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:

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

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:

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

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):

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

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

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

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**

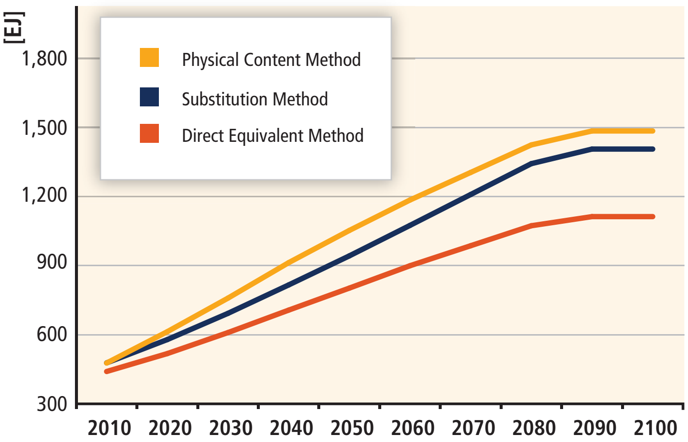

Figure A.II.1 | Comparison of global total primary energy supply between 2010 and 2100 using different primary energy accounting methods based on a 550 ppm CO_2eq stabilization scenario (Loulou et al., 2009).

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

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

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 $R_{\text{conv}} \approx 0.3$ 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 $\frac{E_{PB}}{R_{\text{conv}}}$ 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

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

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

(which, for example, coincides with the standard German VDI 4600 definition). Here, $\frac{E_{\text{out annual}}}{R_{\text{conv}}}$ 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

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

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

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

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.

Biomass-based power generation (52)

Beals, D., and D. Hutchinson (1993). *Environmental Impacts of Alternative Electricity Generation Technologies: Final Report.* Beals and Associates, Guelph, Ontario, Canada, 151 pp.

Beeharry, R.P. (2001). Carbon balance of sugarcane bioenergy systems. *Biomass & Bioenergy*, **20**(5), pp. 361-370.

Corti, A., and L. Lombardi (2004). Biomass integrated gasification combined cycle with reduced CO_2 emissions: Performance analysis and life cycle assessment (LCA). *Energy*, **29**(12-15), pp. 2109-2124.

Cottrell, A., J. Nunn, A. Urfer, and L. Wibberley (2003). *Systems Assessment of Electricity Generation Using Biomass and Coal in CFBC.* Cooperative Research Centre for Coal in Sustainable Development, Pullenvale, Qld., Australia, 21 pp.

Cowie, A.L. (2004). *Greenhouse Gas Balance of Bioenergy Systems Based on Integrated Plantation Forestry in North East New South Wales, Australia: International Energy Agency (IEA)Bioenergy Task 38 on GHG Balances of Biomass and Bioenergy Systems.* IEA, Paris, France. 6 pp. Available at: www.ieabioenergy-task38.org/projects/task38casestudies/aus-brochure.pdf.

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.

Cuperus, M.A.T. (2003). *Biomass Systems: Final Report.* Environmental and Ecological Life Cycle Inventories for Present and Future Power Systems in Europe (ECLIPSE): N.V. tot Keuring van Electrotechnische Materialen (KEMA) Nederland B.V., Arnhem, The Netherlands, 83 pp.

Damen, K., and A.P.C. Faaij (2003). *A Life Cycle Inventory of Existing Biomass Import Chains for "Green" Electricity Production.* NW&S-E-2003-1, Universiteit Utrecht Copernicus Institute, Department of Science, Technology and Society, Utrecht, The Netherlands, 76 pp.

Daugherty, E.C. (2001). *Biomass Energy Systems Efficiency: Analyzed Through a Life Cycle Assessment.* M.S. Thesis, Lund University, Lund, Sweden, 39 pp.

Dones, R., C. Bauer, R. Bolliger, B. Burger, T. Heck, A. Roder, M.F. Emenegger, R. Frischknecht, N. Jungbluth, and M. Tuchschmid (2007). *Life Cycle Inventories of Energy Systems: Results for Current Systems in Switzerland and Other UCTE Countries.* Ecoinvent Report No. 5, Paul Scherrer Institute, Swiss Centre for Life Cycle Inventories, Villigen, Switzerland, 185 pp. Available at: www.ecolo.org/documents/documents_in_english/Life-cycle-analysis-PSI-05.pdf.

Dowaki, K., H. Ishitani, R. Matsuhashi, and N. Sam (2002). A comprehensive life cycle analysis of a biomass energy system. *Technology*, **8**(4-6), pp. 193-204.

Dowaki, K., S. Mori, H. Abe, P.F. Grierson, M.A. Adams, N. Sam, P. Nimiago, J. Gale, and Y. Kaya (2003). A life cycle analysis of biomass energy system tanking [sic] sustainable forest management into consideration. In: *Greenhouse Gas Control Technologies – 6th International Conference*, Kyoto, Japan, 1-4 October 2002. Pergamon, Oxford, pp. 1383-1388.

Dubuisson, X., and I. Sintzoff (1998). Energy and CO_2 balances in different power generation routes using wood fuel from short rotation coppice. *Biomass & Bioenergy*, **15**(4-5), pp. 379-390.

Elsayed, M.A., R. Matthews, and N.D. Mortimer (2003). *Carbon and Energy Balances for a Range of Biofuel Options.* Resources Research Institute, Sheffield Hallam University, Sheffield, UK, 341 pp.

European Commission (1999). National Implementation. *ExternE: Externalities of Energy.* European Commission, Directorate-General XII, Luxembourg, **20**, 534 pp.

Faaij, A., B. Meuleman, W. Turkenburg, A. van Wijk, B. Ausilio, F. Rosillo-Calle, and D. Hall (1998). Externalities of biomass based electricity production compared with power generation from coal in the Netherlands. *Biomass and Bioenergy*, **14**(2), pp. 125-147.

Faix, A., J. Schweinle, S. Scholl, G. Becker, and D. Meier (2010). (GTI-tcbiomass) life-cycle assessment of the BTO-Process (biomass-to-oil) with combined heat and power generation. *Environmental Progress and Sustainable Energy*, **29**(2), pp. 193-202.

Forsberg, G. (2000). Biomass energy transport – Analysis of bioenergy transport chains using life cycle inventory method. *Biomass & Bioenergy*, **19**(1), pp. 17-30.

Froese, R.E., D.R. Shonnard, C.A. Miller, K.P. Koers, and D.M. Johnson (2010). An evaluation of greenhouse gas mitigation options for coal-fired power plants in the US Great Lakes states. *Biomass and Bioenergy*, **34**(3), pp. 251-262.

Gaunt, J.L., and J. Lehmann (2008). Energy balance and emissions associated with biochar sequestration and pyrolysis bioenergy production. *Environmental Science & Technology*, **42**(11), pp. 4152-4158.

Gmünder, S.M., R. Zah, S. Bhatacharjee, M. Classen, P. Mukherjee, and R. Widmer (2010). Life cycle assessment of village electrification based on straight Jatropha oil in Chhattisgarh, India. *Biomass and Bioenergy*, **34**(3):347-355.

Hanaoka, T., and S.-Y. Yokoyama (2003). CO_2 mitigation by biomass-fired power generation in Japan. *International Energy Journal*, **4**(2), pp. 99-103.

Hartmann, D., and M. Kaltschmitt (1999). Electricity generation from solid biomass via co-combustion with coal - Energy and emission balances from a German case study. *Biomass & Bioenergy*, **16**(6), pp. 397-406.

Heller, M.C., G.A. Keoleian, M.K. Mann, and T.A. Volk (2004). Life cycle energy and environmental benefits of generating electricity from willow biomass. *Renewable Energy*, **29**(7), pp. 1023-1042.

Herrera, I., C. Lago, Y. Lechon, R. Saez, M. Munarriz, and J. Gil (2008). Life cycle assessment of two biomass power generation plants. In: *16th European Biomass Conference & Exhibition*, Valencia, Spain, 2-6 June 2008, pp. 2606-2613.

Hong, S.W. (2007). *The Usability of Switchgrass, Rice Straw, and Logging Residue as Feedstocks for Power Generation in East Texas.* M.S. Thesis, Texas A&M University, College Station, TX, USA, 83 pp.

IEA (2002). *Environmental and Health Impacts of Electricity Generation. A Comparison of the Environmental Impacts of Hydropower with those of Other Generation Technologies.* International Energy Agency (IEA), Paris, France, 239 pp.

Jungmeier, G., and J. Spitzer (2001). Greenhouse gas emissions of bioenergy from agriculture compared to fossil energy for heat and electricity supply. *Nutrient Cycling in Agroecosystems*, **60**(1-3), pp. 267-273.

Jungmeier, G., J. Spitzer, and G. Resch (1998). Environmental burdens over the entire life cycle of a biomass CHP plant. *Biomass and Bioenergy*, **15**(4-5), pp. 311-323.

Lettens, S., B. Muys, R. Ceulemans, E. Moons, J. Garcia, and P. Coppin (2003). Energy budget and greenhouse gas balance evaluation of sustainable coppice systems for electricity production. *Biomass and Bioenergy*, **24**(3), pp. 179-197.

Ma, X., F. Li, Z. Zhao, C. Wu, and Y. Chen (2003). Life cycle assessment on biomass gasification combined cycle and coal fired power plant. In: *Energy and the Environment – Proceedings of the International Conference on Energy and the Environment*, Shanghai, China, 22-24 May, 2003. Shanghai Scientific and Technical Publishers, Shanghai, China, **1**, pp. 209-214.

Malkki, H., and Y. Virtanen (2003). Selected emissions and efficiencies of energy systems based on logging and sawmill residues. *Biomass and Bioenergy*, **24**, pp. 321-327.

Mann, M.K., and P.L. Spath (1997). *Life Cycle Assessment of a Biomass Gasification Combined-Cycle System.* NREL/TP-430-23076, National Renewable Energy Laboratory, Golden, CO, USA, 157 pp.

Mann, M.K., and P.L. Spath (2001). A life-cycle assessment of biomass cofiring in a coal-fired power plant. *Clean Products and Processes*, **3**, pp. 81-91.

Mohan, T. (2005). *An Integrated Approach for Techno-economic and Environmental Analysis of Energy from Biomass and Fossil Fuels.* M.S. Thesis, Texas A&M University, College Station, TX, USA, 200 pp.

Pehnt, M. (2006). Dynamic life cycle assessment (LCA) of renewable energy technologies. *Renewable Energy*, **31**(1), pp. 55-71.

Rafaschieri, A., M. Rapaccini, and G. Manfrida (1999). Life cycle assessment of electricity production from poplar energy crops compared with conventional fossil fuels. *Energy Conversion and Management*, **40**(14), pp. 1477-1493.

Ramjeawon, T. (2008). Life cycle assessment of electricity generation from bagasse in Mauritius. *Journal of Cleaner Production*, **16**(16), pp. 1727-1734.

Renouf, M.A. (2002). *Preliminary LCA of Electricity Generation from Sugarcane Bagasse.* Environmental Energy Center, University of Queensland, Queensland, Australia, 10 pp. Available at: www.docstoc.com/docs/39528266/PRELIMINARY-LCA-OF-ELECTRICITY-GENERATION-FROM-SUGARCANE-BAGASSE.

Robertson, K. (2003). *Greenhouse Gas Benefits of a Combined Heat and Power Bioenergy System in New Zealand.* FORCE Consulting, Kirkland, WA, USA, 16 pp. Available at: www.ieabioenergy-task38.org/projects/task38casestudies/nz_fullreport.pdf.

Saskatchewan Energy Conservation and Development Authority (1994). *Levelized Cost and Full Fuel Cycle Environmental Impacts of Saskatchewan's Electric Supply Options.* SECDA Publication No. T800-94-004, Saskatoon, SK, Canada, 205 pp.

Schaffner, B., K. Persson, U. Nilsson, and J. Peterson (2002). *Environmental and Health Impacts of Electricity Generation. A Comparison of the Environmental Impacts of Hydropower with Those of Other Generation Technologies.* International Energy Agency (IEA), Paris, France, 221 pp. Available at: www.ieahydro.org/reports/ST3-020613b.pdf.

Searcy, E., and P. Flynn (2008). Processing of straw/corn stover: Comparison of life cycle emissions. *International Journal of Green Energy*, **5**(6), pp. 423-437.

Setterwall, C., M. Munter, P. Sarkozi, and B. Bodlund (2003). *Bio-fuelled Combined Heat and Power Systems. Environmental and Ecological Life Cycle Inventories for Present and Future Power Systems in Europe* (ECLIPSE). N.V. tot Keuring van Electrotechnische Materialen (KEMA) Nederland B.V., Arnhem, The Netherlands.

Sikkema, R., M. Junginger, W. Pichler, S. Hayes, and A.P.C. Faaij (2010). The international logistics of wood pellets for heating and power production in Europe: Costs, energy-input and greenhouse gas balances of pellet consumption in Italy, Sweden and the Netherlands. *Biofuels, Bioproducts and Biorefining*, **4**(2), pp. 132-153.

Spath, P.L., and M.K. Mann (2004). *Biomass Power and Conventional Fossil Systems with and without CO_2 Sequestration – Comparing the Energy Balance, Greenhouse Gas Emissions and Economics.* NREL/TP-510-32575. National Renewable Energy Laboratory, Golden, CO, USA, 28 pp.

Styles, D., and M.B. Jones (2007). Energy crops in Ireland: Quantifying the potential life-cycle greenhouse gas reductions of energy-crop electricity. *Biomass & Bioenergy*, **31**(11-12), pp. 759-772.

Tiwary, A., and J. Colls (2010). Mitigating secondary aerosol generation potentials from biofuel use in the energy sector. *Science of the Total Environment*, **408**(3), pp. 607-616.

Wibberley, L. (2001). *Coal in a Sustainable Society.* Australian Coal Association Research Program, Brisbane, Queensland, Australia.

Wibberley, L., J. Nunn, A. Cottrell, M. Searles, A. Urfer, and P. Scaife (2000). *Life Cycle Analysis for Steel and Electricity Production in Australia.* Australian Coal Association Research Program, Brisbane, Queensland, Australia, 36 pp.

Wicke, B., V. Dornburg, M. Junginger, and A. Faaij (2008). Different palm oil production systems for energy purposes and their greenhouse gas implications. *Biomass and Bioenergy*, **32**(12), pp. 1322-1337.

Yoshioka, T., K. Aruga, T. Nitami, H. Kobayashi, and H. Sakai (2005). Energy and carbon dioxide (CO_2) balance of logging residues as alternative energy resources: System analysis based on the method of a life cycle inventory (LCI) analysis. *Journal of Forest Research*, **10**(2), pp. 125-134.

Zhang, Y.M., S. Habibi, and H.L. MacLean (2007). Environmental and economic evaluation of bioenergy in Ontario, Canada. *Journal of the Air and Waste Management Association*, **57**(8), pp. 919-933.

Coal-fired power generation (52)

Akai, M., N. Nomura, H. Waku, and M. Inoue (1997). Life-cycle analysis of a fossil-fuel power plant with CO_2 recovery and a sequestering system. *Energy*, **22**(2-3), pp. 249-256.

Bates, J.L. (1995). *Full Fuel Cycle Atmospheric Emissions and Global Warming Impacts from UK Electricity Generation.* Report Number: ETSU-R-88, Energy Technical Support Unit (ETSU), London, UK, 51 pp. (ISBN 011 515 4027).

Corrado, A., P. Fiorini, and E. Sciubba (2006). Environmental assessment and extended exergy analysis of a "Zero CO_2 Emission," high-efficiency steam power plant. *Energy*, **31**(15), pp. 3186-3198.

Cottrell, A., J. Nunn, A. Urfer, and L. Wibberley (2003). *Systems Assessment of Electricity Generation Using Biomass and Coal in CFBC.* Cooperative Research Centre for Coal in Sustainable Development, Pullenvale, Qld., Australia, 21 pp.

Damen, K., and A.P.C. Faaij (2003). *A Life Cycle Inventory of Existing Biomass Import Chains for "Green" Electricity Production.* NW&S-E-2003-1, Universiteit Utrecht Copernicus Institute, Department of Science, Technology and Society, Utrecht, The Netherlands, 76 pp.

Dolan, S.L. (2007). *Life Cycle Assessment and Emergy Synthesis of a Theoretical Offshore Wind Farm for Jacksonville, Florida.* M.S. Thesis, University of Florida, 125 pp.

Dones, R., U. Ganter, and S. Hirschberg (1999). Environmental inventories for future electricity supply systems for Switzerland. *International Journal of Global Energy Issues*, **12**(1-6), pp. 271-282.

Dones, R., X. Zhou, and C. Tian (2004). Life cycle assessment (LCA) of Chinese energy chains for Shandong electricity scenarios. *International Journal of Global Energy Issues*, **22**(2/3/4), pp. 199-224.

Dones, R., C. Bauer, R. Bolliger, B. Burger, T. Heck, A. Roder, M.F. Emenegger, R. Frischknecht, N. Jungbluth, and M. Tuchschmid (2007). *Life Cycle Inventories of Energy Systems: Results for Current Systems in Switzerland and Other UCTE Countries.* Ecoinvent Report No. 5, Paul Scherrer Institute, Swiss Centre for Life Cycle Inventories, Villigen, Switzerland, 185 pp. Available at: www.ecolo.org/documents/documents_in_english/Life-cycle-analysis-PSI-05.pdf.

Dones, R., C. Bauer, T. Heck, O. Mayer-Spohn, and M. Blesl (2008). Life cycle assessment of future fossil technologies with and without carbon capture and storage. *Life-Cycle Analysis for New Energy Conversion and Storage Systems*,**1041**, pp. 147-158.

European Commission (1995). Coal & Lignite. *ExternE: Externalities of Energy.* Luxembourg, European Commission, Directorate-General XII. **3**, 573 pp.

European Commission (1999). National Implementation. *ExternE: Externalities of Energy.* Luxembourg, European Commission, Directorate-General XII. **20**, 534 pp.

Fiaschi, D., and L. Lombardi (2002). Integrated gasifier combined cycle plant with integrated CO_2 - H_2S removal: Performance analysis, life cycle assessment and exergetic life cycle assessment. *International Journal of Applied Thermodynamics*, **5**(1), pp. 13-24.

Friedrich, R., and T. Marheineke (1996). Life cycle analysis of electric systems: Methods and results. In: *IAEA Advisory Group Meeting on Analysis of Net Energy Balance and Full-energy-chain Greenhouse Gas Emissions for Nuclear and Other Energy Systems*, Beijing, China, 7 October 1994, International Atomic Energy Agency, pp. 67-75. Available at: www.iaea.org/inis/collection/NCLCollectionStore/_Public/28/013/28013414.pdf.

Froese, R.E., D.R. Shonnard, C.A. Miller, K.P. Koers, and D.M. Johnson (2010). An evaluation of greenhouse gas mitigation options for coal-fired power plants in the US Great Lakes States. *Biomass and Bioenergy*, **34**(3), pp. 251-262.

Gorokhov, V., L. Manfredo, M. Ramezan, J. Ratafia-Brown (2000). *Life Cycle Assessment of IGCC.* Systems Phase II Report, Science Applications International Corporation (SAIC), McLean, VA, USA, 162 pp.

Hartmann, D., and M. Kaltschmitt (1999). Electricity generation from solid biomass via co-combustion with coal - Energy and emission balances from a German case study. *Biomass & Bioenergy*, **16**(6), pp. 397-406.

Heller, M.C., G.A. Keoleian, M.K. Mann, and T.A. Volk (2004). Life cycle energy and environmental benefits of generating electricity from willow biomass. *Renewable Energy*, **29**(7), pp. 1023-1042.

Herrick, C.N., A. Sikri, L. Greene and J. Finnell (1995). *Assessment of the Environmental Benefits of Renewables Deployment: A Total Fuel Cycle Analysis of the Greenhouse Gas Impacts of Renewable Generation Technologies in Regional Utility Systems.* DynCorp EENSP, Inc, Alexandria, VA, USA.

Hondo, H. (2005). Life cycle GHG emission analysis of power generation systems: Japanese case. *Energy*, **30**(11-12), pp. 2042-2056.

Jaramillo, P., W.M. Griffin, and H.S. Matthews (2006). *Comparative Life Cycle Carbon Emissions of LNG Versus Coal and Gas for Electricity Generation*, no publisher given, 16 pp. Available at: www.ce.cmu.edu/~gdrg/readings/2005/10/12/Jaramillo_LifeCycleCarbonEmissionsFromLNG.pdf.

Koornneef, J., T. van Keulen, A. Faaij, and W. Turkenburg (2008). Life cycle assessment of a pulverized coal power plant with post-combustion capture, transport and storage of CO_2. *International Journal of Greenhouse Gas Control*, **2**(4), pp. 448-467.

Kreith, F., P. Norton, and D. Brown (1990). *CO_2 Emissions from Coal-fired and Solar Electric Power Plants.* Solar Energy Research Institute (SERI), Golden, CO, USA, 44 pp.

Krewitt, W., P. Mayerhofer, R. Friedrich, A. Truckenmüller, T. Heck, A. Gressmann, F. Raptis, F. Kaspar, J. Sachau, K. Rennings, J. Diekmann, and B. Praetorius (1997). *ExternE National Implementation in Germany.* University of Stuttgart, Stuttgart, Germany, 189 pp.

Lee, K.-M., S.-Y. Lee, and T. Hur (2004). Life cycle inventory analysis for electricity in Korea. *Energy*, **29**(1), pp. 87-101.

Lee, R. (1994). Estimating externalities of coal fuel cycles. In: *External Costs and Benefits of Fuel Cycles, Vol. 3.* Oak Ridge National Laboratory, Oak Ridge, TN, USA, 719 pp.

Lenzen, M. (2008). Life cycle energy and greenhouse gas emissions of nuclear energy: A review. *Energy Conversion and Management*, **49**, pp. 2178-2199. Available at: www.isa.org.usyd.edu.au/publications/documents/ISA_Nuclear_Report.pdf.

Markewitz, P., A. Schreiber, S. Vögele, and P. Zapp (2009). Environmental impacts of a German CCS strategy. *Energy Procedia*, **1**(1), pp. 3763-3770.

Martin, J.A. (1997). A total fuel cycle approach to reducing greenhouse gas emissions: Solar generation technologies as greenhouse gas offsets in U.S. utility systems. In: *Solar Energy (Selected Proceeding of ISES 1995: Solar World Congress. Part IV)*, **59**(4-6), pp. 195-203.

May, J.R. and D.J. Brennan (2003). Life cycle assessment of Australian fossil energy options. *Process Safety and Environmental Protection: Transactions of the Institution of Chemical Engineers, Part B*, **81**(5), pp. 317-330.

Meier, P.J., P.P.H. Wilson, G.L. Kulcinski, and P.L. Denholm (2005). US electric industry response to carbon constraint: A life-cycle assessment of supply side alternatives. *Energy Policy*, **33**(9), pp. 1099-1108.

Meridian Corporation (1989). *Energy System Emissions and Materiel Requirements.* Meridian Corporation, Alexandria, VA, USA, 34 pp.

Odeh, N.A. and T.T. Cockerill (2008). Life cycle analysis of UK coal fired power plants. *Energy Conversion and Management*, **49**(2), pp. 212-220.

Odeh, N.A. and T.T. Cockerill (2008). Life cycle GHG assessment of fossil fuel power plants with carbon capture and storage. *Energy Policy*, **36**(1), pp. 367-380.

Pacca, S.A. (2003). *Global Warming Effect Applied to Electricity Generation Technologies.* PhD Thesis, University of California, Berkeley, CA, USA, 191 pp.

Peiu, N. (2007). Life cycle inventory study of the electrical energy production in Romania. *International Journal of Life Cycle Assessment*, **12**(4), pp. 225-229.

Ruether, J.A., M. Ramezan, and P.C. Balash (2004). Greenhouse gas emissions from coal gasification power generation systems. *Journal of Infrastructure Systems*, **10**(3), pp. 111-119.

San Martin, R.L. (1989). *Environmental Emissions from Energy Technology Systems: The Total Fuel Cycle.* U.S. Department of Energy, Washington, DC, USA, 21 pp.

Saskatchewan Energy Conservation and Development Authority (1994). *Levelized Cost and Full Fuel Cycle Environmental Impacts of Saskatchewan's Electric Supply Options.* SECDA Publication No. T800-94-004, Saskatoon, SK, Canada, 205 pp.

Schreiber, A., P. Zapp, and W. Kuckshinrichs (2009). Environmental assessment of German electricity generation from coal-fired power plants with amine-based carbon capture. *International Journal of Life Cycle Assessment*, **14**(6), pp. 547-559.

SENES Consultants Limited (2005). *Methods to Assess the Impacts on the Natural Environment of Generation Options.* Prepared by SENES Consultants for the Ontario Power Authority, Richmond Hill, ON, Canada, 166 pp.

Shukla, P.R. and D. Mahapatra (2007). Full Fuel Cycle for India. In: *CASES: Cost Assessment of Sustainable Energy Systems.* Document No. 7.1, Indian Institute of Management Ahmedabad (IIMA), Vestrapur, Ahemdabad, India, 10 pp.

Spath, P.L., and M.K. Mann (2004). *Biomass Power and Conventional Fossil Systems with and without CO_2 Sequestration – Comparing the Energy Balance, Greenhouse Gas Emissions and Economics.* NREL/TP-510-32575. National Renewable Energy Laboratory, Golden, CO, USA, 28 pp.

Spath, P.L., M.K. Mann, and D.R. Kerr (1999). *Life Cycle Assessment of Coal Fired Power Production.* National Renewable Energy Laboratory, Golden, CO, USA, 172 pp.

Styles, D., and M.B. Jones (2007). Energy crops in Ireland: Quantifying the potential life-cycle greenhouse gas reductions of energy-crop electricity. *Biomass & Bioenergy*, **31**(11-12), pp. 759-772.

Uchiyama, Y. (1996). Validity of FENCH-GHG study: Methodologies and databases. comparison of energy sources in terms of their full-energy-chain emission factors of greenhouse gases. In: *IAEA Advisory Group Meeting on Analysis of Net Energy Balance and Full-energy-chain Greenhouse Gas Emissions for Nuclear and Other Energy Systems*, Beijing, China, 4-7 Oct 1994, International Atomic Energy Agency (IAEA), pp. 85-94. Available at: www.iaea.org/inis/collection/NCLCollectionStore/_Public/28/013/28013414.pdf.

White, S.W. (1998). *Net Energy Payback and CO_2 Emissions from Helium-3 Fusion and Wind Electrical Power Plants.* PhD Thesis, University of Wisconsin, Madison, WI, USA, 166 pp.

Wibberley, L. (2001). *Coal in a Sustainable Society.* Australian Coal Association Research Program, Brisbane, Queensland, Australia.

Wibberley, L., J. Nunn, A. Cottrell, M. Searles, A. Urfer, and P. Scaife (2000). *Life Cycle Analysis for Steel and Electricity Production in Australia.* Australian Coal Association Research Program, Brisbane, Queensland, Australia, 36 pp.

Zerlia, T. (2003). Greenhouse gases in the life cycle of fossil fuels: Critical points in the assessment of pre-combustion emissions and repercussions on the complete life cycle. *La Rivista dei Combustibili*, **57**(6), pp. 281-293.

Zhang, Y.M., S. Habibi, and H.L. MacLean (2007). Environmental and economic evaluation of bioenergy in Ontario, Canada. *Journal of the Air and Waste Management Association*, **57**(8), pp. 919-933.

Zhang, Y.M., J. McKechnie, D. Cormier, R. Lyng, W. Mabee, A. Ogino, and H.L. MacLean (2010). Life cycle emissions and cost of producing electricity from coal, natural gas, and wood pellets in Ontario, Canada. *Environmental Science & Technology*, **44**(1), pp. 538-544.

Concentrating solar power (13)

Burkhardt, J., G. Heath, and C. Turchi (2010). Life cycle assessment of a model parabolic trough concentrating solar power plant with thermal energy storage. In: *ASME 4th International Conference on Energy Sustainability*, American Society of Mechanical Engineers (ASME), Phoenix, AZ, USA, 17-22 May 2010.

Cavallaro, F., and L. Ciraolo (2006). Life Cycle Assessment (LCA) of Paraboloidal-dish Solar Thermal Power Generation System. In: *1st International Symposium on Environment Identities and Mediterranean Area, ISEIM*, IEEE, Corte-Ajaccio, France, 10-13 July 2006, pp. 260-265.

German Aerospace Center (DLR) (2006). *Trans-Mediterranean Interconnection for Concentrating Solar Power. Final Report.* Institute of Technical Thermodynamics, and Section Systems Analysis and Technology Assessment, German Aerospace Center (DLR), Stuttgart, Germany, 190 pp.

Jacobson, M.Z. (2009). Review of solutions to global warming, air pollution, and energy security. *Energy & Environmental Science*, **2**, pp. 148-173.

Kreith, F., P. Norton, and D. Brown (1990). *CO_2 Emissions from Coal-fired and Solar Electric Power Plants.* SERI/TP-260-3772, Solar Energy Research Institute (SERI), Golden, CO, USA, 44 pp.

Lenzen, M. (1999). Greenhouse gas analysis of solar-thermal electricity generation. *Solar Energy*, **65**(6), pp. 353-368.

Ordóñez, I., N. Jiménez, and M.A. Silva (2009). Life cycle environmental impacts of electricity production by dish/Stirling systems in Spain. In: *SolarPACES 2009*, Berlin, Germany, 15-18 September 2009, 8 pp.

Pehnt, M. (2006). Dynamic life cycle assessment (LCA) of renewable energy technologies. *Renewable Energy*, **31**(1), pp. 55-71.

Piemonte, V., M.D. Falco, P. Tarquini, and A. Giaconia (2010). Life cycle assessment of a high temperature molten salt concentrated solar power plant. In: *20th European Symposium on Computer Aided Process Engineering – ESCAPE20*, Pierucci, S., and G.B. Ferraris (eds.), Elsevier, Naples, Italy, 6-9 June 2010, 6 pp.

Vant-Hull, L. (1992). Solar thermal electricity: An environmentally benign and viable alternative. *Perspectives in Energy*, **2**, pp. 157-166.

Viebahn, P., S. Kronshage, and F. Trieb (2008). *Final Report on Technical Data, Costs, and Life Cycle Inventories of Solar Thermal Power Plants.* Project no: 502687. New Energy Externalities Developments for Sustainability (NEEDS), Rome, Italy, 95 pp. Available at: www.needs-project.org/docs/results/RS1a/RS1a%20D12.2%20Final%20report%20concentrating%20solar%20thermal%20power%20plants.pdf.

Weinrebe, G., M. Bohnke, and F. Trieb (1998). Life cycle assessment of an 80 MW SEGS plant and a 30 MW PHOEBUS power tower. In: *International Solar Energy Conference. Solar Engineering.* ASME, Albuquerque, NM, USA, 14-17 June 1998, pp. 417-424.

Wibberley, L. (2001). *Coal in a Sustainable Society.* Australian Coal Association Research Program, Brisbane, Queensland, Australia.

Geothermal power generation (6)

Frick, S., M. Kaltschmitt, and G. Schroder (2010). Life cycle assessment of geothermal binary power plants using enhanced low-temperature reservoirs. *Energy*, **35**(5), pp. 2281-2294.

Hondo, H. (2005). Life cycle GHG emission analysis of power generation systems: Japanese case. *Energy*, **30**(11-12), pp. 2042-2056.

Karlsdottir, M.R., O.P. Palsson, and H. Palsson (2010). Factors for Primary Energy Efficiency and CO2 Emission of Geothermal Power Production. In: *World Geothermal Congress 2010*, International Geothermal Association, Bali, Indonesia, 25-29 April 2010, 7 pp.

Rogge, S., and M. Kaltschmitt (2003). Electricity and heat production from geothermal energy – An ecologic comparison. *Erdoel Erdgas Kohle/EKEP*, **119**(1), pp. 35-40.

Rule, B.M., Z.J. Worth, and C.A. Boyle (2009). Comparison of life cycle carbon dioxide emissions and embodied energy in four renewable electricity generation technologies in New Zealand. *Environmental Science & Technology*, **43**(16), pp. 6406-6413.

Uchiyama, Y. (1997). Environmental life cycle analysis of geothermal power generating technology; Chinetsu hatsuden gijutsu no kankyo life cycle bunseki. *Denki Gakkaishi (Journal of the Institute of Electrical Engineers in Japan)*, **117**(11), pp. 752-755.

Hydropower (11)

Barnthouse, L.W., G.F. Cada, M.-D. Cheng, C.E. Easterly, R.L. Kroodsma, R. Lee, D.S. Shriner, V.R. Tolbert, and R.S. Turner (1994). *Estimating Externalities of the Hydro Fuel Cycles. Report 6.* Oak Ridge National Laboratory, Oak Ridge, TN, USA, 205 pp.

Denholm, P., and G.L. Kulcinski (2004). Life cycle energy requirements and greenhouse gas emissions from large scale energy storage systems. *Energy Conversion and Management*, **45**(13-14), pp. 2153-2172.

Dones, R., T. Heck, C. Bauer, S. Hirschberg, P. Bickel, P. Preiss, L.I. Panis, and I. De Vlieger (2005). *Externalities of Energy: Extension of Accounting Framework and Policy Applications: New Energy Technologies.* ENG1-CT-2002-00609, Paul Scherrer Institute (PSI), Villigen, Switzerland, 76 pp.

Dones, R., C. Bauer, R. Bolliger, B. Burger, T. Heck, A. Roder, M.F. Emenegger, R. Frischknecht, N. Jungbluth, and M. Tuchschmid (2007). *Life Cycle Inventories of Energy Systems: Results for Current Systems in Switzerland and Other UCTE Countries.* Ecoinvent Report No. 5, Paul Scherrer Institute, Swiss Centre for Life Cycle Inventories, Villigen, Switzerland, 185 pp. Available at: www.ecolo.org/documents/documents_in_english/Life-cycle-analysis-PSI-05.pdf.

Horvath, A. (2005). *Decision-making in Electricity Generation Based on Global Warming Potential and Life-cycle Assessment for Climate Change.* University of California Energy Institute, Berkeley, CA, USA, 16 pp. Available at: repositories.cdlib.org/ucei/devtech/EDT-006.

IEA (1998). *Benign Energy? The Environmental Implications of Renewables.* International Energy Agency, Paris, France, 128 pp.

Pacca, S. (2007). Impacts from decommissioning of hydroelectric dams: A life cycle perspective. *Climatic Change*, **84**(3-4), pp. 281-294.

Rhodes, S., J. Wazlaw, C. Chaffee, F. Kommonen, S. Apfelbaum, and L. Brown (2000). *A Study of the Lake Chelan Hydroelectric Project Based on Life-cycle Stressor-effects Assessment. Final Report.* Scientific Certification Systems, Oakland, CA, USA, 193 pp.

Ribeiro, F.d.M., and G.A. da Silva (2009). Life-cycle inventory for hydroelectric generation: a Brazilian case study. *Journal of Cleaner Production*, **18**(1), pp. 44-54.

Vattenfall (2008). *Vattenfall AB Generation Nordic Certified Environmental Product Declaration EPD® of Electricity from Vattenfall´s Nordic Hydropower.* Report No. S-P-00088, Vattenfall, Stockholm, Sweden, 50 pp.

Zhang, Q., B. Karney, H.L. MacLean, and J. Feng (2007). Life-Cycle Inventory of Energy Use and Greenhouse Gas Emissions for Two Hydropower Projects in China. *Journal of Infrastructure Systems*, **13**(4), pp. 271-279.

Natural gas-fired power generation (40)

Audus, H., and L. Saroff (1995). Full Fuel Cycle Evaluation of CO2 Mitigation Options for Fossil Fuel Fired Power Plant. *Energy Conversion and Management*, **36**(6-9), pp. 831-834.

Badea, A.A., I. Voda, and C.F. Dinca (2010). Comparative Analysis of Coal, Natural Gas and Nuclear Fuel Life Cycles by Chains of Electrical Energy Production. *UPB Scientific Bulletin, Series C: Electrical Engineering*, **72**(2), pp. 221-238.

Bergerson, J., and L. Lave (2007). The Long-term Life Cycle Private and External Costs of High Coal Usage in the US. *Energy Policy*, **35**(12), pp. 6225-6234.

Bernier, E., F. Maréchal, and R. Samson (2010). Multi-Objective Design Optimization of a Natural Gas-combined Cycle with Carbon Dioxide Capture in a Life Cycle Perspective. *Energy*, **35**(2), pp. 1121-1128.

Berry, J.E., M.R. Holland, P.R. Watkiss, R. Boyd, and W. Stephenson (1998). *Power Generation and the Environment: a UK Perspective.* AEA Technology, Oxfordshire, UK, 275 pp.

Dolan, S.L. (2007). *Life Cycle Assessment and Emergy Synthesis of a Theoretical Offshore Wind Farm for Jacksonville, Florida.* M.S. Thesis, University of Florida, 125 pp. Available at: http://etd.fcla.edu/UF/UFE0021032/dolan_s.pdf.

Dones, R., S. Hirschberg, and I. Knoepfel (1996). Greenhouse gas emission inventory based on full energy chain analysis. In: *IAEA Advisory Group Meeting on Analysis of Net Energy Balance and Full-energy-chain Greenhouse Gas Emissions for Nuclear and Other Energy Systems.* Beijing, China, 4-7 October 1994, pp. 95-114. Available at: www.iaea.org/inis/collection/NCLCollectionStore/_Public/28/013/28013414.pdf.

Dones, R., U. Ganter, and S. Hirschberg (1999). Environmental inventories for future electricity supply systems for Switzerland. *International Journal of Global Energy Issues*, **12**(1-6), pp. 271-282.

Dones, R., T. Heck, and S. Hirschberg (2004). Greenhouse gas emissions from energy systems, comparison and overview. *Encyclopedia of Energy*, **3**, pp. 77-95, doi:10.1016/B0-12-176480-X/00397-1.

Dones, R., X. Zhou, and C. Tian (2004). Life cycle assessment (LCA) of Chinese energy chains for Shandong electricity scenarios. *International Journal of Global Energy Issues*, **22**(2/3/4), pp. 199-224.

Dones, R., T. Heck, C. Bauer, S. Hirschberg, P. Bickel, P. Preiss, L.I. Panis, and I. De Vlieger (2005). *Externalities of Energy: Extension of Accounting Framework and Policy Applications: New Energy Technologies.* ENG1-CT-2002-00609, Paul Scherrer Institute (PSI), Villigen, Switzerland, 76 pp.

Dones, R., C. Bauer, R. Bolliger, B. Burger, T. Heck, A. Roder, M.F. Emenegger, R. Frischknecht, N. Jungbluth, and M. Tuchschmid (2007). *Life Cycle Inventories of Energy Systems: Results for Current Systems in Switzerland and Other UCTE Countries.* Ecoinvent Report No. 5, Paul Scherrer Institute, Swiss Centre for Life Cycle Inventories, Villigen, Switzerland, 185 pp. Available at: www.ecolo.org/documents/documents_in_english/Life-cycle-analysis-PSI-05.pdf.

European Commission (1995). Oil & Gas. *ExternE: Externalities of Energy.* European Commission, Directorate-General XII, Luxembourg, **4**, 470 pp.

Frischknecht, R. (1998). *Life Cycle Inventory Analysis for Decision-Making: Scope-Dependent Inventory System Models and Context-Specific Joint Product Allocation.* Dissertation, Swiss Federal Institute of Technology Zurich, Zurich, Switzerland, 256 pp.

Gantner, U., M. Jakob, and S. Hirschberg (2001). Total greenhouse gas emissions and costs of alternative Swiss energy supply strategies. In: *Fifth International Conference on Greenhouse Gas Control Technologies (GHGT-5).* CSIRO Publishing, Cairns, Australia, 13-16 August 2000, pp. 991-996.

Herrick, C.N., A. Sikri, L. Greene, and J. Finnell (1995). *Assessment of the Environmental Benefits of Renewables Deployment: A Total Fuel Cycle Analysis of the Greenhouse Gas Impacts of Renewable Generation Technologies in Regional Utility Systems.* DynCorp EENSP, Inc., Alexandria, VA, USA.

Hondo, H. (2005). Life cycle GHG emission analysis of power generation systems: Japanese case. *Energy*, **30**(11-12), pp. 2042-2056.

IEA (2002). *Environmental and Health Impacts of Electricity Generation. A Comparison of the Environmental Impacts of Hydropower with those of Other Generation Technologies.* International Energy Agency (IEA), Paris, France, 239 pp. Available at: www.ieahydro.org/reports/ST3-020613b.pdf.

Kannan, R., K.C. Leong, R. Osman, and H.K. Ho (2007). Life cycle energy, emissions and cost inventory of power generation technologies in Singapore. *Renewable and Sustainable Energy Reviews*, **11**, pp. 702-715.

Kato, S., and A. Widiyanto (1999). A life cycle assessment scheme for environmental load estimation of power generation systems with NETS evaluation method. In: *International Joint Power Generation Conference.* S.R.H. Penfield and R. McMullen (eds.). American Society of Mechanical Engineers (ASME), Burlingame, CA, USA, 25-28 July 1999, **2**, pp. 139-146.

Krewitt, W., P. Mayerhofer, R. Friedrich, A. Truckenmüller, T. Heck, A. Gressmann, F. Raptis, F. Kaspar, J. Sachau, K. Rennings, J. Diekmann, and B. Praetorius (1997). *ExternE National Implementation in Germany.* University of Stuttgart, Stuttgart, Germany, 189 pp.

Lee, R. (1998). *Estimating Externalities of Natural Gas Fuel Cycles. External Costs and Benefits of Fuel Cycles: A Study by the U.S. Department of Energy and the Commission of the European Communities.* Report No. 4, Oak Ridge National Laboratory and Resources for the Future, Oak Ridge, TN, USA, 440 pp.

Lenzen, M. (1999). Greenhouse gas analysis of solar-thermal electricity generation. *Solar Energy*, **65**(6), pp. 353-368.

Lombardi, L. (2003). Life cycle assessment comparison of technical solutions for CO_2 emissions reduction in power generation. *Energy Conversion and Management*, **44**(1), pp. 93-108.

Martin, J.A. (1997). A total fuel cycle approach to reducing greenhouse gas emissions: Solar generation technologies as greenhouse gas offsets in U.S. utility systems. *Solar Energy (Selected Proceeding of ISES 1995: Solar World Congress. Part IV)*, **59**(4-6), pp. 195-203.

Meier, P.J. (2002). *Life-Cycle Assessment of Electricity Generation Systems and Applications for Climate Change Policy Analysis.* PhD Thesis, University of Wisconsin, Madison, WI, USA, 147 pp.

Meier, P.J., and G.L. Kulcinski (2001). The Potential for fusion power to mitigate US greenhouse gas emissions. *Fusion Technology*, **39**(2), pp. 507-512.

Meier, P.J., P.P.H. Wilson, G.L. Kulcinski, and P.L. Denholm (2005). US electric industry response to carbon constraint: A life-cycle assessment of supply side alternatives. *Energy Policy*, **33**(9), pp. 1099-1108.

Norton, B., P.C. Eames, and S.N.G. Lo (1998). Full-energy-chain analysis of greenhouse gas emissions for solar thermal electric power generation systems. *Renewable Energy*, **15**(1-4), pp. 131-136.

Odeh, N.A., and T.T. Cockerill (2008). Life cycle GHG assessment of fossil fuel power plants with carbon capture and storage. *Energy Policy*, **36**(1), pp. 367-380.

Pacca, S.A. (2003). *Global Warming Effect Applied to Electricity Generation Technologies.* PhD Thesis, University of California, Berkeley, CA, USA, 191 pp.

Phumpradab, K., S.H. Gheewala, and M. Sagisaka (2009). Life cycle assessment of natural gas power plants in Thailand. *International Journal of Life Cycle Assessment*, **14**(4), pp. 354-363.

Raugei, M., S. Bargigli, and S. Ulgiati (2005). A multi-criteria life cycle assessment of molten carbonate fuel cells (MCFC) – A comparison to natural gas turbines. *International Journal of Hydrogen Energy*, **30**(2), pp. 123-130.

Riva, A., S. D'Angelosante, and C. Trebeschi (2006). Natural gas and the environmental results of life cycle assessment. *Energy*, **31**(1), pp. 138-148.

Saskatchewan Energy Conservation and Development Authority (1994). *Levelized Cost and Full Fuel Cycle Environmental Impacts of Saskatchewan's Electric Supply Options.* SECDA Publication No. T800-94-004, Saskatoon, SK, Canada, 205 pp.

SENES Consultants Limited (2005). *Methods to Assess the Impacts on the Natural Environment of Generation Options.* Prepared by SENES Consultants for the Ontario Power Authority, Richmond Hill, Ontario, Canada, 166 pp.

Spath, P.L., and M.K. Mann (2000). *Life Cycle Assessment of a Natural Gas Combined-Cycle Power Generation System.* NREL/TP-570-27715, National Renewable Energy Laboratory, Golden, CO, USA, 54 pp.

Spath, P.L., and M.K. Mann (2004). *Biomass Power and Conventional Fossil Systems with and without CO_2 Sequestration – Comparing the Energy Balance, Greenhouse Gas Emissions and Economics.* NREL/TP-510-32575. National Renewable Energy Laboratory, Golden, CO, USA, 28 pp.

Uchiyama, Y. (1996). Validity of FENCH-GHG study: Methodologies and databases. comparison of energy sources in terms of their full-energy-chain emission factors of greenhouse gases. In: *IAEA Advisory Group Meeting on Analysis of Net Energy Balance and Full-energy-chain Greenhouse Gas Emissions for Nuclear and Other Energy Systems*, Beijing, China, 4-7 Oct 1994, International Atomic Energy Agency (IAEA), pp. 85-94. Available at: www.iaea.org/inis/collection/NCLCollectionStore/_Public/28/013/28013414.pdf.

World Energy Council (2004). *Comparison of Energy Systems Using Life Cycle Assessment.* World Energy Council, London, UK, 67 pp.

Nuclear power (32)

AEA Technologies (2005). *Environmental Product Declaration of Electricity from Torness Nuclear Power Station.* British Energy, London, UK, 52 pp.

AEA Technologies (2006). *Carbon Footprint of the Nuclear Fuel Cycle.* British Energy, London, UK, 26 pp.

Andseta, S., M.J. Thompson, J.P. Jarrell, and D.R. Pendergast (1998). Candu reactors and greenhouse gas emissions. In: *Canadian Nuclear Society 19th Annual Conference.* D.B. Buss and D.A. Jenkins (eds.), Canadian Nuclear Association, Toronto, Ontario, Canada, 18-21 October 1998.

AXPO Nuclear Energy (2008). *Beznau Nuclear Power Plant.* Axpo AG, Baden, Germany, 21 pp.

Badea, A.A., I. Voda, and C.F. Dinca (2010). Comparative analysis of coal, natural gas and nuclear fuel life cycles by chains of electrical energy production. *UPB Scientific Bulletin, Series C: Electrical Engineering*, **72**(2), pp. 221-238.

Beerten, J., E. Laes, G. Meskens, and W. D'haeseleer (2009). Greenhouse gas emissions in the nuclear life cycle: A balanced appraisal. *Energy Policy*, **37**(12), pp. 5056-5058.

Dones, R., S. Hirschberg, and I. Knoepfel (1996). Greenhouse gas emission inventory based on full energy chain analysis. In: *IAEA Advisory Group Meeting on Analysis of Net Energy Balance and Full-energy-chain Greenhouse Gas Emissions for Nuclear and Other Energy Systems.* Beijing, China, 4-7 October 1994, pp. 95-114. Available at: www.iaea.org/inis/collection/NCLCollectionStore/_Public/28/013/28013414.pdf.

Dones, R., X. Zhou, and C. Tian (2004). Life cycle assessment (LCA) of Chinese energy chains for Shandong electricity scenarios. *International Journal of Global Energy Issues*, **22**(2/3/4), pp. 199-224.

Dones, R., T. Heck, C. Bauer, S. Hirschberg, P. Bickel, P. Preiss, L.I. Panis, and I. De Vlieger (2005). *Externalities of Energy: Extension of Accounting Framework and Policy Applications: New Energy Technologies.* ENG1-CT-2002-00609, Paul Scherrer Institute (PSI), Villigen, Switzerland, 76 pp.

Dones, R., C. Bauer, R. Bolliger, B. Burger, T. Heck, A. Roder, M.F. Emenegger, R. Frischknecht, N. Jungbluth, and M. Tuchschmid (2007). *Life Cycle Inventories of Energy Systems: Results for Current Systems in Switzerland and Other UCTE Countries.* Ecoinvent Report No. 5, Paul Scherrer Institute, Swiss Centre for Life Cycle Inventories, Villigen, Switzerland, 185 pp. Available at: www.ecolo.org/documents/documents_in_english/Life-cycle-analysis-PSI-05.pdf.

Dones, R., C. Bauer, and T. Heck (2007). *LCA of Current Coal, Gas and Nuclear Electricity Systems and Electricity Mix in the USA.* Paul Scherrer Institute, Villigen, Switzerland, 4 pp.

Frischknecht, R. (1998). *Life Cycle Inventory Analysis for Decision-Making: Scope-Dependent Inventory System Models and Context-Specific Joint Product Allocation.* Dissertation, Swiss Federal Institute of Technology Zurich, Zurich, Switzerland, 256 pp.

Fthenakis, V.M., and H.C. Kim (2007). Greenhouse-gas emissions from solar electric- and nuclear power: A life-cycle study. *Energy Policy*, **35**(4), pp. 2549-2557.

Hondo, H. (2005). Life cycle GHG emission analysis of power generation systems: Japanese case. *Energy*, **30**(11-12), pp. 2042-2056.

Kivisto, A. (1995). Energy payback period and carbon dioxide emissions in different power generation methods in Finland. In: *IAEE International Conference.* International Association for Energy Economics, Washington, D.C., 5-8 July 1995, pp. 191-198.

Krewitt, W., P. Mayerhofer, R. Friedrich, A. Truckenmüller, T. Heck, A. Gressmann, F. Raptis, F. Kaspar, J. Sachau, K. Rennings, J. Diekmann, and B. Praetorius (1997). *ExternE National Implementation in Germany.* University of Stuttgart, Stuttgart, Germany, 189 pp.

Lecointe, C., D. Lecarpentier, V. Maupu, D. Le Boulch, and R. Richard (2007). *Final Report on Technical Data, Costs and Life Cycle Inventories of Nuclear Power Plants.* D14.2 – RS 1a, New Energy Externalities Developments for Sustainability (NEEDS), Rome, Italy, 62 pp. Available at: www.needs-project.org/RS1a/RS1a%20D14.2%20Final%20report%20on%20nuclear.pdf.

Lenzen, M., C. Dey, C. Hardy, and M. Bilek (2006). *Life-cycle Energy Balance and Greenhouse Gas Emissions of Nuclear Energy in Australia.* ISA, University of Sydney, Sydney, Australia, 180 pp.

Meridian Corporation (1989). *Energy System Emissions and Materiel Requirements.* Meridian Corporation, Alexandria, VA, USA, 34 pp.

Rashad, S.M., and F.H. Hammad (2000). Nuclear power and the environment: Comparative assessment of environmental and health impacts of electricity-generating systems. *Applied Energy*, **65**(1-4), pp. 211-229.

San Martin, R.L. (1989). *Environmental Emissions from Energy Technology Systems: The Total Fuel Cycle.* U.S. Department of Energy, Washington, DC, USA, 21 pp.

Saskatchewan Energy Conservation and Development Authority (1994). *Levelized Cost and Full Fuel Cycle Environmental Impacts of Saskatchewan's Electric Supply Options.* SECDA Publication No. T800-94-004, Saskatoon, SK, Canada, 205 pp.

Tokimatsu, K., T. Asami, Y. Kaya, T. Kosugi, and E. Williams (2006). Evaluation of lifecycle CO_2 emissions from the Japanese electric power sector in the 21st century under various nuclear scenarios. *Energy Policy*, **34**(7), pp. 833-852.

Uchiyama, Y. (1996). Validity of FENCH-GHG study: Methodologies and databases. comparison of energy sources in terms of their full-energy-chain emission factors of greenhouse gases. In: *IAEA Advisory Group Meeting on Analysis of Net Energy Balance and Full-energy-chain Greenhouse Gas Emissions for Nuclear and Other Energy Systems*, Beijing, China, 4-7 Oct 1994, International Atomic Energy Agency (IAEA), pp. 85-94. Available at: www.iaea.org/inis/collection/NCLCollectionStore/_Public/28/013/28013414.pdf.

Uchiyama, Y. (1996). Life cycle analysis of electricity generation and supply systems: Net energy analysis and greenhouse gas emissions. In: *Electricity, Health and the Environment: Comparative Assessment in Support of Decision Making*, International Atomic Energy Agency (IAEA), Vienna, Austria, 16-19 October 1995, pp. 279-291.

Vattenfall (2007). *Summary of Vattenfall AB Generation Nordic Certified Environmental Product Declaration, EPD® of Electricity from Ringhals Nuclear Power Plant.* S-P-00026 2007-11-01, Vattenfall, Stockholm, Sweden, 4 pp.

Vattenfall (2007). *Vattenfall AB Generation Nordic Certified Environmental Product Declaration, EPD, of Electricity from Forsmark Nuclear Power Plant.* Report No. S-P-00088, Vattenfall, Stockholm, Sweden, 59 pp.

Voorspools, K.R., E.A. Brouwers, and W.D. D'Haeseleer (2000). Energy content and indirect greenhouse gas emissions embedded in 'emission-free' power plants: Results for the low countries. *Applied Energy*, **67**(3), pp. 307-330.

White, S.W., and G.L. Kulcinski (1999). *'Birth to Death' Analysis of the Energy Payback Ratio and CO_2 Gas Emission Rates from Coal, Fission, Wind, and DT Fusion Power Plants.* University of Wisconsin, Madison, WI, USA, 17 pp.

Wibberley, L. (2001). *Coal in a Sustainable Society.* Australian Coal Association Research Program, Brisbane, Queensland, Australia.

Yasukawa, S., Y. Tadokoro, and T. Kajiyama (1992). Life cycle CO_2 emission from nuclear power reactor and fuel cycle system. In: *Expert Workshop on Life-cycle Analysis of Energy Systems, Methods and Experience.* Paris, France, 21-22 May 1992, pp. 151-160.

Yasukawa, S., Y. Tadokoro, O. Sato, and M. Yamaguchi (1996). Integration of indirect CO_2 emissions from the full energy chain. In: *IAEA Advisory Group Meeting on Analysis of Net Energy Balance and Full-energy-chain Greenhouse Gas Emissions for Nuclear and Other Energy Systems.* Beijing, China, pp. 139-150. Available at: www.iaea.org/inis/collection/NCLCollectionStore/_Public/28/ 013/28013414.pdf.

Ocean energy (5)

Parker, R.P.M., G.P. Harrison, and J.P. Chick (2008). Energy and carbon audit of an offshore wave energy converter. *Proceedings of the Institution of Mechanical Engineers, Part A: Journal of Power and Energy*, **221**(8), pp. 1119-1130.

Rule, B.M., Z.J. Worth, and C.A. Boyle (2009). Comparison of life cycle carbon dioxide emissions and embodied energy in four renewable electricity generation technologies in New Zealand. *Environmental Science & Technology*, **43**(16), pp. 6406-6413.

Sorensen, H.C., and S. Naef (2008). *Report on Technical Specification of Reference Technologies (Wave and Tidal Power Plant).* New Energy Externalities Developments for Sustainability (NEEDS), Rome, Italy and SPOK Consult, Kopenhagen, Denmark, 59 pp.

Wibberley, L. (2001). *Coal in a Sustainable Society.* Australian Coal Association Research Program, Brisbane, Queensland, Australia.

Woollcombe-Adams, C., M. Watson, and T. Shaw (2009). Severn Barrage tidal power project: Implications for carbon emissions. *Water and Environment Journal*, **23**(1), pp. 63-68.

Oil-fired power generation (10)

Bates, J.L. (1995). *Full Fuel Cycle Atmospheric Emissions and Global Warming Impacts from UK Electricity Generation.* ETSU, London, UK, 51 pp.

Berry, J.E., M.R. Holland, P.R. Watkiss, R. Boyd, and W. Stephenson (1998). *Power Generation and the Environment: a UK Perspective.* AEA Technology, Oxfordshire, UK, 275 pp.

Dones, R., S. Hirschberg, and I. Knoepfel (1996). Greenhouse gas emission inventory based on full energy chain analysis. In: *IAEA Advisory Group Meeting on Analysis of Net Energy Balance and Full-energy-chain Greenhouse Gas Emissions for Nuclear and Other Energy Systems.* Beijing, China, 4-7 October 1994, pp. 95-114. Available at: www.iaea.org/inis/collection/NCLCollectionStore/_Public/28/013/28013414.pdf.

Dones, R., U. Ganter, and S. Hirschberg (1999). Environmental inventories for future electricity supply systems for Switzerland. *International Journal of Global Energy Issues*, **12**(1-6), pp. 271-282.

Dones, R., T. Heck, C. Bauer, S. Hirschberg, P. Bickel, P. Preiss, L.I. Panis, and I. De Vlieger (2005). *Externalities of Energy: Extension of Accounting Framework and Policy Applications: New Energy Technologies.* ENG1-CT-2002-00609, Paul Scherrer Institute (PSI), Villigen, Switzerland, 76 pp.

Dones, R., C. Bauer, R. Bolliger, B. Burger, T. Heck, A. Roder, M.F. Emenegger, R. Frischknecht, N. Jungbluth, and M. Tuchschmid (2007). *Life Cycle Inventories of Energy Systems: Results for Current Systems in Switzerland and Other UCTE Countries.* Ecoinvent Report No. 5, Paul Scherrer Institute, Swiss Centre for Life Cycle Inventories, Villigen, Switzerland, 185 pp. Available at: www.ecolo.org/documents/documents_in_english/Life-cycle-analysis-PSI-05.pdf.

European Commission (1995). Oil & Gas. *ExternE: Externalities of Energy.* European Commission, Directorate-General XII, Luxembourg, **4**, 470 pp.

Gagnon, L., C. Belanger, and Y. Uchiyama (2002). Life-cycle assessment of electricity generation options: The status of research in year 2001. *Energy Policy*, **30**, pp. 1267-1279.

Hondo, H. (2005). Life cycle GHG emission analysis of power generation systems: Japanese case. *Energy*, **30**(11-12), pp. 2042-2056.

Kannan, R., C.P. Tso, R. Osman, and H.K. Ho (2004). LCA-LCCA of oil fired steam turbine power plant in Singapore. *Energy Conversion and Management*, **45**, pp. 3091-3107.

Solar photovoltaic (26)

Alsema, E.A. (2000). Energy pay-back time and CO_2 emissions of PV systems. *Progress in Photovoltaics*, **8**(1), pp. 17-25.

Alsema, E.A., and M.J. de Wild-Scholten (2006). Environmental Impacts of Crystalline Silicon Photovoltaic Module Production. In: *13th CIRP International Conference on Life Cycle Engineering*, Leuven, Belgium, 31 May - 2 Jun, 2006. Available at: www.mech.kuleuven.be/lce2006/Registration_papers.htm.

Dones, R., T. Heck, and S. Hirschberg (2004). Greenhouse gas emissions from energy systems, comparison and overview. *Encyclopedia of Energy*, **3**, pp. 77-95.

Frankl, P., E. Menichetti, M. Raugei, S. Lombardelli, and G. Prennushi (2005). *Final Report on Technical Data, Costs and Life Cycle Inventories of PV Applications.* Ambiente Italia, Milan, Italy, 81 pp.

Fthenakis, V.M., and E. Alsema (2006). Photovoltaics energy payback times, greenhouse gas emissions and external costs: 2004 - early 2005 status. *Progress in Photovoltaics: Research and Applications*, **14**(3), pp. 275-280.

Fthenakis, V., and H.C. Kim (2006). Energy use and greenhouse gas emissions in the life cycle of CdTe photovoltaics. In: *Life-Cycle Analysis Tools for "Green" Materials and Process Selection, Materials Research Society Symposium 2006.* S. Papasavva and V.M.P.O. Fthenakis (eds.), Materials Research Society, Boston, MA, 28-30 November 2005, **895**, pp. 83-88.

Fthenakis, V.M., and H.C. Kim (2007). Greenhouse-gas emissions from solar electric- and nuclear power: A life-cycle study. *Energy Policy*, **35**(4), pp. 2549-2557.

Garcia-Valverde, R., C. Miguel, R. Martinez-Bejar, and A. Urbina (2009). Life cycle assessment study of a 4.2 kW(p) stand-alone photovoltaic system. *Solar Energy*, **83**(9), pp. 1434-1445.

Graebig, M., S. Bringezu, and R. Fenner (2010). Comparative analysis of environmental impacts of maize-biogas and photovoltaics on a land use basis. *Solar Energy*, **84**(7), pp. 1255-1263.

Greijer, H., L. Karlson, S.E. Lindquist, and A. Hagfeldt (2001). Environmental aspects of electricity generation from a nanocrystalline dye sensitized solar cell system. *Renewable Energy*, **23**(1), pp. 27-39.

Hayami, H., M. Nakamura, and K. Yoshioka (2005). The life cycle CO_2 emission performance of the DOE/NASA solar power satellite system: a comparison of alternative power generation systems in Japan. *IEEE Transactions on Systems, Man, and Cybernetics, Part C: Applications and Reviews*, **35**(3), pp. 391-400.

Hondo, H. (2005). Life cycle GHG emission analysis of power generation systems: Japanese case. *Energy*, **30**(11-12), pp. 2042-2056.

Ito, M., K. Kato, K. Komoto, T. Kichimi, H. Sugihara, and K. Kurokawa (2003). An analysis of variation of very large-scale PV (VLS-PV) systems in the world deserts. In: *3rd World Conference on Photovoltaic Energy Conversion (WCPEC).* WCPEC, Osaka, Japan, 11-18 May 2003, **C**, pp. 2809-2814.

Kannan, R., K.C. Leong, R. Osman, H.K. Ho, and C.P. Tso (2006). Life cycle assessment study of solar PV systems: An example of a 2.7 kWp distributed solar PV System in Singapore. *Solar Energy*, **80**(5), pp. 555-563.

Lenzen, M., C. Dey, C. Hardy, and M. Bilek (2006). *Life-cycle Energy Balance and Greenhouse Gas Emissions of Nuclear Energy in Australia.* ISA, University of Sydney, Sydney, Australia, 180 pp.

Muneer, T., S. Younes, P. Clarke, and J. Kubie (2006). *Napier University's School of Engineering Life Cycle Assessment of a Medium Sized PV Facility in Edinburgh. EuroSun.* ES06-T10-0171, The Solar Energy Society, Glasgow, 157 pp.

Pacca, S.A. (2003). *Global Warming Effect Applied to Electricity Generation Technologies.* PhD Thesis, University of California, Berkeley, CA, USA, 191 pp.

Pehnt, M. (2006). Dynamic life cycle assessment (LCA) of renewable energy technologies. *Renewable Energy*, **31**(1), pp. 55-71.

Pehnt, M., A. Bubenzer, and A. Rauber (2002). Life cycle assessment of photovoltaic systems–Trying to fight deep-seated prejudices. In: *Photovoltaics Guidebook for Decision Makers.* A. Bubenzer and J. Luther (eds.), Springer, Berlin, Germany, pp. 179-213.

Reich-Weiser, C. (2010). *Decision-Making to Reduce Manufacturing Greenhouse Gas Emissions.* PhD Thesis, University of California, Berkeley, CA, USA, 101 pp.

Reich-Weiser, C., T. Fletcher, D.A. Dornfeld, and S. Horne (2008). Development of the Supply Chain Optimization and Planning for the Environment (SCOPE) tool - Applied to solar energy. In: *2008 IEEE International Symposium on Electronics and the Environment.* IEEE, San Francisco, CA, 19-21 May 2008, 6 pp.

Sengul, H. (2009). *Life Cycle Analysis of Quantum Dot Semiconductor Materials.* PhD Thesis, University of Illinois, Chicago, IL, USA, 255 pp.

Stoppato, A. (2008). Life cycle assessment of photovoltaic electricity generation. *Energy*, **33**(2), pp. 224-232.

Tripanagnostopoulos, Y., M. Souliotis, R. Battisti, and A. Corrado (2006). Performance, cost and life-cycle assessment study of hybrid PVT/AIR solar systems. *Progress in Photovoltaics: Research and Applications*, **14**(1), pp. 65-76.

Uchiyama, Y. (1997). Life cycle analysis of photovoltaic cell and wind power plants. In: *IAEA Advisory Group Meeting on the Assessment of Greenhouse Gas Emissions from the Full Energy Chain of Solar and Wind Power*, International Atomic Energy Agency, Vienna, Austria, 21-24 October 1996, pp. 111-122.

Voorspools, K.R., E.A. Brouwers, and W.D. D'Haeseleer (2000). Energy content and indirect greenhouse gas emissions embedded in 'emission-free' power plants: Results for the low countries. *Applied Energy*, **67**(3), pp. 307-330.

Wind energy (49)

Ardente, F., M. Beccali, M. Cellura, and V. Lo Brano (2008). Energy performances and life cycle assessment of an Italian wind farm. *Renewable & Sustainable Energy Reviews*, **12**(1), pp. 200-217.

Berry, J.E., M.R. Holland, P.R. Watkiss, R. Boyd, and W. Stephenson (1998). *Power Generation and the Environment: a UK Perspective.* AEA Technology, Oxfordshire, UK, 275 pp.

Chataignere, A., and D. Le Boulch (2003). *Wind Turbine (WT) Systems: Final Report.* Energy de France (EDF R&D), Paris, France, 110 pp.

Crawford, R.H. (2009). Life cycle energy and greenhouse emissions analysis of wind turbines and the effect of size on energy yield. *Renewable and Sustainable Energy Reviews*, **13**(9), pp. 2653-2660.

Dolan, S.L. (2007). *Life Cycle Assessment and Emergy Synthesis of a Theoretical Offshore Wind Farm for Jacksonville, Florida.* M.S. Thesis, University of Florida, 125 pp. Available at: http://etd.fcla.edu/UF/UFE0021032/dolan_s.pdf.

Dones, R., T. Heck, C. Bauer, S. Hirschberg, P. Bickel, P. Preiss, L.I. Panis, and I. De Vlieger (2005). *Externalities of Energy: Extension of Accounting Framework and Policy Applications: New Energy Technologies.* ENG1-CT-2002-00609, Paul Scherrer Institute (PSI), Villigen, Switzerland, 76 pp.

Dones, R., C. Bauer, R. Bolliger, B. Burger, T. Heck, A. Roder, M.F. Emenegger, R. Frischknecht, N. Jungbluth, and M. Tuchschmid (2007). *Life Cycle Inventories of Energy Systems: Results for Current Systems in Switzerland and Other UCTE Countries.* Ecoinvent Report No. 5, Paul Scherrer Institute, Swiss Centre for Life Cycle Inventories, Villigen, Switzerland, 185 pp. Available at: www.ecolo.org/documents/documents_in_english/Life-cycle-analysis-PSI-05.pdf.

DONG Energy (2008). *Life Cycle Approaches to Assess Emerging Energy Technologies: Final Report on Offshore Wind Technology.* DONG Energy, Fredericia, Denmark, 60 pp.

Enel SpA (2004). *Certified Environmental Product Declaration of Electricity from Enel's Wind Plant in Sclafani Bagni (Palermo, Italy).* Enel SpA, Rome, Italy, 25 pp.

European Commission (1995). Wind & Hydro. *ExternE: Externalities of Energy.* European Commission, Directorate-General XII, Luxembourg, **6**, 295 pp.

Frischknecht, R. (1998). *Life Cycle Inventory Analysis for Decision-Making: Scope-Dependent Inventory System Models and Context-Specific Joint Product Allocation.* Dissertation, Swiss Federal Institute of Technology Zurich, Zurich, Switzerland, 256 pp.

Hartmann, D. (1997). FENCH-analysis of electricity generation greenhouse gas emissions from solar and wind power in Germany. In: *IAEA Advisory Group Meeting on Assessment of Greenhouse Gas Emissions from the Full Energy Chain of Solar and Wind Power.* IAEA, Vienna, Austria, 21-24 October 1996, pp. 77-87.

Hondo, H. (2005). Life cycle GHG emission analysis of power generation systems: Japanese case. *Energy*, **30**(11-12), pp. 2042-2056.

Jacobson, M.Z. (2009). Review of solutions to global warming, air pollution, and energy security. *Energy & Environmental Science*, **2**, pp. 148-173.

Jungbluth, N., C. Bauer, R. Dones, and R. Frischknecht (2005). Life cycle assessment for emerging technologies: Case studies for photovoltaic and wind power. *International Journal of Life Cycle Assessment*, **10**(1), pp. 24-34.

Khan, F.I., K. Hawboldt, and M.T. Iqbal (2005). Life cycle analysis of wind-fuel cell integrated system. *Renewable Energy*, **30**(2), pp. 157-177.

Krewitt, W., P. Mayerhofer, R. Friedrich, A. Truckenmüller, T. Heck, A. Gressmann, F. Raptis, F. Kaspar, J. Sachau, K. Rennings, J. Diekmann, and B. Praetorius (1997). *ExternE National Implementation in Germany.* University of Stuttgart, Stuttgart, Germany, 189 pp.

Kuemmel, B., and B. Sørensen (1997). *Life-cycle Analysis of the Total Danish Energy System.* IMFUFA, Roskilde Universitetscenter, Roskilde, Denmark, 219 pp.

Lee, Y.-M., and Y.-E. Tzeng (2008). Development and life-cycle inventory analysis of wind energy in Taiwan. *Journal of Energy Engineering*, **134**(2), pp. 53-57.

Lenzen, M., and U. Wachsmann (2004). Wind turbines in Brazil and Germany: An example of geographical variability in life-cycle assessment. *Applied Energy*, **77**(2), pp. 119-130.

Liberman, E.J. (2003). *A Life Cycle Assessment and Economic Analysis of Wind Turbines Using Monte Carlo Simulation.* M.S. Thesis, Air Force Institute of Technology, Wright-Patterson Air Force Base, OH, USA, 162 pp.

Martínez, E., F. Sanz, S. Pellegrini, E. Jiménez, and J. Blanco (2009). Life-cycle assessment of a 2-MW rated power wind turbine: CML method. *The International Journal of Life Cycle Assessment*, **14**(1), pp. 52-63.

McCulloch, M., M. Raynolds, and M. Laurie (2000). *Life-Cycle Value Assessment of a Wind Turbine.* The Pembina Institute, Drayton Valley, Alberta, Canada, 14 pp.

Nadal, G. (1995). Life cycle direct and indirect pollution associated with PV and wind energy systems. In: *ISES 1995: Solar World Congress.* Fundacion Bariloche, Harare, Zimbabwe, 11-15 September 1995, pp. 39

Pacca, S.A. (2003). *Global Warming Effect Applied to Electricity Generation Technologies.* PhD Thesis, University of California, Berkeley, CA, USA, 191 pp.

Pacca, S.A., and A. Horvath (2002). Greenhouse gas emissions from building and operating electric power plants in the upper Colorado River Basin. *Environmental Science & Technology*, **36**(14), pp. 3194-3200.

Pehnt, M. (2006). Dynamic life cycle assessment (LCA) of renewable energy technologies. *Renewable Energy*, **31**(1), pp. 55-71.

Pehnt, M., M. Oeser, and D.J. Swider (2008). Consequential environmental system analysis of expected offshore wind electricity production in Germany. *Energy*, **33**(5), pp. 747-759.

Proops, J.L.R., P.W. Gay, S. Speck, and T. Schröder (1996). The lifetime pollution implications of various types of electricity generation. An input-output analysis. *Energy Policy*, **24**(3), pp. 229-237.

Rule, B.M., Z.J. Worth, and C.A. Boyle (2009). Comparison of life cycle carbon dioxide emissions and embodied energy in four renewable electricity generation technologies in New Zealand. *Environmental Science & Technology*, **43**(16), pp. 6406-6413.

Rydh, J., M. Jonsson, and P. Lindahl (2004). *Replacement of Old Wind Turbines Assessed from Energy, Environmental and Economic Perspectives.* University of Kalmar, Department of Technology, Kalmar, Sweden, 33 pp.

Saskatchewan Energy Conservation and Development Authority (1994). *Levelized Cost and Full Fuel Cycle Environmental Impacts of Saskatchewan's Electric Supply Options.* SECDA Publication No. T800-94-004, Saskatoon, SK, Canada, 205 pp.

Schleisner, L. (2000). Life cycle assessment of a wind farm and related externalities. *Renewable Energy*, **20**(3), pp. 279-288.

Spitzley, D.V., and G.A. Keoleian (2005). *Life Cycle Environmental and Economic Assessment of Willow Biomass Electricity: A Comparison with Other Renewable and Non-renewable Sources.* Report No. CSS04-05R, University of Michigan, Center for Sustainable Systems, Ann Arbor, MI, USA, 69 pp.

Tremeac, B., and F. Meunier (2009). Life cycle analysis of 4.5 MW and 250 W wind turbines. *Renewable and Sustainable Energy Reviews*, **13**(8), pp. 2104-2110.

Uchiyama, Y. (1997). Life cycle analysis of photovoltaic cell and wind power plants. In: *IAEA Advisory Group Meeting on the Assessment of Greenhouse Gas Emissions from the Full Energy Chain of Solar and Wind Power*, International Atomic Energy Agency, Vienna, Austria, 21-24 October 1996, pp. 111-122.

van de Vate, J.F. (1996). Comparison of the greenhouse gas emissions from the full energy chains of solar and wind power generation. In: *IAEA Advisory Group Meeting organized by the IAEA Headquarters.* IAEA, Vienna, Austria, 21-24 October 1996, pp. 13.

Vattenfall AB (2003). *Certified Environmental Product Declaration of Electricity from Vattenfall AB's Swedish Windpower Plants.* Vattenfall, Stockholm, Sweden, 31 pp.

Vattenfall AB (2010). *Vattenfall Wind Power Certified Environmental Product Declaration EPD of Electricity from Vattenfall's Wind Farms.* Vattenfall Wind Power, Stockholm, Sweden, 51 pp.

Vestas Wind Systems A/S (2006). *Life Cycle Assessment of Electricity Produced from Onshore Sited Wind Power Plants Based on Vestas V82-1.65 MW turbines.* Vestas, Randers, Denmark, 77 pp.

Vestas Wind Systems A/S (2006). *Life Cycle Assessment of Offshore and Onshore Sited Wind Power Plants Based on Vestas V90-3.0 MW Turbines.* Vestas, Randers, Denmark, 60 pp.

Voorspools, K.R., E.A. Brouwers, and W.D. D'Haeseleer (2000). Energy content and indirect greenhouse gas emissions embedded in 'emission-free' power plants: Results for the low countries. *Applied Energy*, **67**(3), pp. 307-330.

Waters, T.M., R. Forrest, and D.C. McConnell (1997). Life-cycle assessment of wind energy: A case study based on Baix Ebre Windfarm, Spain. In: *Wind Energy Conversion 1997: Proceedings of the Nineteenth BWEA Wind Energy Conference*, R. Hunter (ed.), Mechanical Engineering Publications Limited, Heriot-Watt University, Edinburgh, UK, 16-18 July 1997, pp. 231-238.

Weinzettel, J., M. Reenaas, C. Solli, and E.G. Hertwich (2009). Life cycle assessment of a floating offshore wind turbine. *Renewable Energy*, **34**(3), pp. 742-747.

White, S. (2006). Net energy payback and CO_2 emissions from three Midwestern wind farms: An update. *Natural Resources Research*, **15**(4), pp. 271-281.

White, S.W., and G.L. Kulcinski (1998). *Net Energy Payback and CO_2 Emissions from Wind-Generated Electricity in the Midwest.* UWFDM-1092, University of Wisconsin, Madison, WI, USA, 72 pp.

White, S.W., and G.L. Kulcinski (1999). *'Birth to Death' Analysis of the Energy Payback Ratio and CO_2 Gas Emission Rates from Coal, Fission, Wind, and DT Fusion Power Plants.* University of Wisconsin, Madison, WI, USA, 17 pp.

Wibberley, L. (2001). *Coal in a Sustainable Society.* Australian Coal Association Research Program, Brisbane, Queensland, Australia.

World Energy Council (2004). *Comparison of Energy Systems Using Life Cycle Assessment.* World Energy Council, London, UK, 67 pp.

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.

A.II.5.3.2 List of references

CEC (2008). *2007 Environmental Performance Report of California's Electrical Generation System.* California Energy Commission (CEC) Final Staff Report, CA, USA.

Cohen, G., D.W. Kearney, C. Drive, D. Mar, and G.J. Kolb (1999). *Final Report on the Operation and Maintenance Improvement Program for Concentrating Solar Plants.* Sandia National Laboratories Technical Report-SAND99-1290, doi:10.2172/8378, Albuquerque, NM, USA.

Dziegielewski, B., and T. Bik (2006). *Water Use Benchmarks for Thermoelectric Power Generation.* Research Report of the Department of Geography and Environmental Resources, Southern Illinois University, Carbondale, IL, USA.

EPRI (2002). *Water and sustainability (Volume 2): an assessment of water demand, supply, and quality in the U.S.-the next half century.* Technical Report 1006785, Electric Power Research Institute (EPRI). Palo Alto, CA, USA.

EPRI and US DOE (1997). *Renewable Energy Technology Characterizations.* EPRI Topical Report-109496, Electric Power Research Institute (EPRI) and U.S. Department of Energy (US DOE), Palo Alto, CA and Washington, DC, USA.

Feeley, T.J., L. Green, J.T. Murphy, J. Hoffmann, and B.A. Carney (2005). *Department of Energy / Office of Fossil Energy's Power Plant Water Management R & D Program.* National Energy Technology Laboratory, Pittsburgh, PA, USA, 18 pp. Available at: www.netl.doe.gov/technologies/coalpower/ewr/pubs/IEP_Power_Plant_Water_R%26D_Final_1.pdf.

Feeley, T.J., T.J. Skone, G.J. Stiegel, A. Mcnemar, M. Nemeth, B. Schimmoller, J.T. Murphy, and L. Manfredo (2008). Water: A critical resource in the thermoelectric power industry. *Energy*, **33**, pp. 1-11.

Fthenakis, V., and H.C. Kim (2010). Life-cycle uses of water in U.S. electricity generation. *Renewable and Sustainable Energy Reviews*, **14**, pp. 2039-2048.

Gleick, P. (1992). Environmental consequences of hydroelectric development: The role of facility size and type. *Energy*, **17**(8), pp. 735-747.

Gleick, P. (1993). *Water in Crisis: A Guide to the World's Fresh Water Resources.* Oxford University Press, New York, NY, USA.

Hoffmann, J., S. Forbes, and T. Feeley (2004). *Estimating Freshwater Needs to Meet 2025 Electricity Generating Capacity Forecasts.* National Energy Technology Laboratory Pittsburgh, PA, USA, 12 pp. Available at: www.netl.doe.gov/technologies /coalpower/ewr/pubs/Estimating%20Freshwater%20Needs%20to%20 2025.pdf.

Inhaber, H. (2004). Water use in renewable and conventional electricity production. *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects*, **26**, pp. 309-322, doi:10.1080/00908310490266698.

Kelly, B. (2006). *Nexant Parabolic Trough Solar Power Plant Systems Analysis-Task 2: Comparison of Wet and Dry Rankine Cycle Heat Rejection.* Subcontractor Report-NREL/SR-550-40163, National Renewable Energy Laboratory (NREL), Golden, CO, USA. Available at: www.nrel.gov/csp/troughnet/pdfs/40163.pdf.

Leitner, A. (2002). *Fuel from the Sky: Solar Power's Potential for Western Energy Supply.* Subcontractor Report-NREL/SR 550-32160, National Renewable Energy Laboratory (NREL), Golden, CO, USA. Available at: www.nrel.gov/csp/pdfs/32160.pdf.

Mann, M., and P. Spath (1997). *Life Cycle Assessment of a Biomass Gasification Combined-Cycle System.* Technical Report-TP-430-23076, National Renewable Energy Laboratory (NREL), Golden, CO, USA. Available at: www.nrel.gov/docs/legosti/fy98/23076.pdf.

Meridian (1989). *Energy System Emissions and Material Requirements.* Meridian Corporation Report to U.S. Department of Energy (DOE), Washington, DC, USA.

NETL (2007). *Cost and Performance Baseline for Fossil Energy Plants-Volume 1: Bituminous Coal and Natural Gas to Electricity Final Report.* DOE/NETL-2007/1281, National Energy Technology Laboratory (NETL), Pittsburgh, PA, USA. Available at www.netl.doe.gov/energy-analyses/pubs/BitBase_FinRep_2007.pdf.

NETL (2007). *Power Plant Water Usage and Loss Study. 2007 Update.* National Energy Technology Laboratory (NETL), Pittsburgh, PA, USA. Available at: www.netl.doe.gov/technologies/coalpower/gasification/pubs/pdf/WaterReport_Revised%20May2007.pdf.

NETL (2009). *Estimating Freshwater Needs to Meet Future Thermoelectric Generation Requirements.* DOE/NETL-400/2009/1339, National Energy Technology Laboratory (NETL), Pittsburgh, PA, USA. Available at: www.netl.doe.gov/energy-analyses/pubs/2009%20Water%20Needs%20Analysis%20-%20Final%20%289-30-2009%29.pdf.

NETL (2009). *Existing Plants, Emissions and Capture – Setting Water-Energy R&D Program Goals.* DOE/NETL-2009/1372, National Energy Technology Laboratory (NETL), Pittsburgh, PA, USA. Available at: www.netl.doe.gov/technologies/coalpower/ewr/water/pdfs/EPEC%20water-energy%20R%26D%20goal%20update%20v.1%20may09.pdf.

Sargent & Lundy (2003). *Assessment of Parabolic Trough and Power Tower Solar Technology Cost and Performance Forecasts.* NREL/SR-550-34440, National Renewable Energy Laboratory (NREL), Golden, CO, USA. Available at: www.nrel.gov/docs/fy04osti/34440.pdf.

Stoddard, L., J. Abiecunas, and R.O. Connell (2006). *Economic, Energy, and Environmental Benefits of Concentrating Solar Power in California.* NREL/SR-550-39291, National Renewable Energy Laboratory (NREL), Golden, CO, USA. Available at: www.nrel.gov/docs/fy06osti/39291.pdf.

Torcellini, P., N. Long, and R. Judkoff (2003). *Consumptive Water Use for U.S. Power Production.* Technical Report-TP-550-33905, National Renewable Energy Laboratory (NREL), Golden, CO, USA. Available at: www.nrel.gov/docs/fy04osti/33905.pdf.

Turchi, C., M. Wagner, and C. Kutscher (2010). *Water Use in Parabolic Trough Power Plants: Summary Results from WorleyParsons' Analyses.* NREL/TP-5500-49468, National Renewable Energy Laboratory (NREL), Golden, CO, USA. Available at: www.nrel.gov/docs/fy11osti/49468.pdf.

US DOE (2009). *Concentrating Solar Power Commercial Application Study: Reducing Water Consumption of Concentrating Solar Power Electricity Generation.* Report to Congress. U.S. Department of Energy (DOE), Washington, DC, USA.

Viebahn, P., S. Kronshage, F. Trieb, and Y. Lechon (2008). *Final Report on Technical Data, Costs, and Life Cycle Inventories of Solar Thermal Power Plants.* Project 502687, New Energy Externalities Developments for Sustainability (NEEDS), Brussels, Belgium, 95 pp. Available at: www.needs-project.org/RS1a/RS1a%20D12.2%20Final%20report%20concentrating%20solar%20thermal%20power%20plants.pdf.

WorleyParsons (2009). *Analysis of Wet and Dry Condensing 125 MW Parabolic Trough Power Plants.* WorleyParsons Report No. NREL-2-ME-REP-0002-R0, WorleyParsons Group, North Sydney, Australia.

WorleyParsons (2009). *Beacon Solar Energy Project Dry Cooling Evaluation.* WorleyParsons Report No. FPLS-0-LI-450-0001, WorleyParsons Group, North Sydney, Australia.

WorleyParsons (2010). *Material Input for Life Cycle Assessment Task 5 Subtask 2: O&M Schedules.* WorleyParsons Report No. NREL-0-LS-019-0005, WorleyParsons Group, North Sydney, Australia.

WorleyParsons (2010). *Parabolic Trough Reference Plant for Cost Modeling with the Solar Advisor Model.* WorleyParsons Report, WorleyParsons Group, North Sydney, Australia.

WRA (2008). *A Sustainable Path: Meeting Nevada's Water and Energy Demands.* Western Resource Advocates (WRA), Boulder, CO, USA, 43 pp. Available at: www.westernresourceadvocates.org/water/NVenergy-waterreport.pdf.

Yang, X., and B. Dziegielewski (2007). Water use by thermoelectric power plants in the United States. *Journal of the American Water Resources Association*, **43**, pp. 160-169.

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).

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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 (Burghrr, 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.

References

Aven, T., and E. Zio (2011). Some considerations on the treatment of uncertainties in risk assessment for practical decision making. *Reliability Engineering and System Safety*, **96**, pp. 64-74.

Beerten, J., E. Laes, G. Meskens, and W. D'haeseleer (2009). Greenhouse gas emissions in the nuclear life cycle: A balanced appraisal. *Energy Policy*, **37**(12), pp. 5056-5058.

BP (2009). *BP Statistical Review of World Energy.* BP, London, UK.

Burgherr, P., and S. Hirschberg (2005). *Comparative assessment of natural gas accident risks.* PSI Report No. 05-01, Paul Scherrer Institut, Villigen, Switzerland.

Burgherr, P., and S. Hirschberg (2007). Assessment of severe accident risks in the Chinese coal chain. *International Journal of Risk Assessment and Management*, **7**(8), pp. 1157-1175.

Burgherr, P., and S. Hirschberg (2008). A comparative analysis of accident risks in fossil, hydro and nuclear energy chains. *Human and Ecological Risk Assessment*, **14**(5), pp. 947 - 973.

Burgherr, P., S. Hirschberg, and E. Cazzoli (2008). *Final report on quantification of risk indicators for sustainability assessment of future electricity supply options. NEEDS Deliverable no D7.1 - Research Stream 2b. NEEDS project.* New Energy Externalities Developments for Sustainability, Brussels, Belgium.

Burgherr, P., S. Hirschberg, A. Hunt, and R.A. Ortiz (2004). *Severe accidents in the energy sector. Final Report to the European Commission of the EU 5th Framework Programme "New Elements for the Assessment of External Costs from Energy Technologies" (NewExt).* DG Research, Technological Development and Demonstration (RTD), Brussels, Belgium.

Burgherr, P., P. Eckle, S. Hirschberg, and E. Cazzoli (2011). *Final Report on Severe Accident Risks including Key Indicators.* SECURE Deliverable No. D5.7.2a. Security of Energy Considering its Uncertainty, Risk and Economic implications (SECURE), Brussels, Belgium. Available at: gabe.web.psi.ch/pdfs/secure/SECURE%20-%20Deliverable_D5-7-2%20-%20Severe%20Accident%20Risks.pdf.

Caithness Windfarm Information Forum (2010). *Summary of Wind Turbine Accident data to 30th September 2010.* Caithness Windfarm Information Forum, UK. Available at: www.caithnesswindfarms.co.uk/fullaccidents.pdf.

Chernobyl Forum (2005). *Chernobyl's legacy: health, environmental and socio-economic impacts and recommendations to the governments of Belarus, the Russian Federation and Ukraine. The Chernobyl Forum: 2003–2005.* Second revised version. International Atomic Energy Agency (IAEA), Vienna, Austria.

Colli, A., D. Serbanescu, and B.J.M. Ale (2009). Indicators to compare risk expressions, grouping, and relative ranking of risk for energy systems: Application with some accidental events from fossil fuels. *Safety Science*, **47**(5), pp. 591-607.

Dannwolf, U.S., and F. Ulmer (2009). *AP6000 Report - Technology risk comparison of the geothermal DHM project in Basel, Switzerland - Risk appraisal including social aspects.* SERIANEX Group - Trinational Seismis Risk Analysis Expert Group, RiskCom, Pforzheim, Germany.

Elahi, S. (2011). Here be dragons…exploring the 'unknown unknowns'. *Futures*, **43**(2), pp. 196-201.

Felder, F.A. (2009). A critical assessment of energy accident studies. *Energy Policy*, **37**(12), pp. 5744-5751.

Fisher, B.S., N. Nakicenovic, K. Alfsen, J. Corfee Morlot, F. de la Chesnaye, J.-C. Hourcade, K. Jiang, M. Kainuma, E. La Rovere, A. Matysek, A. Rana, K. Riahi, R. Richels, S. Rose, D. van Vuuren, and R. Warren (2007). Issues related to mitigation in the long term context. In: *Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change.* B. Metz, O.R. Davidson, P.R. Bosch, R. Dave, and L.A. Meyer (eds.), Cambridge University Press, pp. 169-250.

Frankl, P., E. Menichetti and M. Raugei (2005). *Final Report on Technical Data, Costs and Life Cycle Inventories of PV Applications.* NEEDS: New Energy Externalities Developments for Sustainability. Ambiente Italia, Milan, Italy, 81 pp.

Fthenakis, V.M., and H.C. Kim (2007). Greenhouse-gas emissions from solar electric- and nuclear power: A life-cycle study. *Energy Policy*, **35**(4), pp. 2549-2557.

Fthenakis, V.M., and H.C. Kim (2010). Life-cycle uses of water in U.S. electricity generation. *Renewable and Sustainable Energy Reviews*, **14**(7), pp. 2039-2048.

Fthenakis, V.M., H.C. Kim, A. Colli, and C. Kirchsteiger (2006). Evaluation of risks in the life cycle of photovoltaics in a comparative context. In: *21st European Photovoltaic Solar Energy Conference*, Dresden, Germany, 4-8 September 2006.

Gagnon, L. (2008). Civilisation and energy payback. *Energy Policy*, **36**, pp. 3317-3322.

Gipe, P. (2010). *Wind Energy Deaths Database - Summary of Deaths in Wind Energy.* No publisher specified. Available at: www.wind-works.org/articles/BreathLife.html.

Gleick, P. (1993). *Water in Crisis: A Guide to the World's Fresh Water Resources.* Oxford University Press, New York, NY, USA.

Gregory, R., and S. Lichtenstein (1994). A hint of risk: tradeoffs between quantitative and qualitative risk factors. *Risk Analysis*, **14**(2), pp. 199-206.

Haimes, Y.Y. (2009). On the complex definition of risk: A systems-based approach. *Risk Analysis*, **29**(12), pp. 1647-1654.

Herendeen, R.A. (1988). Net energy considerations. In: *Economic Analysis of Solar Thermal Energy Systems.* R.E. West and F. Kreith (eds.), The MIT Press, Cambridge, MA, USA, pp. 255-273.

Hirschberg, S., G. Spiekerman, and R. Dones (1998). *Severe Accidents in the Energy Sector - First Edition.* PSI Report No. 98-16. Paul Scherrer Institut, Villigen PSI, Switzerland.

Hirschberg, S., P. Burgherr, G. Spiekerman, and R. Dones (2004a). Severe accidents in the energy sector: Comparative perspective. *Journal of Hazardous Materials*, **111**(1-3), pp. 57-65.

Hirschberg, S., P. Burgherr, G. Spiekerman, E. Cazzoli, J. Vitazek, and L. Cheng (2003a). Assessment of severe accident risks. In: *Integrated Assessment of Sustainable Energy Systems in China. The China Energy Technology Program - A framework for decision support in the electric sector of Shandong province. Alliance for Global Sustainability Series Vol. 4.* Kluwer Academic Publishers, Amsterdam, The Netherlands, pp. 587-660.

Hirschberg, S., P. Burgherr, G. Spiekerman, E. Cazzoli, J. Vitazek, and L. Cheng (2003b). *Comparative Assessment of Severe Accidents in the Chinese Energy Sector.* PSI Report No. 03-04. Paul Scherrer Institut, Villigen PSI, Switzerland.

Hirschberg, S., R. Dones, T. Heck, P. Burgherr, W. Schenler, and C. Bauer (2004b). *Sustainability of Electricity Supply Technologies under German Conditions: A Comparative Evaluation.* PSI-Report No. 04-15. Paul Scherrer Institut, Villigen, Switzerland.

Huettner, D.A. (1976). Net energy analysis: an economic assessment. *Science*, **192**(4235), pp. 101-104.

IEA (2009). *World Energy Outlook 2009.* International Energy Agency, Paris, France, pp. 670-673.

IEA (2010a). *Energy Balances of Non-OECD Countries; 2010 Edition.* International Energy Agency, Paris, France.

IEA (2010b). *Key World Energy Statistics.* International Energy Agency, Paris France.

IEA/OECD/Eurostat (2005). *Energy Statistics Manual.* Organisation for Economic Co-operation and Development and International Energy Agency, Paris, France.

Inhaber, H. (2004). Water use in renewable and conventional electricity production. *Energy Sources*, **26**(3), pp. 309-322.

IPCC (1996). *Climate Change 1995: Impacts, Adaptation, and Mitigation of Climate Change - Scientific-Technical Analysis. Contribution of Working Group II to the Second Assessment Report of the Intergovernmental Panel on Climate Change.* R.T. Watson, M.C. Zinyowera, and R.H. Moss (eds.), Cambridge University Press, 879 pp.

IPCC (2000). *Special Report on Emissions Scenarios.* N. Nakicenovic and R. Swart (eds.), Cambridge University Press, 570 pp.

Jacobson, M.Z. (2009). Review of solutions to global warming, air pollution, and energy security. *Energy and Environmental Science*, **2**(2), pp. 148-173.

Jelen, F.C., and J.H. Black (1983). *Cost and Optimitization Engineering.* McGraw-Hill, New York, NY, USA, 538 pp.

Jungbluth, N., C. Bauer, R. Dones and R. Frischknecht (2005). Life cycle assessment for emerging technologies: Case studies for photovoltaic and wind power. *International Journal of Life Cycle Assessment*, **10**(1), pp. 24-34.

Kristensen, V., T. Aven, and D. Ford (2006). A new perspective on Renn and Klinke's approach to risk evaluation and management. *Reliability Engineering and System Safety*, **91**, pp. 421-432.

Kubiszewski, I., C.J. Cleveland, and P.K. Endres (2010). Meta-analysis of net energy return for wind power systems. *Renewable Energy*, **35**(1), pp. 218-225.

Leach, G. (1975). Net energy analysis - is it any use? *Energy Policy*, **3**(4), pp. 332-344.

Lenzen, M. (1999). Greenhouse gas analysis of solar-thermal electricity generation. *Solar Energy*, **65**(6), pp. 353-368.

Lenzen, M. (2008). Life cycle energy and greenhouse gas emissions of nuclear energy: A review. *Energy Conversion and Management*, **49**(8), pp. 2178-2199.

Lenzen, M., and J. Munksgaard (2002). Energy and CO_2 analyses of wind turbines – review and applications. *Renewable Energy*, **26**(3), pp. 339-362.

Lenzen, M., C. Dey, C. Hardy, and M. Bilek (2006). *Life-Cycle Energy Balance and Greenhouse Gas Emissions of Nuclear Energy in Australia.* Report to the Prime Minister's Uranium Mining, Processing and Nuclear Energy Review (UMPNER), ISA, University of Sydney, Sydney, Australia. Available at: http://www.isa.org.usyd.edu.au/publications/documents/ISA_Nuclear_Report.pdf.

Lightfoot, H.D. (2007). Understand the three different scales for measuring primary energy and avoid errors. *Energy*, **32**(8), pp. 1478-1483.

Loulou, R., M. Labriet, and A. Kanudia (2009). Deterministic and stochastic analysis of alternative climate targets under differentiated cooperation regimes. *Energy Economics*, **31**(Supplement 2), pp. S131-S143.

Macknick, J. (2009). *Energy and Carbon Dioxide Emission Data Uncertainties.* International Institute for Applied Systems Analysis (IIASA) Interim Report, IR-09-032, IIASA, Laxenburg, Austria.

Martinot, E., C. Dienst, L. Weiliang, and C. Qimin (2007). Renewable energy futures: Targets, scenarios, and pathways. *Annual Review of Environment and Resources*, **32**(1), pp. 205-239.

Morita, T., J. Robinson, A. Adegbulugbe, J. Alcamo, D. Herbert, E. Lebre la Rovere, N. Nakicenivic, H. Pitcher, P. Raskin, K. Riahi, A. Sankovski, V. Solkolov, B.d. Vries, and D. Zhou (2001). Greenhouse gas emission mitigation scenarios and implications. In: *Climate Change 2001: Mitigation; Contribution of Working Group III to the Third Assessment Report of the IPCC.* Metz, B., Davidson, O., Swart, R., and Pan, J. (eds.), Cambridge University Press, pp. 115-166.

Nakicenovic, N., A. Grubler, and A. McDonald (eds.) (1998). *Global Energy Perspectives.* Cambridge University Press.

Neely, J.G., A.E. Magit, J.T. Rich, C.C.J. Voelker, E.W. Wang, R.C. Paniello, B. Nussenbaum, and J.P. Bradley (2010). A practical guide to understanding systematic reviews and meta-analyses. *Otolaryngology-Head and Neck Surgery*, **142**, pp. 6-14.

NETL (2007a). *Cost and Performance Baseline for Fossil Energy Plants-Volume 1: Bituminous Coal and Natural Gas to Electricity Final Report.* DOE/NETL-2007/1281, National Energy Technology Laboratory, Pittsburgh, PA, USA.

NETL (2007b). *Power Plant Water Usage and Loss Study. 2007 Update.* National Energy Technology Laboratory, Pittsburgh, PA, USA. Available at: www.netl.doe.gov/technologies/coalpower/gasification/pubs/pdf/WaterReport_Revised%20May2007.pdf.

Perry, A.M., W.D. Devine, and D.B. Reister (1977). *The Energy Cost of Energy - Guidelines for Net Energy Analysis of Energy Supply Systems.* ORAU/IEA(R)-77-14, Institute for Energy Analysis, Oak Ridge Associated Universities, Oak Ridge, TN, USA, 106 pp.

Renewable UK (2010). *Offshore Windfarms Operational.* Renewable UK. Available at: www.renewable-manifesto.com/ukwed/offshore.asp.

Renn, O., A. Klinke, G. Busch, F. Beese, and G. Lammel (2001). A new tool for characterizing and managing risks. In: *Global Biogeochemical Cycles in the Climate System.* E.D. Schulze, M. Heimann, S. Harrison, E. Holland, J. Lloyd, I. Prentice, and D. Schimel (eds.), Academic Press, San Diego, CA, USA, pp. 303-316.

Roth, S., S. Hirschberg, C. Bauer, P. Burgherr, R. Dones, T. Heck, and W. Schenler (2009). Sustainability of electricity supply technology portfolio. *Annals of Nuclear Energy*, **36**, pp. 409–416.

Rotty, R.M., A.M. Perry, and D.B. Reister (1975). *Net Energy from Nuclear Power.* IEA Report, Institute for Energy Analysis, Oak Ridge Associated Universities, Oak Ridge, TN, USA.

Samson, S., J. Reneke, and M.M. Wiecek (2009). A review of different perspectives on uncertainty and risk and analternative modeling paradigm. *Reliability Engineering and System Safety*, **94**, pp. 558-567.

Sovacool, B.K. (2008a). The cost of failure: a preliminary assessment of major energy accidents, 1907–2007. *Energy Policy*, **36**, pp. 1802-1820.

Sovacool, B.K. (2008b). Valuing the greenhouse gas emissions from nuclear power: A critical survey. *Energy Policy*, **36**(8), pp. 2950-2963.

Stirling, A. (1999). Risk at a turning point? *Journal of Environmental Medicine*, **1**, pp. 119-126.

UN Statistics (2010). *Energy Balances and Electricity Profiles – Concepts and definitions.* UN Statistics, New York, NY, USA. Available at: unstats.un.org/unsd/energy/balance/concepts.htm.

Ungers, L.J., P.D. Moskowitz, T.W. Owens, A.D. Harmon, and T.M. Briggs (1982). Methodology for an occupational risk assessment: an evaluation of four processes for the fabrication of photovoltaic cells. *American Industrial Hygiene Association Journal*, **43**(2), pp. 73-79.

Voorspools, K.R., E.A. Brouwers, and W.D. D'haeseleer (2000). Energy content and indirect greenhouse gas emissions embedded in 'emission-free' plants: results from the Low Countries. *Applied Energy*, **67**, pp. 307-330.

WBGU (2000). *World in Transition: Strategies for Managing Global Environmental Risks. Flagship Report 1998.* German Advisory Council on Global Change (WBGU). Springer, Berlin, Germany.

WEC (1993). *Energy for Tomorrow's World. WEC Commission global report.* World Energy Council, London, UK.

WRA (2008). *A Sustainable Path: Meeting Nevada's Water and Energy Demands.* Western Resource Advocates (WRA), Boulder, CO, USA, 43 pp. Available at: www.westernresourceadvocates.org/water/NVenergy-waterreport.pdf.