatia, Ukraine, British Virgin Islands, Cayman Islands, Falkland Islands (Malvinas), French Southern Territories, Aland Islands, Andorra, Channel Islands, Faroe Islands, Gibraltar, Greenland, Guernsey, Holy See (Vatican City State), Iceland, Isle of Man, Jersey, Liechtenstein, Monaco, New Zealand, Norway, San Marino, Svalbard and Jan Mayen, Switzerland

DC-G20 (Developing Countries - G20): China, Hong Kong, India, Indonesia, South Korea, Taiwan, Argentina, Brazil, Mexico, Saudi Arabia, South Africa, Turkey

DC-OTHER (Developing Countries): American Samoa, British Indian Ocean Territory, Brunei Darussalam, Christmas Island, Cocos (Keeling) Islands, Cook Islands, Fiji, French Polynesia, Heard Island and McDonald Islands, Korea (Democratic People's Republic of), Lao People's Democratic Republic, Macao, Malaysia, Maldives, Marshall Islands, Micronesia (Federated States of), Mongolia, Nauru, New Caledonia, Niue, Norfolk Island, Northern Mariana Islands, Pakistan, Palau, Papua New Guinea, Philippines, Pitcairn, Sri Lanka, Thailand, Tokelau, Tonga, Viet Nam, Wallis and Futuna, Albania, Armenia, Azerbaijan, Bosnia and Herzegovina, Georgia, Kazakhstan, Kyrgyzstan, Macedonia, Moldova (Republic of), Montenegro, Serbia, Serbia and Montenegro, Tajikistan, Turkmenistan, Uzbekistan, Anguilla, Antarctica, Antigua and Barbuda, Aruba, Bahamas, Barbados, Belize, Bermuda, Bolivia, Bouvet Island, Chile, Colombia, Costa Rica, Cuba, Dominica, Dominican Republic, Ecuador, El Salvador, French Guiana, Grenada, Guadeloupe, Guatemala, Guyana, Honduras, Jamaica, Martinique, Montserrat, Netherlands Antilles, Nicaragua, Panama, Paraguay, Peru, Puerto Rico, Saint Kitts and Nevis, Saint Lucia, Saint Vincent and the Grenadines, South Georgia and the South Sandwich Islands, Suriname, Trinidad and Tobago, Turks and Caicos Islands, Uruguay, Venezuela, Algeria, Bahrain, Botswana, Burkina Faso, Cameroon, Cape Verde, Congo, Congo (The Democratic Republic of the), Cote d'Ivoire, Egypt, Gabon, Ghana, Iran, Iraq, Israel, Jordan, Kenya, Kuwait, Lebanon, Libya, Mauritius, Mayotte, Morocco, Namibia, Nigeria, Oman, Palestinian Territory, Qatar, Reunion, Saint Helena, Sao Tome and Principe, Seychelles, Swaziland, Syrian Arab Republic, Tanzania, Tunisia, United Arab Emirates, Western Sahara, Zimbabwe, Guam, Saint Pierre and Miquelon

LDC (Least Developed Countries): Afghanistan, Bangladesh, Bhutan, Cambodia, Kiribati, Myanmar, Nepal, Samoa, Solomon Islands, Timor-Leste, Tuvalu, Vanuatu, Haiti, Angola, Benin, Burundi, Central African Republic, Chad, Comoros, Djibouti, Equatorial Guinea, Eritrea, Ethiopia, Gambia, Guinea, Guinea-Bissau, Lesotho, Liberia, Madagascar, Malawi, Mali, Mauritania, Mozambique, Niger, Rwanda, Senegal, Sierra Leone, Somalia, Sudan, Togo, Uganda, Yemen, Zambia

INT TRA (International transport): Int. Aviation, Int. Shipping

A.II.7 Mapping of Emission Sources to Sectors

The list below shows how emission sources are mapped to sectors throughout the AR5. This defines unambiguous system boundaries for the sectors as represented in Chapters 7-11 in the report and enables a discussion and representation of emission sources without double-counting.

Emission sources refer to the definitions by the IPCC Task Force on National Greenhouse Gas Inventories (TFI)(IPCC, 2006). Where further disaggregations were required, additional source categories were introduced consistent with the underlying datasets (IEA, 2012c; JRC/PBL, 2012). This information appears in the following systematic sequence throughout this section:

Emission Source Category (Chapter Emission Source Category Numbering)

Emission Source (Sub-)Category (IPCC Task force definition) [gases emitted by emission source (CO2 data set used)]

A common dataset is used across WG III AR5 chapters to ensure coherency consistent representation of emission trends across the report. Uncertainties of this data are discussed in the respective chapters (chapter 1; chapter 5; chapter 11). CO_2 emissions from fossil fuel combustion are taken from IEA (2012c), the remaining CO_2 and non-CO_2 greenhouse gas emissions are taken from EDGAR (JRC/PBL, 2012).

[Author note: While it is the aim to use this data consistently throughout the report, this is not fully the case for the Second Order Draft (SOD), but will be updated for the Final Draft (FD).]

A.II.7.2 Energy

Electricity & heat (7.1)

Power Generation (1A1a) [CO2 (IEA), CH4, N2O]

- Electricity and heat production (1A1a1) [CO2 (IEA)]
- Public Combined Heat and Power gen. (1A1a2) [CO2 (IEA)]
- Public Heat Plants (1A1a3) [CO2 (IEA)]
- Public Electricity Generation (own use) (1A1a4) [CO2 (IEA)]
- Electricity Generation (autoproducers) (1A1a5) [CO2 (IEA)]
- Combined Heat and Power gen. (autoprod.) (1A1a6) [CO2 (IEA)]
- Heat Plants (autoproducers) (1A1a7) [CO2 (IEA)]

Public Electricity and Heat Production (biomass) (1A1ax) [CH4, N2O]

Petroleum refining (7.2)

Other Energy Industries (1A1bc) [CO2 (IEA)]

Manufacture of solid fuels (7.3)

Other transformation sector (BKB, etc.) (1A1r) [CH4, N2O]

Manufacture of Solid Fuels and Other Energy Industries (biomass) (1A1cx) [CH4, N2O]

Fuel production and transport (7.4)

Fugitive emissions from solids fuels except coke ovens (1B1r) [CO2 (EDGAR), CH4, N2O]

Oil and Natural Gas (1B2) [CH4, N2O]

Others (7.5)

Electrical Equipment Use (incl. site inst.) (2F8b) [SF6]

Fossil fuel fires (7A) [CO2 (EDGAR), CH4, N2O]

Indirect N2O emissions from energy (7.6)

Indirect N2O from NOx emitted in cat. 1A1 (7B1) [N2O]

Indirect N2O from NH3 emitted in cat. 1A1 (7C1) [N2O]

A.II.7.3 Transport

Aviation (8.1)

Domestic air transport (1A3a) [CO2 (IEA), CH4, N2O]

Road transportation (8.2)

Road transport (incl. evap.) (foss.) (1A3b) [CO2 (IEA), CH4, N2O]

Road transport (incl. evap.) (biomass) (1A3bx) [CH4, N2O]

Adiabatic prop.: tyres (2F9b) [SF6]

Rail transportation (8.3)

Rail transport (1A3c) [CO2 (IEA), CH4, N2O]

Non-road transport (rail, etc.) (fos.) (biomass) (1A3cx) [CH4, N2O]

Navigation (8.4)

Inland shipping (fos.) (1A3d) [CO2 (IEA), CH4, N2O]

Inland shipping (fos.) (biomass) (1A3dx) [CH4, N2O]

Others incl. indirect N2O emissions from transport (8.5)

Non-road transport (fos.) (1A3e) [CO2 (IEA), CH4, N2O]

- Pipeline transport (1A3e1) [CO2 (IEA)]

- Non-specified transport (1A3er) [CO2 (IEA)]

Non-road transport (fos.) (biomass) (1A3ex) [CH4, N2O]

Refrigeration and Air Conditioning Equipment (HFC) (Transport) (2F1a1) [HFC]

Indirect N2O from NOx emitted in cat. 1A3 (7B3) [N2O]

Indirect N2O from NH3 emitted in cat. 1A3 (7C3) [N2O]

International Aviation (8.6)

Memo: International aviation (1C1) [CO2 (IEA), CH4, N2O]

International Shipping (8.7)

Memo: International navigation (1C2) [CO2 (IEA), CH4, N2O]

A.II.7.4 Buildings

Commercial (9.1)

Commercial and public services (fos.) (1A4a) [CO2 (IEA), CH4, N2O]

Commercial and public services (biomass) (1A4ax) [CH4, N2O]

Residential (9.2)

Residential (fos.) (1A4b) [CO2 (IEA), CH4, N2O]

Residential (biomass) (1A4bx) [CH4, N2O]

Others (9.3)

Refrigeration and Air Conditioning Equipment (HFC) (Building) (2F1a2) [HFC]

Fire Extinguishers (2F3) [PFC]

Aerosols/ Metered Dose Inhalers (2F4) [HFC]

Adiabatic prop.: shoes and others (2F9a) [SF6]

Soundproof windows (2F9c) [SF6]

Indirect N2O Emissions from Buildings (9.4)

Indirect N2O from NOx emitted in cat. 1A4 (7B4) [N2O]

Indirect N2O from NH3 emitted in cat. 1A4 (7C4) [N2O]

A.II.7.5 Industry

Ferrous and non-ferrous metals (10.1)

Fuel combustion coke ovens (1A1c1) [CH4, N2O]

Blast furnaces (pig iron prod.) (1A1c2) [CH4, N2O]

Iron and steel (1A2a) [CO2 (IEA), CH4, N2O]

Non-ferrous metals (1A2b) [CO2 (IEA), CH4, N2O]

Iron and steel (biomass) (1A2ax) [CH4, N2O]

Non-ferrous metals (biomass) (1A2bx) [CH4, N2O]

Fuel transformation coke ovens (1B1b1) [CO2 (EDGAR), CH4]

Metal Production (2C) [CO2 (EDGAR), CH4, PFC, SF6]

- Iron and Steel Production (2C1) [CO2 (EDGAR)]
  - Crude steel production total (2C1a) [CO2 (EDGAR)]
  - Blast furnaces (2C1b) [CO2 (EDGAR)]
- Aluminum production (primary) (2C3) [PFC]
- SF6 Used in Aluminium and Magnesium Foundries (2C4) [SF6]
  - Magnesium foundries: SF6 use (2C4a) [SF6]
  - Aluminium foundries: SF6 use (2C4b) [SF6]

Chemicals (10.2)

Chemicals (1A2c) [CO2 (IEA), CH4, N2O]

Chemicals (biomass) (1A2cx) [CH4, N2O]

Production of chemicals (2B) [CH4, N2O]

Production of Halocarbons and SF6 (2E) [HFC, SF6]

Other product use (3D) [N2O]

Cement production (10.3)

Cement production (2A1) [CO2 (EDGAR)]

Landfill & waste incineration (10.5)

Solid waste disposal on land (6A) [CH4]

Waste incineration (6C) [CO2 (EDGAR), CH4, N2O]

Other waste handling (6D) [CH4, N2O]

Wastewater treatment (10.4)

Wastewater handling (6B) [CH4, N2O]

Other industries (10.6)

Pulp and paper (1A2d) [CO2 (IEA), CH4, N2O]

Food and tobacco (1A2e) [CO2 (IEA), CH4, N2O]

Other industries (stationary) (fos.) (1A2f) [CO2 (IEA), CH4, N2O]

- Non-metallic minerals (1A2f1) [CO2 (IEA)]

Transport equipment (1A2f2) [CO2 (IEA)]

Machinery (1A2f3) [CO2 (IEA)]

Mining and quarrying (1A2f4) [CO2 (IEA)]

Wood and wood products (1A2f5) [CO2 (IEA)]

Construction (1A2f6) [CO2 (IEA)]

Textile and leather (1A2f7) [CO2 (IEA)]

Non-specified industry (1A2f8) [CO2 (IEA)]

Pulp and paper (biomass) (1A2dx) [CH4, N2O]

Food and tobacco (biomass) (1A2ex) [CH4, N2O]

Off-road machinery: mining (diesel) (1A5b1) [CH4, N2O]

Lime production (2A2) [CO2 (EDGAR)]

Limestone and Dolomite Use (2A3) [CO2 (EDGAR)]

Production of other minerals (2A7) [CO2 (EDGAR)]

Refrigeration and Air Conditioning Equipment (PFC) (2F1b) [PFC]

Foam Blowing (2F2) [HFC]

F-gas as Solvent (2F5) [PFC]

Semiconductor Manufacture (2F7a) [HFC, PFC, SF6]

Flat Panel Display (FPD) Manufacture (2F7b) [PFC, SF6]

Photo Voltaic (PV) Cell Manufacture (2F7c) [PFC]

Electrical Equipment Manufacture (2F8a) [SF6]

Accelerators/HEP (2F9d) [SF6]

Misc. HFCs/SF6 consumption (AWACS, other military, misc.) (2F9e) [SF6]

Unknown SF6 use (2F9f) [SF6]

Indirect N2O Emissions from Industry (10.7)

Indirect N2O from NOx emitted in cat. 1A2 (7B2) [N2O]

Indirect N2O from NH3 emitted in cat. 1A2 (7C2) [N2O]

A.II.7.6 AFOLU

Fuel combustion (11.1)

Agriculture and forestry (fos.) (1A4c1) [CO2 (IEA), CH4, N2O]

Off-road machinery: agric./for. (diesel) (1A4c2) [CH4, N2O]

Fishing (fos.) (1A4c3) [CO2 (IEA), CH4, N2O]

Non-specified Other Sectors (1A4d) [CO2 (IEA), CH4, N2O]

Agriculture and forestry (biomass) (1A4c1x) [CH4, N2O]

Fishing (biomass) (1A4c3x) [, N2O]

Non-specified other (biomass) (1A4dx) [CH4, N2O]

Livestock (11.2)

Enteric Fermentation (4A) [CH4]

Manure management (4B) [CH4, N2O]

Rice cultivation (11.3)

Rice cultivation (4C) [CH4]

Direct soil emissions (11.4)

CO2 from agricultural lime application (4D4b) [CO2 (EDGAR)]

Agricultural soils (direct) (4Dr) [N2O]

Forrest fires and decay (11.5)

Savanna burning (4E) [CH4, N2O]

Forest fires (5A) [CO2 (EDGAR), CH4, N2O]

Grassland fires (5C) [CH4, N2O]

Forest Fires-Post burn decay (5F2) [CO2 (EDGAR), N2O]

Peat fires and decay (11.6)

Agricultural waste burning (4F) [CH4, N2O]

Peat fires and decay of drained peatland (5D) [CO2 (EDGAR), CH4, N2O]

Indirect N2O emissions from AFOLU (11.7)

Indirect Emissions (4D3) [N2O]

Indirect N2O from NOx emitted in cat. 5 (7B5) [N2O]

Indirect N2O from NH3 emitted in cat. 5 (7C5) [N2O]

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