Systematic Review and Meta-Analysis of Life Cycle Assessments for Wood Energy Services

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Summary

Environmental impacts of the provision of wood energy have been analyzed through life cycle assessment (LCA) techniques for many years. Systems for the generation of heat, power, and combined heat and power (CHP) differ, and methodological choices for LCA can vary greatly, leading to inconsistent findings. We analyzed factors that promote these findings by conducting a systematic review and meta-analysis of existing LCA studies for wood energy services. The systematic review investigated crucial methodological and systemic factors, such as system boundaries, allocation, transportation, and technologies, for transformation and conversion of North American and European LCA studies. Meta-Analysis was performed on published results in the impact category global warming (GW). A total of 30 studies with 97 systems were incorporated. The studies exhibit great differences in their systemic and methodological choices, as well as their functional units, technologies, and resulting outcomes. A total of 44 systems for the generation of power, with a median impact on GW of 0.169 kilograms (kg) of carbon dioxide equivalents (CO_2-eq) per kilowatt-hour (kWh_{el}), were identified. Results for the biomass fraction only show a median impact on GW of 0.098 kg CO_2-eq * $kWh_{el}{}^{-1}$. A total of 31 systems producing heat exhibited a median impact on GW of 0.040 kg CO_2-eq * $kWh_{th}{}^{-1}$. With a median impact on GW of 0.066 kg CO_2-eq * $kWh_{el+th}{}^{-1}$, CHP systems show the greatest variability among all analyzed wood energy services. To facilitate comparisons, we propose a methodological approach for the description of system boundaries, the basis for calculations, and reporting of findings.

Introduction

The generation of energy services (heat, power, or combined heat and power [CHP]) from wood is seen as a promising option to replace nonrenewable energy sources and, consequently, reduce associated greenhouse gas (GHG) emissions (Gielen et al. 2000). This positive effect of wood energy is further strengthened by its regional availability and renewable character (Steirer 2010; UNECE 2010). Nevertheless, the provision, transformation, and conversion of wood energy services also cause detrimental environmental effects. Among other factors, nonrenewable resources and fuels employed during the individual life cycle stages, as well as non-CO_2 (carbon dioxide) emissions during the combustion of wood fuels, have a significant impact on global warming (GW). Typically, the environmental effects of products and services are analyzed by life cycle assessment (LCA) studies. Even for comparable bioenergy services, however, the lack of a standardized, transparent assessment methodology for solid biomass fuels (e.g., for wood) leads to a wide range of different approaches,

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methodological choices, and, consequently, a great variety of results. The field of LCA is already covered by several standards and guidelines, such as the EN ISO 14040 (ISO 2006a) series or the Joint Research Center's International Reference Life Cycle Data System (ILCD) Handbook (EC 2010), which cover LCA in a wide sense. Many times, however, these generalized guidelines are not able to effectively deal with the wide variety of modeling choices and problems of the multitude of goods and services that are being analyzed through LCAs today. As a reaction and in order to streamline and harmonize LCA execution, the LCA community has, in recent years, commenced the formulation of product-specific guidelines, the Product Category Rules (PCRs). For a variety of goods and services, PCRs have already been published (e.g., dairy and construction products), but many products remain to be covered. Though wood is a renewable resource, it is not an infinite resource. Therefore, it is necessary to identify the most beneficial and efficient utilization of wood using a standardized and recognized methodology for the assessment of solid bioenergy impacts. The assessment of GHG emissions is a crucial building block in this methodology. On the basis our previous work, a contribution to a consistent methodology for the assessment of environmental effects of the provision of raw wood has been proposed (Klein et al. 2014), whereas this current article expands the scope of Klein and colleagues (2014) into subsequent phases in the life cycle of wood, with a focus on its energy-related uses. To summarize and synthesize the current state of knowledge and stimulate discussion on further challenges in methodological development, we conducted a systematic review and meta-analysis on the basis of the following research questions:

1. Which systematic and methodological choices are currently made by the scientific community in order to assess the envrionmental burdens of wood energy?
2. What is the range of published GHG emissions and which factors have an influence on these results?
3. Which suggestions can be made for the harmonization of LCA methodologies to create more transparent and comparable results for wood energy systems?

Methodology

To synthesize and discuss approaches, issues, and findings of wood energy LCAs, we conducted a systematic review of existing literature followed by a meta-analysis of published results. The process of identifying and evaluating multiple studies on a topic using a clearly defined methodology is called systematic review. Meta-Analysis is an effective, rigorous statistical approach to synthesize data from multiple studies, preferably obtained from a systematic review, in order to enlarge the sample size from smaller studies to test the original hypotheses (Neely et al. 2010). Through the systematic review procedure, a transparent analysis of key scientific contributors could be conducted with minimal bias. The review was followed by a meta-analysis that included statistical synthesis of findings to obtain reliable conclusions, otherwise unavailable from individual studies alone (Tranfield et al. 2003). The systematic review followed the "STARR-LCA" principle, a standardized technique for assessing and reporting LCA studies (Zumsteg et al. 2012). Zumsteg and colleagues (2012) proposes a nine-step checklist for efficiently conducting consistent systematic reviews of LCAs commencing with the description of the review protocols employed. They further propose to tie features and findings of individual studies together with an appropriate method for synthesis. In the case of this review, both quantitative and qualitative synthesis methods were applied.

Systematic Review Protocol

Literature for this review was located by databases such as Web of Knowledge or scientific search engines such as Science Direct, Springer Link, and Wiley Online Library. Google Scholar search was also included when the above-mentioned databases could not provide matches. Additionally, references in available literature were used to locate new literature.

For the database search, combinations of synonyms of the terms LCA ("life cycle assessment," "life cycle analysis," and "environmental analysis"), wood ("biomass," "wood residue," forest wood," "forest residue," "sawmill residue," "woody biomass," "chip," and "pellet"), and energy ("heat," "electricity," "power," "CHP," "combined heat and power," and "bioenergy") were employed.

A first practical screening of available literature based on information provided in titles, abstracts, keywords, and the results determined the inclusion of specific literature in a further screening step. In this subsequent step, studies were excluded that:

- Were published before 2000 in order to reflect the state of the art and recent developments,
- Were non-English-language studies,
- Were not conducted for a European, North American, or comparable regions (with respect to climate, forestry, and wood use practices),
- Were not published in peer-reviewed journals (with the exception of Bauer [2008]),
- Were limited to the life cycle of a wood fuel without any conversion processes (fuel to energy) included in the analysis,
- Were concerned with energy from waste wood, short rotation wood, or any other agricultural biomass,
- Did not contain results based on the application of LCA, and
- Did not include comparable, quantitative findings, such as results for the impact category GW.

After this second screening, 30 studies deemed suitable remained for a descriptive analysis.

Descriptive Analysis (Qualitative Synthesis)

For the descriptive analysis, we chose a set of decisive parameters that were identified in the 30 individual studies and that were consistent with the recommendations for major aspects of energy generation LCAs provided in Jungmeier and colleagues (2003). Parameters for the descriptive analysis:

- System boundaries,
- Reference system,
- Data sources,
- Functional units,
- Allocation procedures,
- Reported impact categories and characterization method,
- Wood feedstock properties,
- Conversion technology,
- Combustion capacity and efficiency and cocombustion rates,
- Transportation distances and types, and
- Energy service provided (power, heat, and CHP).

All 30 studies were analyzed according to these parameters. Because many studies (n = 22) are concerned with more than one system or case study (e.g., through integration of various scenarios for the above-mentioned parameters), the total number of individual systems that were assessed was 97. For the list of the 97 systems, see supporting information S2 on the Journal's website.

Meta-Analysis (Quantitative Synthesis)

In addition to the descriptive analyses, we conducted a meta-analysis, in which all published mid-point impact category GW-equivalent results were recalculated to the common functional unit of kilograms of carbon dioxide equivalents per kilowatt-hour (kg CO_2-eq * kWh^{-1}). The impact category GW was chosen because, unlike other impact categories, all of the studies provided findings for this category. The results were grouped according to provided energy service (heat, power, and CHP), conversion technology (thermochemical conversion [TC], direct conversion [DC], and cocombustion [CC]) and combustion capacity (>100 megawatts [MW], ≤100 MW, and not specified [NS]). Additionally, for CC systems, the biomass fraction of emission was extracted to remove the influence of fossil emissions on the overall findings. Especially for heating systems and small-scale power and CHP generating systems, a further partitioning into groups of combustion capacities below 100 MW would be favorable owing to the impacts of the size of the combustion facility, but the provided data were insufficient for this stratification. In this current form, the meta-analysis, without any normalization or harmonization of key parameters between the studies, can only show the spread of results per group. Unfortunately, the published results included in the 30 studies do not provide the appropriate level of detail required for harmonization, thereby demonstrating, at this stage of the review, that a standardized, transparent documentation is necessary. One hundred twenty-two individual values, which are based on variations in key parameters and are derived from the 97 systems, form the basis of the meta-analysis.

All quantitative descriptions and statistical analyses were conducted using STATISTICA 10 software.

Results and Discussion

Descriptive Analysis of Wood Energy Life Cycle Assessments

This section presents an overview of the reviewed studies and key information. Results are summarized in table 1. In accord with the systematic review protocol described in the section *Systematic Review Protocol*, a total of 30 studies were identified. Although the number of LCAs related to biomass is quite large, forest biomass LCAs for energy purposes are less numerous. The reason may be the nature of wood, which is considered a raw material with low inherent emissions associated with its life cycle. Although many studies show that emissions caused by the provision of raw wood might be small, subsequent life cycle stages may generate considerable emissions.

Publication Date

To select the most current studies, in terms of both LCA methodology and technologies applied, the systematic review protocol was designed to include only studies after the year 2000, with the exception of Hartmann and Kaltschmitt (1999), which was already conducted under the ISO 14040ff. standards. The majority of the studies reviewed (n = 19; 63%) were published in the last 5 years (2010–2014), indicating that the awareness of LCA in the scientific community, as well as the general public and policy makers, has increased. For the fulfillment of the European Union's (EU) 20-20-20 goal in particular, LCAs play a crucial role in quantifying emission reduction options and strategies (EC 2009,2010b).

Geographical Context

Most studies have been found for Europe (n = 21), followed by North America (n = 8), and one Japanese study. Within Europe, the majority of studies originate from Norway (n = 4) and Germany (n = 4).

Technologies

For reasons of comparability, in this study, the process of transformation is defined as the transformation of wood to wood fuel (e.g., chipping, pelletizing, and torrefaction), whereas the term conversion means the conversion of wood fuel to energy.

Given that the technology associated with conversion of wood to energy or an energy carrier is one of the main factors to be considered in an LCA of wood energy generation (Jungmeier et al. 2003), the 97 systems assessed in this study were classified into groups according to conversion technology. Additionally, LCAs were grouped according to the provided energy service (heat, power, or CHP) (table 1). A total of 44 systems are purely concerned with the LCA of power generation, whereas 31 system LCAs focused on heat generation. The remaining

Table 1 General description of analyzed wood energy LCA studies

Ref	Authors	Year	Country	Systems assessed	Product			Conversion technology	Goal of study	Reference system	Data sources
					Heat	Power	CHP				
1	Bauer	2008	EU	6		x		DC/CC	Assessment and comparison of different fuel chains and identification of hotspots for electricity production through LCA	FF	ED, ecoinvent
2	Caserini and colleagues	2010	IT	6	x		x	DC	LCA of domestic and centralized biomass combustion for heat and CHP	FF	L, ED, DB
3	Cespi and colleagues	2013	IT	2	x			DC	Comparison of environmental impacts of two wood-based combustion systems: a wood stove and a pellet stove with best available technology	FF/RE	L, ecoinvent
4	Damen and Faaij	2005	NL	4	x	x	x	CC/DC	Evaluation of impacts of pellet cofiring in comparison to classical use of pellets without import	FF/RE	ED, L, Gemis, ecoinvent
5	Esteban and colleagues	2014	SPA	9	x			DC	Comparative environmental evaluation of wood fuel for heating boilers of varying power levels	FF	ED, GP
6	Fan and colleagues	2010	USA	5		x		TC	Investigation of environmental effects of different feedstocks and technologies for pyrolysis oil combustion for power generation	FF/RE	ED, L
7	Felder and Dones	2007	CH	2	x			TC/DC	Comparison of ecological impacts of SNG heating systems with standard heating systems	FF/RE	ecoinvent, ED
8	Froese and colleagues	2010	USA	1		x		CC	Evaluation of GHG mitigation potentials in coal power plants through co-firing with biomass	FF	L, DB
9	Ghafghazi and colleagues	2011	CAN	1			x	DC	LCA of four heat source options for the base-load system of a district heating center	FF	ED, L, ecoinvent
10	Guest and colleagues	2011	NOR	3			x	TC	Assessment of impacts and most suitable plant size for CHP production and distribution	NS	ED, S, ecoinvent, Gemis

(Continued)

Table 1 Continued

Ref	*Authors*	*Year*	*Country*	*Systems assessed*	*Product*			*Conversion technology*	*Goal of study*	*Reference system*	*Data sources*
					Heat	*Power*	*CHP*				
11	Hartmann and Kaltschmitt	1999	GER	1		x		CC	Analyses of selected environmental effects of biomass co-combustion with hard coal	FF	NS
12	Henkel and colleagues	2009	GER	1	x			DC	Comparison of environmental performance of different heating systems of the present and the near future	FF/RE	Gemis
13	Henning and Gawor	2012	GER	3		x	x	DC/CC	Identification of German biomass conversion pathways with the smallest environmental impacts	FF/RE	ecoinvent, DB, L
14	Jäppinen and colleagues	2013	FIN	5	x	x	x	DC/CC/TC	Assessment of GHG emissions of forest bioenergy supply and utilization in Finland	FF	L, I
15	Katers and colleagues	2012	USA	1	x			DC	Assessment of environmental impacts of wood pellet manufacturing and use	FF	ED, U.S. LCI DB
16	Mälkii and Virtanen	2003	FIN	6			x	DC	Evaluation of environmental performance of six wood chip energy systems	NS	ED
17	Mann and Spath	2001	USA	2		x		CC	Assessment of impacts and trade-offs of biomass cofiring in coal power plants	FF	ED, L
18	Pa and colleagues	2013	CAN	2	x			DC	Investigation of consequences of using wood pellets to replace firewood for residential heating in BC, CAN	RE	ecoinvent, DB
19	Pehnt	2006	GER	7	x	x		DC	Status-quo emissions of renewable energy systems and dynamic analysis for future foreground and background systems and energy mixes	FF/RE	DB, L
20	Petersen Raymer	2006	NOR	6	x			DC	Analyses of GHG emissions, substitutions, GHG reduction potentials, and major sources of uncertainty of various kinds of wood energy	NS	ED

(Continued)

Table 1 Continued

Ref	Authors	Year	Country	Systems assessed	Product			Conversion technology	Goal of study	Reference system	Data sources
					Heat	Power	CHP				
21	Pucker and colleagues	2012	AUT	4	x			TC/DC	Analysis of GHG and energy balances of the production and use of bio-SNG for space heat	RE	Gemis
22	Puy and colleagues	2010	SPA	1			x	TC	Analyses of environmental loads and hotspots of postconsumer wood and forest residues gasification	NS	ED, ecoinvent v.1.2
23	Royo and colleagues	2012	SPA	1		x		CC	Assessment of biomass cofiring potentials and GHG emissions reductions for large territories	FF	
24	Kabir and Kumar	2012	CAN	6		x		CC	Analysis of environmental impacts of biomass cofiring	FF	ED,L
25	Siegl and colleagues	2011	AUT	2			x	DC/TC	Assessment of direct life cycle emissions and hotspots from electricity generation in small scale biomass plants	NS	I, ecoinvent v.1.3
26	Sjølie and Solberg	2011	NOR	9	x	x	x	DC/CC	Analysis of GHG emissions, FF emission reductions potentials, hotspots, and substitution economics of pellets produced in Western Europe	FF	L
27	Solli and colleagues	2009	NOR	1	x			DC	Evaluation of environmental effects of wood-based household heating in new stoves	RE	ED, L
28	Steubing and colleagues	2011	CH	3	x	x	x	TC	Analyses of environmental impacts of production and use of SNG from lignocellulosic biomass by gasification and catalytic methanation	FF/RE	ED, ecoinvent 2.2
29	Tabata and colleagues	2011	J	1		x		CC	Evaluation of GHG reduction potentials of the cofiring of semicarbonized fuel from woody biomass	FF	ED, L
30	Zhang and colleagues	2010	CAN	4		x		CC/DC	Evaluation of emissions of 100% wood pellet firing and cofiring with coal	FF	ED, DB, L

Note: CC = cocombustion; CHP = combined heat and power; DB = unspecified database; DC = direct combustion; ED = empirical data; FF = fossil fuel, GHG = greenhouse gas; GP = Gabi Professional Database; I = interviews; L = literature; LCA = life cycle assessment; NS = not specified; RE = renewable energy; S = simulation; SNG = synthetic natural gas; TC = thermochemical; U.S. LCI DB = U.S. Life Cycle Inventory Database.

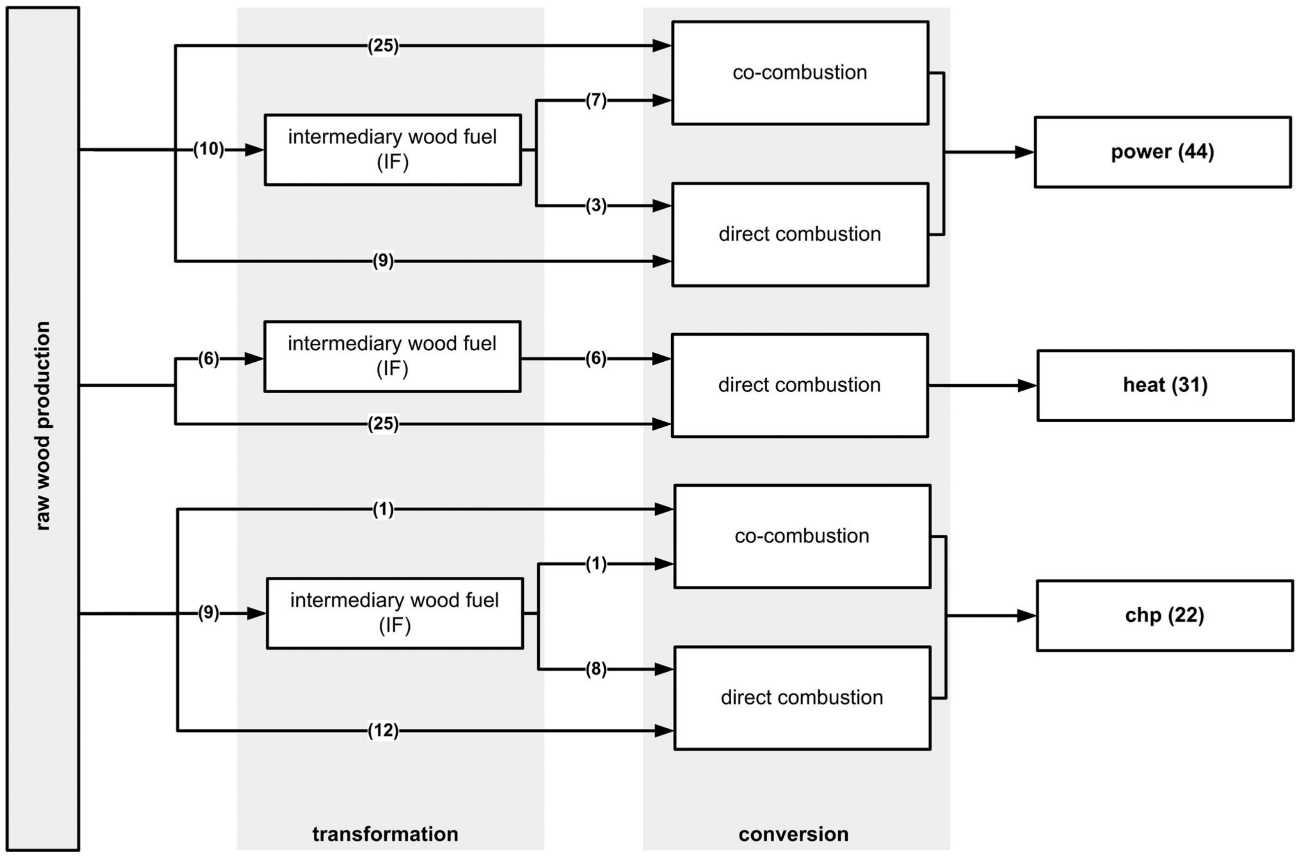

Figure 1 Transformation and conversion technologies employed by LCA studies. Numbers depict the amount of systems concerned with the respective technology and or service.

22 systems analyze CHP systems. For the generation of electricity, mainly the CC of virgin wood (n = 25) and intermediary wood fuels (n = 7) (production of, e.g., synthetic natural gas [SNG], pyrolysis oil, or torrefied wood pellets through the application of a TC pretreatment of the wood) with fossil fuels (FFs) or the DC of virgin wood (n = 9), or an intermediary fuel (n = 3) is assessed. Systems concerned with the generation of heat and CHP employ a wide range of technologies. In this group, two systems were identified wherein CHP was generated through a CC process (System 26/I [Sjølie and Solberg 2011] or System 14/D [Jäppinen et al. 2013]). The remainder of the CHP-generating systems employ either DC (n = 12) or the addition of the production of an intermediary fuel followed by the DC of said intermediary wood fuel (n = 8). The generation of heat is carried out primarily through DC (n = 25) or the combustion of intermediary wood fuels (n = 6) (figure 1).

Data Sources

The majority of studies are based on empirical data (ED) for their system assessments. Additionally, literature (L) and databases play an important role, whether for the fore- or background system. The most commonly used database is the Swiss ecoinvent database, followed by the German Gemis database, as well as other unspecified databases (DB) (table 1). Several other data sources, such as simulations (S), expert interviews (I), the Gabi Professional (GP) and U.S. Life Cycle Inventory (U.S. LCI) database, were also employed. The utilization of each data source is as follows: ED: n = 18; L: n = 15; ecoinvent: n = 11; Gemis: n = 4; DB: n = 6; I: n = 2; S: n = 1; U.S. LCI: n = 1; GP: n = 1. It was additionally assessed whether the studies rely solely on secondary data (n = 9) or if only primary data without a specified database or literature source are utilized (n = 2).

Reference System

The type of reference system employed was also analyzed for the 30 studies. Although the newer trend of also referencing against a renewable energy system is observable (2005–2014; n = 8), the classic fossil reference system is particularly prevalent in recent studies (2010–2014; n = 11). This is owing to the increased attention of biomass in CC applications in recent years. In total, 14 of the analyzed studies employ a fossil reference system, whereas eight studies choose a combination of fossil and renewable fuels. Three studies reference their results against a purely renewable energy system, whereas five studies do not specify any reference system.

System Description

The specification of system boundaries is an early and crucial step in the realization of an LCA because it defines included processes and specifies which processes remain outside of the scope

Table 2 Systems identified in the systematic review, sorted by provided energy service

	System (supporting information S2 on the Web)	Conversion			Feedstock					Biomass procurement		Transportation				
Ref		Technology	Power (MW)	Net efficiency	FW/FWR	IWR	LHV (MJ/kg)	MC (%)	IF	Comprehensive	Harvest/ collection only	Length (km)	Type	BEOL	CE	FU
Power																
13	C	DC	4.0	20	x		NS	NS		x		NS	NS	x	NS	1 kWh_{el}
6	E	TC	5.0	40.9	x		18	0	PO	x		23.72	L			1 kWh_{el}
6	D	TC	9.6	39	x		18	0	PO	x		33.7	L			1 kWh_{el}
6	F	DC	10.0	18	x		18	0		x		17.97	L			1 kWh_{el}
6	G	DC	10.0	25	x		18	0		x		15.25	L			1 kWh_{el}
6	A	CC	19.6	33	x		18	0	PO	x		51.34	L			1 kWh_{el}
1	A	DC	20.0	32	x		7.9	35.1		x		25–1,000	L, R, B		x	1 kWh_{el}
6	C	CC	20.2	34	x		18	0	PO	x		51.34	L			1 kWh_{el}
6	B	CC	25.0	42	x		18	0	PO	x		51.34	L			1 kWh_{el}
28	B	TC	200.0	57	x		NS	12.8	SNG	x		24	L (28t)		x	1 m^3 SNG
30	B	CC	215.0	33.2	x		19.5[a]	5	Pellet	x		115[b], 1,350	L[b], R			1 kWh_{el}
30	C	DC	215	31.8	x		19.5[a]	5	Pellet	x		115[b], 1,350	L[b], R			1 kWh_{el}
30	D	DC	250	31.4	x		19.5[a]	5	Pellet	x		115[b], 180, 890	L[b], R, V			1 kWh_{el}
17	B	CC	350	31.1	x	x	18.295	50				80.5	L 40%, R 60%	x	x	1 kWh_{el}
23	A	CC	350	35.5	x		20.16[a]	<20		x		100	L	x	x	1 TJ_{el}
17	A	CC	350	31.5	x	x	18.295	50				80.5	L 40%, R 60%	x	x	1 kWh_{el}
1	B	CC	400	40	x		7.9	35.1		x		25–1,000	L, R, B		x	1 kWh_{el}
1	E	DC	400	59	x		7.9	35.1	SNG	x		50–1,000	L, R, B		x	1 kWh_{el}
1	F	CC	400	40	x		7.9	35.1	SNG	x		50–1,000	L, R, B		x	1 kWh_{el}
24	A	CC	450	35	x		20[a]	45	T. Pellet		x	51	L	x	x	1 MWh_{el}
24	B	CC	450	35	x		20[a]	45			x	47	L	x	x	1 MWh_{el}
24	C	CC	450	35	x		20[a]	45	Pellet		x	47	L	x	x	1 MWh_{el}
24	D	CC	450	35	x		20[a]	50	T. Pellet	x		13	L	x	x	1 MWh_{el}
24	E	CC	450	35	x		20[a]	50		x		12	L	x	x	1 MWh_{el}
24	F	CC	450	35	x		20[a]	50	Pellet	x		12	L	x	x	1 MWh_{el}
30	A	CC	490	35.2	x		19.5[a]	5	Pellet	x		115[b], 180, 890	L[b], R, V			1 kWh_{el}
11	A	CC	509	43.2	x		NS	NS			x	40	L		x	1 kWh_{el}
4	A/B	CC	600	39.5		x	18.03	6	Pellet	x		50–75[b], 75, 60, 5,000, 52	L[b], L, L, V, B			1 kWh_{el}

(Continued)

Table 2 Continued

Ref	System (supporting information S2 on the Web)	Conversion: Technology	Conversion: Power (MW)	Conversion: Net efficiency	Feedstock: FW/FWR	Feedstock: IWR	Feedstock: LHV (MJ/kg)	Feedstock: MC (%)	Feedstock: IF	Biomass procurement: Comprehensive	Biomass procurement: Harvest/ collection only	Transportation: Length (km)	Transportation: Type	BEOL	CE	FU
8	A	CC	600	NS	x		18.3	15		x		200	L			1 kWh_{el}
1	C	CC	800	46	x		7.9	35.1		x		25–1,000	L, R, B		x	1 kWh_{el}
1	D	CC	950	43.2	x		7.9	35.1		x		25–1,000	L, R, B		x	1 kWh_{el}
29	A	CC	1000	NS	x		26.6	NS	T. Pellet	x		10^b, 1,330	L^b, Bu		x	1 MJ_{el}
14	B	CC	NS	40	x		9.34–11.63	36–47		x		0.214^b	NS			1 MJ_{el}
19	A/C	DC	NS	NS	x		NS	NS		NS		NS	NS		x	1 kWh_{el}
19	B	CC	NS	NS	x		NS	NS		NS		NS	NS		x	1 kWh_{el}
26	A/B/E/G/H	CC	NS	31.5	x		17.30	10	Pellet	x		120^b, 5,000, 1,000, 50	L^b, V [EBH], V [EBH], L	x	x	1 GJ
26	C	CC	NS	31.5	x		17.30	10	Pellet	x		80^b, 640, 1,000, 50	L^b, V [EBH], V [EBH], L	x	x	1 GJ
26	D	CC	NS	31.5	x		17.30	10	Pellet	x		120^b, 5,000, 1,000, 50	L^b, V [FBH], V [EBH], L	x	x	1 GJ
Heat																
7	A	TC	0.01	96	x		NS	15	SNG	x		25^b	L^b	x	x	1 MJ_{th}
12	A	DC	0.01	73	x	x	17.8	NS	Pellet			100^b, 100	L^b, L		NS	1 kWh_{th}
21	A/B/C	TC	0.01	85	x		NS	NS	SNG		x	NS	NS		x	1 MWh_{th}
21	D	DC	0.01	NS	x		NS	NS			x	NS	NS		x	1 MWh_{th}
3	A	DC	0.015	60	x		13	20				10^b, 240	L^b, L	x	x	1 MJ_{th}
3	B	DC	0.015	64		x	17	10	Pellet			10^b, 30	L^b, L	x	x	1 MJ_{th}
5	A	DC	0.035	NS	x		13.7	24		x		13.25^b, 30	S^b, TR			1 kWh_{th}
7	B	DC	1	85	x		NS	15		x		25^b	L^b	x	x	1 MJ_{th}
9	A	DC	2.5	75		x	19^a	8	Pellet	x		111^b, 781	L^b, R		x	1 MWh_{th}
4	D	DC	21.3	78		x	18.03	6	Pellet	x		53–75^b, 75	L^b, L			1 kWh
28	A	TC	100	96	x		NS	12.8	SNG	x		24^b	L^b	x	x	1 m^3 SNG
2	A/B/C	DC	NS	NS	x		14.1	20.0		x		425	L	x	NS	1 t dry
2	D	DC	NS	NS	x		16.7	7.4	Pellet	x		425	L	x	NS	1 t dry
14	E	TC	NS	NS	x		9.34–11.63	36–47	PO	x		0.214^b, 440	FWD^b, L			1 MJ_{th}
15	A	DC	NS	83	x	x	NS	35	Pellet	x		200	NS			1 MJ_{th}
18	A	DC	NS	NS	x	x	19.4	5.6	Pellet		x	106^b, 25, 400, 50	MDV^b, HDV, MDV			1 year

(Continued)

Table 2 Continued

		Conversion			Feedstock					Biomass procurement		Transportation				
Ref	System (supporting information S2 on the Web)	Technology	Power (MW)	Net efficiency	FW/FWR	IWR	LHV (MJ/kg)	MC (%)	IF	Comprehensive	Harvest/ collection only	Length (km)	Type	BEOL	CE	FU
18	B	DC	NS	NS	x		16.4	18			x	5^b, 75	MDV^b, MDV			1 year
19	D/E	DC	NS	NS	x		NS	NS		NS		NS	NS		x	1 kWh_{th}
20	A	DC	NS	NS	x		15.23	10.0–18.0			x	25^b, 204	L^b, L			1 m³
20	B	DC	NS	NS	x		14.1	10.0–19.0			x	25^b, 204	L^b, L			1 m³
20	C	DC	NS	NS		x	14.6	NS				64	L			1 m³
20	D	DC	NS	NS		x	NS	NS	Pellet			119^b, 15	L^b, L			1 t
20	E	DC	NS	NS		x	NS	NS				50	L			1 m³
20	F	DC	NS	NS		x	7.8–22.6	NS				64	L			1 m³
26	F	DC	NS	80	x		17.30	10		x		120^b, 5,000, 550	L^b, V [EBH], L	x	x	1 GJ
27	A	DC	NS	NS	x		18.60	20		x		50^b, 180	L^b, L			1 kWh_{th}
CHP																
10	A	TC	0.1	76	x	x	12.9 [FWR]	30	SNG	x		29^b, 15	L^b, L	x	x	1 MJ_{chp}
22	A	TC	0.25	58	x		15	15	SNG		x	10–50^b	L^b	x	x	1 GJ_{chp}
10	B	TC	1	86	x	x	12.9 [FWR]	30	SNG	x		39^b, 15	L^b, L	x	x	1 MJ_{chp}
13	A	DC	1	83	x		NS	NS		x		NS	NS	x		1 kWh_{el}
13	B	TC	3	73	x		NS	NS	SNG	x		NS	NS	x		1 kWh_{el}
2	E	DC	8	NS	x	x	12.1	30.0		x		30	L	x		1 t dry
4	C	DC	21.3	74.8		x	18.03	6	Pellet	x		53–75^b, 75	L^b, L			1 kWh
10	C	TC	50	90	x	x	12.0 [IWR]	30	SNG	x		115^b, 110	L^b, L	x	x	1 MJ_{chp}
2	F	DC	100	NS	x	x	11.3	35.0		x		100	L	x		1 t dry
28	C	TC	100	75	x		NS	12.8	SNG	x		24^b	L^b		x	1 m³ SNG
14	C	TC	140	NS	x		9.34–11.63	36–47	SNG	x		0.214^b	FWD^b			1 MJ_{chp}
14	A	DC	300	NS	x		9.34–11.63	36–47		x		0.214^b	FWD^b			1 MJ_{chp}
14	D	CC	900	NS	x		9.34–11.63	36–47	T. Pellet	x		0.214^b, 230	FWD^b, L			1 MJ_{chp}
16	A/B/C/D	DC	NS	NS	x		NS	NS		x		NS	NS			1 MWh_{chp}
16	E/F	DC	NS	NS		x	NS	NS		x		NS	NS			1 MWh_{chp}
25	A	DC	NS	NS	x		NS	NS		x		77.49	L	x	x	1 kWh_{el}
25	B	TC	NS	NS	x		NS	NS		x		37	L	x	x	1 kWh_{el}
26	I	CC	NS	75	x		17.30	10		x		120^b, 5,000, 1,000, 50	L^b, V [EBH], V [EBH], L	x	x	1 GJ

Note: Identical systematic parameters are consolidated.

[a] Higher heating value.

[b] Transport from forest.

B = barge; BEOL = biomass end of life; BP = biomass production; BU = bulker; CC = cocombustion; CE = capital equipment; DC = direct combustion; EBH = empty backhaul; EW = energy wood; FBH = full backhaul; FU = functional unit; FW = forest wood; FWD = forwarder; FWR = forest wood residues; GJ = gigajoules; HDV = heavy-duty vehicle; HR = harvesting residues; IF = intermediary wood fuel; IWR = industrial wood residue; kWh = kilowatt-hours; L = lorry (truck); LHV = lower heating value; m^3 = square meters; MC = moisture content; MDV = medium-duty vehicle; MJ = megajoules; MWh = megawatt-hours; NS = not specified; PO = pyrolysis oil; R = rail; SK = skidder; SNG = synthetic natural gas; ST = stumps; t = tonnes; TC = thermochemical; TJ = terajoules; TM = transmission; T. Pellet = torrefied pellet; TP = transportation; TR = tractor; V = vessel; WR = industrial wood residues.

of the study. Contrastingly, we observed that, in the analyzed studies, the definition of system boundaries and the subsequent inclusion of life cycle stages and specific processes were sometimes conducted in an arbitrary fashion. This was because of the fact that the definition of the life cycle of energy wood (no conversion of the wood fuel to energy included), in contrast to the life cycle of a wood energy service (heat, power, or CHP), can cause issues when defining whether a study's scope is "cradle to grave" or "cradle to gate." In many studies, cradle-to-grave is defined as "from resource extraction to combustion," thus claiming to having covered the complete life cycle of the wood fuel. This, however, neglects the biomass end-of-life (BEOL) phase, the treatment of wood ash. In other studies (n = 11), cradle to grave includes the BEOL phase. Additionally, the "cradle" life cycle stage is not uniformly defined for all studies. Whereas some studies model the complete production of wood in the forest beginning from forest stand establishment, other studies define cradle as just the collection of wood in the forest or the final harvesting of the wood (table 2).

Further, many studies claim to cover all emissions associated with the life cycle of the wood energy service, but they often neglect the transmission of that energy as well as necessary machinery and infrastructure. Only 8 of the 97 wood energy systems include the modeling of transmission technologies and/or losses, whereas 14 studies give no information about machinery or infrastructure expenditures. Obviously, for some energy services, the inclusion of transmission technology is more important than for others. For example, when assessing a wood power generation system in reference to a fossil system, transmission can be neglected because of the equality of processes. On the other hand, for CHP systems that take a crediting approach (e.g., through the additional generation of heat) toward the generated power, the transmission system should be included.

Therefore, it is not sufficient to only specify whether the analyzed system is cradle to grave or cradle to gate. Clear information on which processes or process groups are integrated needs to be provided for each study. Accordingly, all studied systems were analyzed with respect to included processes and life cycle stages and reclassified accordingly (figure 2). A total of 35 systems were classified as "cradle to gate; from raw wood production to combustion," with three systems also including the transmission of energy. A total of 30 systems were classified as "cradle to grave; from forest production to ash disposal," again with three systems including the transmission of energy. A total of 15 systems were classified as "gate to gate; from harvesting or collection of wood to combustion," whereas one system was classified as "gate to grave; from forest road to ash disposal." Some systems concerned with wood energy from industrial wood residues (IWRs), or combinations of forest and residue wood, treat these residues as waste and thus do not burden them with emissions from the preceding raw wood production phase. As such, five IWR systems were classified as "gate to gate; from IWR collection to combustion," increasing the total number of "gate to gate" systems to 20. In contrast to these systems, some studies do assign a burden to IWRs (n = 8). These are included in the 35 cradle-to-gate systems mentioned above. For five systems, the choice of system boundary was unclear, and for six systems, no system boundary was specified.

Provision of Raw Wood

In terms of individual system components, starting with the step of raw wood production, 67systems include the modeling of wood production in the forest. The resolution in this step can range from a detailed description and analysis of relevant processes to just a general note of the inclusion of raw wood production in the overall model. A total of 13 systems do not include the associated emissions of raw wood production, but focus only on the harvesting or collecting of wood or wood residues. Ten systems do not give any specifications on whether or not raw wood production is included and to what extent (table 2).

Feedstocks

With respect to wood feedstocks, forest wood is employed in 75% (n = 73) of the systems. In these cases, either forest raw wood for energy purposes (47%), forest wood residues (29%), or a combination of both (24%) is considered. How and if the allocation of impacts for different assortments is carried out during this step is disclosed for five systems (7%). In one case, raw wood production is allocated by mass, and in four cases, by the economic value of the different outputs. Further, 30% of the systems do not specify fuel properties inherent to the wood feedstock. For the rest of the systems, lower heating values (LHVs) between 7.9 megajoules per kilogram (MJ/kg) at a moisture content (MC) of w = 35% and 19.5 MJ/kg at a moisture content of w = 5% are reported (table 2). In this range, a variety of, sometimes unlikely, combinations of LHVs and MC are described in individual studies (e.g., 20 MJ/kg at w = 50%). The reason for these combinations may be the utilization of higher heating values for wood during the calculations and the negligence of wood water contents in transportation, conversion, and other processes. Further, a drying step may have been included in the system, but not disclosed in the study. Most studies, however, that offer these unlikely combinations of heating values and MC do not provide the required information. Therefore, it was assumed that calculations were made employing the figures provided by the studies. A total of 13 systems rely solely on the input of industrial wood residues as a feedstock. Nine of those systems specify a heating value that was used for the calculations, and seven systems supply both heating value and MC (6% to 10%) (table 2). Here, the allocation of environmental impacts is carried out for five systems, all allocated by mass. Eleven systems employ a combination of forest wood, forest wood residues, and industrial wood residues. A total of 29 systems lack information concerning either the employed LHVs, the MC of the feedstock, or both. Further, 14 systems provide ash contents for the employed feedstock, whereas 59 systems provide information on the wood species or type. A total of 29 of those 59 systems specified only whether a hardwood or a softwood is harvested and combusted.

It is remarkable that studies analyzing the use of wood, in these cases for the generation of energy, do not provide

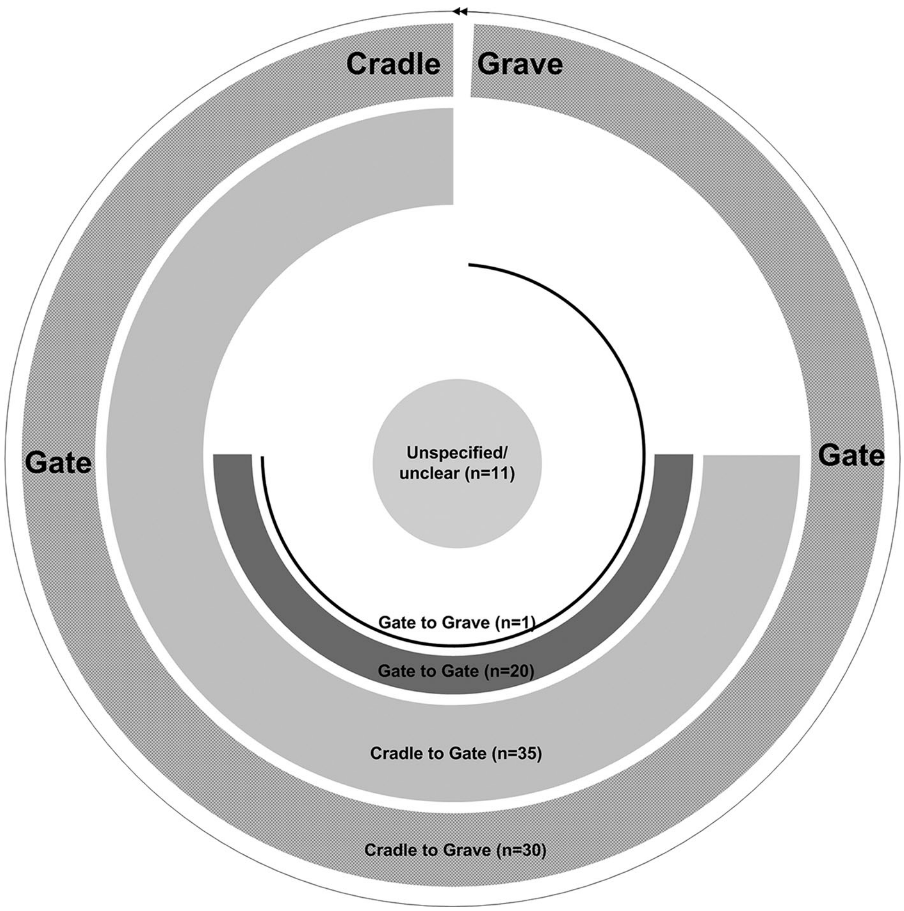

Figure 2 Choice of system boundaries for the 97 analyzed systems in 30 studies. Width of bars represents the amount of systems employing the respective system boundaries.

sufficient information concerning integral fuel properties, such as ash contents (for BEOL), heating values, and related MCs, even though these properties can have a major impact on the results. Additionally, this lack of information makes it challenging to comprehend, reproduce, and compare the researchers' analyses and results. The provision of complete fuel properties is one step to achieving comparability and transparency, one of the most frequent demands toward the improvement of the LCA methodology, and focal point of the EU's Product Environmental Footprinting Initiative (EU 2013).

Transportation

The majority of studies (81%) incorporate some form of transportation processes to their models. Hence, a wide variety of transportation means and distances are included, ranging from short distance skidder transportation to forest roads, to inland waterway transportation by barges, and overseas transportation with bulk carriers over a distance of up to 5,000 kilometers (table 2). Seven systems address only transportation from the forest road to the transformation or conversion site. The remaining 72 systems either contain both transportation steps (from forest to the place of transformation, from transformation to conversion) or make no explicit mention of whether the transportation from forest to transformation is included or what means of transportation is included in the model. Because environmental impacts of transportation vary to a great degree depending on mode and distance, the ability to compare studies, especially when only aggregated results are published, is very limited. This is further enhanced by the lack of information provided in some studies, in which no specification concerning size, type, or even distance of transportation is provided. Other case studies specify that transports are carried out (e.g., by lorry [truck] or a comparable vehicle), but no indication on the process specifics are provided, such as payloads, emissions standards, or how full and empty backhauls are treated.

Transformation

The transformation of wood to fuel is included in the majority of systems. Whereas all systems technically require the reduction of the size of wood (e.g., through chipping or splitting), not all studies disclose information about those processes. Subsequent to the size reduction, some systems use the wood to manufacture further intermediary wood fuels, such as pellets, pyro-oil, SNG, or torrefied pellets. As a result, we respectively identified 24, 6, 15, and 4 systems that produce these intermediary wood fuels. These constitute a total of 50% of all systems assessed. The remainder either directly utilizes the wood chips for monocombustion or CC or do not specify details on transformation.

Conversion

Because only systems concerned with the generation of energy from wood were analyzed, as opposed to energy wood systems (i.e., systems lacking the conversion of the wood fuel to energy), all systems include the conversion of wood fuel to energy. The conversion of wood for the generation of power is carried out in plants with firing capacities ranging from 4 to 1,000 MW. Twenty percent of the 44 power generation systems are below 100 MW, 41% have a firing capacity between 100 and 500 MW, and six systems (13%) are above 500 MW. The remainder of systems (n = 11) are unspecified concerning the combustion facility's firing capacity. All systems above 200 MW are systems where CC applications of wood were assessed by us, whereas the DC of wood takes place below 25 MW (with some exceptions for two hypothetical DC scenarios) (Zhang et al. 2010). For all power-generating CC systems (n = 32), the wood is combusted alongside an FF (hard coal: n = 18; lignite: n = 6; natural gas: n = 2; fuel oil: n = 2; peat: n = 1; and NS: n = 3). Electrical efficiencies range from 20% to 59% for an SNG power generation system (Bauer 2008). The conversion of wood for the generation of heat is analyzed in 31 systems and involves firing capacities between 0.01 and 100 MW, thus occurring on a much smaller scale than power generation of power. Eighty-five percent of the systems that disclose firing capacities are below 2 MW and 60% below 0.1 MW. The majority of systems (n = 18), however, are unspecified in regard to firing capacities. This is also the case for the employed thermal efficiencies, where 20 systems (62%) provide no information, even though it is one of the most important parameters for any energy-based LCA (Cherubini et al. 2009). Within those systems that disclose information on conversion characteristics, the highest thermal efficiencies are achieved for the SNG heating systems (up to 96%), whereas the wood and pellet stove heating systems exhibit the lowest efficiencies (60% and 64%, respectively). CHP generation (n = 22) takes place in facilities with a firing capacity between 0.1 and 900 MW, with 36% (N = 8) systems under 50 MW. Eighteen percent (n = 4) are in the range of 100 to 300 MW, and one study is concerned with the generation of CHP through the CC of torrefied pellets with hard coal at a firing capacity of 900 MW (Jäppinen et al. 2013). Unfortunately, only nine systems specify combustion efficiencies, ranging from 58% to 90%. Only 13 systems disclose firing capacities (table 2).

Capital Equipment

The last system component to be analyzed in this study was capital equipment, which is equipment that is used to manufacture the product or service (e.g., skidders and conversion facilities). Fifty percent (n = 49) of systems stated that capital equipment is included in the assessment. The degree and detail of inclusion, however, is not disclosed (e.g., the service life). Of the systems, 42 do not include capital equipment and six do not provide information on capital equipment.

Allocation After Conversion

Because the process of conversion creates two outputs for CHP systems, allocation procedures are encountered. Information published by the individual studies is limited because only 11 systems (50%) make clear mention about allocation during this life cycle phase. Environmental impacts are allocated toward the two products, in the case of CHP, onto power and heat, respectively. This is the case for seven systems and is carried out in all cases in accord with the products' exergetic content, which takes the higher thermodynamic quality of power into consideration. Additionally, three systems carry out an allocation by energy content, thus assuming an equal quality for both forms of energy. Further, Hartmann and Kaltschmitt (1999) mention an allocation during the conversion phase. In this case, allocation is carried out for emissions associated with the capital equipment necessary for combustion in a CC system. Those emissions are allocated to the power output generated solely through wood, utilizing the biomass co-firing rate. In all other systems, specific information concerning allocation is not provided. Additionally, many studies follow substitution (Sjølie and Solberg 2011) or avoided burden approaches (Damen and Faaij 2005). The influence of these approaches can be assumed to be great. For the comparison of LCAs, additional results excluding substitution or avoided burden effects are favorable.

Functional Units

Functional units (FUs) range input-related functional units such as 1 tonne (t) of dry biomass to typical energy output-related FUs, such as 1 kWh, 1 MJ, or even the yearly energy output of a power plant or region. Encountered input-related FUs are 1 t of dry biomass, 1 cubic meter (m^3), or 1 t (MC unspecified) with an occurrence of n = 7, n = 1, and n = 5, respectively. For output-related FUs (n = 85), the majority (n = 80) are typical output FUs (table 2). Three systems provide results based on two FUs. These systems generate CHP. Consequently, results are disclosed on the basis of both 1 MJ_{el} and 1 MJ_{th} (Guest et al. 2010). Two system results are based on the yearly heat output of the respective residential heating appliance (Pa et al. 2013). Recalculation to a more common FU could be achieved by the yearly emissions with the amount of heat provided by the system. The results for three systems are based on the amount of power, heat, or CHP delivered by 1 m^3 of SNG in different facilities, thus enabling a convenient comparison within the three systems (Steubing et al. 2011).

Life Cycle Impact Assessment: Impact Categories

During the life cycle impact assessment (LCIA), environmental impacts are typically specified for several impact categories. Those categories shall be consistent with the goal of the study (ISO 2006a). For all LCAs analyzed in this study, problem-oriented midpoint impact categories are used. Additionally, endpoint and hybrid methods, the combination of mid- and endpoint approaches, are encountered to a lesser degree, both with an occurrence of 10%. Half of the studies report the applied characterization method, whereas the remainder did not provide information on this issue. For these studies, however, CML equivalent impact categories (Guinée 2002) could be identified.

In total, 15 individual impact categories are encountered. Impacts on GW were assessed in 100% of the studies. Acidification (AC) and eutrophication (ET) impacts appeared in 41% and 18% of the studies, respectively. Particulate matter (PM) emissions are reported in 27% of the studies. Energy resource-related analyses (e.g., the renewable and nonrenewable primary energy demand) are incorporated in 63% of the assessments. In order to objectively assess the emissions from wood energy systems, it is necessary to account for biogenic carbon during the whole life cycle. This issue has been covered by several researchers already (Helin et al. 2013). However, in the analyzed studies, there was little information to be found on this subject. The majority assumed, without clearly stating the basis for this assumption, that climate effects related to biogenic carbon are nonexistent.

Meta-Analysis of Wood Energy Life Cycle Assessments

This section describes the analyses of LCIA results, as published by the 30 studies. The basis for the comparison of these results is the CML midpoint impact category GW because it is represented in 100% of the studies. Other, less-frequent impact categories, such as AC, ET, and particulate emissions, were not considered owing to the lack of results published in the studies. Additionally, studies providing only endpoint impact categories or FUs unsuitable for recalculation were excluded.

In total, 122 results from different scenarios were included in the quantitative assessment of GW. These results were grouped by the provided energy service (heat, power, and CHP) and recalculated to kg CO_2-eq * kWh^{-1} of provided energy service.

Figure 3 shows the aggregated results for GW through the generation of CHP (n = 27), heat (n = 28), and power (n = 67), as well as for the biomass fraction (power_bf; n = 66) of power-generating CC systems.

Ccombined Heat and Power Generation

For the generation of CHP, the mean impact on GW is 0.187 kg CO_2-eq * kWh_{el}^{-1} (±0.25 standard deviation [SD]) with a median of 0.066 kg CO_2-eq * kWh_{el}^{-1} (figure 3). The divergence between the mean and the median can be explained by the asymmetric distribution of values, with the majority of results in the lower range. This is largely attributed to the different methodological choices the authors of the respective studies made, for example, by choosing a specific allocation method (Henning and Gawor 2012) or by including biogenic carbon emissions in their results (Puy et al. 2010). The gap between minimum and maximum values is widened by choices pertaining to system boundaries for the generation of CHP, with studies including (Guest et al. 2011) or excluding the transmission of heat. Because only one aggregated result is published in most cases, the subtraction of these system components was not possible.

The generation of CHP with a power capacity above 100 MW has a median impact on GW of 0.011 kg CO_2-eq * kWh_{el}^{-1}; below 100 MW, the median impact on GW is 0.068 kg CO_2-eq * kWh_{el}^{-1} and 0.53 kg CO_2-eq * kWh_{el}^{-1} for systems without published combustion capacities (figure 4). One outlier was encountered in the group with capacities ≤100 MW. We assumed that Puy and colleagues (2010) include the emission of biogenic C (carbon stored in the wood and emitted as a result of combustion) in their published results (0.871 kg CO_2-eq * kWh_{el}^{-1}), which can have a substantial influence on the statistical result.

Heat Generation

The generation of heat (Figure 3) shows a mean impact on GW of 0.051 kg CO_2-eq * kWh_{th}^{-1} (±0.056 SD) and a median of 0.040 kg CO_2-eq * kWh_{th}^{-1}. One extreme value of 0.18 kg CO_2-eq * kWh_{th}^{-1} (Katers et al. 2012) was encountered. This system is concerned with the generation of heat through pellets in North America. The pellets were comprised of a mix of forest wood and industrial wood residues at two MCs (>35%/<35%), which could be a reason for the higher GW results.

Of the studies, 40% disclose thermal combustion capacities (figure 4); 100% of those of the results that are based on thermal capacities below 100 MW_{th} (81% below 1 MW) (GW, median 0.047 kg CO_2-eq * kWh_{th}^{-1}). The remainder of the results are not based on published combustion capacities (GW, median 0.053 kg CO_2-eq * kWh_{th}^{-1}).

Power Generation

The generation of power shows the highest spread in values of all three energy services, with a mean impact on GW of 0.398 kg CO_2-eq * kWh_{el}^{-1} (±0.388 SD) and a median of 0.169 kg CO_2-eq * kWh_{el}^{-1}. The lower range of values predominantly comprised systems in which the generation of power through DC in small- (Henning and Gawor 2012) to medium-scale (Bauer 2008) power plants or CC systems where only the emissions of the wood fraction are reported (Sjølie and Solberg 2011). Accordingly, high-range values include both fossil and wood fuel emissions (Kabir and Kumar 2012). In these cases, the distribution of the results was primarily determined by the cofiring rate. Because quantitative analyses and comparisons to other energy services are hindered by the inclusion of the fossil emissions in CC results, we recalculated those results for only the biomass fraction (power_bf) of CC power generating systems (figure 4). Consecutively, the mean impact on GW is 0.122 kg CO_2-eq * kWh_{el}^{-1} (±0.087 SD), with a median of 0.098 kg CO_2-eq * kWh_{el}^{-1}. Because the influence of cofiring rates and FF emissions are eliminated, the spread of results is determined primarily by different methodological choices and system boundaries. One system was removed from the assessment owing to the inclusion of avoided methane (CH_4) emissions from of wood landfilling (Mann and Spath 2001).

Because the generation of power takes place predominantly in existing, large-scale fossil power plants, a trend could also

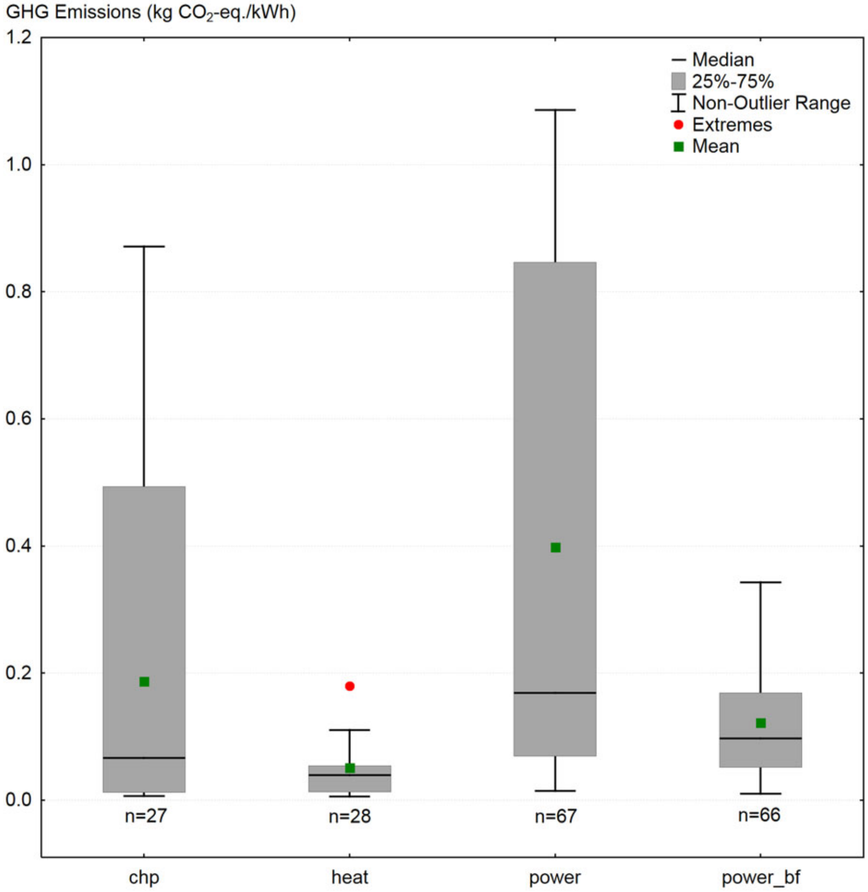

Figure 3 GHG emissions (kg CO_2-eq * kWh^{-1}) of combined heat and power (CHP), heat, power, and the biomass fraction (power_bf) of power generating systems. GHG = greenhouse gas; kg CO_2-eq = kilograms of carbon dioxide equivalents; kWh = kilowatt-hours.

be observed by grouping the results according to power plant size (figure 4). The median impact on GW of power_bf above 100 MW_{el} ($n = 39$) is 0.109 kg CO_2-eq * $kWh_{el}{}^{-1}$. Observed was a minimum impact on GW of 0.035 kg CO_2-eq * $kWh_{el}{}^{-1}$ (Hartmann and Kaltschmitt 1999) owing to the treatment of wood as a by-product, short transportation assumptions, and high electrical efficiencies, as well as a maximum of 0.343 kg CO_2-eq * $kWh_{el}{}^{-1}$ (Royo et al. 2012), possibly owing to the employed emissions factor for biomass combustion. Even though all conversion efficiencies were not disclosed by the studies, it has to be assumed that they are the reason for the lower emissions of larger power plants' capacities above 500 MW_{el}.

The median impact on GW of power_bf below 100 MW_{el} ($n = 12$) is 0.067 kg CO_2-eq * $kWh_{el}{}^{-1}$. These low values are achieved predominantly for monocombustion systems in the range of 4 to 20 MW_{el}. As stated in Jungmeier and colleagues (2003), conversion technologies and efficiencies are major aspects in the environmental assessment of energy generation LCAs. Nevertheless, the capacities for 15 power-generating systems were not reported (GW, median 0.057 kg CO_2-eq * $kWh_{th}{}^{-1}$). Ninety-two percent of power-generating systems reported combustion efficiency.

Methodological Proposal

This review revealed the highly diverse approaches authors chose when conducting LCAs for wood energy services. Even though methodological guidelines for conducting LCA studies exist (ISO 2006a, 2006b), the complex nature of raw wood production and wood energy generation systems led to a wide variety of product systems and, as a consequence, to a broad range of results. This is further amplified by factors such as the choice of system boundary, conversion technology, and the way in which results are published. It should be ensured that LCAs for the same energy service or conversion technology are conducted in a way that gives the scientific community the possibility to comprehend, reproduce, and compare results with their own findings. As such, we propose the application of certain measures to facilitate comparability of future LCA results.

System Description

As our review shows, one of the biggest factors hindering the comprehension and reproduction of past LCA findings is the unclear or incomplete description of the system in question. Many times, the system description is made up of only a sentence such

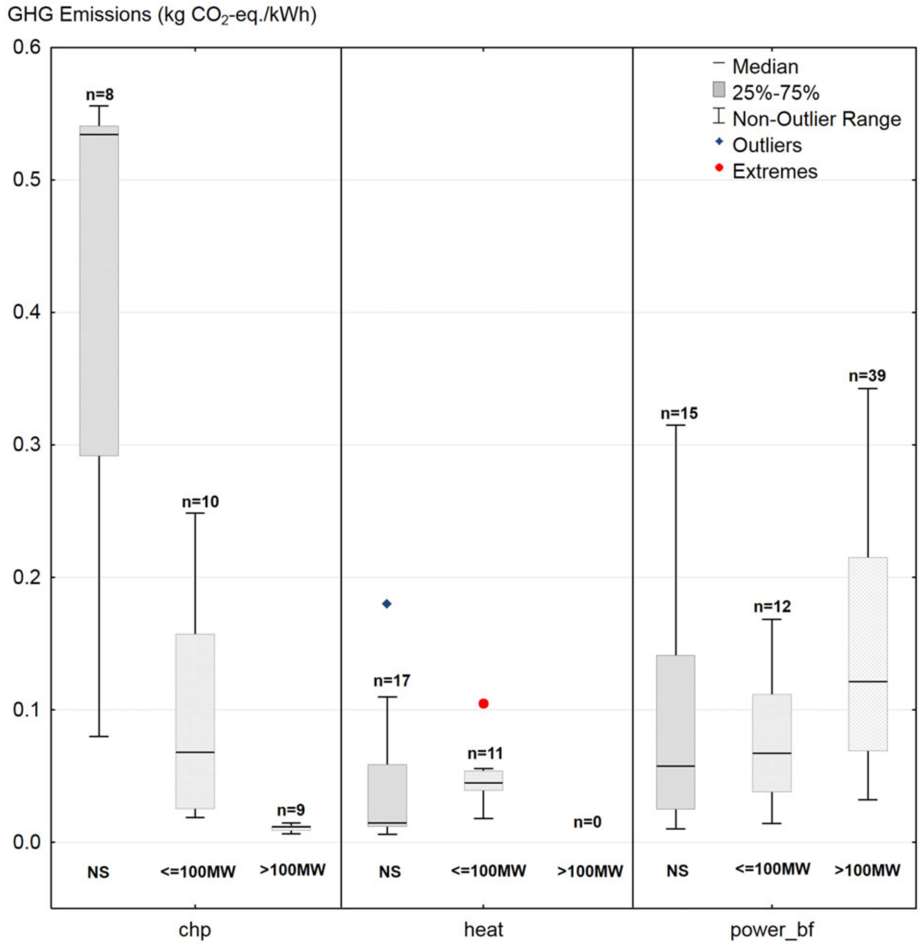

Figure 4 GHG emissions (kg CO_2-eq * kWh^{-1}) of wood energy services (combined heat and power [CHP], heat, and biomass fraction of power generating systems) by combustion capacity. GHG = greenhouse gas; kg CO_2-eq = kilograms of carbon dioxide equivalents; kWh = kilowatt-hours; NS = not specified; MW = megawatts; power_bf = heat, power, and the biomass fraction.

as "from cradle to gate." The complex nature of bio-based LCAs, with multiple interlocking systems (e.g., biomass systems, transformation system, conversion system, and the life cycle of the energy service) forming the entirety of the bioenergy system, demands a more structured approach for the description of the system boundaries during the definition of the goal and scope of an LCA study. In accord with DIN EN 15804—Sustainability of Construction Works (CEN 2012), figure 5 was developed for wood energy services. It depicts the proposal for an enhanced standardized approach for the system boundary description, processes to be included, the publication of results, and important parameters for LCA modeling. In addition to stating whether a system is cradle to gate or cradle to grave, the LCA practitioner should specify the exact system components that are integrated in the assessment and publish the results accordingly.

Indicating the product or service with which the LCA is concerned, as well as the geographical region, site, timescale of the study, and the process groups to be included, is necessary. Additionally, system components not included in the study should be specified, along with the reasons they are not included.

We propose seven process groups with all processes concerned with the provision of wood to be consolidated into a group [A] with further possibilities for specification provided in subgroups [A1] to [A5]. It should be clearly stated whether the complete production of raw wood in the forest (A1 to A4), or only certain harvesting or collection activities (e.g., A4.5), are integrated. If IWR, for example as a coproduct of a sawmill process, forms one of the inputs for the wood energy system (A5), it should be stated whether they have been allocated with an environmental burden or whether all burdens are associated with the main product. For this case, the life cycle of the wood energy service would start with process group [B]. A detailed description of process group [A] can be found in our previous work (Klein et al. 2014).

In the subsequent life cycle phase, the wood is transformed into a wood fuel, for example, through chipping, pelletization, or gasification. Additionally, in some cases, the wood fuel is stored or packaged. Environmental impacts of these steps can be indicated in [B1.1]. Further, information pertaining to the technology of the actual transformation of the biomass to wood fuel (e.g., by chemical, mechanical, or biological transformation)

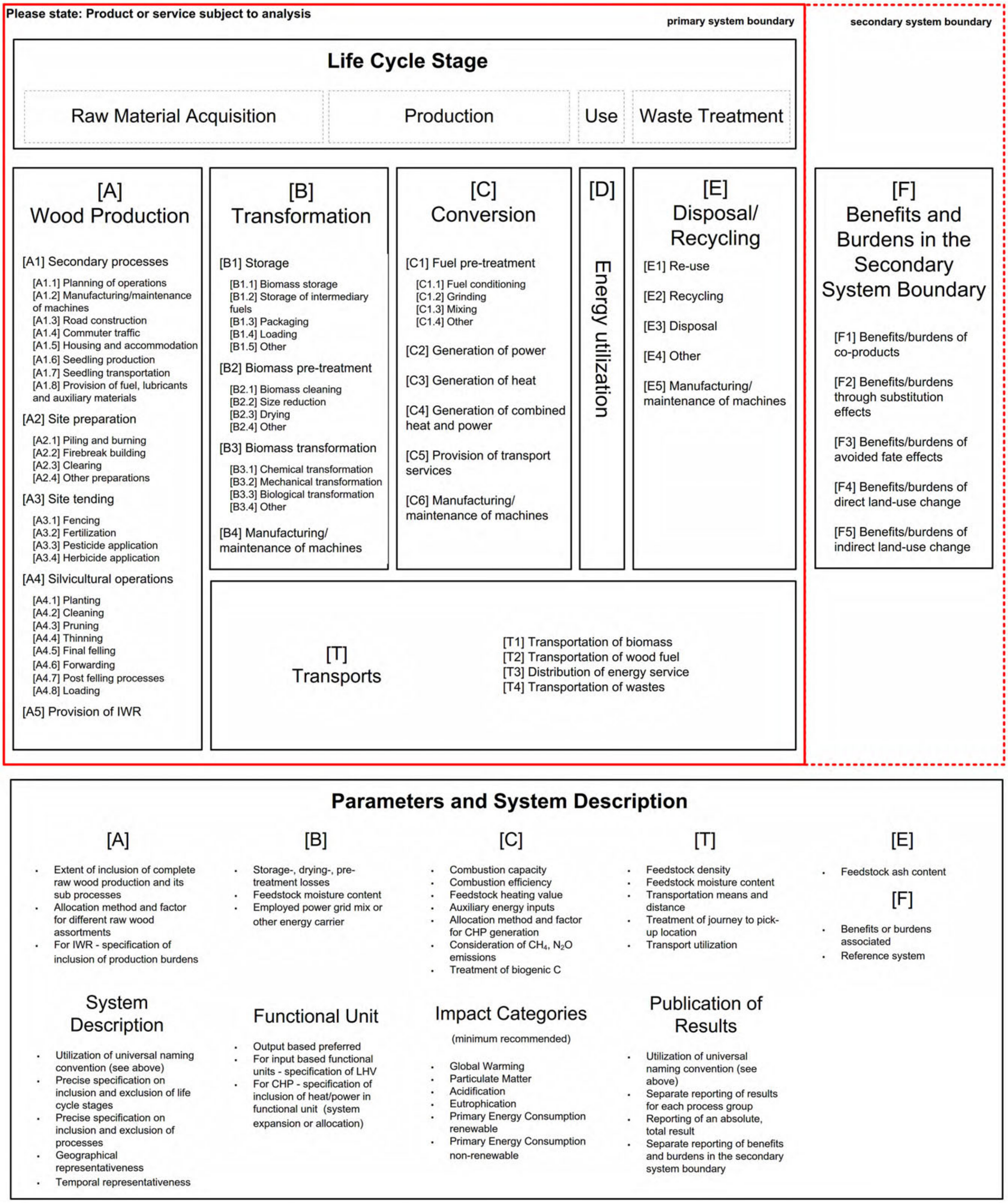

Figure 5 Template for the description of the analyzed system, the reporting of results, as well as parameters and system description components.

can be indicated in [B3]. Again, the included transformation processes must be clearly specified. Because of the significant influence this life cycle phase can have (e.g., through drying processes [B2.3] or pelletization [B3.2] with electricity), specific information, such as the employed electrical power mix, should be provided for relevant subprocess groups.

During the conversion of the wood fuel to energy [C], it should be stated whether a pretreatment (e.g., drying

[C1.1]/grinding [C1.2]/mixing [C1.3]) of the wood fuel was included in the fuel pretreatment [C1]. The manner in which the fuel is converted into an energy service, for example, power [C2], heat [C3], CHP [C4], or a transportation service [C5], shall be specified. In addition to the information given in the proposed systematic framework, attention should be paid to CH_4 and nitrous oxide (N_2O) emissions resulting from the combustion process. CH_4 formation is especially common in small combustion devices where a strong correlation between CH_4 and carbon monoxide emissions can be observed. The formation of N_2O is sensitive to the temperature during combustion and will occur between 500 and 950°C, therefore making fluidized bed combustion devices prone to N_2O formation (Tsupari et al. 2005). Additionally, it must be clearly stated how biogenic carbon is treated ("omit or emit").

Process group [D] relating to potential environmental effects from the use of wood energy services was created, but not further described in our proposal, given that it was not at the core of our study. Group [D] is meant to complete the full life cycle of an energy service. Example processes that could be located here are the pump power consumption or materials in space-heating applications.

During the last stage of the life cycle, waste treatment, information on the handling of wood ash shall be supplied [E]. Emissions and utilization of wood ash in the construction industry [E2] as a fertilizer [E2] or during disposal [E3] shall be specified here. Even though many studies neglect this phase, it is necessary to include information in process group [E] in order to complete the life cycle of the biomass.

Group [T] provides specific information pertaining to transportation processes. It was found that transportation types and lengths varied greatly among the studies. In many cases, however, it was not clear how, and to what extent, transportation processes were integrated. Nevertheless, it has to be assumed that, for certain scenarios (e.g., transatlantic shipping and European truck transportation), transportation-related emissions can have a substantial influence on the overall result. Therefore, providing detailed information on the means and lengths of transportation for subprocesses [T1] through [T4], including decisive factors such as payload or fuel consumption, is necessary (figure 5).

In addition, it should further be stated which equipment was used during the individual processes of the provision of wood [A1.2], the transformation [B4] and conversion [C6] of the wood fuel, as well as the disposal or recycling of residues [E5].

Group [F] is located in the secondary system boundary and is concerned with benefits and/or burdens not directly associated with the provision of the energy service. Here, effects such as potential emissions from land-use change [F4/5] or crediting approaches (e.g., credits generated through the substitution of other goods and services [F2]), the additional provision of coproducts [F1] or avoided fate effects [F3] shall be disclosed. It was found that these effects can have a great impact on the results and should therefore be specified in detail in a supplemental section [F]. Separating the process group [F] from the rest of the system offers the possibility of depicting both direct environmental effects as well as (after adding associated benefits and burdens from group [F]) the total consequences of the provision of a wood energy service. Additionally, for the comparison of energy systems, results, which are not influenced by group [F] effects, are preferable. Information provided in group [F] should always be strictly informative, implying that the sole publication of total environmental effects including group [F] should be refrained from. Naturally, not all wood energy systems are comprised of all components shown in figure 5. Nevertheless, the ability to comprehend, recalculate, and compare results can be greatly increased through the application of the aspects outlined above.

Parameters for Wood Energy Life Cycle Assessments

As with the system description in the section *System Description*, information regarding the basis for calculations for each process group should be clearly described (see supporting information S1 on the Web). For process group [A], information concerning allocation procedures during raw wood and IWR production shall be specified. For group [B] storage, drying, pretreatment, and transformation losses, as well as feedstock MCs, should be included. For group [C], combustion efficiencies and capacities, as well as the feedstock lower heating values, need to be described. Additionally, any allocation procedures for CHP generation should be stated (e.g., whether allocation was carried out on the basis of energy or exergy content). For process group [E], the feedstock ash content should be included, whereas group [T] requires the density and MC of the feedstock. For group [F], information related to the reference system or certain benefiting or burdening values (e.g., land-use change) should be disclosed.

Publication of Results

Following the guidelines, as described in the *System Description* section (figure 5), enables the LCA practitioner to publish results in a consistent manner. By clearly stating which results summarize which subprocess group, it is possible to add or remove certain process groups or subprocess groups in order to facilitate the comparability of the published result with one's own findings. Additionally, by reporting only the direct emissions caused by the system (e.g., process groups [A]+[B]+[C]+[D]+[E]+[T]), without aggregating the effects from process group [F] into one result, the process of reproducing the study results can be greatly facilitated. In conclusion, this review found that the publication of one result, including all life cycle stages and potential effects from group [F], is very detrimental to the efforts for comparing LCA results. It is therefore our recommendation to report separate results for each individual process group ([A],[B],[C],[D],[E],[T]), a direct total result ([A]+[B]+[C]+[D]+[E]+[T]), and, if effects from group [F] are encountered, to publish the total results including effects from group [F] separately. This will enable the convenient, transparent comparison of individual wood energy services and generation technologies not only for the total result, but also on the scale of the individual life cycle phase or process group.

In addition to reporting impacts to GW, further process results for AC and ET, which have already been widely adopted for bioenergy LCAs, should be considered. A factor of great importance for wood energy systems not represented in many LCAs, however, is the emission of PM. In the case of Germany, the generation of wood energy, especially heat from small combustion devices, is one of the largest sources of PM emissions, contributing 27% of the total emissions of PM (Ewens 2014). We propose to integrate the assessment of PM in future wood energy LCAs based on recommendations by the EC (2010).

Conclusions

Based on our literature review and meta-analysis, the following conclusions can be drawn:

1. Methodological choices for assessing the environmental impacts of wood energy are diverse. The development of harmonized, standardized approaches is limited.

Our review has shown that one of the major weaknesses in achieving comparability of results for many studies is inadequate provision of supporting information in regard to the description of system boundaries, feedstock properties (LHV and MC), combustion capacities, and efficiencies.

2. Results of published GHG emissions show a wide spread (CHP, median 0.066 kg CO_2-eq * kWh_{el+th}^{-1}; heat, median 0.040 kg CO_2-eq * kWh_{th}^{-1}; power, median 0.169 kg CO_2-eq * kWh_{el}^{-1}; power biomass fraction only, median 0.098 kg CO_2-eq * kWh_{el}^{-1}). Decisive factors are LCA modeling choices as well as classical systemic factors. Transparent system descriptions and consistent calculations can accelerate the process of comparability (supporting information S1 on the Web). Special attention should also be paid to N_2O and CH_4 emissions when claiming the climate neutrality of wood combustion, given that these, often neglected gases can have a large impact on the GHG emissions of a wood energy system.

Further, it was shown that the majority of studies focus on the assessment of impacts on GW. Especially for wood energy systems, however, further key aspects, such as ET and AC effects as well as the emission of PM associated with the combustion of the wood fuel, should be assessed.

3. We propose the use of a standard template for the description of wood energy systems (figure 5) and encourage the provision of supplementary information documents containing all critical variables. Additionally, the results of wood energy LCAs should be published in a disaggregated fashion, giving the reader the possibility to compare and comprehend results on a process, group, or life cycle phase basis. This could also be accomplished using the template suggested (figure 5).

4. If external effects from process group [F] are additionally assessed, results should be published separately for the direct emissions of the energy system and the external effects.

This review contributes to the current discussion of harmonization of GHG calculation methodologies and the sustainability of solid biomass for the generation of energy.

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Supporting Information

Additional Supporting Information may be found in the online version of this article at the publisher's web site:

Supporting Information S1: This supporting information S1 includes the basis of calculation for each process group.

Supporting Information S2: This supporting information S2 lists the 97 wood energy services systems assessed.