Chapter:	Annex II			
Title:	Methods and Metrics			
(Sub)Section:	All			
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Remarks:	First Order Draft (FOD)			
Version:	1			
File name:	WGIII_AR5_Draft1_AnxII			
Date:	17 July 2012		Template Version:	5

Table of changes

No	Date	Version	Place	Description	Editor
1	TT.MM.JJJJ	01		initial Version	

Turquoise highlights are inserted comments from Authors or TSU i.e. [AUTHORS/TSU: ….]

Annex II: Methods and Metrics

Contents

A.II.1 Standard units and unit conversion

The following section 2.1.1 introduces standard units of measurement that are used throughout this report. This includes Système International (SI) units, SI-derived units and other non-SI units as well the standard prefixes for basic physical units. It builds upon similar material from previous IPCC reports.

In addition to establishing a consistent set of units for reporting throughout the report, harmonized conventions for converting units as reported in the scientific literature have been established and are summarized in Section 2.1.2 (physical unit conversion) and Section 2.1.3 (monetary unit conversion).

A.II.1.1 Standard units

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

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

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

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

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

Monetary units	**Unit**	**Symbol**
Currency (Market Exchange Rate)	constant US Dollar 2010	USD2010
Emission- and Climate-related units	**Unit**	**Symbol**
Emissions	Metric Tonnes	t
CO2 Emissions	Metric Tonnes CO2	tCO2
CO2-equivalent Emissions	Metric Tonnes CO2-equivalent	tCO2-e
Abatement Costs and Emissions Prices/Taxes	constant US Dollar 2010 per metric tonne	USD2010/t
CO2 concentration or mixing ratio (µmol mol–1)	Parts per million (10^6)	ppm
CH4 concentration or mixing ratio (µmol mol–1)	Parts per billion (10^9)	ppb
N2O concentration or mixing ratio (µmol mol–1)	Parts per billion (10^9)	ppb
Energy-related units	**Unit**	**Symbol**
Energy	Joule	J
Electricity and Heat generation	Watt Hours	Wh
Power (peak capacity)	Watt (Watt thermal, Watt electric)	W
Capacity Factor	Percent	%

Technical and Economic Lifetime	years	yr
Specific Energy Investment Costs	USD2010/kW (peak capacity)	USD2010/kW
Energy Costs (e.g. LCOE) and Prices	constant US Dollar 2010 per GJ or US Cents 2010 per kWh	USD2010/GJ and USct2010/kWh
Land-related units	**Unit**	**Symbol**
Area	hectare	ha

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

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

A.II.1.2 Physical unit conversion

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

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

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

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

Table A.II.7: Conversion table for common energy units (NAS, 2007; IEA, 2010a)

To:		TJ	Gcal	Mtoe	Mtce	MBtu	GWh
From:	multiply by:						
Tera Joule	TJ	1	2.39E+02	2.39E-05	3.41E-05	9.48E+02	2.78E-01
Giga Calorie	Gcal	4.19E-03	1	1.00E-07	1.43E-07	3.97E+00	1.16E-03
Mega Tonne Oil Equivalent	Mtoe	4.19E+04	1.00E+07	1	1.43E+00	3.97E+07	1.16E+04
Mega Tonne Coal Equivalent	Mtce	2.93E+04	7.00E+06	7.00E-01	1	2.78E+07	8.14E+03

Million British Thermal Units	MBtu	1.06E-03	2.52E-01	2.52E-08	3.60E-08	1	2.93E-04
Giga Watt Hours	GWh	3.60E+00	8.60E+02	8.60E-05	0.000123	3.41E+03	1

A.II.1.3 Monetary unit conversion

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

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

To convert from year X local currency unit (LCU_X) to 2010 US Dollars (USD_{2010}) two steps are necessary:

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

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

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

Consistent with the choice of the World Bank databases as the primary source for GDP and other financial data throughout the report, deflators and exchange rates from the World Bank's World Development Indicators and Global Development Finance database (World Bank, 2012) 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 Levelised costs

In response to mitigation policies, different technologies are deployed across different sectors. To facilitate a meaningful comparison of economics across diverse options at the technology level, the metric of "levelised costs" is used throughout several chapters of this report. On the energy supply side, the levelised costs of energy are used and described in Section 2.2.1. They are matched by the levelised costs of conserved energy on the demand side which are introduced in Section 2.2.2 [note that for the FOD the part on levelised costs of conserved energy is still missing].

A.II.2.1 Levelised costs of energy

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

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

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

(Eq. 1)

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

After solving for LCOE this gives:

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

(Eq. 2)

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

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

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

(Eq. 3)

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

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

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

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

Taking these shortcomings into account, there seems to be a clear understanding that LCOE are not intended to be a definitive guide to actual electricity generation investment decisions e.g. (IEA and NEA, 2005; DTI, 2006). Some studies suggest that the role of levelised costs is to give a ‘first order assessment’ (EERE, 2004) of project viability. In order to capture the existing uncertainty, sensitivity analyses, which are sometimes based on Monte Carlo methods, are frequently carried out in numerical studies (Darling et al., 2011). 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, 2010b).

A.II.2.2 Levelised costs of conserved energy

[note for reviewers: The concept of “levelised costs of conserved energy” (LCCE) will be used in the energy end-use chapters of the report and therefore it is planned to add a section, briefly introducing the concept and methodological foundations to this annex.]

A.II.3 Primary energy accounting

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

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

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

- *the physical energy content method* adopted, for example, by the OECD, the International Energy Agency (IEA) and Eurostat (IEA/OECD/Eurostat, 2005),
- *the substitution method* which is used in slightly different variants by BP (2009) and the US Energy Information Administration, both of which publish international energy statistics, and
- *the direct equivalent method* that is used by UN Statistics (2010) and in multiple IPCC reports that deal with long-term energy and emission scenarios (Nakicenovic and Swart, 2000; Morita et al., 2001; Fisher et al., 2007; Fischedick et al., 2011).

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

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

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

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

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

The accounting of combustible sources, including all fossil energy forms and biomass, includes some ambiguities related to the definition of the heating value of combustible fuels. The higher heating value (HHV), also known as gross calorific value (GCV) or higher calorific value (HCV), includes the latent heat of vaporisation of the water produced during combustion of the fuel. In contrast, the lower heating value (LHV) (also: net calorific value (NCV) or lower calorific value (LCV)) excludes this latent heat of vaporization. For coal and oil, the LHV is about 5% less than the HHV, for most forms of natural and manufactured gas the difference is 9-10%, while for electricity and heat there is no difference as the concept has no meaning in this case (IEA, 2010a).

In the Working III Fifth Assessment Report, IEA data are utilized, but energy supply is reported using the *direct equivalent method*. In addition, the reporting of combustible energy quantities, including primary energy, should use the LHV which is consistent with the IEA energy balances (IEA, 2010a; b).Table 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 2008 based on IEA data (IEA, 2010b) [to be updated with 2010 data from IEA which is expected to become available by fall 2012]. In current statistical energy data, the main differences in absolute terms appear when comparing nuclear and hydro power. As they both produced comparable amounts of electricity in 2008, under both *direct equivalent* and *substitution methods*, their share of

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[1] As the amount of heat produced in nuclear reactors is not always known, the IEA estimates the primary energy equivalent from the electricity generation by assuming an efficiency of 33%, which is the average of nuclear power plants in Europe (IEA, 2010b).

meeting total final consumption is similar, whereas under the *physical energy content method,* nuclear is reported at about three times the primary energy of hydro.

Table A.II.8: Comparison of global total primary energy supply in 2008 using different primary energy accounting methods (data from IEA (2010b)) [to be updated with 2010 data from IEA which is expected to become available by fall 2012]

	Physical content method		**Direct equivalent method**		**Substitution method**[2]	
	EJ	**%**	**EJ**	**%**	**EJ**	**%**
Fossil fuels	418.15	81.41	418.15	85.06	418.15	79.14
Nuclear	29.82	5.81	9.85	2.00	25.90	4.90
Renewables	65.61	12.78	63.58	12.93	84.27	15.95
Bioenergy	50.33	9.80	50.33	10.24	50.33	9.53
Solar	0.51	0.10	0.50	0.10	0.66	0.12
Geothermal	2.44	0.48	0.41	0.08	0.82	0.16
Hydro	11.55	2.25	11.55	2.35	30.40	5.75
Ocean	0.00	0.00	0.00	0.00	0.01	0.00
Wind	0.79	0.15	0.79	0.16	2.07	0.39
Other	0.03	0.01	0.03	0.01	0.03	0.01
Total	513.61	100.00	491.61	100.00	528.35	100.00

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 (2010a; b) offer a much wider set of indicators which allows tracing the flow of energy from the resource to final energy use. For instance, complementing total primary energy consumption by other indicators, such as total final energy consumption (TFC) and secondary energy production (e.g., electricity, heat), using different sources helps link the conversion processes with the final use of energy.

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

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

The anthropogenic contributions to climate change, caused by fossil fuel combustion, land conversion for agriculture, commercial forestry and infrastructure, and numerous agricultural and industrial processes, result from the use of natural resources, i.e. the manipulation of material and energy flows by humans for human purposes. Climate mitigation research has a long tradition of addressing the energy flows and associated emissions, however, the sectors involved in energy supply and use are coupled with each other through material stocks and flows, which leads to feedbacks and delays. These linkages between energy and material stocks and flows have, despite their considerable relevance for GHG emissions, so far gained little attention in climate change

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

mitigation (and adaptation). The research agendas of industrial ecology and ecological economics with their focus on the socioeconomic metabolism (Fischer-Kowalski and Haberl, 2007)(Wolman, 1965a; Ayres and Simonis, 1994a), (Baccini and Brunner, 1991) a.k.a. biophysical economy (Cleveland et al., 1984), can complement energy assessments in important manners and support the development of a broader framing of climate mitigation research as part of sustainability science. Socioeconomic metabolism consists of the physical stocks and flows with which a society maintains and reproduces itself (Fischer-Kowalski and Haberl, 2007). These research traditions have a broader sustainability perspective, addressing the dynamics, efficiency and emissions of production systems that convert or utilize resources to provide goods and services to final consumers. Central to the socio-metabolic research methods are material and energy balance principles applied at various scales ranging from individual production processes to companies, regions, value chains, economic sectors, and nations.

A.II.4.1 Carbon footprinting and input-output analysis

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

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

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

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[3] So far, only GHG emissions related to fossil fuel combustion and cement production are included in the „carbon footprint“; GHG emissions related to land-use change are at present not included.

footprint of different consumption categories like food, mobility, and clothing (Hertwich and Peters, 2009).

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

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. 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. 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. Efforts to provide a higher level of detail of environmentally relevant sectors and to now-cast tables are under way.

A.II.4.2 Life cycle assessment

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

LCA plays an increasingly important role in climate mitigation research (SRREN Annex II, Moomaw et al. (2011)). In this report, Life cycle assessment has been used to quantify the greenhouse gas emissions associated with technologies used for GHG mitigation, e.g., wind power, heat recovery ventilation systems or carbon capture and storage. LCAs thus provide an estimate for the technical emissions reductions offered by these technologies. LCA has also been used to quantify co-benefits and detrimental side effects of mitigation technologies and measures, including other environmental problems and the use of resources such as water, land, and metals.

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

Various modeling choices and assumptions become part of LCA. Not all LCAs are useful for understanding the contribution of technologies or measures to climate mitigation. With their focus on products and functional units within specific contexts, some LCAs describe situations that are not generalizable. As an example, there are a number of LCAs of bioenergy systems that show negative emissions of greenhouse gases, indicating that the systems contribute to the absorption of CO_2 from the atmosphere. What these systems do is that they produce a byproduct that is used as animal fodder. The system is then credited with the impacts of a different fodder, and the LCA has credited the bioenergy system with the reduced impact from the production of the fodder that was replaced. While such an assessment practice may be useful within a specific corporate decision context, it is not useful for statements about the large-scale application of bioenergy within a context of a possible transition to a low-emissions economy. In a transition context, it cannot be assumed that highly emitting animal fodder systems would be still available for replacement.

LCA was developed with the intention to quantify resource use and emissions associated with existing or prospective product systems, where the association reflects physical causality within economic systems. Departing from this descriptive approach, it has been proposed to model a wider socioeconomic causality describing the consequences of actions in LCA (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. Consequential LCAs are dependent on the decision context.

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

Some LCAs take into account behavioral responses to different technologies (Takase et al., 2005; Girod et al., 2011). Here, two issues must be distinguished. One is the use of the technology. For example, it has been found that better insulated houses consistently are heated or cooled to higher/lower average temperature (Haas and Schipper, 1998)(Greening et al., 2001). Not all of the theoretically possible technical gain in energy efficiency results in reduced energy use (Sorrell and Dimitropoulos, 2008). Such direct rebound effects can be taken into account through an appropriate definition of the energy services compared, which do not necessarily need to be identical in terms of the temperature or comfort levels. Another issue is larger rebound or spill-over effects. A better insulated house leads to energy savings. Both questions of (1) whether the saved energy would then be used elsewhere in the economy rather than not produced, and (2) what the consumer does with the money saved, are not part of the product system. 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.

A.II.4.3 Material flow analysis

Material flow analysis (MFA) – including substance flow analysis (SFA) – is a method for describing, modeling (using socio-economic and technological drivers), simulating (scenario development), and visualizing the socioeconomic stocks and flows of matter and energy in systems defined in space and time to inform policies on resource and waste management and pollution control. Mass- and energy balance consistency is enforced at the level of goods and/or individual substances. As a result of the application of consistency criteria they are useful to analyze feedbacks within complex systems, e.g.

the interrelations between diets, food production in cropland and livestock systems, and availability of area for bioenergy production (e.g., (Erb et al., 2012)).

The concept of socioeconomic metabolism (Ayres and Kneese, 1969), (Ayres and Simonis, 1994b), (Baccini and Brunner, 1991), (Boulding, 1972), (Fischer-Kowalski and Haberl, 1997), (Martinez-Alier, 1987) 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, 1965b) or other socioeconomic subsystems. Similarly comprehensive methods that apply the same system boundaries have been developed to account for energy flows (Haberl, 2001a), (Haberl, 2001b), (Haberl et al., 2006), carbon flows (Erb et al., 2008) and biomass flows (Krausmann et al., 2008) and are often subsumed in the Material and Energy Flow Accounting (MEFA) framework (Haberl et al., 2004). Other MFAs have been conducted for analyzing the cycles of individual substances (e.g., carbon, nitrogen, or phosphorus cycles; (Erb et al., 2008)) or metals (e.g., copper, iron, or cadmium cycles; (Graedel and Cao, 2010)) within socio-economic systems. A third group of MFAs have a focus on individual processes with an aim to balance a wide variety of goods and substances (e.g., waste incineration, shredder plant, or city).

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

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

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

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