Chapter 26
LCA of Energy Systems

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Abstract Energy systems are essential in the support of modern societies' activities, and can span a wide spectrum of electricity and heat generation systems and cooling systems. Along with their central role and large diversity, these systems have been demonstrated to cause serious impacts on human health, ecosystems and natural resources. Over the past two decades, energy systems have thus been the focus of more than 1000 LCA studies, with the aim to identify and reduce these impacts. This chapter addresses LCA applications to energy systems for generation of electricity and heat. The chapter gives insight into the LCA practice related to such systems, offering a critical review of (i) central methodological aspects, including the definition of the goals and scopes of the studies, their coverage of the system life cycle and the environmental impacts, and (ii) key findings of the studies, particularly aimed at identifying environmental hotspots and impact patterns across different energy sources. Based on this literature review recommendations and guidelines are issued to LCA practitioners on key methodological aspects that are important for a proper conduct of LCA studies of energy systems and thus ensuring the reliability of the LCA results provided to decision- and policy-makers.

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26.1 Introduction

Over the past decades, energy systems have increasingly received attention from stakeholders, including from high policy-makers, due to the combination of four major factors. Although different trends can be observed across countries, energy demand is expected to keep increasing worldwide, hence putting an increasing pressure on the supply side. The total primary energy supply, which amounted to 560 EJ globally in 2012, is thus expected to increase by 20–35% by 2040 (IEA 2015a). Conventional fossil resources are still anticipated to absorb that increase although depletion issues, in particular of conventional oil resources, have been widely acknowledged. As a result, initiatives to find alternative resources to fulfil the services that are currently relying on petroleum products have emerged (e.g. electric transportation to replace fossil-fuelled ones; see Chap. 27). In parallel, the increasing risk of disruptions of oil and natural gas supplies have led nations to define strategies to ensure secured energy supply, including establishing of emergency oil stocks for short-term disruptions and/or long-term planning to transition to more renewable and local sources (IEA 2014). Finally, energy systems are the primary source of anthropogenic greenhouse gas (GHG) emissions responsible for climate change. Electricity and heat production alone were thus responsible for 25% of the total GHG emissions in the world in 2010 while transportation was reported to account for 14% (IPCC 2014). In that setting, the key role of energy systems as support for entire economies combined with the triple issues of fossil resource depletion, climate change and energy security has put them at the centre of the sustainability debate. The development and dissemination of renewable energy technologies, deployment of carbon capture and storage systems, fuel switching, continued use of nuclear power and gains in energy efficiency are mechanisms, which can help mitigate these issues and have therefore become the focus of most energy policies (IEA 2015b).

Energy systems embody a wide range of systems and technologies and can be regarded as a “supporting sector”, i.e. a sector that feeds into all other application sectors, e.g. transportation, building sectors, industrial sectors, etc. In relation to life cycle assessment (LCA), it therefore means that energy systems can be considered relevant to nearly all LCA studies ever done until now. According to Chen et al. (2014) and Hou et al. (2015), between 1998 and 2013, approximately 7500 scientific articles and proceedings papers were published in the field of life cycle assessment and 1067 of them could be categorised within the subject “Energy and Fuels” . Simply taking the keywords “energy systems”, “energy technologies”, “power systems”, “power plants”, “electricity systems”, “heat systems”, combined with LCA leads to the non-exhaustive identification in Web of Science of 674 scientific articles published up to 2015, see Fig. 26.1. Matching the pattern observed by Chen et al. (2014) for all LCA-related publications, an exponential trend can be observed.

Energy systems and technologies considered in this chapter are limited to the energy supply systems and can be categorised in two major groups: electricity and heat production systems and fuels for transportation. Further differentiation can be done depending on energy sources (e.g. coal, wind, nuclear power, etc.),

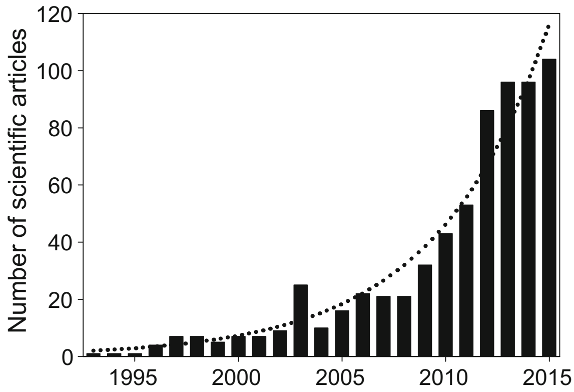

Fig. 26.1 Number of scientific articles addressing LCA and energy systems (non-exhaustive; total retrieved of 674 papers). Search made in ISI Web of Science using the keyword LCA combined with either "energy systems", "energy technologies", "power systems", "power plants", "electricity systems" or "heat systems" (Thomson Reuters, New York, NY). Exponential trend displayed in dotted line (r^2 = 0.95)

technology types (e.g. concentrated solar power and photovoltaics for solar power), application types (e.g. electricity or heat only, or combined heat and power plants), or fuel types (e.g. trains running from electricity or diesel in railway transportation). Overall, these sub-categories and differentiations are not addressed exhaustively in this chapter, which is intended to remain overarching and generic to all energy systems. In addition, the present chapter is limited to only addressing LCA in relation to electricity and heat production systems and therefore does not cover fuels for transportation. For the latter, the reader is referred to Chap. 27, which addresses e-mobility and touches upon that topic in relation to road transportation, and Chap. 30, which specifically addresses biofuels.

26.2 Literature Review

This section is intended to provide a non-exhaustive overview of research in the field of LCA applied to electricity and heat systems. It aims to provide an analysis of the key points of published LCA studies, addressing both methodological aspects and main findings.

26.2.1 Goal and Scope of the Studies

LCA studies on electricity and heat systems can roughly be divided into two main categories, which differ by the scoping/scaling, complexity and overarching goals of the study:

1. Studies assessing a specific energy technology/source/system at a power plant level (with possible inclusion of transport and distribution system) or sub-power plant level (e.g. specific component of the system). The goals of the study typically include weak-point analyses for eco-design, reporting/documentation of environmental performances of a newly developed technology, benchmarking against other technologies using the same or other energy sources (renewables and/or non-renewables).
2. Studies assessing energy systems in a context perspective, typically at meso- and large-scale. These studies relate the supply systems to context-dependent parameters, including the energy demand, types/settings of the application of the system, etc. They are primarily associated with goals oriented towards policy analysis or decision- and policy-making at urban, national or regional scales. They include retrospective and foresight studies looking into national energy scenarios, penetration of renewables into electricity grid mixes, installation and deployment of micro-grids for buildings, etc.

Most LCA studies made on energy systems are Category 1 studies, while the conduct of Category 2 studies is typically post-2010. Over the years, Category 1 studies have been commissioned and/or performed by electricity suppliers and researchers in academia for individual technologies, energy sources and national or regional grid mixes. The accumulated large pool of data can now be found in LCI databases, such as ecoinvent (Weidema et al. 2013), where hundreds of single processes, differentiated by energy sources, technologies and locations and typically defined as the supply of 1 KWh or 1 MJ, are available to LCA practitioners. A non-exhaustive glimpse of Category 1 studies is provided in Sect. 26.3.1 and in Table 26.4 (placed in Appendix); an overview of Category 2 studies is given in Table 26.1.

The definitions of the scope of the studies vary significantly between the two categories of studies as well as within a same category. Most of the choices with regard to the scope definition are not harmonised and are often made by the LCA practitioners based on previous studies and/or reference guidelines, such as the ISO standards or the ILCD Handbook. An example is the choice of the LCI modelling framework, with studies relying on attributional modelling with use of allocation while others use consequential modelling (see Sect. 8.5). These choices are not always clearly justified in studies, in particular with respect to the goal of the study.

Although not always transparently reported in the past studies, an important step in the scope definition is the elaboration of a properly defined functional unit (FU). Because Category 2 studies look at the energy system in relation to its context while Category 1 studies do not, different functional units can be observed. Two major types of functional units can be found in Category 1 studies: (i) FUs defined as the generation of 1 kWh or MJ of electricity/heat at power plant/heat unit, and (ii) FUs defined as the supply of xx kWh of electricity to the grid (thus including the energy transport and distribution systems). These definitions are by far the most common and relate to studies looking at the output of the energy production system. Other types of functional units, with more focus on the fuel inputs to the system, can also

Table 26.1 Examples of Category 2 studies i.e. systemic, context-driven studies

Scale	Functional unit	Short description (incl. modelling)	Reference
Macro-scale (global); prospective	(*Not explicitly defined*) Interpreted as the supply of electricity to match the global demand up to 2050 (demand fixed by different scenarios)	– Assessment of environmental impacts associated with the BLUE Map scenario compared to the business as usual scenario, as defined by the International Energy Agency over the period 2007–2050 – Use of a hybrid LCA model combining multi-regional input–output model and process LCIs. Inclusion of a dynamic perspective (e.g. evolution of grid mixes over time, etc.)	Hertwich et al. (2015)
Macro-scale (global, regional, national); retrospective	(*Not explicitly defined*) (i) Supply of electricity matching demand in each country in a given year (demand fixed by statistics for each country in each year); (ii) 1 kWh of electricity consumed in a given country in a given year	– Retrospective assessment of environmental impacts from electricity generated in each country/region over the period 1980–2011 – Use of process LCI and historical statistics on electricity produced from different energy sources and technologies in each country/region	Laurent and Espinosa (2015)
Macro-scale (EU); prospective	(*Not explicitly defined*) Interpreted as the supply of electricity matching the demand in the EU for the period 2005–2010	– Assessment of environmental impacts caused by each of two policy scenarios over 2005–2010: bioenergy policy and business as usual policy – Use of consequential LCA to capture impacts of the policy implementation, e.g. increase in biomass demand in non-EU countries	Dandres et al. (2011)
Macro-scale (EU); prospective	(*Not explicitly defined*) Interpreted as the supply of electricity matching the demand in the EU in the year 2050	– Assessment of environmental impacts associated with 44 scenarios electricity supply in the EU in 2050 – Use of a hybrid LCA model combining multi-regional input–output model and process LCIs, incl. requirements for accommodating the variability of wind and solar power (e.g. storage) and changes in grid mixes for production processes	Berril et al. (2016)

(continued)

Table 26.1 (continued)

Scale	Functional unit	Short description (incl. modelling)	Reference
Macro-scale (Mexico); present perspective	Total annual amount of electricity generated by public sector in 2006, i.e. 225,079 GWh	– Assessment of environmental impacts of electricity generation in Mexico in 2006 – Process LCI data used	
	Santoyo-Castelazo et al. (2011)		
Macro-scale (Estonia); prospective	1 MWh of grid electricity consumed in Estonia	– Comparative assessment of 3 scenarios for 2020 (i.e. nuclear, oil shale, natural gas scenarios) compared to "current" situation in 2002 – Correction of process LCI to adapt future scenarios	Koskela et al. (2007)
Macro-scale (Denmark); prospective	1 kWh of electricity consumed in Denmark	– Comparative assessment of 2 scenarios for 2030 (2030-Green and business as usual) in Denmark compared to "current" situation in 2010 – Consequential LCA to model possible future Danish power systems (future changes for power generation technologies included)	Turconi et al. (2014)
Macro-scale (United Arab Emirates); prospective	Supply of 1 kWh of net electricity	– Comparative assessment of a number of scenarios for 2020, 2030 and 2050 (planned policies, planned policies with carbon capture and storage systems after 2030, nuclear scenario, renewables scenario), also compared to "current" situation in 2010 – Technologies foreseen in use in 2030 based on literature sources. Combination with process LCI.	Treyer and Bauer (2016)
Meso-scale (Island of Koh Jig); present/ prospective	Supply of 265 kWh of electricity per day to Koh Jig Island for 20 years (i.e. 1934.5 MWh)	– Three alternative microgrid systems of electrification for the entire island of Koh Jig (1.2 km^2) – Interpreted as attributional model with system expansion used for recovered materials only (not energy)	Smith et al. (2015)
Meso-scale (house); present	Total power generation in one year	– Comparisons of 9 different power generation systems to sustain energy requirements of a standalone mobile house in Turkey	Sevencan and Ciftcioglu (2013)

be found in literature, e.g. studies assessing different fuel inputs to a power plant and focusing on their different energy contents.

With regard to Category 2 studies, the functional unit is often defined as the supply of an amount of energy based on the demand of the country, region or entity supported by the energy systems under study in a temporal perspective, i.e. past, present or future-oriented (see Table 26.1) illustrating the variety of Category 2 studies. As reported in Table 26.1, two main types of functional units are often used. They differ by the amount of energy, which defines the "quantity" aspect of the functional unit. This quantity may either match the total energy demand/consumption defined by the scenario(s) considered (e.g. Hertwich et al. 2015; Berril et al. 2016) or be normalised to the consumption of one kWh for all scenarios (e.g. Turconi et al. 2014). In the former, some practical challenges may arise. In studies encompassing a wide scoping with several scenarios and sub-systems, the quantification of the functional unit may thus become difficult. For example, in Laurent and Espinosa (2015), the environmental impacts associated with the electricity generated in each country in the world for each year within the period 1980–2011 were assessed. It means that for national assessments, as many functional units as numbers of countries and numbers of years included in the study need to be quantitatively defined although the primary functions are the same, i.e. the supply/generation of electricity matching the demand in each country and each year. Similar issues can be observed in future-oriented studies, for example in Hertwich et al. (2015), where the potential environmental impacts of the BLUE map scenario (IEA 2015b) are compared against those of the business as usual scenario: each scenario entails different energy demands, which are accounted for in the analysis of the results to demonstrate the benefits of renewables in electricity supply systems. As indicated above, other studies, which have assessed future energy scenarios, have defined their functional units as one kWh of electricity consumed/generated (e.g. Turconi et al. 2014; Treyer and Bauer 2016).

26.2.2 Life Cycle Coverage

One of the strengths of LCA is the adoption of a life cycle perspective (see Chap. 2). Including all the life cycle stages, from the raw materials extraction to the final disposal stage, is important to prevent environmental burden-shifting from one life cycle stage to another. For example, renewable energy technologies are often improperly flagged as "green" in different media. However, this denomination often only holds when they are considered solely in their use stage and mainly in relation to climate change impacts (see also Sect. 26.2.3). Renewables have important environmental impacts outside their use/operation stage, e.g. production (see Sect. 26.3.1). Therefore, when taking the whole life cycle of renewables-based energy systems, one may demonstrate that they are "greener" than fossil-based energy systems, but they are not free of any environmental impacts.

In LCA studies of energy systems, the life cycle has often been truncated, in particular with the disregard of the disposal stage and, to a lesser extent, of the use stage. Arvesen and Hertwich (2012) thus showed in a review of LCA studies of wind power (44 reviewed studies) that the manufacturing stage was the only life cycle stage common to all studies. Most studies were reported to consider the operation and maintenance of the wind power plants even though different assumptions we made. The end-of-life was either omitted or modelled using assumptions for the decommissioning and recovery of materials/energy. Likewise, in their review of LCA studies of thin-film photovoltaics (PV) systems, Chatzisideris et al. (2016) found that out of 46 studies, all addressed the production stage (incl. raw materials extraction) while only 29 (i.e. 63% of studies) and 11 (i.e. 24%) studies encompassed the use and disposal stages, respectively.

As indicated in Sects. 26.2.3 and 26.3.1, environmental impacts of renewable energy sources stem from the production of the different materials, infrastructure and equipment supporting the systems, e.g. PV modules and supporting infrastructure for photovoltaics (e.g. Espinosa et al. 2015), or components of wind turbines (e.g. Arvesen and Hertwich 2012). Important positive effects can arise in the total environmental burden of the systems when materials are recycled at the end-of-life of the systems, thus substituting the production of virgin materials, or when energy recovery accompanies incineration of materials, thus substituting the generation of heat and electricity from conventional, often fossil-based energy sources. Although inconsistencies and lack of transparency have been observed across studies addressing the disposal stage, most studies point out the high relevance of the disposal stage in the total environmental burden of the energy systems (e.g. Arvesen and Hertwich 2012; Espinosa et al. 2015). In addition, for some energy sources, specific environmental impacts are largest during their use/operations, e.g. water use impacts for hydropower (Pfister et al. 2011). These observations thus highlight the great risk of truncating the life cycle of the energy systems and only limiting it to the materials and production stages. Important biases may be associated with results of such narrowly scoped studies, for example if a study points out high impacts during the production of materials while overlooking that these materials end up being recycled with high efficiency in the disposal stage, thus reducing considerably their respective environmental impacts.

26.2.3 Impact Coverage

Because of the strong focus of energy policies on mitigating climate change and maximising energy efficiency, a large majority of the LCA studies focusing on energy systems have limited their impact assessment to the sole quantification of life cycle GHG emissions (expressed in mass unit of CO_2 equivalents) and energy demand (e.g. use of cumulative energy demand indicator, energy payback time). A number of reviews focusing on specific energy technologies or systems have identified and reported such patterns. Examples of such reviews include Schreiber et al. (2012), who focused on electricity generation with use of carbon capture and storage (CCS) systems (15 studies), Arvesen and Hertwich (2012), who reviewed LCA studies of wind power (44 studies), and Chatzisideris et al. (2016), who assessed the body of LCA studies on thin-film photovoltaics (33 studies). In some situations, this simplification is a conscious choice made by the authors of the studies, who sometimes acknowledge the limitations of the study and recommend that other environmental impacts be considered (e.g. Burkhardt et al. 2012). Other situations show ambiguity as to whether the authors are aware that GHG emission accountings and energy demand assessments do not necessarily represent the total environment burden. Such authors often use the terms "environmental impacts", "life cycle assessment", "environmental LCA" to refer to assessments or studies that only deal with life cycle GHG emission and/or energy demand accountings, and, more importantly, without making clear to the reader the distinction between them and the possible limitations to their conclusions (e.g. Sherwani et al. 2010; Chua et al. 2014).

The inclusion of a limited number of environmental impacts may invalidate the support provided to decision-makers if one aims to assess the total environmental burden of a system or technology. Such situations can be the result of environmental burden-shifting from one impact category to another, i.e. if decisions directed to reducing one impact inadvertently lead to increase in others, which are overlooked in the assessment. Figure 26.2 illustrates this phenomenon at the level of individual energy sources by considering the switch from fossil fuels to renewables per kWh of electricity produced (updated from Laurent et al. 2012).

When moving from fossil-based energy sources (in brown dots in Fig. 26.2) to renewables (coloured dots), reductions of 1–2 orders of magnitude in the climate change impacts (x-axes) are observed for a same electricity output. What is interesting is that other environmental impacts such as acidification and particulate matter (Fig. 26.2a, b) are being decreased at the same time because these stem from the same emission sources as for GHG emissions. However, for other environmental impacts, notably the toxicity-related impacts (Fig. 26.2c) or non-renewable resource depletion (Fig. 26.2d), such trend may not be observed and while the climate change impacts are being reduced, these impacts may remain at the same level or even increase. This is for example suggested for wind power or solar power in Fig. 26.2c, d, where the human toxicity impacts and resource depletion impacts are, respectively, comparable and increased compared to those of electricity produced from natural gas or hard coal (due to larger emissions of heavy metals and use of rare metals through the life cycle of the energy systems).[1]

Therefore, a study only assessing climate change runs the risk to overlook these trends in other environmental impacts and provide recommendations to policy- and decision-makers that could either be further optimised, or worse, lead to

[1]Note that these results may also be sensitive to the selected LCIA methods (particularly for resource depletion, for which no widely accepted indicator exists) and to the LCI data present in ecoinvent database (differences in system boundaries of technologies; disregard of evolving technological level in renewable energy sources).

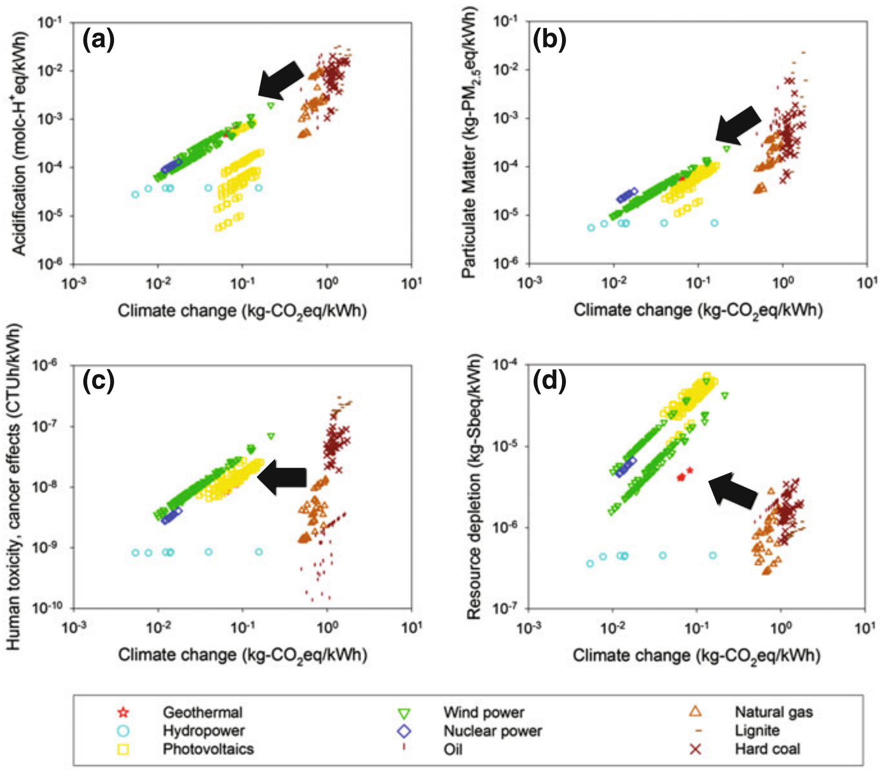

Fig. 26.2 Selected environmental impacts for electricity production plotted against climate change impacts: **a** Acidification, **b** particulate matter, **c** human toxicity—cancer effects, **d** resource depletion (updated from Laurent et al. 2012). *Black arrows* reflect the trends when switching from fossils to renewable energy sources; they are marked for indicative purpose and disregard variations across energy sources. Logarithmic scales are used on both axes. Study performed using ecoinvent 3.1 LCI database and ILCD LCIA methodology in SimaPro LCA software

unsustainable pathways (Laurent et al. 2012). At the level of national electricity mixes, occurrences of environmental burden-shifting have been observed in the past. A prime example is the French grid mix, for which the switch from fossils to nuclear power after the oil crisis in the 70s has contributed to decrease the climate change impacts from the electricity sector by more than 60% between 1980 and 2011 (in spite of increased electricity demand) whereas other environmental impacts have increased in the same period, e.g. ca. 50% for freshwater ecotoxicity impacts and ca. 600% for ionising radiation (Laurent and Espinosa 2015). This calls for covering the whole spectrum of environmental impacts when performing life cycle assessments of energy systems.

26.3 Main Findings of Published LCA Studies

26.3.1 Analysis of Environmental Hotspots

The life cycle of heat and electricity generation systems can be regarded as the inter-section of two life cycles: (i) the life cycle of the power plant unit, including the transmission and transport infrastructure and the equipment at the plant; and (ii) the life cycle of the fuels (see Fig. 26.3). The latter is irrelevant for systems relying on wind power, solar power, hydropower and geothermal power, for which the energy source is assumed directly available without additional processes than those already encompassed in the life cycle of the power plant itself. These are also energy sources for which no fuel combustion takes place.

LCA studies have demonstrated that two different patterns exist in the localization of the largest environmental impacts in the life cycles of heat and electricity generation systems, with a major distinction between systems based on fossils, biomass and nuclear power (i.e. where there is fuel combustion) and those relying on wind power, solar power, hydropower and geothermal power (i.e. where no fuel combustion occurs).

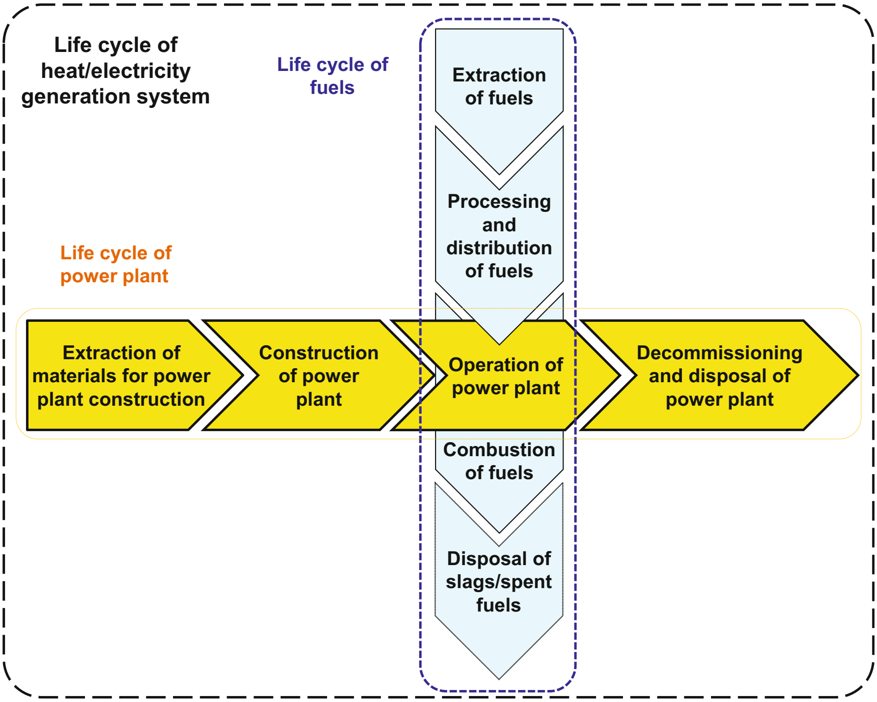

Fig. 26.3 Life cycle of heat and electricity generation systems with intersecting life cycles of the power plant and the fuel required for the operations

In that regard, the capital goods (e.g. power plant facilities, turbines, machineries, etc.) are a relevant part of the systems to address, in particular the extent to which they contribute to the overall environmental burden and their ability to be disregarded or not by practitioners. While capital goods are the main drivers of the impacts for hydropower, wind, solar and geothermal power (no fuel), and hence should not be disregarded for those systems, their contributions in other systems, e.g. fossil-based, is less obvious. Frischknecht et al. (2007) have thus demonstrated a dependency on the type of impact categories considered in the assessment. Generally, the non-toxicity impact categories, such as climate change, are negligibly affected by capital goods whereas toxicity-related impact categories and resource use and depletion impacts (e.g. metal depletion) are more sensitive to the inclusion of capital goods. Capital goods may thus contribute to 94% and 85% to metal/mineral depletion and land use for coal-fired power plant systems, respectively (Frischknecht et al. 2007). For natural gas power plants, other impact categories may also be significantly affected by capital goods, e.g. if the natural gas supply in the assessed region relies on long-distance gas transport (Frischknecht et al. 2007). Assuming a full coverage of environmental impacts, these results therefore call for the systematic inclusion of capital goods when assessing energy systems. Note that these are included by default in many process-based LCI databases, e.g. ecoinvent 3 (Weidema et al. 2013).

Other distinctions can also be observed within the two aforementioned categories of systems, but they are often limited to specific impact categories (e.g. water use or land use between wind and geothermal power) and are technology-dependent (e.g. reservoir-based *vs*. run-of-river hydropower). Table 26.2 provides an overview of the environmental hotspots per impact category and major energy source based on the generation of a kWh-unit of electricity. A summary per group of energy source is provided in the following subsections.

26.3.1.1 Coal-, Gas- and Oil-Based Systems

With the exception of metal/mineral resource depletion indicators, which indicate distribution of impacts between the materials requirements for the power plant construction and those of the infrastructure for the mining activities, all impacts stem predominantly from the operation in the use stage of the power plants, in particular from the life cycle of the coal, gas or oil fuels.

Three major environmental hotspots can thus be identified: (i) the mining activities, which contribute to freshwater eutrophication and toxicity-related impacts through the resulting spoils, to water use, land use and fossils depletion categories through the use of these resources, and to metal depletion (i.e. mining infrastructure); (ii) the fuel combustion, which is a major contributor to all airborne-emission-driven impacts such as climate change, acidification, terrestrial and marine eutrophication, particulate matter or toxicity-related impacts; and (iii) the disposal of the heavy metals contained in the combustion slag and bottom ashes, which primarily contribute to toxicity-related impact categories.

Table 26.2 Location of environmental hotspots in heat and electricity generation systems per impact category for each energy source (colour coding differentiating the patterns)

Impact categories	Coal	Nat. gas	Oil	Nuclear power	Wind power	Solar power	Hydro-power	Geo-thermal	Biomass
Climate change	U (U)	U (U)	U (U)	U (RP)	RP	RP	RP	RP	U (RP/U)
Stratospheric ozone depletion	U (RP)	U (RP)	U (RP)	U (RP)	RP	RP	RP	U	U (RP)
Acidification	U (U)	U (U)	U (U)	U (RP)	RP	RP	RP	RP	U (RP/U)
Terrestrial eutrophication	U (U)	U (U)	U (U)	U (RP)	RP	RP	RP	RP	U (RP/U)
Freshwater eutrophication	U (RP)	U (RP)	U (RP)	U (RP)	RP	RP	RP	RP	U (RP/U)
Marine eutrophication	U (U)	U (U)	U (U)	U (RP)	RP	RP	RP	RP	U (RP/U)
Photochemical ozone formation	U (U)	U (U)	U (U)	U (RP)	RP	RP	RP	RP	U (RP/U)
Ionising radiation (human health)	U (RP)	U (RP)	U (RP)	U (D)	RP	RP	RP	RP	U (RP)
Particulate matter	U (U)	U (U)	U (U)	U (RP)	RP	RP	RP	RP	U (RP/U)
Human toxicity	U (RP/U/D)	U (RP/U/D)	U (RP/U/D)	U (RP/D)	RP/D	RP/D	RP/D	RP/D	RP/U (RP/U/D) /D
Ecotoxicity	U (RP/U/D)	U (RP/U/D)	U (RP/U/D)	U (RP/D)	RP/D	RP/D	RP/D	RP/D	RP/U (RP/U/D) /D
Water use	U (RP)	U (RP/U)	U (RP/U)	U (U)	RP	RP	RP/U	U	U (RP)
Land use	U (RP)	U (RP)	U (RP)	U(RP)	RP/U	RP/U	RP/U	RP/U	U (RP/D)
Fossils depletion	U (RP)	U (RP)	U (RP)	U (RP)	RP	RP	RP	RP	U (RP)
Metal/mineral resource depletion	RP/U (RP)	RP/U (RP)	RP/U (RP)	U (RP/D)	RP/D	RP/D	RP/D	RP/D	RP/D

Based on assessments of ecoinvent 3.1 energy production processes using ReCiPe and ILCD LCIA methodologies (Weidema et al. 2013; Huijbregts et al. 2015; Hauschild et al. 2013). Sensitivity to long-term emissions for freshwater eutrophication and toxicity-related impacts was included in the identification of the hotspots (addition of life cycle stage hotspots when inclusion, if different picture from exclusion)

For fossil-based, bio-based and nuclear power, the life cycle of the fuels is considered part of the use/operation stage of the power plants (see Fig. 26.3). The first letter code therefore indicates the position of the hotspots within the life cycle of the power plants; the letter code in the brackets further specifies the hotspots when stemming from the operations of the power plant by giving their positions within the life cycle of the fuel. Same designations are used to represent the different life cycle stages. For the power plants: *RP* raw materials extraction and construction of power plants; *U* use/operation stage of the heat/electricity generation plant; *D* decommissioning/disposal of the plant. For the fuels: *RP* mining operations and/or resource production (e.g. biomass), refining and distribution, *U* fuel combustion; *D* slag or spent fuel disposal

26.3.1.2 Nuclear Power Systems

All impacts are concentrated in the life cycle of the nuclear fuel (i.e. operation of the power plant). A large number of impacts, including climate change, stratospheric ozone depletion, acidification, eutrophication, photochemical ozone formation, particulate matter, fossil depletion and land use primarily stem from the extraction and processing of the uranium, for which important energy supplies are needed (e.g. diesel for machineries, electricity/heat). The extraction of uranium also contributes to uranium resource depletion, typically accounted for in the metal depletion impact category. Toxicity-related impacts (dominated by long-term emissions of heavy metals) and freshwater eutrophication also arise from this process due to the disposal of the tailings and spoils from the mining activities. The disposal of the spent nuclear fuel is a second important source of impacts, in particular for ionising radiation, for which it is the primary source, and for toxicity-related impacts and metal depletion, both resulting from the requirements of steel for the fuel conditioning (e.g. steel canisters, etc.). A third hotspot stems from the significant water requirements during the operations of the nuclear power plant, which dominate the water use impacts.

26.3.1.3 Biomass-Based Systems

Environmental impacts of bioenergy systems are largely influenced by the type of fuel used, hence a majority of the impacts stemming from the operations of the plant and more specifically from the life cycle of the fuel. Impacts such as climate change, acidification, eutrophication, photochemical ozone formation, fossils depletion and particulate matter may stem from either the biofuel or biogas combustion itself or from the biomass production, i.e. from growing and harvesting (e.g. first generation biofuels; see Chap. 30 on biofuels and bioproducts). If the energy source is a bio-waste or residue not utilised elsewhere, processes associated with this waste stream should not be accounted for in the assessment, thus shifting the environmental impacts for these categories solely to the combustion processes (e.g. incineration, biogas plants).

Because of the large variability across fuels, toxicity-related impacts can stem from any place in the life cycles of the power plants and the fuels. For example, if bio-waste is used as fuel and has no content of toxic elements, the hotspots will arise from the life cycle of the power plant itself, while the hotspots will lie in the production of the fuel if the fuel production is considered and requires high energy requirements and/or is associated with important direct emissions of toxic substances (e.g. pesticides in farming practices).

Likewise, for water use and land use, different fuels will have different hotspots. Water use impacts would typically be concentrated in the production of the biomass (if any is considered and if irrigation is applied). Land use impacts will also stem from the production of the fuels, which may also entail indirect land use impacts (see Weiss et al. 2012). For further details on LCA applied to biomass systems, the reader is referred to Chap. 30.

26.3.1.4 Wind, Solar, Geothermal and Hydropower Systems

All impacts but land use and water use impacts stem from the production of the power plant unit (incl. raw materials extraction). The exact sources of the impacts vary from one energy source to another as well as across technologies within a same energy source. The production of the raw materials and components of the power plant unit, such as PV modules (e.g. Si wafers), wind turbines (steel, composite materials) or dams (reinforced steel), are the primary causes to most impact categories including climate change, acidification, photochemical ozone formation, eutrophication, particulate matter, ionising radiation, water use and fossils depletion. These contributions are largely explained by the large energy requirements in these manufacturing processes, e.g. steel production. With respect to freshwater eutrophication and toxicity-related impact categories, the sulfidic tailings and spoils from mining activities contribute significantly to the impacts due to emissions of heavy metals and phosphorous compounds. For human toxicity and ecotoxicity, the disposal of the scrap metals (e.g. steel, copper) is also an important contributor, notably for renewable technologies like solar power or wind power. These disposal processes, along with the metal extraction processes at the beginning of the life cycle, contribute to metal depletion, which can be influenced by the presence of recycling. Water use impacts show different hotspots depending on the energy source and technology in use. Water requirements in the production of the components for wind and solar power plants as well as for run-of-river hydropower plants drive the impacts for these energy sources, while reservoir-based hydropower and geothermal power plants concentrate the water use impacts during their operations. Same dependencies can also be observed for land use, which typically can stem from either the mining operations (e.g. photovoltaics, run-of-river hydropower) or the installation sites and the associated distribution network (e.g. wind farms, reservoir-based hydropower, geothermal power).

26.3.2 Key Findings

Because of the large number of LCA studies on energy systems, providing a comprehensive analysis of their findings can easily become a laborious exercise. Instead, Table 26.4 in Appendix provides an overview of main findings of LCA studies assessing different energy technologies, including environmental performances, environmental hotspots, etc. For further details, the reader is referred to the references provided in Table 26.4; several of them are reviews performed on LCAs of specific energy sources or technologies. Figure 26.4 additionally provides an illustration of the variations of results for selected impact categories across fossil-based and renewable energy sources and technologies.

26.3.2.1 Technology Dependence

As reflected in Fig. 26.4, there is a strong dependence of the impact results on the type of technologies, even within a same energy source. Two parameters are particularly important in the differentiation of the technologies and their resulting impacts: the existence of cleaning technologies and the conversion efficiencies of the plant (Turconi et al. 2013). Existence of cleaning technologies has been shown to potentially yield significant reductions in impacts, e.g. use of carbon capture and storage (CCS) systems for reducing climate change for coal and natural gas power plants (see Fig. 26.4) or cleaning of the coal prior to combustion to reduce downstream emissions and associated environmental impacts (see Ryberg et al. 2015). However, it is important to note that these cleaning technologies often target one or few specific impact categories (e.g. CCS systems to reduce climate change impacts), and may thus lead to burden-shifting from those targeted impact categories to other environmental problems. See for example the changes in the impact results for particulate matter between systems with and systems without CSS systems for coal and natural gas in Fig. 26.4. While climate change impacts are significantly reduced by the implementation of CCS systems, these impacts tend to increase. This reinforces the need to encompass a full impact coverage.

The power plant conversion efficiencies are another influential source of differentiated impact results across technologies. They are calculated as the ratio between the useful energy output (as electricity and/or heat) and the energy input. Power plant efficiencies typically range within 30–45% for coal and natural gas (conventional), 90% for hydropower, 30–50% for wind turbines, 5–20% for solar cells (large variations between technologies), etc. These efficiencies are constrained by theoretical maximums determined by thermodynamics laws (i.e. Carnot's efficiency law). However, improvement of these efficiencies, particularly for thermal power sources (coal, gas, oil), can be made by introducing energy recovery systems that will increase that theoretical maximum. This is for example the case when implementing combined cycles, where the waste heat from the first cycle is used through additional cycles to recover more energy (e.g. in gas power plants). Co-generation of heat and power can also significantly increase these efficiencies, for example in utilising the waste heat from the power plants to district heating purposes. Such co-generation systems can then result in efficiencies above 90%.

26.3.2.2 Performances Across Energy Sources

Most studies include comparisons of heat or electricity produced from different energy sources, e.g. to position the analysed system(s) relative to the currently applied system with respect to environmental impacts. Trends vary considerably

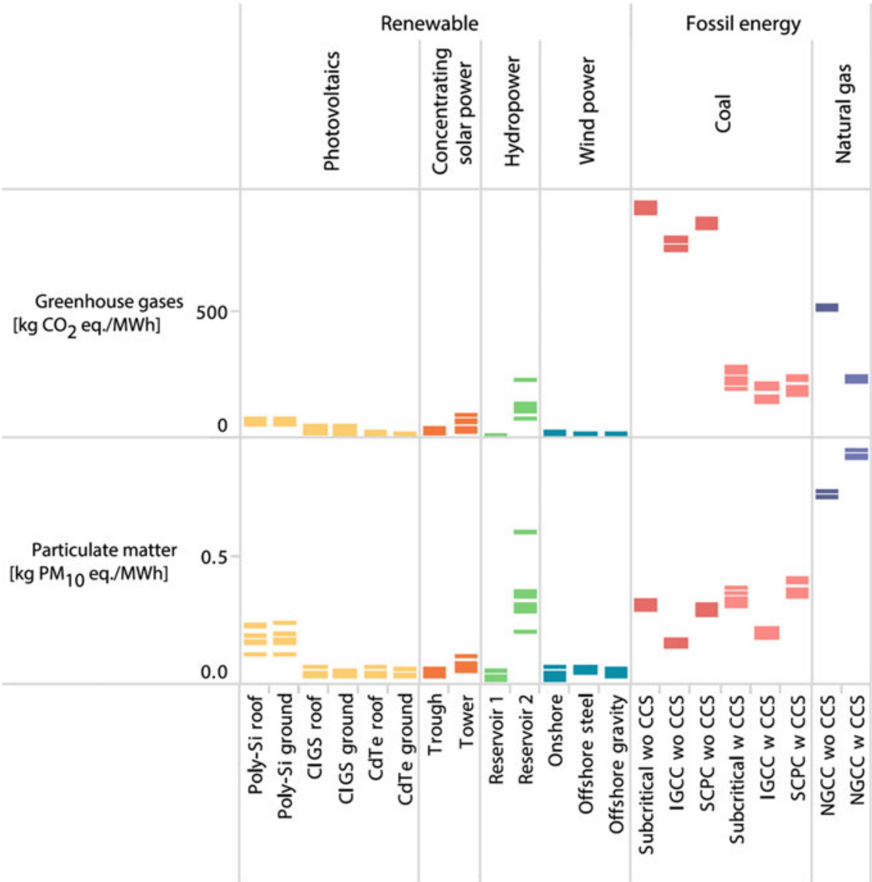

Fig. 26.4 Ranges of impact results for climate change and particulate matter impacts for different energy sources and technologies (extracted from Hertwich et al. 2015). *CCS* CO_2 capture and storage, *CdTe* cadmium telluride, *CIGS*: copper indium gallium selenide, *IGCC* integrated gasification combined cycle coal-fired power plant, *NGCC* natural gas combined cycle power plant, *Offshore gravity* offshore wind power with gravity-based foundation, *Offshore steel* offshore wind power with steel-based foundation, *Reservoir 2* type of hydropower reservoirs used as a higher estimate, *SCPC* supercritical pulverized coal-fired power plant

depending on the technology assessed (see above) and the assumptions made in the assessment (e.g. modelling and coverage of life cycle and impacts; see Sects. 26.2.2 and 26.2.3). Higher shares of renewables and nuclear power in energy systems are typically associated with lower environmental impacts for several impact categories, including climate change and eutrophication (e.g. Hertwich et al. 2015; Laurent and Espinosa 2015). Other impact categories show less conclusive results, e.g. toxicity-related impacts, land use impacts and water use impacts, e.g. land use and water use impacts from hydropower reported as larger than those of fossils-based power generation (e.g. Hellweg and Mila ì Canals 2014; Hertwich et al.

2015). Metal depletion is often reported to be an impact category where renewables perform worse than fossil-based systems (Hertwich et al. 2015; Berril et al. 2016; Laurent et al. 2012). Overall, at a global scale, two patterns seem to characterise the use of electricity generation technologies in current electricity supply systems, with developing economies having relied on energy policies ineffectively targeting environmental problems, thus resulting in "dirtier grid mixes", while developed economies, which progressively integrate higher shares of renewables, move towards "cleaner grid mixes" (Laurent and Espinosa 2015). With respect to renewables, wind power often emerges as the renewable technology with the lowest overall environmental impact (Hertwich et al. 2015; Berril et al. 2016; Astrubali et al. 2015). For example, although including a large variability in the impact results, solar power is reported to lead to higher impacts than wind power per unit of electricity produced due to large impacts stemming from material production and a lower ability to generate electricity over the same period of time (Hertwich et al. 2015; Berril et al. 2016).

In the assessment of renewables, two alternative, noteworthy indicators have often been used as criteria for assessing system performances: the energy payback time (EPBT) and the energy return on investment (EROI). The EPBT is defined as the time (typically in years) for a system to compensate for the use of energy for its production, installation and end-of-life, and start producing more energy than what has been invested through its life cycle. For example, if a system has a lifetime of 20 years and its EPBT was found to be 3 years, it means that "free energy" is produced for 17 years. The EROI is defined as the amount of usable energy supplied by a system in its lifetime over the energy required to produce, implement and dispose of it, which is equal to the EPBT, and is dimensionless (e.g. 20:3 in the example above). EROI ratios below one are not considered viable technologies on the market. PV technologies are currently associated with EPBT of 1–4.1 years, with cadmium telluride (CdTe) and copper indium gallium diselenide (CIGS) technologies showing lowest EPBTs, and EROI of 8.7–34.2 (Bhandari et al. 2015). Albeit outdated to some extent, wind power technologies typically show EPBT of few months to 1–2 years with typical ERIO of 8–40 among recent studies (Davidsson et al. 2012). Such figures are comparable to the performances of some fossil-based energy sources, such as natural gas and oil, for which ERIO are decreasing due to lower availability of the resources (increasing amount of energy spent to recover oil or natural gas).

26.4 Specific Methodological Issues

From the published LCA studies of energy systems a number of issues can be identified. They relate to either influential methodological choices or assumptions on which no consensus currently exists, or to inconsistencies or malpractice observed in studies (most of them being noted in Sect. 26.2). This section, therefore, builds on Sect. 26.2 (and contains several cross-references to it) to focus on key issues that are central to the consistency and reliability of the assessment results, and it provides guidelines and recommendations to address them when performing LCA of energy systems.

26.4.1 General Issues

The review performed in Sect. 26.2 highlighted a latent problem of transparency in the LCA studies on energy systems. Important methodological aspects and assumptions are often not sufficiently documented. In addition to compromising the reproducibility principle that each study should fulfill, it makes the results difficult to interpret and compare across studies. Examples of poorly reported aspects include the handling of multifunctional processes, e.g. use of system expansion, the data sourcing, the use of electricity mixes, which are not always specified, the accounting of energy used and produced, for which different methods can be used, the coverage of the life cycle inventories (e.g. materials required), the potentially missing impact pathways (e.g. no accounting of rare earth metals), or the assumptions made to model the disposal stage. Such lack of transparency is not a problem specific to LCA studies applied to energy systems (e.g. LCA of waste management systems, see Chap. 35).

To remediate this issue, some review studies have provided guidance to ensure a better reporting and harmonisation in the LCA practice (e.g. Davidsson et al. 2012, for wind power; Frischknecht et al. 2016 for PV power systems). In general, LCA practitioners are strongly recommended to use Appendices (for reports) or Supporting Information (for scientific publications) to document clearly and transparently their data, methodological assumptions and modelling (see overall guidance in Methodological Chaps. 8 and 9 of this textbook).

26.4.2 Goal and Scope Definition

Building on the review presented in Sect. 26.2, four key aspects are addressed below for the goal and scope definition: (i) the definition of the functional unit, (ii) the scoping of the system boundaries, (iii) the selection of the impact categories and (iv) the LCI modelling framework and handling of multifunctional processes.

26.4.2.1 Functional Unit

The functional unit must be defined as the primary service provided by the system, i.e. its “raison d’être”. The role of the energy systems assessed in LCA studies typically consists in supplying electricity or heat to allow other activities to operate. As a consequence, for studies under Categories 1 and 2 (see Sect. 26.2.1), the functional unit needs to be defined based on an energy output (whether it meets a known demand or not). An example of malpractice is the definition of functional units based on a specific area of PV modules in comparative studies of PV technologies. Such definitions prevent to account for different efficiencies of the compared PV module alternatives, and hence for their different electricity amounts generated from a same PV module area (see Box 8.1 in Chap. 8; case 1). It is therefore important to relate to the main function of the system when defining the functional unit.

Defining an appropriate functional unit also contributes to ensure a comparability of alternatives or scenarios in the performed LCA studies. In studies with a demand-driven context that compare base-load with intermittent energy technologies, such as wind power or PV power systems, this can however be challenging due to the different "reliability of supply" of the two systems. This can usually be eluded by modelling the intermittent source with a storage system (Gagnon et al. 2002) or by adding a compensating source whenever the intermittent source cannot supply electricity. Similar challenges arise when comparing electricity supply systems matching base-load electricity demand with those matching peak-load electricity demand (Turconi et al. 2013).

In line with the review presented in Sect. 26.2, two categories of studies were identified from the published LCA studies applied to electricity and heat systems: (i) studies assessing specific energy technologies/sources/systems at a power plant or sub-power plant level, and (ii) studies, typically at meso- and large-scale, assessing energy systems in a context perspective (see details in Sect. 26.2.1). These call for different definitions of functional units, which are gathered from LCA practice; they are provided in Table 26.3, which provides recommendations for practitioners undertaking LCA of energy supply systems.

Table 26.3 Recommendations for defining functional units of energy systems (non-exhaustive list of situations)

Type of situations/goal of studies	Recommendations for FU definition
Category 1 studies (power plant or sub-power plant level)	
Focus on fuel input comparisons (with disregard of energy output)	Provision of xx MJ of fuel energy content (or primary energy) to power plant z
Focus on supply of electricity and/or heat	-"Generation of 1 kWh or MJ of electricity/heat at power plant/heat unit in country x" (without transport and distribution system) -"Supply of 1 kWh of electricity to the grid in country x" (with transport and distribution system)
Category 2 studies (context perspective; meso- and large-scale assessments)	
Investigation of how the environmental impacts of the grid mix will change/evolve	Supply or consumption of 1 kWh of net electricity in country or region x
Investigation of environmental impacts from whole electricity supply system over time (with consideration of demand)	Supply of electricity to match the global demand in country or region x in year y (quantified demand fixed by different scenarios)

As reflected in Table 26.3, a simplistic functional unit defined as the supply or consumption of a unit of electricity output (e.g. 1 kWh) is often appropriate to the case study. One important exception is, however, the assessment of meso- or large-scale systems taken in their context and with consideration of energy demands modelled as scenario analyses. With a simplistic definition of the functional unit as indicated above, such studies become limited to only address the question of how the environmental impacts of the grid mix will change. As indicated in Laurent and Espinosa (2015) with assessments of national electricity supply systems, a scenario A may show lower environmental impacts than a scenario B on a 1 kWh-basis (grid mix level) but a reversed tendency may be observed when accounting for the total demand. The total demand may indeed differ between Scenario A and Scenario B because of different energy policies, which could for example influence the consumers' behaviour and their overall demand in different ways, lead to different efficiencies in the smart grid for matching the demand with the supply, integrate different measures for energy efficiencies, etc. A total demand, which ends up higher in Scenario A than in Scenario B, may therefore compensate the better performances of the grid mix in Scenario A, thus resulting in Scenario B being the most environmentally preferable. These observations can be linked to the differences between eco-efficiency (here: the grid mix having lower environmental impacts, but with no guarantee of overall reduction of environmental impacts at the societal level) and eco-effectiveness (here: the whole electricity supply system to support the total demand having lower impacts, thus ensuring lower environmental impacts at societal level). Chapter 5 addresses these concepts in a more generic and detailed way. Consequently, in studies supporting policy analysis or policy-making, and where scenarios need to be assessed, it is important that the whole perspective, including not only the changes on the electricity grid mix but also the changes in the demand, be encompassed in the analysis of the results. And this is why the functional unit may have different quantities relating to the energy demands in its definition (since these vary from one system to another), while still maintaining comparability of the energy systems/scenario under study.

26.4.2.2 System Boundaries

The life cycle of the energy systems should include both the life cycle of the power plants and that of the fuels, the latter being relevant for all energy sources but wind, solar, geothermal and hydropower sources due to the absence of fuel per se. For hydropower and geothermal power sources, the use of water (which could be regarded as the fuel to some extent) and the associated impacts should, however, be carefully evaluated. For fossil-based and biomass-based systems, the life cycle of the fuel is important to include, as it is the main source of impacts (see Table 26.2).

As a general rule, to avoid overlooking any potentially large impacts and possible burden-shifting, the practitioners are recommended to include the entire life cycle of electricity and heat generation systems. In practice, this can sometimes be challenging, for example in the inclusion of the power plant life cycle. Based on the analysis in Table 26.2, practitioners are invited to consider the following guidance to scope the system boundaries of their electricity and heat generation systems, including as a minimum:

1. The life cycle of the fuels for all fossil-based, nuclear-based and biomass-based systems. The life cycle of power plants (excluding the operation stage, thus mainly consisting of the plant construction and decommissioning) typically shows minor contributions to most environmental impacts associated with the supply of heat and electricity (see Sect. 26.3.1).
2. The life cycle of the power plants and equipment for renewable energy systems. Environmental impacts typically stem from the production stage and possible crediting can be gained through the disposal stage, which thus should not be dismissed.

Note that these rules are general, non-exhaustive and are not technology-specific: the practitioner shall still adopt a case-by-case approach before ruling out part of the energy system life cycles. Although Table 26.2, which shows environmental hotspots per life cycle stage and per energy technology, may be used as a screening step, the practitioners should assess any possible exceptions to these patterns in relation to their systems under study. For example, in situations (1), for biomass-based energy systems relying on waste, little impacts may be credited to the waste generation itself (e.g. zero-burden assumption), possibly making the life cycle of the power plants non-negligible in the total environmental burden: in such cases, the life cycle of the power plants should be comprehensively covered. The addition of carbon capture and storage system to fossil-fuelled power plants is another example, where the practitioners should also look into the life cycle of the power plants.

26.4.2.3 Selection of Impact Coverage

As reflected in the review of the impact coverage in Sects. 26.2.3 and 26.3.1, to avoid burden-shifting from one impact category to another, all impact categories are relevant for inclusion when assessing electricity and heat generation systems. In particular, practitioners should put emphasis on consistently including toxicity-related and resource-use-based impact categories in addition to the non-toxicity-related impact categories, such as climate change, acidification or eutrophication. Toxicity-related impacts associated with renewables-based electricity production have been shown to potentially remain at the same level as those related to fossil-based electricity production. A sole focus on climate change can thus be deceiving if one aims to assess the total environmental burden. Resource use indicators often turn out to be highly relevant for renewable energy sources, e.g. water use for hydropower, metal depletion for wind and solar power, land use for bioenergy systems, hydropower and wind power, etc.

26.4.2.4 LCI Modelling Framework and Handling of Multifunctional Processes

The ILCD guidelines being only recently available, a limited number of studies have performed LCAs on energy systems while attempting to follow these guidelines. The LCI modelling framework and handling of multifunctional processes have thus often been limited to choosing between the attributional and consequential modelling and in the selection of materials and energy mixes used in system expansion.

In practice, energy systems do not differ from other systems when it comes to define the LCI modelling framework and the respective handling of multifunctional processes. Examples of multifunctionality in energy systems typically include the co-generation of heat and electricity or the recycling of materials, which can affect the production stage (recycled materials used for construction/production of power plants, e.g. wind turbines) and the disposal stage (materials sent to recycling, e.g. PV module components, batteries, etc.). To address those, the detailed methodological guidance provided in Chap. 8 is therefore sufficient; the steps can be summarised as follows:

- In line with the identified decision context situations (i.e. A, B, C1, C2) in the goal definition, decide which of consequential or attributional modelling framework should be adopted.
- Characterise the multifunctional processes, for which subdivision, system expansion or allocation is required.
- In cases of system expansion: identify which processes should be used.
- In cases of allocation: identify, determine and describe the allocation key(s) used.

The detailed documentation of the processes used for system expansion or of the allocation key(s) should be reported in the LCI analysis section. Procedures and guidelines to do so are given in Chap. 9, to which the reader is referred for details. In the following Section, details are specifically provided to address allocation of energy co-generation processes and marginal energy mixes in system expansion cases, with a particular focus on the marginal technologies, respectively.

26.4.3 Inventory Analysis and System Modelling

The data collection and the building of the modelling generally do not differ from that of other systems, and guidance from Chap. 9 can thus be followed for performing the LCA phase. Our aspects are, however, emphasised in below sections, as they require attention from LCA practitioners in specific situations: (i) the LCI data availability to match the temporal, technological and spatial representativeness; (ii) the allocation principles for electricity and heat co-generation processes; (iii) the identification and modelling of marginal energy technologies; and (iv) the comprehensive scoping of the sensitivity analyses. Other aspects of relevance are the use of IO modelling, which are increasingly used for large-scale assessments of energy systems, and the modelling of indirect land use change, particularly relevant for bio-based systems; the reader is referred to Chaps. 14 and 30, respectively, which specifically address these issues.

26.4.3.1 LCI Data Availability with Temporal, Technological and Spatial Requirements

As indicated in Chaps. 8 and 9, the data collected in the LCI phase should match to the best possible extent the required data representativeness indicated in the scope definition. This aspect, which can be relatively simple for some product systems, can be challenging for some energy systems, for example when performing future-oriented studies or when assessing emerging technologies. Below are a number of points that should be considered along with guidance to address them, wherever applicable:

- *Systems with a time-oriented perspective*: the temporal and technological representativeness must be carefully addressed, e.g. in studies comparing different scenarios and different technologies in the future. Besides the definition of scenarios, LCA practitioners should ensure that the collected LCI data integrate a prospective dimension, e.g. including future technology developments, future evolutions of the market and future practices (e.g. in waste management). A typical example is the consideration of electricity mixes in consistency with the time period imposed by the scenarios analysed in the study. Evolutions of these mixes over time should thus be considered. Even more relevant in future-oriented modelling than in conventional case studies, it is important to document any assumptions or choices that make the modelling diverge from the data representativeness requirements as such discrepancies often can significantly influence the conclusions (and should thus be tested in sensitivity analysis). Future-oriented LCA is further discussed in Chap. 21.
- *Systems with spatial variation*: the spatial representativeness should be addressed, e.g. in studies with specific locations. Energy systems are strongly country- or region-specific, e.g. electricity grid mixes can vary considerably from one country to another. The modelling of energy systems should capture these geographical specificities with sufficient accuracy. LCI processes for electricity grid mixes are typically the best covered in available LCI databases, e.g. 50 countries differentiated in ecoinvent v.3 database (Treyer and Bauer 2013, 2014). If LCI processes are not readily available, LCA practitioners should either create processes or adapt existing ones to match the local or regional conditions (e.g. adapting the electricity grid mix in an ecoinvent process for a given country).

As indicated in Chap. 8, the geographical, temporal and technological representativeness are intertwined and it is likely that the two above aspects/sets of recommendations will apply to the same study, e.g. studies assessing the future deployment of a new energy technology on the market, including a comparison with existing ones.

26.4.3.2 Allocation of Electricity and Heat Co-generation Processes

In the case of allocation, energy indicators could be needed to perform allocation of co-generation processes. Three approaches may be selected: (i) allocation of all impacts to one of the output, electricity or heat, assuming that it is the main purpose of the process, (ii) allocation based on the energy content, assuming that a MJ of electricity is equal to a MJ of heat, thus using the respective electricity and heat outputs to derive the allocation key, and (iii) allocation based on the energy quality, recognising the higher quality of electricity over heat, for example in using exergy of the electricity and heat outputs as a basis for the allocation key (Fruergaard et al. 2009). Exergy indicates the extent of the energy that can be converted to work: while electricity has an exergy factor of 1, heat has a variable exergy factor typically around 0.15–0.20 depending on the temperature of the delivered heat and the temperature of the surroundings (Fruergaard et al. 2009). Approach (i) is rare and requires to be well argued by the practitioner if used. Approaches (ii) and (iii) are the most commonly applied approaches for allocation of energy processes. Note that allocation based on energy quality will associate most of the burden to electricity, while allocation based on energy content will shift most of the burden to heat production.

26.4.3.3 Modelling of Marginal Energy Technologies

By definition, marginal data represent the technology or process actually affected by the changes (Weidema et al. 1999). The time perspective is important to consider when identifying that technology or process. For example, if an increase in electricity demand in a country like Denmark that relies heavily on wind turbines for electricity generation occurs in an hour or day when wind blows, the marginal technology for electricity supply at that moment could be wind power (and may change later on if wind stops). This type of very short-term/instantaneous marginal is however not relevant in LCA studies, where aggregation over time is performed. Averages of marginal technologies would be more relevant to use, for example estimating that wind is the marginal technology for a cumulative two months of the year and other sources are marginal technologies for the remaining cumulative 10 months. This leads to the creation of mixes of marginal technologies. Such examples only consider short-term marginal technologies, i.e. existing technologies capable to respond to a change in demand (no impact on capital investments). They should be distinguished from long-term marginal technologies, i.e. technologies for which the production capacities are impacted in a long-term perspective (e.g. >10 years), like the closure of old coal-fired power plants or the installation of new wind turbines.

For studies in decision context situation B, a mixed consequential/attributional modelling is required, with the use of system expansion for solving process multifunctionality. The processes impacted by structural changes in the background system should be modelled using mixes of long-term marginal processes while the others are modelled using short-term marginal or average processes (see Chap. 8).

Difficulties arise in identifying and determining the mixes of long-term marginal processes, and important differences in the results might arise depending on what marginal technologies are assumed (e.g. renewables versus fossils-based energy sources). Although Chap. 9 provides some practical guidance to support LCA practitioners in that effort, to which the reader is referred, no consensus currently exists on ways to identify these mixes of long-term marginal technologies. This results in important uncertainties for processes that are included in nearly all LCAs. With respect to energy processes, if these are decisive for the outcome of the study, the use of explorative scenarios is typically recommended to model several possible mixes of long-term marginal technologies (e.g. Schmidt et al. 2011; Münster et al. 2013). LCA practitioners should include these as part of their sensitivity analyses, which will thus enable them to assess and understand the range of potential environmental consequences associated with the implementation of their analysed systems.

26.4.3.4 Importance of Sensitivity Analysis

As part of the LCI analysis phase, practitioners need to prepare the basis for uncertainty and sensitivity analyses (see Chap. 9). This can be regarded as a scoping and identification of key parameters that need to be varied in the assessments. This identification is an iterative process, e.g. going back and forth with the LCIA phase and the results obtained to pinpoint the processes and associated key parameters that are influential on the results.

With respect to energy systems, there is a case dependency on which parameters to include. As for any LCA studies, the identification of major modelling assumptions, such as the identification of mixes of long-term marginal technologies or the inclusion of indirect land use change effects, should systematically lead to sensitivity analyses. Additional sensitivity analyses may also stem from the large application of LCA to emerging technologies and/or to systems taken in a prospective dimension (e.g. future-oriented assessments). These types of studies are associated with large uncertainties due to the use of scenarios and the inadequacy of data (e.g. lab-scale data for an emerging energy technology to represent a fully deployed system in the future) or, worse, the lack of it (data not yet generated). Such situations call for sensitivity analyses to address the temporal dimension and inherent uncertainties in the modelling. Practitioners are therefore recommended to develop explorative scenarios based on all key parameters pertaining to the evolution of the technologies or systems in time. Examples of such parameters include the efficiencies of the plants, the lifetime of the infrastructure, the type and performances of disposal routes (e.g. recycling), the emission factors, etc.

26.5 Conclusions

This chapter provides a glimpse at how LCA has been applied to energy systems and technologies in the past two decades and what learnings can be gained from the large body of LCA studies. The review provided herein is not intended to be exhaustive because of the large extent and diversity of energy systems. Nevertheless, it brings sufficient insights to realise that the application of some key methodological steps could be improved. For example, a comprehensive coverage of the system life cycle (e.g. including the often-overlooked disposal or decommissioning stage) and of all relevant environmental impacts (e.g. not just addressing climate change or energy-related questions) should be better ensured in future studies.

Life cycle assessment is still a relatively young field and the methodology is constantly being improved. In that respect, several methodological aspects relevant to assessments of energy systems need to be further developed and accepted within the LCA community. Some of them relate to the LCI or system modelling, e.g. the inclusion of indirect land use change for bio-based systems or methodologies to consistently identify mixes of long-term marginal technologies. Others relate to LCIA and are not necessarily specific to energy systems, like for example the assessment of climate change impacts in a dynamic perspective (e.g. relevant to use of carbon capture and storage systems). The inclusion of the temporal perspective in LCA studies of energy systems is particularly relevant as many policy makers currently define and/or fine-tune energy pathways for the future decades (e.g. IEA 2014), and require foresight assessments that can anticipate the impacts in the future from current and forthcoming energy technologies. Frameworks for consistently conducting such foresight LCA studies still need to be developed (Laurent and Espinosa 2015). This development can also be expected to run in parallel to a continued increase in the application of LCA to large-scale energy systems, such as electricity supply systems at urban, national or regional scales, and thus efficiently and effectively support high-level energy policy-makers.

Appendix

See Table 26.4.

Table 26.4 Non-exhaustive overview of LCA studies assessing the different energy technologies/sources

Energy sources/technology focus	Main findings
Hard coal and lignite Direct combustion, gasification combustion, flue gas cleaning, physical/chemical cleaning process, carbon capture and storage technologies	– Emissions in combustion processes and supporting processes (e.g. demineralization of fuels) drive the impacts, with process efficiency and types of technology (e.g. direct combustion vs. gasification combustion, inclusion of cleaning processes, etc.) as key factors (e.g. Gagnon et al. 2002; Turconi et al. 2013; May and Brennan 2003; Ryberg et al. 2015; Masanet et al. 2013). Fuel supply chain contributes to a lesser extent, with contributions depending on plant settings, e.g. existence of flue gas cleaning system, and fuel type, e.g. sulphur content, metal content (Dones et al. 2005) – Important emission reductions can be achieved (e.g. on old power plants) via cleaning of the fuels although environmental trade-offs exist between the added impacts from cleaning processes and the resulting saved impacts (e.g. Nomura et al. 2001; Ryberg et al. 2015). This also induces shift of impacts from the combustion processes to the cleaning processes or to other parts of the life cycle (e.g. fuel supply chain) – The review/meta-analysis by Schreiber et al. (2012) showed that the three carbon capture and storage technologies (post-combustion, oxyfuel, pre-combustion) lead to the expected reductions in climate change impacts but to increases in many other environmental impacts regardless of capture technology, time horizon and fuel type (coal, lignite or natural gas). Three influential parameters are the (i) power plant efficiency and the added energy requirements from capture process, (ii) the CO_2 capture efficiency and purity, (iii) the fossil fuel origin and composition (Schreiber et al. 2012)
Natural gas Single-cycle or combined cycle turbines	– The majority of the literature has a narrow scope on CO_2 emissions and NO_x and SO_2, to a lesser extent – Emissions of greenhouse gases dominated by use stage, but with significant contributions also from the fuel provision due to fugitive emissions of methane and energy requirements in gas extraction and transportation (Gagnon et al. 2002; Dones et al. 2005; Masanet et al. 2013) – For use of carbon capture and storage technologies, see above row on hard coal and lignite (Schreiber et al. 2012)
Shale gas Combined cycle gas turbines	– Albeit with large uncertainties and variability in the impact results, depending on assumptions and types of technology in use, impact results from various studies suggest that shale gas seems comparable to conventional gas for climate change, with ranges of with a range of 416–730 g CO_2-eq/kWh. Taking the study by Stamford and Azapagic (2014) on electricity in UK from shale gas produced by fracking, it ranges within 412–1102 g CO_2-eq/kWh, thus in the lower end of fossil fuels but in the higher end of the renewables (see also Fig. 26.4). Toxicity impacts are found to be higher than for conventional gas (Stamford and Azapagic 2014) – Differences of impacts with other energy sources are due to assumptions regarding fugitive emissions during shale gas extraction and due to differences in the recoverable resources (Stamford and Azapagic 2014)

(continued)

Table 26.4 (continued)

Energy sources/technology focus	Main findings
Oil Fuel oil cycle	– Emissions (e.g. GHG, NO_x) mainly stem from the use/operations of the power plant. Like-for coal, fuel supply chain contributes to a lesser extent, with contributions depending on plant settings, e.g. existence of flue gas cleaning system, and fuel type, e.g. sulphur content, metal content (Dones et al. 2005) – Energy utilisation efficiencies are an additional influential parameter, inducing variations in the impact results, e.g. base-load power plants with efficiencies up to 58% (ca. 530 g CO_2-eq/kWh) versus peak-load power plants with efficiencies of 30–40% (ca. 750–900 g CO_2-eq/kWh) (Turconi et al. 2013)
Nuclear energy Closed/open fuel cycles, pressurized/boiling water reactors	– Large focus on GHG and little focus on other environmental impacts (Turconi et al. 2013; Poinssot et al. 2015a, b) – Nuclear energy production is the most important activity source, which contributes to the impact category ionising radiation in LCA studies – Uranium extraction and enrichment processes are the drivers for most environmental impacts, i.e. >70% (Poinssot et al. 2015a, b; Masanet et al. 2013) – Large variability in emission factors (and resulting impacts) depending on the type of technology and the assessment approaches, incl. assumptions on uranium extraction and enrichment processes and handling of nuclear waste (Warner et al. 2012; Turconi et al. 2013). For climate change, such variations of up to one order of magnitude were observed in studies (Turconi et al. 2013; Masanet et al. 2013) – Ecodesign initiatives should focus on optimising nuclear fuel cycle, reduce impacts at mining of uranium, and improving the recycling of uranium and plutonium from spent fuel (Poinssot et al. 2015a, b; Masanet et al. 2013)
Wind power On-shore, off-shore (less common	– Important focus on emissions and/or energy accounting, e.g. EPBT (e.g. Wang and Sun 2012; Dolan and Heath 2012; Schleisner 2000) – Manufacturing of the wind turbines is the only life cycle stage that is common to all LCA studies (Arvesen and Hertwich 2012). Other stages are omitted in some studies – On-shore and offshore turbines can have similar emission factors because larger emissions during the construction phase of offshore turbines can be compensated by their higher efficiency during use (Turconi et al. 2013) – The environmental impact of wind technologies is concentrated mainly in the manufacturing stage and to a smaller extent in the disposal stage but is at a minimum in the operational/use stage. Impact per generated power is strongly influenced by the operating lifetime, quality of wind resource, conversion efficiency and size of the wind turbines (Masanet et al. 2013; Caduff et al. 2012)

(continued)

Table 26.4 (continued)

Energy sources/technology focus	Main findings
	– Three major components mainly contribute to the overall environmental impacts: rotor (due to fibre glass), tower (incl. foundation; due to reinforced steel) and nacelle (due to energy-requiring fibre glass and use of copper in different electrical components) (Martinez et al. 2009; DONG Energy 2008) – Disposal stage can contribute to significant decreases of impacts when recycling of valuable materials replaces production of virgin materials (Martinez et al. 2009; Weinzettel et al. 2009)
Solar power—Photovoltaics technologies e.g. crystalline silicon (Si) photovoltaics (PV), cadmium telluride PV, copper indium gallium diselenide PV, organic PV, perovskites, etc.	– Large body of studies assessing PV technologies (see reviews—total of over 400 studies—by Hsu et al. 2012; Kim et al. 2012; Gerbinet et al. 2014; Sherwani et al. 2010; Chatzisideris et al. 2016). Large focus on climate change and energy indicators, e.g. EPBT and EROI – Large variability in the results due to differences in methodological choices (e.g. system boundaries) and to types/specificities of systems assessed, e.g. source of electricity used in manufacturing, solar panel typology, climatic conditions, irradiation (Sherwani et al. 2010; Masanet et al. 2013) – For Si-PV technology, impacts stem mainly from the manufacturing stage due to the energy requirements in the upstream processes, e.g. production of Si and PV wafers. Gains in energy efficiencies are foreseen, e.g. as already observed with Si ingot growth by the Czochralsky process (Frankl et al. 2006) – Balance of system (BOS) components, e.g. inverters, insulators, supporting structure, have largely been omitted in past studies and only recently have started to be included in LCA studies (Gerbinet et al. 2014; Espinosa et al. 2015). Results suggest that their impacts are not negligible (e.g. Espinosa et al. 2015; Gerbinet et al. 2014) – In organic photovoltaics, silver used as electrode is overall the largest source of impacts (e.g. toxicity-related impacts, metal depletion), thus calling for establishing efficient recovery systems in the disposal stage (Espinosa et al. 2015) – Disposal stage/end-of-life of the materials has been largely omitted in past LCA studies (e.g. see reviews of Gerbinet et al. 2014; Chatzisideris et al. 2016). Recycling the material in PV modules is already economically viable, mainly for concentrated and large-scale applications. Projections are that between 80 and 96% of the glass, ethylene vinyl acetate, and metals (tellurium, selenium, lead) will be recycled. Other metals, such as cadmium, tellurium (Te), tin, nickel, aluminium and copper, should be saved or they can be recycled by other methods (IPCC 2012). Recycling of materials has been demonstrated to be influential on the impact results in some LCA studies (e.g. Espinosa et al. 2015)
Solar power—Concentrated solar power technologies	– Studies have primarily focused on parabolic trough and tower technologies, and to a lesser extent on parabolic dish – Overall, studies have a strong focus on climate change and energy indicators, with little consideration of other environmental impacts (e.g. land use)

(continued)

Table 26.4 (continued)

Energy sources/technology focus	Main findings
e.g. solar towers, parabolic trough, dish Stirling (i.e. parabolic dish), linear Fresnel reflectors	– For parabolic trough plants, the solar field was reported to be a main driver of impacts, primarily stemming from the manufacturing stage due to the steel, molten salt and synthetic oil requirements (e.g. Burkhardt et al. 2011; Ehtiwesh et al. 2016). The storage system was reported to have a relatively lower contribution to environmental impacts. While Burkhardt et al. (2011) report a significant contribution from the power plant unit, Ehtiwesh et al. (2016) found a negligible influence. Differences in the methodologies considered and in the assumptions made may explain these discrepancies, and more comprehensive studies are needed – Studies have suggested that the electrical efficiency is important for the environmental performances of the systems, e.g. fewer mirrors for a same electrical output yielding lower impacts (e.g. land use, etc.) (e.g. Viebahn et al. 2008)
Hydropower Reservoir-type, run-of-river (both small and large scale)	– Materials manufacturing and construction of plants are important drivers of the impacts, e.g. cement, reinforced steel, electric equipment and energy used in construction activities. Remoteness of hydropower plants increasing contribution from construction and transportation stages and decreasing transmission efficiencies (Suwanit and Gheewala 2011; De Miranda and da Silva 2010; Masanet et al. 2013) – Differentiation of impacts between run-of-river and reservoir technologies due to important aspects, e.g. CH_4 emissions from anaerobic degradation of biological materials in reservoirs for climate change; evaporative losses of water for water use in reservoirs; large stagnant water areas in reservoirs causing eutrophication, land use and human toxicity impacts (Masanet et al. 2013). Large influence of these aspects on the impact results, thus leading to large variations in the impact results in the literature as a consequence of different assumptions (Masanet et al. 2013; Suwanit and Gheewala 2011) – Strong focus on climate change and energy indicators (CED, EPBT). Other impacts addressed to a lesser extent, with less consideration for land use, water use and toxicity-related impacts – None of the retrieved studies made quantitative considerations regarding the secondary utilisation of water (drinking, irrigation or navigation purposes)
Geothermal power Hydrothermal resources producing hot water and/or steam	– Few LCA studies on geothermal power plants (Bayer et al. 2013), coupled with high degree of technology- and site-specificity of the case studies, e.g. Italy (Buonocore et al. 2015; Bravi and Basosi 2014) or Germany (Frick et al. 2010; Lacirignola and Blanc 2013), make it difficult to generalise (Bayer et al. 2013) – The assessment of toxicity-related impacts, e.g. from heavy metals, have not been sufficiently addressed in past studies to discuss their potential relevance in geothermal power generation (Bayer et al. 2013) – Strong influence of quality of geothermal source, maturity of the plant, conversion efficiency, etc.
Bioenergy	See Sect. 26.3.1, Cherubini and Strømman (2011) and the extensive discussion in Chap. 30

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