ANNEX

II

Metrics & Methodology

Coordinating Lead Authors:
Volker Krey (IIASA/Germany), Omar Masera (Mexico)

Lead Authors:
Geoffrey Blanford (USA/Germany), Thomas Bruckner (Germany), Roger Cooke (USA), Karen Fisher-Vanden (USA), Helmut Haberl (Austria), Edgar Hertwich (Austria/Norway), Elmar Kriegler (Germany), Daniel Mueller (Switzerland/Norway), Sergey Paltsev (Belarus/USA), Lynn Price (USA), Steffen Schlömer (Germany), Diana Ürge-Vorsatz (Hungary), Detlef van Vuuren (Netherlands), Timm Zwickel (Germany)

Contributing Authors:
Kornelis Blok (Netherlands), Stephane de la Rue du Can (France/USA), Greet Janssens-Maenhout (Belgium/Italy), Dominique Van Der Mensbrugghe (Italy/USA), Alexander Radebach (Germany), Jan Steckel (Germany)

This annex should be cited as:

Krey V., O. Masera, G. Blanford, T. Bruckner, R. Cooke, K. Fisher-Vanden, H. Haberl, E. Hertwich, E. Kriegler, D. Mueller, S. Paltsev, L. Price, S. Schlömer, D. Ürge-Vorsatz, D. van Vuuren, and T. Zwickel, 2014: Annex II: Metrics & Methodology. In: *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel and J.C. Minx (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Contents

This annex on methods and metrics provides background information on material used in the Working Group III Contribution to the Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report (WGIII AR5). The material presented in this annex documents metrics, methods, and common data sets that are typically used across multiple chapters of the report. The annex is composed of three parts: Part I introduces standards metrics and common definitions adopted in the report; Part II presents methods to derive or calculate certain quantities used in the report; and Part III provides more detailed background information about common data sources that go beyond what can be included in the chapters. While this structure may help readers to navigate through the annex, it is not possible in all cases to unambiguously assign a certain topic to one of these parts, naturally leading to some overlap between the parts.

Part I: Units and definitions

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 (IPCC, 2001; Moomaw et al., 2011).

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)
Ionizing Radiation Dose	sievert	Sv	J kg^-1

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

Monetary units	Unit	Symbol
Currency (Market Exchange Rate, MER)	constant US Dollar 2010	USD_{2010}
Currency (Purchasing Power Parity, PPP)	constant International Dollar 2005	$Int\$_{2005}$
Emission- and Climate-related units	**Unit**	**Symbol**
Emissions	Metric tonnes	t
CO_2 Emissions	Metric tonnes CO_2	tCO_2
CO_2-equivalent Emissions	Metric tonnes CO_2-equivalent*	tCO_2eq
Abatement Costs and Emissions Prices/Taxes	constant US Dollar 2010 per metric tonne	USD_{2010}/t
CO_2 concentration or Mixing Ratio (μmol mol−1)	Parts per million (10^6)	ppm
CH_4 concentration or Mixing Ratio (μmol mol−1)	Parts per billion (10^9)	ppb
N_2O concentration or Mixing Ratio (μmol mol−1)	Parts per billion (10^9)	ppb
Radiative forcing	Watts per square meter	W/m^2
Energy-related units	**Unit**	**Symbol**
Energy	Joule	J
Electricity and Heat generation	Watt Hours	Wh
Power (Peak Capacity)	Watt (Watt thermal, Watt electric)	W ($W_{th,}$ W_e)
Capacity Factor	Percent	%
Technical and Economic Lifetime	Years	yr
Specific Energy Investment Costs	US Dollar 2010 per 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 $USct_{2010}/kWh$
Passenger-Distance	passenger-kilometer	p-km
Payload-Distance	tonne-kilometer	t-km
Land-related units	**Unit**	**Symbol**
Area	Hectare	ha

Note:

* CO_2-equivalent emissions in this report are—if not stated otherwise—aggregated using global warming potentials (GWPs) over a 100-year time horizon, often derived from the IPCC Second Assessment Report (IPCC, 1995a). A discussion about different GHG metrics can be found in Sections 1.2.5 and 3.9.6 (see Annex II.9.1 for the GWP values of the different GHGs).

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

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}). This only applies to monetary quantities reported in market exchange rates (MER), and not to those reported in purchasing power parity (PPP, unit: Int$).

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.

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.

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

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 gross domestic product (GDP) (see Section A.II.9) 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 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 RC5, RC10 (Region Categorization 5 and 10, respectively), see Table A.II.8, and ECON4 (income-based economic categorization), see Table A.II.9. RC10 is a breakdown of RC5 and can be aggregated to RC5 as shown in Table A.II.8. Note that for some exceptional cases in this report there are minor deviations from the RC5 and RC10 definitions given here. In addition to these three standard aggregations some chapters feature an 11 region aggregation (GEA R11) used in the Global Energy Assessment (GEA, 2012) and other studies.

A.II.2.1 RC10

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, United Kingdom, Turkey

POECD (Pacific OECD): Australia, Japan, New Zealand

EIT (Economies in Transition): Croatia, Cyprus, Czech Republic, Estonia, Latvia, Lithuania, Malta, Poland, Russian Federation, Slovakia,

Table A.II.8 | Description of regions in the RC5 and RC10 region sets.

RC5		RC10	
OECD-1990	OECD Countries in 1990	**NAM**	North America
		WEU	Western Europe
		POECD	Pacific OECD (Japan, Australia, New Zealand)
EIT	Economies in Transition (sometimes referred to as 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	Non-OECD Asia	**EAS**	East Asia
		SAS	South Asia
		PAS	South-East Asia and Pacific
INT TRA	International transport	**INT TRA**	International transport

Slovenia, Kyrgyzstan, Tajikistan, Armenia, Georgia, Moldova (Republic of), Ukraine, Uzbekistan, Albania, Azerbaijan, Belarus, Bosnia and Herzegovina, Bulgaria, Hungary, Kazakhstan, Macedonia, Montenegro, Romania, Serbia, Serbia and Montenegro, Turkmenistan

Table A.II.9 | ECON4 income-based economic country aggregations.

HIC	High-income countries
UMC	Upper-middle income countries
LMC	Lower-middle income countries
LIC	Low income countries
INT-TRA	International transport

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

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

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

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

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

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

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

A.II.2.2 RC5

For country mapping to each of the RC5 regions see RC10 mappings (Section A.II.2.1) and their aggregation to RC5 regions in Table A.II.8. It should be noted that this region set was also used in the so-called Representative Concentration Pathways (RCPs, see Section 6.3.2) and therefore has been adopted as a standard in integrated modelling scenarios (Section A.II.10).

A.II.2.3 ECON4

High Income (HIC): Aland Islands, Andorra, Anguilla, Antarctica, Antigua and Barbuda, Aruba, Australia, Austria, Bahamas, Bahrain, Barbados, Belgium, Bermuda, Bouvet Island, British Indian Ocean Territory, British Virgin Islands, Brunei Darussalam, Canada, Cayman Islands, Channel Islands, Chile, Christmas Island, Cocos (Keeling) Islands, Croatia, Curacao, Cyprus, Czech Republic, Denmark, Equatorial Guinea, Estonia, Falkland Islands (Malvinas), Faroe Islands, Finland, France, French Guiana, French Polynesia, French Southern Territories, Germany, Gibraltar, Greece, Greenland, Guadeloupe, Guam, Guernsey, Heard Island and McDonald Islands, Holy See (Vatican City State), Iceland, Ireland, Isle of Man, Israel, Italy, Japan, Jersey, Kuwait, Latvia, Liechtenstein, Lithuania, Luxembourg, Malta, Martinique, Mayotte, Monaco, Montserrat, Netherlands, Netherlands Antilles, New Caledonia, New Zealand, Norfolk Island, Northern Mariana Islands, Norway, Oman, Pitcairn, Poland, Portugal, Puerto Rico, Qatar, Reunion, Russian Federation, Saint Helena, Saint Kitts and Nevis, Saint Pierre and Miquelon, San Marino, Saudi Arabia, Singapore, Sint Maarten, Slovakia, Slovenia, South Georgia and the South Sandwich Islands, South Korea, Spain, Svalbard and Jan Mayen, Sweden, Switzerland, Tokelau, Trinidad and Tobago, Turks and Caicos Islands, United Arab Emirates, United Kingdom, United States, Uruguay, US Minor Outlying Islands, US Virgin Islands, Wallis and Futuna

Upper Middle Income (UMC): Albania, Algeria, American Samoa, Angola, Argentina, Azerbaijan, Belarus, Belize, Bosnia and Herzegovina, Botswana, Brazil, Bulgaria, China, Colombia, Cook Islands, Costa Rica, Cuba, Dominica, Dominican Republic, Ecuador, Fiji, Gabon, Grenada, Hungary, Iran, Iraq, Jamaica, Jordan, Kazakhstan, Lebanon, Libya, Macedonia, Malaysia, Maldives, Marshall Islands, Mauritius, Mexico, Montenegro, Namibia, Niue, Palau, Panama, Peru, Romania, Saint Lucia, Saint Vincent and the Grenadines, Serbia, Serbia and Montenegro, Seychelles, South Africa, Suriname, Thailand, Tonga, Tunisia, Turkey, Turkmenistan, Tuvalu, Venezuela

Lower Middle Income (LMC): Armenia, Bhutan, Bolivia, Cameroon, Cape Verde, Congo, Cote d'Ivoire, Djibouti, Egypt, El Salvador, Georgia, Ghana, Guatemala, Guyana, Honduras, India, Indonesia, Kiribati, Laos (People's Democratic Republic), Lesotho, Mauritania, Micronesia (Federated States of), Moldova (Republic of), Mongolia, Morocco, Nauru, Nicaragua, Nigeria, Pakistan, Palestine, Papua New Guinea, Paraguay, Philippines, Samoa, Sao Tome and Principe, Senegal, Solomon Islands, South Sudan, Sri Lanka, Sudan, Swaziland, Syrian Arab Republic, Timor-Leste, Ukraine, Uzbekistan, Vanuatu, Viet Nam, Western Sahara, Yemen, Zambia

Low Income (LIC): Afghanistan, Bangladesh, Benin, Burkina Faso, Burundi, Cambodia, Central African Republic, Chad, Comoros, Congo (The Democratic Republic of the), Eritrea, Ethiopia, Gambia, Guinea, Guinea-Bissau, Haiti, Kenya, Korea (Democratic People's Republic of), Kyrgyzstan, Liberia, Madagascar, Malawi, Mali, Mozambique, Myanmar, Nepal, Niger, Rwanda, Sierra Leone, Somalia, Tajikistan, Tanzania, Togo, Uganda, Zimbabwe

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

A.II.2.4 GEA R11

The 11 regions of GEA R11 are similar to the above RC10 and consist of North America (NAM), Western Europe (WEU), Pacific OECD (POECD [PAO]), Central and Eastern Europe (EEU), Former Soviet Union (FSU), Centrally Planned Asia and China (CPA), South Asia (SAS), Other Pacific Asia (PAS), Middle East and North Africa (MNA [MEA]), Latin America and the Caribbean (LAM [LAC]) and Sub-Saharan Africa (SSA [AFR]). The differences to RC10 are the following:

- RC10 EIT is split in GEA R11 FSU and EEU. To FSU belong Armenia, Azerbaijan, Belarus, Georgia, Kazakhstan, Kyrgyzstan, Republic of Moldova, Russian Federation, Tajikistan, Turkmenistan, Ukraine and Uzbekistan and to EEU belong Albania, Bosnia and Herzegovina, Bulgaria, Croatia, Czech Republic, Estonia, Macedonia, Hungary, Latvia, Lithuania, Montenegro, Poland, Romania, Serbia, Slovak Republic and Slovenia.
- GEA R11 NAM matches RC10 NAM plus Puerto Rico and the British Virgin Islands.
- GEA R11 LAM matches RC10 LAM without Puerto Rico and the British Virgin Islands.
- GEA R11 CPA matches RC10 EAS plus Cambodia, Laos (People's Democratic Republic), Viet Nam, without South Korea.
- GEA R11 PAS matches RC10 PAS plus South Korea and Taiwan, Province of China, without Cambodia, Laos (People's Democratic Republic), Viet Nam.

Part II: Methods

A.II.3 Costs metrics

Across this report, a number of different metrics to characterize cost of climate change 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 'levelized costs' is used throughout several chapters (7, 8, 9, 10, and 11) of this report in various forms (Section A.II.3.1). In holistic approaches to 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.3.2.

A.II.3.1 Levelized costs

Levelizing costs means to express all lifetime expenditures of a stream of relatively homogeneous outputs that occur over time as cost per unit of output. Most commonly, the concept is applied to electricity as an output. It is also being applied to express costs of other streams of outputs such as energy savings and greenhouse gas (GHG) emission savings. Each of these metrics provides a benchmark for comparing different technologies or practices of providing the respective output. Each also comes with a set of context-specific caveats that need to be taken into account for correct interpretation. Various literature sources caution against drawing too strong conclusions from these metrics. The levelized cost of energy (LCOE), the levelized cost of conserved energy (LCCE), and the levelized cost of conserved carbon (LCCC) are used throughout the WGIII AR5 to provide output-specific benchmarks for comparison. They are explained and discussed below in the mentioned order.[1]

A.II.3.1.1 Levelized cost of energy

Background

In order to compare energy supply technologies from an economic point of view, the concept of 'levelized cost of energy' (LCOE, also called levelized unit cost or levelized generation cost) frequently is applied (IEA and NEA, 2005; IEA, 2010a; Fischedick et al., 2011; Lar-

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[1] This section, however, does not take into account the implications for additional objectives beyond energy supply (LCOE), energy savings (LCCE) or mitigation (LCCC)—often referred to as co-benefits and adverse side-effects (see Glossary in Annex I). In particular, external costs are not taken into account if they are not internalized (e.g., via carbon pricing).

son et al., 2012; Turkenburg et al., 2012; UNEP, 2012; IRENA, 2013). Simply put, 'levelized' cost of energy is a measure that can be loosely defined as 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 levelized 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.

General formula and simplifications

According to the definition given above, "the levelized 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):

$$\sum_{t=0}^{n} \frac{E_t \cdot LCOE}{(1+i)^t} := \sum_{t=0}^{n} \frac{Expenses_t}{(1+i)^t} \qquad \text{(Equation A.II.1)}$$

where *LCOE* are the levelized cost of energy, E_t is the energy delivered in year *t* (which might vary from year to year), $Expenses_t$ 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:

$$LCOE := \frac{\sum_{t=0}^{n} \frac{Expenses_t}{(1+i)^t}}{\sum_{t=0}^{n} \frac{E_t}{(1+i)^t}} \qquad \text{(Equation A.II.2)}$$

Note that while it appears as if energy amounts were discounted in Equation A.II.2, this is just an arithmetic result of rearranging Equation A.II.1 (Branker et al., 2011). In fact, originally, revenues are discounted and not energy amounts per se (see Equation A.II.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, levelized cost can be determined by (IEA, 2010a):

$$LCOE := \frac{\sum_{t=0}^{n} \frac{I_t + O\&M_t + F_t + C_t + D_t}{(1+i)^t}}{\sum_{t=0}^{n} \frac{E_t}{(1+i)^t}} \qquad \text{(Equation A.II.3)}$$

In simple cases, where the energy *E* provided annually is constant during the lifetime of the project, this translates to:

$$LCOE := \frac{CRF \cdot NPV\ (Lifetime\ Expenses)}{E} = \frac{Annuity\ (Lifetime\ Expenses)}{E} \qquad \text{(Equation A.II.4)}$$

where $CRF := \frac{i}{1-(1+i)^{-n}}$ is the capital recovery factor and *NPV* the net present value of all lifetime expenditures (Suerkemper et al., 2011). For the simplified case, where the annual costs are also assumed constant over time, this can be further simplified to (*O&M* costs and fuel costs *F* constants):

$$LCOE = \frac{CRF \cdot I + O\&M + F}{E} \qquad \text{(Equation A.II.5)}$$

Where *I* is the upfront investment, *O&M* are the annual operation and maintenance costs, *F* are the annual fuel costs, and *E* is the annual energy provision. The investment *I* should be interpreted (here and also in Equations A.II.7 and A.II.9) as the sum of all capital expenditures needed to make the investment fully operational discounted to t = 0. These might include discounted payments for retrofit payments during the lifetime and discounted decommissioning costs at the end of the lifetime. Where applicable, annual O&M costs have to take into account revenues for by-products and existing carbon costs must be added or treated as part of the annual fuel costs.

Discussion of LCOE

The LCOE of a technology is only one indicator for its economic competitiveness, but there are more dimensions to it. Integration costs, time dependent revenue opportunities (especially in the case of intermittent renewables), and relative environmental impacts (e.g., external costs) play an important role as well (Heptonstall, 2007; Fischedick et al., 2011; Joskow, 2011a; Borenstein, 2012; Mills and Wiser, 2012; Edenhofer et al., 2013a; Hirth, 2013). Joskow (2011b) 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 these comparisons fail to take into account the different production schedule and the associated differences in the market value of the electricity that is provided. An extended criticism of the concept of LCOE as applied to renewable energies is provided by (Edenhofer et al., 2013b).

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 (IEA and NEA, 2005; DTI, 2006). Some studies suggest that the role of levelized 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, 2010a).

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, 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 photovoltaic (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 (Fischedick et al., 2011).

A.II.3.1.2 Levelized cost of conserved energy

Background

The concept of 'levelized cost 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 purchasing cost per unit of energy. In essence the concept, similarly to LCOE, also annualizes 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).

General formula and simplifications

The conceptual formula for LCCE is essentially the same as Equation A.II.4 above, with *ΔE* meaning in this context the amount of energy saved annually (Suerkemper et al., 2011):

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

(Equation A.II.6)

In the case of assumed annually constant O&M costs over the lifetime, this simplifies to (equivalent to Equation A.II.5) (Hansen, 2012):

$$\text{LCCE} = \frac{\text{CRF} \cdot \Delta \text{I} + \Delta \text{O\&M}}{\Delta \text{E}}$$ (Equation A.II.7)

Where *ΔI* is the difference in investment costs of an energy saving measure (e.g., in USD) as compared to a baseline investment; *ΔO&M* is the difference in annual operation and maintenance costs of an energy saving measure (e.g., in USD) as compared to the baseline in which the energy saving measure is not implemented; *ΔE* 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. It should be stressed once more that this equation is only valid if *ΔO&M* and *ΔE* are constant over the lifetime. As LCCE are designed to be compared with complementary levelized cost of energy supply, they do not include the annual fuel cost difference. Any additional monetary benefits that are associated with the energy saving measure must be taken into account as part of the O&M difference.

Discussion of LCCE

The main strength of the LCCE 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 purchasing cost values for determining the profitability of the investment (Suerkemper et al., 2011).

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 (see Section 9.3 and 9.6). 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 LCCE value can be many times higher. This is one of the main challenges in interpreting LCCE.

Another challenge in the calculation of LCCE should be pinpointed. 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. Thus, in the calculation of the LCCE for a CFL replacing an incandescent lamp the saved investments in multiple incandescent lamps should be taken into account (Ürge-Vorsatz, 1996). In such a case, as in some other cases, too, the difference in annualized investment cost can be negative resulting in negative LCCE values. Negative LCCE 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.

Taking into account incremental operation and maintenance cost can be important for applications where those are significant, 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 LCCEs or cost savings (Ürge-Vorsatz, 1996). In case of such negative incremental investment cost, some peculiarities may occur. For instance, as can be seen from Equation A.II.7, LCCE decrease (become more negative) with increasing *CRF*, e.g., as a result of an increase in discount rates.

A.II.3.1.3 Levelized cost of conserved carbon

Background

Many find it useful to have a simple metric for identifying the costs of GHG emission mitigation. The metric can be used for comparing mitigation costs per unit of avoided emissions, and comparing these specific emission reduction costs for different options, within a company, within a sector, or even between sectors. This metric is often referred to as levelized cost of conserved carbon (LCCC) or specific GHG mitigation costs. There are several caveats, which will be discussed below, after the general approach is introduced.

General formula and simplification

For calculation of specific mitigation costs, the following, equation holds, where ΔC is the annual reduction in GHG emissions achieved through the implementation of an option. The equation is equivalent to Equations A.II.4 and A.II.6.

$$\mathrm{LCCC} := \frac{\mathrm{CRF} \cdot \mathrm{NPV}(\Delta \mathrm{LifetimeExpenses})}{\Delta \mathrm{C}} = \frac{\mathrm{Annuity}(\Delta \mathrm{LifetimeExpenses})}{\Delta \mathrm{C}}$$

(Equation A.II.8)

Also this equation can be simplified under the assumption of annual GHG emission reduction, annual O&M costs and annual benefits ΔB being constant over the lifetime of the option.

$$\mathrm{LCCC} = \frac{\mathrm{CRF} \cdot \Delta \mathrm{I} + \Delta \mathrm{O\&M} - \Delta \mathrm{B}}{\Delta \mathrm{C}}$$ (Equation A.II.9)

Where ΔI is the difference in investment costs of a mitigation measure (e.g., in USD) as compared to a baseline investment; $\Delta O\&M$ is the difference in annual operation and maintenance costs (e.g., in USD) and ΔB denotes the annual benefits, all compared to a baseline for which the option is not implemented. Note that annual benefits include reduced expenditures for fuels, if the investment project reduces GHG emissions via a reduction in fuel use. As such LCCC depend on energy prices.

An important characteristic of this equation is that LCCC can become negative if ΔB is bigger than the sum of the other two terms in the numerator.

Discussion of LCCC

Several issues need to be taken into account when using LCCC. First of all, the calculation of LCCC for one specific option does not take into account the fact that each option is implemented in a system, and the value of the LCCC of one option will depend on whether other options will be implemented or not (e.g., because the latter might influence the specific emissions of the background system). To solve this issue, analysts use integrated models, in which ideally these interactions are taken into account (see Chapter 6). Second, energy prices and other benefits are highly variable from region to region, rarely constant over time, and often difficult to predict. This issue is relevant for any analysis on mitigation, but it is always important to be aware of the fact that even if one single LCCC number is reported, there will be substantial uncertainty in that number. Uncertainty tends to increase from LCOE to LCCE, for example, due to additional uncertainty with regard to the choice of the baseline, and even further for LCCC, since not only a baseline needs to be defined, but furthermore the monetary benefit from energy savings needs to be taken into account (if the mitigation measure affects energy consumption). Moving from LCOE to LCCC in the field of energy supply technologies, for instance, results in comparing LCOE differences to the differences of the specific emissions of the mitigation technology compared to the reference plant (Rubin, 2012). As Sections 7.8.1 and 7.8.2 have shown, LCOE and specific emissions exhibit large uncertainties in their own, which result in an even exaggerated uncertainty once combined to yield the LCCC. Third, options with negative costs can occur, for example, in cases where incremental investment cost are taken to be negative. Finally, there is also a debate whether options with negative costs can occur at all, as it apparently suggests a situation of non-optimized behaviour. For further discussion of negative costs, see Box 3.10 in Chapter 3 of this report.

Levelized costs of conserved carbon are used to determine abatement cost curves, which are frequently applied in climate change decision making. The merits and shortcoming of abatement cost curves are discussed in the IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation (SRREN) (Fischedick et al., 2011) and in Chapter 3 (Section 3.9.3) of the AR5. In order to avoid some of the shortcomings of abatement cost curves, the AR5 opted to use integrated modelling scenarios in order to evaluate the economic potential of specific mitigation options in a consistent way. Integrated models are able to determine the economic potential of single mitigation options within the context of (other) competing supply-side and demand-side options by taking their interaction and potential endogenous learning effects into account. The results obtained in this way are discussed in Chapter 6.

A.II.3.2 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 3.9.3 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 measure of overall mitigation cost than those focused on individual income and consumption, because it is an output-related measure that in addition to consumption also includes investment, imports and exports, and government spending. Aggregate consumption and GDP losses are only available from an analysis of the policy impact on the full economy. Common cost measures used in studies of the policy impact on specific economic sectors, such as the energy sector, are the reduction in consumer and producer surplus and the 'area under the marginal abatement cost function'.

From a practical perspective, different modelling frameworks applied in mitigation analysis are capable of producing different cost estimates (Section 6.2). Therefore, when comparing cost estimates across 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 the reduction of consumer and producer surplus are used for partial equilibrium models. Costs are generally measured relative to a baseline scenario without mitigation policy. Consumption losses can be expressed in terms of, inter alia, the reduction of baseline consumption in a given year or the annual average reduction of consumption growth in the baseline over a given time period.

One popular measure used in different studies to evaluate the economic implications of mitigation actions is the emissions price, often presented in per tonne of CO_2 or per tonne of CO_2-equivalent (CO_2eq). 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, i.e., the cost of an incremental reduction of emissions by one unit. 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 existing or new policies and measures, such as regulatory policies that aim at reducing GHG emissions (e.g., feed-in tariffs, subsidies to low-carbon technologies, renewable portfolio standards) 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 important to calculate the total cost of mitigation over the entire lifetime of a policy. The application of discounting is common practice in economics when comparing costs over time. In Chapter 3, Section 3.6.2 provides some theoretical background on the choice of discount rates in the context of cost-benefit analysis (CBA), where discounting is crucial, because potential climate damages, and thus benefits from their avoidance, will occur far in the future, are highly uncertain, and are often in the form of non-market goods. In Chapter 6, mitigation costs are assessed primarily in the context of cost-effectiveness analysis, in which a target for the long-term climate outcome is specified and models are used to estimate the cost of reaching it, under a variety of constraints and assumptions (Section 6.3.2). These scenarios do not involve the valuation of damages and the difficulties arising from their aggregation. Nonetheless, the models surveyed in Chapter 6 consider transformation pathways over long time horizons, so they must specify how decision makers view intertemporal tradeoffs.

The standard approach is to use a discount rate that approximates the interest rate, that is, the marginal productivity of capital. Empirical estimates of the long-run average return to a diversified portfolio are typically in the 4%–6% range. In scenarios where the long-term target is set, the discounting approach will have an effect only on the speed and shape of the mitigation schedule, not on the overall level of stringency (note that this is in sharp contrast to cost-benefit analysis, where the discounting approach is a strong determinant of the level of stringency). Although a systematic comparison of alternative discounting approaches in a cost-effectiveness setting does not exist in the literature, we can make the qualitative inference that when a policy-maker places more (less) weight on the future, mitigation effort will be shifted sooner (later) in time. Because of long-lived capital dynamics in the energy system, and also because of expected technical change, mitigation effort in a cost-effectiveness analysis typically begins gradually and increases over time, leading to a rising cost profile. Thus, an analogous inference can be made that when a policy-maker places more (less) weight on the future, mitigation costs will be higher (lower) earlier and lower (higher) later.

Estimates of the macroeconomic cost of mitigation usually represent direct mitigation costs and do not take into account co-benefits or adverse side-effects of mitigation actions (see red arrows in Figure A.II.1). Further, these costs are only those of mitigation; they do not capture the benefits of reducing CO_2eq concentrations and limiting climate change.

Two further concepts are introduced in Chapter 6 to classify cost estimates (Section 6.3.6). The first is an idealized implementation approach in which a ubiquitous price on carbon and other GHGs is applied across the globe in every sector of every country and which rises over time at a rate that reflects the increase in the cost of the next available unit of emissions reduction. The second is an idealized implementation environment of efficient global markets in which there are no pre-existing distortions or interactions with other, non-climate market failures. An idealized implementation approach minimizes mitigation costs in an idealized implementation environment. This is not necessarily the case in non-idealized environments in which climate policies interact with existing distortions in labour, energy, capital, and land markets. If those market distortions persist or are aggravated by climate policy, mitigation costs tend to be higher. In turn, if climate policy is brought to bear on reducing such distortions, mitigation costs can be lowered by what has been frequently called a double dividend of climate policy (see blue arrows in Figure A.II.1). Whether or not such a double dividend is available will depend on assumptions about the policy environment and available climate policies.

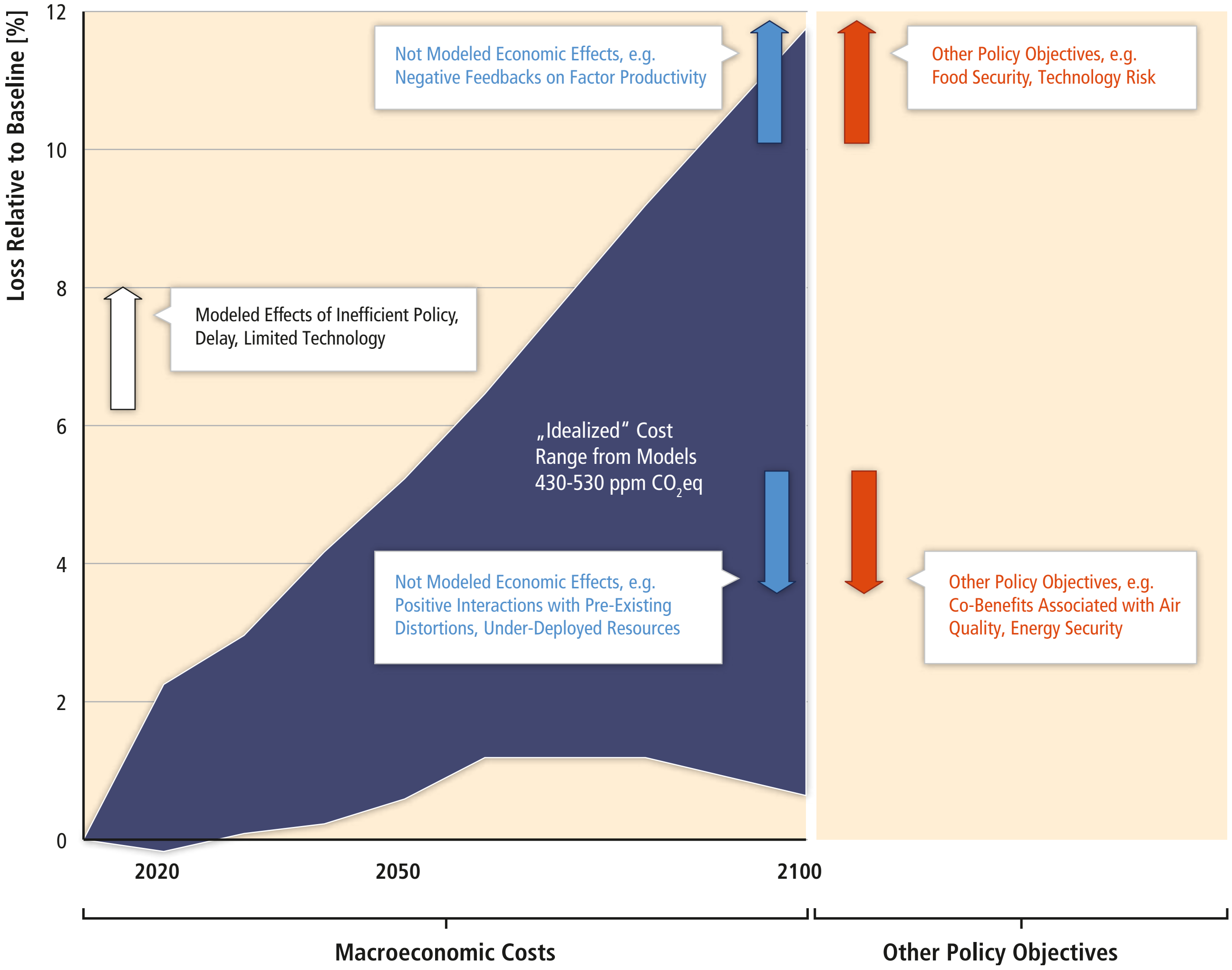

Figure A.II.1 | Modelled policy costs in a broader context. The plotted range summarizes costs expressed as percentage loss relative to baseline across models for cost-effective scenarios reaching 430–530 ppm CO_2eq. Scenarios were sorted by total NPV costs for each available metric (loss in GDP, loss in consumption, area under marginal abatement cost curve as a fraction of GDP). The lower boundary of the plotted range reflects the minimum across metrics of the 25th percentile, while the upper boundary reflects the maximum across metrics of the 75th percentile. A comprehensive treatment of costs and cost metrics, including the effects of non-idealized scenario assumptions, is provided in Section 6.3.6. Other arrows and annotations indicate the potential effects of considerations outside of those included in models. Source: WGIII AR5 Scenario Database.

A.II.4 Primary energy accounting

Following the standard set by the SRREN, this report adopts the direct-equivalent accounting method for the reporting of primary energy from non-combustible energy sources. The following section largely reproduces Annex A.II.4 of the SRREN (Moomaw et al., 2011) with some updates and further clarifications added.

Different energy analyses use a variety of accounting methods that lead to different quantitative outcomes for both reporting of current primary energy use and primary 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 U.S. Energy Information Administration (EIA, 2012a, b, Table A6), both of which publish international energy statistics; and

Table A.II.10 | 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*	
	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

* 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 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 of electricity. Nuclear energy is calculated from the gross generation by assuming a 33 % thermal conversion efficiency[2], 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 the U.S. Energy Information Administration (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.

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 (IPCC, 1995b; 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 vaporization 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 % smaller than the HHV, for natural gas and derived gases the difference is roughly 9–10 %, while the concept does not apply to non-combustible energy carriers such as electricity and heat for which LHV and HHV are therefore identical (IEA, 2012a).

In the WGIII AR5, IEA data are utilized, but energy supply is reported using the *direct equivalent method*. In addition, the reporting of com-

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[2] 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).

bustible energy quantities, including primary energy, should use the LHV which is consistent with the IEA energy balances (IEA, 2012a; b). Table A.II.10 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 2010, 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.

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 and secondary energy production (e.g., of electricity, heat), using different sources helps link the conversion processes with the final use of energy.

A.II.5 Indirect primary energy use and CO_2 emissions

Energy statistics in most countries of the world and at the International Energy Agency (IEA) display energy use and carbon dioxide (CO_2) emissions from fuel combustion directly in the energy sectors. As a result, the energy sector is the major source of reported energy use and CO_2 emissions, with the electricity and heat industries representing the largest shares.

However, the main driver for these energy sector emissions is the consumption of electricity and heat in the end use sectors (industry, buildings, transport, and agriculture). Electricity and heat mitigation opportunities in these end use sectors reduce the need for producing these energy carriers upstream and therefore reduce energy and emissions in the energy sector.

In order to account for the impact of mitigation activities in the end use sectors, a methodology has been developed to reallocate the energy consumption and related CO_2 emissions from electricity and heat produced and delivered to the end use sectors (de la Rue du Can and Price, 2008).

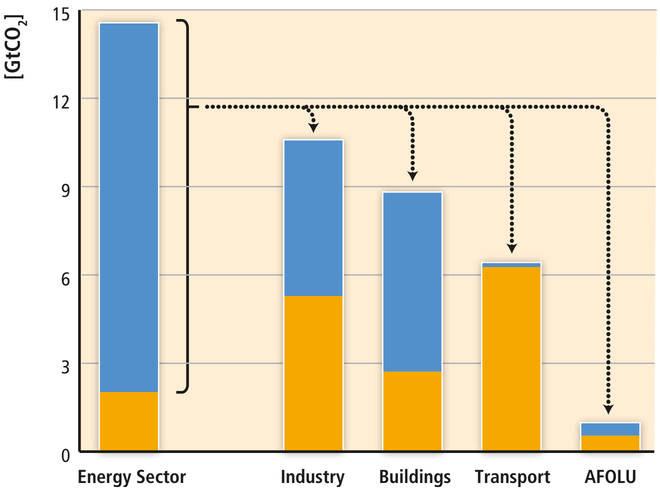

Figure A.II.2 | Energy sector electricity and heat CO_2 emissions calculated for the end-use sectors in 2010. Note that industry sector CO_2 emissions do not include process emissions. Data source: (IEA, 2012b; c).

Using IEA data, the methodology calculates a series of primary energy factors and CO_2 emissions factors for electricity and heat production at the country level. These factors are then used to re-estimate energy and emissions from electricity and heat produced and delivered to the end use sectors proportionally to their use in each end-use sectors. The calculated results are referred to as primary energy[3] and indirect CO_2 emissions.

The purpose of allocating primary energy consumption and indirect CO_2 emissions to the sectoral level is to relate the energy used and the emissions produced along the entire supply chain to provide energy services in each sector (consumption-based approach). For example, the consumption of one kWh of electricity is not equivalent to the consumption of one kWh of coal or natural gas, because of the energy required and the emissions produced in the generation of one kWh of electricity.

Figure A.II.2 shows the resulting reallocation of CO_2 emissions from electricity and heat production from the energy sector to the industrial, buildings, transport, and agriculture sectors at the global level based on the methodology outlined in de la Rue du Can and Price (2008) and described further below.

A.II.5.1 Primary electricity and heat factors

Primary electricity and heat factors have been derived as the ratio of fuel inputs of power plants relative to the electricity and heat delivered. These factors reflect the efficiency of these transformations.

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[3] Note that final energy and primary energy consumption are different concepts (Section A.II.3.4). Final energy consumption (sometimes called site energy consumption) represents the amount of energy consumed in end use applications whereas primary energy consumption (sometimes called source energy consumption) in addition includes the energy required to generate, transmit and distribute electricity and heat.

Primary Electricity Factor:

$$PEF = \frac{\sum_{e,p} EI}{\sum_{p} EO - E\,OU - E\,DL}$$

Where

- *EI* is the total energy (e) inputs for producing Electricity in TJ
- *EO* is the total Electricity Output produced in TJ
- *E OU* is the energy use for own use for Electricity production
- *E DL* is the distribution losses needed to deliver electricity to the end use sectors

Primary Heat Factor:

$$PHF = \frac{\sum_{e,p} HI}{\sum_{p} HO - H\,OU - H\,DL}$$

Where

- *HI* is the total energy (e) inputs for producing Heat in TJ
- *HO* is the total Heat Output produced in TJ
- *H OU* is the energy use for own use for Heat production
- *H DL* is the distribution losses needed to deliver heat to the end use sectors

p represents the 6 plant types in the IEA statistics (Main Activity Electricity Plant, Autoproducer Electricity Plant, Main Activity CHP plant, Autoproducer CHP plant, Main Activity Heat Plant and Autoproducer Heat Plant)

e represents the energy products

It is important to note that two accounting conventions were used to calculate these factors. The first involves estimating the portion of fuel input that produces electricity in combined heat and power plants (CHP) and the second involves accounting for the primary energy value of non-combustible fuel energy used as inputs for the production of electricity and heat. The source of historical data for these calculations is the International Energy Agency (IEA, 2012c; d).

For the CHP calculation, fuel inputs for electricity production were separated from inputs for heat production according to the fixed-heat-efficiency approach used by the IEA (IEA, 2012c). This approach fixes the efficiency for heat production equal to 90 %, which is the typical efficiency of a heat boiler (except when the total CHP efficiency was greater than 90 %, in which case the observed efficiency is used). The estimated input for heat production based on this efficiency was then subtracted from the total CHP fuel inputs, and the remaining fuel inputs to CHP were attributed to the production of electricity. As noted by the IEA, this approach may overstate the actual heat efficiency in certain circumstances (IEA, 2012c; d).

As described in Section A.II.4 in more detail, different accounting methods to report primary energy use of electricity and heat production from non-combustible energy sources, including non-biomass renewable energy and nuclear energy, exist. The direct equivalent accounting method is used here for this calculation.

Global average primary and electricity factors and their historical trends are presented in Figure A.II.3. Average factors for fossil power and heat plants are in the range of 2.5 and 3 and factors for non-biomass renewable energy and nuclear energy are by convention a little above one, depending on heat and electricity own use consumption and distribution losses.

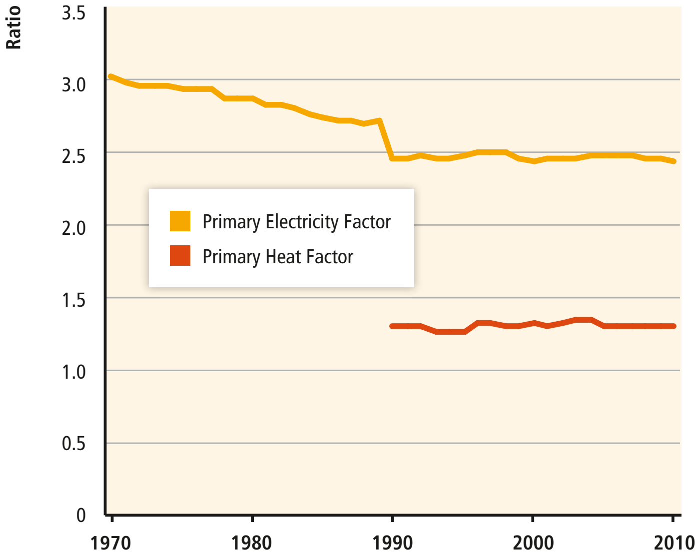

Figure A.II.3 | Historical primary electricity and heat factors. Data source: (IEA, 2012b).

A.II.5.2 Carbon dioxide emission factors

Carbon dioxide emission factors for electricity and heat have been derived as the ratio of CO_2 emissions from fuel inputs of power plants relative to the electricity and heat delivered. The method is equivalent to the one described above for primary factors. The fuel inputs have in addition been multiplied by their CO_2 emission factors of each fuel type as defined in IPCC (2006). The calculation of electricity and heat related CO_2 emission factors are conducted at the country level. Indirect carbon emissions related to electricity and heat consumption are then derived by simply multiplying the amount of electricity and heat consumed with the derived electricity and heat CO_2 emission factors at the sectoral level.

When the results of the methodology described above to estimate end-use CO_2 emissions from electricity and heat production are compared with the reported IEA direct emissions from the heat and electricity sectors there is an average difference of + 1.36 % over the years 1970 to 2010, indicating a slight overestimation of global CO_2 emissions. This difference varies by year, with the largest negative dif-

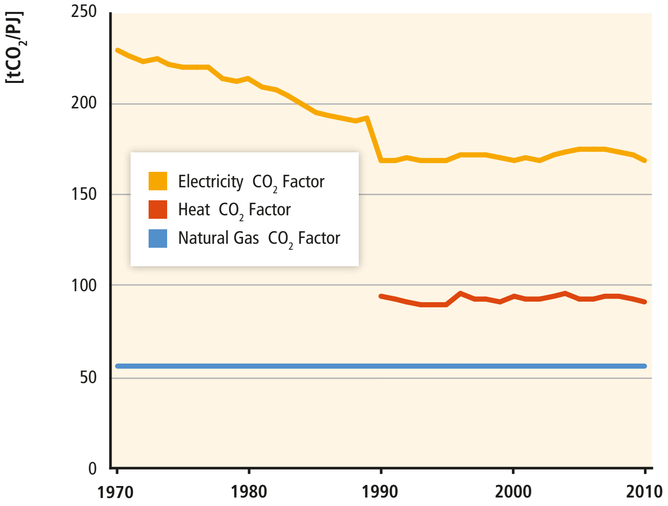

Figure A.II.4 | Historical electricity and heat CO$_2$ emissions factors. Data source: (IEA, 2012b; c).

ference in 1976 (-2.99 %) and the largest positive difference in 1990 (3.23 %).

The cross-sectoral annual total indirect carbon emissions were then normalized to the direct emission from electricity and heat production on the global level.

Figure A.II.4 shows the historical electricity CO$_2$ emission factors. The factors reflect both the fuel mix and conversion efficiencies in electricity generation and the distribution losses. Regions with high shares of non-fossil electricity generation have low emissions coefficients. For example, Latin America has a high share of hydro power and therefore a low CO$_2$ emission factor in electricity generation.

Primary heat and heat carbon factors were also calculated however, due to irregularity in data availability over the years at the global level, only data from 1990 are shown in the figures.

The emission factor for natural gas, 56.1 tCO$_2$ per PJ combusted, is shown in the graph for comparison.

A.II.6 Material flow analysis, input-output analysis, and lifecycle assessment

In the WGIII AR5, findings from material flow analysis, input-output analysis, and lifecycle assessment are used in Chapters 1, 4, 5, 7, 8, 9, 11, and 12. The following section briefly sketches the intellectual background of these methods and discusses their usefulness for mitigation research, and discusses some relevant assumptions, limitations, and methodological issues.

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. 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) also known as the biophysical economy (Cleveland et al., 1984), can complement energy assessments in important manners and support the development of a broader framing of mitigation research as part of sustainability science. The socio-economic 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 can be used 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.

An important application of these methods is carbon footprinting, i. e., the determination of lifecycle GHG emissions of products, organizations, households, municipalities, or nations. The carbon footprint of products usually determined using lifecycle assessment, while the carbon footprint of households, regional entities, or nations is commonly modeled using input-output analysis.

A.II.6.1 Material flow analysis

Material flow analysis (MFA)—including substance flow analysis (SFA)—is a method for describing, modelling (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 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; Kennedy et al., 2007) or other socioeconomic subsystems. Similarly comprehensive methods that apply the same system boundaries have been developed to account for energy flows (Haberl, 2001a; b; 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 socioeconomic 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 (Haberl et al., 2011; Erb et al., 2012).

Anthropogenic stocks (built environment) play a crucial role in socio-metabolic systems: (1) they provide services to the inhabitants, (2) their operation often requires energy and releases emissions, (3) any increase or renewal/maintenance of these stocks requires materials, and (4) 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 carbon 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 (Milford et al., 2013; Pauliuk et al., 2013a), the aluminium industry (Liu et al., 2011, 2012), the vehicle stock (Pauliuk et al., 2011; Melaina and Webster, 2011), or the building stock (Pauliuk et al., 2013b).

A.II.6.2 Input-output analysis

Input-output (IO) 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 an environmentally desirable global division of labour (Stromman et al., 2009). Important for mitigation research, input-output analysis has been used to estimate the GHG 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 by specific groups of society (Lenzen and Schaeffer, 2004), regions (Turner et al., 2007), or institutions (Larsen and Hertwich, 2009; Minx et al., 2009; Peters, 2010; Berners-Lee et al., 2011).[4]

Global, multiregional input-output models are currently seen as the state-of-the-art tool to quantify 'consumer responsibility' (Chapter 5) (Hertwich, 2011; Wiedmann et al., 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 mitigation research are the quantification of the total CO_2 emissions embodied in global trade (Peters and Hertwich, 2008), the growth of net emissions embodied in trade from non-Annex B to Annex B countries (Peters et al., 2011b), 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 GHG 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 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, but efforts to disaggregate tables to provide more detail in environmentally relevant sectors exist (Tukker et al., 2013). Many models 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 nowcast tables are currently under development (Lenzen et al., 2012).

A.II.6.3 Lifecycle assessment

Product lifecycle 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 lifecycle 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.

Lifecycle assessment plays an increasingly important role in climate mitigation research (SRREN Annex II, Moomaw et al., 2011). In WGIII AR5, lifecycle assessment has been used to quantify the GHG emissions associated with mitigation technologies, e.g., wind power, heat recovery ventilation systems, or carbon dioxide capture and storage. Lifecycle assessment is thus used to compare different ways to deliver the same functional unit, such as one kWh of electricity.

Lifecycle assessment 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. Impact assessment methods have been developed to model a wide range of impact pathways.

A range of approaches is used in LCA to address the climate impact of environmental interventions, starting from GHG through other pollutants (such as aerosols) to the inclusion of geophysical effects such as albedo changes or indirect climate effects (Bright et al., 2012), also exploring radiation-based climate metrics (Peters et al., 2011a). The timing of emissions and removals has traditionally not been considered, but issues associated with biomass production and use have given rise to a approaches to quantify the effects of carbon sequestration and temporary carbon storage in long-lived products (Brandão et al., 2013; Guest et al., 2013; Levasseur et al., 2013) and of temporarily increased atmospheric CO_2 concentrations from 'carbon-neutral' bioenergy systems (Cherubini et al., 2011).

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[4] GHG emissions related to land-use change have not yet been addressed in MRIO-based carbon footprint analysis due to data limitations.

Life-cycle inventories are normally derived from empirical information on actual processes or modelled based on engineering calculations. A key aspect of lifecycle 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 lifecycle 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. Modelling 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. Lifecycle assessment, 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.

Lifecycle assessment 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 modelled as such (Guinée et al., 2010).

For climate change 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 change 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 behavioural 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 spillover 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 lifecycle 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.7 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^{-a} 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.

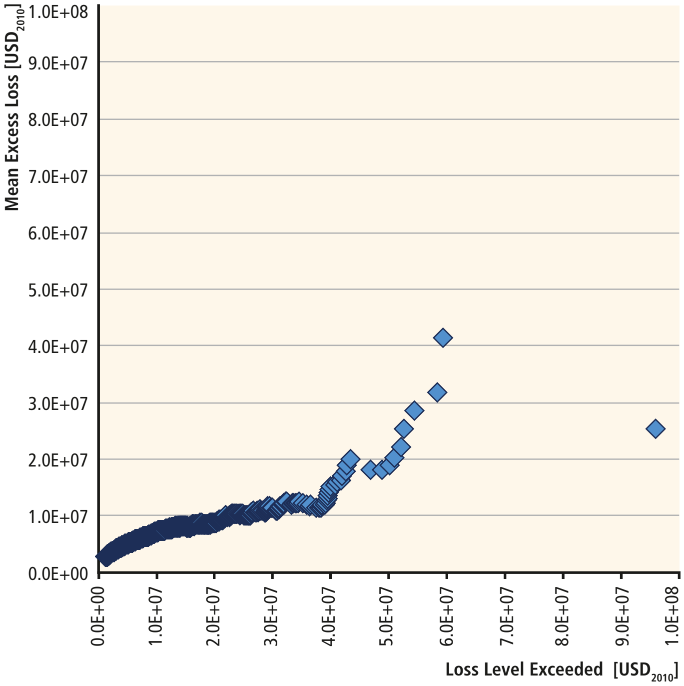

Figure A.II.6 | Mean excess curve of US crop insurance indemnities paid from the US Department of Agriculture's Risk Management Agency, aggregated by county and year for the years 1980 to 2008 in USD_{2010}. Note: The vertical axis gives mean excess loss, given loss at least as large as the horizontal axis. Source: adapted from (Kousky and Cooke, 2009).

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* – *x* given that *X* exceeds *x*. If *X* is regularly varying with tail index $\alpha > 1$, the mean excess curve of *X* is asymptotically linear with slope $1/(\alpha\text{-}1)$. 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 United States, per county per year per dollar income (hereby correcting for growth in exposure, Figure A.II.5) and insurance indemnities for crop loss per county per year in the United States (Figure A.II.6). 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).

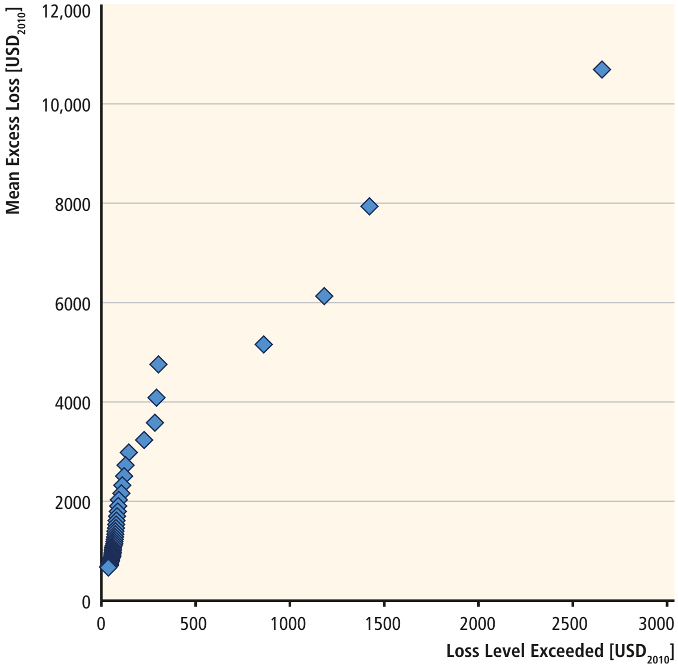

Figure A.II.5 | Mean excess curve for US flood insurance claims from the National Flood Insurance Program per dollar income per county per year for the years 1980 to 2008 in USD_{2010}. Considering dollar claims per dollar income in each county corrects for increasing exposure. Note: The vertical axis gives mean excess loss, given loss at least as large as the horizontal axis. Source: adapted from (Kousky and Cooke, 2009).

A.II.8 Growth rates

For the calculation of annual growth rates as frequently shown in this report, a number of different methods exist, all of which lead to slightly different numerical results. If not stated otherwise, the annual growth rates shown, have been derived using the *Log Difference Regression* technique or *Geometric Average,* techniques which can be shown to be equivalent.

The Log Difference Regression growth rate r_{LD} is calculated the following way:

$$r_{LD} = e^{\beta} - 1 \quad with \quad \beta = \frac{1}{T-1}\sum_{t=2}^{T} \Delta ln X_t \qquad \text{(Equation A.II.10)}$$

The *Geometric Average* growth rate r_{GEO} is calculated as shown below:

$$r_{GEO} = \left(\frac{X_T}{X_1}\right)^{\frac{1}{T-1}} - 1 \qquad \text{(Equation A.II.11)}$$

Other methods that are used to calculate annual growth rates include the *Ordinary Least Square* technique and the *Average Annual Growth Rate* technique.

Part III: Data sets

A.II.9 Historical data

To aid coherency and consistency, core historic data presented throughout the report uses the same sources and applied the same methodologies and standards—these are detailed here:

- The standard country aggregations to regions are detailed in Section A.II.2.
- The central historic GHG emission data set was based on IEA (2012c) and Emissions Database for Global Atmospheric Research (EDGAR) (JRC/PBL, 2013) data. This data set provides annual emissions on a country level for the time span 1970 to 2010. The two sources are mapped as described in Section A.II.9.1.
- As default dataset for GDP in Purchasing Power Parity (PPP) World Bank data was supplemented according to the methodology described in Section A.II.9.2.
- The data sources and methodology for historic indirect emissions from electricity and heat production are defined in Section A.II.5.
- Lifecycle GHG emission data sets of energy supply technologies, predominantly used in Chapter 7, are introduced in Section A.II.9.3. The underlying methodology is explained in Section A.II.6 of this Annex.

A.II.9.1 Mapping of emission sources to sectors

The list below shows how emission sources are mapped to sectors throughout the WGIII 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 disaggregated data was required, additional source categories were introduced consistent with the underlying datasets (IEA, 2012c; JRC/PBL, 2013). 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 (CO_2 data set used)]

A common dataset ('IEA/EDGAR') is used across WGIII AR5 chapters to ensure consistent representation of emission trends across the report. Uncertainties of this data are discussed in the respective chapters (Chapter 1; Chapter 5; and Chapter 11). CO_2 emissions from fossil fuel combustion are taken from IEA (2012c), the remaining CO_2 and non-CO_2 GHG emissions are taken from EDGAR (JRC/PBL, 2013), see the following sections for categories and sources used. For the FOLU subsector EDGAR (JRC/PBL, 2013) represents land-based CO_2 emissions from forest and peat fires and decay to approximate the CO_2 flux from anthropogenic emission sources.

Following general scientific practice, 100-year GWPs from the IPCC Second Assessment Report (SAR) (Schimel et al., 1996) are used as the index for converting GHG emissions to common units of CO_2-equivalent emissions in EDGAR (JRC/PBL, 2013). The following gases and associated GWPs based on the SAR are covered in EDGAR: CO_2 (1), CH_4 (21), N_2O (310), HFC-125 (2800), HFC-134a (1300), HFC-143a (3800), HFC-152a (140), HFC-227ea (2900), HFC-23 (11700), HFC-236fa (6300), HFC-245fa (560), HFC-32 (650), HFC-365mfc (1000), HFC-43–10-mee (1300), C_2F_6 (9200), C_3F_8 (7000), C_4F_{10} (7000), C_5F_{12} (7500), C_6F_{14} (7400), C_7F_{16} (7400), c-C_4F_8 (8700), CF_4 (6500), SF_6 (23900).

A.II.9.1.1 Energy (Chapter 7)

Electricity & heat (7.1)

Power and Heat Generation (1A1a) [CO_2 (IEA), CH_4, N_2O]
  Public Electricity Plants (1A1a1) [CO_2 (IEA)]
  Public Combined Heat and Power Generation (1A1a2) [CO_2 (IEA)]
  Public Heat Plants (1A1a3) [CO_2 (IEA)]
  Public Electricity Generation (own use) (1A1a4) [CO_2 (IEA)]
  Electricity Generation (autoproducers) (1A1a5) [CO_2 (IEA)]
  Combined Heat and Power Generation (autoproducers) (1A1a6) [CO_2 (IEA)]
  Heat Plants (autoproducers) (1A1a7) [CO_2 (IEA)]
Public Electricity and Heat Production (biomass) (1A1ax) [CH_4, N_2O]

Petroleum refining (7.2)

Other Energy Industries (1A1bc) [CO_2 (IEA)]

Manufacture of solid fuels (7.3)

Other transformation sector (BKB, etc.) (1A1r) [CH_4, N_2O]

Manufacture of Solid Fuels and Other Energy Industries (biomass) (1A1cx) [CH_4, N_2O]

Fuel production and transport (7.4)

Fugitive emissions from solids fuels except coke ovens (1B1r) [CO_2 (EDGAR), CH_4, N_2O]

Flaring and fugitive emissions from oil and Natural Gas (1B2) [CO_2 (EDGAR), CH_4, N_2O]

Others (7.5)

Electrical Equipment Manufacture (2F8a) [SF_6]

Electrical Equipment Use (includes site installation) (2F8b) [SF_6]

Fossil fuel fires (7A) [CO_2 (EDGAR), CH_4, N_2O]

Indirect N2O emissions from energy (7.6)

Indirect N_2O from NO_x emitted in cat. 1A1 (7B1) [N_2O]

Indirect N_2O from NH_3 emitted in cat. 1A1 (7C1) [N_2O]

A.II.9.1.2 Transport (Chapter 8)

Aviation (8.1)

Domestic air transport (1A3a) [CO_2 (IEA), CH_4, N_2O]

Road transportation (8.2)

Road transport (includes evaporation) (fossil) (1A3b) [CO_2 (IEA), CH_4, N_2O]

Road transport (includes evaporation) (biomass) (1A3bx) [CH_4, N_2O]

Adiabatic prop: tyres (2F9b) [SF_6]

Rail transportation (8.3)

Rail transport (1A3c) [CO_2 (IEA), CH_4, N_2O]

Non-road transport (rail, etc.) (fossil) (biomass) (1A3cx) [CH_4, N_2O]

Navigation (8.4)

Inland shipping (fossil) (1A3d) [CO_2 (IEA), CH_4, N_2O]

Inland shipping (fossil) (biomass) (1A3dx) [CH_4, N_2O]

Others incl. indirect N_2O emissions from transport (8.5)

Non-road transport (fossil) (1A3e) [CO_2 (IEA), CH_4, N_2O]
  Pipeline transport (1A3e1) [CO_2 (IEA)]
  Non-specified transport (1A3er) [CO_2 (IEA)]
Non-road transport (fossil) (biomass) (1A3ex) [CH_4, N_2O]
Refrigeration and Air Conditioning Equipment (HFC) (Transport) (2F1a1) [HFC]
Indirect N_2O from NO_x emitted in cat. 1A3 (7B3) [N_2O]
Indirect N_2O from NH_3 emitted in cat. 1A3 (7C3) [N_2O]

International Aviation (8.6)

Memo: International aviation (1C1) [CO_2 (IEA), CH_4, N_2O]

International Shipping (8.7)

Memo: International navigation (1C2) [CO_2 (IEA), CH_4, N_2O]

A.II.9.1.3 Buildings (Chapter 9)

Commercial (9.1)

Commercial and public services (fossil) (1A4a) [CO_2 (IEA), CH_4, N_2O]

Commercial and public services (biomass) (1A4ax) [CH_4, N_2O]

Residential (9.2)

Residential (fossil) (1A4b) [CO_2 (IEA), CH_4, N_2O]

Residential (biomass) (1A4bx) [CH_4, N_2O]

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) [SF_6]

Soundproof windows (2F9c) [SF_6]

Indirect N_2O emissions from buildings (9.4)

Indirect N_2O from NO_x emitted in cat. 1A4 (7B4) [N_2O]

Indirect N_2O from NH_3 emitted in cat. 1A4 (7C4) [N_2O]

A.II.9.1.4 Industry (Chapter 10)

Ferrous and non-ferrous metals (10.1)

Fuel combustion coke ovens (1A1c1) [CH_4, N_2O]
Blast furnaces (pig iron prod.) (1A1c2) [CH_4, N_2O]
Iron and steel (1A2a) [CO_2 (IEA), CH_4, N_2O]
Non-ferrous metals (1A2b) [CO_2 (IEA), CH_4, N_2O]
Iron and steel (biomass) (1A2ax) [CH_4, N_2O]
Non-ferrous metals (biomass) (1A2bx) [CH_4, N_2O]
Fuel transformation coke ovens (1B1b1) [CO_2 (EDGAR), CH_4]
Metal Production (2C) [CO_2 (EDGAR), CH_4, PFC, SF_6]
  Iron and Steel Production (2C1) [CO_2 (EDGAR)]
    Crude steel production total (2C1a) [CO_2 (EDGAR)]
  Ferroy Alloy Production (2C2) [CO_2 (EDGAR)]
  Aluminum production (primary) (2C3) [PFC]
  SF6 Used in Aluminium and Magnesium Foundries (2C4) [SF_6]
    Magnesium foundries: SF_6 use (2C4a) [SF_6]
    Aluminium foundries: SF_6 use (2C4b) [SF_6]
  Non-ferrous metals production (2Cr) [CO_2 (EDGAR)]

Chemicals (10.2)

Chemicals (1A2c) [CO_2 (IEA), CH_4, N_2O]

Chemicals (biomass) (1A2cx) [CH_4, N_2O]

Production of chemicals (2B) [CO_2 (EDGAR), CH_4, N_2O]
Production of Halocarbons and SF6 (2E) [HFC, SF6]
Non-energy use of lubricants/waxes (2G) [CO_2 (EDGAR)]
Solvent and other product use: paint (3A) [CO_2 (EDGAR)]
Solvent and other product use: degrease (3B) [CO_2 (EDGAR)]
Solvent and other product use: chemicals (3C) [CO_2 (EDGAR)]
Other product use (3D) [CO_2 (EDGAR), N_2O]

Cement production (10.3)

Cement production (2A1) [CO_2 (EDGAR)]

Landfill & waste incineration (10.4)

Solid waste disposal on land (6A) [CH_4]
Waste incineration (6C) [CO_2 (EDGAR), CH_4, N_2O]
Other waste handling (6D) [CH_4, N_2O]

Wastewater treatment (10.5)

Wastewater handling (6B) [CH_4, N_2O]

Other industries (10.6)

Pulp and paper (1A2d) [CO_2 (IEA), CH_4, N_2O]
Food and tobacco (1A2e) [CO_2 (IEA), CH_4, N_2O]
Other industries (stationary) (fossil) (1A2f) [CO_2 (IEA), CH_4, N_2O]
  Non-metallic minerals (1A2f1) [CO_2 (IEA)]
  Transport equipment (1A2f2) [CO_2 (IEA)]
  Machinery (1A2f3) [CO_2 (IEA)]
  Mining and quarrying (1A2f4) [CO_2 (IEA)]
  Wood and wood products (1A2f5) [CO_2 (IEA)]
  Construction (1A2f6) [CO_2 (IEA)]
  Textile and leather (1A2f7) [CO_2 (IEA)]
  Non-specified industry (1A2f8) [CO_2 (IEA)]
Pulp and paper (biomass) (1A2dx) [CH_4, N_2O]
Food and tobacco (biomass) (1A2ex) [CH_4, N_2O]
Off-road machinery: mining (diesel) (1A5b1) [CH_4, N_2O]
Lime production (2A2) [CO_2 (EDGAR)]
Limestone and Dolomite Use (2A3) [CO_2 (EDGAR)]
Production of other minerals (2A7) [CO_2 (EDGAR)]
Refrigeration and Air Conditioning Equipment (PFC) (2F1b) [PFC]
Foam Blowing (2F2) [HFC]
F-gas as Solvent (2F5) [PFC]
Semiconductor Manufacture (2F7a) [HFC, PFC, SF_6]
Flat Panel Display (FPD) Manufacture (2F7b) [PFC, SF_6]
Photo Voltaic (PV) Cell Manufacture (2F7c) [PFC]
Other use of PFC and HFC (2F9) [HFC, PFC]
Accelerators/HEP (2F9d) [SF_6]
Misc. HFCs/SF_6 consumption (AWACS, other military, misc.) (2F9e) [SF6]
Unknown SF_6 use (2F9f) [SF_6]

Indirect N_2O emissions from industry (10.7)

Indirect N_2O from NO_x emitted in cat. 1A2 (7B2) [N_2O]
Indirect N_2O from NH_3 emitted in cat. 1A2 (7C2) [N_2O]

A.II.9.1.5 AFOLU (Chapter 11)

Fuel combustion (11.1)

Agriculture and forestry (fossil) (1A4c1) [CO_2 (IEA), CH_4, N_2O]
Off-road machinery: agric./for. (diesel) (1A4c2) [CH_4, N_2O]
Fishing (fossil) (1A4c3) [CO_2 (IEA), CH_4, N_2O]
Non-specified Other Sectors (1A4d) [CO_2 (IEA), CH_4, N_2O]
Agriculture and forestry (biomass) (1A4c1x) [CH_4, N_2O]
Fishing (biomass) (1A4c3x) [N_2O]
Non-specified other (biomass) (1A4dx) [CH_4, N_2O]

Livestock (11.2)

Enteric Fermentation (4A) [CH_4]
Manure management (4B) [CH_4, N_2O]

Rice cultivation (11.3)

Rice cultivation (4C) [CH_4]

Direct soil emissions (11.4)

Other direct soil emissions (4D4) [CO_2 (EDGAR)]
Agricultural soils (direct) (4Dr) [N_2O]

Forrest fires and decay (11.5)

Savannah burning (4E) [CH_4, N_2O]
Forest fires (5A) [CO_2 (EDGAR), CH_4, N_2O]
Grassland fires (5C) [CH_4, N_2O]
Forest Fires-Post burn decay (5F2) [CO_2 (EDGAR), N_2O]

Peat fires and decay (11.6)

Agricultural waste burning (4F) [CH_4, N_2O]
Peat fires and decay of drained peatland (5D) [CO_2 (EDGAR), CH_4, N_2O]

Indirect N_2O emissions from AFOLU (11.7)

Indirect Emissions (4D3) [N_2O]
Indirect N_2O from NO_x emitted in cat. 5 (7B5) [N_2O]
Indirect N_2O from NH_3 emitted in cat. 5 (7C5) [N_2O]

A.II.9.1.6 Comparison of IEA and EDGAR CO_2 emission datasets

As described above the merged IEA/EDGAR historic emission dataset uses emission data from IEA (2012c) and EDGAR (JRC/PBL, 2013). Here we compare IEA/EDGAR to the pure EDGAR dataset (JRC/PBL, 2013). The comparison details the differences between the two datasets as the remaining CO_2 and non-CO_2 GHG emissions are identical between the two datasets. Table A.II.11 maps EDGAR categories to the IEA categories used in IEA/EDGAR forming 21 groups. Figure A.II.7 shows the quantitative differences for aggregated global emissions of these 21 groups between the two sources.

Table A.II.11 | Mapping of IEA (2012c) and EDGAR (JRC/PBL, 2013) CO_2 emission categories. Figure A.II.7 shows the quantitative difference for each Comparison Group (using Comparison Group number as reference).

Comparison Groups		EDGAR		IEA	IEA/EDGAR category
number	group name	IPCC category	category name	category name	
1	Power Generation	1A1a	Public electricity and heat production	Main activity electricity plants	1A1a1
				Main activity CHP plants	1A1a2
				Main activity heat plants	1A1a3
				Own use in electricity, CHP and heat plants	1A1a4
				Autoproducer electricity plants	1A1a5
				Autoproducer CHP plants	1A1a6
				Autoproducer heat plants	1A1a7
2	Other Energy Industries	1A1c1	Fuel combustion coke ovens	Other energy industry own use	1A1bc
		1A1c2	Blast furnaces (pig iron prod.)		
		1A1r	Other transformation sector (BKB, etc.)		
3	Iron and steel	1A2a	Iron and steel	Iron and steel	1A2a
4	Non-ferrous metals	1A2b	Non-ferrous metals	Non-ferrous metals	1A2b
5	Chemicals	1A2c	Chemicals	Chemical and petrochemical	1A2c
6	Pulp and paper	1A2d	Pulp and paper	Paper, pulp and printing	1A2d
7	Food and tobacco	1A2e	Food and tobacco	Food and tobacco	1A2e
8	Other Industries w/o NMM	1A2f	Other industries (incl. offroad) (fos.)	Transport equipment	1A2f2
				Machinery	1A2f3
				Mining and quarrying	1A2f4
				Wood and wood products	1A2f5
				Construction	1A2f6
				Textile and leather	1A2f7
				Non-specified industry	1A2f8
9	Non-metallic minerals	1A2f-NMM	Non-metallic minerals (cement proxy)	Non-metallic minerals	1A2f1
10	Domestic air transport	1A3a	Domestic air transport	Domestic aviation	1A3a
11	Road transport (incl. evap.) (foss.)	1A3b	Road transport (incl. evap.) (foss.)	Road	1A3b
12	Rail transport	1A3c	Non-road transport (rail, etc.) (fos.)	Rail	1A3c
13	Inland shipping (fos.)	1A3d	Inland shipping (fos.)	Domestic navigation	1A3d
14	Other transport	1A3e	Non-road transport (fos.)	Pipeline transport	1A3e1
				Non-specified transport	1A3er
				Non-energy use in transport	1A3er
15	Commercial and public services (fos.)	1A4a	Commercial and public services (fos.)	Commercial and public services	1A4a
16	Residential (fos.)	1A4b	Residential (fos.)	Residential	1A4b
17	Agriculture and forestry (fos.)	1A4c1	Agriculture and forestry (fos.)	Agriculture/forestry	1A4c1
		1A4c2	Off-road machinery: agric./for. (diesel)		
		1A5b1	Off-road machinery: mining (diesel)		
18	Fishing (fos.)	1A4c3	Fishing (fos.)	Fishing	1A4c3
19	Non-specified Other Sectors	1A4d	Non-specified other (fos.)	Non-specified other	1A4d
20	Memo: International aviation	1C1	International air transport	Memo: International aviation bunkers	1C1
21	Memo: International navigation	1C2	International marine transport (bunkers)	Memo: International marine bunkers	1C2

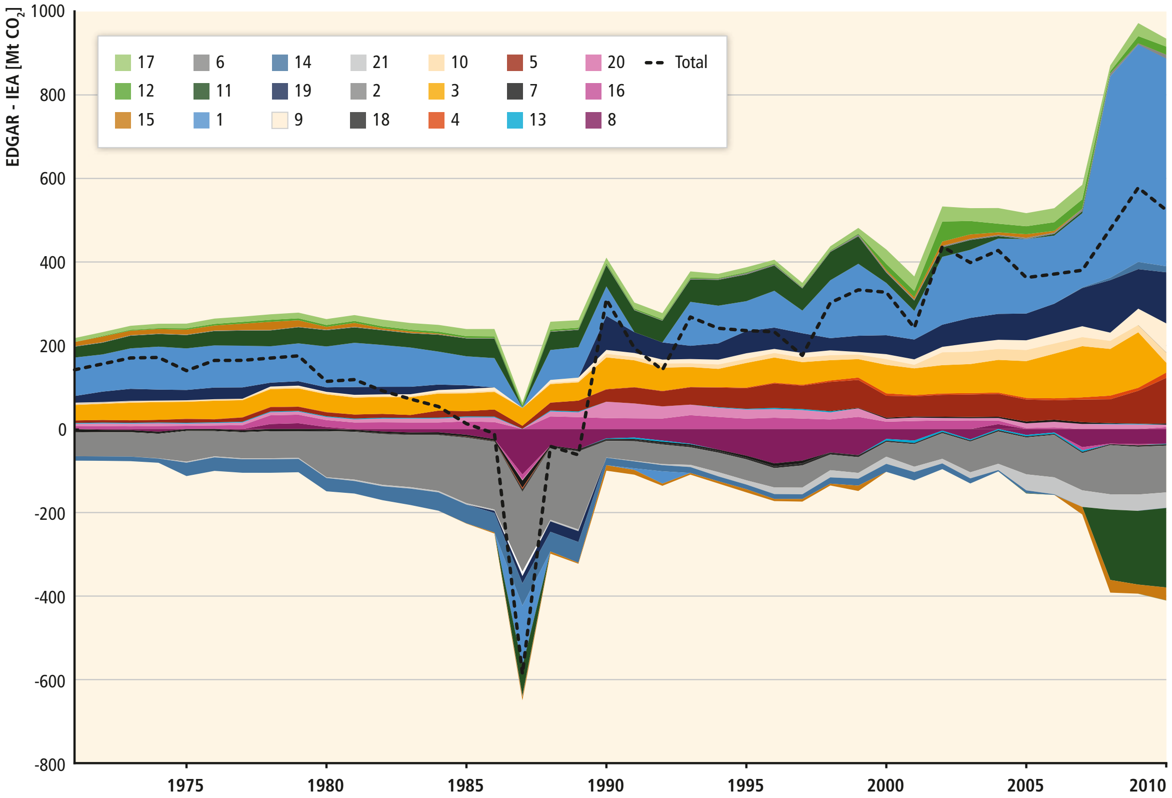

Figure A.II.7 | Difference of CO$_2$ emissions between analogous IEA (2012c) and EDGAR (JRC/PBL, 2013) categories as detailed in Table A.II.11. (Numbers in key refer to Table A.II.11 Comparison Groups).

A.II.9.2 Historic GDP PPP data

As default dataset for GDP in Purchasing Power Parity (PPP) World Bank data was used (World Bank, 2013). In line with the methodology described in Section A.II.1.3 and by Nordhaus (2007) the initial dataset (1980–2012 PPP in constant Int$$_{2011}$[5]) was extended backwards using World Bank GDP growth rates in constant local currency unit[6]. Further data gaps were closed extending World Bank data by applying growth rates as supplied by the IMF (2012) for 1980 and later. For gaps prior to 1980 Penn World Tables (PWT)(Heston et al., 2011) was used. In addition, missing countries were added using PWT (Heston et al., 2011)(Cuba, Puerto Rico, Marshall Islands, Somalia, Bermuda), IMF (2012) (Kosovo, Myanmar, Tuvala, Zimbabwe) and IEA (Dem Rep. Korea, Gibraltar, Netherlands Antilles) GDP data.

A.II.9.3 Lifecycle greenhouse gas emissions

In Chapter 7, Figure 7.6 and 7.7, the lifecycle GHG emissions of different technologies are compared. This section describes how these numbers are derived. The air pollutant emission numbers in Figure 7.8 are from (Hertwich et al., 2013). The assessment of GHG emissions and other climate effects associated with electricity production technologies presented here is based on two distinct research enterprises.

The first effort started with the review of lifecycle GHG emission started for SRREN (Sathaye et al., 2011). This work was extended to a harmonization of LCA studies following the approach by Farrell et al. (2006) and resulted in a set of papers published a special issue of the *Journal of Industrial Ecology* (Brandão et al., 2012; Heath and Mann, 2012). The collected data points of LCA results of GHG emissions of different technologies from this comprehensive review are available online in tabular and chart form at http://en.openei.org/apps/LCA/ and have been obtained from there, but the underlying scientific papers from the peer reviewed literature are referred to here.

The second effort is a broader study of lifecycle environmental impacts and resource requirements under way for the International Resource Panel (Hertwich et al., 2013). The study aims at a consistent technology comparison where lifecycle data collected under uniform instructions in a common format are evaluated in a single assessment model based on a common set of background processes. The model is capable of evaluating environmental impacts in nine different regions and reflecting the background technology at three different points in time (2010/30/50). It addresses more complete inventories than common process-based analysis through the use of hybrid LCA.

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[5] http://data.worldbank.org/indicator/NY.GDP.MKTP.PP.KD

[6] http://data.worldbank.org/indicator/NY.GDP.MKTP.KN

Table A.II.12 | Methane emission (gCH4/MJ_{LHV}) from coal and gas production (Burnham et al., 2012). Based on the minimum, mean, and maximum values provided by Burnham, the parameters μ and σ of a lognormal distribution were estimated. Coal is the weighted average of 60 % from underground mines and 40 % from surface mines.

	Min	Mean	Max	μ	σ
Underground coal mining	0.25	0.34	0.45	−1.09	0.147
Surface coal mining	0.025	0.05	0.068	−3.09	0.291
Natural gas production	0.18	0.52	1.03	−0.75	0.432

Table A.II.13 | Efficiency ranges assumed in power generation assumed in the calculation of fugitive emissions. The best estimate plant efficiency are based on NETL (NETL, 2010a; b; c; d; e) with ranges based (Singh et al., 2011a; Corsten et al., 2013). Note that the min and max efficiencies are not derived from the literature and were not used to calculate direct emissions; rather, they are used only to establish the possible range of fugitive emissions.

	Direct emissions (tCO_2eq/MWh)			Efficiency (% based on LHV)			Infrastructure & Supplies (tCO_2eq/MWh)		
Technology	Min	Average	Max	Max	Average	Min	Min	Average	Max
Gas—Single Cycle	0.621	0.667	0.706	33.1	30.8	29.1	0.001	0.002	0.002
Coal—average	0.913	0.961	1.009	33.3	35.0	36.8	0.010	0.011	0.013
Gas—average	0.458	0.483	0.507	39.9	42.0	44.1	0.001	0.002	0.003
Gas—Combined Cycle	0.349	0.370	0.493	59.0	55.6	41.7	0.001	0.002	0.002
Coal—PC	0.673	0.744	0.868	47.6	43.0	36.9	0.008	0.010	0.012
Coal—IGCC	0.713	0.734	0.762	44.9	43.6	42.0	0.003	0.004	0.006
CCS—Coal—Oxyfuel	0.014	0.096	0.110	35	30.2	27	0.014	0.017	0.023
CCS—Coal—PC	0.095	0.121	0.138	32	29.4	27	0.022	0.028	0.036
CCS—Coal—IGCC	0.102	0.124	0.148	34	32.3	27	0.008	0.010	0.013
CCS—Gas—Combined Cycle	0.030	0.047	0.098	49	47.4	35	0.007	0.009	0.012

The GHG emissions for coal carbon dioxide capture and storage (CCS), PV, concentrating solar power (CSP), and wind power associated with the two different efforts have been compared and have been found to be in agreement. The data has been supplemented by selected literature data where required. The specific numbers displayed come from following data sources.

A.II.9.3.1 Fossil fuel based power

For fossil fuel based power, three different sources of emissions were distinguished: (1) direct emissions from the power plant, (2) emissions of methane from the fuel production and delivery system, and (3) the remaining lifecycle emissions, mostly connected to the infrastructure of the entire energy system including the power plant itself, and supplies such as solvents. Each of these emissions categories was assessed separately, because emerging findings on methane emissions required a reassessment of the lifecycle emissions of established studies, which often use only a generic emissions factor. In our work, probability distributions for emissions from the three different systems were assessed and combined through a Monte Carlo analysis.

Fugitive emissions: The most important source of indirect emissions of fossil fuel based power is the supply of fuel, where fugitive emissions of methane are a major source of GHG gases. We have revisited the issue of fugitive methane emissions given new assessments of these emissions. As described in Section 7.5.1, fugitive emissions were modelled as the product of a log-normal distributions based on the parameters specified in Table A.II.12 and the efficiencies given by a triangular distribution with the parameters specified in Table A.II.13.

The data for the infrastructure component is from Singh et al. (2011a). A uniform distribution was used in the Monte Carlo Analysis. The data is provided in Table A.II.13. Direct emissions and associated efficiency data for Natural Gas Combined Cycle (NGCC) with and without CCS is from Singh et al. (2011b). Minimum and maximum numbers are from Corsten et al. (2013, Table 4), with an assumed direct/indirect share of 40 % and 60 %. For pulverized coal, Corsten et al. (2013, Table 5) reports characterized impacts, with direct and indirect emission shares for pulverized coal with and without CCS. For Integrated Gasification Combined Cycle (IGCC), calculations were performed by Hertwich et al. (2013) based on data obtained from NETL (2010a; d). For oxyfuel, the best estimate is based on a 90 % separation efficiency from Singh et al. (2011a) with the range assuming higher separation efficiency as indicated by Corsten et al. (2013). Ranges are based on Corsten et al. (2013) also considering the ranges reported by NETL (2010a; b; c; d; e). Triangular distributions were used in the Monte Carlo simulation. The contribution analysis shown in Figure 7.6 is based on Singh et al. (2011a) with adjustments to the higher fugitive emissions based on Burnham (2012) and lower average efficiencies and hence direct emissions for gas fired power as obtained from the distributions above.

A log-normal distribution does not have well-defined maximum and minimum values. The range in Figures 7.6 and 7.7 hence shows the 1st to 99th percentile.

A.II.9.3.2 Nuclear power

The data on nuclear power was taken from Lenzen (2008) and Warner and Heath (2012). There is no basis in the literature as far as we know to distinguish between 2nd and 3rd generation power plants.

A.II.9.3.3 Renewable energy

Concentrated solar power: The data range is based on both the assessments conducted for the International Resource Panel (Hertwich et al., 2013) work based on the analysis of Viebahn et al. (2011), Burkhardt et al. (2011), Whitaker et al. (2013), and the review of Burkhardt et al. (2012).

Photovoltaic power: Ranges are based largely on the reviews of Hsu et al. (2012) and Kim et al. (2012). The analysis of newer thin-film technologies analyzed in Hertwich et al. (2013) indicates that recent technical progress has lowered emissions.

Wind power: The data is based on the review of Arvesen and Hertwich (2012) and has been cross-checked with Dolan and Heath (2012) and Hertwich et al. (2013).

Ocean Energy: There have been very few LCAs of ocean energy devices. The numbers are based on the Pelamis (Parker et al., 2007) and Oyster wave energy device (Walker and Howell, 2011), the SeaGen tidal turbine (Douglas et al., 2008; Walker and Howell, 2011), and tidal barrages (Woollcombe-Adams et al., 2009; Kelly et al., 2012). Based on these available assessments, tidal turbines have the lowest GHG emissions and tidal barrages the highest.

Hydropower: The indirect emissions of hydropower are largely associated with fossil fuel combustion in the construction of the plant. The data presented here is based on SRREN (Kumar et al., 2011). The data was cross-checked with a recent review (Raadal et al., 2011) and analysis (Moreau et al., 2012).

The issue of biogenic emissions resulting from the degradation of biomass in reservoirs had been reviewed in SRREN, however, without providing estimates of the size of biogenic GHG emissions per kWh. Please note that only CH_4 emissions are included in the analysis. N_2O emissions have not been broadly investigated, but are assumed to be small (Demarty and Bastien, 2011). Carbon dioxide emissions can be substantial, but these emissions represent carbon that would probably have oxidized elsewhere; it is not clear what fraction of the resulting CO_2 would have entered the atmosphere (Hertwich, 2013). We have hence excluded biogenic CO_2 emissions from reservoirs from the assessment. The distribution of biogenic methane emissions comes from an analysis of methane emissions per kWh of power generated by Hertwich (2013) based on literature data collected and reviewed by Barros et al. (2011). Independent estimates based on recent empirical studies (Maeck et al., 2013) come to similar results. For the maximum number (2 kg CO_2eq/kWh), a specific power station analyzed by Kemenes et al. (2007) was chosen; as it is not clear that the much higher value from the 99th percentile of the distribution determined by Hertwich (2013) is really realistic.

Biomass: Life-cycle direct global climate impacts of bioenergy come from the peer-reviewed literature from 2010 to 2012 and are based on a range of electric conversion efficiencies of 27–50 %. The category "Biomass—dedicated and crop residues" includes perennial grasses, like switchgrass and miscanthus, short rotation species, like willow and eucalyptus, and agricultural byproducts, like wheat straw and corn stover. "Biomass—forest wood" refers to forest biomass from long rotation species in various climate regions. Ranges include global climate impacts of CO_2 emissions from combustion of regenerative biomass (i.e., biogenic CO_2) and the associated changes in surface albedo following ecosystem disturbances, quantified according to the IPCC framework for emission metrics (Forster et al., 2007) and using 100-year GWPs as characterization factors (Cherubini et al., 2012).

These impacts are site-specific and generally more significant for long rotation species. The range in "Biomass—forest wood" is representative of various forests and climates, e.g., aspen forest in Wisconsin (US), mixed forest in Pacific Northwest (US), pine forest in Saskatchewan (Canada), and spruce forest in Southeast Norway. In areas affected by seasonal snow cover, the cooling contribution from the temporary change in surface albedo can be larger than the warming associated with biogenic CO_2 fluxes and the bioenergy system can have a net negative impact (i.e., cooling). Change in soil organic carbon can have a substantial influence on the overall GHG balance of bioenergy systems, especially for the case "Biomass—dedicated and crop residues", but are not covered here due to their high dependence on local soil conditions and previous land use (Don et al., 2012; Gelfand et al., 2013).

Additional information on the LCA of bioenergy alternatives is provided in Section 11.A.4.

A.II.10 Scenario data

A.II.10.1 Process

The AR5 Scenario Database comprises 31 models and 1,184 scenarios, summarized in Table A.II.14. In an attempt to be as inclusive as possible, an open call for scenarios was made through the Integrated Assessment Modeling Consortium (IAMC) with approval from the IPCC

Table A.II.14 | Contributing models to the WGIII AR5 Scenario Database.

Model (versions)	Economic coverage and feedback	Myopic/ Foresight	Regional and emissions* detail	Representation of climate and land use	Cost measures	Scenario Publications	Number of Scenarios included in AR5 database
AIM-Enduse (12.1; backcast 1.0)	Partial equilibrium	Myopic	32 regions; 5 substances (v. 12.1)/8 substances (v. backcast 1.0)	None	Energy system cost mark-up (v 12.1; backcast 1.0)/area under marginal abatement cost curve (backcast 1.0)	(Akashi et al., 2014; Kriegler et al., 2014b; Tavoni et al., 2014)	41
BET (1.5)	General equilibrium	Foresight	32 regions; CO_2 only	Climate damages; no land use	Consumption loss, GDP loss, energy system cost mark-up	(Yamamoto et al., 2014)	23
DNE21+ (v.11, v.12)	Partial equilibrium	Foresight	54 regions; 6 substances (v.11)/13 substances (v.12)	Temperature change; no land use	Energy system cost mark-up	(Akimoto et al., 2012; Wada et al., 2012; Kriegler et al., 2014a; Riahi et al., 2014; Sano et al., 2014)	43
EC-IAM 2012	General equilibrium	Foresight	11 regions; 6 substances	Climate damages; no land use	Consumption loss, GDP loss, energy system cost mark-up, welfare loss	(Kriegler et al., 2014c)	21
Ecofys Energy Model	Partial equilibrium	Myopic	1 region; 3 substances	No climate; land use for bioenergy	Energy system cost mark-up	(Deng et al., 2012)	1
ENV-Linkages (WEO2012)	General equilibrium	Myopic	15 regions; 6 substances	No climate; land use for food consumption	Consumption loss, GDP loss, equivalent variation, welfare loss	(Kriegler et al., 2014c)	17
FARM (3.0)	General equilibrium	Myopic	15 regions; CO_2 only	No climate; land use by land type for bioenergy and food consumption	Consumption loss, GDP loss, equivalent variation, welfare loss	(Sands et al., 2014)	12
GCAM (2.0, 3.0, 3.1, MiniCAM)	Partial equilibrium	Myopic	14 regions; 13 substances	Temperature change; Land use by land type for bioenergy and food consumption	Area under marginal abatement cost curve	(Calvin et al., 2009a, 2012, 2013, 2014; Iyer et al., 2014; Kriegler et al., 2014b; Tavoni et al., 2014)	139
GEM-E3-ICCS	General equilibrium	Myopic	37 regions; 11 substances	No climate; land use for food consumption	Consumption loss, GDP loss, equivalent variation	(Kriegler et al., 2014a)	11
GRAPE (ver1998, ver2011)	General equilibrium	Foresight	15 regions; 5 substances	Temperature change; land use by land type for food consumption	Consumption loss, GDP loss	(Calvin et al., 2012; Kriegler et al., 2014c)	14
GTEM REF32	General equilibrium	Myopic	13 regions; 5 substances	No climate; land use for food consumption and crop prices	Consumption loss, GDP loss, welfare loss	(Mi et al., 2012)	4
IEEJ (ver.2011)	Econometric	Foresight	43 regions; CO_2 only	Temperature change; no land use	Energy system cost mark-up	(Matsuo et al.)	2
IGSM	General equilibrium	Myopic	16 regions; 12 substances	Climate damages; land use by land type for bioenergy, food consumption and crop prices	Consumption loss, GDP loss, equivalent variation, welfare loss; area under marginal abatement cost curve; energy system cost mark-up	(Prinn et al., 2011)	5
IMACLIM (v1.1)	General equilibrium	Myopic	12 regions; CO_2 only	Temperature change; no land use	Welfare loss, GDP loss, consumption loss, equivalent variation	(Bibas and Méjean, 2014; Kriegler et al., 2014a; Riahi et al., 2014)	53
IMAGE (2.4)	Partial equilibrium	Myopic	26 regions; 13 substances	Temperature change; land use by land type for bioenergy and food consumption	Area under marginal abatement cost curve	(van Vliet et al., 2009, 2014; van Ruijven et al., 2012; Lucas et al., 2013; Kriegler et al., 2014a; b; Riahi et al., 2014; Tavoni et al., 2014)	79
iPETS (1.2.0)	General equilibrium	Foresight	9 regions; CO_2 only	Land use for food consumption	Consumption loss, GDP loss, welfare loss	(O'Neill et al., 2012)	4
KEI-Linkages	General equilibrium	Myopic	13 regions; CO_2 only	No climate; land use for food consumption and crop prices	Consumption loss, equivalent variation	(Lim and Kim, 2012)	4

Model (versions)	Economic coverage and feedback	Myopic/ Foresight	Regional and emissions* detail	Representation of climate and land use	Cost measures	Scenario Publications	Number of Scenarios included in AR5 database
MARIA23_org	General equilibrium	Foresight	23 regions; 6 substances	Temperature change and climate damage; land use by land type for bioenergy and food consumption	Welfare loss, GDP loss, consumption loss, GDP loss, energy system cost mark-up	(Mori, 2012)	5
MERGE (AME, EMF22, EMF27)	General equilibrium	Foresight	9 (AME)/8 (EMF22) regions; 7 (AME,EMF22) /12 (EMF27) substances	Climate damages; no land use	Consumption loss, GDP loss, welfare loss	(Blanford et al., 2009, 2014b; Calvin et al., 2012)	44
MERGE-ETL (2011)	General equilibrium	Foresight	9 regions; 5 substances	Temperature change; no land use	Consumption loss, GDP loss, welfare loss	(Marcucci and Turton, 2014; Kriegler et al., 2014a; Riahi et al., 2014)	48
MESSAGE (V.1, V.2, V.3, V.4)	General equilibrium	Foresight	11 regions; 10 (V.1)/13 (V.2, V.3, V.4) substances	Temperature change; land use by land type for bioenergy (all versions)	GDP loss, energy system cost mark-up (all versions); area under marginal abatement cost curve (V.1, V.3, V.4); consumption loss (V.3, V.4)	(Krey and Riahi, 2009; Riahi et al., 2011, 2012, 2014; van Vliet et al., 2012; Kriegler et al., 2014a; b; McCollum et al., 2014; Tavoni et al., 2014)	140
Phoenix (2012.4)	General equilibrium	Myopic	24 regions; CO_2 only	Radiative forcing; land as factor of production in agriculture and forestry (including feedstocks for biofuels)	Welfare loss, GDP loss, consumption loss, equivalent variation	(Fisher-Vanden et al., 2012; Kriegler et al., 2014c)	31
POLES (AMPERE, EMF27, AME)	Partial equilibrium/ econometric	Myopic	57 regions (AMPERE, EMF27)/47 regions (AME); 6 substances	No climate; land use by land type for bioenergy (AMPERE, AME)	Area under marginal abatement cost curve	(Dowling and Russ, 2012; Griffin et al., 2014; Kriegler et al., 2014a; Riahi et al., 2014)	79
REMIND (1.1, 1.2, 1.3, 1.4, 1.5)	General equilibrium	Foresight	11 regions; CO_2 only (1.1, 1.2)/4 substances (1.3)/ 6 substances (1.4)/6–9 substances (1.5)	Temperature change; land use emissions via MAC (1.2, 1.3, 1.4) and from a land use model (MAgPIE; 1.5)	Consumption loss, GDP loss, welfare loss	(Leimbach et al., 2010; Luderer et al., 2012a; b; Arroyo-Currás et al., 2013; Bauer et al., 2013; Aboumahboub et al., 2014; Tavoni et al., 2014; Klein et al., 2014; Kriegler et al., 2014a; b; Riahi et al., 2014)	158
SGM	General equilibrium	Myopic	8 regions; CO_2 only	None	Consumption loss, GDP loss, equivalent variation, area under marginal abatement cost curve	(Calvin et al., 2009b)	7
TIAM-ECN	Partial equilibrium	Foresight	15 regions; 3 Substances	Radiative forcing; no land use	Energy cost increase; energy system cost mark-up	(Kober et al., 2014; Kriegler et al., 2014b; Tavoni et al., 2014)	12
TIAM-World (2007, 2012.02, Mar2012)	Partial equilibrium	Foresight	16 regions; 3 Substances	Temperature change; land use for bioenergy	Area under marginal abatement cost curve (all versions); welfare loss (2012.02); energy system cost mark-ups (2007, Mar2012)	(Loulou et al., 2009; Labriet et al., 2012; Kanudia et al., 2014)	41
TIMES-VTT	Partial equilibrium	Foresight	17 regions; 6 Substances	Temperature change; no land use	Consumption loss, energy system cost mark-ups	(Koljonen and Lehtilä, 2012)	6
WITCH (AME, AMPERE, EMF22, EMF27, LIMITS, RECIPE, ROSE)	General equilibrium	Foresight	13 regions/ 12 regions (RECIPE); 6 Substances	Temperature change (AME, AMPERE); climate damages (EMF22, EMF27; no land use	Consumption loss, GDP loss, welfare loss, energy system cost mark-ups	(Bosetti et al., 2009; de Cian et al., 2012; Massetti and Tavoni, 2012; De Cian et al., 2014; Kriegler et al., 2014a; b; Marangoni and Tavoni, 2014; Riahi et al., 2014; Tavoni et al., 2014)	132
WorldScan2	General equilibrium	Myopic	5 regions; 8 Substances	No climate; land use for food consumption	Welfare loss, GDP loss, equivalent variation	(Kriegler et al., 2014a)	8

* The substances reported under emissions detail include GHGs, radiatively and chemically active substances where the reference list includes the following set of 13 substances: CO_2, CH_4, N_2O, CFCs, HFCs, SF_6, CO, NO_x, VOC, SO_2, BC, OC, and NH_3.

Table A.II.15 | Model inter-comparison exercises generating transformation pathway scenarios included in AR5 Scenario Database.

Model Intercomparison Exercise	Year Completed	Number of Models in WGIII AR5 scenario database	Number of Scenarios in WGIII AR5 scenario database	Areas of Harmonization	Lead Institution	Overview Publication
ADAM (Adaptation and Mitigation Strategies—Supporting European Climate Policy)	2009	1	15	Technology availability, Mitigation policy	Potsdam Institute for Climate Impact Research (PIK)	(Edenhofer et al., 2010)
AME (Asian Modeling Exercise)	2012	16	83	Mitigation policy	Pacific Northwest National Laboratories (PNNL)	(Calvin et al., 2012)
AMPERE (Assessment of Climate Change Mitigation Pathways and Evaluation of the Robustness of Mitigation Cost Estimates)	2013	11	378	Technology availability; mitigation policy; GDP; population	Potsdam Institute for Climate Impact Research (PIK)	AMPERE2: (Riahi et al., 2014) AMPERE3: (Kriegler et al., 2014a)
EMF 22 (Energy Modeling Forum 22)	2009	7	70	Technology availability, mitigation policy	Stanford University	(Clarke et al., 2009)
EMF 27 (Energy Modeling Forum 27)	2013	16	362	Technology availability, mitigation policy	Stanford University	(Blanford et al., 2014a; Krey et al., 2014; Kriegler et al., 2014c)
LIMITS (Low Climate Impact Scenarios and the Implications of required tight emissions control strategies)	2014	7	84	Mitigation policies	Fondazione Eni Enrico Mattei (FEEM)	(Kriegler et al., 2014b; Tavoni et al., 2014)
POeM (Policy Options to engage Emerging Asian economies in a post-Kyoto regime)	2012	1	4	Mitigation policies	Chalmers University of Technology	(Lucas et al., 2013)
RECIPE (Report on Energy and Climate Policy in Europe)	2009	2	18	Mitigation policies	Potsdam Institute for Climate Impact Research (PIK)	(Luderer et al., 2012a)
RoSE (Roadmaps towards Sustainable Energy futures)	2013	3	105	Mitigation policy; GDP growth; population growth, fossil fuel availability	Potsdam Institute for Climate Impact Research (PIK)	(Bauer et al., 2013; De Cian et al., 2013; Calvin et al., 2014; Chen et al., 2014; Luderer et al., 2014)

WGIII Technical Support Unit. To be included in the database, four criteria had to be met. First, only scenarios published in the peer-reviewed literature could be considered, per IPCC protocol. Second, the scenario had to contain a minimum set of required variables and some basic model and scenario documentation (meta data) had to be provided. Third, only models with at least full energy system representation were considered given that specific sectoral studies were assessed in Chapters 8–11. Lastly, the scenario had to provide data out to at least 2030. Scenarios were submitted by entering the data into a standardized data template that was subsequently uploaded to a database system[7] administered by the International Institute of Applied System Analysis (IIASA).

A.II.10.2 Model inter-comparison exercises

The majority of scenarios (about 95 %) included in the database were generated as part of nine model inter-comparison exercises, summarized in Table A.II.15. The Energy Modeling Forum (EMF), established at Stanford University in 1976, is considered one of the first major efforts to bring together modelling teams for the purpose of model inter-comparison. Since its inception, EMF and other institutions have worked on a large number of model inter-comparison projects with topics ranging from energy and the economy, to natural gas markets, to climate change mitigation strategies. Recent model inter-comparison studies have focused on, for example, delayed and fragmented mitigation, effort sharing, the role of technology availability and energy resources for mitigation and have looked into the role of specific regions (e.g., Asia) in a global mitigation regime.

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[7] https://secure.iiasa.ac.at/web-apps/ene/AR5DB

Table A.II.16 | Scenario classifications.

Name	Climate Category	Carbon Budget 2050 and 2100 Category		Negative Emissions Category	Overshoot Category	Technology Category	Policy Category
Binning criterion	Radiative forcing (total or Kyoto), CO_2 budget	Cumulative CO_2 emissions budget to 2100	Cumulative CO_2 emissions budget to 2050	Maximum annual net negative emissions	Overshoot of 2100 forcing levels	Availability of negative emissions and other technology	Scenario definitions in Model Intercomparison Projects (MIPs)
# of classes	7 classes (1–7)	7 classes (1–7)	7 classes (1–7)	2 classes (N1, N2)	2 classes (O1, O2)	4 classes (T0–T3)	11 classes (P0–P7, P1+, P3+, P4+)
Notes	Extended to models that do not report forcing based on CO_2 budgets. Extrapolated to a subset of 2050 scenarios.		Classes for 2050 budgets cannot be unambiguously mapped to climate outcomes and thus overlap	Only for scenarios that run out to 2100	Only for models that run out to 2100 and report full or Kyoto forcing		

A.II.10.3 Classification of scenarios

The analysis of transformation pathway or scenario data presented in Chapters 1, 6, 7, 8, 9, 10 and 11 uses a common classification scheme to distinguish the scenarios along several dimensions. The key dimensions of this classification are:

- Climate Target (determined by 2100 CO_2eq concentrations and radiative forcing or carbon budgets)
- Overshoot of 2100 CO_2eq concentration or radiative forcing levels
- Scale of deployment of carbon dioxide removal or net negative emissions
- Availability of mitigation technologies, in particular carbon dioxide removal (CDR) or negative emissions technologies
- Policy configuration, such as immediate mitigation, delayed mitigation, or fragmented participation

Table A.II.16 summarizes the classification scheme for each of these dimensions, which are discussed in more detail in the following sections.

A.II.10.3.1 Climate category

Climate target outcomes are classified in terms of radiative forcing as expressed in CO_2-equivalent concentrations (CO_2eq). Note that in addition to CO_2eq concentrations, also CO_2eq emissions are used in the WGIII AR5 to express the contribution of different radiative forcing agents in one metric. The CO_2-equivalent concentration metric refers to the hypothetical concentration of CO_2 that would result in the same instantaneous radiative forcing as the total from all sources, including aerosols[8]. By contrast, the CO_2eq emissions metric refers to a sum of Kyoto GHG emissions weighted by their global warming potentials (GWPs, see Chapter 3, Section 3.9.6) as calculated in the SAR (IPCC, 1995a), for consistency with other data sources. It is important to note that these are fundamentally different notions of 'CO_2-equivalence'.

There are several reasons to use radiative forcing as an indicator for anthropogenic interference with the climate system and—in the case of climate policy scenarios—mitigation stringency: 1) it connects well to the Representative Concentration Pathways (RCPs) used in CMIP5 (see WGI AR5), 2) it is used as a definition of mitigation target in many modelling exercises, 3) it avoids problems introduced by the uncertainty in climate sensitivity, and 4) it integrates across different radiative forcing agents. These advantages outweigh some difficulties of the radiative forcing approach, namely that not all model scenarios in the WGIII AR5 Scenario Database fully represent radiative forcing, and that there is still substantial natural science uncertainty involved in converting emissions (a direct output of all models investigated in Chapter 6) into global radiative forcing levels.

To rectify these difficulties, the following steps were taken:

1. The emissions of all scenarios in the WGIII AR5 Scenario Database (see following bullets for details) were run through a single climate model MAGICC6.3 (where applicable) to establish comparability between the concentration, forcing, and climate outcome between scenarios. This removes natural science uncertainty due to different climate model assumptions in integrated models. The MAGICC output comes with an estimate of parametric uncer-

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[8] More technically speaking, CO_2-equivalent concentrations can be converted to forcing numbers using the formula log(CO_2eq / CO_2_preindustrial) / log(2) · RF(2 x CO_2) with *RF(2 x CO_2) = 3.7 W/m^2* the forcing from a doubling of preindustrial CO_2 concentration.

tainty within the MAGICC framework (Meinshausen et al., 2009, 2011a; b). Calculated MAGICC radiative forcing values are mean values given these uncertainties. MAGICC closely reflects the climate response of General Circulation Model (GCM) ensembles such as studied in CMIP5, and therefore can be considered a useful yardstick for measuring and comparing forcing outcomes between scenarios (Schaeffer et al., 2013). Emissions scenarios were harmonized to global inventories in 2010 to avoid a perturbation of climate projections from differences in reported and historical emissions that were assumed for the calibration of MAGICC (Schaeffer et al., 2013). The scaling factors were chosen to decline linearly to unity in 2050 to preserve as much as possible the character of the emissions scenarios. In general, the difference between harmonized and reported emissions is very small. The MAGICC runs were performed independently of whether or not a model scenario reports endogenous climate information, and both sets of information can deviate. As a result, MAGICC output may no longer fully conform to 'nameplate' targets specified in the given scenarios and as originally assessed by the original authors. Nevertheless, given the benefit of comparability both between AR5 scenarios and with WGI climate projections, scenarios were classified based on radiative forcing derived from MAGICC.

2. As a minimum requirement to apply MAGICC to a given emissions scenario, CO_2 from the fossil fuel and industrial (FF&I) sector, CH_4 from FF&I and land use sectors, and N_2O from FF&I and land use sectors needed to be reported. In case of missing land-use related CO_2 emissions the average of the RCPs was used. If fluorinated gas (F-gas), carbonaceous aerosols and/or nitrate emissions were missing, those were added by interpolating data from RCP2.6 and RCP8.5 on the basis of the energy-related CO_2 emissions of the relevant scenario vis-à-vis these RCPs. If scenarios were part of a model intercomparison project and gases, or forcers were missing, data was used from what was diagnosed as a "central" model for the same scenario (Schaeffer et al., 2013). As a minimum requirement to derive not only Kyoto forcing, but also full anthropogenic forcing, sulfur emissions in addition to CO_2, CH_4, and N_2O needed to be reported. Forcing from mineral dust and land use albedo was fixed at year-2000 values.

3. For the remaining scenarios, which only run to 2050 or that do not fulfill the minimum requirements to derive Kyoto forcing with MAGICC, an auxiliary binning based on cumulative CO_2 emissions budgets was implemented. Those scenarios came from models that only represent fossil fuel and industry emissions or only CO_2 emissions. The categorization of those scenarios is discussed below and includes a considerable amount of uncertainty from the mapping of CO_2 emissions budgets to forcing outcomes. The uncertainty increases significantly for scenarios that only run to 2050. In many cases, 2050 scenarios could only be mapped to the union of two neighbouring forcing categories given the large uncertainty.

The CO_2-equivalent concentrations were converted to full anthropogenic forcing ranges by using the formula in footnote 8, assuming CO_2_preindustrial = 278 ppm and rounding to the first decimal. All scenarios from which full forcing could be re-constructed from MAGICC were binned on this basis (Table A.II.17). Those scenarios that only allowed the re-construction of Kyoto forcing were binned on the basis of the adjusted Kyoto forcing scale that was derived from a regression of Kyoto vs. full forcing on the subset of those scenarios that reported both quantities. Thus, the binning in terms of Kyoto forcing already entails an uncertainty associated with this mapping.

We note the following:

- CO_2 equivalent and forcing numbers refer to the year 2100. Temporary overshoot of the forcing prior to 2100 can occur. The overshoot categories (see Section A.II.10.3.3) can be used to further control for overshoot.
- No scenario included in the WGIII AR5 Scenario Database showed lower forcing than 430 ppm CO_2eq and 2.3 W/m^2, respectively, so no lower climate category was needed.
- When labeling the climate categories in figures and text, the CO_2-equivalent range should be specified, e.g., 430–480 ppm CO_2eq for Category 1. If neighbouring categories are lumped into one bin, then the lower and upper end of the union of categories should be named, e.g., 430–530 ppm CO_2eq for Categories 1 & 2 or > 720 ppm CO_2eq for Categories 6 and 7.

Table A.II.17 | Climate forcing classes (expressed in ppm CO_2eq concentration levels).

Category	Forcing categories (in ppm CO_2eq)	Full anthropogenic forcing equivalent [W/m^2]	Kyoto forcing equivalent [W/m^2]	Centre	RCP (W/m^2)
1	430–480	2.3–2.9	2.5–3.1	455	2.6
2	480–530	2.9–3.45	3.1–3.65	505	-
3	530–580	3.45–3.9	3.65–4.1	555	(3.7)
4	580–650	3.9–4.5	4.1– 4.7	650	4.5
5	650–720	4.5–5.1	4.7–5.3		
6	720–1000	5.1–6.8	5.3–7.0	860	6
7	> 1000	> 6.8	> 7.0	-	8.5

Table A.II.18 | 2011–2100 emissions budget binning (rounded to 25 $GtCO_2$).

2100 Emissions Category	Cumulated 2011–2100 CO_2 emissions [$GtCO_2$]	Associated Climate forcing category	Forcing (in ppm CO_2eq)
1	350–950	1	430–480
2	950–1500	2	480–530
3	1500–1950	3	530–580
4	1950–2600	4	580–650
5	2600–3250	5	650–720
6	3250–5250	6	720–1000
7	> 5250	7	> 1000

Table A.II.19 | 2011–2050 emissions budget binning (rounded to 25 $GtCO_2$).

2050 Emissions Category	Cumulated 2011–2050 CO_2 emissions [$GtCO_2$]	Associated Climate forcing category if negative emissions are available (Classes T0 or T2 below)	Associated Climate forcing category if negative emissions are not available (Classes T1 or T3 below)
1	< 825	1	1
2	825–1125	1–2	2
3	1125–1325	2–4	3–4
4	1325–1475	3–5	4–5
5	1475–1625	4–6	5–6
6	1625–1950	6	6
7	> 1950	7	7

A.II.10.3.2 Carbon budget categories

The classification of scenarios in terms of cumulative CO_2 emissions budgets is mainly used as an auxiliary binning to map scenarios that do not allow the direct calculation of radiative forcing (see above) to forcing categories (Tables A.II.18 and A.II.19). However, it is also entertained as a separate binning across scenarios for diagnostic purposes. The mapping between full anthropogenic forcing and CO_2 emissions budgets has been derived from a regression over model scenarios that report both quantities (from the models GCAM, MESSAGE, IMAGE, MERGE, REMIND) and is affected by significant uncertainty (Figure A.II.8). This uncertainty is the larger the shorter the time span of cumulating CO_2 emissions is. Due to the availability of negative emissions, and the inclusion of delayed action scenarios in some studies, the relationship of 2011–2050 CO_2 emissions budgets and year 2100 radiative forcing was weak to the point that a meaningful mapping was hard to identify (Figure A.II.9). As a remedy, a mapping was only attempted for 2050 scenarios that do not include a strong element of delayed action (i.e., scenario policy classes P0, P1, P2 and P6; see Section A.II.10.3.6), and the mapping was differentiated according to whether or not negative emissions would be available (scenario technology classes T0–T3, see Section A.II.10.3.5). As a result of the weak relationship between budgets and radiative forcing, 2050 CO_2 emissions budget categories could only be mapped to the union of neighbouring forcing categories in some cases (Table A.II.19).

CO_2 emissions numbers refer to total CO_2 emissions including emissions from the AFOLU sector. However, those models that only reported CO_2 fossil fuel and industrial emissions were also binned according to this scheme. This can be based on the simplifying assumption that net land use change emissions over the cumulation period are zero.

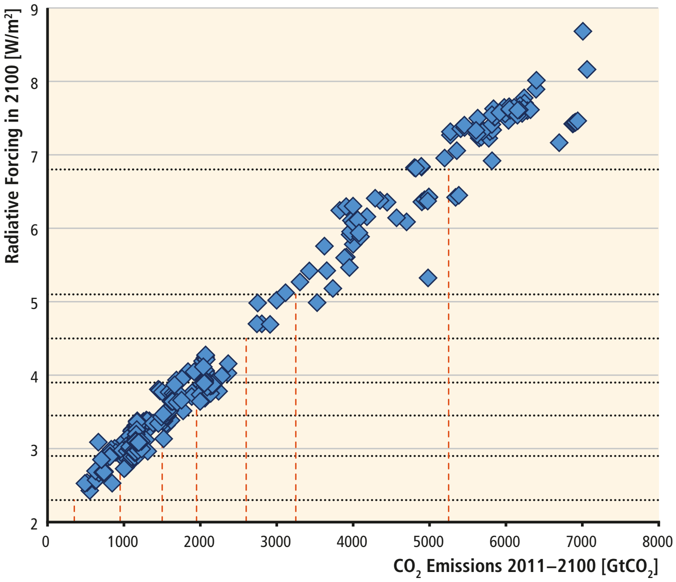

Figure A.II.8 | Regression of radiative forcing against 2011–2100 cumulative CO_2 emissions. Scenarios of full forcing models GCAM, MERGE, MESSAGE, REMIND and IMAGE were used for this analysis. Regression was done separately for each model, and resulting budget ranges averaged across models.

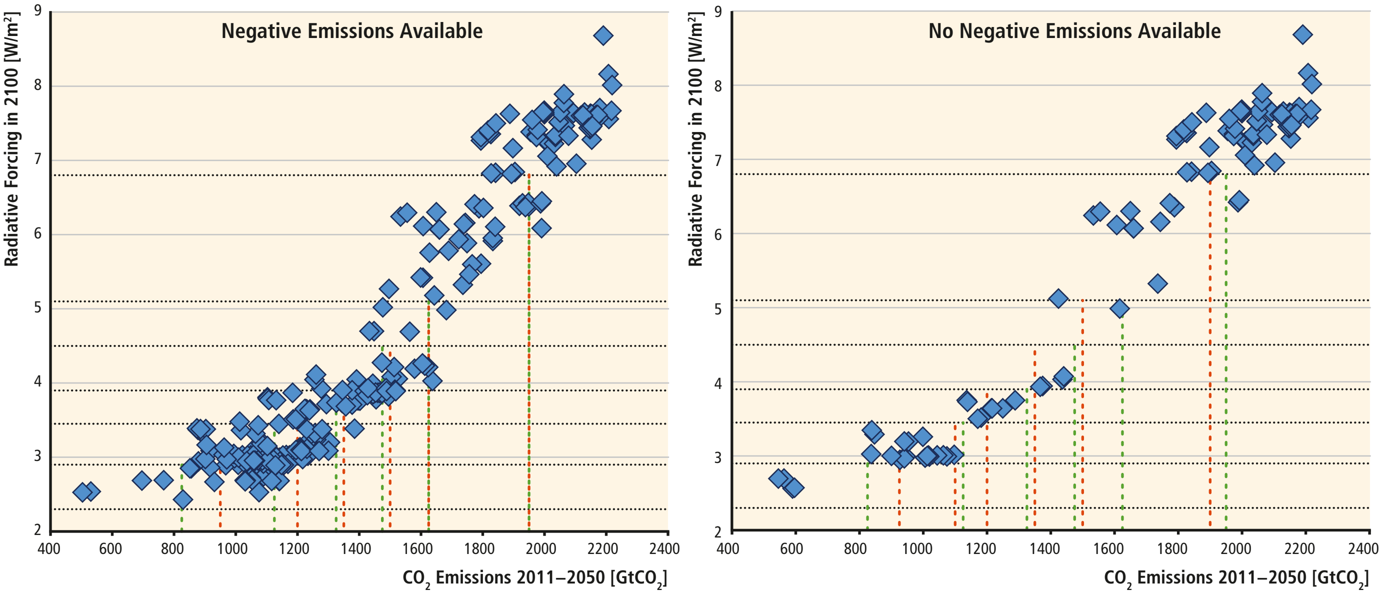

Figure A.II.9 | Regression of radiative forcing against 2011–2050 CO_2 emissions. Red lines show mean results of fit and depend on whether (left panel) or not (right panel) negative emissions are available. Green lines show harmonized bins between both categories for the mapping in Table A.II.19.

A.II.10.3.3 Overshoot category

The overshoot categorization shown in Table A.II.20 applies to the maximum overshoot of the 2100 radiative forcing level before 2100. The binning is only applied to models running until 2100. If full radiative forcing was not available, Kyoto forcing was used. If radiative forcing information was not available, no assignment was made.

A.II.10.3.4 Negative emissions category

The negative emissions categories apply to the maximum amount of net negative CO_2 emissions (incl. land use) in any given year over the 21st century. Scenarios with very large annual fluxes of negative emissions are also able to overshoot strongly, because the overshoot can be compensated with large net negative emissions within a relatively short period of time. Only a small number of scenarios show net negative emissions larger than 20 $GtCO_2$/yr, which was used to separate scenarios with large negative emissions from those with bounded negative emissions (Table A.II.21).

A.II.10.3.5 Technology category

The technology dimension of the categorization scheme indicates the technology availability in a given scenario. We identify two key factors:

1. the availability of negative emissions or CDR technologies that can be either confined by restrictions stipulated in the scenario definition or by the fact that the model does not represent negative emissions technologies, and
2. the restricted use of the portfolio of mitigation technologies that would be available in the model with default technology assumptions.

Combining these two factors lead to four distinct technology categories as shown in Table A.II.22.

Table A.II.20 | Overshoot categories.

Small Overshoot	*Large Overshoot*
< 0.4 W/m²	*> 0.4 W/m²*
O1	O2

Table A.II.21 | Negative emissions categories.

Bounded net negative emissions	*Large net negative emissions*
< 20 $GtCO_2$/yr	*> 20 $GtCO_2$/yr*
N1	N2*

* The GCAM 3.0 scenario EMF27–450-FullTech came in at –19.96 GtCO2/yr and was also included in class N2.

Table A.II.22 | Technology categories.

No restriction	**No negative emissions model**	**Restriction, but with negative emissions**	**No negative emissions and (other) restrictions**
Neg. Emissions			
T0	T1	T2	T3

Note that some scenarios improve technology performance over the default version (e. g., larger biomass availability, higher final energy intensity improvements, or advanced / expanded technology assumptions). These cases were not further distinguished and assigned to T0 and T1, if no additional technology restrictions existed.

A.II.10.3.6 Policy category

Policy categories are assigned based on scenario definitions in the study protocols of model intercomparison projects (MIPs). The policy categories summarize the type of different policy designs that were investigated in recent studies (Table A.II.23). We stress that the long-term target level (where applicable) is not part of the policy design categorization. This dimension is characterized in terms of climate categories (see above). Individual model studies not linked to one of the larger MIPs were assigned to baseline (P0) and immediate action (P1) categories where obvious, and otherwise left unclassified. The residual class (P7) contains the G8 scenario from the EMF27 study (Table A.II.15), with ambitious emissions caps by Annex I countries (starting immediately) and Non-Annex I countries (starting after 2020), but with a group of countries (fossil resource owners) never taking a mitigation commitment over the 21st century. The RECIPE model intercomparison project's delay scenarios start acting on a global target already in 2020, and thus are in between categories P1 and P2. P0 does not include climate policy after 2010 (it may or may not include Kyoto Protocol commitments until 2012), while P1 typically assumes full 'when', 'where' and 'what' flexibility of emissions reductions in addition to immediate action on a target (so called idealized implementation scenarios). The scenario class P6 characterizes the case of moderate fragmented action throughout the 21st century, without aiming at a long term global target, usually formulated as extrapolations of the current level of ambition. Policy categories P2 to P4 describe variants of adopting a global target or a global carbon price at some later point in the future. With the important exception of the AMPERE2 study, all scenarios in the P2-P4 class assume a period of regionally fragmented action prior to the adoption of a global policy regime. For further details of the scenario policy categories P2-P6, see the individual studies listed in Table A.II.15.

For the policy categories P1 (Idealized), P3 (Delay 2030), and P4 (Accession to Price Regime) subcategories P1+, P3+ and P4+ respectively exist for which in addition to climate policy supplementary policies (Supp.)(e. g., infrastructure polices) that are not part of the underlying baseline scenario have been included. These categories have been assigned to the climate policy scenarios of the IMACLIM v1.1 model from the AMPERE project to distinguish them from similar scenarios (e. g., EMF27) where these supplementary policies were not included and therefore policy costs are generally higher.

A.II.10.3.7 Classification of baseline scenarios

Baseline scenarios used in the literature are often identical or at least very close for one model across different studies. However, in some exercises, characteristics of baseline scenarios, such as population and economic growth assumptions, are varied systematically to study their influence on future emissions, energy demand, etc. Table A.II.24 below provides an overview of unique Kaya-factor decompositions of baseline scenarios in the AR5 scenario database. The results are shown in Figures 6.1 and 6.2 in Chapter 6.

Table A.II.23 | Policy categories.

Category		Target adoption	Staged accession	Long-term frag / Free rider	MIPs
P0	Baseline	None	No	N/A	All
P1	Idealized	Immediate	No	No / No	All
P1+	Idealized + Supp. Policies	Immediate	No	No / No	AMPERE2, AMPERE3
P2	Delay 2020	Model year after 2020	No	No / No	RoSE, LIMITS
P3	Delay 2030	Model year after 2030	No	No / No	RoSE, LIMITS, AMPERE2
P3+	Delay 2030 + Supp. Policies	Model year after 2030	No	No / No	AMPERE2
P4	Accession to Price Regime	None	Yes (2030–2050)	No / No	AMPERE3
P4+	Accession to Price Regime + Supp. Policies	None	Yes (2030–2050)	No / No	AMPERE3
P5	Accession to Target	Yes (starting 2010)	Yes (2030–2070)	No / No	EMF22
P6	Fragmented Ref Pol	No	N/A	Yes / Yes (EMF27)— No (Other)	EMF27, RoSE, LIMITS, AMPERE3
P7	Other cases	N/A	N/A	N/A	EMF27, RECIPE

Table A.II.24 | Classification of unique Kaya factor projections in the baseline scenario literature.

Study	Models Contributing Global Results	Population			Per Capita Income				Energy Intensity		Carbon Intensity
		Harmonized		Unharmonized	Harmonized			Unharmonized	Unharmonized		Unharmonized
		High	Default		High	Default	Low		Default	Fast	
ADAM	1			1				1	1		3
AME	16			16				16	15		15
AMPERE	11		11			10		10	10	9	65
EMF22	7			7			1	7	8		8
EMF27	16			16				31	16	15	119
GEA	1			1				0	0		1
LIMITS	7			7				7	7		7
POeM	1			1				1	1		1
RECIPE	1			1				1	1		1
RCP 8.5	1	1					2		1		1
RoSE	3	3	3		5	3	7		15		31
Other	2			2				2	1		1
	67	4	14	52	5	13	10	76	76	24	253
				= 70				= 104		= 100	

Notes:
All AMPERE scenarios harmonized population along a default trajectory
RoSE specified two harmonized population trajectories: default and high
RCP 8.5 was based on an intentionally high population trajectory
In all other cases, no guidance was given regarding population harmonization
AMPERE scenarios specified a default harmonization of GDP
One model in AMPERE (IMAGE) did not follow GDP harmonization, thus it was classified as unharmonized
AMPERE WP2 (9 of 11 participated) specified an alternative low energy intensity baseline with unharmonized implications for per capita income
One model in EMF22 (MERGE) included an alternative baseline with intentionally low per capita income
EMF27 specified an alternative low energy intensity baseline (15 of 16 ran it) with unharmonized implications for per capita income
ROSE specified several alternative GDP baselines, some run by all three models, others by only one or two
In all other cases, no guidance was given regarding per capita income or GDP harmonization
One study included a model not reporting data for GDP: GEA (MESSAGE)
Three studies included a model not reporting data for total primary energy: AME (Phoenix); AMPERE (GEM-E3); and Other (IEEJ)
No study successfully harmonized energy demand, thus scenarios are classified as default if a low energy intensity baseline was not specifically indicated
Alternative supply technology scenarios generally do not affect energy intensity, thus only default supply technology scenarios are classified

A.II.10.4 Comparison of integrated and sectorally detailed studies

In Section 6.8 of this report, but also in a number of other sections, integrated studies included in the AR5 Scenario Database that is described in Sections A.II.10.1 to A.II.10.3 above are compared to sectorally detailed studies assessed in Chapters 8, 9, and 10 that deal with the end-use sectors transport, buildings and industry respectively. Table A.II.25 provides an overview of the sectorally detailed studies that are included in this comparison. It should be noted that not all studies provide the data necessary to derive final energy demand reduction compared to baseline and low-carbon fuel shares as, for example, shown in Figure 6.37 and 6.38. In addition, some of the sectorally detailed studies do not cover the entire sector, but restrict themselves to the most important services within a sector (e.g., space heating and cooling and hot water provision in the buildings sector).

Table A.II.25 | Sectorally detailed energy end-use studies compared to transformation pathways.

Sector	Study (Literature Reference)	Scenario Name	Scenario Type
Transport (Ch. 8)	World Energy Outlook 2012 (IEA, 2012e)	New Policies	Base
		450 Scenario	Policy
	Energy Technology Perspectives 2008 (IEA, 2008)	Baseline	Base
		ACT Map	Policy
		BLUE Map	Policy
		BLUE conservative	Policy
		BLUE EV	Policy
		BLUE FCV	Policy
	Energy Technology Perspectives 2010 (IEA, 2010b)	Baseline	Base
		BlueMap	Policy
	Energy Technology Perspectives 2012 (IEA, 2012f)	4DS	Policy
		2DS	Policy
	Global Energy Assessment (Kahn Ribeiro et al., 2012)	REF	Base
		GEA-Act	Policy
		GEA-Supply	Policy
		GEA-Mix	Policy
		GEA-Efficiency	Policy
	World Energy Technology Outlook 2050 (EC, 2006)	Hydrogen Scenario	Policy
	World Energy Council 2011 (WEC, 2011)	Freeway	Base
		Tollway	Policy
	Asia/World Energy Outlook 2011 (IEEJ, 2011)	Enhanced Development Scenario	Policy
Buildings (Ch. 9)	World Energy Outlook 2010 (IEA, 2010c)	Current Policies	Base
		450 Scenario	Policy
	Energy Technology Perspectives 2010 (IEA, 2010b)	Baseline	Base
		BlueMap	Policy
	3CSEP HEB (Ürge-Vorsatz et al., 2012)	Frozen efficiency	Base
		Deep efficiency	Policy
	Harvey (Harvey, 2010)	High Slow efficiency no heat pump	Base
		High Fast efficiency with heat pump	Policy
	The Energy Report (WWF/Ecofys/OMA, 2011; Deng et al., 2012)	Baseline	Base
		The Energy Report	Policy
Industry (Ch. 10)	Energy Technology Perspectives 2012 (IEA, 2012f)	6DS Low-demand	Base
		6DS High-demand	Base
		4DS Low-demand	Policy
		4DS High-demand	Policy
		2DS Low-demand	Policy
		2DS High-demand	Policy
	Energy Technology Transitions for Industry (IEA, 2009)	BLUE low	Policy
		BLUE high	Policy
	Global Energy Assessment (Banerjee et al., 2012)	Energy Efficient Scenario	Policy
	Energy [R]evolution 2012 (GWEC et al., 2012)	Reference Scenario	Base
		Energy [R]evolution	Policy
	The Energy Report (WWF/Ecofys/OMA, 2011; Deng et al., 2012)	The Energy Report	Policy

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