ANNEX II

Methodology

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A.II.1 Introduction

Parties need to agree upon common data, standards, supporting theories and methodologies. This annex summarizes a set of agreed upon conventions and methodologies. These include the establishment of metrics, determination of a base year, definitions of methodologies and consistency of protocols that permit a legitimate comparison between alternative types of energy in the context of climate change phenomena. This section defines or describes these fundamental definitions and concepts as used throughout this report, recognizing that the literature often uses inconsistent definitions and assumptions.

This report communicates uncertainty where relevant, for example, by showing the results of sensitivity analyses and by quantitatively presenting ranges in cost numbers as well as ranges in the scenario results. This report does not apply formal IPCC uncertainty terminology because at the time of approval of this report, IPCC uncertainty guidance was in the process of being revised.

A.II.2 Metrics for analysis in this report

A number of metrics can simply be stated or are relatively easy to define. Annex II provides the set of agreed upon metrics. Those which require further description are found below. The units used and basic parameters pertinent to the analysis of each RE type in this report include:

- International System of Units (SI) for standards and units
- Metric tonnes (t) CO_2, CO_2eq
- Primary energy values in exajoules (EJ)
- IEA energy conversion factors between physical and energy units
- Capacity: GW thermal (GW_t), GW electricity (GW_e)
- Capacity factor
- Technical and economic lifetime
- Transparent energy accounting (e.g., transformations of nuclear or hydro energy to electricity)
- Investment cost in USD/kW (peak capacity)
- Energy cost in USD_{2005}/kWh or USD_{2005}/EJ
- Currency values in USD_{2005} (at market exchange rate where applicable, no purchasing power parity is used)
- Discount rates applied = 3, 7 and 10%
- World Energy Outlook (WEO) 2008 fossil fuel price assumptions
- Baseline year = 2005 for all components (population, capacity, production, costs). Note that more recent data may also be included (e.g., 2009 energy consumption)
- Target years: 2020, 2030 and 2050.

A.II.3 Financial assessment of technologies over project lifetime

The metrics defined here provides the basis from which one renewable resource type (or project) can be compared to another. To make projects or resources comparable, at least in terms of costs, costs that may occur at various moments in time (e.g., in various years) are represented as a single number anchored at one particular year, the reference year (2005). Textbooks on investment appraisal provide background on the concepts of constant values, discounting, net present value calculations, and levelized costs, for example (Jelen and Black, 1983).

A.II.3.1 Constant (real) values

The analyses of costs are in constant or real[1] dollars (i.e., excluding the impacts of inflation) based in a particular year, the base year 2005, in USD. Specific studies on which the report depends may use market exchange rates as a default option or use purchasing power parities, but where these are part of the analysis, they will be stated clearly and, where possible, converted to USD_{2005}.

When the monetary series in the analyses are in real dollars, consistency requires that the discount rate should also be real (free of inflationary components). This consistency is often not obeyed; studies refer to 'observed market interest rates' or 'observed discount rates', which include inflation or expectations about inflation. 'Real/constant' interest rates are never directly observed, but derived from the ex-post identity:

$$(1+m) = (1+i) \times (1+f) \qquad (1)$$

where

m = nominal rate (%)
i = real or constant rate (%)
f = inflation rate (%)

The reference year for discounting and the base year for anchoring constant prices may differ in studies used in the various chapters; where possible, an attempt was made to harmonize the data to reflect discount rates applied here.

A.II.3.2 Discounting and net present value

Private agents assign less value to things further in the future than to things in the present because of a 'time preference for consumption' or to reflect a 'return on investment'. Discounting reduces future cash flows by a value less than 1. Applying this rule on a series of net cash flows in real USD, the net present value (NPV) of the project can be ascertained and, thus, compared to other projects using:

$$NPV = \sum_{j=0}^{n} \frac{Net\ cash\ flows\ (j)}{(1+i)^j} \qquad (2)$$

where

n = lifetime of the project
i = discount rate

1 The economists' term 'real' may be confusing because what they call real does not correspond to observed financial flows ('nominal', includes inflation); 'real' reflects the actual purchasing power of the flows in constant dollars.

This report's analysts have used three values of discount rates (i = 3, 7 and 10%) for the cost evaluations. The discount rates may reflect typical rates used, with the higher ones including a risk premium. The discount rate is open to much discussion and no clear parameter or guideline can be suggested as an appropriate risk premium. This discussion is not addressed here; the goal is to provide an appropriate means of comparison between projects, renewable energy types and new versus current components of the energy system.

A.II.3.3 Levelized cost

Levelized costs are used in the appraisal of power generation investments, where the outputs are quantifiable (MWh generated during the lifetime of the investment). The levelized cost is the unique break-even cost price where discounted revenues (price x quantities)[2] are equal to the discounted net expenses:

$$C_{Lev} = \frac{\sum_{j=0}^{n} \frac{Expenses_j}{(1+i)^j}}{\sum_{j=0}^{n} \frac{Quantities_j}{(1+i)^j}} \qquad (3)$$

where

C_{Lev} = levelized cost
n = lifetime of the project
i = discount rate

A.II.3.4 Annuity factor or capital cost recovery factor

A very common practice is the conversion of a given sum of money at moment 0 into a number n of constant annual amounts over the coming n future years:

Let A = annual constant amount in payments over n years
Let B = cash amount to pay for the project in year 0

A is obtained from B using a slightly modified equation 2: the lender wants to receive B back at the discount rate i. The NPV of the n times A receipts in the future therefore must exactly equal B:

$$\sum_{j=1}^{n} \frac{A}{(1+i)^j} = B, \text{ or}: A\sum_{j=1}^{n} \frac{1}{(1+i)^j} = B \qquad (4)$$

We can bring A before the summation because it is a constant (not dependent on j).

The sum of the discount factors (a finite geometrical series) is deductible as a particular number. When this number is calculated, A is found by dividing B by this number. This is known as the *Capital Recovery Factor* (*CRF*) but may be known as the *Annuity Factor* 'δ'. Like NPV, the annuity factor δ depends on the two parameters i and n:

$$\delta = \frac{i \times (1+i)^n}{(1+i)^n - 1}$$

The CRF (or δ) can be used to quickly calculate levelized costs for very simple projects where investment costs during one given year are the only expenditures and where production remains constant over the lifetime (n):

$$C_{Lev} \times Q = B \times \delta, \text{ or}: C_{Lev} = (B \times \delta)/Q \qquad (5)$$

or where one can assume that operation and maintenance (O&M) costs do not change from year to year:

$$C_{Lev} = \frac{B \times \delta + O\&M}{Q} \qquad (6)$$

where

C_{Lev} = levelized cost
B = investment cost
Q = production
$O\&M$ = annual operating and maintenance costs
n = life time of the project
i = discount rate

A.II.4 Primary energy accounting

This section introduces the primary energy accounting method used throughout this report. Different energy analyses use different accounting methods that lead to different quantitative outcomes for reporting both 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 as noted by Lightfoot, 2007 and Martinot et al., 2007. An overview of differences in primary energy accounting from different statistics has been described (Macknick, 2009) and the implications of applying different accounting systems in long-term scenario analysis were illustrated by Nakicenovic et al., (1998).

Three alternative methods are predominantly used to report primary energy. While the accounting of combustible sources, including all fossil energy forms and biomass, is unambiguous and 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 Organisation for Economic Cooperation and Development (OECD), the International Energy Agency (IEA) and Eurostat (IEA/OECD/Eurostat, 2005),

2 This is also referred to as Levelized Price. Note that, in this case, MWh would be discounted.

- *The substitution method*, which is used in slightly different variants by BP (2009) and the US Energy Information Administration (EIA online glossary), each 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).

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 downstream 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 energy; and
- Electricity for hydro, wind, tide/wave/ocean and solar photovoltaic (PV) energy.

Using this method, the primary energy equivalent of hydropower 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,[3] that is, 1 kWh = (3.6 ÷ 0.33) = 10.9 MJ. For geothermal energy, 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 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 a 38% conversion efficiency to electricity generated from nuclear and hydropower, whereas the World Energy Council used 38.6% for nuclear and non-combustible renewable sources (WEC, 1993) and the EIA uses still different values. Macknick (2009) provides a more complete overview. For useful heat generated from non-combustible energy sources, other conversion efficiencies are used.

The *direct equivalent method* counts one unit of secondary energy provided from non-combustible sources as one unit of primary energy, that is, 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, 1995; Nakicenovic and Swart, 2000; Morita et al., 2001; Fisher et al., 2007), because it deals with fundamental transitions of energy systems that rely to a large extent on low-carbon, non-combustible energy sources.

3 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 for nuclear power plants in Europe (IEA, 2010b).

In this report, IEA data are utilized, but energy supply is reported using the *direct equivalent method*. The major difference between this and the *physical energy content method* will appear in the amount of primary energy reported for electricity production by geothermal heat, concentrating solar thermal, ocean temperature gradients or nuclear energy. Table A.II.1 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, 2010a). In current statistical energy data, the main differences in absolute terms appear when comparing nuclear and hydropower. Since they both produced a comparable amount of electricity globally in 2008, under both *direct equivalent* and *substitution methods*, their share of meeting total final consumption is similar, whereas under the *physical energy content method*, nuclear is reported at about three times the primary energy of hydropower.

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 the IEA (2010a) 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 with other indicators, such as total final energy consumption and secondary energy production (e.g., electricity, heat), using different sources helps link the conversion processes with the final use of energy. See Figure 1.16 and the associated discussion for a summary of this approach.

For the purpose of this report, the *direct equivalent method* is chosen for the following reasons.

- It emphasizes the secondary energy perspective for non-combustible sources, which is the main focus of the analyses in the technology chapters (Chapters 2 through 7).

- All non-combustible sources are treated in an identical way by using the amount of secondary energy they provide. This allows the comparison of all non-CO_2-emitting renewable and nuclear energy sources on a common basis. Primary energy of fossil fuels and biomass combines both the secondary energy and the thermal energy losses from the conversion process. When fossil fuels or biofuels are replaced by nuclear systems or other renewable technologies than biomass, the total of reported primary energy decreases substantially (Jacobson, 2009).

- Energy and CO_2 emissions scenario literature that deals with fundamental transitions of the energy system to avoid dangerous anthropogenic interference with the climate system over the long term (50 to 100 years) has used the direct equivalent method most frequently (Nakicenovic and Swart, 2000; Fisher et al., 2007).

Table A.II.1 | Comparison of global total primary energy supply in 2008 using different primary energy accounting methods (data from IEA, 2010a).

	Physical content method		Direct equivalent method		Substitution method[1]	
	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
Renewable:	65.61	12.78	63.58	12.93	84.27	15.95
Bioenergy[2]	*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**

Notes:

1 For the substitution method, conversion efficiencies of 38% for electricity and 85% for heat from non-combustible sources were used. BP uses the conversion value of 38% for electricity generated from hydro and nuclear sources. BP does not report solar, wind and geothermal in its statistics; here, 38% for electricity and 85% for heat is used.

2 Note that IEA reports first-generation biofuels in secondary energy terms (the primary biomass used to produce the biofuel would be higher due to conversion losses, see Sections 2.3 and 2.4).

Table A.II.2 shows the differences in the primary energy accounting for the three methods for a scenario that would produce a 550 ppm CO_2eq stabilization by 2100.

While the differences between applying the three accounting methods to current energy consumption are modest, differences grow significantly when generating long-term lower CO_2 emissions energy scenarios where non-combustion technologies take on a larger relative role (Table A.II.2). The accounting gap between the different methods becomes bigger over time (Figure A.II.1). There are significant differences in individual non-combustible sources in 2050 and even the share of total renewable primary energy supply varies between 24 and 37% across the three methods (Table A.II.2). The biggest absolute gap (and relative difference) for a single source is for geothermal energy, with about 200 EJ difference between the direct equivalent and the physical energy content method, and the gap between hydro and nuclear primary energy remains considerable. The scenario presented here is fairly representative and by no means extreme. The chosen 550 ppm stabilization target is not particularly stringent nor is the share of non-combustible energy very high.

A.II.5 Lifecycle assessment and risk analysis

This section describes methods and underlying literature and assumptions of analyses of energy payback times and energy ratios (A.II.5.1),

Table A.II.2 | Comparison of global total primary energy supply in 2050 using different primary energy accounting methods based on a 550 ppm CO_2eq stabilization scenario (Loulou et al., 2009).

	Physical content method		Direct equivalent method		Substitution method	
	EJ	%	EJ	%	EJ	%
Fossil fuels	581.6	55.2	581.56	72.47	581.6	61.7
Nuclear	81.1	7.7	26.76	3.34	70.4	7.8
Renewable:	390.1	37.1	194.15	24.19	290.4	30.8
Bioenergy	*120.0*	*11.4*	*120.0*	*15.0*	*120.0*	*12.7*
Solar	*23.5*	*2.2*	*22.0*	*2.8*	*35.3*	*3.8*
Geothermal	*217.3*	*20.6*	*22.9*	*2.9*	*58.1*	*6.2*
Hydro	*23.8*	*2.3*	*23.8*	*3.0*	*62.6*	*6.6*
Ocean	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*
Wind	*5.5*	*0.5*	*5.5*	*0.7*	*14.3*	*1.5*
Total	**1,052.8**	**100**	**802.5**	**100**	**942.4**	**100**

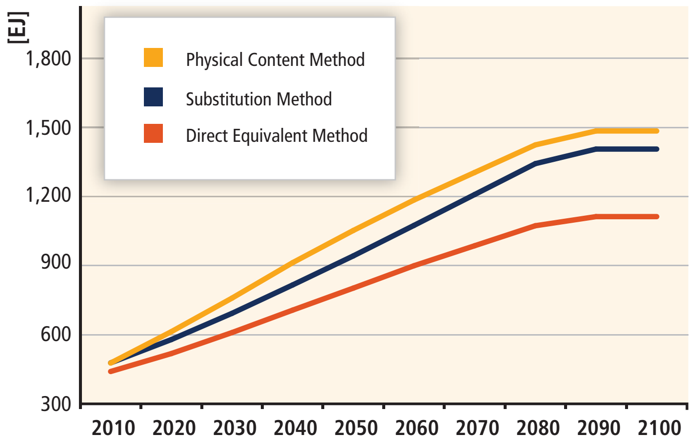

Figure A.II.1 | Comparison of global total primary energy supply between 2010 and 2100 using different primary energy accounting methods based on a 550 ppm CO_2eq stabilization scenario (Loulou et al., 2009).

lifecycle GHG emissions (A.II.5.2), operational water use (A.II.5.3) and hazards and risks (A.II.5.4) of energy technologies as presented in Chapter 9. Results of the analysis carried out for lifecycle GHG emissions are also included in Sections 2.5, 3.6, 4.5, 5.6, 6.5 and 7.6. Please note that the literature bases for the reviews in A.II.5.2 and A.II.5.3 are included as lists within the respective sections.

A.II.5.1 Energy payback time and energy ratio

The Energy Ratio, *ER* (also referred to as the energy payback ratio, or the Energy Return on Energy Investment, *EROEI*; see Gagnon, 2008), of an energy supply system of power rating *P* and load factor λ, is defined as the ratio

$$ER = \frac{E_{life}}{E} = \frac{P \times 8760\,hy^{-1} \times \lambda \times T}{E}$$

of the lifetime electricity output E_{life} of the plant over its lifetime *T*, and the total (gross) energy requirement *E* for construction, operation and decommissioning (Gagnon, 2008). In calculating *E*, it is a convention to a) exclude the energy from human labour, energy in the ground (fossil and minerals), energy in the sun, and hydrostatic potential, and b) not to discount future against present energy requirements (Perry et al., 1977; Herendeen, 1988). Further, in computing the total energy requirement *E*, all its constituents must be of the same energy quality (for example only electricity, or only thermal energy, see the 'valuation problem' discussed in Leach (1975), Huettner (1976), Herendeen (1988), and especially Rotty et al. (1975, pp. 5-9 for the case of nuclear energy)). Whilst *E* may include derived and primary energy forms (for example electricity and thermal energy), it is usually expressed in terms of primary energy, with the electricity component converted to primary energy equivalents using the thermal efficiency $R_{conv} \approx 0.3$ of a typical subcritical black-coal-fired power station as the conversion factor. This report follows these conventions. *E* is sometimes reported in units of kWh_e/MJ_{prim}, and sometimes in units of kWh_e/kWh_{prim}. Whilst the first option chooses the most common units for either energy form, the second option allows the reader to readily understand the percentage or multiple connecting embodied energy and energy output. Moreover, it has been argued (see Voorspools et al., (2000, p. 326)) that in the absence of alternative technologies, electricity would have to be generated by conventional means. We therefore use kWh_e/kWh_{prim} in this report.

Applying the lifecycle energy metric to an energy supply system allows defining an *energy payback time*. This is the time t_{PB} that it takes the system to supply an amount of energy that is equal to its own energy requirement *E*. Once again, this energy is best measured in terms of the primary energy equivalent $\frac{E_{PB}}{R_{conv}}$ of the system's electricity output E_{PB} over the payback time. Voorspools et al. (2000, p. 326) note that were the system to pay back its embodied primary energy in equal amounts of electricity, energy payback times would be more than three times as long.

Mathematically, the above condition reads

$$E = \frac{E_{PB}}{R_{conv}} = \frac{P \times 8760\,hy^{-1} \times \lambda \times t_{PB}}{R_{conv}}$$

, and leads to

$$t_{PB} = \frac{E}{\frac{P \times 8760\,hy^{-1} \times \lambda}{R_{conv}}} = \frac{E}{\frac{E_{out\,annual}}{R_{conv}}}$$

(which, for example, coincides with the standard German VDI 4600 definition). Here, $\frac{E_{out\,annual}}{R_{conv}}$ is the system's annual net energy output expressed in primary energy equivalents. It can be shown that the Energy Ratio *ER* (or *EROEI*) and the energy payback time t_{PB} can be converted into each other according to

$$t_{PB} = \frac{E\,T}{\frac{E_{out\,annual}\,T}{R_{conv}}} = \frac{E\,T}{\frac{E_{life}}{R_{conv}}} = \frac{R_{conv}}{E\,R}T \;.$$

Note that the energy payback time is not dependent on the lifetime *T*, because

$$t_{PB} = \frac{E\,R_{conv}}{P \times 8760\,hy^{-1} \times \lambda} \;.$$

Energy payback times have been partly converted from energy ratios found in the literature (Lenzen, 1999, 2008; Lenzen and Munksgaard, 2002; Lenzen et al., 2006; Gagnon, 2008; Kubiszewski et al., 2010) based on the assumed average lifetimes given in Table 9.8 (Chapter 9). Note that energy payback as defined in the glossary (Annex I) and used in some technology chapters refers to what is defined here as energy payback time.

A.II.5.2 Review of lifecycle assessments of electricity generation technologies

The National Renewable Energy Laboratory (NREL) carried out a comprehensive review of published lifecycle assessments (LCAs) of electricity generation technologies. Of 2,165 references collected, 296 passed screens, described below, for quality and relevance and were entered into a database. This database forms the basis for the assessment of lifecycle greenhouse gas (GHG) emissions from electricity generation technologies in this report. Based on estimates compiled in the database, plots of published estimates of lifecycle GHG emissions appear in each technology chapter of this report (Chapters 2 through 7) and in Chapters 1 and 9, where lifecycle GHG emissions from RE technologies are compared to those from fossil and nuclear electricity generation technologies. The following subchapters describe the methods applied in this review (A.II.5.2.1), and list all references that are shown in the final results, sorted by technology (A.II.5.2.2).

A.II.5.2.1 Review methodology

Broadly, the review followed guidelines for *systematic reviews* as commonly performed, for instance, in the medical sciences (Neely et al., 2010). The methods of reviews in the medical sciences differ somewhat from those in the physical sciences, in that there is an emphasis on multiple, independent reviews of each candidate reference using predefined screening criteria; the formation of a review team composed of, in this case, LCA experts, technology experts and literature search experts that meets regularly to ensure consistent application of the screening criteria; and an exhaustive search of published literature to ensure no bias by, for instance, publication type (journal, report, etc.).

It is critical to note at the outset that this review did not alter (except for unit conversion) or audit for accuracy the estimates of lifecycle GHG emissions published in studies that pass the screening criteria. Additionally, no attempt was made to identify or screen for outliers, or pass judgment on the validity of input parameter assumptions. Because estimates are plotted as published, considerable methodological inconsistency is inherent, which limits comparability of the estimates both within particular power generation technology categories and across the technology categories. This limitation is partially counteracted by the comprehensiveness of the literature search and the breadth and depth of literature revealed. Few attempts have been made to broadly review the LCA literature on electricity generation technologies. Those that do exist tend to focus on individual technologies and are more limited in comprehensiveness compared to the present review (e.g., Lenzen and Munksgaard, 2002; Fthenakis and Kim, 2007; Lenzen, 2008; Sovacool, 2008b; Beerten et al., 2009; Kubiszewski et al., 2010).

The review procedure included the following steps: literature collection, screening and analysis.

Literature collection

Starting in May of 2009, potentially relevant literature was identified through multiple mechanisms, including searches in major bibliographic databases (e.g., Web of Science, WorldCat) using a variety of search algorithms and combinations of key words, review of reference lists of relevant literature, and specialized searches on websites of known studies series (e.g., European Union's ExternE and its descendants) and known LCA literature databases (e.g., the library contained within the SimaPro LCA software package). All collected literature was first categorized by content (with key information from every collected reference recorded in a database) and added to a bibliographic database.

The literature collection methods described here apply to all classes of electricity generation technologies reviewed in this report except for oil and hydropower. LCA data for hydropower and oil were added at a later stage to the NREL database and have therefore undergone a less comprehensive literature collection process.

Literature screening

Collected references were independently subjected to three rounds of screening by multiple experts to select references that met criteria for quality and relevance. References often reported multiple GHG emission estimates based on alternative scenarios. Where relevant, the screening criteria were applied at the level of the scenario estimate, occasionally resulting in only a subset of scenarios analyzed in a given reference passing the screens.

References having passed the first quality screen included peer-reviewed journal articles, scientifically detailed conference proceedings, PhD theses, and reports (authored by government agencies, academic institutions, non-governmental organizations, international institutions, or corporations) published after 1980 and in English. Attempts were made to obtain English versions of non-English publications and a few exceptions were translated. The first screen also ensured that the accepted references were LCAs, defined as analyzing two or more lifecycle phases (with exceptions for PV and wind energy given that the literature demonstrates that the vast majority of lifecycle GHG emissions occur in the manufacturing phase (Frankl et al., 2005; Jungbluth et al., 2005)).

All references passing the first screen were then directly judged based on more stringent quality and relevance criteria:

- Employed a currently accepted attributional LCA and GHG accounting method (consequential LCAs were not included because their results are fundamentally not comparable to results based on attributional LCA methods; see Section 9.3.4 for further description of attributional and consequential LCAs);
- Reported inputs, scenario/technology characteristics, important assumptions and results in enough detail to trace and trust the results; and
- Evaluated a technology of modern or future relevance.

For the published results to be analyzed, estimates had to pass a final set of criteria:

- To ensure accuracy in transcription, only GHG emission estimates that were reported numerically (i.e., not only graphically) were included.

- Estimates duplicating prior published work were not included.

- Results had to have been easily convertible to the functional unit chosen for this study: grams of CO_2eq per kWh generated.

Table A.II.3 reports the counts of references at each stage in the screening process for the broad classes of electricity generation technologies considered in this report.

Analysis of estimates

Estimates of lifecycle GHG emissions from studies passing both screens were then analyzed and plotted. First, estimates were categorized by technology within the broad classes considered in this report, listed in Table A.II.3. Second, estimates were converted to the common functional unit of g CO_2eq per kWh generated. This conversion was performed using no exogenous assumptions; if any were required, that estimate was not included. Third, estimates of total lifecycle GHG emissions that included contributions from either land use change (LUC) or heat production (in cases of cogeneration) were removed. This step required that studies that considered LUC- or heat-related GHG emissions had to report those contributions separately such that estimates included here pertain to the generation of electricity alone. Finally, distributional information required for display in box and whisker plots were calculated: minimum, 25th percentile value, 50th percentile value, 75th percentile value and maximum. Technologies with data sets composed of less than five estimates (e.g., geothermal) have been plotted as discrete points rather than superimposing synthetic distributional information.

The resulting values underlying Figure 9.8 are shown in Table A.II.4. Figures displayed in technology chapters are based on the same data set, yet displayed with a higher level of resolution regarding technology subcategories (e.g., on- and offshore wind energy).

A.II.5.2.2 List of references

Below, all references for the review of lifecycle assessments of greenhouse gas emissions from electricity generation that are shown in the final results in this report are listed, sorted by technology and in alphabetical order.

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Table A.II.3 | Counts of LCAs of electricity generation technologies ('references') at each stage in the literature collection and screening process and numbers of scenarios ('estimates') of lifecycle GHG emissions evaluated herein.

Technology category	References reviewed	References passing the first screen	References passing the second screen	References providing lifecycle GHG emissions estimates	Estimates of lifecycle GHG emissions passing screens
Biopower	369	162	84	52	226
Coal	273	192	110	52	181
Concentrating solar power	125	45	19	13	42
Geothermal Energy	46	24	9	6	8
Hydropower	89	45	11	11	28
Natural gas	251	157	77	40	90
Nuclear Energy	249	196	64	32	125
Ocean energy	64	30	6	5	10
Oil	68	45	19	10	24
Photovoltaics	400	239	75	26	124
Wind Energy	231	174	72	49	126
TOTALS	**2165**	**1309**	**546**	**296**	**984**
% of total reviewed		60%	25%	14%	
% of those passing first screen			42%	23%	
% of those passing second screen				54%	

Note: Some double counting is inherent in the totals given that some references investigated more than one technology.

Table A.II.4 | Aggregated results of literature review of LCAs of GHG emissions from electricity generation technologies as displayed in Figure 9.8 (g CO_2eq/kWh).

Values	Bio-power	Solar		Geothermal Energy	Hydropower	Ocean Energy	Wind Energy	Nuclear Energy	Natural Gas	Oil	Coal
		PV	CSP								
Minimum	-633	5	7	6	0	2	2	1	290	510	675
25th percentile	360	29	14	20	3	6	8	8	422	722	877
50th percentile	18	46	22	45	4	8	12	16	469	840	1001
75th percentile	37	80	32	57	7	9	20	45	548	907	1130
Maximum	75	217	89	79	43	23	81	220	930	1170	1689
CCS min	-1368								65		98
CCS max	-594								245		396

Note: CCS = Carbon capture and storage, PV = Photovoltaic, CSP = Concentrating solar power.

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A.II.5.3 Review of operational water use of electricity generation technologies

This overview describes the methods of a comprehensive review of published estimates of operational water withdrawal and consumption intensity of electricity generation technologies. Results are discussed in Section 9.3.4.4 and shown in Figure 9.14.

A.II.5.3.1 Review methodology

Lifecycle water consumption and withdrawal literature for electricity generating technologies was reviewed, but due to lack of quality and breadth of data, the review focused exclusively on operational water use. Lifecycle literature considered here are studies that passed the screening process used in this report's review of lifecycle GHG emissions from electricity generation technologies (see A II.5.2). Upstream water use for biofuel energy crops is not subject of this section.

This review did not alter (except for unit conversion) or audit for accuracy the estimates of water use published in studies that passed the screening criteria. Also, because estimates are used as published, considerable methodological inconsistency is inherent, which limits comparability. A few attempts have been made to review the operational water use literature for electricity generation technologies, though all of these were limited in their comprehensiveness of either technologies or of primary literature considered (Gleick, 1993; Inhaber, 2004; NETL, 2007a,b; WRA, 2008; Fthenakis and Kim, 2010). The present review therefore informs the discourse of this report in a unique way.

Literature collection

The identification of relevant literature started with a core library of references held previously by the researchers, followed by searching in major bibliographic databases using a variety of search algorithms and combinations of key words, and then reviewing reference lists of every collected reference. All collected literature was added to a bibliographic database. The literature collection methods described here apply to all classes of electricity generation technologies reviewed in this report.

Literature screening

Collected references were independently subjected to screening to select references that met criteria for quality and relevance. Operational water use studies must have been written in English, addressed operational water use for facilities located in North America, provided sufficient information to calculate a water use intensity factor (in cubic metres per megawatt-hour generated), made estimates of water consumption that did not duplicate others previously published, and have been in one of the following formats: journal article, conference proceedings, or report (authored by government agencies, nongovernmental organizations, international institutions, or corporations). Estimates of national average water use intensity for particular technologies, estimates of existing plant operational water use, and estimates derived from laboratory experiments were considered equally. Given the paucity of available estimates of water consumption for electricity generation technologies and that the estimates that have been published are being used in the policy context already, no additional screens based on quality or completeness of reporting were applied.

Analysis of estimates

Estimates were categorized by fuel technology and cooling systems. Certain aggregations of fuel technology types and cooling system types were made to facilitate analysis. Concentrating solar power includes both parabolic trough and power tower systems. Nuclear includes pressurized water reactors and boiling water reactors. Coal includes subcritical and supercritical technologies. For recirculating cooling technologies, no distinction is made between natural draft and mechanical draft cooling tower systems. Similarly, all pond-cooled systems are treated identically. Estimates were converted to the common functional unit of cubic meters per MWh generated. This conversion was performed using no exogenous assumptions; if any were required, that estimate was not analyzed.

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A.II.5.4 Risk analysis

This section introduces the methods applied for the assessment of hazards and risks of energy technologies presented in Section 9.3.4.7, and provides references and central assumptions (Table A.II.5).

A large variety of definitions of the term risk exists, depending on the field of application and the object under study (Haimes, 2009). In engineering and natural sciences, risk is frequently defined in a quantitative way: risk (R) = probability (p) × consequence (C). This definition does not include subjective factors of risk perception and aversion, which can also influence the decision-making process, that is, stakeholders may make trade-offs between quantitative and qualitative risk factors (Gregory and Lichtenstein, 1994; Stirling, 1999). Risk assessment and evaluation is further complicated when certain risks significantly transcend everyday levels; their handling posing a challenge for society (WBGU, 2000). For example, Renn et al. (2001) assigned risks into three categories or areas, namely (1) the normal area manageable by routine operations and existing laws and regulations, (2) the intermediate area, and (3) the intolerable area (area of permission). Kristensen et al. (2006) proposed a modified classification scheme to further improve the characterization of risk. Recently, additional aspects such as critical infrastructure protection, complex interrelated systems and 'unknown unknowns' have become a major focus (Samson et al., 2009; Aven and Zio, 2011; Elahi, 2011).

The evaluation of the 'hazards and risks' of various energy technologies as presented in Section 9.3.4.7 builds upon the approach of comparative risk assessment as it has been established at the Paul Scherrer Institut (PSI) since the 1990s;[4] at the core of which is the Energy-Related Severe Accident Database (ENSAD) (Hirschberg et al., 1998, 2003a; Burgherr et al., 2004, 2008; Burgherr and Hirschberg, 2005). The consideration of full energy chains is essential because an accident can happen in any chain stage from exploration, extraction, processing and storage, long distance transport, regional and local distribution, power and/or heat generation, waste treatment, and disposal. However, not all these stages are applicable to every energy chain. For fossil energy chains (coal, oil, natural gas) and hydropower, extensive historical experience is contained in ENSAD for the period 1970 to 2008. In the case of nuclear power, Probabilistic Safety Assessment (PSA) is employed to address hypothetical accidents (Hirschberg et al., 2004a). In contrast, consideration of renewable energy technologies other than hydropower is based on available accident statistics, literature review and expert judgment because of limited or lacking historical experience. It should be noted that available analyses have limited scope and do not include

4 In a recent study, Felder (2009) compared the ENSAD database with another energy accident compilation (Sovacool, 2008a). Despite numerous and partially substantial differences between the two data sets, several interesting findings with regard to methodological and policy aspects were addressed. However, the study was based on the first official release of ENSAD (Hirschberg et al., 1998), and thus disregarded all subsequent updates and extensions. Another study by Colli et al. (2009) took a slightly different approach using a rather broad set of so-called Risk Characterization Indicators, however the actual testing with illustrative examples was based on ENSAD data.

probabilistic modelling of hypothetical accidents. This may have bearing particularly on results for solar PV.

No consensus definition of the term 'severe accident' exists in the literature. Within the framework of PSI's database ENSAD, an accident is considered to be severe if it is characterized by one or several of the following consequences:

- At least 5 fatalities or
- At least 10 injured or
- At least 200 evacuees or
- An extensive ban on consumption of food or
- Releases of hydrocarbons exceeding 10,000 metric tons or
- Enforced clean-up of land and water over an area of at least 25 km^2 or
- Economic loss of at least 5 million USD_{2000}

For large centralized energy technologies, results are given for three major country aggregates, namely for OECD and non-OECD countries as well as EU 27. Such a distinction is meaningful because of the substantial differences in management, regulatory frameworks and general safety culture between highly developed countries (i.e., OECD and EU 27) and the mostly less-developed non-OECD countries (Burgherr and Hirschberg, 2008). In the case of China, coal chain data were only analyzed for the years 1994 to 1999 when data on individual accidents from the China Coal Industry Yearbook (CCIY) were available, indicating that previous years were subject to substantial underreporting (Hirschberg et al., 2003a,b). For the period 2000 to 2009, only annual totals of coal chain fatalities from CCIY were available, which is why they were not combined with the data from the previous period. For renewable energy technologies except hydropower, estimates can be considered representative for developed countries (e.g., OECD and EU 27).

Comparisons of the various energy chains were based on data normalized to the unit of electricity production. For fossil energy chains the thermal energy was converted to an equivalent electrical output using a generic efficiency factor of 0.35. For nuclear, hydropower and new renewable technologies the normalization is straightforward since the generated product is electrical energy. The Gigawatt-electric-year (GW_e yr) was chosen because large individual plants have capacities in the neighbourhood of 1 GW of electrical output (GW_e). This makes the GW_e yr a natural unit to use when presenting normalized indicators generated within technology assessments.

A.II.6 Regional definitions and country groupings

The IPCC SRREN uses the following regional definitions and country groupings, largely based on the definitions of the *World Energy Outlook 2009* (IEA, 2009). Grouping names and definitions vary in the published literature, and in the SRREN in some instances there may be slight deviations from the standard below. Alternative grouping names that are used in the SRREN are given in parenthesis.

Africa

Algeria, Angola, Benin, Botswana, Burkina Faso, Burundi, Cameroon, Cape Verde, Central African Republic, Chad, Comoros, Congo, Democratic Republic of Congo, Côte d'Ivoire, Djibouti, Egypt, Equatorial Guinea, Eritrea, Ethiopia, Gabon, Gambia, Ghana, Guinea, Guinea-Bissau, Kenya, Lesotho, Liberia, Libya, Madagascar, Malawi, Mali, Mauritania, Mauritius, Morocco, Mozambique, Namibia, Niger, Nigeria, Reunion, Rwanda, Sao Tome and Principe, Senegal, Seychelles, Sierra Leone, Somalia, South Africa, Sudan, Swaziland, United Republic of Tanzania, Togo, Tunisia, Uganda, Zambia and Zimbabwe.

Annex I Parties to the United Nations Framework Convention on Climate Change

Australia, Austria, Belarus, Belgium, Bulgaria, Canada, Croatia, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Italy, Japan, Latvia, Liechtenstein, Lithuania, Luxembourg, Monaco, Netherlands, New Zealand, Norway, Poland, Portugal, Romania, Russian Federation, Slovak Republic, Slovenia, Spain, Sweden, Switzerland, Turkey, Ukraine, United Kingdom and United States.

Eastern Europe/Eurasia (also sometimes referred to as 'Transition Economies')

Albania, Armenia, Azerbaijan, Belarus, Bosnia and Herzegovina, Bulgaria, Croatia, Estonia, Georgia, Kazakhstan, Kyrgyzstan, Latvia, Lithuania, the former Yugoslav Republic of Macedonia, the Republic of Moldova, Romania, Russian Federation, Serbia, Slovenia, Tajikistan, Turkmenistan, Ukraine, and Uzbekistan. For statistical reasons, this region also includes Cyprus, Gibraltar and Malta.

European Union

Austria, Belgium, Bulgaria, Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, Netherlands, Poland, Portugal, Romania, Slovak Republic, Slovenia, Spain, Sweden and United Kingdom.

G8

Canada, France, Germany, Italy, Japan, Russian Federation, United Kingdom and United States.

Latin America

Antigua and Barbuda, Aruba, Argentina, Bahamas, Barbados, Belize, Bermuda, Bolivia, Brazil, the British Virgin Islands, the Cayman Islands,

Table A.II.5 | Overview of data sources and assumptions for the calculation of fatality rates and maximum consequences.

Coal

- ENSAD database at PSI; severe (≥5 fatalities) accidents.[1]
- OECD: 1970-2008; 86 accidents; 2,239 fatalities. EU 27: 1970-2008; 45 accidents; 989 fatalities. Non-OECD without China: 1970-2008; 163 accidents; 5.808 fatalities (Burgherr et al., 2011).
  Previous studies: Hirschberg et al. (1998); Burgherr et al. (2004, 2008).
- China (1994-1999): 818 accidents; 11,302 fatalities (Hirschberg et al., 2003a; Burgherr and Hirschberg, 2007).
- China (2000-2009): for comparison, the fatality rate in the period 2000 to 2009 was calculated based on data reported by the State Administration of Work Safety (SATW) of China.2 Annual values given by SATW correspond to total fatalities (i.e., severe and minor accidents). Thus for the fatality rate calculation it was assumed that fatalities from severe accidents comprise 30% of total fatalities, as has been found in the China Energy Technology Program (Hirschberg et al., 2003a; Burgherr and Hirschberg, 2007). Chinese fatality rate (2000-2009) = 3.14 fatalities/GW_eyr.

Oil

- ENSAD database at PSI; severe (≥5 fatalities) accidents.[1]
- OECD: 1970-2008; 179 accidents; 3,383 fatalities. EU 27: 1970-2008; 64 accidents; 1,236 fatalities. Non-OECD: 1970-2008; 351 accidents; 19,376 fatalities (Burgherr et al., 2011).
  Previous studies: Hirschberg et al. (1998); Burgherr et al. (2004, 2008).

Natural Gas

- ENSAD database at PSI; severe (≥5 fatalities) accidents.[1]
- OECD: 1970-2008; 109 accidents; 1,257 fatalities. EU 27: 1970-2008; 37 accidents; 366 fatalities. Non-OECD: 1970-2008; 77 accidents; 1,549 fatalities (Burgherr et al., 2011).
  Previous studies: Hirschberg et al. (1998); Burgherr et al. (2004, 2008); Burgherr and Hirschberg (2005).

Nuclear

- Generation II (Gen. II) - Pressurized Water Reactor, Switzerland; simplified Probabilistic Safety Assessment (PSA) (Roth et al., 2009).
- Generation III (Gen. III) - European Pressurized Reactor (EPR) 2030, Switzerland; simplified PSA (Roth et al., 2009).
  Available results for the above described EPR point towards significantly lower fatality rates (early fatalities (EF): 3.83E-07 fatalities/GW_eyr; latent fatalities (LF): 1.03E-05 fatalities/GW_eyr; total fatalities (TF): 1.07E-05 fatalities/GW_eyr) due to a range of advanced features, especially with respect to Severe Accident Management (SAM) active and passive systems. However, maximum consequences of hypothetical accidents may increase (ca. 48,800 fatalities) due to the larger plant size (1,600 MW) and the larger associated radioactive inventory.
- In the case of a severe accident in the nuclear chain, immediate or early (acute) fatalities are of minor importance and denote those fatalities that occur in a short time period after exposure, whereas latent (chronic) fatalities due to cancer dominate total fatalities (Hirschberg et al., 1998). Therefore, the above estimates for Gen. II and III include immediate and latent fatalities.
- Three Mile Island 2, TMI-2: The TMI-2 accident occurred as a result of equipment failures combined with human errors. Due to the small amount of radioactivity released, the estimated collective effective dose to the public was about 40 person-sievert (Sv). The individual doses to members of the public were extremely low: <1 mSv in the worst case. On the basis of the collective dose one extra cancer fatality was estimated. However, 144,000 people were evacuated from the area around the plant. For more information, see Hirschberg et al. (1998).
- Chernobyl: 31 immediate fatalities; PSA-based estimate of 9,000 to 33,000 latent fatalities (Hirschberg et al., 1998).
- PSI's Chernobyl estimates for latent fatalities range from about 9,000 for Ukraine, Russia and Belarus to about 33,000 for the entire northern hemisphere in the next 70 years (Hirschberg et al., 1998). According to a recent study by numerous United Nations organizations, up to 4,000 persons could die due to radiation exposure in the most contaminated areas (Chernobyl Forum, 2005). This estimate is substantially lower than the upper limit of the PSI interval, which, however, was not restricted to the most contaminated areas.

Hydro

- ENSAD Database at PSI; severe (≥5 fatalities) accidents.[1]
- OECD: 1970-2008; 1 accident; 14 fatalities (Teton dam failure, USA, 1976). EU 27: 1970-2008; 1 accident; 116 fatalities (Belci dam failure, Romania, 1991) (Burgherr et al., 2011).
- Based on a theoretical model, maximum consequences for the total failure of a large Swiss dam range between 7,125 and 11,050 fatalities without pre-warning, but can be reduced to 2 to 27 fatalities with 2 hours pre-warning time (Burgherr and Hirschberg, 2005, and references therein).
- Non-OECD: 1970-2008; 12 accidents; 30,007 fatalities. Non-OECD without Banqiao/Shimantan 1970-2008; 11 accidents; 4,007 fatalities; largest accident in China (Banqiao/Shimantan dam failure, China, 1975) excluded (Burgherr et al., 2011).
- Previous studies: Hirschberg et al. (1998); Burgherr et al. (2004, 2008).

Photovoltaic (PV)

- Current estimates include only silicon (Si) technologies, weighted by their 2008 market shares, i.e., 86% for c-Si and 5.1% for a-Si/u-Si.
- The analysis covers risks of selected hazardous substances (chlorine, hydrochloric acid, silane and trichlorosilane) relevant in the Si PV life cycle.
- Accident data were collected for the USA (for which a good coverage exists), and for the years 2000 to 2008 to ensure that estimates are representative of currently operating technologies.
- Database sources: Emergency Response Notification System, Risk Management Plan, Major Hazard Incident Data Service, Major Accidents Reporting System, Analysis Research and Information on Accidents, Occupational Safety and Health Update.
- Since collected accidents were not only from the PV sector, the actual PV fatality share was estimated, based on the above substance amounts in the PV sector as a share of the total USA production, as well as data from the ecoinvent database.
- Cumulated fatalities for the four above substances were then normalized to the unit of energy production using a generic load factor of 10% (Burgherr et al., 2008).
- Assumption that 1 out of 100 accidents is severe.[3]
- Current estimate for fatality rate: Burgherr et al. (2011).
- Maximum consequences represent an expert judgment due to limited historical experience (Burgherr et al., 2008).
- Previous studies: Hirschberg et al. (2004b); Burgherr et al. (2008); Roth et al. (2009).
- Other studies: Ungers et al. (1982); Fthenakis et al. (2006); Fthenakis and Kim (2010).

Continued next Page →

Wind Onshore
• Data sources: Windpower Death Database (Gipe, 2010) and Wind Turbine Accident Compilation (Caithness Windfarm Information Forum, 2010). • Fatal accidents in Germany in the period 1975-2010; 10 accidents; 10 fatalities. 3 car accidents, where driver distraction from wind farm is given as reason, were excluded from the analysis. • Assumption that 1 out of 100 accidents is severe.[3] • Current estimate for fatality rate: Burgherr et al. (2011). • Maximum consequences represent an expert judgment due to limited historical experience (Roth et al., 2009). • Previous study: Hirschberg et al. (2004b).
Wind Offshore
• Data sources: see onshore above. • Up to now there were 2 fatal accidents during construction in the UK (2009 and 2010) with 2 fatalities, and 2 fatal accidents during research activities in the USA (2008) with 2 fatalities. • For the current estimate, only UK accidents were used, assuming a generic load factor of 0.43 (Roth et al., 2009) for the currently installed capacity of 1,340 MW (Renewable UK, 2010). • Assumption that 1 out of 100 accidents is severe.[3] • Current estimate for fatality rate: Burgherr et al. (2011). • Maximum consequences: see onshore above.
Biomass: Combined Heat and Power (CHP) Biogas
• ENSAD Database at PSI; severe (≥5 fatalities) accidents.[1] Due to limited historical experience, the CHP Biogas fatality rate was approximated using natural gas accident data from the local distribution chain stage. • OECD: 1970-2008; 24 accidents; 260 fatalities (Burgherr et al., 2011). • Maximum consequences represent an expert judgment due to limited historical experience (Burgherr et al., 2011). • Previous studies: Roth et al. (2009).
Enhanced Geothermal System (EGS)
• For the fatality rate calculations, only well drilling accidents were considered. Due to limited historical experience, exploration accidents in the oil chain were used as a rough approximation because of similar drilling equipment. • ENSAD Database at PSI; severe (≥5 fatalities) accidents.[1] • OECD: 1970-2008; oil exploration, 7 accidents; 63 fatalities (Burghehr, et al. 2011). • For maximum consequences an induced seismic event was considered to be potentially most severe. Due to limited historical experience, the upper fatality boundary from the seismic risk assessment of the EGS project in Basel (Switzerland) was taken as an approximation (Dannwolf and Ulmer, 2009). • Previous studies: Roth et al. (2009).

Notes: 1. Fatality rates are normalized to the unit of energy production in the corresponding country aggregate. Maximum consequences correspond to the most deadly accident that occurred in the observation period. 2. Data from SATW for the years 2000 to 2005 were reported in the China Labour News Flash No. 60 (2006-01-06) available at www.china-labour.org.hk/en/node/19312 (accessed December 2010). SATW data for the years 2006 to 2009 were published by Reuters, available at www.reuters.com/article/idUSPEK206148 (2006), uk.reuters.com/article/idUKPEK32921920080112 (2007), uk.reuters.com/article/idUKTOE61D00V20100214 (2008 and 2009), (all accessed December 2010). 3. For example, the rate for natural gas in Germany is about 1 out of 10 (Burgherr and Hirschberg, 2005), and for coal in China about 1 out of 3 (Hirschberg et al., 2003b).

Chile, Colombia, Costa Rica, Cuba, Dominica, the Dominican Republic, Ecuador, El Salvador, the Falkland Islands, French Guyana, Grenada, Guadeloupe, Guatemala, Guyana, Haiti, Honduras, Jamaica, Martinique, Montserrat, Netherlands Antilles, Nicaragua, Panama, Paraguay, Peru, St. Kitts and Nevis, Saint Lucia, Saint Pierre et Miquelon, St. Vincent and the Grenadines, Suriname, Trinidad and Tobago, the Turks and Caicos Islands, Uruguay and Venezuela.

Middle East

Bahrain, the Islamic Republic of Iran, Iraq, Israel, Jordan, Kuwait, Lebanon, Oman, Qatar, Saudi Arabia, Syrian Arab Republic, the United Arab Emirates and Yemen. It includes the neutral zone between Saudi Arabia and Iraq.

Non-OECD Asia (also sometimes referred to as 'developing Asia')

Afghanistan, Bangladesh, Bhutan, Brunei Darussalam, Cambodia, China, Chinese Taipei, the Cook Islands, East Timor, Fiji, French Polynesia, India, Indonesia, Kiribati, the Democratic People's Republic of Korea, Laos, Macau, Malaysia, Maldives, Mongolia, Myanmar, Nepal, New Caledonia, Pakistan, Papua New Guinea, the Philippines, Samoa, Singapore, Solomon Islands, Sri Lanka, Thailand, Tonga, Vietnam and Vanuatu.

North Africa

Algeria, Egypt, Libyan Arab Jamahiriya, Morocco and Tunisia.

OECD – Organisation for Economic Cooperation and Development

OECD Europe, OECD North America and OECD Pacific as listed below. Countries that joined the OECD in 2010 (Chile, Estonia, Israel and Slovenia) are not yet included in the statistics used in this report.

OECD Europe

Austria, Belgium, the Czech Republic, Denmark, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Italy, Luxembourg, the Netherlands, Norway, Poland, Portugal, the Slovak Republic, Spain, Sweden, Switzerland, Turkey and the United Kingdom.

OECD North America
Canada, Mexico and the United States.

OECD Pacific
Australia, Japan, Korea and New Zealand.

OPEC (Organization of Petroleum Exporting Countries)
Algeria, Angola, Ecuador, Islamic Republic of Iran, Iraq, Kuwait, Libya, Nigeria, Qatar, Saudi Arabia, United Arab Emirates and Venezuela.

Sub-Saharan Africa
Africa regional grouping excluding the North African regional grouping and South Africa.

A.II.7 General conversion factors for energy

Table A.II.6 provides conversion factors for a variety of energy-related units.

Table A.II.6 | Conversion factors for energy units (IEA, 2010b).

To:	TJ	Gcal	Mtoe	MBtu	GWh
From:	**multiply by:**				
TJ	1	238.8	2.388×10^{-5}	947.8	0.2778
Gcal	4.1868×10^{-3}	1	10^{-7}	3.968	1.163×10^{-3}
Mtoe	4.1868×10^{4}	10^{7}	1	3.968×10^{7}	11,630
MBtu	1.0551×10^{-3}	0.252	2.52×10^{-8}	1	2.931×10^{-4}
GWh	3.6	860	8.6×10^{-5}	3,412	1

Notes: MBtu: million British thermal unit; GWh: gigawatt hour; Gcal: gigacalorie; TJ: terajoule; Mtoe: megatonne of oil equivalent.

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