Fakultät Wissenschaftszentrum Weihenstephan für Ernährung, Landnutzung und Umwelt
Lehrstuhl für Holzwissenschaft

Life Cycle Assessment of Wood Energy Services on a Regional Scale: Methodological Development and Case Study Application

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Vollständiger Abdruck der von der Fakultät Wissenschaftszentrum Weihenstephan für Ernährung, Landnutzung und Umwelt der Technischen Universität München zur Erlangung des akademischen Grades eines

Doktors der Naturwissenschaften (Dr. rer. nat.)

genehmigten Dissertation.

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Die Dissertation wurde am 22.12.2016 bei der Technischen Universität München eingereicht und durch die Fakultät Wissenschaftszentrum Weihenstephan für Ernährung, Landnutzung und Umwelt am 31.05.2017 angenommen.

Acknowledgements

During the last four years, I was fortunate enough to meet a multitude of inspiring people that were of great support towards this work.

For creating exceptional conditions both in respect to the working environment as well as the support during the PHD phase, I would like to thank Prof. Dr. Klaus Richter (TUM). I would like to thank Prof. Dr. Stefan Pelz (HFR) who is responsible for nurturing the idea of pursuing a PHD study in the first place. As such, he was of valuable aid towards the final decision of pursuing a PHD study and, furthermore during the PHD phase, as my graduate school mentor.

I would like to express my deepest gratitude to Prof. Dr. Gabriele Weber-Blaschke (TUM) for being an awesome head of the material flow management group, in which I had the privilege of working and writing this dissertation, and for creating very favorable conditions towards the project and dissertation work. Her tireless and devoted attitude, as well as her personal interest in all things concerning sustainability and the success of the members of her working group was a great assistance towards the delivery of quality outcomes in respect to the project ExpRessBio, the publications which were created together as well as towards this dissertation. Furthermore, her commitment created a very positive working environment where it was easy to get together with the members of the working group and contemplate complex LCA problems. These brainstorming sessions are often the key to successful LCA, since almost all practitioners are faced with the same questions at some point in their career. In this respect I would also like to thank Karin Höglmeier greatly for the many discussions and the pleasant company while sharing an office. And I would also like to say sorry for letting your plants die. Furthermore, this work greatly benefited from the contributions of several master and bachelor students, to whom I wish the best in their future activities. These students are: Bettina Joa, Amrei Weber, Florian Krause, Fabian Bosch and Maren Herter.

One of the biggest thanks has to be given to Dr. Daniel Klein (LWF) who, as a colleague working on the ExpRessBio project, is responsible of shaping and enhancing much of the research presented in this dissertation. His patience and ability to tackle complex questions played an important role towards our work. Thank you also for the many great coffee break and travel discussions.

The research presented in this dissertation was embedded in the project ExpRessBio (Expert Group on Resource Management in Bioenergy), funded by the Bavarian State Ministry for Food, Agriculture and Forestry (StMELF). The project has been an intense learning experience due to the complex and interdisciplinary nature of the many tackled challenges. The project was successfully completed thanks to the colleagues from the Technology and Support Centre Straubing (TFZ), Dr. Edgar Remmele, Dr. Daniela Dressler and Karsten Engelmann, the Bavarian State Research Center for Agriculture (LFL), Dr. Matthias Effenberger, Dr. Mona Maze and Dr. Omar Hijazi, the Bavarian State Institute for Forestry (LWF), Dr. Christoph Schulz and Dr. Daniel Klein, the Science Center Straubing (WZS) and Weihenstephan-Triesdorf University of Applied Sciences (HSWT), Prof. Dr. Hubert Röder, Prof. Dr. Peter Zerle, Martina Serdjuk and André Tiemann and the Chair of Organic Agriculture and Agronomy (ÖLB), Prof. Dr. Kurt-Jürgen Hülsbergen, Taras Bryzinski and Tobias Böswirth.

Further, I would like to thank the members of the newly founded Professorship for Wood Bioprocesses at TUM, Prof. Philipp Benz, Lara Hassan and Nils Thieme, for the many great lunch break distractions. Yet another thanks to Prof. Philipp Benz for agreeing to act as the chairman for the PHD commission and for Prof. Stefanie Hellweg (ETH), Prof. Gabriele Weber-Blaschke and Prof. Klaus Richter, as members of the examination board, for their supervision and review of this dissertation.

Finally I would like to thank my wife Lisa and my parents Christa and Hannes for their invaluable support, for their constructive feedback and for their trust in my abilities before and during my PHD time.

Abstract

This dissertation addresses the methodological development of tools for the reproducible assessment of environmental impacts of wood and wood energy and applies these methods onto heating in the case study region of Bavaria.

Wood energy is a cornerstone in the satisfaction of past, present and future energy demands as well as the mitigation of climate change. As such, it plays a crucial role in a multitude of national and regional energy strategies. However, positive benefits in respect to climate change do not universally translate to other environmental impacts, such as e.g. the emission of particulate matter. As such, the majority of heating related particulate matter emissions in Bavaria are caused by the combustion of wood.

Typically, the environmental impacts of products and services are analyzed through Life Cycle Assessments (LCA). For many products and services, standardized calculation approaches for LCA have already been introduced and adopted. For wood and wood energy LCAs, which have been carried out for more than 20 years, no such standardized approach has yet been implemented. Therefore, comparisons between individual studies are often impossible or inadvisable. However, comparable methods are required in order to identify the true magnitude of potential benefits and burdens associated with the use of wood for the provision of energy, as propagated by national and regional energy- and climate change strategies.

To develop comparable and reproducible methods, two systematic reviews and consecutive meta-analyses concerned with the production of wood and the energetic utilization of wood were carried out and further defined in the ExpRessBio methods handbook. This handbook extends the methodological proposal developed by the two review studies. Based on the outcomes of these studies, among others, methodological provisions in respect to the description of system boundaries, the publication of parameters and results, the handling of co-products and the selection of appropriate environmental indicators were proposed.

In order to evaluate the current and future role of wood heating, the most important utilization for energy wood in the case study area of Bavaria, a direct application of the developed methods was carried out in a subsequent step. The role of wood heating was assessed via Life Cycle Assessments of the current and future shares of all individual energy carriers utilized for the provision of heat in Bavaria, i.e. the Bavarian heating mix. To analyze the environmental effects of shifts in the heating mix, e.g. through polices, emission factors of the comprising energy carriers and the Bavarian heating mix as well as relevant substitution percentiles were determined. Analyses were carried out for the indicators of Global Warming (GWP), particulate matter emissions (PM), freshwater eutrophication (ET),

acidification (AC) and the non-renewable primary energy consumption (PE). In 2011 a total amount of 663.715 TJ of final energy was used for the provision of heat in Bavaria. Solid biofuels exhibit the third largest share of 12.6%. In total 49.6 Mt CO_2-eq. * yr^{-1} (GW) and 14,555 t of $PM_{2.5}$-eq. * yr^{-1} (PM) were emitted for heating in Bavaria. Current policies entail a GHG reduction potential of approx. 1 Mt CO_2-eq. * yr^{-1} (-2%) while increasing the amount of energy wood by 15%. The maximum, hypothetical share of solid biofuels for the heating mix cannot surpass 25%, while the climate change mitigation performance of the current use of solid biofuels is approx. 6.4 Mt CO_2-eq. * yr^{-1}. GHG-emissions would be 13% higher and PM emissions 77% lower without this energetic use of wood.

In order to identify mitigation potentials through wood heating, in a subsequent step, displacement factors for all assessed wood heating systems were determined and a transferable methodology for the calculation of displacement factors, which is adaptable to other regions, was proposed. Since the magnitude of mitigation benefits associated with wood use can vary greatly, depending on regional parameters such as e.g. the displaced fossil reference or heating mix, displacement factors, considering region-specific production conditions and substituted products are required when assessing the precise contribution of wood biomass towards the mitigation of environmental impacts. In order to showcase regional effects, we created weighted displacement factors for the region of Bavaria, based on installed capacities of individual wood heating systems and the harvested tree species assortments distribution. A focus was put on the indicators of Global Warming and particulate matter emissions. The study reveals that greenhouse gas (GHG) displacements between −57 g CO_2-eq. $*$ MJ^{-1} of useful energy, through the substitution of natural gas with a spruce pellets heating system, and −165 g CO_2-eq. $*$ MJ^{-1}, through the substitution of power utilized for heating with a modern beech split log heating system, can be achieved. Furthermore, a GHG displacement of −90.3 g CO_2-eq. $*$ MJ^{-1} for the substitution of the fossil heating mix could be identified. It was shown that the GHG mitigation of wood use is overestimated through the common use of light fuel oil as the only reference system.

The created methodological foundation can aid in the development of further harmonized LCA methodologies for the assessment of wood products, e.g. in the form of a product category rule (PCR) and support comparison between LCA studies in a transparent manner. Already, the methodological approaches have been included in the ExpRessBio methods handbook concerned with the assessment of environmental and economic impacts of bioenergy production in Bavaria. In respect to the environmental effects of shifts in the Bavarian heating mix and the mitigation of environmental impacts through wood heating, the results can aid in the definition of the current and future role of wood energy, and can support decision making pertaining the future of wood energy in the study region.

Zusammenfassung

Die vorliegende Dissertation beschäftigt sich mit der Entwicklung von Methoden zur reproduzierbaren Untersuchung von Umwelteinflüssen der Rohholzproduktion und energetischen Nutzung von Holz sowie der Anwendung der entwickelten Methoden auf die Holzenergienutzung in der Untersuchungsregion Bayern.

Holz stellt ein zentrales Mittel zur Deckung der früheren, aktuellen und zukünftigen Nachfrage an Energie, sowie zur Minderung des Klimawandels dar. Aus diesem Grund spielt die Holzenergie eine zentrale Rolle in einer Vielzahl von nationalen und regionalen Energiekonzepten. Allerdings lassen sich die positiven Eigenschaften der Holzenergie im Hinblick auf die Minderung des Klimawandels nicht bedingungslos auf andere Umweltwirkungen übertragen. So ist die Holzenergie, zum Beispiel für einen Großteil der wärmebedingten Feinstaubemissionen in Bayern verantwortlich.

Grundsätzlich werden Umwelteinflüsse von Produkten und Dienstleistung mit Hilfe von Lebenszyklusanalysen (LCA) untersucht. Für eine Vielzahl dieser Produkte und Dienstleistungen haben daher schon standardisierte Berechnungsmethoden Einfluss in der Fachwelt gefunden. Dagegen liegt für Holz und dessen energetische Nutzung, wofür bereits seit über 20 Jahren LCAs durchgeführt werden, eine analoge Standardmethode nicht vor. Aus diesem Grund sind Vergleiche zwischen einzelnen Studien im Themenfeld der Holznutzung oft nicht möglich, wodurch die Bestimmung der tatsächlichen Höhe von Umweltlasten und Umweltentlastungen nicht möglich ist. Da der Holznutzung allerdings eine wichtige Rolle im Klimaschutz beigemessen wird ist die Entwicklung vergleichbarer und reproduzierbarer Untersuchungsmethoden zwingend erforderlich.

Zur Entwicklung dieser reproduzierbaren Untersuchungsmethoden wurden zwei systematische Review Studien im Bereich der LCA von Holz und Holzenergie, gefolgt von Meta-Analysen durchgeführt und im Methodenhandbuch des Projektes ExpRessBio weiterentwickelt. Auf dieser Grundlage konnten, unter Anderem, Vorgehensweisen bezüglich der Definition von Systemgrenzen, der Darstellung von Ergebnissen und Berechnungsparametern, dem Umgang mit Co-Produkten und der Auswahl geeigneter Umweltindikatoren erarbeitet werden.

Zur Untersuchung der momentanen und zukünftigen Rolle des Heizens mit Holz, der wichtigsten energetischen Holznutzung in der Untersuchungsregion Bayern, wurden die vorher entwickelten Methoden direkt zur Anwendung gebracht. Die Untersuchung wurde mit Hilfe von LCAs der momentanen und zukünftigen Anteile einzelner Energieträger zur Bereitstellung von Wärme, dem sogenannten Wärmemix, durchgeführt. Zur Untersuchung der Umweltwirkungen eines sich verändernden Wärmemixes, z.B. hervorgerufen durch

politische Richtlinien, wurden die Emissionsfaktoren der Energieträger des Wärmemixes sowie Substitutionsfaktoren zwischen den einzelnen Energieträgern erhoben und angewendet. Analysiert wurden die Indikatoren Klimawandel (GW), Feinstaub (PM), Eutrophierung (ET), Versauerung (AC) und der Bedarf an nicht-erneuerbarer Primärenergie (PE). Insgesamt wurden im Jahr 2011 663,715 TJ Endenergie zur Bereitstellung von Wärme in Bayern aufgewendet, wobei feste Biobrennstoffe wie Holz den drittgrößten Anteil von 12,6% darstellten. Hierfür wurden 49,6 Mio. t CO_2-Äq. * a^{-1} (GW) und 14.555 t $PM_{2.5}$-Äq. * a^{-1} (PM) emittiert. Das Energiekonzept der bayerischen Staatsregierung, welches einen Anstieg der Energieholznutzung um 15% vorsieht, würde hierbei zu einer Reduktion von Treibhausgasen um circa 1 Mio. t CO_2-Äq. * a^{-1} (-2%) führen. Der maximale, hypothetische Anteil der festen Biobrennstoffe am Wärmemix ist 25%, bei 100%iger energetischer Holznutzung. Die momentane Klimaschutzleistung der Nutzung von festen Biobrennstoffen zur Bereitstellung von Wärme liegt bei 6,4 Mio. t CO_2-Äq. * a^{-1}. Ohne diese energetische Holznutzung würden die gesamten Treibhausgasemissionen um 13% höher und die Feinstaubemissionen um 77% niedriger ausfallen.

Zur Identifikation der Minderungspotentiale von Holzheizungen wurden im Anschluss Vermeidungsfaktoren für alle untersuchten Holzenergiesysteme erstellt. Des Weiteren wurde eine Vorgehensweise zum Transfer der Berechnungen auf andere Regionen aufgezeigt. Da die Höhe der Minderungspotentiale aufgrund von regionalen Unterschieden, wie spezifischer Produktionsbedingungen oder dem verdrängten Mix an fossilen Referenzsystemen, stark schwanken kann, sind Verdrängungsfaktoren die diese regionalen Aspekte berücksichtigen nötig, um die tatsächliche Höhe der Minderung darzustellen. Um diesen regionalen Aspekten Rechnung zu tragen wurden, unter Anderem, gewichtete Verdrängungsfaktoren, anhand der installierten Leistung einzelner Heizsysteme, sowie der Verteilung geernteter Holzsortimente in Bayern, integriert. Der Fokus der Untersuchungen liegt auf den Minderungspotentialen im Bereich der Treibhausgas- und Feinstaubemissionen. Die Verdrängung von Treibhausgasen durch Holzheizungen je MJ Endenergie liegt zwischen -57 g CO_2-Äq. $\ast$ MJ^{-1}, durch die Substitution von Erdgas mit Pellet Heizsystem, und -165 g CO_2-Äq. $\ast$ MJ^{-1}, durch die Substitution von Strom zur Bereitstellung von Wärme mit modernen Buchen-Scheitholz Heizsystemen. Des Weiteren konnte gezeigt werden, dass die Vermeidungspotentiale von Holzheizsystemen oft durch die Nutzung von leichtem Heizöl als einzigem Referenzsystem überbewertet werden.

Die erarbeiteten Methoden erleichtern den Vergleich und die Reproduzierbarkeit von LCA-Studien und können zur Weiterentwicklung einer weitgehend harmonisierten LCA Methode zur Analyse von Holzprodukten, z.B. in Form einer Produktgruppenregel (PCR), beitragen. Die Untersuchungsmethoden haben in diesem Sinne bereits Einfluss in das ExpRessBio

Methodenhandbuch gefunden, welches die Analyse der ökologischen und ökonomischen Auswirkungen der Bioenergieproduktion in Bayern zum Ziel hat. In Bezug auf die Veränderungen in der Zusammensetzung des bayerischen Wärmemixes sowie der Minderung von Umwelteinflüssen durch das Heizen mit Holz, können die Ergebnisse bei der Definition der momentanen und zukünftigen Rolle der Holzenergie beitragen und die fundierte Entscheidungsfindung zur Zukunft der Holzenergie unterstützen.

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Abbreviations

AC	Acidification
BAT	Best-available technology
CHP	Combined heat and power
EC	European Commission
EF	Emission factor
EEG	Erneuerbare Energien Gesetz (German Renewable Energy Act)
EOL	End of life
EPD	Environmental Product Declaration
ET	Eutrophication
GHG	Greenhouse gas
IEA	International Energy Agency
iluc	Indirect land-use change
ISO	International Organization for Standardization
GW	Global warming
IWR	Industrial wood residues
LCA	Life Cycle Assessment
LFO	Light fuel oil
LHV	Lower heating value
LPG	Liquid propane gas
luc	Land-use change
MC	Moisture content

Abbreviations (continued)

MJ	Megajoule
PCR	Product Category Rule
PE	Primary energy consumption
PM	Particulate matter
w	Water content

1 Introduction

The research presented in this dissertation was embedded in the project ExpRessBio, funded by the Bavarian State Ministry for Food, Agriculture and Forestry (StMELF).

ExpRessBio (Expert group resource management bioenergy in Bavaria) is a Bavarian research project with the aim to analyze and optimize agricultural and forestry biomass production for the provision of bioenergy and raw materials under the aspects of resource efficiency and environmental impacts. Additional goals were the economical evaluation of agricultural and forestry process chains in Bavaria. The specific focus of the research conducted for this dissertation was the analysis of issues related to the utilization of wood for energy.

1.1. Problem statement

Having reached an agreement on common goals for the reduction of greenhouse gas emissions based on legal force in December 2015 in Paris, the member states are faced with the development of strategies, i.e. climate action plans, towards the fulfillment of goals set in Paris and in earlier non-binding agreements. Member states agreed the long term goal to limit the increase in global average temperature to well below 2°C above pre-industrial levels, Furthermore, they agreed to the need for global emissions to peak as soon as possible and to undertake rapid reductions thereafter in accordance with the best available science (UNFCCC 2015). Already well before the Paris Agreement, the utilization of wood has been associated with benefits towards the mitigation of climate change, and as such has played an important role for many countries' climate action plans and other national and regional policies. In Germany, policies such as the Renewable Energy Act (EEG) and the Bavarian Energy Concept (BAYERISCHE STAATSREGIERUNG 2011) are responsible for an increased utilization of wood as fuel for the provision of energy due to its positive impact on energy security as well as the benefits associated with the substitution of conventional energy carriers. The International Energy Agency (IEA) states that the use of biomass can lead to greenhouse gas savings and the reduction of other environmental burdens. Biomass can further aid in meeting the global energy demand, support the economic development of rural communities and assist in the improvement of the management of resources and wastes (BAUEN ET AL. 2009). Coupled with the reduction of reserves and increase in prices for non-renewable resources (BMWI 2015) the demand for wood is expected to grow and projected to eclipse supply by 2030 (MANTAU ET AL. 2010; UNECE 2011). However, positive benefits of wood use in respect to climate change cannot be universally attributed to the resource of wood, but rather to the circumstances of production, processing, transportation and use.

Especially for wood being transported over long distances and which originates from non-sustainable forestry, climate benefits can potentially be compromised. Furthermore, in many cases, the provision of energy through wood entails substantial emissions of particulate matter and can be responsible for the diminution of plant nutrients in the soil, e.g. through whole tree harvesting regimes (GÖTTLEIN 2016). A sustainable biomass use is not without challenges however. According to IEA, main challenges are the technical innovation to further increase the efficiency of biomass conversion, the competition for land as well as the competition towards opposing utilization pathways. Further challenges are the competitiveness with other energy sources, as well as bioenergy infrastructure and logistics (BAUEN ET AL. 2009). Therefore, in order to address the projected resource scarcity, to fulfill GHG reductions targets and to minimize negative impacts on human health and environment, it is imperative to use local wood as efficiently as possible (EC 2011).

1.2. State of knowledge

In order to maximize resource efficiency and minimize environmental impacts of wood use, concepts such as the e.g. cascading of wood (HÖGLMEIER 2015) and the adaptation of Life Cycle Assessment (LCA) on wood products (RICHTER & SELL 1992) have been studied in the past. LCA constitutes the scientific basis for the identification of environmental impacts of products and services. The methodology has evolved from its origins in energy analysis in the 1960s and 70s into a wide ranging tool used to determine impacts of products or entire multi-product systems over several environmental and resource indicators (MCMANUS & TAYLOR 2015). As such, LCA tracks and assess environmental impacts from a systems perspective, pinpointing approaches for improvement without the shifting of burdens to other, external systems. It is seen as a valuable screening tool to identify environmental hotspots in complex value chains of products, organizations, consumers or even countries (HELLWEG & MILÀ I CANALS 2014).

For biomass, in order to ensure the minimization of environmental impacts, a life cycle perspective is required to recognize key issues along the production pathway (ZAH ET AL. 2007; SCHARLEMANN & LAURANCE 2008; TILMAN ET AL. 2009). This life cycle perspective includes the assessment of environmental effects from a cradle to grave perspective and the evaluation of external effects occurring through the utilization of the relevant product or service (i.e. substitution) (CHERUBINI ET AL. 2009; STEUBING 2011). A recent study carried out by the German Federal Ministry of Food and Agriculture (BMEL) postulates that the total climate mitigation potential from forests is founded on four sectors, i.e. the carbon storage in forests (58 Mt CO_2) and wood products (2 Mt CO_2), and the substitution through a material- (30 Mt CO_2) and energetic utilization of wood (36 Mt CO_2). As such, in excess of 50% of the total climate mitigation potential from forests can be allotted to the utilization of forest resources (HEUER ET AL. 2016; KÖHL ET AL. 2009). This importance of the actual utilization of wood for climate mitigation has now, after much debate (THRÄN ET AL. 2016; DFWR 2016), been incorporated into the updated German Federal Climate Action Plan 2050 (BMUB 2016). As seen on the example of forestry, where only the carbon sequestration in forests is accounted for, this can lead to substantial underestimations of the climate mitigation potential of forests and wood use. As such, the disregard of key drivers towards climate mitigation from wood utilization, i.e. the substitution of conventional products and energy carriers, can instigate incorrect assumptions towards the future of forest management and wood product use in Germany. This illustrates the importance of a systemic perspective when assessing environmental impacts of products and services and that the total contribution of forests towards climate change mitigation is the sum of the effects of carbon sequestration and storage in forests, carbon storage in harvested wood products, substitution of wood products for functionally equivalent materials and substitution of wood for other sources of energy as well as the displacement of emissions from forests outside the EU (RÜTER ET AL. 2016).

1.3. Research gap

In contrast to many LCAs from different fields, such as the chemical or aluminum industry, production circumstances for bio-based products are, due to long production cycles and the anisotropic and hygroscopic nature of most biomass, quite diverse, which can lead to a wide range of approaches towards the assessment. Therefore, and in conjunction with the nonexistence of standardized methodologies for the assessment of environmental impacts from wood production and wood utilization, frequently non-comparable and non-reproducible results are generated and published. Though standards for LCA exist in the form of ISO 14040, ISO 14044 (ISO 2006, 2009), the complex nature of bio based products requires a more rigid approach towards the assessment of environmental impacts in order to identify the most beneficial use of the resource. For the LCA in the forestry and wood sector, which has been practiced for more than 20 years (KLEIN ET AL. 2015), many studies published today impede on one of the fundamental principles of science, reproducibility. The main reason for this is the lack of product specific guidelines in the ISO standards (ISO 2006, 2009) and the lack of specified guidelines, e.g. in the form of a product category rule (PCR) for the forestry and wood sector. As such, key features like the transparent and harmonized description of the product system, adequate allocation procedures and the style of reporting results lead to a wide range of LCAs that are incomparable and which do not offer the possibility for meta-analysis, which is a statistical approach to synthesize data, e.g. LCA results, from multiple studies (NEELY ET AL. 2010).

Additionally, the lack of a methodology that offers comparable, reproducible and transparent results hinders the assessment of environmental impacts of wood use on a global scale, including the climate mitigation potential. Therefore, it is unclear what the magnitude of environmental benefits of wood use are, and if benefits exist. This leads to the question if the promotion of the energetic use of wood, e.g. through the European Commission, the EEG or the Bavarian energy concept, is justified.

In respect to the assessment of environmental impacts of wood use, many studies are focused on the generation of energy, transportation fuels or heat from a product system perspective (WOLF ET AL. 2015A). However, for topics, such as climate mitigation, where benefits do not directly occur locally and effects represent the sum of influence of a variety of different actors, systemic perspectives (e.g. for regions) are frequently better suited. A systemic approach for the assessment of greenhouse gas emissions has been carried out for the material- and energetic use of biomass in the past (SATHRE & O'CONNOR 2010). However, this study, like many others in the field (FELDER & DONES 2007; GHAFGHAZI ET AL. 2011; KATERS ET AL. 2012; ESTEBAN ET AL. 2014; JÄPPINEN ET AL. 2014), was conducted with some generalizations in respect to the reference system composition, i.e. the provision of heat is represented by only one or two major energy carriers rather than an actual mix. Due to the diverse and decentralized structure of the provision of heat, the above-mentioned generalization is especially apparent for this energy service. A fact that is unfavorable, since the provision of heat is potentially the most important energy service in respect to the amount of final energy, the respective amounts of consumed wood and the potential environmental benefits and burdens. As such, heating is responsible for more than 50% of total final energy expended in Germany (AGEB 2013). Therefore, when assessing the environmental impacts of heating, the assessment methodology should also reflect the magnitude of importance towards the energy service, in that the degree of detail adequately reflects the composition of the heating sector in the relevant study area.

1.4. Objective and research questions

The long term and superordinate goals for this research is the reduction of environmental impacts associated with the provision and utilization of wood. As such, the development of a methodology, solving the above-mentioned challenges towards the assessment of environmental impacts from forestry and wood utilization in Bavaria, was a main goal for this research. As such, the creation of a reproducible and transparent assessment methodology was one of the key development tasks. In respect to the application of this methodology, the assessment of environmental impacts from wood heating in Bavaria was incorporated in the dissertation. A key objective was the integration of a systemic perspective, which reflects the interdependencies of different energy carriers for Bavarian heating and aims at delivering a comprehensive assessment of associated environmental impacts.

For the initial part of the dissertation two review studies with the following research questions were performed.

1. Which methods for the assessment of the life cycle of raw wood products and their subsequent utilization for the purpose of providing energy are prevalent in current literature and how can they be further developed?
2. Which methodological aspects, including the transfer of methods towards bioenergy from agricultural resources, require further development and harmonization?
3. What is the range of environmental effects of raw wood products and wood energy in current literature and by which factors is the magnitude of results influenced?

In subsequence to the reviews (KLEIN ET AL. 2015; WOLF ET AL. 2015A), the developed methodology was applied onto the generation of wood energy in the state of Bavaria. The following research questions were addressed.

4. Which environmental impacts are caused by the regional provision of heat from solid biofuels (i.e. wood) in Bavaria, what is the contribution of these systems to the total emissions in the state and what are potential alterations of environmental impacts caused by certain bioenergy goals outlined in policies or scientific publications?

As a direct application of obtained results (KLEIN ET AL. 2016; WOLF ET AL. 2016B), updated and comprehensive factors for the mitigation of environmental impacts through wood heating systems could be deduced. The following research questions were addressed.

5. What is the magnitude of displacement effects for different wood heating systems in respect to climate change and particulate matter emissions in Bavaria and how can the approach be transferred to other countries or regions outside of the study region?

2 Overview of publications

Initially, in order to identify the current practices of LCA in the forestry and wood energy sectors and to derive a reproducible, precise and harmonized methodological proposal, two review studies, including meta-analyses were conducted and an initial proposal for a harmonized assessment methodology proposed. Subsequently, in order to apply the methodology onto the case study region of Bavaria, LCA studies for both the provision of wood from Bavarian forests (KLEIN ET AL. 2015) (not covered in this dissertation) and the energetic utilization for heat, as well as the impacts of the entire heating sector and shifts in these impacts through e.g. policy, were analyzed. In a last step, to complete the evaluation of the direct systems emissions identified in publications three, mitigation effects through the displacement of other energy carriers with wood were assessed (FIGURE 1). The following section presents these publications.

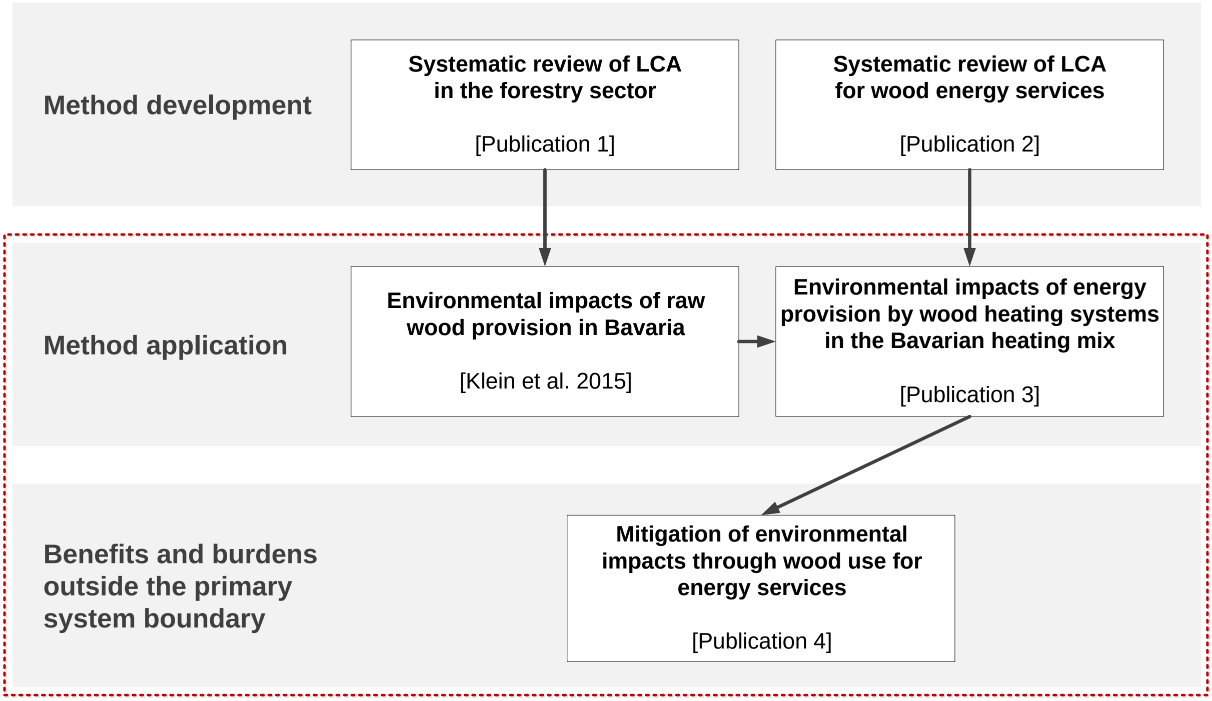


Figure 1 *Overview of publications in the context of this dissertation. The red line depicts the case study application.*

2.1. Publication 1: 20 years of Life Cycle Assessment (LCA) in the forestry sector: state of the art and a methodical proposal for the LCA of forest production

Daniel Klein, Christian Wolf, Christoph Schulz, Gabriele Weber-Blaschke

2015, International Journal of Life Cycle Assessment. DOI: 10.1007/s11367-015-0847-1

Abstract

Although methodologies for the LCA of forest production have been conducted since the early 1990s, consistent and comprehensive LCA studies are still lacking for the forestry sector. In order to support better comparability between LCA studies, we analyzed the problems and differences by conducting a descriptive and quantitative analysis of existing LCA studies of forest production. Important issues were, among others, the goal of the studies, system boundaries, functional units, impact categories and involved processes. In addition, a quantitative analysis in respect to the impact on Global Warming (GW) published by individual studies was performed. The studies showed large differences between methodical assumptions and their subsequent results. For GW, a range between 2.4–59.6 kg CO_2-eq. * m^{-3} over bark from site preparation to forest road delivery and 6.3–67.1 kg CO_2-eq. * m^{-3} over bark from site preparation to plant gate or consumer delivery could be identified. Results varied as a function of the included processes and decisive assumptions, e.g., regarding productivity rates or fuel consumption of machineries. Raw wood products are widely declared as “carbon neutral,” but the above-mentioned results show that absolute carbon neutrality is incorrect, although the GW is low compared to the carbon storage of the raw wood product (range of C-emitted/C-stored in wood is 0.008–0.09 from forest to plant gate or consumer). Thereby, raw wood products can be described as “low emission raw materials” if long-term in situ carbon losses by changed forest management or negative direct or indirect land use change effects (LUC, iLUC) can be excluded. In order to realize improved comparisons between LCA studies in the forestry sector in the future, we propose a methodical approach regarding the harmonization of system boundaries, functional units, considered processes, and allocation assumptions.

Contribution

Daniel Klein is the main author of the publication. Christian Wolf co-developed the systematic review protocol and methodological proposal and is responsible for the deduction of system visualization as well as the joint interpretation of the results and discussion parts of this study. Christoph Schulz and Gabriele Weber-Blaschke supported the development of the study in respect to the conceptualization and redacted the publication.

2.2. Publication 2: Systematic review and meta-analysis of Life Cycle Assessments for wood energy services

Christian Wolf, Daniel Klein, Gabriele Weber-Blaschke, Klaus Richter

2015, Journal of Industrial Ecology. DOI: 10.1111/jiec.12321

Abstract

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 publically available LCA studies for wood energy services. The systematic review investigated crucial methodological and systemic factors, such as system boundaries, allocation, 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 subsequent outcomes. A total of 44 systems for the generation of power, with a median impact on GW of 0.169 kg CO2-eq. * $\mathrm{kWh_{el}^{-1}}$, were identified. Results for the biomass fraction, i.e. the emissions associated with the share of biomass in co-combustion systems, show a median impact on GW of 0.098 kg CO2-eq. * $\mathrm{kWh_{el}^{-1}}$. A total of 31 systems producing heat exhibited a median impact on GW of 0.040 kg CO2-eq. * $\mathrm{kWh_{th}^{-1}}$. With a median impact on GW of 0.066 kg CO2-eq. * $\mathrm{kWh_{el+th}^{-1}}$, CHP systems show the greatest range 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, which can support the development of a bioenergy product category rule (PCR).

Contribution

Christian Wolf was responsible for the study design, carried out the assessment and wrote the article. Daniel Klein supported the statistical analyses for the meta-analyses, provided valuable input towards the system description template and redacted the publication. Gabriele Weber-Blaschke and Klaus Richter supported the development of the study in respect to its concept, research structure and level of detail, and contributed to the editing process.

2.3. Publication 3: Environmental effects of shifts in a regional heating mix through variations in the utilization of solid biofuels

Christian Wolf, Daniel Klein, Klaus Richter, Gabriele Weber-Blaschke

2016, Journal of Environmental Management. DOI: 10.1016/j.jenvman.2016.04.019

Abstract

Solid biofuels, i.e. wood, play an important role in present and future national and global climate change mitigation policies. Wood energy, while displaying favorable properties in respect to the mitigation of climate change also exhibits several drawbacks, such as potentially high emission of particulate matter on a regional scale and with regional impacts. To assess the environmental effects of shifts in the heating mix, emission factors of the comprising energy carriers and the Bavarian heating mix were determined. Through the application of regionalized substitution percentiles the environmental effects caused by shifts in the amount of final energy provided by solid biofuels could be identified. For this purpose, four scenarios, based on political and scientific specifications were assessed. In 2011 a total amount of 663.715 TJ of final energy was used for the provision of heat in Bavaria, with solid biofuels exhibiting the third largest share of 12.6%. Environmental effects were evaluated through LCA calculating the indicator values for Global Warming (GW), particulate matter emissions (PM), freshwater eutrophication (ET), acidification (AC) and the non-renewable primary energy consumption (PE). The heating mix in Bavaria (baseline) caused emissions of 49.6 Mt CO_2-eq. * yr^{-1} (GW), 14,555 t of $PM_{2.5}$-eq. * yr^{-1} (PM), 873.4 t P-eq. * yr^{-1} (ET), and 82.299 kmol H^+ eq. * yr^{-1} (AC), for which 721,745 TJ of primary energy were expended. Current policies entail a GHG reduction potential of approx. 1 Mt CO_2-eq. * yr^{-1} while increasing the amount of energy wood by 15%. The maximum, hypothetical share of solid biofuels for the heating mix cannot surpass 25%, while the climate change mitigation performance of the current use of solid biofuels is approx. 6.4 Mt CO_2-eq. * yr^{-1}. GHG-emissions would be 13% higher and PM emissions 77% lower without this energetic use of wood. The results aid in the definition of the current and future role of wood energy in the study region of Bavaria.

Contribution

Christian Wolf was responsible for the study design, carried out the assessment and wrote the article. Daniel Klein provided data for the evaluation of wood production and redacted the publication. Gabriele Weber-Blaschke and Klaus Richter supported the development of the study in respect to the structure and conceptual approach and critically reviewed and guided the editing process.

2.4. Publication 4: Mitigating environmental impacts through the energetic use of wood: Regional displacement factors generated by means of substituting non-wood heating systems

Christian Wolf, Daniel Klein, Klaus Richter, Gabriele Weber-Blaschke

2016, Science of the Total Environment. DOI: 10.1016/j.scitotenv.2016.06.021

Abstract

Wood biomass, especially when applied for heating, plays an important role for mitigating environmental impacts such as climate change and the transition towards higher shares of renewable energy in national or regional energy mixes. However, the magnitude of mitigation benefits and burdens associated with wood use can vary greatly depending on regional parameters such as the displaced fossil reference or heating mix. Therefore, displacement factors, considering region-specific production conditions and substituted products are required when assessing the precise contribution of wood biomass towards the mitigation of environmental impacts. We carried out Life Cycle Assessments (LCA) of wood heating systems for typical conditions in Bavaria and substitute energy carriers with a focus on climate change and particulate matter emissions. In order to display regional effects, we created weighted displacement factors for the region of Bavaria, based on installed capacities of individual wood heating systems and the harvested tree species distribution. The study reveals GHG displacements between −57 g CO_2-eq.∗ MJ^{-1} of useful energy through the substitution of natural gas with a 15 kW spruce pellets heating system and −165 g CO_2-eq.∗ MJ^{-1} through the substitution of power utilized for heating with a modern 6 kW beech split log heating system. It was shown that the GHG mitigation potentials of wood utilization are overestimated through the common use of light fuel oil as the only reference system. We further propose a methodology for the calculation of displacement factors which is adaptable to other regions worldwide. Based on our approach it is possible to generate displacement factors for wood heating systems which enable accurate decision-making for project planning in households, heating plants, communities and also for entire regions.

Contribution

Christian Wolf was responsible for the study design, carried out the assessment and wrote the article. Daniel Klein provided data for the evaluation of wood production and redacted the publication. Gabriele Weber-Blaschke and Klaus Richter supported the development of the study in respect to the structure and conceptual approach and critically reviewed and guided the editing process.

3 Systematic review, meta-analysis and methodological development

(Publication 1 and 2: Klein et al. 2015 and Wolf et al. 2015a)

3.1. Problem statement and objectives

The assessment of environmental effects of products and services has been carried out for more than two decades by the application of Life Cycle Assessment (LCA). The concept of LCA as a methodology is not very complex, but to assess the consequences of a methodological decision and the subsequent reiteration process can be very challenging. These methodological decisions could be e.g. the choice of the system boundary and temporal system boundary, allocation procedures or the inclusion or exclusion (e.g. cut-off) of certain processes. Furthermore, LCA can be strongly influenced by the practitioner. As such, results, e.g. for the emissions of harmful substances into air, water and soil, based on similar assumptions can differ greatly. Therefore, an initial point for the research was the need to identify key methodological concepts of LCA, and especially the LCA of bio-based products, and to derive best practice approaches onto the subsequent research. This was done via two initial systematic review studies for the sectors of forest production (i.e. the production of raw wood in the forest) and the provision of wood energy, of which the results are presented in the following chapter. While the parts for methodology and conclusion contain both reviews, the results section was split into three parts in order to cover the different studies and sections in greater detail. For both publications, the main goals were the identification of methodological approaches and range of GHG emissions for the LCA of raw wood and the energetic use as well as the deduction of proposals for an improved, more harmonized methodology of Life Cycle Assessments for the above mentioned products and services.

3.2. Methodology

Due to the need to synergize and discuss approaches for LCA in the forest and wood sector a systematic review followed by meta-analysis was performed for both, wood production and wood use. Systematic review is the process of evaluating studies concerned with the same subject based on the application of a clearly defined review methodology with the goal to identify, in this case, methodological similarities, variances and to derive propositions for enhancing the comparability of studies and results. Data compiled through the systematic review was further examined by the application of meta- analysis, which is a statistical approach to synthesize data from multiple studies (NEELY ET AL. 2010). Through meta-analysis it is possible to derive conclusions otherwise unavailable from the individual studies alone (TRANFIELD ET AL. 2003). The systematic review was conducted according to the STARR-LCA principle (ZUMSTEG ET AL. 2012), which is a standardized methodology for the systematic review of LCA studies. STARR-LCA includes a check list and provisions for the consistent execution of a systematic review and the qualitative and quantitative synthesis.

3.2.1. Systematic review protocol

Studies were located by utilizing pertinent databases for scientific content, such as Science Direct or Web of Science, and screened according to the systematic review protocol, which defines a limit for the scope of the systematic review. For inclusion in the systematic review each study had to meet several criteria. Studies were excluded that e.g. were published before the year 2000, in order to reflect the state of the art and recent developments, were not conducted for a European, North American, or comparable region (with respect to climate, forestry, and wood use practices) or were not published in peer-reviewed journals.

Additionally, several exclusion criteria specific to the systematic review for forest production (KLEIN ET AL. 2015) and the utilization of wood for the generation of energy (WOLF ET AL. 2015A) were employed. For the systematic review concerned with LCA of forest production, studies were excluded that e.g. were concerned with short rotation coppices, since these areas do not represent forestry, but rather agricultural land uses. The systematic review concerned with the LCA for wood energy services excluded studies that were limited to the life cycle of a wood fuel without any conversion processes, or were concerned with energy from waste wood or recovered wood, short rotation wood, or other agricultural biomasses.

A total of 28 studies were selected for the systematic review of forest production, and 30 studies were selected for the systematic review of the energetic utilization of wood.

3.2.2. The descriptive analysis (qualitative analysis)

Studies fulfilling the above-mentioned criteria were subsequently analyzed in a descriptive manner following the provisions of JUNGMEIER ET AL. (2003) which includes recommendations for major methodological aspects of energy related LCAs. Parameters for this descriptive analysis were: author, year, country, system boundaries, reference system, data sources, functional units, allocation procedures, transportation distances and transportation types as well as impact categories and characterization method employed. The systematic review for forest production additionally analyzed these parameters: forest type, stand description, tree species, treatment regime, raw wood product as well as the development stage or system. The systematic review concerned with the LCA for the energetic utilization of wood additionally analyzed these parameters: energy service provided (power, heat, CHP), wood feedstock properties, conversion technology, combustion capacity and efficiency as well as the co-combustion rates (if applicable).

3.2.3. Meta-analysis (quantitative analysis)

In order to gain insights into the range of climate impacts associated with the production of raw wood in the forest and the energetic use of wood, meta-analyses were carried out for the respective sectors. Due to a lack of published data, the meta-analysis was restricted to the assessment of climate impacts.

Results for the forest production, on the basis of 1 m³ over bark (ob) of green wood, were summarized into six different process groups: site preparation (SP), site tending (ST), silvicultural operation (SO), secondary processes (SEP), transport (T) and chipping (C). Since a diverse range of functional units were employed by the different studies, a recalculation of results towards a unified functional unit of 1 m³ ob, on the basis of tree-specific wood densities and carbon- or energy contents, was carried out. Recalculation from a surface area functional unit (e.g. hectares) was conducted via the total harvested timber volumes of the respective land area.

The results for the provision of wood energy services, recalculated to the basis of 1 kilowatt-hour (kWh), were grouped according to the provided energy service (i.e. heat, power or CHP), as well as the conversion technology (i.e. direct mono combustion, intermediary wood fuel technologies like e.g. gasification, co-combustion), and combustion capacities. Additionally, for larger scale co-combustion systems, the assessment was expanded to depict only the environmental impacts associated with the biomass fraction of the co-combustion system. This enables a comparison between the different conversion pathways, i.e. direct combustion, co-combustion, and thermochemical transformation.

Since only a small amount of studies provided disaggregated results it was impossible to further harmonize the meta-analysis by adding or removing specific system components. As a result, the meta-analysis can only depict the range of results for current LCAs of wood energy utilization, rather than a direct comparison of equal systems.

3.3. Results and discussion

3.3.1. Forest production

(Publication 1: Klein et al. 2015)

Qualitative analysis

Most studies identified and evaluated had been carried out for the regions of North America, Scandinavia and Germany, while no studies for the region of Eastern Europe or Russia could be found. In almost all cases, LCA was carried out for the forest types of temperate or boreal forests with some studies concerned with Mediterranean forests. LCA studies for the forestry sector still provided a very limited amount of results based on actual scientific research. In many cases this might be due to the fact that the forestry system had not actually been the main focus of an LCA study, but rather one part of a more complex industrial system, like e.g. the generation of heat from wood chips or the life cycle of a building. An additional aspect might be the notion that forestry in general creates only minor negative environmental impacts, and therefore the resolution of modeling is rather low. In many studies aggregated third party processes (i.e. inventory data from databases such as ecoinvent (SWISS CENTRE FOR LIFE CYCLE INVENTORIES 2013) or PE Professional (THINKSTEP AG 2015)) are used. However, it could be observed that this situation has somewhat changed over the past years, with an increasing number of LCA studies explicitly covering the topic of LCA in forestry. This might be due to the increase in global biomass demand for the purpose of generating energy from forestry resources, an enhanced awareness of the public towards the environmental effects of products in general and also policy targets towards reducing GHG emission which necessitate a sound quantification of environmental effects.

Since most studies were focused on high economic value tree species, 54% of studies were concerned with spruce, 25% with pine and 14% with Douglas fir. For beech, which is one of the most important hardwood species in Europe and of predominant importance as local biofuel, thus exhibiting a further projected rise in importance in the future (UNECE 2011; WEBER-BLASCHKE ET AL. 2015), no studies could be identified. In line with these findings is the detected dominance of highly or fully mechanized treatment and harvesting regimes, employing heavier machinery, such as harvesters.

In respect to system boundaries, the majority of studies followed a cradle to gate approach with the “gate” either defined as the forest road or the actual plant gate (e.g. saw mill, pellet mill). When witnessing the great importance of the transportation phase (see section “quantitative analysis”), it can already be deduced that a very broad definition of the term “gate” can often lead to incorrect comparisons when employing it as the sole indicator for what the actual system is comprised of. This can lead to the negligence of upstream processes, the subsequent underestimation of environmental impacts and a limitation of comparability across studies. For the actual forest management systems, four starting points for the assessment could be identified: assessment beginning with seedling production, site preparation, planting, and harvesting. Procedures for the definition of temporal boundaries were also divers and exhibited whole rotation-, single intervention- or management year approaches. In terms of spatial boundaries stand level and regional level approaches could be identified.

Twelve different functional units could be identified, ranging from units specifying volume (e.g. 1 m^3) or wood mass (e.g. 1 t) to units specifying land area and/or time (e.g. hectares/year) as well as units specifying chemical or physical properties such as 1 t of carbon or the energy content of the wood. In many cases however, important properties required for meta-analysis, such as the wood moisture content, were not disclosed. Therefore, the accurate description of system boundaries and included processes is one of the main concerns for the subsequent methodological proposal (see section 3.3.3).

The allocation of burdens to the multi-output system of forest production is also not approached in a uniform way, with the majority of studies not even mentioning how, or if allocation took place, or how it was prevented. Only 20% of the studies clearly stated that allocation was not necessary. Around one third of studies specified allocation on the basis of mass and 10% of the studies specified allocation on the basis of market prices. However, an allocation by mass on the basis of 1 m^3 or 1 t leads to uniform GHG emission for all products and co-products making this form of allocation typically unsuitable for these functional units. Differences only occur on a hectare basis when the amount of harvested timber volumes for the respective products and co-products differ, a fact that many authors might not be aware of.

Quantitative analysis

Depending on the amount and type of included parameter (e.g. technical processes, tree species, productivity rates) and other assumptions (e.g. temporal system boundaries, allocation), results for the impact category of IPCC Global Warming (GW) excluding biogenic CO_2 exhibit a wide range (2.4 – 59.6 kg CO_2-eq. * m^{-3} ob), with a mean impact for systems from site preparation to forest road of 14.3 kg CO_2-eq. * m^{-3} ob and a median of 13.0 kg CO_2-eq. * m^{-3} ob. Adding transports to this system type, increases the range to 6.3 – 67.1 kg CO_2-eq. * m^{-3} ob. When taking the carbon ratio into account, which is the amount of carbon (expressed in CO_2-eq) that has to be emitted (i.e. GHG emissions caused by production and transportation processes) in order to deliver 1 t of carbon (in the form of wood, expressed in CO_2-eq) to the plant gate, approximately 8-90 kg CO_2-eq have to be emitted to provide the wood ($\frac{\mathrm{C}_{\mathrm{emitted}}}{\mathrm{C}_{\mathrm{absorbed}}} = \{0.008 \ldots\ 0.09\}$). Results clearly show that forest production is very divers and can lead to a great range of results for the impact category of GW. As such, it is not recommended to treat forest production like a steady system with uniform, or no impacts at all. It is therefore incorrect to state that forest raw wood products are carbon-neutral. However, although raw wood exhibits a certain impact on GW compared to many other materials, it can be considered a “low GHG-emission raw material” if in situ carbon stock changes are non-apparent. These carbon stock changes, especially from non-sustainable forestry can lead to substantial GHG emissions, in many cases much higher than the emissions associated with the direct forestry processes itself (RØYNE ET AL. 2016). This fact also becomes evident when overserving the above mentioned carbon ratio. Even though it is sometimes difficult to estimate carbon stock changes, they form an integral part of any thorough and holistic LCA of forestry systems. Results including emissions caused by carbon stock changes should be reported separately to the results of direct forestry production however, in order to understand the origins for each emission source and to be able to optimize the system.

3.3.2. Wood energy services

(Publication 2: Wolf et al. 2015a)

Qualitative analysis

In the public, wood energy services had been perception similarly to forest raw wood, in that impacts on the environment associated with the life cycle of wood energy services was considered low. Therefore, even though bioenergy LCAs, e.g. from agricultural biomass, are quite numerous, the number of suitable studies for systematic review and meta-analysis in the wood energy sector used to be relatively limited. Nevertheless an increasing amount of wood energy LCAs in recent years, due to the great interest and sometimes controversial discussion, could also be observed. An overview of parameters for the qualitative analysis of wood energy services is compiled in FIGURE 2.

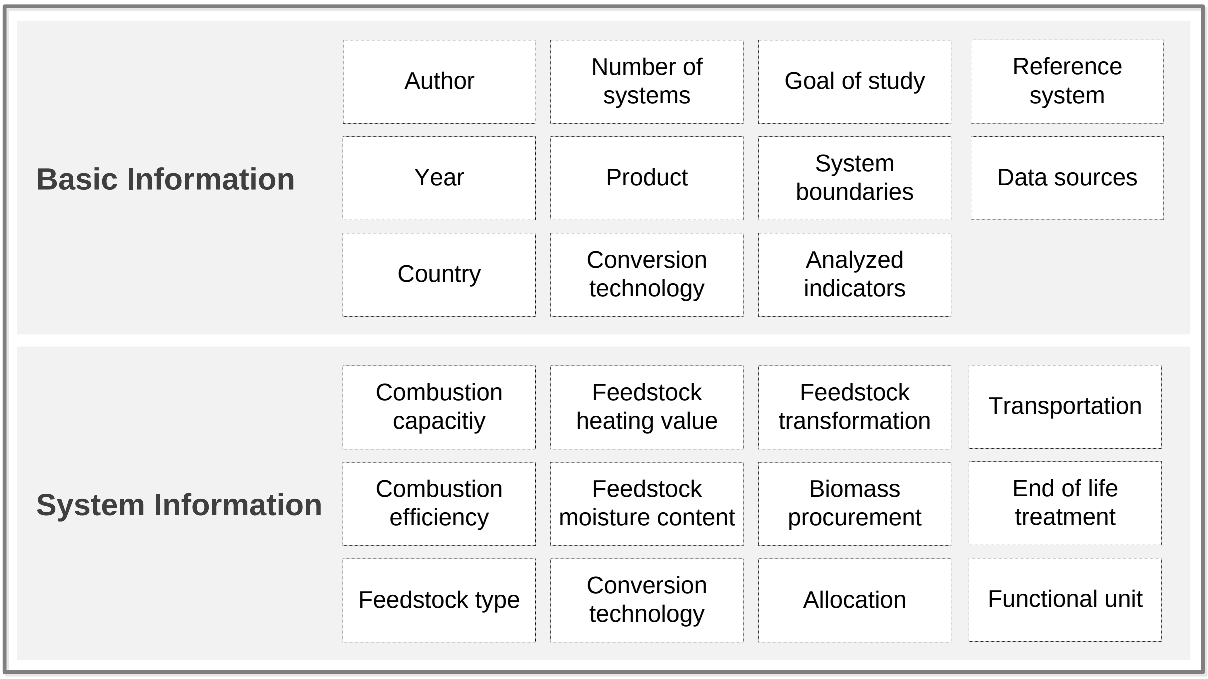


Figure 2 *Systematic review parameters for LCAs of wood energy services.*

Most studies concerned with the LCA of wood energy services could be located for Europe and North America and were published after 2010. A total number of 97 individual systems originating from 30 studies were analyzed, of which 44 systems were concerned with the generation of power, 31 systems were concerned with the provision of heat and the remaining 22 systems analyzed the provision of combined heat and power. In these groups the wood biomass was either directly combusted, either as a sole fuel or in co-combustion, or pretreated into an intermediary wood fuel (FIGURE 3).

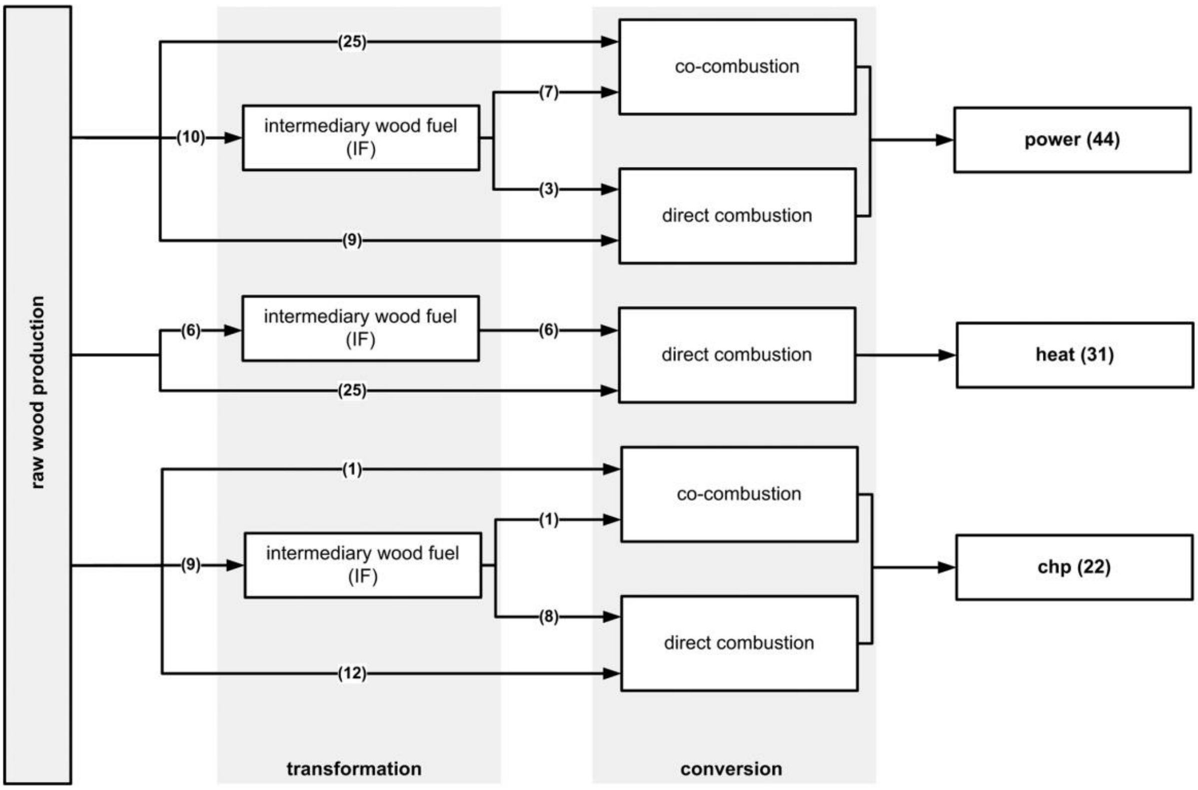


Figure 3 *Transformation and conversion technologies of analyzed wood energy LCA studies. Numbers depict the amount of systems concerned with the respective technology. chp=combined heat and power. (source: Wolf et al. 2015a, fig. 1, p. 749).*

One of the most frequently encountered problems during the systematic review of wood energy services was the unprecise definition of system boundaries. Many studies only stated whether the studied system was modeled as e.g. “cradle to gate” or “cradle to grave” without actually specifying which processes were included in the assessment and which processes were omitted. It was concluded that a precise description of system boundaries is one of the most important issues when aiming for comparable LCA studies. Therefore a more comprehensive approach for system description was proposed (see chapter 3.3.3).

Analyzing individual processes published in the studies, beginning with the provision of raw wood, showed that the modeling resolution for forest production varies greatly, e.g. from a detailed coverage of relevant processes to just a general note of inclusion or no mention of the process at all. However, as shown in 3.3.1, impacts can be substantial and should not be omitted just because the modeling might be complex or no primary data was obtainable.

With respect to the reported feedstock properties, such as the moisture content, the lower heating value (LHV) and ash contents, arguably some of the most important parameters for any wood energy LCA, reported information was often vague, implausible or even nonexistent. This results in a large number of studies that infringe upon one of the most integral principles of science, reproducibility.

The conversion of wood fuel to power or CHP mainly takes place in larger sized installations, while the provision of heat occurs on a much smaller scale, with 60% of systems exhibiting combustion capacities below 100 kW. Similarly to the above mentioned important feedstock properties, a large number of studies failed to provide information on the efficiency of the combustion process. These two aspects, however, are at the core of every energy-related LCA, since they act as scaling factor for all previous upstream processes and flows. In this respect, the feedstock LHV scales all processes before combustion, while the combustion efficiency scales the whole system until after combustion, giving great importance to both parameters. Therefore, these parameters are fundamental to the reproducibility of studies and should be provided in every energy related LCA.

Quantitative analysis

The impact on GW (excluding biogenic CO_2) for the provision of heat exhibits a mean of 0.051 kg CO_2-eq. * kWh^{-1} and a median of 0.04 kg CO_2-eq. * kWh^{-1} (FIGURE 4). The meta-analysis results for heat show the smallest range of impacts in comparison to power and CHP. The small range of results is caused by the similarities between most heating systems in terms of included processes, the lack of allocation and similar efficiencies during combustion. In contrast, for CHP and power generating systems a multitude of methodological choices and technologies cause a much greater spread of results. For CHP, the type of allocation has the biggest impact. Here, the choice between exergetic and energetic allocation can have a substantial impact on the results. While exergetic allocation takes the different thermodynamic qualities of heat and power into account, energetic allocation neglects this effect. This can lead to an underestimation of emissions associated with the generation of the power fraction of CHP. Therefore, CHP exhibits the greatest spread of results for all analyzed wood energy services (when taking only the biomass fraction of pure power generating co-combustion systems into account), with a mean impact on GW of 0.187 kg CO_2-eq. * kWh^{-1} and a median of 0.066 kg CO_2-eq. * kWh^{-1}. Most systems where biomass was used to generate power employ co-combustion. Published results therefore often include the emissions associated with the generation of 1 kWh of electrical power, which is comprised of the emissions of the share of primary fuel, e.g. coal, and the emissions of the share of biomass. Emissions are therefore weighted according to the co-combustion rate, which, for our analyzed studies, ranged between 5% and 20%. These weighted emissions of course are not suitable for comparison with other technologies for the generation of power from biomass, with the intention of identifying a suitable utilization for wood resources. Instead only the emissions associated with the biomass fraction of power generating systems (power_bf) was taken into consideration. For this purpose, the emissions associated with the fossil fuel employed during co-combustion were subtracted via the share of the total fuel input in conjunction with the emissions of the reference system, which, in the case of most co-combustion systems, is the single combustion of the fossil fuel. For this fraction a mean impact on GW of 0.112 kg CO_2-eq. * kWh^{-1} and a median of 0.098 kg CO_2-eq. * kWh^{-1} could be observed. For power generating systems where no co-combustion, but rather a direct mono-combustion of wood biomass is modeled, emissions on the lower end of the scale could be identified (median 0.067 kg CO_2-eq. * kWh^{-1}).

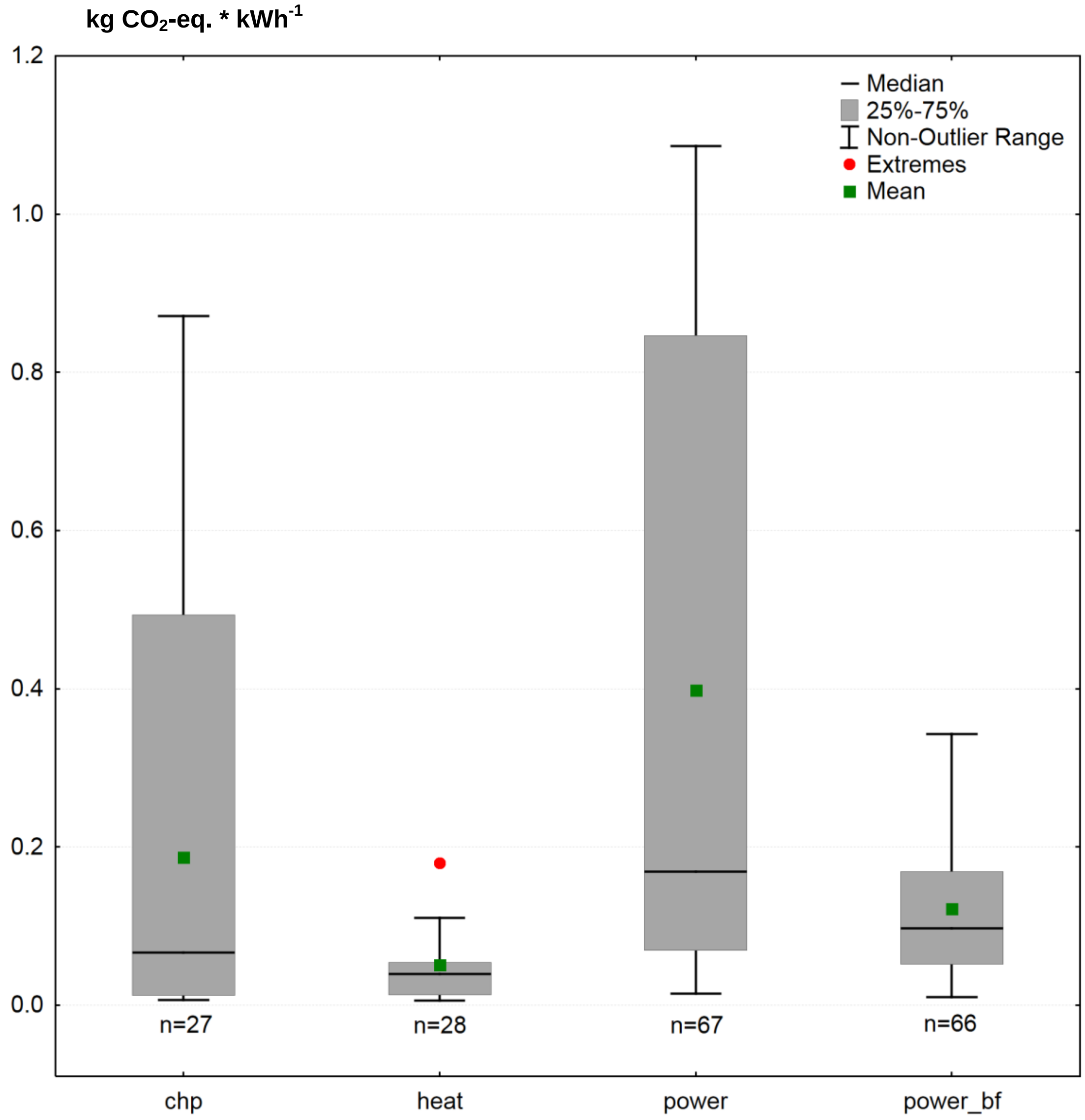


Figure 4 *Impact on Global Warming (GW) of combined heat and power (CHP), heat, power, and the biomass fraction of power generating systems (power_bf). n=number of analyzed systems. (source: modified from Wolf et al. 2015, fig. 3, p. 757).*

3.3.3. Proposal of methodological approaches for LCAs concerned with wood energy services

(Publication 1 and 2: Klein et al. 2015 and Wolf et al. 2015a)

Both reviews revealed highly divers approaches for the LCA of forest production and the provision of wood energy leading to a great range of results published. Not only are bio-based products rather complex in respect to LCA modeling, but also a multitude of different system boundaries and allocation procedures amplify the spread of results further. Since one of the main points of criticism towards LCA is the sometimes lacking transparency, recommendations for strengthening the reproducibility and comparability of studies were developed in succession to both reviews.

System description

One of the biggest factors in creating intransparent and non-reproducible LCA results in our review was in most cases an inadequate description of system boundaries and included processes. In many cases, authors felt that the description of a system by one sentence was sufficient, stating that a system was e.g. “cradle to gate”. However, especially for bio-based products, e.g. due to long production cycles and interlocking or cascading product systems, system description requires a more structured approach. Therefore, a proposal for a standardized system description template, including process nomenclature (FIGURE 5) and important modeling parameters (TABLE 1; TABLE 2) was created. In this template, system description is broken down into discreet process groups representing major life cycle phases of wood products ([A] wood production, [B] transformation, [C] conversion, [D] utilization, [E] disposal/recycling, [T] transports], [F] benefits and burdens in the secondary system), with the boundary, upstream processes (i.e. secondary processes) included in each process. Following this template, LCA practitioners have the possibility to create more transparent and comparable LCA studies by stating specifically which processes are included in the assessment. However, the system description should not only report which processes are included, but also which processes are omitted and why. Processes for which no data could be obtained need to be indicated, and a best estimation or a range of estimations should be given.

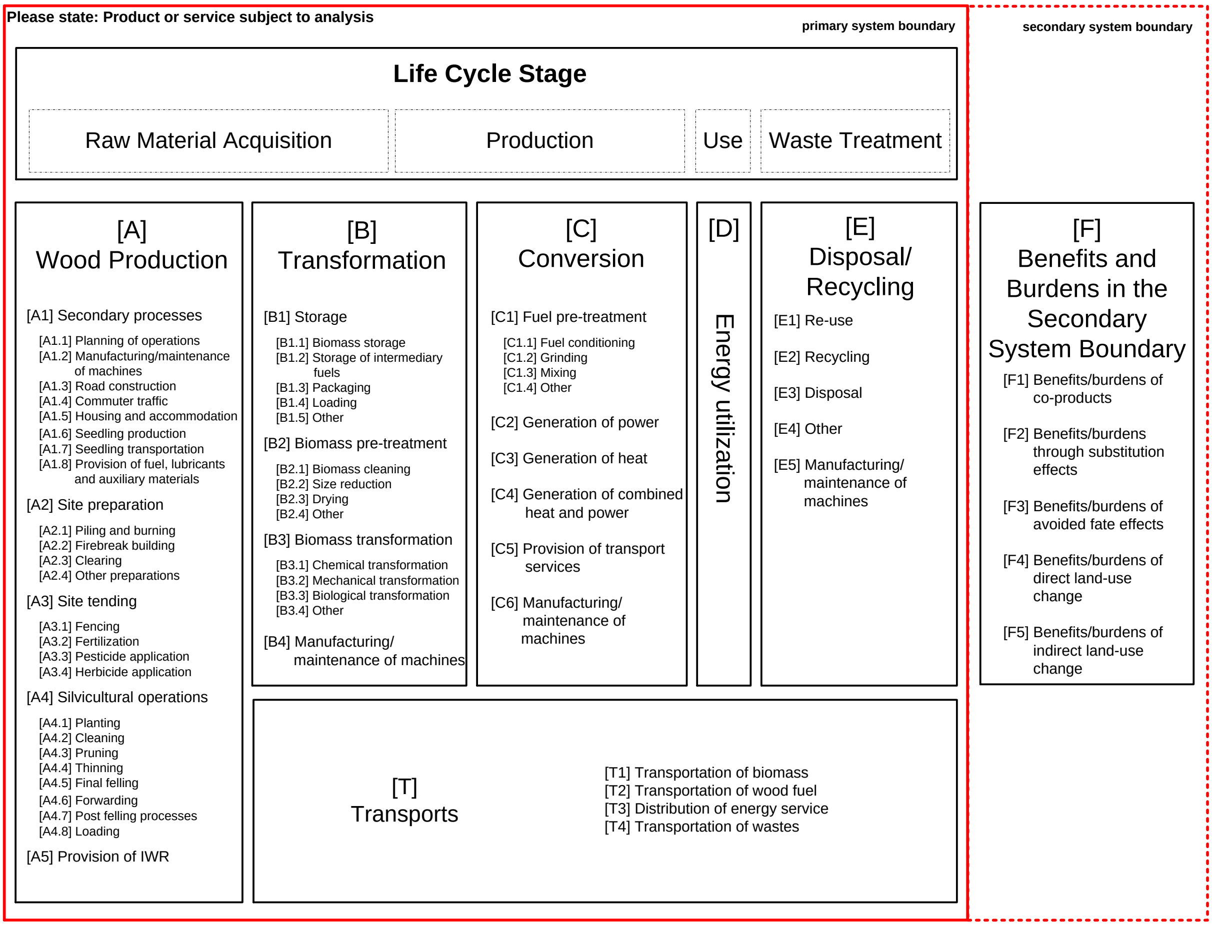


Figure 5 *Template for the description of system components and reporting of results. IWR=industrial wood residues, LHV=lower heating value, CHP=combined heat and power. (source: modified from Wolf et al. 2015, fig. 5, p. 759).*

Especially for forest production systems, the description of temporal boundaries is crucial since forests are managed within tree-specific rotation periods of several decades yielding different amounts of harvested wood and varying wood quality through various management techniques employed for thinning and harvesting. Generally, two approaches, a “whole rotation” approach and a “single moment” approach, can be adopted for forest production. The “whole rotation” approach theoretically includes the entire lifespan of a forest system, including all processes that lead to the establishment of the forest, the harvesting infrastructure as well as the management and harvesting of trees. In contrast the “single moment” approach only takes into account one specific management measure, often times a thinning e.g. for energy wood, or a final felling for the harvest of mature trees. Of course, this very simplified approach neglects many processes that were required to establish the site (which leads to the underestimation of emissions), but can nevertheless be valuable, e.g. when estimating the impacts of forestry on a regional or country scale. We propose to employ the “whole rotation” approach for assessments on the stand level as a general methodology for forest production LCAs.

Modeling parameters

Important parameters for LCA such as the moisture contents of raw wood and wood fuel, wood densities and the yield per hectare need to be disclosed, in order to be able to recalculate to different functional units and to reproduce the results. A list of systemic and general parameters that should be disclosed in order to enhance reproducibility is presented in TABLE 1 and TABLE 2. For forest production, a functional unit of 1 m³ ob is proposed, since calculations purely on a hectare or annual basis can be misleading. Nevertheless, if important parameters, as mentioned above, are disclosed, an assessment for an entire stand (or larger) can be published additionally. Emissions of wood energy systems can be expressed in the functional unit of 1 MJ or 1 kWh of final energy provided. Conversion efficiencies and LHV will make a recalculation of results to an input related functional unit, e.g. 1 t of biomass, possible.

Table 1 *Systemic parameters for LCAs of wood energy services. (source: modified from Wolf et al. 2015).*

Process Group	Criteria	Remark
[A]	extent of inclusion of complete raw wood production and its sub processes	“single moment” or “whole rotation” approach
	allocation method for different raw wood assortments	mass allocation or economical allocation, state allocation factors
	for IWR - specification of inclusion of production burdens	IWR: waste or resource
[B]	storage-, drying-, pre-treatment losses	[%] by weight, or [%] by volume
	Feedstock and moisture content	for drying, [%] wet basis/ [%] dry basis
	employed power grid mix	emission factor, e.g. [kg CO_2- eq. * kWh^{-1}]
[C]	combustion capacities	determines capital equipment, logistics, storage and efficiencies, [kW]
	combustion efficiency	[%] net, annual efficiency preferable
	feedstock heating value	lower heating [MJ/kg] value in conjunction with moisture content
	allocation method for CHP generation	energy or exergy (preferable), state allocation factors
	consideration of CH_4, N_2O emissions	especially for small heating devices
	treatment of biogenic C (emit or omit)	sustainable wood sourcing? Y/N
[E]	feedstock ash content	[%] by weight, or [%] by volume
[F]	benefits or burdens associated	informative
	reference system	for substitution, e.g. [kg CO_2- eq. * kWh^{-1}]
[T]	feedstock density	[kg*m^{-3}] dry basis
	feedstock moisture content	[%] wet basis/[%] dry basis
	transportation means	lorry, barge, etc. - [km] one way
	treatment of journey to pick-up location	full or empty backhauls, round trip
	transport utilization	[%]

Table 2 *General parameters for LCAs of wood energy services. (source: modified from Wolf et al. 2015).*

Issue	Criteria	Remark
System Description	utilization of universal naming convention	See Figure 5
	precise specification on inclusion and exclusion of life cycle stages	See Figure 5
	precise specification on inclusion and exclusion of processes	See Figure 5
	geographical representativeness	continent, country, state, climate
	temporal representativeness	technological state
Functional Unit	output based	[MJ], [kWh]
	for input based functional units, LHV and density need to be disclosed additionally	LHV [$MJ*kg^{-1}$], density [$kg*m^{-3}$]
	CHP: specify inclusion of heat/power in functional unit (System Expansion or allocation)	[MJ_{chp}], or [MJ_{el} + credit], or $MJ_{el/th}$
Impact Categories	Global Warming	[kg CO_2- eq.]
	Particulate Matter	[g $PM_{2.5}$- eq.]
	Acidification	[kg SO_2- eq.]
	Eutrophication	[kg P- eq.]
	Primary Energy Demand-renewable and Primary Energy Demand–non renewable	LHV [MJ]
Publication of Results	utilization of universal naming convention	See Figure 5
	report results for each process group separately	[A],[B],[C],[D],[E],[T],[F]
	report an absolute, total result	[A]+[B]+[C]+[D]+[E]+[T]
	report benefits and burdens in the secondary system boundary separately	[F] in [%] or absolute

Allocation

Allocation for forest production should be executed according to the general provisions of ISO 14044, where allocation is to be avoided by either subdividing or expanding the system. For forest production systems where raw wood products and their production chains (industrial wood, round wood, energy wood) can be differentiated from one another, subdivision is the most favorable option. If allocation cannot be avoided, allocation by mass in conjunction with the yield of each raw wood product can be applied. Due to the possibility of fluctuating market prices, an economic allocation should generally be avoided. If parameters for economic allocation are published, as is recommended, the additional inclusion of a scenario for economic allocation could be of interest.

For wood energy systems, allocation can be encountered in several life cycle phases and subsequently several approaches can be recommended. The first allocation encountered is a potential allocation of environmental burdens of forest production (see above for the recommended allocation approach). If wood fuels are produced through the utilization of co-products, e.g. pellets which are produced from saw mill residues, an economic allocation can be advantageous, since it reflects the reasons for carrying out a sawmill operation more accurately. Since saw mills operate to produce sawn wood, rather than saw dust, the main burden should also be allocated to the main product of an operation. Additionally, since only the relation of the main product to the co-product is of interest at this stage, as opposed to the different utilization pathways for raw wood assortments, economic allocation is adequate. For CHP systems, the allocation of environmental burdens onto heat and power should be carried out based on exergy, taking into account the different thermodynamic qualities of heat and power respectively (see chapter 3.3.4). Whichever allocation procedure is employed, it is necessary to specify the relevant allocation procedures and allocation factors.

Publication of results

All results should be published in a disaggregated fashion. This means that for each individual process group a separate result as well as a total result should be published. It was identified during the review study that aggregated results led to a great loss of information and comparability for the respective study. It is therefore recommended to publish separate results for each process group ([A],[B],[C],[D],[E],[T]), a result representing the total direct emissions of the product system ([A]+[B]+[C]+[D]+[E]+[T]) and if effects from group [F] are present, to publish results of sub groups in [F], and a total result including effects from group [F] separately.

Furthermore, additional impact categories to GW, due to potential tradeoffs between impacts, should be incorporated into the assessment. Hence, the optimization purely towards the reduction of impacts on GW can lead to greatly increased impacts in other impact categories, such as land use, eutrophication, acidification or particulate matter emissions.

Adhering to these provisions will improve the comparability of LCAs for bio-based products.

Discussion

In the past, a variety of policies, norms and initiatives such as e.g. certification bodies or research organizations have covered the topic of methodologies in LCA (FIGURE 6). Here, publications range from policies giving clear guidance towards the calculation methodologies for GHG reduction potentials (EC 2009) to general guidelines in respect to LCA (ISO 2006) or forest management (BAYERISCHE STAATSREGIERUNG 2005), all while being relevant to the individual LCA practitioner. Furthermore, even though the general framework for the creation of LCAs for wood energy is influenced by a variety of these publications (DIN EN ISO 14040 and DIN EN ISO 14044, the Federal and Bavarian Forestry Act, ILCD Handbook and BMU Methods Handbook Bioenergy) no adequate methodology which ensures transparent and reproducible methodology and results is currently available.

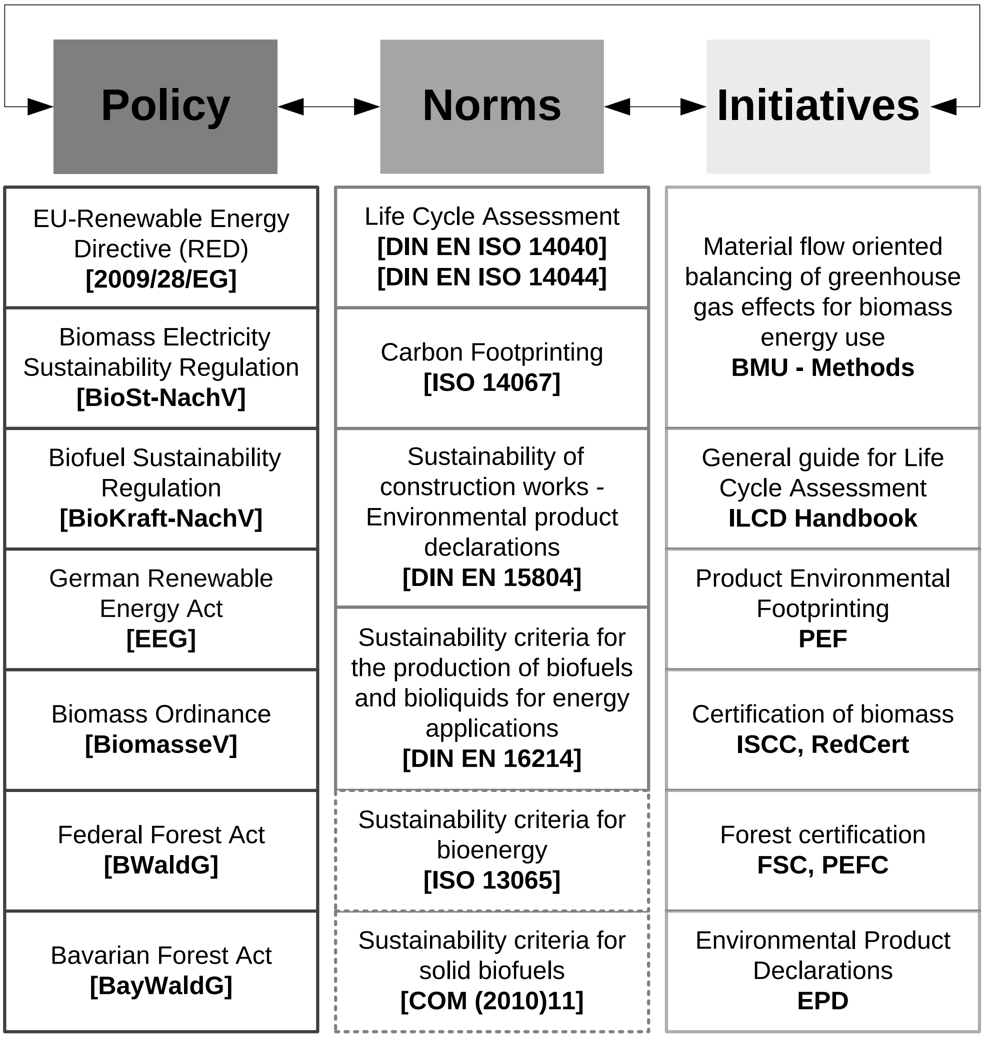


Figure 6 *Interconnected policies, norms and initiatives in the framework of the environmental assessment of bio-based products and services*

In 2010 a first recommendation for suitability requirements for solid biofuels (COM (2010)11) was published by the European Commission (EC 2010B). Here, general recommendations for all biofuels in the electricity, heating and cooling applications were provided without specifically distinguishing between different product groups and production pathways in a similar fashion to the Environmental Product Declaration system (EPD) (employing Product Category Rule (PCR) guidelines), thus lacking the necessary assessment resolution. In 2015 the production and use of bioenergy was recognized to possess potential in mitigating climate change, promoting energy security and fostering sustainable development in ISO 13065 – sustainability criteria for bioenergy (ISO 2015). The standards aims to “provide a framework for considering environmental, social and economic aspects that can be used to facilitate the evaluation and comparability of bioenergy production and products, supply chains and applications” (ISO 2015). The standard aims to achieve this however, without actually describing different bioenergy processes and production methods thus acknowledging that compliance with the standard does not determine the sustainability of processes or products. How the assessment of sustainability can be achieved without the analysis of individual processes or products and how comparability can be assured with this approach is not clear. This illustrates again the need for a transparent and harmonized assessment methodology that covers sustainability criteria on a PCR basis, with a clear description of all sustainability criteria for individual processes and products. These requirements are a central part of this research.

While many of the associated publications cover certain fundamental methodological aspects, e.g. the choice of reference system in the EU-Renewable Energy Directive (EC 2009), the most basic but also most important aspect is often neglected, which is the enhancement of reproducibility. As such, in many cases this is caused by the unprecise definition of system boundary and respective included or excluded processes. The lack of this information however, is accompanied by the inability to recreate and retrace basic assumptions and subsequent results. With the initial description of the systems (FIGURE 5) and its subsequent enhancement and development in later stages of the research (FIGURE 7) it is now possible to mitigate the issue of lacking reproducibility and strengthen the confidence in the comparability and credibility of results obtained via LCA. Especially for bioenergy, a topic not uncritically discussed in recent years, this is an important step to enhance the understanding of environmental impacts and to promote potentials for positive environmental benefits associated with the use of bioenergy. Furthermore, it could be shown that the general methodologies and guidelines specified in the relevant publications (FIGURE 6) do not provide enough precision to ensure a standardized approach towards the assessment of bioenergy. In many cases fundamental parameters in bioenergy LCAs, such as allocation requires dedicated provisions, a requirement that no current guideline before this research was able to offer.

The methodological proposal covers many aspects of the LCA of forest products and wood energy services, but the practical implementation of certain aspects in later stages of the research also revealed several shortcomings. As such, in many cases it is insufficient to state the functional unit of a biomass system as “1 MJ”, since it is unclear whether the system is terminated before combustion, after combustion or after the transmission of energy. In this respect, the functional unit of 1 MJ could represent the LHV (system terminated before combustion), the provision of final energy (system terminated after combustion) or the provision of useful energy (system terminated after transmission). Therefore, it is advisable to specify the energy form (primary-, secondary-, final-, useful energy) in addition to the primary function of the system.

The issue of allocation, which was shown to be of great importance for the overall magnitude of results (KLEIN ET AL. 2015; WOLF ET AL. 2015A), needs to be covered in detail, since in many cases it is unclear how e.g. exergetic allocation should be applied (THRÄN & PFEIFFER 2013). Of course, space limitations for journal articles are a factor, but nevertheless, the topic of allocation is such a determining element in many systems that a more detailed explanation would be advantageous. Additionally, it would be favorable to specify why allocation, rather than other methods of dealing with multi-functionality (e.g. substitution, system expansion), was employed at all. The main determining factor towards allocation was the aim for a harmonized methodology that allows direct comparisons of different product systems (e.g. from forestry and agriculture) providing the same goods or services (e.g. heat). For the sake of reproducibility and transparency of LCA results, it is much easier and more flexible to employ allocation factors than to deal with altered impacts arising from system expansion or substitution. Furthermore, allocation is a more convenient method, since no additional systems need to be modeled and allocation factors can be adjusted in retrospect, e.g. for economic allocation when market prices have changed.

In terms of impact assessment several indicators (Global Warming, eutrophication, acidification, particulate matter emissions, as well as the non-renewable primary energy consumption) were proposed according to the strong reappearance of these indicators throughout the studies covered by the systematic reviews. It was realized during implementation, that it is insufficient to state indicators such as eutrophication or acidification without stating the precise calculating method.

In respect to the system description template (FIGURE 5), after prolonged utilization within the EpxRessBio expert team, several adjustments were made (see improvements in FIGURE 7). One aspect, which was unclear in the template, was the status of upstream processes. It was unclear where or if upstream processes were included and whether they were integrated into the main processes itself or not. In this state of the template, it was also not possible to create results for the main production processes separately from the upstream processes. A further issue, especially for many agricultural product systems, was the impossibility to discern between regular transports and on-site (e.g. on the farmstead) logistics in process group [T]. Group [F], located in the secondary system boundary also revealed several shortcomings during application of the template. As such, it was not possible to discern between benefits and burdens that arise due to co-product utilization, waste utilization and the end use of the main product.

These issues have been addressed, further developed and incorporated in the new handbook for the assessment of ecologic and economic effects for product systems based on agricultural and forestry biomass (WOLF ET AL. 2016A) (see chapter 3.3.4), which is one of the outcomes of the ExpRessBio research project.

Similar to other product groups like food, construction products or textiles, where, through the commitment of policy makers, research and the industry, precise methodologies for LCA have been introduced in the form of Product Category Rules (PCR) in the EPD system, the presented research can help to fill methodological gaps and can lay the foundation for a PCR for solid biofuels.

3.3.4. Enhancement and transfer of methodological approaches

(Handbook – ExpRessBio Methods. Wolf et al. 2016a)

A further extension of methods created in the review studies (KLEIN ET AL. 2015; WOLF ET AL. 2015A) was carried out for the ExpRessBio project with the publication of a handbook for the LCA of bioenergy products (in German) (WOLF ET AL. 2016A). ExpRessBio (expert group resource management bioenergy in Bavaria) is a Bavarian research project with the aim to analyze and optimize agricultural and forestry biomass production for the provision of bioenergy and raw materials under the aspects of resource efficiency and their impacts on GW. Additional goals were the economical evaluation of GHG-optimized process chains and the enhancement of an efficient use of agricultural and forestry resources in Bavaria. The handbook extends on the provisions given in the two reviews towards agricultural biomass and further specifies practical guidance towards the transparent description of systems, the procedure of allocation and reference systems. In addition, the handbook provides a practical illustration for the application of the methodology towards 3 example systems based on agricultural and forest biomass (transportation fuel from rapeseed oil, electricity generation from biogas and beech split wood heating).

System Description

At the core of the ExpRessBio methods handbook is the improved system description template. It is based on the template developed in WOLF ET AL. (2015A) (FIGURE 5) but adds, clarifies and improves upon several aspects of the original template (FIGURE 7).

Starting with process group [A], a new sub process group [A5] “provision of resources from preceding systems” was integrated, in order to illustrate the differences between biomass procurement from virgin sources (e.g. agriculture or forestry) and from industrial systems (e.g. industrial wood residues from sawmilling for pellet production), which provide biomass in the form of co-products or waste to the actual bioenergy system. For the latter case, a decision whether the biomass is treated as waste or co-product determines, if environmental burdens of previous production processes are carried over to the actual bioenergy system or not (e.g. through allocation). For the standard case of biomass procurement from forests or agriculture, this question is not an issue. Therefore, a clear distinction between the two cases was necessary, hence the introduction of [A5].

Mentioned in chapter 3.3.3, was the impossibility to discern between regular transports and on-site (e.g. on the farmstead) logistics in process group [T]. For this reason, process group [L] “operational logistics” was created. Through this process group, the LCA practitioner has the possibility to separate logistics processes (e.g. loading, stacking) from true transport processes. [L1] "external logistics" also enables the distinction between all transportation processes that are linked to the actual main material flow (i.e. biomass→bioenergy carrier→bioenergy→waste) from transportation processes that occur throughout the upstream processes.

In order to clearly depict which upstream processes are included in the system and where, process group [V] "upstream processes" was created. By linking the different sub-process groups (e.g. [B1.1]/[C2]) to the respective upstream process in [V], it is possible to discern how upstream processes interconnect to the main product flow. If an LCA practitioner were to model e.g. the combustion of pellets for heat, the electricity required for pelletization [B3.2] and the operation of the heating system [C2], could be named as [B3.2]-[V5] (electricity for pelletization) and as [C2]-[V5] (the electricity for the operation of the heating system) respectively. This is also a convenient way to enhance the possibilities towards the interpretation of results in later stages of the study.

Provisions for process group [E] "waste management", were restructured according to the German act on circular economy ("Kreislaufwirtschaftsgesetz") (BUNDESREPUBLIK DEUTSCHLAND 1994), providing an enhanced possibility towards the specification of end of life (EOL) managements for waste. Furthermore, a clear method towards the accounting of burdens from EOL treatments towards the product system and any subsequent system making use of wastes stemming from the original product system was introduced. Here, all burdens arising from the collection and transport of wastes are allocated to the original product system. Any further burdens from processes required to convert wastes into raw materials or fuels for subsequent systems need to be allocated to the subsequent system making use of the wastes. In conjunction with [A5], process group [E] minimizes the potential for double counting, since these two process groups act as a link to the preceding- and succeeding systems by stating where, and if certain benefits and burdens are accounted for. For cases where energy storage needs to be modeled, e.g. battery applications or heat storage, the process [D2] was incorporated.

Process group [F] was also reworked, in order to discern between benefits and burdens that arise due to co-product utilization, waste utilization and the end use of the main product. These avoided burdens through the end use of the main product were relocated to the process group [G], in order to enhance the distinction between effects that arise from co-products and the main product. Additionally, [F1] "credits for avoided burdens" provides the possibility to depict the avoidance of burdens from previous systems, e.g. for farm fertilizers being used as substrate in biogas plants, rather than the open storage of farm fertilizers (this can entail methane and ammonia emissions).

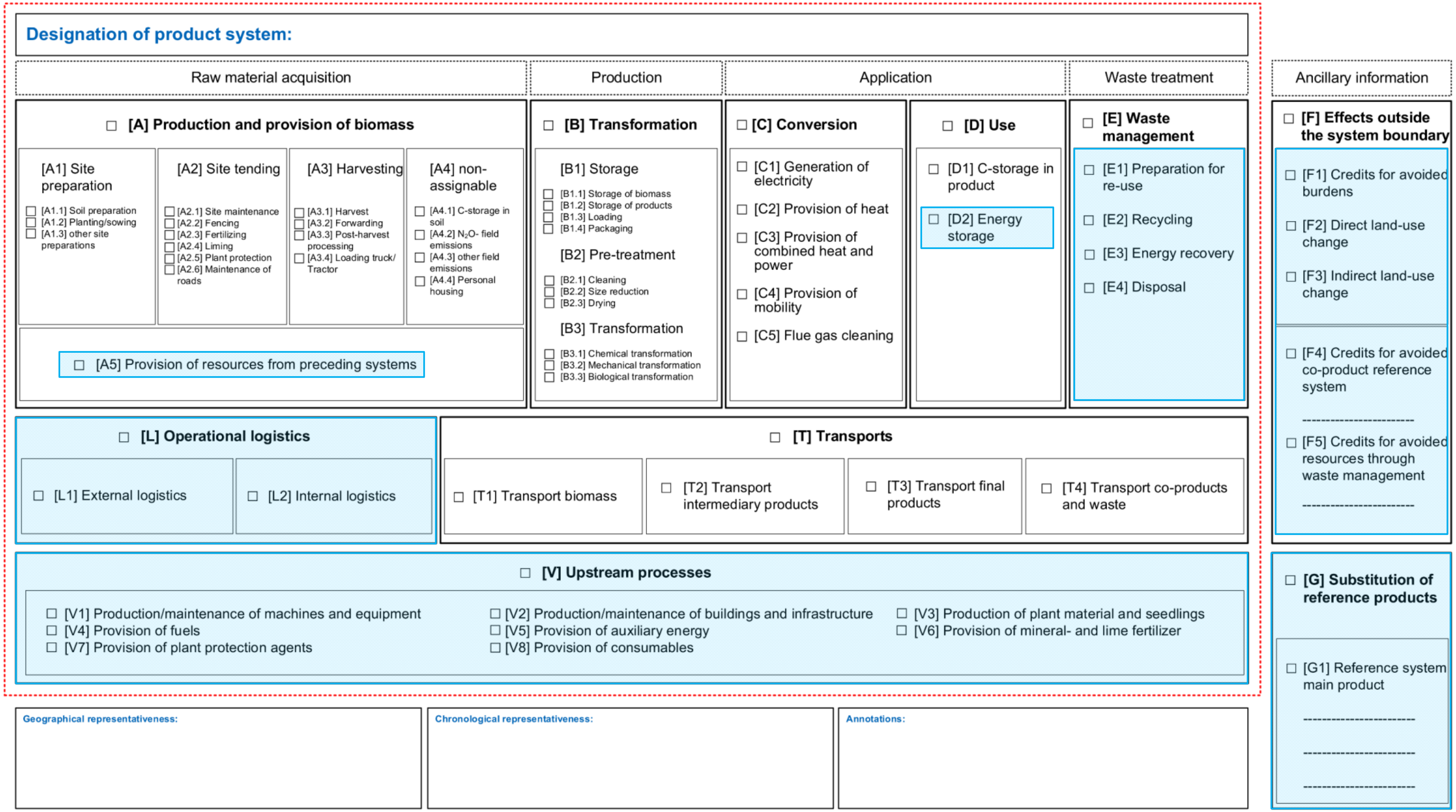


Figure 7 *Enhanced system description template for the analysis of environmental- and economic impacts of product systems from agricultural or forestry resources. Improved aspects in blue. IWR=Industrial wood residues, w=water content. (source: modified from Wolf et al. 2016a, fig.1, p. 24).*

Allocation

Allocation, as mentioned before, is of great importance towards the magnitude of results. Therefore, the provisions for allocation of bioenergy systems have been further specified in the handbook. Especially for the allocation of systems which provide heat and power in a combined fashion (CHP), allocation should be carried out according to the exergy rather than energy, like it is encountered many times, in order to account for the different thermodynamic qualities of power and heat at different temperatures. Exergetic allocation is carried out according to equations 1, 2 and 3 (source: modified from WOLF ET AL. 2016A).

$$AF_{Power} = \frac{W_{el}}{W_{el} + E_Q} \tag{1}$$

with

$$E_Q = Q \cdot \left(1 - \frac{T_U}{T_Q}\right) \tag{2}$$

$$\mathrm{AF}_{\mathrm{Heat}} = 1 - \mathrm{AF}_{\mathrm{Power}} \tag{3}$$

AF_{Power} = allocation factor power
AF_{Heat} = allocation factor heat
W_{el} = amount of feed in power [MJ]
E_Q = exergetic share of heat [MJ]
Q = amount of feed in heat [MJ]
T_U = ambient temperature [K] (reference temperature = 288 K)
T_Q = temperature of heat in [K]

Through the calculated exergetic allocation factors it is subsequently possible to distribute the environmental burdens onto the main- and co-products. However, it is essential for the calculation of exergetic allocation factors to only take into account the amount of heat that is actually utilized. If parts of the generated power or heat are employed within the product system (i.e. as auxiliary energy), these amounts need to be subtracted from the amount of total generated heat. Subsequently, only the amounts of power and heat that leave the process where allocation is occurring can be employed for the calculations.

Impact assessment

Provisions for impact assessment were also further clarified by specifying the precise impact assessment methods to be employed. Impact assessment follows the provisions of the International Reference Life Cycle Data System (ILCD) Handbook, published by the European Commission (EC 2010A) . With the goal of creating comparable LCA results, precise recommendations pertaining the choice of impact categories and impact assessment methodologies are provided in the Handbook. Since this was also one of the main aims of the ExpRessBio project, the provisions of the ILCD Handbook, and the recommended impact assessment methods were adopted. The initial selection of indicators was based on their frequent utilization in the studies encounter during the systematic reviews (KLEIN ET AL. 2015; WOLF ET AL. 2015A). Because of this frequent utilization a certain importance towards the assessment of bioenergy was attributed to these indicators. A further aspect which was encountered in many studies was the inclusion of the assessment of the primary energy consumption (non-renewable). It was chosen to incorporate this aspect and according to the method of “cumulative energy demand” here as well (VDI 1997). Recommended indicators for bioenergy systems and the respective methodology can be seen in TABLE 3.

Table 3 *Recommended environmental indicators and calculation methods for bioenergy systems. NR=non-renewable, w/o=without. (source: modified from Wolf et al. 2016a).*

Indicator	Method	Source
Global warming (w/o biogenic C)	IPCC	IPCC 2007
Particulate matter emissions	RiskPoll	Rabl & Spadaro 2012
Aquatic freshwater eutrophication	EUROTREND	Struijs et al. 2009
Acidification	Accumulated exceedance	Seppälä et al. 2006
Primary energy consumption (NR)*	VDI 4600 - KEA	VDI 1997

**the primary energy consumption is not a typical environmental indicator like the global warming, but is added to this table to show the complete set of assessment criteria*

Reference Systems

In many cases, LCA results for a product system are published in relation to a reference system, i.e. in a relative fashion. This often leads to a major part of the information concerning the system in question being lost (i.e. the absolute emissions of the system), and also disguises the emission factors for the employed reference system. Since the depiction of results in a relative manner is nevertheless an important tool for life cycle impact assessment (LCIA), a section that is aimed at creating harmonized reference systems was included in the handbook. Reference systems for transportation services (Table 4), energy generation services (Table 5) and heating services (Table 9) are included.

Table 4 *Emission factors (EF) for the reference systems of transportation fuel utilization. GW=global warming, PE=primary energy consumption non-renewable, PM=particulate matter, ET=freshwater eutrophication, AC=acidification. (source: modified from Wolf et al. 2016a, tab. 20, p. 94).*

maximum permissible gross laden weight	GW	PE	PM	ET	AC
	[g CO_2-eq.]	[MJ]	[g $PM_{2.5}$-eq.]	[g P-eq.]	[mmol H^+ eq.]
	per tkm				
> 20 t	57.5	0.83	0.0010	0.00157	0.260
14 – 20 t	69.7	1.01	0.0122	0.00190	0.331
12 – 14 t	74.7	1.08	0.0126	0.00204	0.328
7.5 – 12 t	133.0	1.92	0.0225	0.00362	0.586
7.5 t	144.0	2.08	0.0236	0.00392	0.604

Table 5 *Emission factors (EF) for the reference systems of power generation. GW=global warming, PE=primary energy consumption non-renewable, PM=particulate matter, ET=freshwater eutrophication, AC=acidification. (source: modified from Wolf et al. 2016a, tab. 23, p. 96).*

	GW	PE	PM	ET	AC	Share
	[g CO_2-eq.]	[MJ]	[g $PM_{2.5}$-eq.]	[g P-eq.]	[mmol H^+ eq.]	[%]
	per MJ_{el} of final energy					
Power mix GER	178	2.31	0.0149	0.000342	0.320	100.0
Lignite	323	2.84	0.0217	0.000011	0.452	24.8
Hard coal	286	2.88	0.0299	0.000044	0.564	18.6
Nuclear	1	2.78	0.0006	0.000010	0.011	17.8
Natural gas	138	2.23	0.0033	0.000004	0.133	13.8
Wind	3	0.04	0.0015	0.000006	0.012	8.1
Hydro	2	0.01	0.0002	0.000001	0.003	3.9
Biogas	102	1.25	0.0308	0.006820	0.805	3.5
Photovoltaic	14	0.21	0.0130	0.000055	0.074	3.2
Solid biofuels	14	0.15	0.0147	0.003330	0.442	1.9
Waste	194	0.37	0.0048	0.000080	0.355	1.8
Coal gas	285	2.69	0.0127	0.000039	0.592	1.6
Heavy fuel oil	226	2.71	0.0335	0.000039	0.751	1.1

Transfer and adaptation towards other bioenergy pathways

The methods proposed by both literature studies (KLEIN ET AL. 2015; WOLF ET AL. 2015A) were developed with the assessment of environmental impacts of raw wood and the subsequent energetic utilization. However, bioenergy LCAs employing agricultural biomass sometimes face divergent methodological challenges from wood energy LCAs (e.g. importance of field emissions, shorter production timeframes). The aim of the ExpRessBio methods handbook (WOLF ET AL. 2016A) was, to address these challenges. As such, a key difference was the treatment, or inclusion of field emissions through process group [A4], a factor that is not currently necessary for forest systems but of great influence towards certain agricultural systems (DRESSLER ET AL. 2016). Additionally, provisions and recommendations for the treatment of agricultural co-products were provided. This is specifically the case for the generation of biofuel and biogas LCAs, where it is recommended to assess system expansion in addition to allocation, since allocation (following the default method specified by EC (2009)) does not portray the actual use of the co-product in a correct manner.

Furthermore sub-processes specific to the bioenergy production from agricultural biomass were added, (e.g. [A2.3] fertilizing) or harmonized, to be applicable for both agriculture and forestry (e.g. [A.1.1] soil preparation).

Discussion

The methodological principles proposed for bioenergy systems can be extended towards other bio-based products, such as e.g. sawn wood or other wood based products such as particle boards. This work was carried out through a master's thesis, which is an adaptation of the original methodology onto the material utilization of wood (BOSCH 2015). The adapted methodology analyzed existing standards and guidelines, relevant to the assessment of environmental impacts for the material utilization of wood. Relevant publications in this respect are the ISO LCA standards (ISO 2009, 2006), the ILCD Handbook (EC 2010A), DIN 15804 - Sustainability of construction works (DIN EN 2014), the CORRIM research guidelines for life cycle inventories (BRIGGS 2001) and, in order to identify aspects where an adaptation of the original method is required, the original methodology proposed in WOLF ET AL. (2016A). FIGURE 8 depicts some of the key differences and similarities between the individual studies. Here, the adaptation offers alterations to the original methodology in respect to the system description for which the higher degrees of modularization displayed in DIN EN (2014) and WOLF ET AL. (2016A) offers enhanced transparency. Furthermore, differences in respect to the production and maintenance of infrastructure, machines and roads, as well as the production of packaging could be identified and harmonized.

A further enhancement of reproducibility is created by a proposal for a standardized system flow visualization template in the shape of FIGURE 8. The main material flow pathway is centered and directed downwards while passing the individual processes directly connected to the production of the main product. This flow direction represents all materials that will make up the entirety of the finished product. In contrast to this are flows that pass through the system in the direction left to right, and only act as consumables (or represent energy flows) but do not find inclusion into the main product. Examples for these flows are: water, packaging, fuels, electricity, and infrastructure. A similar provision was created for wastes (direction left to right). Here, BOSCH (2015) incorporates a specific grouping of wastes that appear during the production process of the main product (Process group [X]), in order to clearly separate this waste from the wastes occurring at the end of the products life cycle. Additionally, the standardized system flow visualization template (FIGURE 8) can help to solve issues in respect to the definition of the foreground and background system and the terms "upstream" and "downstream". In this respect, it is often unclear if the background system only covers the pre-chains and wastes or also all processes prior to- and after the actual production of the goods. Furthermore, proposals for a harmonization of terms used in standards and literature and a proposal towards allocation procedures are covered in BOSCH (2015). In association with the provisions of WOLF ET AL. (2016A) (3.3.4), the presented provisions assist the reproducibility and comparability of wood products.

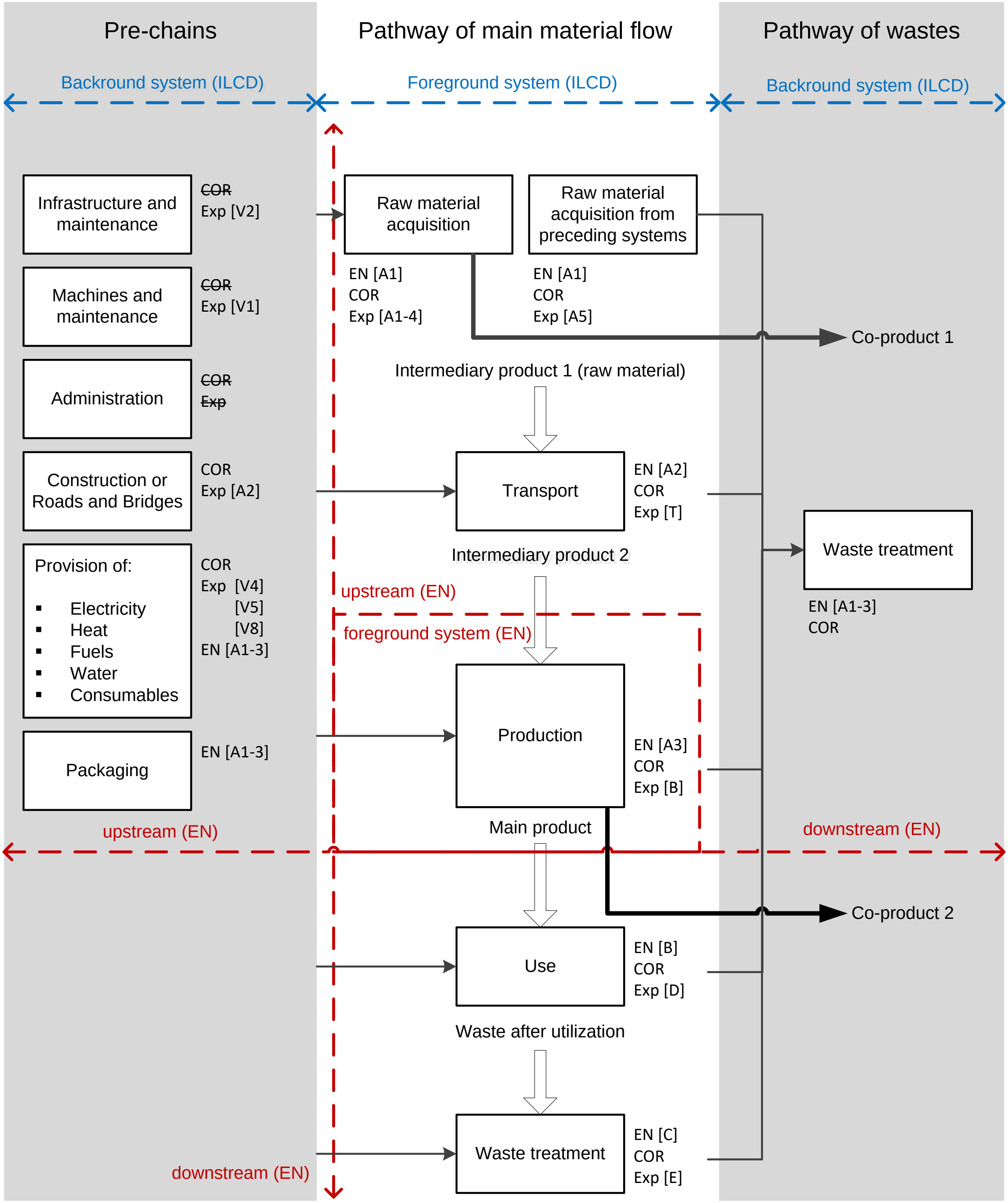


Figure 8 *Similarities and differences in respect to the structuration of product systems and system boundaries between different general standards for LCA and the LCA of wood products. EN=DIN EN 15804; COR=CORRIM; Exp=ExpRessBio; [A]-[E]=modularization. (Source: modified from (Bosch 2015) in accordance with (DIN EN 2014), (Briggs 2001) and (Wolf et al. 2016a).*

Since this development of methodological provisions was carried out in order to assess the regional utilization of Bavarian biomass, a number of factors important towards biomass utilization in other parts of the world, or for imports of biomass, were not covered. If the developed provisions were to be transferred to other regions, potentially with less sustainable forest management practices, aspects such as soil disturbances (REPO ET AL. 2011; BRANDÃO ET AL. 2011) land use-change and indirect land-use change (BERNDES ET AL. 2013) or albedo (CHERUBINI ET AL. 2012) will need to be considered, as results can be considerably influenced by their inclusion (RØYNE ET AL. 2016).Furthermore, due to a lack of an accepted methodology, aspects such as the timing of emissions and the inclusion of biogenic CO2, have not been included in this research. This is also the case for the majority of current approaches for the assessment of environmental impacts of forest products, which choose to neglect the timing of GHG emissions and carbon sequestration. However, the risk of surpassing a tipping point in the world's climate system, and the urgent necessity for imminent impact mitigation can emphasize the need to account for the timing of climate impacts (LEVASSEUR ET AL. 2010; HELIN ET AL. 2013; JØRGENSEN ET AL. 2014). In this respect, LEVASSEUR ET AL. (2010), offer a methodology for a dynamic LCA approach which improves the accuracy of LCA by accounting for the inconsistencies of temporal assessment. This approach consists of the creation of dynamic life cycle inventories, which consider the temporal profile of emissions, in conjunction with time-dependent characterization factors. The method enables the assessment of dynamic LCI in real-time impact scores, for any given time horizon (LEVASSEUR ET AL. 2010). An important aspect of climate impact assessment in respect to forest products is the time frame taken into consideration when calculating the effect of each emission in terms of radiative forcing. Most commonly, a timeframe of 100 years is chosen towards the assessment of the impact of goods and services onto GW (GWP_{100}). However, this choice of timeframe can be of influence towards the relative importance of different types of GHG emissions (RØYNE ET AL. 2016). In this respect, a timeframe of 100 years could be unsuitable when determining a products climate mitigating potential if substantial GHG reductions should be realized in the near future (GOEDKOOP ET AL. 2009). A further issue which is critically discussed is the climate neutrality of biogenic CO_2 emissions. The argument of climate neutrality of biogenic CO_2 emissions is based on the assumption that there is an equilibrium between the C sequestration in forestry and the emissions of C at the end of the products life cycle. However, some publications argue that long timeframes between the emission of C and its subsequent sequestration can lead to an increase in radiative forcing, thus rendering the climate impact of biogenic CO_2 emissions only slightly lower than that of non-biogenic CO_2 emissions (CHERUBINI ET AL. 2011; HELIN ET AL. 2013).

An additional impact of bioenergy production from forest biomass, which will also require further integration into LCA methodologies, is the assessment of nutrient sustainability. Since the majority of German forests are located on nutrient poor soils, harvesting concepts aiming at increasing the amount of wood from forests, e.g. through exposing branches and tree tops to the energetic utilization, are a threat to the overall nutrient sustainability (GÖTTLEIN 2016). Future LCAs need to consider this vital aspect, e.g. in the form of an indicator expressing the nutrient exports through biomass harvesting practices.

In conjunction with the original methodology, aimed at bioenergy (see section 3.3.3), comparability between results can be achieved if LCA practitioners in this field adhere to the proposed guidelines. It is obvious, that these guidelines do not facilitate the LCA practitioners work per se, but LCA should not be steered away from a scientific background towards a general and public accessibility. The scientific assessment of environmental impacts of products and services is the reason LCA was created initially and it is not necessary for the public to fully comprehend all aspects of a study in detail. What is necessary however, is that the public can have the chance to interpret LCA results presented to them, which is only possible, if published results from studies can be relied upon and compared. A major hindering factor towards this goal is also the maximum length of a journal article. Many authors omit vital information in order to not exceed this maximum length, a problem that can be solved by submitting detailed supplementary information files containing the above mentioned aspects for a reproducible LCA. It should be emphasized that the proposed methodology does not correspond to the character of a standard or a norm, and as such its application is voluntary. Many aspects of this methodology are therefore not aimed at limiting the LCA practitioner’s freedom in deciding how to model a system, but rather assist in the creation of transparency, and with it, reproducibility. This, as could be shown in the research presented in the preceding chapters, is of central importance towards the comparable assessment of environmental impacts of bio-based goods and services.

4 Application towards the case study region of Bavaria

(Publication 3 and 4: (Wolf et al. 2016b, 2016c))

4.1. Problem statement and objectives

Raw wood and its utilization for providing energy play a decisive role for the satisfaction of society’s resource and energy needs. Due to the favorable properties of wood and wood energy (e.g. low embodied energy), the resource is also of great importance towards climate change mitigation and thus profoundly relied upon by policy makers. In the past however, regional environmental impacts of wood and wood use have only been covered superficially and in a non-comparable fashion. By employing the tools developed in publication 1 and 2 (KLEIN ET AL. 2015, WOLF ET AL. 2015A) (see section 3.3.3) and the ExpRessBio-methods handbook (WOLF ET AL. 2016A) (see section 3.3.4) in depth assessments for raw wood production under Bavarian conditions (KLEIN ET AL. 2016) and the subsequent utilization of wood for the provision of heat (WOLF ET AL. 2016B) were carried out. In a final step, mitigation potentials through wood heating on a regional scale were assessed (WOLF ET AL. 2016C). Heating was selected for the assessment, since it is the energy service with the highest share (>50%) of final energy in Bavaria (EBERT & VOIGTLÄNDER 2014). Main goals for the assessment of the provision of raw wood were the identification of the magnitude of environmental impacts caused by raw wood production, the identification of decisive factors towards this magnitude and the identification of the contribution of raw wood production in respect to the total GHG emissions of Bavaria. Results of this assessment are disclosed in KLEIN ET AL. (2016).

For publications 3 and 4 (WOLF ET AL. 2016B, WOLF ET AL. 2016C), which analyze the effects of an energetic utilization of Bavarian raw wood, main goals were the identification of environmental impacts associated with individual wood heating systems, the identification of emissions associated with heating in Bavaria, the contribution of wood heating systems in respect to these total emissions as well as the identification of potential alterations of environmental impacts caused by certain policies, scientific assessments or other scenarios. Additionally, for publication 4, the main goal was the deduction of comprehensive and up-to-date mitigation factors for wood heating systems in Bavaria. The scope and the findings of publications 3 and 4 are presented and discussed in the following sections.

4.2. Methodology

Following the methodological provisions proposed in section 3.3.3 and WOLF ET AL. (2016A) (see section 3.3.4), analyses were carried out in order to outline the environmental burdens of wood energy systems in the case study region of Bavaria. The analysis was divided into two sections, the assessment of environmental impacts of wood energy services and the mitigation of environmental impacts through the use of wood energy services

4.2.1. Environmental effects of shifts in a regional heating mix

(Publication 3: Wolf et al. 2016b)

Building on the results obtained from the assessment of raw wood production in the forest, which represents the analysis of environmental impacts of process group [A] ((KLEIN ET AL. 2016), the subsequent utilization of wood for the provision of heat was analyzed. In order to depict impacts associated with the total heating sector and wood heating in particular, it was necessary to identify the composition of the total heating mix in the state, including the share of wood energy, and to determine emission factors of both renewable and non-renewable energy carriers represented in this mix.

In a subsequent step, a number of scenarios were evaluated which entail shifts between the shares of individual energy carriers in the heating mix. These scenarios represent assumptions in regard to the developments of wood heating in the future and are based on political targets, scientific evaluation, as well as a hypothetical minimum and maximum use of wood for heating.

Unlike for power generation, for which the mix (i.e. the shares of energy carriers constituting electricity generation) is readily accessible and openly published, the heating sector, due to its decentralized nature, does not provide a reliable estimation concerning its composition. Therefore, the heating mix was calculated based on information obtained via the Bavarian State Institute for Statistics and Data Processing. The Institute publishes its statistical analysis for final energy consumption in the state annually with a delay of three years. Thus, the data available for this study is related to the final energy consumption in Bavaria of the year 2011.

Emission factors for both renewable and non-renewable energy carriers (including the conversion of said energy carrier to final energy) were deduced via individual Life Cycle Assessments. In the case of wood heating, systems were modeled from wood production [A], for which emission factors were employed originating from KLEIN ET AL. (2016), over wood transformation [B], to wood conversion [C] and wood ash treatment [E], with the addition of transports [T1] and [T2] occurring after raw wood production and wood fuel transformation respectively (FIGURE 9). During wood production in phase [A], typical forestry conditions for Bavaria were assumed (good site conditions for spruce and beech as representatives for softwood and hardwood production respectively), thinning by harvester and moto-manual final felling, forwarding by forwarder for round wood and tractor forwarding for split logs, and transports of 100 km and 10 km for round wood and split wood respectively. In the transformation phase [B], industrial wood, as a source for wood chips, was chipped, while split logs were sawn and split into appropriate length split wood billets. Round wood was hauled to the saw mill, and processed into sawn wood and its co-products, the latter supplied the basis for wood pellets. Environmental burdens of saw milling were allocated on a mass basis onto the co-products. For some wood chips systems and for the pellets systems additional technical drying with biomass was assumed. Pellets and split wood were then subsequently transported to the customer over a length of 100 km and 10 km for pellets and split wood respectively. For the conversion phase [C] the above mentioned wood fuels were combusted in heating appliances with a capacity between 6 kW and 1000 kW and with varying moisture contents (10%-50%). A consecutive treatment of wood ash (disposal and recycling), based on an average ash content of 2%, was also integrated into the assessment [E]. Emission factors for non-renewable energy carriers were modeled via black-box unit processes, based on data provided in the PE Professional database (THINKSTEP AG 2015).

In order to relate impacts of individual wood heating systems to the scale of Bavaria (i.e. the share of wood heating systems of the total final energy for heat), a weighted impact caused by the sum of all wood heating systems was assessed. This weighted emission factor was calculated according to the installed capacity of individual wood heating systems in Bavaria (JOA ET AL. 2015). Forest production was weighted in relation to the harvested timber volumes per assortment and species in Bavaria in 2013, in order to represent a mean emission factor for forestry (TABLE 6).

Table 6 *Total harvested timber volumes in Bavaria (2013). (source: modified from Klein et al. 2016, tab. 4, p. 51).*

	Stem wood	**Industrial wood**	**Split logs**	**Total**
	[Mio. m³]	[Mio. m³]	[Mio. m³]	[Mio. m³]
Spruce	7.808	0.838	3.863	12.509
Pine	1.983	0.230	1.314	3.527
Beech	0.372	0.578	2.543	3.493
Oak	0.208	0.077	0.405	0.690
Total	10.372	1.723	8.124	**20.219**

Impacts originating from shifts in the heating mix, e.g. through an increase or decrease in the amount of wood heating, were assessed by several scenarios. As a baseline, or reference, the emissions of individual heating systems were related to the final energy amounts per energy carrier, which have been identified in the initial stages of this research (FIGURE 10).

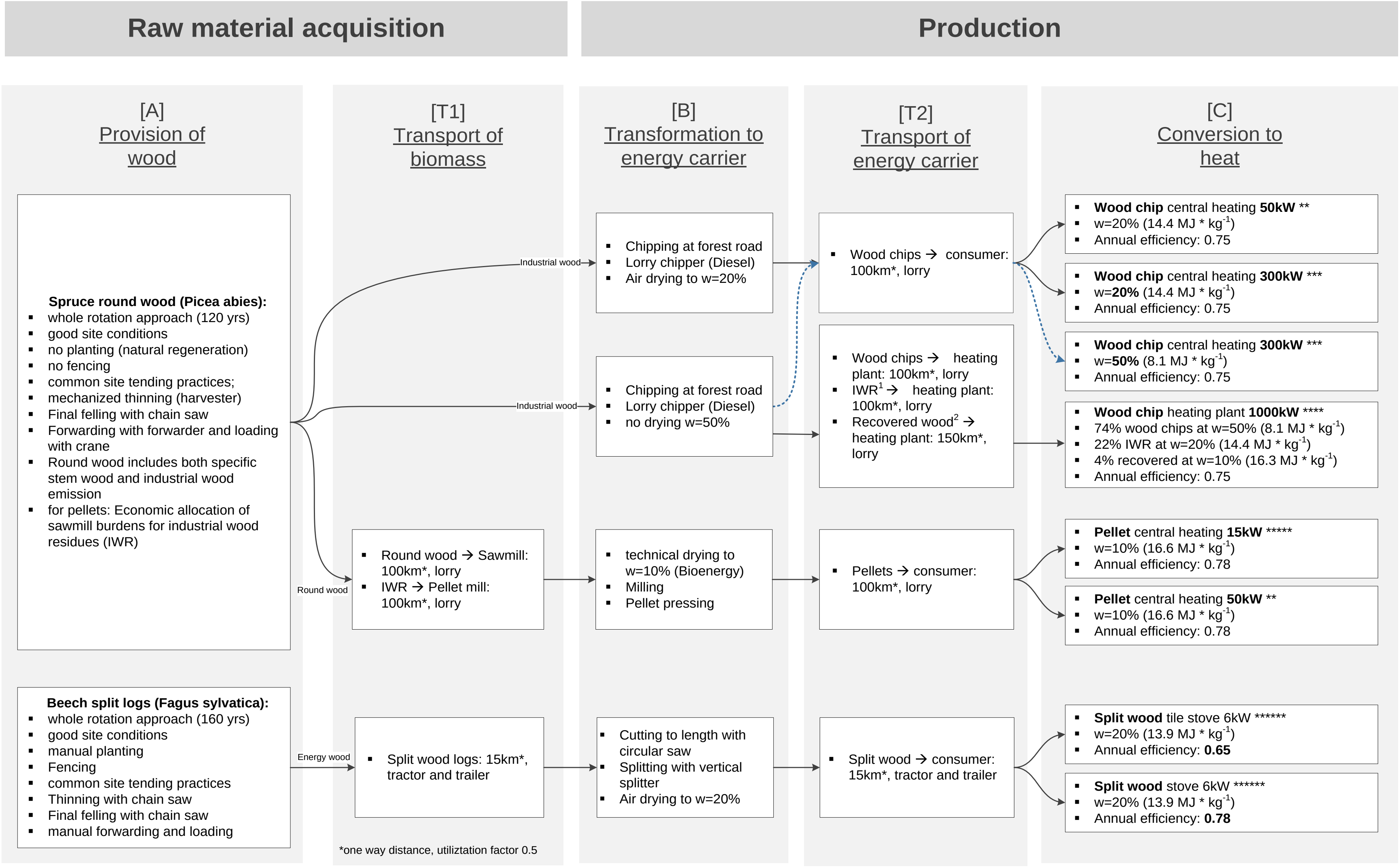
Scenario 1 assessed the effects of the goals set for the promotion of wood heating through the Bavarian energy concept of 2011, which stipulates a 15 % increase for the energetic use of wood until the year 2021. Since the amount of final energy in Bavaria has remained on an almost constant level over the past years, it was assumed that this 15% increase of wood heating displaces other, mostly conventional energy carriers such as natural gas or light fuel oil. The amount and type of substitution taking place was determined according to the most recent substitution percentiles for Germany (TABLE 7).

Table 7 *Substitution percentiles for different wood heating systems in Germany according to (Memmler et al. 2014) and weighted substitution percentiles in relation to installed capacities of individual heating systems in Bavaria in 2013. LFO=light fuel oil. (source: Wolf et al. 2016b, tab. 4, p. 182).*

[%]	LFO	Natural gas	Hard coal	Lignite	District heat	power
Wood stove	40.6	49.9	0.4	1.1	1.8	6.3
Split wood central	65.0	20.0	2.0	3.0	0.0	10.0
Wood pellet central	65.0	20.0	2.0	3.0	0.0	10.0
Solid wood (industry)	7.6	53.5	7.9	16.4	14.6	0.0
Solid wood (heating plant)	0.0	0.0	0.0	0.0	100.0	0.0
Weighted substitution	49.9	31.8	1.4	2.4	6.8	7.6

Scenario 2 was intended to identify, whether potential increments of wood energy stipulated by Bavarian policies can be supported by scientific findings. As such, the scenario was based on WILNHAMMER ET AL. (2012), which concludes that approximately 1.1 $m^3 * ha^{-1} * yr^{-1}$ of energy wood could additionally be sourced from Bavarian private forests. In order to identify limits and potentials of energy wood use, scenario 3 depicted the combustion of the maximum available wood in the state (also wood suitable for material utilization), while scenario 4 analyzed the current performance of wood energy for climate change mitigation. This was carried out by substituting, in accordance with TABLE 7, the current total share of wood energy with other energy carriers.

Impact assessment was carried out for the impact categories of IPCC Global Warming, without biogenic CO_2 (GW), particulate matter emissions (PM), aquatic freshwater eutrophication (ET) and acidification (AC). Furthermore, the primary energy consumption (non-renewable) was assessed (PE). See TABLE 3 for specific impact assessment methodologies.



[1]economic allocation of sawmill burdens for IWR; [2]no burden of prior system for recovered wood;
** valid for capacities between 30-100kW; *** valid for capacities between 100-700kW; **** valid for capacities between 700-5000kW;
***** valid for capacities between 10-30kW; ******valid for capacities between 6-20kW

Figure 9 *Description of life cycle stages, system assumptions and parameters in the modeling of the wood heating systems*. *(source: Wolf et al. 2016c fig. 1, p. 397).*

4.2.2. Mitigation of environmental impacts through wood energy use

(Publication 4: Wolf et al. 2016c)

LCA postulates the interpretation of results as a final step in the assessment. Frequently, this interpretation is carried out by comparing the product system with a reference system, in order to identify benefits and burdens. In the past, for the comparison of wood energy to other energy carriers such as fossil fuels, mostly generalized and often arbitrary displacement factors (i.e. the difference between the emissions of the product system and reference system) were employed, leading to unprecise and inconclusive results. Therefore, as a final step for this research an LCA interpretation was carried out for previously analyzed systems, in which their impacts were compared to the impacts of heat from other, non-wood energy carriers such as e.g. natural gas, light fuel oil or power as well as the weighted mixes with- and without renewable energies. Displacement factors for all energy carriers that constituted the heating mix in 2011 were calculated as follows (see section 4.3.1). Wood heating systems were selected based on an assessment on the amount of different wood heating appliances in the state (Joa et al. 2015). Subsequent LCA was carried out according to Wolf et al. (2016a) with systems being modeled from wood production [A], for which emission factors were employed originating from Klein et al. (2016), over wood transformation into split wood, pellets and wood chips [B], to wood conversion [C]c with the addition of transports [T]. Due to the minor importance towards the selected impacts, wood ash treatment [E] was cut off based on the <1%/95% cut off rule for the impact category of GW. In contrast to the assessments described in section 4.3.1, the systems were modeled for tree species specific fuels (i.e. beech split wood and spruce wood chips and pellets). In order to depict the actual displacement taking place; transmission losses occurring during heat transport after combustion were included (i.e. useful energy). If transmission losses were to be neglected (i.e. final energy), displacements would artificially be higher by the degree of losses not taken into consideration. Emission factors for non-renewable energy carriers were modeled via black-box unit processes, based on data provided in the PE Professional database (thinkstep AG 2015). Table 8 offers an overview of the employed emission factors.

Displacement effects were determined for the impact categories of IPCC Global Warming, without biogenic CO_2 (GW) (IPCC 2007), and particulate matter emissions (PM) (Rabl & Spadaro 2012), in order to show tradeoffs associated with wood energy use. CO_2 from biogenic sources was omitted since it was assumed that the wood originated from sustainable forestry and that carbon stock losses were not to be expected.

In addition to the displacement of individual systems, a weighted displacement caused by the sum of wood heating systems was assessed, which is useful when displacement is to be analyzed on a larger scale than the household scale, e.g. for cities or regions. For this weighted factor, displacement was calculated according to the installed capacity of individual wood heating systems in Bavaria (Joa et al. 2015).Forest production was also weighted, in order to represent a mean emission factor. This emission factor was weighted according to the distribution of timber volumes per assortment and species in Bavaria in 2014 (Table 6).

When employing a weighted wood heating mix in order to determine displacement, it also has to be related to a weighted reference system. In this case the emissions caused by the weighted heating mix, both with and without renewable energies were included as reference systems. Weighting was carried out according to the individual energy carriers' share of final energy for heat in Bavaria in 2011 (Wolf et al. 2016b) (Table 8). Displacement was depicted on the basis of 1 MJ of useful heat and the potential energy from 1 m^3 of wood.

Table *8* *GHG emissions per MJ of **useful** heat, share of Bavarian heating mix of individual energy carriers and the weighted mix of solid biofuels. B=beech, GW=global warming, RE=renewable energies, S=spruce, w=water content. (source: modified from Wolf et al. 2016b).*

Heating energy carriers	**GW per MJ_{th}** [g CO_2-eq.]	**Share of heating mix Bavaria 2011** [%]	**Source**
Natural gas	83.0	42.56	thinkstep AG 2015; Wolf et al. 2016b
Light fuel oil	106.6	21.72	
Power	172.5	9.56	
District heat	91.8	6.67	
Other renewable[1]	28.4	2.45	
Liquid propane gas	105.4	1.98	
Other[2]	101.4	1.27	
Lignite	162.7	1.15	
Hard coal	151.4	0.04	
Solid biofuels – weighted mix[3]	11.4	12.6	
├ Wood chips (50kW/S/w20)	16.2	0.15[4]	Wolf et al. 2016b
├ Wood chips (300kW/S/w20)	15.3	0.15[4]	
├ Wood chips (300kW/S/w50)	17.5	0.15[4]	
├ Wood chips (1MW/Wood mix)	16.1	0.66[4]	
├ Split wood (Stock/6kW/B/w20)	9.7	5.51[4]	
├ Split wood (BAT/6kW/B/w20)	7.4	4.87[4]	
├ Pellet (15kW/S/w10)	25.3	0.56[4]	
└ Pellet (50kW/S/w10)	23.8	0.56[4]	

[1]carrier mix of solar thermal, geothermal, ambient heat, sewage sludge, biogenic waste and biogas technologies; [2]uniform mix of all energy carriers; [3]weighted by installed capacity. Contains individual wood heating systems below; [4]adjusted based on installed capacity of respective system.

4.3. Results and discussion

4.3.1. Environmental effects of shifts in a regional heating mix

(Publication 3: Wolf et al. 2016b)

Emission factors

Results for all analyzed systems based on 1 MJ of final energy for heat (TABLE 9) show an emission factor for the weighted Bavarian heating mix of 0.075 kg CO_2-eq. * MJ^{-1} and 0.086 kg CO_2-eq. * MJ^{-1} for the mix without renewable energies. Due to the still high amounts of non-renewable energy carriers in this mix, substantial GHG emissions in comparison to the wood heating systems could be shown, which exhibit a weighted emission factor of 0.010 kg CO_2-eq. * MJ^{-1}. In contrast, wood heating systems are responsible for large emissions of particulate matter (PM). They exhibit a weighted PM emission factor of 0.139 g $PM_{2.5}$-eq * $MJth^{-1}$, which is the highest emission factor encountered for all heating systems. NUSSBAUMER ET AL. (2008) explain, that the abundance of incomplete combustion during the conversion of wood fuel to wood energy is responsible for these substantial emissions. However, this problem mainly concerns systems employing split wood for the generation of heat as shown through the assessment of individual wood heating systems (WOLF ET AL. 2016B). Nevertheless, since split wood systems comprise more than 82% of the installed capacity in Bavaria (JOA ET AL. 2015), the influence of these high PM emitting systems is substantial. In respect to GW, split wood systems possess the most favorable properties of all wood heating systems. Of course, low efficiencies during the combustion of wood [C] (the most important life cycle phase for these systems) in older split wood systems can somewhat negate this effect, since the reduced efficiency is responsible for increased GHG emissions of approximately 25%. This closes the gap between split wood heating and wood chip heating systems. For wood chips systems, similar to split wood systems, albeit in a lower magnitude, the most important life cycle phase is the conversion phase [C]. Consequently, wood production [A] is of greater importance due to a higher degree of mechanization during harvesting, forwarding and transportation. In contrast to both split wood and wood chips, pellet systems are dominated by the influence of process group [B] transformation towards the impact on GW, due to the amount of power (mostly non-renewable) employed during the production of wood pellets (WOLF ET AL. 2016B).

Table 9 *Emission factors (EF) for the analyzed technologies and the weighted emission factors of the heating mix with and without renewable energies. GW=Global warming, LFO=light fuel oil, LPG=liquid propane gas, PE=primary energy consumption non-renewable, PM=particulate matter, ET=freshwater eutrophication; AC=acidification; RE=renewable energies. (source: modified from Wolf et al. 2016b tab. 5, p.183).*

	GW	**PE**	**PM**	**ET**	**AC**	**Source**
	[kg CO_2-eq.]	[MJ]	[g $PM_{2.5}$-eq.]	[g P-eq.]	[mmol H^+ eq.]	
	per MJ_{th} of **final** energy					
Power	0.171	2.31	0.016	0.000326	0.333	thinkstep AG 2015; Wolf et al. 2016b
Lignite	0.114	1.00	0.008	0.000004	0.160	
Hard coal	0.106	1.07	0.011	0.000017	0.209	
District heat	0.090	1.24	0.005	0.000008	0.132	
LFO	0.085	1.18	0.004	0.000014	0.119	
LPG	0.084	1.17	0.006	0.000034	0.118	
Natural gas	0.066	1.08	0.002	0.000002	0.064	
Other[1]	0.052	0.67	0.041	0.003090	0.154	
Other renewables[2]	0.028	0.52	0.014	0.027600	0.171	
Solid biofuels[3]	0.010	0.102	0.139	0.004500	0.159	Wolf et al. 2016b
Mix without RE[4]	0.086	1.251	0.005	0.000089	0.118	
Mix with RE[4]	0.075	1.088	0.022	0.001320	0.124	

[1]uniform mix of all energy carriers; [2]carrier mix of solar thermal, geothermal, ambient heat, sewage sludge, biogenic waste and biogas technologies; [3]weighted EF by installed capacity; [4]weighted by share of heating mix

Since the generation of power, when assuming the German grid mix, still exhibits large shares of hard coal and lignite as fuel inputs, the resulting emission factor is considerably high (0.171 kg CO_2-eq. * MJ_{el}^{-1}). As such, already relatively small inputs of power into a system can have a substantial impact in regard to the total GHG emissions. In the case of pellet production this input of power is required for the milling of sawmill residues, the subsequent pressing of the pellets, and for the operation of drying kiln. The second most important phase for these systems is wood production [A]. Here, environmental effects of saw milling are allocated onto the main- and co-products, sawn wood and sawmill residues respectively. Typically, allocation in this process group is carried out according to either mass, or market price (recommended). Allocation by market price can lead to a calculatory reduction of total emissions of approximately 25%.

In conclusion, the great reduction of PM emissions for pellet heating systems comes at the price of substantially larger GHG emissions. Since the mitigation potential of pellet systems is still high (see section 4.3.2) and the reduction of PM, which exhibit direct and local harmful effects, is the main challenge for wood energy, pellet systems overall feature the highest potential for a future environmentally friendly utilization of energy wood. This effect is further strengthened when, due to increasing amounts of renewable energy in future power mixes, direct production emissions in process group [B] can be minimized.

Two key parameters are responsible for large shares of the minimization of GHG emissions of wood energy systems, independent of the conversion technology, the wood moisture content (which correlates to the lower heating value (LHV)) and the efficiency of combustion. These two parameters act like scaling factors for all previous upstream processes and flows. In this respect, the moisture content scales all processes before combustion, while the combustion efficiency scales the whole system until after combustion. Optimizing these parameters can have a substantial effect in respect the overall reduction of emission of harmful substances from wood energy systems (WOLF ET AL. 2016B) (DRESSLER ET AL. 2016).

Scenario results

In 2011, a total amount of final energy of approximately 660.000 TJ, provided by several individual energy carriers, were expended for heat in Bavaria (baseline) (WOLF ET AL. 2016B). It could be shown that both, the fuel composition and the amount of final energy have been changing only marginally over the past years, signifying the validity of these findings over an extended period of time i.e. until a substantial reduction of the heating required (e.g. through insulation) can be realized of drastic changes in the composition occur.

The composition of this heating mix is still dominated by non-renewable energy carriers such as natural gas and light fuel oil (LFO), with shares of 42.6% and 21.7% respectively (FIGURE 10). Solid biofuels (e.g. wood) exhibit the third largest share with 12.6%. In total the provision of heat in Bavaria is responsible for approximately 49.6 Mt CO_2-eq. * yr^{-1}, of which the top three energy carriers (natural gas, LFO, solid biofuels) show shares of 37.8%, 24.8%, and 1.7% respectively. In comparison to other, major energy carriers, this shows the favorable properties of solid biofuels in a heating application. Power, often employed for heating through air conditioning or night storage units, exhibits a share of 21.8% of total GHG emissions while only providing 9.6% of the final energy for heat, directly reflecting the substantial losses encountered during the generation of power, as well as the high EFs of lignite and hard coal. Besides impacts on GW, the Bavarian heating mix is also responsible for the emission of particulate matter (PM) in the magnitude of 14,580 t of $PM_{2.5}$-eq * yr^{-1}, of which almost 80% are caused by wood heating systems. Initiatives for the reduction of PM have commenced in Germany in the form of the amendment of the first federal emissions protection regulation (BImSchV) (BMU 2010). Due to future retrofitting or replacement of heating systems, the amendment is bound to have a substantial impact on the emissions of particulate matter from split wood heating systems. If the retrofitting or replacement of inefficient wood heating systems is implemented, and if wood consumption for heat remains on a constant level, a potential future reduction of particulate matter emissions of up to 50% could be realized in the next 30 years (Wilnhammer et al. 2016).

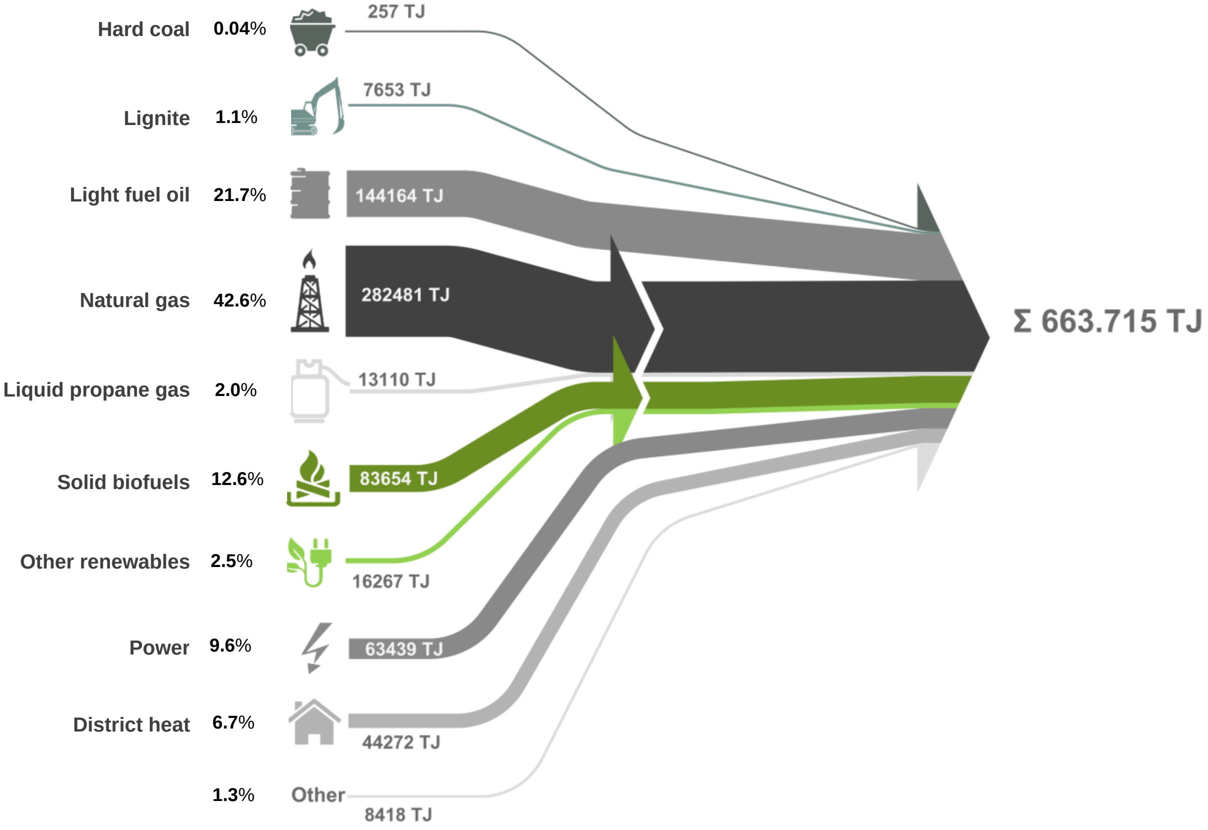


Figure 10 *Baseline heating mix in Bavaria in 2011. LFO=light fuel oil, LPG=liquid propane gas. (source: modified from Wolf et al. 2016b fig. 3, p.187, based on BayLAStDV 2014).*

Results for scenario one (S1) – the Bavarian energy concept stipulating a 15% increase of energy wood until the year 2020, showed a potential climate change mitigation effect of approximately 1 Mt CO_2-eq. * yr^{-1}, which corresponds to a 2% reduction of GHG emissions of heating in Bavaria. Contrastingly, PM emissions would increase, under current circumstances, by 11.6% (Figure 11). Scenario two (S2) – wood mobilization from private forests, where an additional energy wood input of 1.1 m^3 * ha^{-1} * yr^{-1} was assumed, show similar effects to the findings to S1. This more conservative estimation of additional solid biofuel consumption leads to a climate change mitigation effect of approximately 0.73 Mt CO_2-eq. * yr^{-1} which corresponds to a reduction of 1.5% of the total GHG emissions. Scenario three (S3) – 100% energetic wood use, displays the limits for the wood energy sector. Under the hypothetical assumption of a sole use of all produced wood in Bavaria (approximately 20.2 M m³) for the purpose of generating heat, a threshold of 25% of the total final energy for heat, generated from wood cannot be surpassed, which corresponds to a maximum potential climate change mitigation effect of approximately 5.6 Mt CO_2-eq. * yr^{-1}. This means that even if all material use of wood is sacrificed for the generation of energy the current share of final energy can only be doubled. Additionally, it has to be considered, that the GHG mitigation potential through the material utilization of wood and subsequent substitution of non-wood materials is not counted. Since a lack of wood resources leads to direct substitution with other, often less favorable products or direct imports, this tradeoff or any other significant increment in wood energy consumption should be carefully considered. To clarify, since the material use of wood is inhibited, a 100 % energetic use of wood is not realistic or useful, but it clearly indicates that using wood for energetic purposes is in fact a key to fulfilling climate change mitigation goals in Bavaria. However, since the mitigation effects are limited it cannot be the ultimate singular tool. Scenario four (S4) – 0% energetic wood use shows the climate mitigation performance of the current share of solid biofuels in the heating mix. As such, a current climate mitigation performance of approximately 6.4 Mt CO_2-eq. * yr^{-1} could be identified. Without the use of wood for energy emissions for the total heating mix would be 13% higher, which corresponds to 56.05 Mt CO_2-eq. * yr^{-1} (Wolf et al. 2016b).

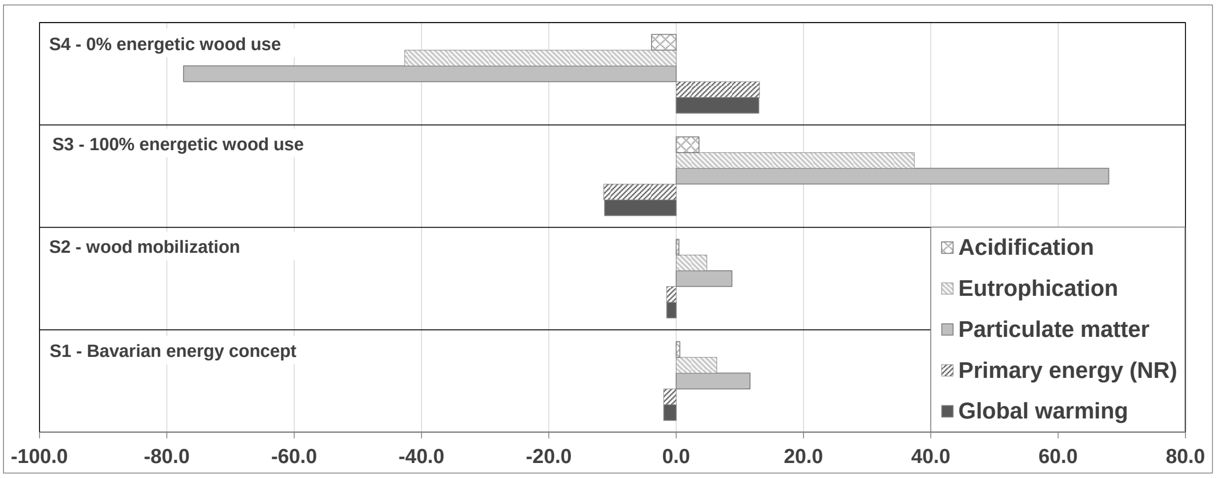


Figure 11 *Relative changes of environmental impacts caused by individual scenarios (S1-S4) in comparison to the baseline conditions (Figure 10). NR=non-renewable, S1-S4=scenarios. (source: modified from Wolf et al. 2016b, fig. 6, p. 189).*

Discussion

As mentioned in (WOLF ET AL. 2016B) the emission associated with wood heating across all systems (i.e. the weighted emission factor for solid biofuels in Bavaria (TABLE 9) is weighted according to the installed capacity of individual systems. Since split wood heating systems represent about 80% of the total installed capacity (JOA ET AL. 2015), the weighted emission factor is strongly influenced by these systems. However, it is unclear whether the installed capacity actually correlates to the amount of wood used in the respective systems. It is conceivable that there are many split wood systems in the state, which are not continuously in operation and therefore do not consume any wood. This might be the opposite for larger scale facilities (which are currently responsibly for only a small share (5%) of the installed capacity in Bavaria (JOA ET AL. 2015)), which operate continuously. As a result, the impact of split wood heating systems towards the weighted emission factor might be overestimated, while technologies with small installed capacities but continuous operation might be underestimated.

WOLF ET AL. (2016B) shows the current and potential influence of the provision of wood heating in Bavaria. However, in order to achieve a holistic assessment of the effects of the total energetic utilization of wood, the integration of impacts associated with the generation of power from wood can be advantageous. Even though, this utilization of wood is only of minor importance, only about 3% of the gross electricity consumption in Bavaria in 2013 were provided through solid biofuels (total renewable share: 34.3%) (EBERT & VOIGTLÄNDER 2014), an integration can further strengthen the assessment.

Furthermore, since the amount of sustainably produced wood from Bavarian and German forests is limited, increments in the amounts of energy provided through forest wood will have direct impacts on the available wood for a material utilization, and vice versa (if no further wood mobilization is a accounted for). Since both the material- and energetic utilization of wood are strongly interconnected and linked to substitution effects, a shift between the two pathways also always entails a shift in the total amount of substitution obtainable from the overall wood use in a study area. Therefore, it is necessary to understand the effects of a modified ratio between the two utilization pathways in order to depict environmental impacts of the total wood utilization system. For the area of heat provided from wood, convenient substitution percentiles could be employed (MEMMLER ET AL. 2014). However, for this total system perspective, incorporating both the material and energetic utilization of wood, no similar approach has yet been devised and therefore other approaches like e.g. the basket of benefits method (WEBER-BLASCHKE ET AL. 2015) need to be considered when integrating wood heating into the overall system.

An additional option to counteract the issue of resource constraints and subsequent shifts between the two utilization pathways is the integration of imports of wood into the study system. Already today, large amounts of wood from potentially non-sustainably managed forests are imported to Germany for the purpose of energy generation (GANG ET AL. 2016). Environmental impacts of these assortments are manifold (e.g. potential reduction of carbon sinks and subsequent non-eligibility for CO_2-neutral combustion) and a reality. For the assessment in (WOLF ET AL. 2016B) a closed system for Bavaria was modeled. However, for the purpose of illustrating the current situation of energy wood utilization in the state, an integration of LCAs for imported wood on the example of SUTER ET AL. (2016), and for recovered wood in accordance with HÖGLMEIER (2015) can be valuable.

4.3.2. Mitigation of environmental impacts through wood energy use

(Publication 4: Wolf et al. 2016c)

Displacement factors

GHG displacement through the utilization of wood for the provision of heat showed a range between -3.1 g CO_2-eq. * MJ^{-1} and -165 g CO_2-eq. * MJ^{-1}, depending on the displaced reference system (TABLE 10). The highest displacement is associated with heat from beech split wood systems due to its inherently low production emissions, followed by heat from wood chip and pellet systems. Considering only the most important reference systems, i.e. reference systems with high shares of final energy in the heating mix according to WOLF ET AL. (2016B), a displacement range between -57.6 g CO_2-eq. * MJ^{-1} and -99.1 g CO_2-eq. * MJ^{-1} for the displacement of natural gas by a 15 kW pellet central heating system and the displacement of LFO by a 6 kW modern split wood stove, could be observed respectively. Since not only beech split wood or spruce chips are being converted to heat, but also spruce split wood and beech chips, changes towards the displacement for variations in wood species were additionally analyzed. For spruce split wood it could be shown that GHG emissions would increase by approx. 15% (due to a lower LHV per m^3) entailing reduced displacements of approx. 2%, 1.5% and 0.9% when displacing natural gas, LFO and power respectively. Combusting beech wood chips instead of spruce wood chips, the displacement factor would be increased by approximately 5.4% for the displacement of natural gas, 4% for the displacement of LFO and 2.4% for the displacement of power. Factors for weighted wood heating systems show a displacement of natural gas, LFO and power of -71.5 g CO_2-eq. * MJ^{-1}, -95.2 g CO_2-eq. * MJ^{-1} and -161 g CO_2-eq. * MJ^{-1} respectively.

Displacing the current heating mix including renewables could be shown to entail GHG mitigation effect of -77.5 g CO_2-eq. * MJ^{-1}, while the displacement of the heating mix excluding renewables provides -90.3 g CO_2-eq. * MJ^{-1}. This displacement factor of -90.3 g CO_2-eq. * MJ^{-1} is recommended (WOLF ET AL. 2016C) when assessing the potential performance of future planned wood energy systems on regional scales, similar to Bavaria in respect to the distribution of energy carriers in the heating mix.

Table 10 *GHG displacement factors (per MJ of useful heat) of heat provided by wood heating systems in Bavaria. Negative values represent reduction of GHG emissions. B=beech, BAT=best available technology, RE=renewable energies, S=spruce, w=water content. (source: modified from Wolf et al. 2016c, tab. 2, p. 398).*

	Natural gas	**Light fuel oil**	**Power**	**District heat**	**Other[3] RE**	**Heat mix[4] +RE**	**Heat mix[3]**
	g CO_2-eq. * MJ^{-1}						
Wood chips (50kW/S/w20)	-66.7	-90.4	-156.2	-75.6	-12.2	-72.2	-85.4
Wood chips (300kW/S/w20)	-67.6	-91.3	-157.2	-76.5	-13.1	-73.1	-86.4
Wood chips (300kW/S/w50)	-65.4	-89.1	-155.0	-74.3	-10.9	-70.9	-84.2
Wood chips (1MW/wood mix)[1]	-66.8	-90.5	-156.4	-75.7	-12.3	-72.3	-85.6
Split wood (Stock/6kW/B/w20)	-73.2	-96.9	-162.7	-82.1	-18.7	-78.7	-91.9
Split wood (BAT/6kW/B/w20)	-75.4	-99.1	-165.0	-84.3	-20.9	-80.9	-94.2
Pellet (15kW/S/w10)	-57.6	-81.3	-147.1	-66.4	-3.1	-63.1	-76.3
Pellet (50kW/S/w10)	-59.1	-82.8	-148.7	-68.0	-4.6	-64.6	-77.9
Technology mix[2]	**-71.5**	**-95.2**	**-161**	**-80.4**	**-17**	**-77**	**-90.3**

[1] Mix of wood chips (74%;w=50%), industrial wood residues (22%;w=20%) and recovered wood (4%;w=10%). [2] Mix weighted by installed capacities of wood heating systems and volumes of harvested tree species. [3] Mix between solar thermal, geothermal, biogas and the biogenic share of the waste. [4] Mix weighted by share of final energy for heat in Bavaria (2011).

Displacement factors on the basis of 1 m^3 are strongly influenced by the individual wood specie's density and respective LHV per m^3. Consequently, a larger spread of results can be observed ({-17 kg CO_2-eq. * m^{-3}…1248 kg CO_2-eq. * m^{-3}}) (Table 11). Weighted factors for displacing the current heating mix including renewables could be shown to be -442 kg CO_2-eq. * m^{-3}, while the displacement of the heating mix excluding renewables is -518 kg CO_2-eq. * m^{-3}. For all systems, the magnitude of displacement factors is influenced by the size of combustion system, i.e. higher combustion capacities lead to higher displacement factors. Also of strong influence are the efficiency of the combustion process and the water content of the biomass. These factors directly influence the amount of biomass, and associated emissions, required for the production of heat. Therefore, higher water contents and lower efficiencies lead to an overall lower displacement factor.

In addition to the displacement factors of individual heating systems, it is convenient to disclose factors applicable for the assessment of GHG reductions on a regional level, i.e. for a town, region, state or country. These displacement factors can be utilized if not one system is replacing another specific system directly, but the impact of a number of different systems being exchanged by a respective wood heating technology or by a weighted mix of wood heating technologies is to be assessed.

The most important factor in respect to the magnitude of displacement, however, is the choice of reference system. Literature concerned with the GHG mitigation potentials of energy wood depicts displacements in a range between -440 kg CO$_2$-eq. * m^{-3} and -675 kg CO$_2$-eq. * m^{-3} (Sathre & O’Connor 2010; Klein et al. 2013; Knauf et al. 2015). For these studies mostly LFO, and in some cases natural gas, or a mix of natural gas and LFO is used as a reference system. However, in order to achieve sufficiently accurate displacement factors, the composition of heating mixes dictates the inclusion of other major energy carriers, such as power. Utilizing the above mentioned standard displacement approaches leads to over- or underestimations of the displacement effect. On the example of Bavaria, taking only into account the displacement of natural gas, as opposed to the actual mix of energy carriers in the heating mix, leads to a decrease of the effect of displacement of approximately 7% (-0.45 M t * yr^{-1}). Taking only into account the displacement of LFO increases the effect of displacement by 20% (+1.6 M t * yr^{-1}). This simplification is mostly due to the previous lack of a defined heating mix for a region or a country, but the impact on the magnitude of displacement occurring, can be substantial. Especially for heat, due to the decentralized provision structure, displacement factors should not be based on a subjective mix of energy carriers. The factors should represent a realistic displacement of individual heating systems, e.g. the individual displacement of natural gas, LFO, power, renewable heating systems or a combination of all. Only with these individual displacements, homeowners and policy makers can assess realistic GHG mitigations caused by a potential shift of heating systems.

Table 11 *GHG displacement factors (per potential useful energy of 1 m³ of wood) of heat provided by wood heating systems in Bavaria. Negative values represent reduction of GHG emissions. B=beech, BAT=best available technology, RE=renewable energies, S=spruce, w=water content. (source: modified from Wolf et al. 2016c, tab. 3, p. 399.*

	Natural gas	**Light fuel oil**	**Power**	**District heat**	**Other[3] RE**	**Heat mix[4] +RE**	**Heat mix[3]**
	kg CO$_2$-eq. * m^{-3}						
Wood chips (50kW/S/w20)	-343	-465	-804	-389	-63	-372	-440
Wood chips (300kW/S/w20)	-348	-470	-809	-394	-67	-376	-444
Wood chips (300kW/S/w50)	-303	-412	-717	-344	-50	-328	-389
Wood chips(1MW/wood mix)[1]	-334	-452	-781	-378	-61	-361	-427
Split wood (Stock/6kW/B/w20)	-462	-611	-1026	-518	-118	-496	-580
Split wood (BAT/6kW/B/w20)	-571	-750	-1248	-638	-158	-612	-713
Pellet(15kW/S/w10)	-314	-443	-802	-362	-17	-344	-416
Pellet (50kW/S/w10)	-322	-452	-811	-371	-25	-352	-425
Technology mix[2]	**-410**	**-546**	**-923**	**-461**	**-97**	**-442**	**-518**

[1]Mix of wood chips (74%;w=50%), industrial wood residues (22%;w=20%) and recovered wood (4%;w=10%). [2]Mix weighted by installed capacities of wood heating systems and volumes of harvested tree species. [3]Mix between solar thermal, geothermal, biogas and the biogenic share of the waste.[4]Mix weighted by share of final energy for heat in Bavaria (2011).

Beside the emission of GHGs, energy systems are also linked to various other environmental impacts, which not always correlate positively with GHG displacement. In the case of wood heating systems, a considerable GHG mitigation potential and simultaneous increase in particulate matter emissions can be identified. Naturally, the different wood heating systems offer different benefits and tradeoffs, but a general improvement towards the reduction of negative environmental effects can be observed. As such, modern split wood stoves exhibit 20-60% reduced particle emission in comparison to old stock units, through the application of new filter techniques and the optimization of combustion. Pellet heating systems only cause 6% of the particle emissions of old stock split wood units (KELZ ET AL. 2012). Nevertheless, particulate matter emissions should not be treated lightly, since direct health hazards caused by the inhalation of PM have been scientifically reported (NUSSBAUMER ET AL. 2008).

Transfer and application in other regions

In order to avoid over- or underestimations of GHG mitigation and other environmental effects of wood heating systems for a specific region, town or country, the development of individual displacement factors using the following approach is suggested (WOLF ET AL. 2016C):

I. Approximation of the specific wood heating technology mix e.g. by using statistics or estimations concerning installed capacities of wood heating systems in a region

II. Identification of the specific heating mix of the respective region by means of final energy statistics

III. Calculation of environmental impacts of all relevant heating systems and a subsequent calculation of a weighted mean GHG emission factor

IV. Estimation of specific displacement factors by comparing the environmental impacts of the heating mix (without the share of solid biofuels) and the heating mix including the wood heating mix.

Discussion

As mentioned in sections 1.3 and 4.3.2 an array of studies concerned with the mitigation of GHGs through the energetic utilization of wood have been published. These studies depict displacements of -440 kg CO_2-eq.$*$ m^{-3} (SUTER ET AL. 2016), -600 kg CO_2-eq.$*$ m^{-3} (TAVERNA ET AL. 2007) (both displacing a mix of LFO and natural gas) and − 675 kg CO2-.$*$ m^{-3} (KÖHL ET AL. 2009) (displacing LFO). Especially for heat however, in order to achieve sufficiently accurate displacement factors, it would be favorable to take the composition of heating mixes into account when determining the magnitude of displacement on a regional scale. Employing these simplified approaches can lead to over- or underestimations of the displacement effect. This can be demonstrated for Bavaria, where a sole displacement of natural gas, as opposed to the actual mix of energy carriers in the heating mix, can lead to a decrease of the total displacement (6.4 M t * yr^{-1}) of approximately 7% (-0.4 M t * yr^{-1}), while the sole displacement of LFO increases the effect by 20% (+1.4 M t * yr^{-1}).

A recent study carried out by the Bavarian State Institute for the Environment (LFU) suggests displacements factors for wood chip, split wood and pellet appliances of 75,9 g CO_2-eq. * MJ^{-1}, 77,5 g CO_2-eq. * MJ^{-1} and 72,0 g CO_2-eq. * MJ^{-1} respectively (LFU 2016). This equates to a relative difference in displacements of -12% for wood chips, -4.5 % for split wood and -20% for pellets. Since the employed emission factors are based on German conditions (UBA 2015) and the emission factors for heating systems only reflect the actual combustion of fuels (i.e. phase [C]) the higher displacement can be explained. These differences demonstrate the need for regionalized displacement factors, as shown in (WOLF ET AL. 2016C), in order to depict the actual magnitude of the occurring displacement.

Even though Bavarian statistics provided the data foundation for the calculations in WOLF ET AL. (2016C), displacement factors are comparable, and can be scaled to overall German conditions. In comparison to Bavaria, a heating mix for Germany, based on STENULL (2010) exhibits 12% lower GHG emissions, for which a higher share of natural gas in the German heating mix is responsible. Consequently, the weighted displacement through wood heating for German conditions is -76 g CO_2-eq. * MJ^{-1} (excluding other renewables) (WOLF ET AL. 2016C).

The combination of GHG- and particulate matter emission analysis has the result that for pellets, which are associated with a relatively high demand of power in the production process, the GHG mitigation improves with the share of renewable energies in the power grid mix, while still maintaining the most favorable $PM_{2.5}$ emissions properties when compared to wood chips or split wood systems. Additionally, since pellets are generally produced from saw mill residues, they follow the credo that the material use of forest wood should, if possible, always be prioritized before the energetic use. This makes pellet heating systems the most favorable option in regards to the sum of environmental effects. Of course, saw mill residues could also be used for the production of particle boards or similar wood products, followed by the subsequent thermal utilization. This pathway possibly offers an enhanced total benefit.

The research approach presented in WOLF ET AL.(2016C) covers a number of different wood heating systems. These systems are not solely responsible for displacements of environmental impacts and only show ranges of several typical appliances. As such, of great interest would be the extension to other forms of renewable energy provision, such as combined heat and power from biogas and wood as well as other renewable energy systems (photovoltaics, solar-thermal, geothermal).

Apart from the current displacement factors for wood heating, it was possible to provide an approach for the transfer of methods to other regions. This approach relies on a certain set of statistical data (i.e. installed capacities of wood heating systems and the final energy balances) in order to generate displacement factors. Not for all regions, however, all statistics required, are always obtainable, thus rendering the application difficult. Nevertheless, as a substitute to e.g. the installed capacities of wood heating systems, wood consumption statistics per wood heating system could be incorporated when calculating the weighted wood heating mix. In respect to the reproducibility of findings, these alterations of the original approach should be disclosed.

As a practical application of this analysis, the results were distributed in the form of a fact sheet published by the Bavarian State Institute of Forestry (WOLF ET AL. 2015B).

5 Synthesis and outlook

The presented research provided assists in achieving the long term and superordinate goals of reducing the environmental impacts associated with the provision and utilization of wood. This is achieved by proposals for methodological improvement which were subsequently practically implemented for the assessment of environmental effects of wood production and the provision of heat (as the most important energetic use of wood) on a regional scale.

This concluding section serves as a final synthesis and answers the research questions raised in section 1.4.

1. **Which methods for the assessment of the life cycle of raw wood products and their subsequent utilization for the purpose of providing energy are prevalent in current literature and how can they be further developed?**

Based on extensive literature review and systematic evaluation of perceptions, the following conclusions could be deduced: There is no accepted and applied methodology currently in place that leads to comparable, transparent and reproducible LCA results for forestry and wood products. Especially, differences in regard to the definition of system boundaries lead to a wide range of published results. A major hindering factor in creating reproducibility of LCA studies, was the publication of results in an aggregated form and the documentation of input data or parameters. Additionally, most studies only considered the impacts of the product system towards Global Warming.

Recommendations

- Enhance reproducibility through a transparent system description and by publishing results for each process group and indirect effects, e.g. credits and substitutions, separately
- Disclose relevant input data, parameters and methods applied
- Include further environmental impacts (besides GW) in the analyses (see section 3.3.4), as these impacts might negatively correlate to system improvements in respect to Global Warming

2. Which methodological aspects, including the transfer of methods towards bioenergy from agricultural resources, require further development and harmonization?

A further extension of guidelines for practitioners were proposed (KLEIN ET AL. 2015; WOLF ET AL. 2015A) and was refined in the framework of an applied research project (WOLF ET AL. 2016A). The refinement further specifies the system description, by giving practical guidance towards the choice of allocation procedure, reference system and impact assessment methods, as well as giving a practical illustration for the application of the methodology for three example systems.

Recommendations

- Minimize methodological gaps for products not covered by the refinement (e.g. material utilization of agricultural biomass).
- Integrate methodological extensions (e.g. BOSCH (2015) for material utilization of wood) into the provisions given by the refinement.
- Submit vital information in respect to the reproducibility of results, in a detailed fashion, as supplementary information in addition to journal articles and reports.
- Investigate further sustainability aspects such as nutrient sustainability and the timing of emissions.

3. What is the range of environmental effects of raw wood products and wood energy in current literature and by which factors is the magnitude of results influenced?

Results obtained via the first literature review, i.e. the review concerned with LCA for the provision of wood show a large spread for the impacts on GW. This large spread is due to differences in tree species, assortments and other parameters, such as the management regime and transport distance. Similar to the results for Bavarian conditions (KLEIN ET AL. 2016) no single footprint for the provision of wood could be identified, and as a consequence it is inadvisable to utilize a standard emission factor or database processes for process group [A] wood production, if the impacts from [A] are estimated to be substantial.

Meta-analysis of wood energy LCAs shows the smallest range of impacts in regard to GW for heat in comparison to power and CHP. This small range of results could be caused by similarities between most heating systems in respect to modeling and technology. For heat, mostly no allocation and similar efficiencies during combustion and a narrower spread of combustion efficiencies is encountered. In contrast, for CHP and power generating systems a multitude of methodological choices and technologies cause a much greater spread of results.

Main decisive factors influencing the magnitude of results were mainly feedstock properties, such as the moisture content, the lower heating value or parameters for the combustion of wood, i.e. combustion efficiencies and capacities. Reported information concerning these parameters was often vague or even implausible, which could be another cause for the wide spread of results.

Recommendations

- The utilization of generalized LCA processes and results for forest products and wood energy should be avoided due to the diverse nature of the production involved.
- Decisive parameters such as e.g. the combustion efficiency, fuel water contents, harvesting productivities and transportation distances are responsible for large spreads of results and should therefore always be disclosed.
- A clear system description following the provisions of FIGURE 7 can aid in the comparison of results and should be included for every published study.

4. **Which environmental impacts are caused by the regional provision of heat from solid biofuels (i.e. wood) in Bavaria, what is the contribution of these systems to the total emissions in the state and what are potential alterations of environmental impacts caused by certain bioenergy goals outlined in policies or scientific publications?**

In respect to climate change, it could be shown that modern split wood systems possess the most favorable properties of all wood heating systems. For older systems, low efficiencies during the combustion of wood [C] can lead to increased GHG emissions of approximately 25% while also entailing substantial emissions of particulate matter. As such, stock split wood heating systems possess the highest PM emission factor of all assessed technologies. Wood chip heating systems offer the second best performance in respect to climate change with the most important life cycle phase being the conversion phase [C], similar to split wood. While exhibiting higher emissions of greenhouse gases (due to the influence of electricity in process group [B]), pellet systems offer compellingly low particulate matter emissions. In general, the most decisive factors influencing the magnitude of emission were the feedstock and combustion properties, namely the LHV and the combustion efficiency. These parameters are of such importance, since they act as scaling factor for all previous upstream processes and flows. In this respect, the feedstock LHV scales all processes before combustion, while the combustion efficiency scales the whole system after combustion.

For the assessment of the Bavarian heating mix and the impacts of wood heating systems on climate change it was found that, the composition of the heating mix is still dominated by non-renewable energy carriers such as natural gas and light fuel oil. However, already in third place, by share of final energy, solid biofuel heating systems could be identified. Furthermore, while solid biofuel heating systems are responsible for a substantial share of heating provided in Bavaria, they only marginally contribute to the climate change impacts of the heating mix. In contrast, it could be shown that the reverse is true for power. Of course, this can be explained by the abundance of lignite and hard coal in the heating mix causing high emissions factors, even though the efficiencies of power heating systems are in many cases substantially better than wood heaters. While only marginally contributing to climate change, wood heating systems are responsible for the majority of particulate matter emissions (approximately 80%) underlining the need for target-oriented legislation with respect to PM reduction in Germany.

Results for the assessment of impacts stipulated by shifts in the composition of the Bavarian heating mix show that a further increase of energy wood utilization entails only marginal additional climate mitigation benefits, while the emissions of particulate matter increase drastically. Furthermore, substantial increments in the amount of energy wood will not lead to equally substantial increments towards the share of wood heating in the Bavarian heating mix. This means that even if all material use of wood is sacrificed for the generation of heat the current share of final energy can only be doubled. Since a lack of wood resources leads to direct substitution with other, often times less favorable products, or direct imports, this tradeoff or any other significant increment in wood energy consumption should be considered carefully. Nevertheless, the benefit of the current share of wood heating is substantial and total GHG emissions would increase by approximately 13% in the absence of wood heating.

Therefore, it can be concluded that a comprehensive strategy for the mitigation of climate change impacts through energy services requires the current capacity of wood heating appliances to be preserved and transitioned towards new and efficient systems, and that tradeoffs through e.g. shifts between material and energetic utilization and imports, be thoroughly assessed.

Recommendations

- Maintain and modernize the current wood heating capacities, in order to maximize the climate mitigation potential. Further increments for the total climate mitigation benefit can arise through process optimization.

- Pellet systems provide the most favorable properties for future reductions of greenhouse gases and particulate matter emissions and should therefore be the primary tool for the modernization of existing wood energy systems
- In order to increase the mitigation potential of wood energy services, important parameters such as the combustion efficiency should be maximized and the wood moisture content minimized
- The effects of an increased utilization of energy wood e.g. through imports of energy wood or shifts between material and energetic utilization, need to be closely assessed in order to determine the additionality of climate mitigation benefits

5. What is the magnitude of displacement effects for different wood heating systems in respect to climate change and particulate matter emissions in Bavaria, and how can the approach be transferred to other countries or regions outside of the study region?

Analysis showed that the most decisive factor towards the magnitude of displacement is the choice of reference system. Unlike many previous studies this assessment employed a weighted mix of energy carriers (representing the structure of heating in Bavaria) as a reference system, in order to depict actual displacement. Utilizing standard displacement factors, e.g. for LFO or natural gas, leads to over- or underestimations of the displacement effect, which can be quite substantial when assessing effects on a regional scale. This approach is proposed as a possible best practice approach in the future.

While previous studies concerned with the GHG mitigation potentials of wood energy depict displacements in a range between -440 kg CO_2-eq. * m^{-3} and -675 kg CO_2-eq. * m^{-3}, it was able to show that for Bavarian conditions a mean displacement factor of approximately 518 kg CO_2-eq. * m^{-3} is more adequate. However, this displacement of GHG also entails a simultaneous increase in particulate matter emissions of 776 g $PM_{2.5}$-eq. * m^{-3}.

Recommendations

- Mitigation benefits of heating should always be calculated against the actual system being replaced. If this system is complex (like e.g. the Bavarian heating mix), a weighted mix of energy carriers, as opposed to a single energy carrier representing the total conventional heating sector, should be employed
- In order to transfer the approach, it is advisable to follow the provision given in section 4.3.2, by creating weighted emission factors for both the sum of replacing systems and the sum of systems being replaced.

Outlook

The presented dissertation covers several topics in terms of the methodological approach and evaluation of environmental effects of raw wood and wood products. For future research, from a single production pathway system perspective, a further refinement of existing individual systems, as well as the assessment of new production pathways and system components should be integrated. A practical example is the technical pre-drying of wood fuels through waste heat or CHP biogas heat, which is a practical solution for the reduction of drying emissions, or the utilization of innovative particulate matter filtration systems for wood combustion systems. Additionally, environmental impacts through life cycle phase [E] disposal and recycling (i.e. the treatment of wood ash), needs further consideration. Here, only very basic assumptions for the treatment of wood ash could be integrated into this dissertation. However, effects through [E] can be manifold, especially for indicators such as eutrophication and acidification, and can act as a direct link towards the circular nature of wood fuels, if wood ash and the nutrients contained, could be reintroduced onto certain production areas rather than used for road construction or brick making. An initial and practical tool for the interpretation of nutrient flows could be developed in the form of a separate impact category aimed at depicting nutrient exports and imports into a system. Of further interest towards the assessment of emissions from heat is the transmission of final energy to the customer and its subsequent utilization in the form of useful heat. Especially for district heating systems, impacts arising through this process can be substantial. For this dissertation it was only possible to calculate transmission losses, but no LCA of the district heating system itself could be implemented, since LCI data was not available. Therefore, for future assessments it would be favorable to incorporate a complete LCA of the transmission stage of heating systems.

In respect to the regional system perspective for the case study region, the chosen approach for this research study could be enhanced by the consideration of external effects, such as imports into the system. It is known, that especially in the bioenergy sector, imports already play an important role and are predicted to further increase in the future (GANG ET AL. 2016). This has the effect that assumptions concerning in-situ carbon stock losses and production circumstances have to be re-evaluated for imported bioenergy carriers used for the generation of energy. Particularly major bioenergy flows into Bavaria, such as e.g. pellets from Canada or split wood from Eastern Europe, have to be taken into consideration, since carbon stock losses caused by the provision of these products cannot be precluded.

Of further interest in respect to the expansion of analyses carried out, is the assessment of changes of environmental impacts caused by shifts in future power grid mixes. Since many current systems are heavily influenced by the high GHG-emission factor of power, which is mainly required to transform raw wood into wood fuels or for the operation of fans and conveyors during drying or combustion, increased shares of renewable energies in future power mixes will also substantially influence the GHG-emissions of current and future heating systems. This is especially important for pellet heating systems, which offer a solution to reduce the high emissions of particulate matter of split wood heating systems, but at the expense of increased GHG emissions. With increasing shares of renewable energies in future power mixes, this tradeoff could be diminished substantially. Additionally, when widening the scope of assessment onto future prospects of environmental impacts of heating, e.g. through an increasing amount of solid biofuels in the heating mix in the future, it would be advisable to incorporate emissions for the fraction of new best available technology (BAT) heating systems. Since it is a fair assumption, that additional amounts of wood fuels will likely be converted into heat by modern BAT systems, emission factors should be updated regularly to reflect this situation. Especially for particulate matter emissions and the emission of non-CO_2 GHGs, such as Methane and Nitrous Oxide, new LCI data will be required. For the assessment of environmental emissions of biofuels in the total energy sector analyses should be extended onto the generation of power and transportation services in order to identify the most resource efficient form of energetic utilization for wood. Ultimately an efficient energetic utilization of wood for the sole generation of power will not be competitive in terms of resource efficiency, but potentials through CHP or co-firing should nevertheless be further analyzed.

In terms of methodology, it is now possible to compare products or services with the same function, e.g. space heating, power, passenger transportation, which originate from different land use regimes such as forestry or agriculture on the basis of the groundwork laid in the presented research (KLEIN ET AL. 2015; WOLF ET AL. 2015A) in conjunction with the recently published handbook for the LCA of bioenergy products (WOLF ET AL. 2016A). This enables the identification of beneficial land use types in respect to the chosen impact category, which has the potential to contribute additional vital information in respect to the environmental performance of products or services to the pure assessments of climate mitigation potentials.

Finally, since the analyses were focused on the impacts of solid biofuels, LCA impact categories relevant to solid biofuels (i.e. acidification, eutrophication, particulate matter emissions) were mainly reported. As a consequence, great shares of the total emissions in these impact categories are dominated by solid biofuels, while conventional energy carriers such as natural gas or LFO play only minor roles. A more comprehensive set of impact categories, also including impact categories that offer higher sensibility to the environmental effects of conventional energy carriers (e.g. resource depletion, human- and eco- toxicity) might offer additional insights in future studies.

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Publications in the context of this dissertation

Publication 1

Reprinted with kind permission from Springer Science + Business Media: The International Journal of Life Cycle Assessment. 20 years of Life Cycle Assessment (LCA) in the forestry sector: state of the art and a methodical proposal for the LCA of forest production.

Daniel Klein, Christian Wolf, Christoph Schulz, Gabriele Weber-Blaschke. 2015. International Journal of Life Cycle Assessment, Volume 20, Issue 4, pp 556-575.

The original can be accessed at http://link.springer.com/article/10.1007/s11367-015-0847-1

Publication 2

Reprinted with kind permission from John Wiley and Sons, Inc.: Journal of Industrial Ecology. Systematic review and meta-analysis of Life Cycle Assessments for wood energy services.

Christian Wolf, Daniel Klein, Gabriele Weber-Blaschke, Klaus Richter. 2015. Journal of Industrial Ecology.

The original can be accessed at http://onlinelibrary.wiley.com/wol1/doi/10.1111/jiec.12321/abstract

Publication 3

Reprinted with kind permission from Elsevier B.V.: Journal of Environmental Management. Environmental effects of shifts in a regional heating mix through variations in the utilization of solid biofuels.

Christian Wolf, Daniel Klein, Klaus Richter, Gabriele Weber-Blaschke. 2016. Journal of Environmental Management, Volume 17, pp 177-191.

The original can be accessed at http://www.sciencedirect.com/science/article/pii/S0301479716301827

Publication 4

Reprinted with kind permission from Elsevier B.V.: Science of the Total Environment. Mitigating environmental impacts through the energetic use of wood: Regional displacement factors generated by means of substituting non-wood heating systems.

Christian Wolf, Daniel Klein, Klaus Richter, Gabriele Weber-Blaschke. 2016. Science of the Total Environment, Volumes 569-570, pp 395-403.

The original can be accessed at http://www.sciencedirect.com/science/article/pii/S0048969716311925

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Ich erkläre an Eides statt, dass ich die bei der promotionsführenden Einrichtung Wissenschaftszentrum Weihenstephan für Ernährung, Landnutzung und Umwelt der TUM zur Promotionsprüfung vorgelegte Arbeit mit dem Titel:

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Int J Life Cycle Assess (2015) 20:556–575
DOI 10.1007/s11367-015-0847-1

20 years of life cycle assessment (LCA) in the forestry sector: state of the art and a methodical proposal for the LCA of forest production

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Received: 13 January 2014 / Accepted: 5 January 2015 / Published online: 20 January 2015

Abstract

Purpose Life cycle assessment (LCA) techniques have been developed since the late 1960s in order to analyze environmental impacts of various products or companies. Although LCA techniques of forest production have been already conducted since the early 1990s, consistent and comprehensive LCA studies are still lacking for the forestry sector. In order to support better comparability between LCA studies, we analyzed the problems and differences by conducting a descriptive and quantitative analysis of existing LCA studies of forest production with special focus on Global Warming Potential (GWP).

Methods We analyzed 22 different peer-reviewed studies, four original reports and two databases. Important issues were, among others, the goal of the studies, system boundaries, functional units, impact categories and involved processes. In addition, a quantitative analysis was purchased where the results of the GWP of the reviewed studies were analyzed.

Results and discussion The studies showed large differences between methodical assumptions and their subsequent results. For the GWP, we found a range of 2.4–59.6 kg CO_2-equiv.*m^{-3} over bark (ob; median=11.8; n=41) from site preparation to forest road and 6.3–67.1 kg CO_2-equiv.*m^{-3} ob (median=17.0; n=36) from site preparation to plant gate or consumer. Results varied as a function of the included processes and decisive assumptions, e.g., regarding productivity rates or fuel consumption of machineries. Raw wood products are widely declared as "carbon neutral," but the above-mentioned results show that absolute carbon neutrality is incorrect, although the GWP is low compared with the carbon storage of the raw wood product (range of C-emitted/C-stored in wood is 0.008–0.09 from forest to plant gate or consumer). Thereby, raw wood products can be described as "low emission raw materials" if long-term in situ carbon losses by changed forest management or negative direct or indirect land use change effects (LUC, iLUC) can be excluded.

Conclusions In order to realize improved comparisons between LCA studies in the forestry sector in the future, we propose some methodical approaches regarding the harmonization of system boundaries, functional units, considered processes, and allocation assumptions. These proposals could help to specify the description of the forest production outlined in existing Product Category Rules for Environmental Product Declarations (e.g., EN ISO 16485 2014 or EN ISO 15804 2012) following EN ISO 14025 (2011) and for carbon footprinting standards like the Publicly Available Specification (PAS) 2050 (2011) or the European Environmental Footprinting Initiative.

Keywords Descriptive/quantitative analysis · Forest production · GWP · LCA · Literature review

1 Introduction

Today's increasing world population goes along with a growing demand for natural resources. As stated in several recent reports, the world's resources will not be sufficient to satisfy the needs for water, alimentation and energy if we continue with the current lifestyle (WWF 2012; Randers 2012). Therefore, determining the most efficient and most conservative use of natural resources is one of today's biggest

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Responsible editor: Jörg Schweinle

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challenges. To analyze and understand ecologic impacts of products or of whole companies, life cycle assessment (LCA) techniques have been developed since the late 1960s (Jensen et al. 1997; Guinée et al. 2011) with subsequent standards on a European scale for conducting a comprehensive and coherent LCA (EN ISO 14040 2009, 14044:2006) and a special standard for carbon footprinting (ISO/TS 14067 2013). Following EN ISO 14040 definitions, a LCA is the "compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system during its lifetime," and thereby, the considered impacts in a LCA can be manifold and imply categories like Global Warming Potential (GWP) and Acidification but also categories like biodiversity. Especially the carbon footprinting of products is a common LCA application since the GWP is currently one of the most discussed and analyzed impact category in the life cycle impact assessment (LCIA). During the last years, public carbon footprints of products have arisen throughout many different industries (Cranston and Hammond 2012), and carbon footprint labeling has developed at the same time (e.g., carbon trust UK, Carbon Footprint of Products Japan).

Products based on biomass are in a special public focus since they can substitute products originated from fossil resources. Their worldwide demand is increasing, and simultaneously, questions regarding ecological consequences of intensified biomass use are becoming more and more important and are currently discussed, e.g., in Schulze et al. (2012). Biomass is often declared as renewable, but the degree of renewability always depends on the amount of nonrenewable inputs into the product system in question. One has to take into account that trees or other plants can grow without any human activities, but with the supply of raw material, non-renewable inputs are introduced into the system. Thus, environmental burdens can arise during different biomass production steps. For instance, cultivation processes can have a significant influence on the environmental impact of biomass products due to process inputs like fertilizer, harvesting machineries, or site preparation (Zah et al. 2007).

For the European forestry and wood products sector, the first tangible LCAs appeared in the 1990s with the aim to scientifically analyze the impacts arising from nonrenewable inputs into a system (Frühwald and Wegener 1993; Karjalainen and Asikainen 1996; Richter and Gugerli 1996; Zimmer and Wegener 1996; Frühwald et al. 1997; Schweinle 1997). Based on the calculations of Greenhouse Gas (GHG) emissions and energy cycles in the life cycle of wood products, Frühwald and Wegener (1993) concluded that wood can substitute more energy intensive materials with higher GHG-burdened footprints during their production and end-of-life stages. Additionally, emissions from fossil resources can be avoided when wood is burned at the end of its life cycle (Frühwald and Wegener 1993). Already at the early stages of LCA application, it has been pointed out that the provision of sound methods plays a prominent role in stages of data acquisition and the interpretation of results and that future holistic and comprehensive LCA findings will form the basis for decision making besides economic and technical aspects (Richter and Sell 1992).

Due to the overall opinion that the provision of wood as raw material does not cause high GHG-emissions, wood and wood products are commonly claimed as "carbon neutral." This opinion is manifested with the consideration that all removed biomass from sustainably managed forests will be sequestered again in the future (Helin et al. 2013), although the definition of carbon neutrality is still controversial discussed (Miner and Gaudreault 2013). Furthermore, there is at present no commonly accepted methodical approach for conducting an LCA in the forestry sector, and important issues like the functional unit or system boundaries differ from study to study. The carbon neutrality of wood as raw material is still to be proven and depends, among other factors, on the management regime. If, e.g., forest products are generated from non-sustainably managed forests and in situ carbon storage decreases at the long-term due to, e.g., land use change, carbon neutrality cannot be confirmed (Zanchi et al. 2011). In the forestry sector, a multitude of processes, from planting to the provision of raw wood material to plant gate, appear, and thereby, several ecologic burdens have to be considered, depending on management regimes, site characteristics, or transportation assumptions.

To our knowledge, there is no comprehensive and quantitative overview of existing peer-reviewed LCA studies of raw wood products, like it is available, e.g., for short rotation coppices (Djomo et al. 2011) or bioenergy systems in general (Cherubini and Strømman 2011). The only forest-related overviews are provided by Heinimann (2012) with the focus on the general methodical foundation of LCA and the state of life cycle modeling and less on a comprehensive and quantitative overview of forest production, and by Helin et al. (2013) dealing only with approaches for the inclusion of the forest carbon cycle in a LCA. In contrast, our study was focused on the analysis of LCA for forestry processes which appear during the entire forest management 20 years after the first LCAs were developed for this sector. We only took into account the environmental impacts (with a special focus on GWP for the quantitative analysis) of the processes related to forest management and did not consider carbon stocks and carbon stock changes in the forest and wood products as well as substitution effects using wood instead of other materials. There is no doubt that, in order to analyze the gross impact of forest management practices on climate change, carbon stocks of both, forest, including land use change effects (LUC, iLUC), and wood products with their subsequent substitution effects have to be considered as it is explained, e.g., by Newell and Vos 2012. But whereas studies dealing with carbon stock changes appeared in a huge number over the last years (see, e.g., Helin et al. 2013; Klein et al. 2013), LCA studies containing GWP results of the different forestry processes are rare, and there is still a need for more comprehensive and comparable studies as also mentioned in Heinimann (2012). In terms of climate change and forestry, one has to differentiate between two central questions: 1. What is the influence of forest management (and land use change) on carbon stocks of forests and harvested wood products? 2. Which amounts of GHG-emissions are caused by forestry processes mainly originated from non-renewable inputs like fossil fuels or construction material for machineries? We emphasize on the latter question analyzing existing LCA studies for the forestry sector. Therefore, a literature review was conducted focusing on the following research questions:

1. Which methodical approaches are used, and in which way do they differ regarding the phases and important aspects in the LCA procedure?
2. How do the GWP results of forestry processes differ between the various studies, and on which facts and assumptions do they depend?
3. Which suggestions can we conclude in order to contribute to a harmonization of LCA studies in the forestry sector?

2 Material and methods

2.1 Requirements for the literature search

We performed a literature search, using *Science Direct* and *ISI Web of Knowledge* databases since they comprise a great number of scientific journals. Furthermore, *Google Scholar* was employed to identify other scientific journals which are not listed in the two above-mentioned databases. We conducted our literature search according to the following criteria:

Only studies were considered

- starting from the year 2000, in order to reflect the actual state of the art and recent developments (the first EN ISO 14040-14043 series started 1997–2000),
- which were conducted for Europe and North America due to the fact that, in many countries outside our geographical boundary, forestry is not always comparable to our understanding of forestry, and thereby, comparing results and methods is not useful,
- which are peer-reviewed or original research papers in English,
- where the results originate from the authors and not from cited literature; exceptions are cited previous studies from the same authors, which have not been published in scientific journals before,
- where the results are not published in other considered literature to avoid double counting,
- where an environmental analysis of the raw wood product (and not subsequent end-products) is the main or at least one of the main objectives,
- where the analysis is based on the LCA methods described in the EN ISO 14040 and 14044,
- where the LCA is an LCA of woodland per definition and not of short rotation woody coppices because of their different management,
- dealing with raw wood production and not with other forest products like, e.g., cork or other ecosystem services,
- which include at least the impact category GWP since it is in the main focus of our quantitative analysis,
- where methods and single processes are described in detail,
- where the GWP results of single processes or at least of the entire forest production are reported separately and not solely aggregated in subsequent process results like, e.g., as a part of a special wood product,
- where a quantitative description and not only general information of the LCA of a forest product chain is presented.

2.2 The descriptive analysis

The selected studies which fulfilled the requirements described in “chapter 2.1” were subsequently analyzed in a descriptive manner. Besides these studies, the forestry models of two LCA databases were calculated and included in our analysis (*PE international* and *ecoinvent*). The main focus of this analysis was placed on the following topics: A general description of the studies (authors, year of publication, country, forest type, region and stand description, type of publication, and further destination of the raw wood product), LCA goal and scope definitions (goal of the study, tree species, treatment regime, raw wood product, development stage/system, system boundaries, functional units, allocation assumptions, included processes and considered impact categories), and other methodical aspects (LCA methods and databases).

To analyze single processes or process groups, respectively, we summarized different subsets of processes to a total of 6 process groups:

- Site preparation (SP): Processes which contain measures before or during planting in order to prepare the site (clearing, firebreak building and maintenance, piling and burning, and soil scarification),
- Site tending (ST): Processes which contain measures during planting or some years after planting in order to improve or to protect the plantation site (fencing, fertilization, pesticide, and herbicide),

- Silvicultural operations (SO): Processes which are directly linked to the tree growth, stand structuring, or the extraction of wood (planting, cleaning, pruning, thinning, final felling, forwarding, post-felling processes (delimbing, measuring, topping, sorting, bundling), and loading on trucks),
- Secondary processes (SEP): off-site processes which are directly linked to the production and supply of raw wood (planning of forestry operations, manufacturing and maintenance of machines, road building and maintenance, commuter traffic and transportation of machinery, housing and accommodation, seed/seedling production, and transportation),
- Transport (T): transportation processes of raw wood products from forest road to gate or consumer,
- Chipping (C): in some cases, chipping is considered if it was conducted on forest road, and therefore, it is included as a single process group.

2.3 The quantitative analysis

In order to analyze the range of GWP of raw wood products under different LCA model assumptions, a quantitative analysis was performed. Therefore, the functional unit of 1 m^3 over bark (ob) of green wood (recently harvested wood) was chosen as a basis for recalculation of results presented in the reviewed studies. 1 m^3 ob was selected because it is used in most studies. Furthermore, this functional unit is the most typical unit to describe forest production. To enable a widespread comparison, results with different functional units were recalculated to 1 m^3 ob by adopting tree-specific wood densities (dry matter/green wood volume) and carbon or energy contents of wood, depending on the functional unit of the respective study. A recalculation of the GWP from a unit land area base (hectares, square meters) to 1 m^3 ob was conducted dividing the entire emissions of the respective area with its total timber volume. The 1 m^3 under bark (ub) was recalculated to 1 m^3 ob assuming a portion of 10 % of bark. Studies where a clear calculation to 1 m^3 ob was not possible were excluded from the quantitative analysis.

For the quantitative analysis, all study results were related to one of the process groups mentioned in "chapter 2.2." Several process groups were aggregated if a separate description of the single processes or process groups was not given. Some studies offered various scenarios with different results; other studies showed only one process chain, often depending on the goal of the respective study. In order to consider different scenarios (e.g., with or without fertilizer) from one study on the one hand but to avoid an "over-weighting" of some studies with many results on the other hand, we only took into account an alternative scenario result from the same study if there was a clear difference caused by different management regimes, site characteristics, or tree species which finally led to a maximum of six values originated from one study. An exception was Schwaiger and Zimmer (2001) who showed results for 11 different countries which could not be seen as scenario results.

All quantitative calculations and statistical analyses were conducted with the STATISTICA 10 software.

3 Results of the analysis and evaluation of the reviewed literature

3.1 Descriptive analysis of the LCA of the forest product chain

A total of 26 studies fulfilled the criteria mentioned in "chapter 2.1." Main characteristics of the analyzed studies and their methodical approaches are shown in Tables 1, 2, 3, and 4. The most important issues are described in detail in the following chapter.

3.1.1 Basic study characteristics

Most studies were found for the USA, the Scandinavian countries, and for Germany. In almost all cases, LCA was applied to temperate (n=13) or boreal forests (n=13); Mediterranean (n=2) and alpine (n=1) sites were rare (Table 1). Studies for Eastern European and Russian forests were not found. There was one study with an overall view for Europe containing a total of 11 countries (Schwaiger and Zimmer 2001). We identified a total number of 28 studies (including two databases) where LCAs for forest production were at least one of the main study objectives. Although LCAs have been discussed in the forestry sector for 20 years already, there is still a poor amount of information based on scientific research as it is also stated in Heinimann (2012). One reason for the small number is that, in many cases, forest production is not the main study objective but rather their subsequent products, e.g., fuel chips or pellets, and environmental impacts of the previous forestry processes are only deduced from literature or calculated starting from the latest stage of the forest product chain, e.g., with the collection of wood residues or chipping, and thereby neglecting important processes of the forest production. The low presentation of LCAs of forest production also might be caused by the overall opinion that their respective processes have only minor environmental impacts, and providing wood for material or energetic purposes is nearly carbon-neutral (Miner and Gaudreault 2013). However, most studies were found from the last years (2010–2013, n=18) and only ten studies from 2000–2009 (including the two databases) which can be interpreted as a considerable signal for an increasing importance of LCAs for forest production (Fig. 1). We explained this trend with an enhanced economic importance of

Table 1 General description of the considered LCA studies

Index	Authors	Year	Country	Forest type	Region_stand description	Goal of the study	p type
1	Schweinle[a]	2000	Germany	Temperate	Mean values for Germany	LCA of raw wood production	DB
2	Schwaiger and Zimmer	2001	Europe	–	–	A comparison of GHG-emissions from forest operations in Europe	OS
3	Zimmer and Kairi	2001	Finland	Boreal	Lohja	LCI of laminated veneer lumber	OS
4	Berg and Lindholm	2005	Sweden	Boreal	Whole Sweden, divided into North, Central, and South	Most significant processes in forest operations regarding GHG-emissions	R
5	White et al.	2005	USA	Temperate	Different ownerships all over Wisconsin	LCA of the forest harvesting process	R
6	Sonne	2006	USA	Temperate	Northwest Pacific, West side of the Cascade Mountains in Washington and Oregon	GHG- emissions from forestry operations	R
7	Werner et al.[2b]	2007	Europe	Temperate	Mean values for Europe	LCA of raw wood production	DB
8	Michelsen et al.	2008	Norway	Boreal	Private owners, Northern part of Norway	the environmental impact from forestry operations	R
9	Gaboury et al.	2009	Canada	Boreal	Quebec	net carbon balance of boreal open woodlands afforestation	R
10	González-Garcia et al.	2009	Sweden, Spain	Boreal, temperate	Case studies in Sweden (61°N, 16°W; 57°N, 14°W) and Spain (43°N, 8°W)	most intensive forest operations which represent the highest contribution to the environmental impact	R
11	Lindholm and Hansson	2010	Sweden	Boreal	South (57°) and North (64°N)	Energy efficiency and the environmental impact of harvesting stumps and logging residues	R
12	Oneil et al.	2010	USA	Temperate	Northeast/North Central and Inland Northwest	life cycle impacts of forest resources	R
13	Whittaker et al.	2010	UK	Temperate	Whole UK	Contribution of timber haulage to the GHG Emissions of the forestry and timber industries	OS
14	Kilpeläinen et al.	2011	Finland	Boreal	Joensuu (South, 62°40′N, 29°30′E), Rovaniemi (North, 66°34′N, 25°50′E)	Life cycle assessment of forest production	R
15	Neupane et al.	2011	USA	Boreal	North-east region, Maine	Life cycle assessment of wood chips	R
16	Routa et al.	2011	Finland	Boreal	62°39′N, 29°37′E, Eastern Finland	Sensitivity of CO_2-emissions of wood energy to different forest management regimes	R
17	Valente et al.	2011	Italy	Alpine	Cavalese, Valle di Fiemme, Trentino	Impacts of a woody biomass supply chain for heating plants in the alpine region	R
18	Whittaker et al.	2011	UK	Temperate	Whole UK	GHG-balance of the use of forest residues for bioenergy production	R
19	Alam et al.	2012	Finland	Boreal	62°39′ N, 29°37′ E; boreal ecosystems	Effects of different tree species, management regimes, site qualities and initial stand density on CO_2-emissions	R
20	Cambria and Pierangeli	2012	Italy	Mediterranean	South Italy (Gauss-Boaga: 2571883E, 4492802 N)	LCI of walnut tree high quality wood production	R
21	Dias and Arroja	2012	Portugal	Mediterranean	Modeled scenarios for typical stands	Environmental impacts of eucalyptus and maritime pine wood production in Portugal	R
22	Engel et al.	2012	Germany	Temperate	A typical German spruce stand	Effects of two mechanized wood harvesting methods in comparison with the use of draft horses for logging on GHG-emissions	R
23	Johnson et al.	2012	USA	Temperate	Inland West and Southeast	Life cycle of biomass collection and wood processing	R
24	Pyörälä et al.	2012	Finland	Boreal	Joensuu (Central, 62°39′N, 29°37′E)	Effects of management on carbon balance of bioenergy use	R
25	González-Garcia et al.	2013a	Germany	Temperate	A representative Douglas-fir stand in Germany in Freiburg region	Life cycle inventory and environmental performance of Douglas-fir round wood production	R

Table 1 (continued)

Index	Authors	Year	Country	Forest type	Region_stand description	Goal of the study	p type
26	González-Garcia et al.	2013b	France	Temperate	Grand Massif Central	Influence of forest management systems on the environmental impacts of Douglas-fir round wood production	R
27	Saud et al.	2013	USA	Temperate	West Virginia	Carbon emissions of timber harvesting	R
28	Valente and Brekke	2013	Norway	Boreal	Lowland and mountain forests in Hedmark and Oppland	Assessing environmental impacts for wood fuel, logging residues and stem wood	OS

p type type of publication, *R* peer-reviewed article, *OS* original study, *DB* database

[a] Literature for PE database

[b] Literature for EcoInvent database

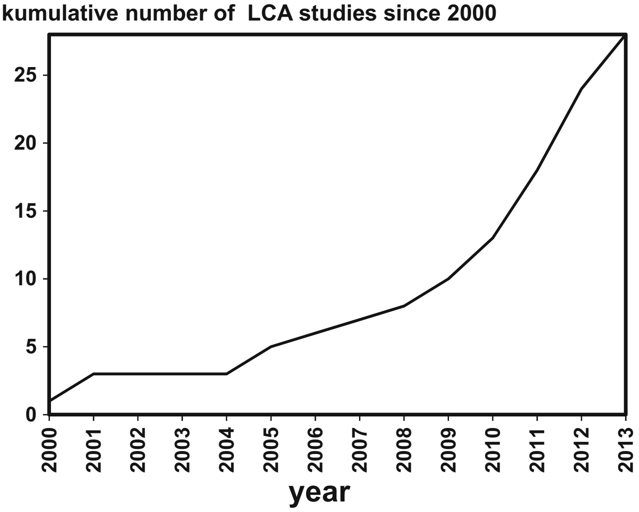


Fig. 1 Cumulative number of LCA studies for forest production since 2000 according to the criteria in this review

biomass especially for energetic purposes (AEBIOM 2012) and a simultaneously increasing public attention regarding environmental impacts of products in general (von Borgstede et al. 2013). Furthermore, European policy target the enhancement of energy from renewable resources to 20 % of the overall energy consumption and a 20 % reduction in EU greenhouse gas emissions from 1990 levels (EU Directive 2009/28, COM 2010). Therefore, LCA studies are crucial to understand and quantify environmental impacts and to avoid possible negative effects of increasing wood use as energy source. We focused our review on European and North-American studies due to the difficulty comparing studies on a worldwide level, e.g., regarding differences in silvicultural treatments or transportation distances. However, we also found studies outside our geographical boundary, e.g., for Eucalyptus in Brazil (Lopes Silva et al. 2013), Australian forests (England et al. 2013), tropical forests in Ghana (Eshun et al. 2010), or Japanese forests and wood products, respectively (Kinjo et al. 2005; Yoshioka et al 2005). Furthermore, there are some German language studies dealing with LCA of forest production which are not included in our review due to the above-mentioned criteria. In addition, only a limited readership could verify this literature (e.g., Albrecht et al. 2008).

Most studies were focused on high economic value tree species. The54 % of the studies concerned spruce, 25 % pine, and 14 % Douglas fir. Although beech is one of the most important hardwood tree species in middle Europe in terms of their distribution area, it was not found in any European study (only for the USA), and the ecoinvent and PE database are the only sources where a LCA for beech can be obtained from for European conditions. In three studies, tree species were not specified. LCA results mostly addressed highly or fully mechanized treatment regimes with a combination of harvester, chainsaw, forwarder, and tractor. Low mechanized product chains with chain saw and horse forwarding were rare and only encountered in two cases.

3.1.2 System boundaries

System boundaries are crucial to identify all relevant processes for a specific LCA. The majority of the reviewed studies followed a cradle-to-gate approach for which two different system boundaries regarding the end-point were detected: from forest to forest road (25 %) and from forest to plant gate (61 %). Only 14 % considered a cradle-to-grave or at least to consumer approach ending at the consumer stage or at recycling, respectively (Table 2). The starting point for the assessment at the forest site differed a lot between studies. Four principal starting points could be detected: Assessment starting from seedling/seed production (39 %), site preparation (18 %), planting (18 %), or harvesting/thinning operations (25 %). Different initial points indicate that not every study included all relevant forestry processes. If one study started, e.g., with harvesting/thinning operations, all former processes were neglected, which leads to an underestimation of the environmental impacts and makes comparisons between studies difficult (see “chapter 3.2”).

In 18 % of all cases, a final application of the raw material was not specified; 43 % of the studies investigated wood for energy purposes and 25 % for pulp wood while 39 % of the studies included wood as raw material for saw mills (multiple applications were found in several studies). It was observed that LCAs were not only carried out for the production of round wood, but, in some cases, also for wood residues, chips, stumps, or whole tree harvestings (Table 2).

There are substantial differences regarding the considered processes (Table 3 and Fig. 2). A total amount of 25 different processes was found (processes with different names but similar or the same meaning were summarized to one process). Processes started from secondary processes and ended with haulage to forest road, chipping, or transportation, depending on the system boundaries of the study.

The most frequently considered processes in the secondary process group were seed/seedling production, road building and maintenance, manufacturing and maintenance of machines, housing and accommodation, and seed/seedling transportation with an appearance between 46 and 21 %. Planning forest operations and housing and accommodation had minor importance (4 % appearance). In four cases, secondary processes were not explained in detail or not considered at all.

Processes concerning site preparation and site tending varied greatly in appearance between 7 and 61 %. In nine cases (32 %), site preparation and in 16 cases (57 %), site tending was not considered. However, the inclusion depends on the respective forest stand management of the study and including processes of the mentioned two process groups like fencing, herbicide treatment, or cleaning is not always necessary and, subsequently, was not always an element of the respective study. But it was not always clear if these processes were not considered because they did not appear in the management regime or due to a lack of data for the corresponding process or if processes were simply not considered without any particular reason. For clarification, these two process groups (site preparation and site tending) should at least be mentioned and explained in every LCA.

Silvicultural operations were found in all studies as it is the core process group of the whole forest production and a decisive criterion of our study review. Thinning, final felling, and forwarding were mentioned in almost all studies (if a study does not specify between thinning and final felling, both were marked in the summary in Table 3). In 79 % of all studies, transport processes of the raw wood material were added to the process chain, and in ten cases (36 %), on-site chipping processes were additionally analyzed. The latter, of course, is not mandatory as not all woody biomass is dedicated to an energetic purpose.

Temporal boundaries are strongly linked to system boundaries. Thus, the reviewed studies differed between a whole rotation period, one single intervention, or one specific year. Severe differences were found regarding the spatial boundaries where in some cases LCA was conducted on a stand level; others were referred to a regional or national scale.

3.1.3 Functional unit

The functional unit is the unit to which all LCA results of a system are referred to. Therefore, it’s clear definition is essential. We found a total of 12 different functional units, expressed by dimension (1 m^3 ob, 1 m^3 ub, 100 m^3, 3 m^3, 4 m^3), by area and/or time (hectares, square meters, and year), by mass (1 t oven dry (od), 1 t carbon (C)) or by energy content (MWh, MJ). In some cases, several functional units were shown. In 61 % of all cases, cubic meter was at least one of the functional units. All other functional units appear in 4–15 % of all cases and indicated a minor priority (Table 4). Of course, the functional unit depends on the goal of the study and on the further use of the raw wood. As a consequence, different study objectives result in different functional units. However, in some cases, this variety causes difficulties for the quantitative comparison. Moisture content was given in 40 % of all studies (including the two databases) whereas the moisture content varied between u=12 and 140 % with most cases between u=30 and 50 %. In two cases, the raw wood was characterized as fresh or dry wood, respectively, and two studies showed total green weight and total round wood weight, respectively. However, about half of all studies did not mention any specification concerning moisture content although this information is crucial, e.g., for different forest and transportation processes.

Table 2 Development stage/system, treatment, tree species, raw wood product, further destination of the raw wood, and system boundary of the considered LCA studies in the forestry sector

Index	Development stage/system	Treatment	Tree species	Raw wood product	Further destination	System boundaries
1	A typical spruce, pine, beech, and oak stand	HM	Norway spruce, Scots pine, Common beech, Oak spec.	Round wood, industrial wood	Saw wood, plywood, veneer, chipboard, energy wood, pulp wood	From planting to plant gate
2	Different representative process chains for European countries	HM, FM	n. s.	Round wood	Not specified	From thinning to plant gate
3	Referred to 1995 for an area of 5,3 Mio ha from private forest owners	n. s.	Norway spruce	Round wood	Veneer lumber	From stand establishment to recycling
4	The present forest situation of Sweden in 1996–1997	FM	Norway spruce, Scots pine, Birch	Round wood	Saw mills, pulp mills, others	From seedling production to plant gate
5	Average of 2000–2003	FM, HM	Aspen, Red White pine	Round wood	Pulpwood, saw logs	From harvesting to plant gate
6	408 combinations with different treatments and rotation periods	HM	Douglas fir	Round wood	n. s.	From seedling production to forest road
7	A typical spruce and beech stand	HM	Norway spruce, Common beech	Round wood, industrial wood, wood residues	n.s.	From planting to forest road
8	Average of 2000–2004;	HM	Norway spruce	Round wood	Sawn timber, pulp wood, chips, energy wood	From planning of forestry operations to plant gate
9	Rotation of 70 years of a open woodland afforestation	n. s.	Black spruce	Round wood	n. s.	From seed production to plant gate
10	Spain: for the year 2006–2007 (40 ha); Inventory data of Central and Southern Sweden	Spain: HM Sweden: FM	*Eucalyptus globulus* (Spain), Norway spruce, Scots pine (Sweden)	Industrial pulpwood	Pulpwood in pulp mill	From site preparation to pulp plant gate
11	Seven different product chains of forest energy	FM	Norway spruce	Chips (logging residues, stumps)	Wood chips for energy plant	From final felling to plant gate
12	On a landscape level, scenarios with rotation between 15 and 60 yrs.	HM	Aspen/birch, spruce/fir, oak/hickory, northern hardwoods	Different logs	Saw mill, plywood, oriented strand board	From regeneration to logs on truck
13	Modeled, commercial stand of Sitka spruce, 50 years rotation period	FM	Sitka spruce	Saw logs, pulp and woody biomass	Saw wood, energy wood	From side establishment to plant gate
14	Modeled stands, 80 years rotation period	FM	Norway spruce	Pulpwood, saw logs, bioenergy	Pulp mill, saw mill, power plant	From seedling production to plant gate
15	Modeled stands	FM	Birch, common beech, maple	Wood chips	Biofuel	From seedling production to wood chips production
16	Modeled stands, 80-year rotation period	n.s.	Norway spruce, Scots pine	Saw logs, pulp, energy biomass, logging residues	Pulp and saw mill, energy wood in power plant	From seedling production to plant gate
17	A whole tree system where the harvest of logging residues is integrated; 2008 and 2009	HM	n. s.	Woody biomass	Wood chips for energy to heating mill	From logging operations to heating plant gate
18	n. s.	HM	Corsican pine, Douglas fir, Japanese larch, Lodgepole pine, Norway spruce, Scots pine, Sitka spruce	Round wood, energy wood (chips, brash bales, whole trees)	Wood chips for energy	From site establishment to consumer

Table 2 (continued)

Index	Development stage/system	Treatment	Tree species	Raw wood product	Further destination	System boundaries
19	Whole production chain of an 80-year rotation period at stand level	FM	Scots pine, Norway spruce	Energy wood	Energy in power plant; timber in pulp and saw mill	From seedling production to plant gate
20	Whole rotation period of 50 years for 7 ha	HM	Walnut tree	Round wood	High-quality wood products	From site preparation to plant gate
21	3 rotations of 12 years (eucalyptus) and a 45 years period (pine)	FM; HM, LM	Eucalyptus, maritime pine	Round wood	n. s.	From site preparation to forest road
22	One thinning operation in a young stand	LM, HM, FM	Norway spruce	Round wood	Not specified	From harvesting to forest road
23	Two case studies: residue recovery operations and whole tree harvest in an early thinning	HM	Softwood	Chips from whole tree chipping	Wood chips for energy	From thinning to plant gate
24	One rotation period (30–80 years) of different management scenarios	n.s.	Norway spruce	Chips	Wood chips for energy mill	From seedling production to plant gate
25	Whole production chain of a 90-year rotation period	HM	Douglas-fir	Round wood	Not specified	From planting to forest road
26	Two case studies (intensive and extensive management), 47- and 60-year rotation periods	HM	Douglas-fir	Round wood	n. s.	From site preparation to forest road
27	Harvesting operations from 2000–2009	FM, HM	Oak, hickory, maple, beech, birch, ash	Round wood	Saw wood	From harvesting to plant gate
28	Modeled stands	FM	Norway spruce	Stem wood, logging residues	Bioenergy	From seedling production to biomass combustion

FM (*fully mechanised*) treatment with harvester and forwarder, *HM* (*highly mechanised*) treatment with harvester or chain saw and forwarder or tractor, *LM* (*Low mechanised*) treatment with harvester or chain saw and forwarding with horse, *n.s.* not specified

Table 3 Considered processes in the analyzed studies

Index	Secondary processes (SEP)							Site preparation (SP)				Site tending (ST)				Silvicultural operations (SO)									
	pf	ma	r	cf	ha	s	str	pb	fb	spr	cr	fe	ft	pe	he	pl	cn	pr	th	ff	fw	pfp	lt	T	C
1			x										x			x	x		x	x	x			x	
2																			x	x	x			x	
3											x					x	x		x	x				x	
4				x		x				x	x		x			x	x		x	x	x			x	
5				x															x	x	x			x	
6						x	x	x		x			x		x	x			x	x					
7		x	x			x										x	x		x	x	x				
8	x		x			x				x			x			x	x	x	x	x	x	x		x	
9			x	x	x	x	x			x						x				x	x		x	x	
10				x						x	x		x	x		x	x		x	x	x		x	x	
11		x		x																x	x	x	x	x	x
12				x		x		x		x			x			x			x	x	x	x	x	x	
13		x	x									x			x				x	x	x	x		x	
14				x		x	x			x						x			x	x	x			x	x
15						x				x	x					x			x	x	x	x		x	x
16						x	x			x			x			x			x	x	x			x	x
17																				x	x	x	x	x	x
18		x	x			x				x		x			x	x			x	x	x			x	x
19				x		x	x			x						x			x	x	x			x	x
20		x	x				x			x		x	x							x	x	x	x	x	
21			x						x	x	x		x			x	x	x		x	x		x		
22		x																	x		x	x			
23		x						x											x	x	x	x	x	x	x
24				x		x				x						x			x	x	x			x	x
25		x	x						x	x						x		x	x	x	x		x		
26		x	x						x	x	x		x		x	x		x	x	x	x		x		
27																			x	x	x	x	x	x	
28						x				x			x	x		x			x	x	x	x		x	x

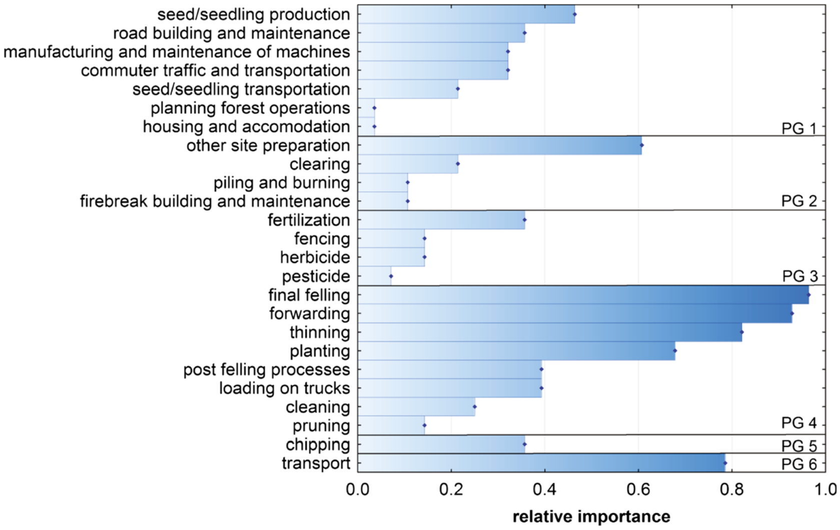
Secondary processes (SEP): *pf* planning forest operations, *ma* manufacturing and maintenance of machines, *r* road building and maintenance, *cf* commuter traffic and transportation of machinery, *ha* housing and accommodation, *s* seed/seedling production, *str* seed/seedling transportation; Site preparation (SP): *pb* piling and burning, *fb* firebreak building and maintenance, *spr* site preparation unspecified (including e.g., soil scarification), cr clearing; Site tending (ST): *fe* fencing, *ft* fertilization, *pe* pesticide, *he* herbicide; Silvicultural operations (*SO*): *pl* planting, *cn* cleaning, *pr* pruning, *th* thinning, *ff* final felling, *fw* forwarding, *pfp* post- felling processes (delimbing, measuring, topping, sorting), *lt* loading on trucks, *T* transport, *C* chipping

3.1.4 Impact categories

Environmental burdens of a system or a process are specified using different impact categories. It is recommended in the EN ISO 14044 that the selection of the impact categories shall reflect a comprehensive set of environmental issues and stated in the International Reference Life Cycle Data System (ILCD) handbook from the JRC (2010) to include all main relevant environmental issues related to the system if the study goal definition does not specifically limit the scope of impacts to be covered. For instance, one can exclusively analyze the GWP of a product. In our review, a total of 14 impact categories were detected within the analyzed 26 studies (databases excluded). Although carbon storage is not defined as an independent impact category but part of the GWP, it was analyzed separately in our comparison in order to specify which studies are only concerned with the GWP of the forestry processes themselves and which studies include the carbon storage of forests or wood products, respectively.

Not all impact categories appeared in the same magnitude (Table 4 and Fig. 3). GWP was the decisive category in our review, and as a consequence, GWP equals 1 (100 %) in Fig. 3, which means that all 26 studies dealt with this impact category. All other impact categories were of minor appearance. Acidification (46 %), Eutrophication (46 %), and Photochemical Ozone Formation (35 %) were identified as the most important impact categories behind the GWP. In 50 % of the studies, carbon storage was

Fig. 2 Relative importance of the unit processes in the analyzed studies; *1*=hundred percent appearance; Process group (PG) *1*: Secondary processes, PG *2*: Site preparation; PG *3*: Site tending, PG *4*: Silvicultural operations



considered, and 23 % of the studies were exclusively focused on GWP including carbon storage. Only 8 % analyzed only GWP of the forestry processes without carbon storage. The strong focus on GWP might be due to the intense public and political debate on climate change in the last years, especially since 1997 when the Kyoto Protocol was signed. Furthermore, many other impact categories are difficult to interpret. One has to take into account that GHG-emissions have a global effect and it does not matter where they appear (except special physical effects regarding emissions caused by aviation near the atmosphere, IPCC 1999). Thus, it is possible to analyze their environmental consequences and normalize the respective results. For instance, one can normalize the GHG-emissions of the respective forestry process, comparing them with the GHG-emissions of a region or an average household. In contrast, the interpretation of many other impact categories like Acidification or Eutrophication is difficult due to their regional context, and it depends on their location of appearance and which region or site is affected. As a consequence, for most other impact categories except carbon storage, results were described in a quantitative manner without discussing their further impacts.

3.1.5 Allocation

The allocation of environmental burdens is needed if a process causes several outputs or products, respectively. Nevertheless, ISO 14040 and 14044 strongly recommend avoiding allocations if possible. Besides many different ecosystem services, the forestry sector is usually concerned with multiple outputs, which is raw wood material in different forms (round wood, industrial wood, woody biomass, wood residues). In 43 % of all studies, allocation procedures were not mentioned at all; in 21 % of all cases, an allocation was explicitly stated as not necessary for the respective study, e.g., because there was only one raw wood product. In 29 % of all cases, an allocation by mass, in three cases (11 %) by market price and in one case by energy content was conducted (two different allocation scenarios in two studies as shown in Table 4). An allocation by mass results in equal GHG-emissions related to the functional unit of 1 m^3 ob or 1 t od and differences can only be found on a hectare base if timber volumes of the respective raw wood products are different. This applies under the assumption that 1 m^3 of wood always has the same dry mass regardless of its characteristics like tree dimension or which compartment of the tree is considered (e.g., stem or branches).

3.1.6 LCA method and databases

Twelve of the 26 studies (without the databases) refer their results to special LCA approaches or to LCA guidelines (ReCiPe Midpoint, CML 2001, EcoIndicator, SETAC or TRACI 2, and the GHG-protocol, respectively). However, more than half of the studies (54 %) did not mention any methodical approach besides the IPCC (2006) guidelines, which was mentioned specifically for the characterization factors, and the EN ISO 14040 and EN ISO 14044 (Table 4). Basic LCA data for products or processes which are needed for forest production modelling were often not derived from specific databases but from literature. Others used specific LCA databases, at least for some processes or products. Where a database was applied, ecoinvent (n=6) was mentioned in most cases. Other databases were Gemis, GHGenius, US Life Cycle Inventory Database, IDEMAT, GREET, or Franklin 98. Data concerning the forest processes themselves were derived from literature or expert surveys.

Table 4 Functional unit (FU), allocation, considered impact categories, LCA software (LCA_{sw}), and LCA method of the considered studies in the forestry sector

Index	FU	Allocation	Impact categories															LCA_{sw}	LCA_{method}
			GWP	ODP	HT	POF	A	EU	ET	LU	RD	IR	WD	FD	S	E	CS		
1	1 t od	Mass																–	[a]
2	1 m^3 ob	n.r.	x														x	n.s.	n.s.
3	3 m^3 ob	Mass	x														x	GaBi, Umberto	n.s.
4	1 m^3 ub	n.s.	x			x	x	x								x		n.s.	n.s.
5	1 t C	n.s.	x														x	n.s.	SETAC
6	1 ha; 100 m^3	n.s.	x														x	n.s.	GHG-Protocol
7	1 m^3 ob	Price																–	[a]
8	1 m^3 ub	n.s.	x		x	x	x	x										n.s.	CML 2001
9	1 ha	n.s.	x														x	n.s.	GHG-Protocol
10	1 m^3 ub	n.s.	x			x	x	x								x		SimaPro	n.s.
11	1 MJ	n.s.	x				x	x								x		n.s.	n.s.
12	n.s.	n.s.	x	x	x	x	x	x	x					x			x	SimaPro	Eco-Indicator
13	ha, 1 t od	Price	x															n.s.	n.s.
14	1 m^2 per year; 1 m^3 ob	Mass	x														x	own LCA tool	n.s.
15	4 m^3	Mass	x	x	x		x	x	x	x		x		x				SimaPro	Eco-Indicator 99
16	1 MWh	Mass	x													x	x	own LCA tool	n.s.
17	1 m^3 ob	n.s.	x													x		n.s.	n.s.
18	1 t od, 1 MWh	Mass, price	x													x		BEATv2	n.s.
19	1 MWh, 1 ha	n.s.	x													x	x	own LCA tool	n.s.
20	1 m^3 ub	n.r.	x	x	x	x	x	x	x		x						x	SimaPro	CML 2001
21	1 m^3 ub	n.r.	x			x	x	x			x							n.s.	CML 2001
22	1 ha, 1 m^3 ob	n.s.	x															n.s.	n.s.
23	1 t od	n.r.	x	x	x		x	x	x						x		x	SimaPro	TRACI2
24	1 MWh per ha and year, m^2 and year	Mass	x														x	own LCA tool,	n.s.
25	1 m^3 ob	n.r.	x	x	x	x	x	x	x	x	x	x	x	x				SimaPro	ReCiPe Midpoint
26	1 ha, 1 m^3 ub	n.r.	x	x		x	x	x		x	x		x	x				SimaPro	ReCiPe Midpoint
27	1,000 m^3 ob	n.s.	x														x	n.s.	n.s.
28	1 m^3 ob	Mass, energy	x	x		x	x	x										SimaPro	CML2

n.s. not specified, *n.r.* not required, *ob* over bark, *od* oven dry; the impact categories are: *GWP* global warming potential, *ODP* ozone depletion, *HT* human toxicity, *POF* photochemical ozone formation, *A* acidification, *EU* eutrophication, *ET* ecotoxicity, *LU* land use, *RD* resource depletion, *IR* ionizing radiation, *WD* water depletion, *FD* fossil fuel depletion, *S* smog, *E* energy consumption, *CS* carbon storage in wood

[a] Different impact categories and methods included; results of this study are based on the ILCD recommendations

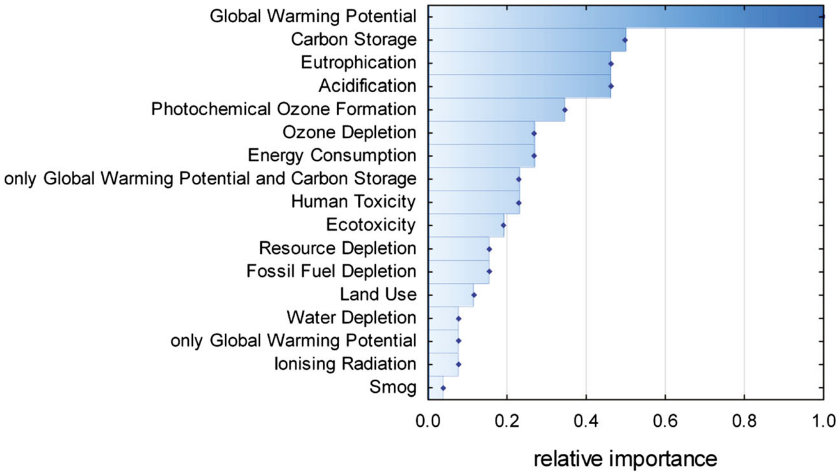


Fig. 3 Relative importance of the impact categories in the analyzed studies; *1*=hundred percent appearance

3.2 Quantitative analysis of the GWP results for the forest production

For the quantitative analysis, a total of 141 values (SP+ST, *n*=14; SP+ST+SO, *n*=36; SP+ST+SO+SEP, *n*=41; SP+ST+SO+SEP+T, *n*=36; SP+ST+SO+SEP+T+C, *n*=14, for abbreviations see "chapter 2.2") from 19 different studies and the two databases from PE international and ecoinvent were suitable and integrated for a comparison of the results. In four cases, the results were not useable because they could not clearly be recalculated to the functional unit of 1m^3 ob (Johnson et al. 2012; Pyörälä et al. 2012; Zimmer and Kairi 2001) or disaggregated in order to outline the results within our system boundaries without subsequent wood use like, e.g., combustion of biomass (Routa et al. 2011). In two cases, the dimensionless EcoIndicator 99 was used and therefore, not comparable to the other results (Oneil et al. 2010; Neupane et al. 2011). Another study was excluded (but discussed separately) due to an uncommon silvicultural treatment with intensive fertilization and fencing (Cambria and Pierangeli 2012). Figure 4 shows the aggregated results of the GWP with ascending aggregation of single process groups.

Mean GWP from site preparation to forest road (SP+ST+SO+SEP) were 14.3 kg CO_2-equiv.*m^{-3} ob (±10.7 SD) whereas the median (13.0 kg CO_2-equiv.*m^{-3} ob) differs about 9 % from the mean. This can be explained by a relatively asymmetric distribution of the single values with more values in the lower range and some outliners in the higher range. Results differed a lot depending on the included processes and assumptions regarding productivity rates or fuel consumption with a minimum of 2.4 and a maximum of 59.6 kg CO_2-equiv.*m^{-3} ob. Adding transport processes of the raw wood material (cradle to plant gate or consumer), GWP increased to a range of 6.3–67.1 kg CO_2-equiv.*m^{-3} ob (median=16.4, mean=19.7). Assuming a mean carbon storage of 734 kg CO_2-equiv.*m^{-3} ob (carbon content=0.5, an estimated mean wood density over all studies=400 kg*m^{-3} ob), the range of the carbon ratio (C-emitted/C-stored in wood) was between 0.008 and 0.09, which implies that, to provide 1 ton of carbon (expressed in CO_2-equiv.) to plant gate or consumer, about 8–90 kg of carbon (expressed in CO_2-equiv.) is released to the atmosphere. Highest values were from White et al. 2005 with ratio between 0.08 and 0.09 due to a very high portion of emissions caused by the provision of the harvest machinery. Chipping processes increased GWP to 20.5 kg CO_2-equiv.*m^{-3} ob (±6.4 SD; median=19.1).

The results of the GWP clearly show that the GWP of the forest production is neither always similar nor always in the same magnitude, and the range of GWP can be broad. One has to take into account that the production and provision of wood raw material is just the first step of a whole wood product chain, and our summary of different GWP values shows that considerable amounts of GHG-emissions could be already caused by the forest production. But it has to be stated that the GHG-emissions, even in the worst case of our analyzed literature, are still low compared with the respective carbon content of the harvested wood (9 %).

Analyzing only the process group SO as the core process group of the whole forest product chain (because it must appear in every model), the GWP values distribution model clearly showed that more than half of the derived GHG-emissions (58 %) were between 1.6 and 6.4 kg CO_2-equiv.*m^{-3} ob (*n*=23, SO total *n*=40 where SO could be calculated separately). In accordance with the results of the SP+ST+SO+SEP summary, there were some outliers (55.9, 47.8 kg CO_2-equiv.*m^{-3} ob, recalculated from White et al. 2005), which enhance the overall mean of SO process group to 8.9 kg CO_2-equiv.*m^{-3}ob, and a median of 4.9 kg CO_2-equiv.*m^{-3}ob, respectively (Fig. 5). The differences between the studies can be explained by their model assumptions, in particular, decisive input parameters like the treatment regime, harvester, and chainsaw productivity as well as fuel consumption.

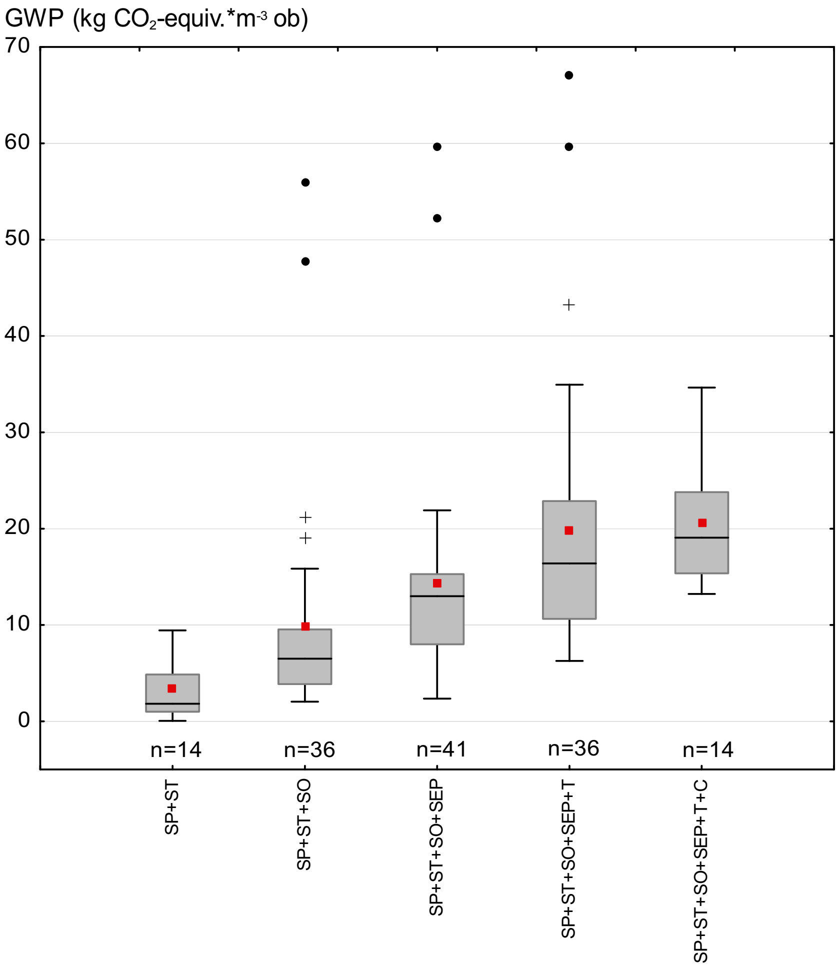


Fig. 4 GWP for different (aggregated) process groups of the forest production. The *line in the box* indicates the median, the *red dot* the mean of the analyzed studies; the *box* is the 25–75 % percentile, the whisker is the non-outlier range; *black dots* and *crosses* are outliers and extremes. *SP* site preparation, *ST* site tending, *SO* silvicultural operations, *SEP* secondary processes, *T* transport, *C* chipping

Our review showed that transport processes of the raw material to the plant gate or consumer were almost in the same magnitude as SO processes (mean=6.9 kg CO$_2$-equiv.*m^{-3} ob, n=28 were transport processes could be calculated separately) and thereby played a decisive role in the total GWP balance.

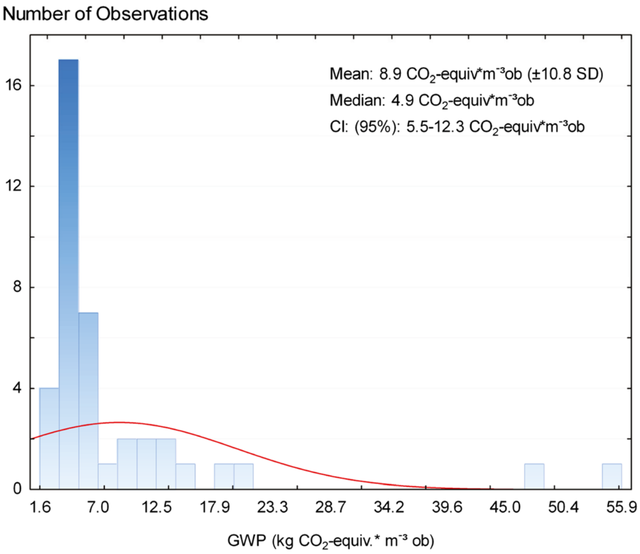


Fig. 5 Distribution model of the GWP (kilograms CO$_2$-equiv.*cubic meter ob) of the SO process group; CI is the 95 % confidence interval'; the *red line* is the modeled distribution

As mentioned above, GHG-emissions can be much higher if special site management is applied. Cambria and Pierangeli (2012), for instance, showed a GHG-emission of 104.6 kg CO$_2$-equiv.*m^{-3} ub to forest road whereas SO only accounts for 4 % of the total emissions. This was due to energy-intensive SP and ST operations including fencing and fertilization. However, the respective walnut tree plantation resembles an agricultural treatment and was not seen as common forest management and thereby excluded from the quantitative analysis. But these results show that values of this magnitude are possible in certain circumstances.

Although the included studies differed a lot in terms of system boundaries, model parameters, or allocation assumptions, a range of GWP values for different process groups can be demonstrated by our literature review. If the forest production is not conducted in a study, one could choose studies from our literature overview which fit best to the respective forest system.

As mentioned above, GWP can be much higher if land use changes appear. Based on our literature data, it is not completely correct to state that forest raw wood products are carbon-neutral. However, the provision of raw wood only counts for a low GWP, compared with many other raw materials like concrete (Petersen and Solberg 2005), and we would call it a “low emission raw material” under the assumption that in situ carbon stock changes can be neglected.

4 Land use, land use change

Land use itself is a relevant impact category and is mentioned in some of the studies in our review (see Fig. 3 and Table 4 for references). Additionally, the influence of Land Use as well as direct Land Use Change and indirect Land Use Change (LU, LUC, iLUC) on total GWP-effects of a forest is of particular interest as it alters the on-site carbon balance. Depending on temporal and spatial system boundaries, net carbon fluxes regarding both directions—carbon sequestration and carbon losses—can influence the total carbon balance of a forest system, e.g., if forest management regimes are changed or forests are converted into other land uses with less carbon storage in the long term. Especially non-sustainable management regimes can lead to severe GHG-emissions, and in many cases, changes in land management can influence the carbon balance of the entire system much more than the emissions caused by the forestry processes. But it is still discussed how LUC and iLUC are incorporated in LCA studies. In particular, iLUC is difficult to estimate, and large uncertainties can arise (Laborde 2011). A holistic LCA of a forestry system should always contain changes in the forest carbon balance, e.g., due to forest management effects, and their respective results should be provided separately and not aggregated in a total GWP in order to understand which GWP are caused by changes in forest management and which are caused by the forestry processes, respectively.

5 Proposals for a generalized LCA method of the forest production

The manifold approaches of our literature review reveal the lack of a general and commonly used method for the LCA of forest production. Although there are several methodical standards and guidelines for LCA and carbon footprints, respectively (e.g., Publicly Available Specification (PAS) 2050:2011, ILCD handbook), and some approaches for biomass product chains (e.g., Thrän et al. 2012), generalized approaches for forest production are not available or still under development (e.g., Biograce 2013). Existent studies differ regarding the choice of system boundaries, considered processes, functional units, or allocation procedures. As it is stated in some studies (e.g., González-García et al. 2013a; Berg and Lindholm 2005; Dias and Arroja 2012) this causes difficulties in comparisons between studies. To ensure comparable LCA results for future LCA studies, we give some suggestions concerning several important methodical questions for forest production, especially focused on the above-mentioned methodological aspects. For general requirements regarding the following topics, see the ISO 14040, 14044, the ISO/TS 14067 for the Carbon Footprint of Products or existing Product Category Rules dealing with wood products like EN ISO 16485 (2014). In detail, the following topics are specified:

5.1 System boundaries

The definition of the system boundary is one of the most important methodical topics and is described in chapter 4.2.3.3 of the EN ISO 14044 and in chapter 6.2.5 in the ISO/TS 14067, respectively. The forest system should start with site preparation processes and end at least at forest road including all relevant primary and secondary processes of the entire forest product chain (from *cradle-to-forest road* as the proposed mandatory system, Fig. 6). Primary processes are processes which immediately take place in the forest. Secondary processes can be defined as processes which do not take place directly in the forest but are crucial in conducting the forest management and to provide raw wood products (see “chapter 2,” Materials and methods and Fig. 6). All processes and process groups of our suggested mandatory system, as shown in Fig. 6, should be implemented into the assessment. It is clear that not every forest system includes all processes since forest management regimes differ and not every process applies. However, if some processes are not required, this should be indicated including an explanation why they are not required. For processes where no information can be obtained and detailed LCA-calculations are not possible, a best estimation or a range of estimations should be given. In cases where even estimations are not possible, the respective processes should not be excluded automatically but marked with an explanation that the respective emissions are not known. Furthermore, in some cases, emissions do not appear. For instance, if planting processes are not required because natural regeneration occurs, this process should be set to zero with a subsequent short explanation regarding the natural regeneration. Furthermore, all single process results should be reported separately to allow sound comparisons with other studies. If single processes cannot be described separately, at least the results of every process group should be provided. Advanced system boundaries are from *site preparation to plant gate*, *to consumer* or *to farm gate* (in case of, e.g., split logs from rural forests) including additional processes like chipping and the transport of raw wood material (facultative system, see Fig. 6).

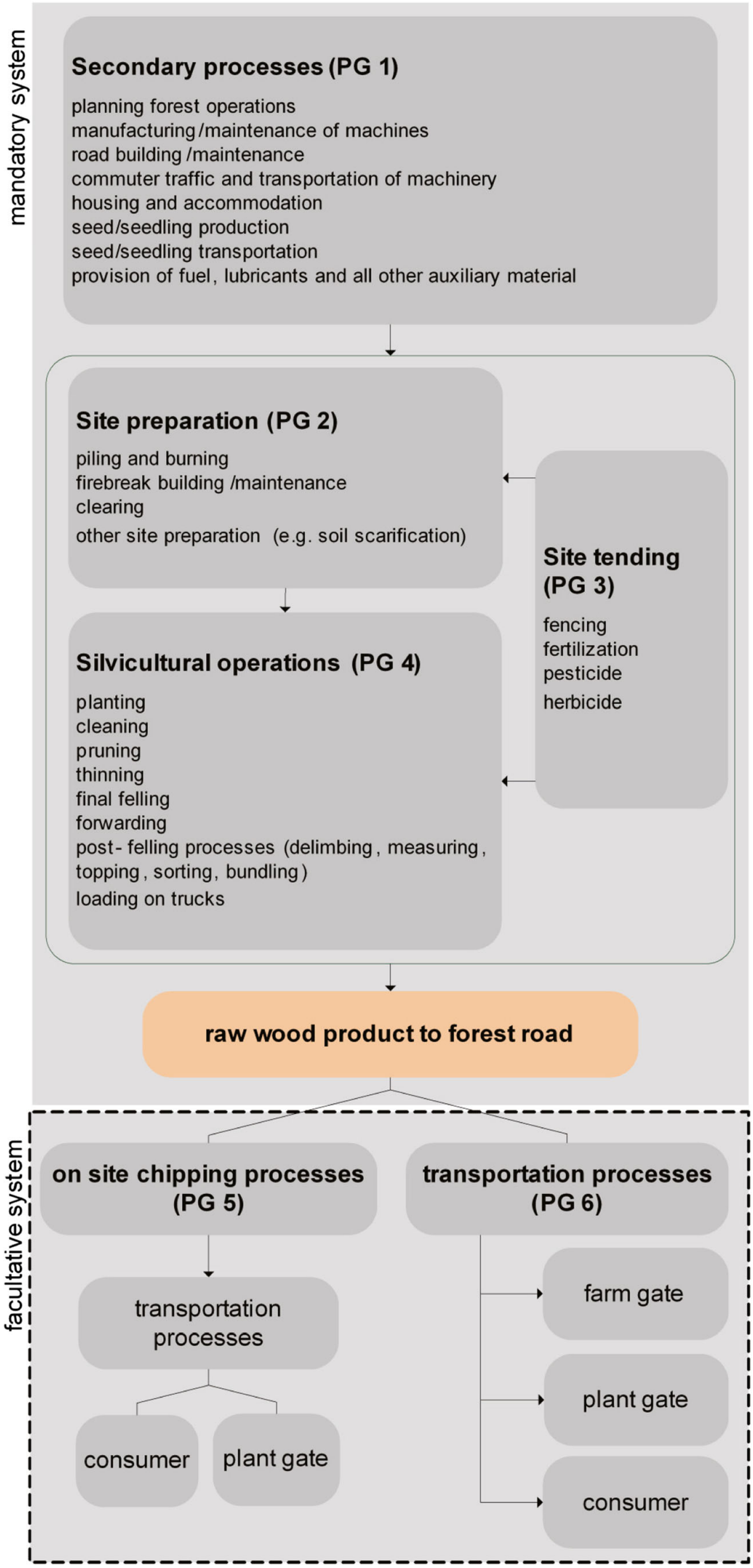


Fig. 6 Proposal for a process chain for raw wood as a base for LCA for forest production

Besides the process based system boundaries, a specification of the temporal system boundaries is crucial. One special characteristic of raw wood products is that, for a defined area, their entire production and provision is distributed over a larger time period and the whole process chain cannot be calculated within 1 year as it is possible for example with many agricultural products. Forests are managed within tree-specific rotation periods containing time frames of several decades with changing wood qualities, tree dimensions, and amounts of harvested wood. In some cases, e.g., permanent forests, no time frame, or rotation period can be defined. Within a rotation period, GWP of, e.g., thinning processes can differ a lot, depending on harvesting productivity rates for different tree dimensions or on the harvest machinery used. For temporal system boundaries, two general approaches can be determined, depending on the goal of the study: A "whole rotation approach" and a "single moment approach." The whole rotation approach considers the entire forest system over the whole rotation period of a forest including all age classes and all processes over the total time period. In contrast, the single moment approach only takes into account one specific time which can be one thinning or the final cutting of a stand. The latter approach hinders the inclusion of all general processes. Therefore, the whole rotation approach should be preferred as it takes the entire system into account. However, the single moment approach can make sense, if, e.g., the current GWP of regions or countries are calculated.

5.2 Considered processes

We suggest using four main process groups in the mandatory product system with their respective processes as shown in Fig. 6 and described in chapter 2: Secondary processes (Process group (PG) 1), Site preparation (PG 2), Site tending (PG 3), and Silvicultural operations (PG 4). As a facultative process, group chipping processes (PG 5) appear if chipping is conducted on site. Of course, transportation processes (PG 6) are crucial in a comprehensive LCA, but including this process group to the LCA of the forest production is not essential as further LCA studies dealing with wood products could also involve this process group.

A clear nomenclature of processes is crucial to allow comparisons between studies. Our literature review showed that, in some cases, different names were used for the same processes or the same process group contained different processes. This can lead to confusion, and therefore, we recommend the nomenclature shown in Fig 6.

Processes can be categorized into specific and general processes. Specific processes are processes whose emissions are directly related to the respective raw wood product. Specific processes are: thinning, final felling, forwarding, post-felling processes, loading on trucks with their respective secondary processes. In contrast, general processes are processes whose emissions cannot be related directly to the raw wood product (e.g., fencing which is dedicated to an area and not to 1 m^3 raw wood). General process emissions have to be related to the whole amount of raw wood which is produced within the studied time and area. For instance, emissions due to fertilization are calculated on an area base within a certain time frame. In order to relate these emissions to a comparable functional unit (e.g., cubic meter), the total amount of emissions due to fertilization has to be distributed to the total amount of raw wood.

Processes which can be cut off the system are not defined within these suggestions, because there is no generalized and consistent information about which processes can certainly be removed from the system due to a small contribution to the entire environmental impacts.

5.3 Functional unit

The rules for the functional unit are regulated in 4.2.3.2 in EN ISO 14044 and in 6.2.3 in ISO/TS 14067, respectively. As a default, results should be referred to 1 m^3 ob as it is the most common functional unit in forestry. In addition to the default functional unit, information about the moisture content and wood density shall be given in order to enable a calculation of additional functional units like 1 t biomass od, 1 t of carbon, 1 MJ (lower heating value), or 1 ha, depending on the subsequent use of the wood. The raw wood product is usually the base for different final products, and its inherent ecological impacts represent just a part of the entirety of impacts. Therefore, calculating the impacts only on a hectare or annual base without any product-based unit would not be helpful.

5.4 Impact categories

Our literature study shows a variety of analyzed impact categories ($n=14$). In this review, only the forest production part is considered (which is described in, e.g., EN ISO 15804 2012 as module A1), excluding the subsequent wood production chain. Both parts have to be taken into account regarding the selection of impact categories, because the relevance of impact categories might be different. For the forest production impact categories like, e.g., acidification or land use have high relevance in addition to GWP, whereas other impact categories like particulate matter can be relevant for industrial processes. Thus, in order to give a comprehensive environmental analysis, as many impact categories as possible other than GWP should be considered, although they are more difficult to interpret. One has to take into account that processes can have positive GWP effects on the one hand but perhaps negative effects regarding other impact categories. Only analyzing the GWP could lead to wrong conclusions regarding the environmental impacts of processes. Thus, a more comprehensive LCA including, e.g., the recommended impact categories from the ILCD handbook (JRC 2011) should be favored over a pure carbon footprinting and accordingly defined in the goal and scope of a study.

5.5 Allocation

According to 4.3.4 of EN ISO 14044 and 6.3.6.1 of ISO/TS 14067, allocation should be avoided by either dividing the single processes into two or more processes or expanding the product system. For the forest production, the first option (subdivision) is useful if all raw wood products can be divided into specific process chains and calculated separately (e.g., round wood, industrial wood, energy wood) since the respective processes can differ from each other (e.g., post-felling processes) and environmental impacts depend on tree characteristics or specific processing procedures like, e.g., chipping. Especially diameter at breast height or the diameter of the sorted stem, respectively, is a decisive factor as trees with lower dimensions produce a higher GWP due to higher fuel consumption and lower productivity rates referred to 1 m^3.

Results allocated by market price being the only outcome of a study can hamper comparisons of LCAs from different studies due to the fact that prices can vary a lot within time and region. Thus, we suggest that, if allocation between the different raw wood products cannot be avoided, allocation by mass (or volume) should be used in order to allow a good comparison between different studies. However, comparisons, e.g., between high-quality wood for material purposes and fuel wood under the assumption of different market prices for each raw product can be interesting, and the analysis of different allocation approaches could be included additionally.

6 Conclusions and outlook

The following three main findings can be deduced from our literature review: (1) There is still no widely accepted and applied consistent method for the LCA of forest production. Especially system boundaries, functional units or allocation assumptions and methods differed from study to study. (2) The results of the GWP varied considerably between studies, depending on the processes included and decisive assumptions like productivity rates and fuel consumption of machineries. However, the GWP varies only on a low scale, compared with the carbon stored in wood. (3) The above-mentioned suggestions regarding system boundaries, considered processes, functional units, and allocation assumptions could help to specify forest production, e.g., in upcoming or existing Environmental Product Declarations based on EN ISO 14025 (2011)or Product Category Rules dealing with wood products, e. g., in EN ISO 16485 (2014).

Acknowledgments This study was part of the project “Experts Group Resource Management Bioenergy in Bavaria” (“ExpRessBio-Expertengruppe Bioenergie Bayern”) and founded by the Bavarian State Ministry of Food, Agriculture and Forestry.

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II

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

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Keywords:

biomass
combined heating and power (CHP)
energy
harmonization
industrial ecology
life cycle assessment (LCA)

Supporting information is available on the *JIE* Web site

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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DOI: 10.1111/jiec.12321

Editor managing review: Stefanie Hellweg

Volume 20, Number 4

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.

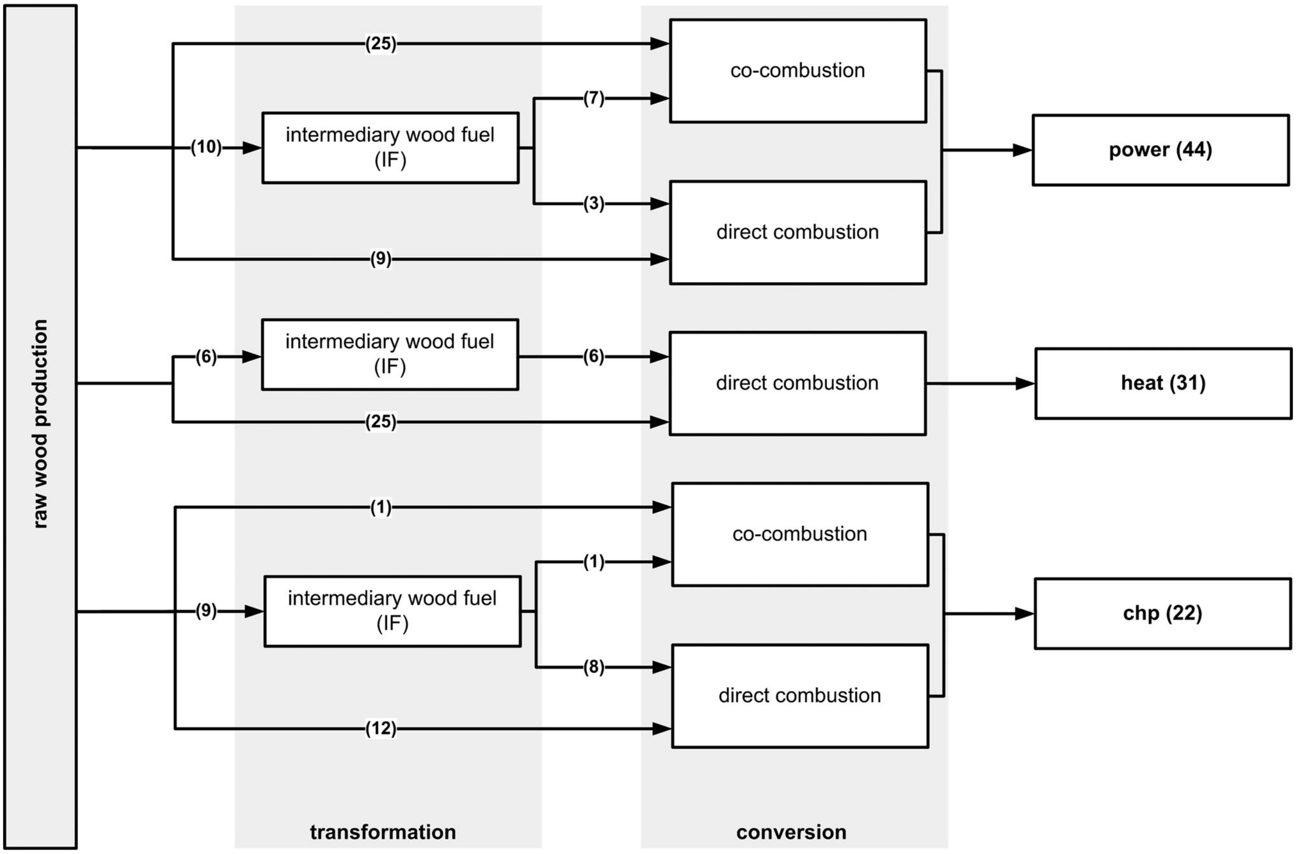

Figure 1 Transformation and conversion technologies employed by LCA studies. Numbers depict the amount of systems concerned with the respective technology and or service.

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

		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*
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

		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*
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 m^3
20	B	DC	NS	NS	x		14.1	10.0–19.0			x	25^b, 204	L^b, L			1 m^3
20	C	DC	NS	NS		x	14.6	NS				64	L			1 m^3
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 m^3
20	F	DC	NS	NS		x	7.8–22.6	NS				64	L			1 m^3
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 m^3 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

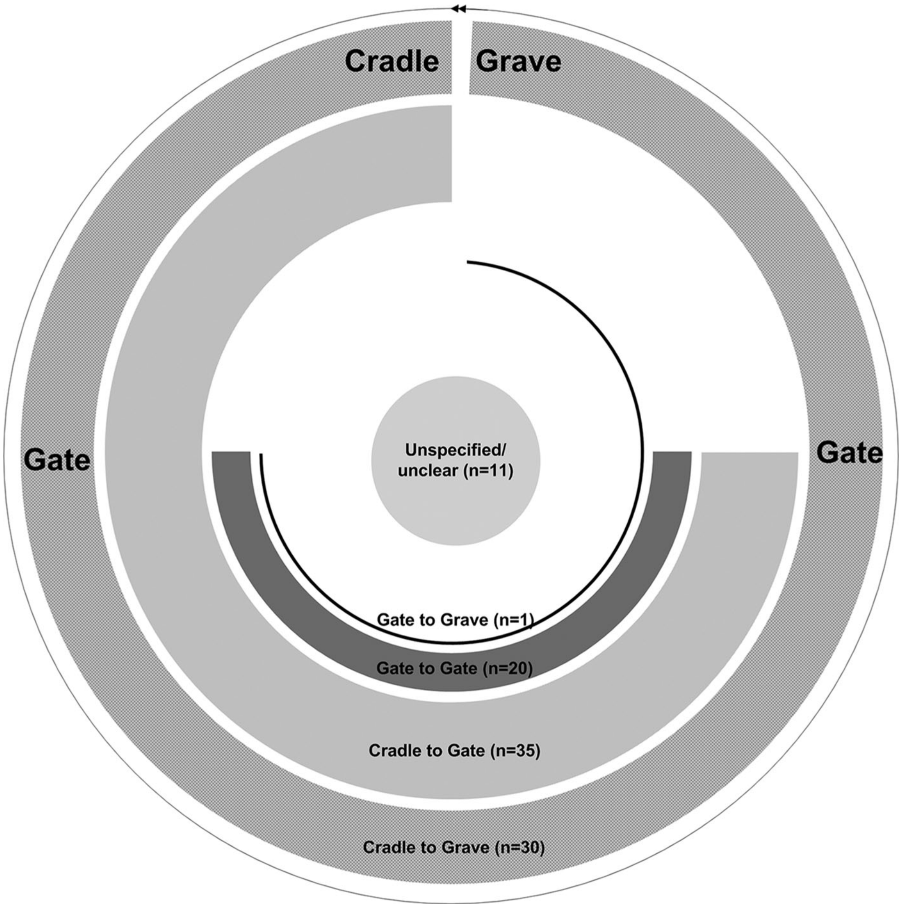

Figure 2 Choice of system boundaries for the 97 analyzed systems in 30 studies. Width of bars represents the amount of systems employing the respective system boundaries.

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

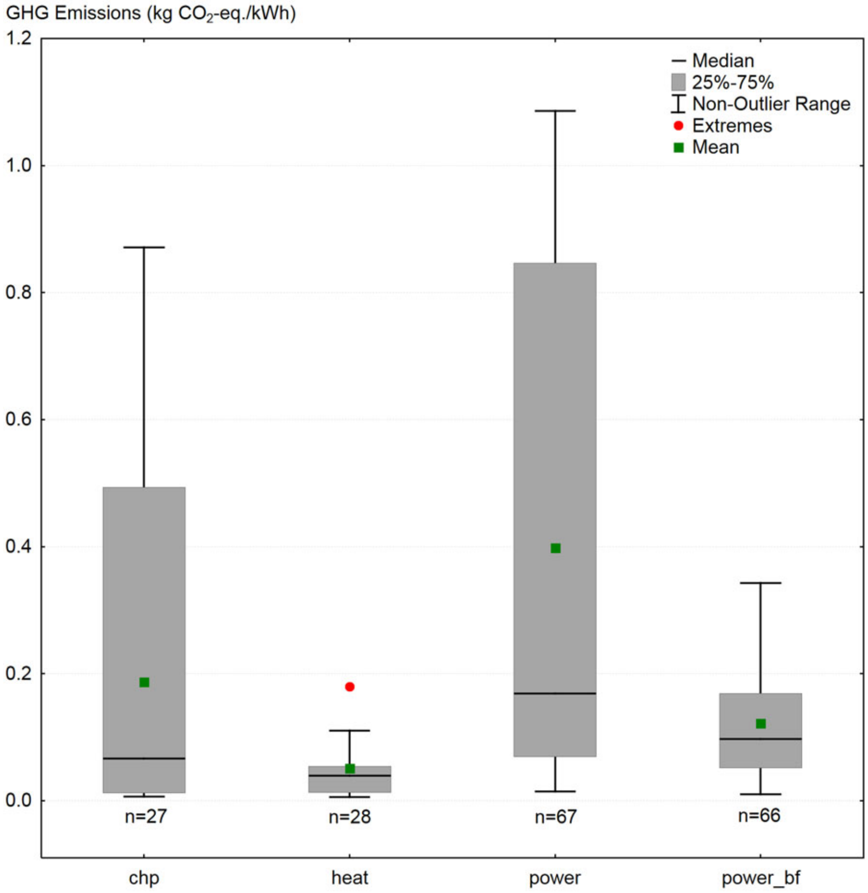

Figure 3 GHG emissions (kg CO_2-eq * kWh^{-1}) of combined heat and power (CHP), heat, power, and the biomass fraction (power_bf) of power generating systems. GHG = greenhouse gas; kg CO_2-eq = kilograms of carbon dioxide equivalents; kWh = kilowatt-hours.

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

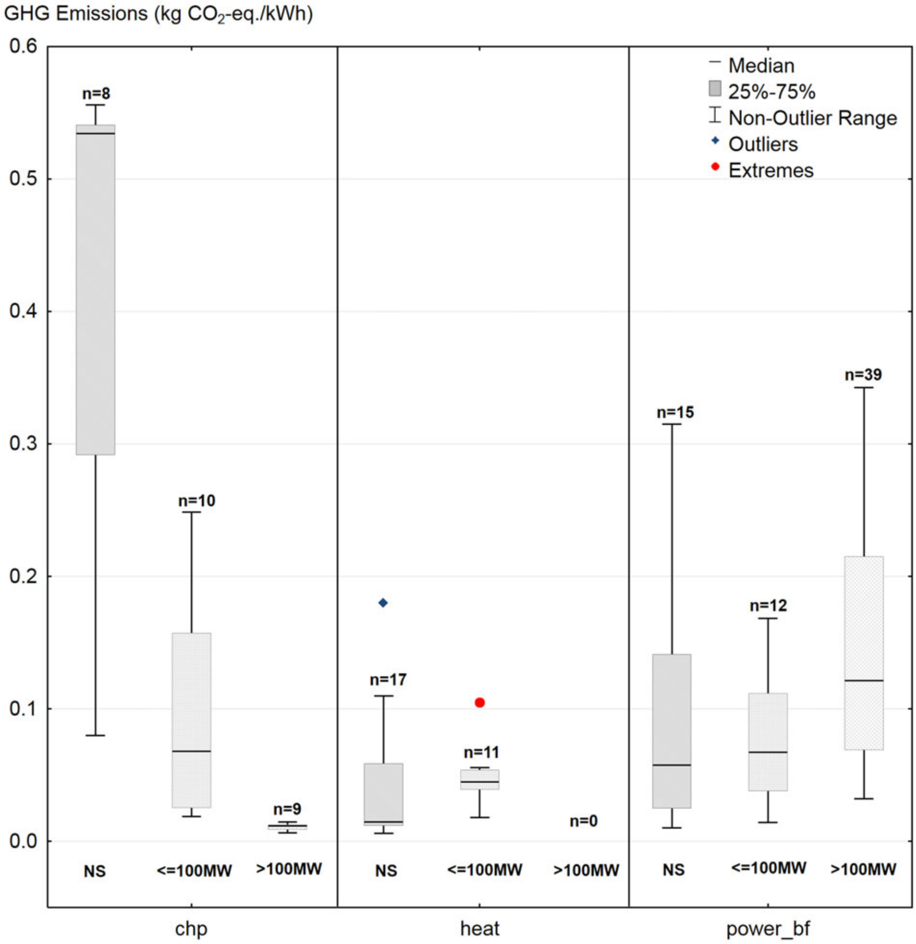

Figure 4 GHG emissions (kg CO_2-eq * kWh^{-1}) of wood energy services (combined heat and power [CHP], heat, and biomass fraction of power generating systems) by combustion capacity. GHG = greenhouse gas; kg CO_2-eq = kilograms of carbon dioxide equivalents; kWh = kilowatt-hours; NS = not specified;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

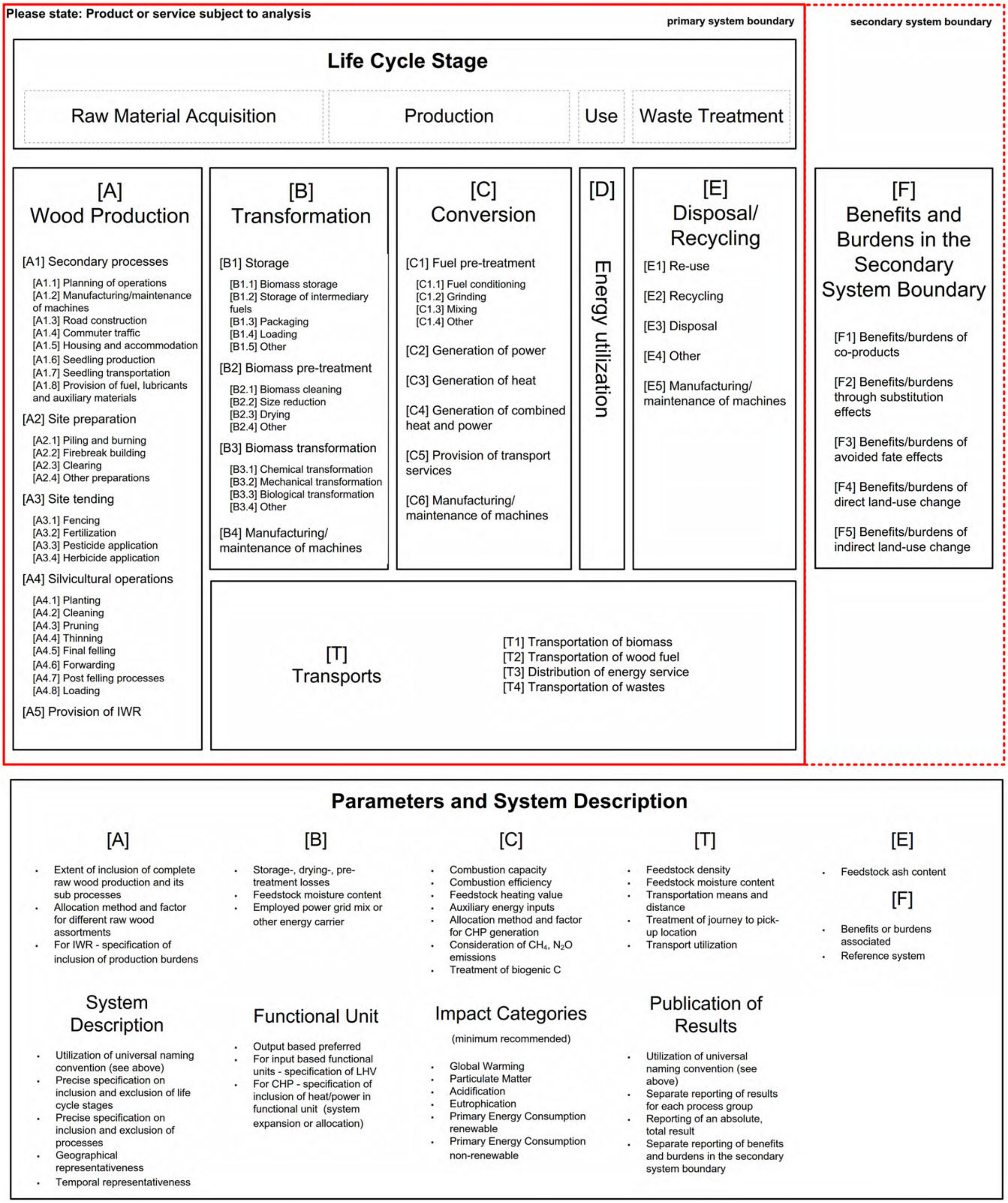

Figure 5 Template for the description of the analyzed system, the reporting of results, as well as parameters and system description components.

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.

Acknowledgments

This study was part of the project “Experts Group Resource Management Bio-energy in Bavaria” (“ExpRessBio-ExpertengruppeBioenergie Bayern”). The authors thank the Bavarian State Ministry of Food, Agriculture and Forestry and the Bavarian State Ministry of Economic Affairs and Media, Energy and Technology for funding.

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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.

III

Journal of Environmental Management 177 (2016) 177–191

Contents lists available at ScienceDirect

Journal of Environmental Management

journal homepage: www.elsevier.com/locate/jenvman

Research article

Environmental effects of shifts in a regional heating mix through variations in the utilization of solid biofuels

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ARTICLE INFO

Article history:
Received 11 September 2015
Received in revised form
6 April 2016
Accepted 8 April 2016

Keywords:
Environmental impact
Heat
Energy
Wood
LCA
Greenhouse gas

ABSTRACT

Solid Biofuels, i.e. wood, play an important role in present and future national and global climate change mitigation policies. Wood energy, while displaying favorable properties for the mitigation of climate change also exhibits several drawbacks, such as potentially high emission of particulate matter. To assess the environmental effects of shifts in the heating mix, emission factors of the comprising energy carriers and the Bavarian heating mix were determined. Through the application of regionalized substitution percentiles the environmental effects caused by shifts in the amount of final energy provided by solid biofuels could be identified. For this purpose, four scenarios, based on political and scientific specifications were assessed. In 2011 a total amount of 663.715 TJ of final energy was used for the provision of heat in Bavaria, with solid biofuels exhibiting the third largest share of 12.6% (83% of renewable heat). Environmental effects were evaluated through life cycle assessments assessing the impact categories of Global Warming (GW), Particulate Matter emissions (PM), Freshwater Eutrophication (ET) and Acidification (AC). Additionally, the non-renewable primary energy consumption (PE) was analyzed. The heating mix in Bavaria (Baseline) causes emissions of 49.6 Mt CO_2-eq. * yr^{-1}(GW), 14.555 t of $PM_{2.5}$-eq. * yr^{-1} (PM), 873.4 t P-eq. * yr^{-1} (ET), and 82.299 kmol H^+ eq. * yr^{-1} (AC), for which 721,745 TJ of primary energy were expended. Current policies entail a GHG reduction potential of approximately 1 Mt CO_2-eq. * yr^{-1} while increasing the amount of energy wood by 15%. The maximum, hypothetical share of solid biofuels of the heating mix cannot surpass 25%, while the climate change mitigation performance of the current use of solid biofuels is approximately 6.4 Mt CO_2-eq. * yr^{-1}. GHG-emissions would be 13% higher and PM emissions 77% lower without this energetic use of wood. Furthermore, our calculations allow for new specified displacement factors through energy substitution, based on the current wood energy mix for regionalized conditions.

1. Introduction

In order to mitigate the effects of global warming, Germany has set targets to increase the share of renewable energies in the transport sector, the generation of power and also for the provision of heat. As such, a total share of renewable energies of the gross energy consumption of 18% for the year 2020 and 50% for the year 2050 was agreed upon (BMU, 2014). While renewable energies already play an important role in these three sectors, especially for the provision of heat, solid biofuels, e.g. wood, are indispensable with a share of more than 70% of the renewable energy expended for heating in Germany and more 83% in Bavaria. The provision of heat with wood, while having favorable properties for the mitigation of climate change (Cohen et al., 2004), also faces severe drawbacks, such as a high amount of particulate matter emissions, which are the cause for various health concerns (Nussbaumer et al., 2008). As stated by the World Health Organization, the current concentration of particulate matter causes an average loss of 10.2 months of lifetime in Germany (Cohen et al., 2004). Additionally, the energetic utilization of wood through burning causes emissions that contain a very significant fraction of what has become accepted as the second most important global warming agent, particulate black carbon (Bond et al., 2013), which is also reflected in the publications of the IPCC (Myhre et al.). Therefore, the reduction of these hazardous pollutants is a main

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http://dx.doi.org/10.1016/j.jenvman.2016.04.019
0301-4797/

Abbreviations

AC	Acidification
CHP	Combined Heat and Power
EF	Emission Factor
ET	Eutrophication
GHG	Greenhouse Gas
GW	Global Warming
IWR	Industrial Wood Residues
LCA	Life Cycle Assessment
LFO	Light Fuel Oil
LHV	Lower Heating Value
LPG	Liquid Propane Gas
MC	Moisture Content
NMVOC	Non-Methane Volatile Organic Compounds
PE	Primary Energy Consumption
w	Water Content

goal when assessing the environmental impacts of wood energy systems. The reduction of PM emissions has been initiated in Germany in the form of the amendment of the 1. federal emissions protection regulation (BImSchV) (BMU, 2010), which will have substantial impact on the emissions of particulate matter from split wood and wood chips heating systems. Nevertheless, solid biofuels play a decisive role in the transition away from conventional energy carriers towards renewable energies and subsequent reductions of environmental effects. This role is also reflected in the current energy concept of the Bavarian state government. However, the magnitude of the contribution of solid biofuels towards reaching these goals, both through an increment in solid biofuel volume and the displacement of conventional energy carriers, remains unclear.

The identification of environmental effects of products or services can be assessed through Life Cycle Assessments (LCA), a widely employed and recognized tool for this purpose. However, biomass LCA systems are complex in nature, due to inconstant volumes at different moisture contents, as well as embodied renewable energy and carbon. Beginning with the complex topic of the provision of wood (Klein et al., 2015), originating from the multifaceted ecosystem of the forest with its various functions besides just the provision of wood, to questions of transformation and conversion of the resource, to its end of life phase (Höglmeier et al., 2015), the highly diverse treatment options for wood, and biomass in general, pose a multitude of methodological and systematic challenges. As a consequence, harmonized and standardized approaches for biomass LCAs are still lacking (Wolf et al., 2015). The correct description and application of system boundaries, feedstock properties (LHV, MC), combustion capacities and efficiencies is one step towards generating comparable and reliable biomass emission factors and current emissions of power and heating mixes. In order to assess the contribution of solid biofuels for the transition to renewable energies in general and explicitly for climate change mitigation, it is necessary to identify the current share of solid biofuels in the sectors of transportation, electricity and heating. For transportation and electricity, this data is readily available. In contrast, for the provision of heat, due to its decentralized structure, no previous studies are available. However, it is this sector where solid biofuels, and especially wood, offer the greatest potentials (Muench and Guenther, 2013) due to relatively low impacts associated with the transformation and conversion processes of wood heating systems.

In order to depict effects of shifts in the amount of wood heating in the study region, it is necessary to determine the mix of different energy carriers for the provision of heat and their interaction when an increasing amount of heating from wood is introduced into the system. It is furthermore the objective of the presented study to generate reliable emissions factors, to classify the most beneficial utilization pathways, to identify climate change mitigation potential through the current and future use of wood and to develop a methodology which is transferable to other countries to assess these questions. In our research we are addressing the following research questions:

1. What is the composition of the current Bavarian heating mix and what share does the provision of heat from solid biofuels have in this mix?
2. What are regionalized emissions factors for heat from solid biofuels in the state and which parameters are of importance towards the different environmental impacts?
3. What are the total emissions of the current heating mix in Bavaria?
4. What shifts of total emissions occur for certain political and scientific scenarios for the development of wood in the heating mix?

2. Material and methods

2.1. Determination of heating mix

The basis for calculation concerning the environmental effects of the Bavarian heating mix is comprised by the statistics published by the Bavarian State Institute for Statistics and Data Processing. Every year, with a delay of three years, the Institute publishes its statistical analysis for final energy consumption in the state. Thus the most up to date data available for this study is related to the final energy consumption in Bavaria in the year 2011 (BayLAStDV, 2014a). In the energy balance the volume and utilization of energy carriers in Bavaria is detailed for a specific timeframe and sectors. Energy carriers in the energy balance and this study are: hard coal, lignite, light fuel oil (LFO), liquid petroleum gas (LPG), natural gas, solid biofuels and other renewables, power, district heat and other energy carriers. We chose to utilize these terms, and especially the term solid biofuels instead of wood, to keep consistency with the terms found in the statistics. The group “other renewables” consists of solar thermal- and geothermal heating, ambient heat, sewage sludge, biogenic waste and biogas, whereas the group “other energy carriers” is not further specified and was therefore treated as a uniform mix of all the above-mentioned energy carriers (BayLAStDV, 2014c) (Table 1). The sectors that were taken into consideration in this study encompass all consumers of final energy in Bavaria, i.e. industry and households including commerce, trade and services, but excluding transportation (BayLAStDV, 2014b). In order to extract the Bavarian heating mix from the energy balance the amount of power used for the purpose of generating heat has to be identified. Only a part of the statistically reported final energy amounts for power is used for heating purposes, while other parts may be used in a different fashion (e.g. cooling). As such, shares of final energy that are included in the balance are not necessarily employed for the provision of heat. However, no data on this amount was obtainable for Bavaria, which necessitated the use of German statistics in this regard, assuming that Bavaria mirrors the German conditions. As such, a weighted share of the total power used for heating purposes of 10.2% for households (11.5% for private household, 6.9% for the commerce, trade and service sector) and 7.8% for the industry

Table 1
Modeling approaches and data sources of energy carriers in the Bavarian heating mix. DE = German conditions.

System	Technology	Data sources
Natural gas	Mix of natural gas technologies	DE – thermal energy from natural gas – thinkstep AG, 2015
Light fuel oil (LFO)	Mix of LFO technologies	DE – thermal energy from light fuel oil (LFO) – thinkstep AG, 2015
Liquid petroleum gas (LPG)	Mix of LPG technologies	DE: thermal energy from liquid propane gas (LPG) – thinkstep AG, 2015
Hard coal	Mix of hard coal technologies	DE – thermal energy from hard coal- thinkstep AG, 2015
Lignite	Mix of lignite technologies	DE – thermal energy from lignite- thinkstep AG, 2015
District heat	Carrier mix – natural gas 65%, hard coal 24%, LFO 5.5%, HFO 5.5%	Gärtner et al., 2013
Power	German grid mix	DE – grid mix – thinkstep AG, 2015
Solid biofuels	Mix of wood energy technologies weighted according to installed capacity of pellet- split wood- and wood chip firing systems	Klein et al., 2016 Joa et al., 2015 thinkstep AG, 2015 Ecoinvent
Other renewables	Carrier mix of solar thermal, geothermal, ambient heat, sewage sludge, biogenic waste and biogas technologies	Hijazi 2015 PE Professional – thinkstep AG, 2015
Other energy carriers	Uniform mix of all above mentioned systems	

sector was utilized, as reported in AGEB (2013). These assumptions can be verified when comparing to Ebert and Voigtländer (2014), where only a small deviation between our sum of final energy for heat and the amount provided in their study of 6.46% could be identified. Additionally, the statistics provided may not present a complete picture of all energy carriers, as well as their final energy amounts and shares, utilized for the provision of heat in the state. Especially for renewable energies, Ebert and Voigtländer (2014) depict larger shares for these energy carriers (+2.8%)

2.2. *Determination of heating mix emission – non-solid biofuels emission factors*

In order to obtain the total emissions associated with the generation of heat in Bavaria, the above defined heating mix, i.e. the shares of energy carriers were multiplied with the corresponding emission factors. As such, emission factors for all energy carriers represented in the Bavarian final energy consumption statistic had to be developed. For all conventional energy carriers Life Cycle Assessments (LCA) in the form of black-box unit processes, based on data provided in the PE Professional database (thinkstep AG, 2015), were conducted (Table 1). These aggregated processes are based on a technology mix for the respective country and can be used for comparisons on a larger scale. The system “other renewables” was modelled as a mix of energy carriers in accordance to (BayLAStDV, 2014c), with shares of 41.2% for solar thermal, 31.2% for geothermal, 17.7% for biogenic waste, 7.4% for ambient heat, 2.5% for biogas technologies and 0.07% for sewage sludge. All calculations of heat from biogas via combined heat and power (CHP) are based on Hijazi (2015), whereas all other energy carriers in this system are again based on black-box unit processes in the PE Professional database (thinkstep AG, 2015).

2.3. *Determination of heating mix emission – solid biofuels emission factors*

The system for solid biofuels was assessed in a more detailed fashion as shown in Wolf et al. (2015) (Fig. 1). It comprises various technologies for the generation of heat from wood, i.e. through the combustion of wood chips, pellets and split wood. Comprehensive LCAs, in accordance to DIN EN ISO 14044 (2006), were conducted for wood heating systems representative for the state of Bavaria. These LCAs include all life cycle stages of the wood energy service and commence with an in depth analysis of forest management schemes in the state. After subsequent transportation and transformation steps, the wood energy carrier (e.g. wood chips, pellets, split wood) is converted into final energy in one of eight heating systems (Table 2). Resulting emission factors were collated to the installed capacity of the respective heating system (Fig. 2) in Bavaria according to Joa et al. (2015), in order to generate a weighted emission factor for the total amount of solid biofuels in the reference year. Wood energy LCAs are complex due to methodological aspects concerning, e.g. biogenic carbon or long production periods. Therefore, it is ideal to follow a standardized scheme for the creation of biomass LCAs (Wolf et al., 2015) and the assessment of each individual life cycle stage (Fig. 1).

2.3.1. *Wood production*

Each system for the production of heat from solid biofuels, e.g. wood, starts with the process group [A] “wood production”, where the provision of raw wood is outlined. This process group is subdivided into [A1] site preparation, [A2] site tending and [A3] biomass harvesting with a subsequent biomass transport [T1] from forest road to plant/farm gate. A detailed description of the conditions under which process group [A] was modelled can be found in (Klein et al., 2015). For the present study, forest biomass supply chains typical for Bavarian forestry conditions were modelled, based on the following assumptions: Raw wood production is outlined in forest stands on good site conditions for the four main tree species in Bavaria (spruce, pine, beech and oak) over tree specific rotation periods (between 120 and 180 years). All LCA results are provided separately for round wood, industrial wood and split wood, i.e. energy wood. Process group [A1] with [A1.2] manual planting, [A2] with [A2.1] cleaning, [A2.2] fencing, [A2.5] road building and maintenance, [A3] with [A3.1] felling with harvester in thinning operations and chain saw in final felling operations, [A3.2] forwarding with forwarder for round wood and manual forwarding for split logs, [A3.3] loading of round wood on truck by crane and of split logs on tractor by hand and [T1] biomass transport with truck for round wood (200 km, utilization factor 0.5) and tractor for split logs (20 km, utilization factor 0.5). All LCA calculations are based on individually modelled pure forest stands for each tree species (Klein et al., 2016). The results used for the present study indicate mean values over the tree specific rotation period.

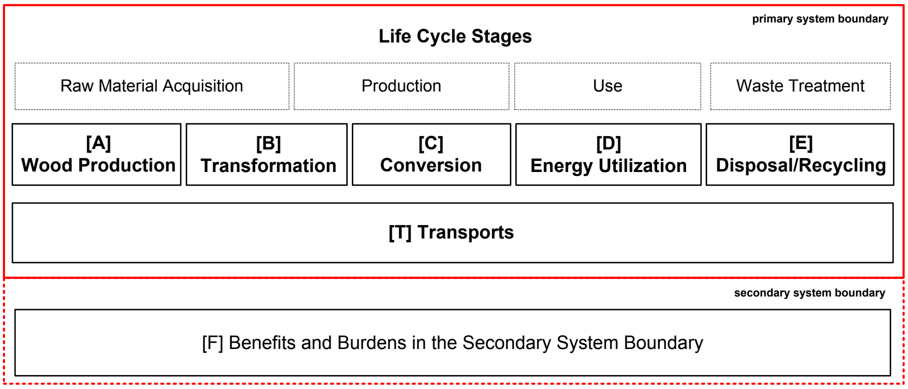

Fig. 1. Template for the description of the analyzed system (for Details see Wolf et al., 2015).

Table 2
Overview of analyzed wood heating systems and key parameters. IWR = Industrial wood residues; LHV = Lower heating value; L = Lorry transport; T = Tractor transport; [T1] = Biomass Transport; [T2] = Transport of bio-energy carrier.

ID	Description	Water content [%]	Weighted LHV [MJ/kg]	Transport [km]	Capacity [kW]	Annual efficiency [%]	Installed capacity 2013 [MWth]
1.1	Wood chips central heating [50 kW]	20	14.2	[T2] L 200	50	75	262
1.2	Wood chips central heating [300 kW/w = 20%]	20	14.2	[T2] L 200	300	75	262
1.3	Wood chips central heating [300 kW/w = 50%]	50	7.9	[T2] L 200	300	75	262
1.4	Heating Plant, wood chips[a], IWR[b], recovered wood[c]	50[a]/20[b]/10[c]	7.9[a]/14.4[b]/16.5[c]	[T1] L 700[d]	1000	75	1165
2.1	Split wood, wood stove	20	14.2	[T1] T 20 [T2] T 20	6	78	8551[e]
2.2	Split wood, tile stove	20	14.2	[T1] T 20 [T2] T 20	6	65	9678
3.1	Wood pellets central heating [15 kW]	10	16.5	[T1] L 200 [T2] L 200	15	78	975
3.2	Wood pellets central heating [50 kW]	10	16.5	[T1] L 200 [T2] L 200	50	78	975
						Σ	22,130

[d] Total transport distance for forest wood chips, IWRs and recovered wood.
[e] Includes installed capacity for split wood use in central heating (1685 MWth).

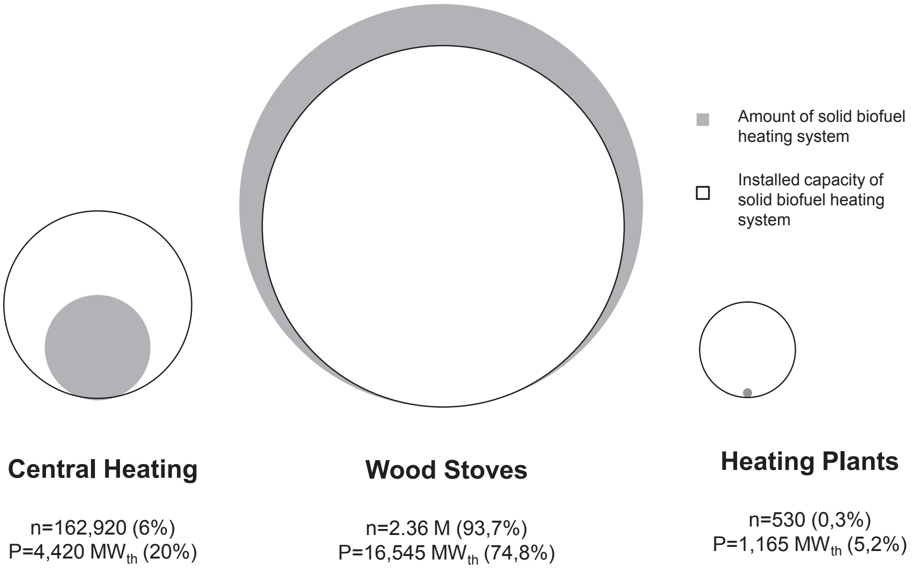

Fig. 2. Amount and installed capacity of wood heating systems in Bavaria, modified from Joa et al. (2015).

The results for each wood assortment are weighted according to the tree species distribution of the harvested timber volumes for the reference year 2013 (Table 3), which leads to a specified tree species weighted mean LCA result for the respective reference year. LCA results corresponding to one m^3 of raw wood over bark are calculated to one ton of oven dry mass using tree specific wood

Table 3
Harvested timber volumes for the main tree species in Bavaria in 2013 in M m^3 under bark (Klein et al., 2016).

Tree species	Stem wood	Industrial wood	Energy wood	Total
Spruce	7.808	0.838	3.863	12.509
Pine	1.983	0.230	1.314	3.527
Beech	0.372	0.578	2.543	3.493
Oak	0.208	0.077	0.405	0.690
Σ	10.372	1.723	8.124	20.219

densities (dry matter/fresh wood volume) leading to a mean dry mass value per m^3 of wood, again utilizing the tree species distribution of harvested timber volumes in 2013. Based on these calculations, a mean lower heating value for the entire timber volume can be calculated via tree specific heating values at specified water contents appropriate for the individual conversion processes.

2.3.2. *Wood transformation*

After wood production [A] and transportation [T1], the biomass is transformed into a usable energy carrier, e.g. wood chips, wood pellets or split wood, in the process group [B] “transformation”. For the production of forest wood chips, industrial wood is used. The mechanical transformation of the wood into wood chips is carried out by an agricultural diesel tractor (100 kW) which chips the wet wood ($w = 50\%$) into smaller particle sizes. Transformation losses are assumed to be approximately 1% of mass for chipping and 3% for the subsequent air drying of the chips to $w = 20\%$, if applicable (König, 2009). For the heating plant system, recovered wood ($w = 10\%$), transported 150 km with a utilization factor of 0.5, and industrial wood residues ($w = 20\%$) transported 100 km by a lorry with a utilization factor of 0.5, are combusted additionally. Respective shares are forest wood chips: 74%, industrial wood residues: 22% and recovered wood: 4% (Wittkopf, 2012). Industrial wood residues (IWR) are produced via a mass-allocated sawing process. For the production of split wood, logs are cut to 33 cm lengths and then split via an agricultural tractor attachment (Höldrich et al., 2006). Losses are calculated to 2% for splitting and sawing and 3% for subsequent air drying to $w = 20\%$. Transportation of split wood by a tractor was assumed to be 20 km with a utilization factor of 0.5. For the production of wood pellets, mainly IWRs are used. Therefore, IWRs as a byproduct of the production of sawn wood from stem wood was modelled. Allocation was carried out by mass. A transportation of IWRs by a lorry was assumed as 200 km with a utilization factor of 0.5, after which, the IWRs are dried to $w = 10\%$. Drying requires the input of auxiliary energy in the form of power and an energy input, in this case heat from wood chips, for the evaporation of the water bound in the wood (2442 MJ/kg of H_2O). Afterwards, with an input of electrical power of approximately 3% of the pellets energy content (Hartmann et al., 2013), the dried IWR can be pressed into pellets. Finished pellets are transported 200 km with a utilization factor of 0.5.

2.3.3. *Wood conversion*

In the following process group [C] “conversion” for the generation of heat, the dried wood energy carriers are combusted in 8 different heating systems, which were modified from the Ecoinvent database (Bauer, 2012) (Table 2). Four wood chip heating systems, one small scale- (50 kW) and two medium scale- (300 kW) domestic heating systems, as well as a heating plant (1 MW) were taken into consideration. Dried chips ($w = 20\%$) but also green chips ($w = 50\%$), in the case of one of the medium scale domestic heating system and the heating plant, were fired. For pellet combustion, domestic systems with a firing capacity of 15 kW and 50 kW respectively were assessed. The consumption of split wood for thermal energy, which is the most important bioenergy carrier in Bavaria (Gaggermeier et al., 2014) was analyzed via combustion in two typical split wood heating systems. The first system, which represents the majority of split wood household heating systems in respect to the final energy consumption (34.5%) in Germany, is the tiled stove (German: “Kachelofen”). Emissions for this heating system was adjusted for CO, NO_x, SO_2, CH_4, NMVOC, N_2O and particulate matter based on Struschka et al. (2008), to reflect the state of technology. The second system is modelled to represent a typical wooden stove, the second most common split wood heating system in respect to final energy consumption in Germany (24.1%) (Struschka et al., 2008). The system is conforming to newest German regulations concerning air pollution control (BMU, 2010). By including both split wood systems it was our aim to represent the current state of split wood firing in Germany, with a part of the stoves already being in conformity to the air pollution regulations issued by the government. Annual efficiencies are derived from Stuible et al. (2014), which are based on the evaluation of the German “Marktanreizprogramm”, a political incentive tool for the promotion of renewable energies in the country. Energy contents (lower heating value (LHV) at water contents of 50%, 20% and 10%) and oven dry densities over green volume for different tree species were integrated into the assessment via the utilization of harvesting volumes of the four tree species. This allowed for the calculation of a weighted LHV for the total of all harvested wood differentiating the selected water contents and a weighted green wood density for this wood mix. An additional differentiation of LHV was made for the three raw wood product assortments (stem wood, industrial wood, split wood) depending on their respective harvested volumes in the state. Of course, for solid biofuels such as pellets, not 100% of the biomass comes from Bavaria (considerable volumes are imported). However, since the installed capacity for pellet heating systems is still relatively low we consider the above-mentioned assumptions to be reasonable. Further system components are auxiliary energy demands and the construction and maintenance of infrastructure, e.g. storage or combustion appliances. All systems also contain the treatment of wood ash in the end of life [E] phase. An average ash content of 2% was assumed (LFU, 2009).

2.4. *Scenario assumptions*

2.4.1. *Baseline*

By relating the above-mentioned emission factors to the respective final energy consumptions in Bavaria in the year 2011, the status baseline emissions in 2011 can be calculated. In order to assess the effectiveness of certain politically, scientifically or hypothetically induced shifts in the final energy consumption or the share of solid biofuels, i.e. wood, in the energy balance, four scenarios were defined.

2.4.2. *Scenario 1: Bavarian Energy Concept 2011*

Scenario one is based on the political goals for solid biofuels of the Bavarian government, as stated in the Bavarian energy concept of 2011 (Bayerische Staatsregierung, 2011). There it is that the energetic use of domestic wood can be increased by 15% from 4.8 Mt in 2011 to 5.5 Mt in 2021 without any increased competition between the material and energetic use of wood. Consecutively, for scenario 1, we increased the amount of final energy for solid biofuels by 15% and reduced relevant other energy carriers by employing the most up to date substitution percentiles provided by the Federal Ministry for the Environment (Memmler et al., 2014). These **substitution percentiles** represent the shares of conventional energy carriers (e.g. LFO, natural gas, etc.) replaced by solid biofuel heating systems (Table 4). These substitution percentiles are specific to a certain technology, e.g. a pellet central heating system

Table 4
Substitution percentiles for different wood heating systems in Germany (Memmler et al., 2014) and weighted substitution percentiles in relation to installed capacities in Bavaria for the year 2013.

	LFO (%)	Natural Gas (%)	Hard coal (%)	Lignite (%)	District heat (%)	Power (%)
Wood Stove	40.6	49.9	0.4	1.1	1.8	6.3
Split wood central	65.0	20.0	2.0	3.0	0.0	10.0
Wood Pellet central	65.0	20.0	2.0	3.0	0.0	10.0
Solid biomass (Industry)	7.6	53.5	7.9	16.4	14.6	0.0
Solid biomass (Heating plant)	0.0	0.0	0.0	0.0	100.0	0.0
Weighted Substitution	49.9	31.8	1.4	2.4	6.8	7.6

or a split wood heating system. However, when increasing the share of wood in the final energy balance, no single set of substitution percentile can be employed, since different technologies for the conversion of wood to final energy are used in the state. Therefore, a weighted set of substitution percentiles was determined by relating the individual factors specific to one technology to their installed capacity in Bavaria (Table 4).

2.4.3. Scenario 2: wood mobilization from private forests

Scenario 2 is based on a study carried out for Bavaria by Wilnhammer et al. (2012). The study comes to the conclusion that based on data from 2006 to 2008, approximately 1.1 m^3 ha^{-1} * a^{-1} of fuel wood can, in addition to the baseline conditions, be sourced from small scale private forest owners in the state. The threshold for the size of privately owned forest to qualify for this additionally potential was set to a maximum of 100 ha, which amounts in approximately 1.1 M ha in total (Wilnhammer et al., 2012). The threshold of 100 ha was chosen, since privately owned forests above this size are likely to be professionally managed and therefore, mobilization potentials are deemed lower. The mean dry mass in conjunction with the mean lower heating value was utilized to calculate the final energy amounts, which subsequently were added to the baseline.

2.4.4. Scenario 3: 100% energetic wood use

Scenario 3 is of hypothetical nature and is intended to show the limits towards the impacts wood energy system can have on the total emissions in Bavaria. As such, this scenario is representing a 100% use of the total amount of harvested wood (20.218.778 m^3 under bark) in the state for the sole generation of heat (157.062 TJ).

2.4.5. Scenario 4: 0% energetic wood use

Consecutively, scenario 4 shows the reverse effects in comparison to Scenario 3. It depicts a hypothetical 0% energetic use of wood, showing the consequence if no wood would be used for energetic purposes. This indicates the current performance of wood, e.g. for climate change mitigation. For scenario 3 and 4, the mean dry mass, mean heating value and substitution percentiles, as described for the other scenarios were employed.

2.5. Impact assessment

Impact assessment was carried out according to the provisions of the International Reference Life Cycle Data System (ILCD) Handbook, published by the European Commission (European Commission, 2010a). With the goal of creating comparable LCA results, precise recommendations pertaining the choice of impact categories and impact assessment methodology are provided in the Handbook. Accordingly, for the selected impact categories in this study, the respective impact assessment methodologies as described in the ILCD Handbook were utilized (European Commission, 2010b). Selected and evaluated impact categories for this study are IPCC Global Warming, without biogenic CO_2 in kg CO_2-eq. (GW) (Intergovernmental Panel on Climate Change, 2007), particulate matter emissions following the RiskPoll method (Rabl and Spadaro, 2012) in kg PM2.5-eq. (PM), aquatic freshwater eutrophication (Struijs et al., 2009) in kg P-eq. (ET) and acidification (accumulated exceedance) (Seppälä et al., 2006) in mol of H+ eq. (AC). Furthermore, the primary energy consumption (non-renewable) in MJ was assessed. In addition to the directly climate relevant impact categories of GW and PE, Freshwater eutrophication was integrated due to the importance of nutrient enrichment effects of biomass systems, e.g. through fertilization, which can cause shifts in species composition and biomass production (Guinée, 2002). Aquatic eutrophication only takes into account limiting nutrients (nitrogen (N), phosphor (P)) to the growth of aquatic biomass. These emissions of P and N can be converted to biomass through the composition of algae on a molecular level, thus providing characterization factors that are independent of local environmental conditions (Struijs et al., 2009). Of course, the ultimate fate of the P and N emissions in an ecosystem depend on many factors, such as the availability of the nutrients for the plant life, i.e. their degree of oxidation, which typically requires some form of treatment to supply P which is available for plants (Bridle and Pritchard, 2004). Acidifications, i.e. acidifying pollutants have a wide variety of impacts on soils, water, organisms and building materials (Guinée, 2002) and were integrated therefore. Since wood energy systems in particular are related to high volumes of particulate matter emissions ($PM_{2.5}$), which are linked to various health concerns, including these is of great importance (Nussbaumer et al., 2008). The functional unit for all systems integrated in this study was 1 MJ_{th} of useful thermal energy (excluding the transmission of heat inside buildings).

3. Results and discussion

3.1. The Bavarian heating mix and emission factors of individual energy carriers

For each energy carrier, emission factors (EF) for environmental effects in the impact categories of IPCC Global Warming (GW) without biogenic CO_2, primary energy consumption (non-renewable) (PE), particulate matter emissions (PM), aquatic freshwater eutrophication (ET) and acidification (AC) were calculated. Additionally, a weighted (by share of final energy) total EF representing the Bavarian heating mix and a weighted total EF without renewable energies could also be reported for 2013 (Table 5). For the impact category of GW the highest EF can be identified for the provision of heat from power (0.171 kg CO_2-eq. * MJ_{th}^{-1}) because of the high primary energy factor, which in turn is mirrored in the PE consumption, which is also the highest EF in comparison of all energy carriers (2.31 MJ * MJ_{th}^{-1}). At the lower end of the scale, renewable energies (0.028 kg CO_2-eq. * MJ_{th}^{-1}) and solid biofuels, e.g. wood (0.010 kg CO_2-eq. * MJ_{th}^{-1}) in particular can be located, due to the inherently low energy (PE: 0.102 MJ * MJ_{th}^{-1}) and material inputs required in the production system of solid biofuels as also shown in

Table 5
Emission factors (EF) for the analyzed technologies and the weighted emission factors according to the heating mix with and without renewable energies. GW = Global Warming; LFO = light fuel oil; LPG = liquid propane gas; PE = Primary Energy Consumption non-renewable; PM = Particulate Matter; ET = Freshwater Eutrophication; AC = Acidification; RE = renewable energies.

	GW without biogenic CO^2 (IPCC, 2007)	PE (non-renewable)	PM (Rabl and Spadaro, 2012)	ET (Struijs et al., 2009)	AC (Seppälä et al., 2006)
	[kg CO_2-eq.]	[MJ]	[kg PM2.5-eq]	[kg P-eq.]	[mol H^+ eq.]
	per MJth of Final Energy				
Power	0.171	2.31	1.5965E-05	3.26E-07	3.33E-04
Lignite	0.114	1.00	7.6764E-06	4.26E-09	1.60E-04
Hard Coal	0.106	1.07	1.1119E-05	1.65E-08	2.09E-04
District Heat	0.090	1.24	5.3316E-06	8.05E-09	1.32E-04
LFO	0.085	1.18	3.6036E-06	1.41E-08	1.19E-04
LPG	0.084	1.17	6.3708E-06	3.38E-08	1.18E-04
Natural Gas	0.066	1.08	1.5872E-06	2.15E-09	6.41E-05
Other	0.052	0.67	4.1125E-05	3.09E-06	1.54E-04
Other Renew.	0.028	0.52	1.4490E-05	2.76E-05	1.71E-04
Solid Biofuels[a]	0.010	0.102	1.3909E-04	4.50E-06	1.59E-04
Without RE[b]	0.086	1.251	4.8032E-06	8.89E-08	1.18E-04
Σ with RE[b]	0.075	1.088	2.1967E-05	1.32E-06	1.24E-04

[a] Weighted EF by installed capacity.
[b] Weighted by share of heating mix.

Cherubini and Strømman (2011). For the impact category of GW, the weighted EF of the Bavarian heating mix is 0.075 kg CO_2-eq. * MJ_{th}^{-1} and 0.086 kg CO_2-eq. * MJ_{th}^{-1} for the mix without renewable energies. The major shares of final energy of natural gas and light fuel oil (LFO) are influential to the magnitude of EFs. Since the Bavarian heating mix has not been calculated in the past, a reference can only be sought in the previously calculated prospective German heating mix (Pehnt, 2006), which exhibits emissions of 0.0815 kg CO_2-eq. * MJ_{th}^{-1} in 2010. Due to lower shares of renewable energies for the provision of heat in Germany, the deviation of 8.6% is acceptable.

Contrary to the favorable properties of wood towards the impacts of GW, solid biofuels exhibit the highest factor for PM emissions (0.139 g $PM_{2.5}$-eq. * MJ_{th}^{-1}), eight times higher than the second highest PM emitting energy carrier, which is heat from power with 0.0160 g $PM_{2.5}$-eq. * MJ_{th}^{-1}. The combustion of wood, i.e. the conversion of secondary energy to final energy ([C]), is responsible for more than 90% of the PM emissions of solid biofuels due to an abundant incomplete combustion of wood (Nussbaumer et al., 2008). The lowest EF for PM is exhibited by natural gas (0.0016 g $PM_{2.5}$-eq. * MJ_{th}^{-1}). For the impact category of PM, the weighted EF of the Bavarian heating mix is 0.0219 g PM2.5-eq. * MJ_{th}^{-1} and 0.0048 g $PM_{2.5}$-eq. * MJ_{th}^{-1} for the mix without the influence of renewable energies. The considerable share of solid biofuels the Bavarian heating mix demonstrates, is strongly influential towards the total weighted EF.

For the impact category ET, the lowest and highest EFs are exhibited by lignite and the group of "other renewables" with 4.26E-09 kg P-eq. * MJ_{th}^{-1} and 2.76E-05 kg P-eq. * MJ_{th}^{-1}. For ET the group of "other renewables" is dominated by the eutrophication effects of near-surface geothermal heating applications, i.e. heat pumps operating with power which have a share of over 30% of this group's final energy consumption. Since only aggregated black box processes were available for the assessment of this group of energy carriers it cannot be verified if the provision of power in Germany (with a high share of fossil energy carriers) or other production processes are responsible for these relatively high ET EFs. Solid biofuels also exhibit a high ET EF of 4.50E-06 kg P-eq. * MJ_{th}^{-1}. Responsible for an average of over two thirds of this EF is the assumption of the end of life treatment of wood ash, which is deposited to a dump site or a compost box where P-equivalent emissions can potentially support biomass growth in aquatic ecosystems. Of course, partly responsible for the relatively high ET EFs for solid biofuels is the choice for the end of life phase. When wood ash is used as fertilizer, as part of a liming mixture or deposited (e.g. on a compost) high ET EFs are to be expected. Conversely, smaller ET EFs can be expected for a material use of the wood ash from larger heating systems (e.g. in the cement – or road construction industry following the collection and secondary combustion). For most wood heating systems, the remaining third is split relatively evenly between process group [A] and [T]. Considering different end of life treatments for the wood ash, e.g. as material in road construction or brick manufacturing, can therefore greatly reduce the impact of wood heating systems in the impact category of ET. Additionally, the transfer of NO_x and NH_3 emission from air (through combustion) to the marine environment are responsible for increased ET EFS. As such, approximately 32% of NO_x and 17% of NH_3 emissions from e.g. combustion ultimately reach the marine environment (Huijbregts and Seppälä, 2001). For the impact category of ET, the weighted EF of the Bavarian heating mix is 1.32E-06 kg P-eq. * MJ_{th}^{-1} and 8.89E-08 kg P-eq. * MJ_{th}^{-1} for the mix without the influence of renewable energies.

The highest EF in the impact category AC is contributed by power to heat (3.33E-04 mol H+ eq. * MJ_{th}^{-1}), due to relatively high emissions of SO_2, NO_x and NH_3 associated with the combustion of lignite and hard coal. The conversion of hard coal possesses the second highest EF with 2.09E-04 mol H+ eq. * MJ_{th}^{-1}. Since hard coal plays an important part in the German grid mix, the high EF of hard coal is also an explanation for the high EF of power. Natural gas exhibits the lowest EF in this impact category with 6.41E-05 mol H+ eq. * MJ_{th}^{-1} because of overall low emission of SO_2, NO_x and NH_3. All other energy carriers possess relatively uniform EFs for AC within a range of 1.18E-04 mol H+ eq. * MJ_{th}^{-1} to 1.71E-04 mol H+ eq. * MJ_{th}^{-1}. For the impact category of AC, the weighted EF of the Bavarian heating mix is 1.24E-04 mol H+ eq. * MJ_{th}^{-1} and 1.18E-04 mol H+ eq. * MJ_{th}^{-1} for the mix without renewable energies.

3.2. Emission factors of solid biofuel systems and influencing parameters

A closer look towards the assessed solid biofuels systems (Table 2) reveals, that the split wood systems generally have the most favorable properties in the impact category of GW with 0.007 kg CO_2-eq. * MJ_{th}^{-1} for the wood stove (ID 2.1) and almost 30% higher emissions for older tile stove (ID 2.2) technologies (0.0092 kg CO_2-eq. * MJ_{th}^{-1}) (Table 6). The biggest share (approx. 64%) of these emissions is allocated to the conversion of the wood [C] which is almost exclusively comprised of Methane (CH_4) and

Table 6
Emission Factors for individual life cycle phases of the analyzed wood heating systems per MJ_{th} of final energy. GW = Global Warming; PE = Primary Energy Consumption non-renewable; PM = Particulate Matter; ET = Freshwater Eutrophication; AC = Acidification; w = water content; A = provision of wood; B = transformation; C = conversion; E = disposal/recycling; T = transport.

ID	Description	Impact	Unit	Σ	[A]	[B]	[C]	[E]	[T]
1.1	Wood chips, central heating [50 kW]	**GW**	**[kg CO_2-eq.]**	**0.0124**	**0.0034**	**0.0010**	**0.0052**	**0.0000**	**0.0028**
		PE	[MJ]	0.1570	0.0476	0.0147	0.0538	0.0001	0.0409
		PM	[kg $PM_{2.5}$-eq.]	3.27E-05	3.07E-06	1.30E-07	2.89E-05	3.58E-09	6.64E-07
		ET	[kg P-eq.]	2.63E-06	2.20E-07	4.12E-08	1.54E-07	2.00E-06	2.19E-07
		AC	[mol of H^+ eq.]	1.27E-04	1.27E-05	1.05E-05	8.41E-05	8.03E-08	2.00E-05
1.2	Wood chips, central heating [300 kW/w = 20%]	**GW**	**[kg CO_2-eq.]**	**0.0115**	**0.0034**	**0.0010**	**0.0043**	**0.0000**	**0.0028**
		PE	[MJ]	0.1512	0.0476	0.0147	0.0479	0.0001	0.0409
		PM	[kg $PM_{2.5}$-eq.]	4.24E-05	3.07E-06	1.30E-07	3.86E-05	4.33E-09	6.64E-07
		ET	[kg P-eq.]	1.57E-06	2.20E-07	4.12E-08	7.56E-08	1.01E-06	2.19E-07
		AC	[mol of H^+ eq.]	1.23E-04	1.27E-05	1.05E-05	7.99E-05	7.62E-08	2.00E-05
1.3	Wood chips, central heating [300 kW/w = 50%]	**GW**	**[kg CO_2-eq.]**	**0.0135**	**0.0038**	**0.0018**	**0.0048**	**0.0000**	**0.0031**
		PE	[MJ]	0.1738	0.0531	0.0254	0.0496	0.0002	0.0456
		PM	[kg $PM_{2.5}$-eq.]	6.45E-05	3.42E-06	2.25E-07	6.01E-05	6.77E-09	7.41E-07
		ET	[kg P-eq.]	2.26E-06	2.46E-07	7.12E-08	1.15E-07	1.58E-06	2.44E-07
		AC	[mol of H^+ eq.]	1.76E-04	1.42E-05	1.82E-05	1.21E-04	1.19E-07	2.23E-05
1.4	Wood chips, heating plant [1000 kW]	**GW**	**[kg CO_2-eq.]**	**0.0144**	**0.0055**	**0.0011**	**0.0042**	**0.0000**	**0.0036**
		PE	[MJ]	0.2186	0.1039	0.0155	0.0467	0.0001	0.0525
		PM	[kg $PM_{2.5}$-eq.]	6.48E-05	4.05E-06	1.37E-07	5.97E-05	5.09E-09	8.85E-07
		ET	[kg P-eq.]	1.80E-06	2.51E-07	4.34E-08	6.80E-08	1.19E-06	2.48E-07
		AC	[mol of H^+ eq.]	1.52E-04	2.33E-05	1.11E-05	8.99E-05	8.95E-08	2.71E-05
2.1	Split wood, wood stove	**GW**	**[kg CO_2-eq.]**	**0.0070**	**0.0014**	**0.0009**	**0.0042**	**0.0000**	**0.0005**
		PE	[MJ]	0.0485	0.0171	0.0121	0.0115	0.0002	0.0077
		PM	[kg $PM_{2.5}$-eq.]	1.48E-04	2.57E-07	1.01E-06	1.67E-04	7.03E-09	7.96E-07
		ET	[kg P-eq.]	4.49E-06	6.91E-08	4.21E-08	3.33E-07	3.92E-06	1.18E-07
		AC	[mol of H^+ eq.]	2.02E-04	7.15E-06	9.15E-06	1.82E-04	1.58E-07	3.07E-06
2.2	Split wood, tile stove	**GW**	**[kg CO_2-eq.]**	**0.0092**	**0.0017**	**0.0010**	**0.0059**	**0.0000**	**0.0005**
		PE	[MJ]	0.0572	0.0205	0.0146	0.0138	0.0002	0.0082
		PM	[kg $PM_{2.5}$-eq.]	1.69E-04	3.08E-07	1.22E-06	1.46E-04	8.43E-09	8.82E-07
		ET	[kg P-eq.]	5.37E-06	8.29E-08	5.05E-08	4.00E-07	4.71E-06	1.32E-07
		AC	[mol of H^+ eq.]	1.20E-04	8.58E-06	1.10E-05	9.70E-05	1.89E-07	3.02E-06
3.1	Wood pellets, central heating [15 kW]	**GW**	**[kg CO_2-eq.]**	**0.0261**	**0.0069**	**0.0087**	**0.0063**	**0.0000**	**0.0042**
		PE	[MJ]	0.4753	0.2305	0.1218	0.0625	0.0001	0.0604
		PM	[kg $PM_{2.5}$-eq.]	4.74E-05	1.62E-06	8.51E-06	3.62E-05	2.78E-09	1.04E-06
		ET	[kg P-eq.]	2.98E-06	1.04E-07	4.59E-07	6.32E-07	1.55E-06	2.28E-07
		AC	[mol of H^+ eq.]	1.82E-04	2.53E-05	3.20E-05	9.25E-05	6.24E-08	3.25E-05
3.2	Wood pellets, central heating [50 kW]	**GW**	**[kg CO_2-eq.]**	**0.0246**	**0.0069**	**0.0087**	**0.0047**	**0.0000**	**0.0042**
		PE	[MJ]	0.4619	0.2305	0.1218	0.0491	0.0001	0.0604
		PM	[kg $PM_{2.5}$-eq.]	3.79E-05	1.62E-06	8.51E-06	2.67E-05	2.78E-09	1.04E-06
		ET	[kg P-eq.]	2.55E-06	1.04E-07	4.59E-07	2.01E-07	1.55E-06	2.28E-07
		AC	[mol of H^+ eq.]	1.79E-04	2.53E-05	3.20E-05	8.95E-05	6.24E-08	3.25E-05

Nitrous Oxide (N_2O) emissions. The provision [A] and the transformation [B] of wood have shares of approximately 19% and 12%, respectively. This amounts to a reduction of GHG-emissions between the older tile stove and the modern wood stove of approximately 25%. In comparison to previous studies, the same improvement of EFs with the introduction of modern technologies (approx. −30% GHG − emissions) can be observed (Solli et al., 2009).

Wood chip central heating systems exhibit emissions between 0.0115 kg CO_2-eq. * MJ_{th}^{-1} for the 300 kW central heating system utilizing dried wood (ID 1.2) and 0.0135 kg CO_2-eq. * MJ_{th}^{-1} for the 300 kW central heating system utilizing green wood (ID 1.3). The biggest share, as with split wood heating systems albeit considerably lower, is located in process group [C] with a range of 42% up to 50% depending on the conversion properties. Consequently, process groups [A] (approx. 28%) and additionally, [T] (approx. 23%) are of greater influence in the wood chip heating systems. A more mechanized approach to harvesting and greater transportation distances, in comparison to split wood, is an explanation. In comparison to literature data, our results are within the range of previously published results, with 0.01125 kg CO_2-eq. * MJ_{th}^{-1} (Pucker et al., 2012) and 0.029 kg CO_2-eq. * MJ_{th}^{-1} (Esteban et al., 2014). However, Esteban et al. (2014) includes carbon stock changes in the forest due to forest management practices, averaged over 100 years, which are responsible for the considerably higher emissions published in this study.

In contrast to the above mentioned wood chip heating systems, the heating plant (ID 1.4) exhibits the greatest share of emissions in [A] (55%), since in the heating plant three different wood inputs are combusted (industrial wood residues (IWR), recovered wood and wood chips). In the case of IWRs the emissions of the production process of sawn wood were partly allocated onto the IWRs. Also the conversion of wood to energy is more efficient in terms of flue gas cleaning and stable combustion properties in the heating plant, thus reducing emissions of [C]. In comparison to Pehnt (2006) who modelled the combustion of forest wood residues (0.006 kg CO_2-eq. * MJ_{th}^{-1}) the biomass procurement in our scenario is adapted to Bavarian conditions and combusts a mix of wood types, which are responsible for more than half of the total emissions. This is the reason for the considerably higher emissions modelled for our heating plant.

For pellet heating systems, an impact on GW between 0.0246 kg CO_2-eq. * MJ_{th}^{-1} for the 50 kW system (ID 3.2) and 0.0261 kg CO_2-eq. * MJ_{th}^{-1} for the 15 kW system (ID 3.1) could be identified. The 50 kW systems being more efficient in process group [C]. In contrast to all other systems, process group [B] transformation exhibits the highest share of emissions. Electrical power for the transformation of wood to wood-pellets (for grinding and pelletization) is responsible for the increased shares. Process groups [A] (approx. 27%) and [C] (approx. 19–24%) possess the second- and third largest share with [A] again considering the allocated IWR system. In comparison to other pellet heating systems our results exhibit higher emissions. Damen and Faaij (2005) show emissions of 0.011 kg CO_2-eq. * MJ_{th}^{-1}, for Canadian pellet heating conditions, where considerably lower shares of coal and higher shares of hydro-energy are determining the electricity mix. Additionally, infrastructure and the biomass end of life phase were neglected in this study.

From a standpoint of GW mitigation, split wood heating systems have the most favorable properties with pellets exhibiting the worst properties. This is somewhat compensated by favorable properties in other impact categories. Consecutively, pellet systems offer the best results for emissions of PM for [C] with 0.027 g PM2.5-eq. * MJ_{th}^{-1} for ID 3.2 (50 kW) (71%). Other particle emissions during [T], e.g. through grinding and pelletization, negate this to a certain degree, with a share of 17%–27% of total pellet PM emissions (0.38 g PM2.5-eq. * MJ_{th}^{-1}). Split wood systems (ID 2.1/ID 2.2) exhibit the overall worst properties in this impact category with 0.15 g $PM_{2.5}$-eq. * MJ_{th}^{-1} for ID 2.1 and 0.17 g $PM_{2.5}$-eq. * MJ_{th}^{-1} for ID 2.2 with process group [C] being responsible for 98% of all PM emissions due to the incomplete combustion of solid biofuels (Nussbaumer et al., 2008). With the large share of split wood heat in the final energy balance of the Bavarian heating mix, this EF heavily influences the particle emissions of the weighted EF for solid biofuels. In general, process group [C] has the biggest influence on the emissions of particles due to the above-mentioned reason. In contrast, for the impact category ET, in most cases, process group [E], ash disposal, is of the highest importance due to the amounts of P, in conjunction with its high characterization factor for aquatic ET, contained in the ash. Additionally Diesel consumption in process groups [A] and [T] can have considerable impact on ET scores, with shares up to 14% for [A] and 15% for [T]. Especially for systems where fresh wood with a low heating value is used, the importance of process groups [A] and [T] increases. This effect however, is not only the case for ET, but for all impact categories. The lowest values for ET are exhibited by ID 1.2 (300 kW-dry wood chips) with 1.57E-06 kg P-eq. * MJ_{th}^{-1}, whereas ID 2.2 (tile stove-split wood) possesses the highest ET score of 5.37E-06 kg P-eq. * MJ_{th}^{-1} which is mostly due to variations in the efficiency of the conversion technology and the subsequent amount of wood ash produced. Again, the choice of treatment in [E] has considerable impact for these two systems. Whereas ID 1.2 deposits over half of the produced wood ash, ID 2.2 treats the wood ash under the assumption of a composting. The consumption of power in the production and conversion of pellets is also responsible for a considerable share of ET emissions in these systems with a total ET score of 2.98E-06 kg P-eq. * MJ_{th}^{-1} for ID 3.1–15 kW ([T] = 15%; [C] = 21%). The emission of acidifying substances (e.g. SO_2, NO_x) primarily takes place in process group [C] with shares between 59% and 91% for all wood heating systems. The degree of mechanization and transportation also corresponds to increased AC emissions. As such, efficient split wood heating systems (ID2.2 – tile stove) possesses the most favorable properties in this impact category (1.2E-04 mol H+ eq. * MJ_{th}^{-1}). On the example of the two split wood systems the importance of a modernized combustion infrastructure can be demonstrated, since the second split wood system (ID2.1 – wood stove) offers the least favorable score in this impact category (2.02E-04 mol H+ eq. * MJ_{th}^{-1}) (Table 6). This can be explained by the low efficiency (manual feeding, no moisture monitoring, non-expert handling) and combustion properties of the system in question resulting in shares of upwards of 98% for the process group [C] in this impact category. For more mechanized systems (pellets and wood chips) AC emissions react to the degree of energy inputs into the system, e.g. in the form of machinery, power or transportation.

3.3. Scenario results

3.3.1. Baseline

In 2011, 663.715 TJ of final energy in the form of thermal energy for heating were provided. Compared to previous years (2008–2010), no distinctive gains or decreases can be identified. Although, efforts are made to reduce the demand for thermal energy for heating in buildings (e.g. through insulation or efficient heating systems, the provision and demand for thermal energy remain almost constant). The provision of heat in the state (the Bavarian heating mix) is still dominated by fossil energy carriers, i.e. Natural Gas and LFO with shares of 42.6% and 21.7% respectively (Fig. 3). Due to its relatively favorable GW EF natural gas is responsible for a smaller share in this impact category (37.8%), while LFO exhibits a share of 24.8% of the total GHG emissions of the Bavarian heating mix, which has total impact on GW of approximately 49.6 Mt CO_2-eq. * yr^{-1} (Table 7). Renewable energies, with a share of 15.1% of final energy, also play an important role. Within the group of renewable energies, solid biofuels, e.g. wood, are responsible for a share of approximately 84% and 12.6% of the total final energy for heat. The group of “other renewables” has a share of 2.5%. A recent study, which was carried out by the authority of the Bavarian government, finds considerably larger final energy amounts and shares for renewable energies, as well as a total final energy amount that is approximately 3% lower than our findings (Ebert and Voigtländer, 2014). Ebert and Voigtländer (2014) state that renewable energies have a share of 17.9% of the total final energy used for heat, whereas we identified a share of 15.1%. Since their findings are, in some cases, based on assumptions or expert interpretations, the information provided does not allow for adjustment to be made to the official statistics. As such, it was necessary for us to use the official data provided in the Bavarian Energy Balance, while possibly undervaluing the share of renewables.

District heat, LPG, lignite, hard coal and others exhibit a combined share of 11.1% (Table 7). While providing more than 16% of the total final energy, renewable energies are only responsible for approx. 1.7% of the entire heating mix's total impact on GW. In contrary, with a share of GW impacts of 21.8%, power for heat, i.e. electric heaters, night storage heaters, air conditioners, only contribute about 9.6% to the total final energy for heat in Bavaria (Fig. 5).

In order to provide the amount of 663.715 TJ of final energy, 721.987 TJ of non-renewable primary energy were expended. However, the impact category Particulate Matter (PM) is heavily dominated by the influence of solid biofuels with a share of 79.8% (11.636 t of $PM_{2.5}$-eq), which is explained by the large share of split wood heating systems currently employed in the state. In total, 14.580 t of $PM_{2.5}$-eq. * yr^{-1} were emitted in 2011 for the provision of heat. Efforts to reduce the specific PM emissions have been initiated in Germany in the form of the amendment of the 1. federal emissions protection regulation (BImSchV) (BMU, 2010), which is bound to have substantial impact on the emissions of particulate matter from split wood and wood chips heating systems due to future retrofitting or replacement of heating systems. If this the retrofitting or replacement of inefficient wood heating systems is implemented, a potential future reduction of particulate matter emissions of up to 50% could be realized in the next 30 years, if wood consumption for heat remains on a constant level. However, if the consumption of wood for energy will increase, the particulate matter emission targets set by the BImSchV could be in jeopardy (Wilnhammer et al., 2016).

For ET almost all non-renewable energy carriers show very low shares between 0.1% (natural gas) and 2.4%. In contrast, renewable

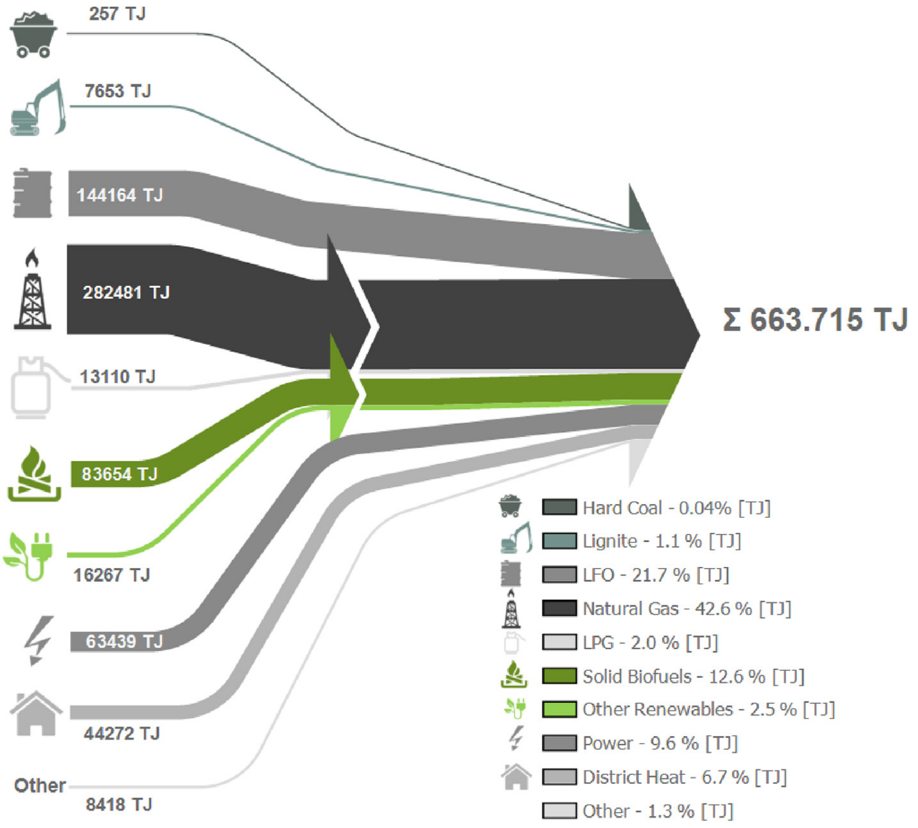

Fig. 3. Baseline heating mix in Bavaria in 2011 per energy carrier. LFO = light fuel oil; LPG = liquid propane gas.

energies exhibit a combined share of 94.2%. In total 876.1 t P-eq. * yr^{-1} were emitted for the provision of heat in Bavaria.

Shares of contribution to the total AC are proportional, except for natural gas (reduced), solid biofuels (elevated) and power (elevated), to the energy carrier's share of final energy. In total 82.468 kmol H+ eq. * yr^{-1} were emitted in 2011 for the provision of heat. The biggest contributor is power with a share of 25.6% (Table 7).

For the emissions of the heating mix, and the employed EFs for solid biofuels, a weighted EF according to the individual technologies installed capacity in the state, based on Joa et al. (2015) was employed. Other sources state varying amounts of installed heating systems and also of installed capacities (Gaggermeier et al., 2014). Employing the figures published in Gaggermeier et al. (2014) would result in a shift of the weighted EF, because the study exhibits a lower number of split wood systems, thus reducing the impact these systems have on the weighted EF, potentially increasing e.g. the impact on GW but decreasing the PM emissions. Since the final energy amounts in respect to solid biofuels remain the same, shifts in total emissions are a possibility but are assumed to be negligible. Furthermore, an additional effect of a shift in weighting factors would lead to changes in the weighted substitution percentiles. Again, this can lead to changes in the sum of total emissions. The LCA systems for solid biofuels are based on typical regional production processes. As such, transportation distances as well as the employed machinery and fuels can vary for more specialized scenarios. However, since it was our aim to assess the heating mix on a regional scale, such as the region of Bavaria, we opted to depict typical production processes. Furthermore, we wanted to show the influence of solid biofuels on the heating mix's emissions, thus LCA impact categories relevant to solid biofuels were reported. In consequence, we see great shares of the total emissions in these impact categories being dominated by solid biofuels, while conventional energy carriers such as natural gas or LFO play only minor roles. A more comprehensive set of impact categories, also including impact categories that offer higher sensibility to the environmental effects of conventional energy carriers might be favorable. This shortcoming is especially prevalent for the impact category of ET, where renewable energies play the most important role. In this impact category, the group of “other renewables” with a share of only 2.5% of the final energy is responsible for 51.3% of the ET emissions, with near-surface geothermal heat (heat pumps) being responsible for the majority of these emissions. A further analysis of this fact would be favorable, but was impossible due to the nature of the data sets used.

3.3.2. *Wood utilization scenarios for the provision of heat in Bavaria*

Emissions for scenario one (S1) – Bavarian Energy Concept 2011, based on the political goals for solid biofuels (a 15% increment of raw wood for energetic purposes) and subsequent reductions of other energy carriers via application of adequate substitution percentiles (Table 4) show an additional potential for aiding national climate change mitigation actions through the use of wood of approximately 1 Mt CO_2-eq. * yr^{-1}. This is an approximate decrease of 2% of the total GHG-emissions of the heating sector (Fig. 6). Reductions are mainly achieved through the displacement of LFO (−4.3%) and natural gas (−1.4%). But simultaneously, an increase of 11.6% of PM emissions and 6.4% of ET emissions can be expected. The assumptions in S1 would lead to total GHG – emissions of 48.64 Mt CO_2-eq. * yr^{-1}. Without the possible reductions of PM through German regulations (BMU, 2010), the rise in PM emissions is also consistent with the findings of Weber-Blaschke et al. (2015) and Wilnhammer et al. (2015).

Table 7
Emissions of the analyzed scenarios for a provided amount of 663.715 TJ_{th} of final energy for heating. GW = Global Warming; PE = Primary Energy Consumption non-renewable; PM = Particulate Matter; ET = Freshwater Eutrophication; AC = Acidification.

Scenario		GW without biogenic CO_2 (IPCC, 2007)		PE (non-renewable)		PM (Rabl and Spadaro, 2012)		ET (Struijs et al., 2009)		AC (Seppälä et al., 2006)	
		[Mt. CO_2-eq.]	[%]	[TJ]	[%]	[t. $PM_{2.5}$-eq]	[%]	[t. P-eq.]	[%]	[kmol H^+ eq.]	[%]
Baseline	Natural Gas	18.75	37.8	304,462	42.2	448	3.1	0.6	0.1	18,110	22.0
	LFO	12.30	24.8	169,880	23.5	520	3.6	2.0	0.2	17,168	20.8
	Power	10.83	21.8	146,720	20.3	1013	6.9	20.7	2.4	21,117	25.6
	District Heat	3.98	8.0	55,056	7.6	236	1.6	0.4	0.0	5855	7.1
	LPG	1.10	2.2	15,308	2.1	84	0.6	0.4	0.1	1541	1.9
	Lignite	0.87	1.8	7680	1.1	59	0.4	0.0	0.0	1223	1.5
	Solid Biofuels	0.85	1.7	8555	1.2	11,636	79.8	376.3	42.9	13,318	16.1
	Other Renew.	0.46	0.9	8390	1.2	236	1.6	449.7	51.3	2786	3.4
	Other	0.43	0.9	5661	0.8	346	2.4	26.0	3.0	1298	1.6
	Hard Coal	0.03	0.1	274	0.0	3	0.0	0.0	0.0	54	0.1
	Σ	**49.61**		**721,987**		**14,580**		**876.1**		**82,468**	
Bavarian Energy Concept	Natural Gas	18.48	38.0	300,161	42.4	442	2.7	0.6	0.1	17,854	21.5
	LFO	11.76	24.2	162,497	23.0	497	3.1	1.9	0.2	16,422	19.8
	Power	10.67	21.9	144,492	20.4	997	6.1	20.4	2.2	20,797	25.1
	District Heat	3.91	8.0	53,996	7.6	231	1.4	0.3	0.0	5742	6.9
	LPG	1.10	2.3	15,308	2.2	84	0.5	0.4	0.0	1541	1.9
	Solid Biofuels	0.98	2.0	9838	1.4	13,381	82.2	432.7	46.4	15,315	18.5
	Lignite	0.84	1.7	7377	1.0	56	0.3	0.0	0.0	1175	1.4
	Other Renew.	0.46	1.0	8390	1.2	236	1.4	449.7	48.2	2786	3.4
	Other	0.43	0.9	5661	0.8	346	2.1	26.0	2.8	1298	1.6
	Hard Coal	0.01	0.0	88	0.0	1	0.0	0.0	0.0	17	0.0
	Σ	**48.64**		**707,809**		**16,272**		**932.1**		**82,946**	
Wood Mobilization – Private Forest	Natural Gas	18.55	37.9	301,219	42.3	444	2.8	0.6	0.1	17,917	21.6
	LFO	11.89	24.3	164,314	23.1	502	3.2	2.0	0.2	16,606	20.0
	Power	10.71	21.9	145,041	20.4	1001	6.3	20.5	2.2	20,876	25.2
	District Heat	3.93	8.0	54,257	7.6	233	1.5	0.4	0.0	5770	7.0
	LPG	1.10	2.3	15,308	2.2	84	0.5	0.4	0.0	1541	1.9
	Solid Biofuels	0.95	1.9	9522	1.3	12,952	81.7	418.8	45.6	14,824	17.9
	Lignite	0.85	1.7	7452	1.0	57	0.4	0.0	0.0	1186	1.4
	Other Renew.	0.46	0.9	8390	1.2	236	1.5	449.7	49.0	2786	3.4
	Other	0.43	0.9	5661	0.8	346	2.2	26.0	2.8	1298	1.6
	Hard Coal	0.01	0.0	134	0.0	1	0.0	0.0	0.0	26	0.0
	Σ	**48.88**		**711,298**		**15,855**		**918.3**		**82,829**	
100% Energetic Use	Natural Gas	17.20	39.0	279,299	43.7	411	1.7	0.6	0.0	16,613	19.4
	Power	9.87	22.4	133,691	20.9	923	3.8	18.9	1.6	19,242	22.5
	LFO	9.17	20.8	126,685	19.8	387	1.6	1.5	0.1	12,803	15.0
	District Heat	3.53	8.0	48,851	7.6	209	0.9	0.3	0.0	5195	6.1
	Solid Biofuels	1.60	3.6	16,062	2.5	21,846	89.2	706.4	58.7	25,004	29.3
	LPG	1.10	2.5	15,308	2.4	84	0.3	0.4	0.0	1541	1.8
	Lignite	0.67	1.5	5910	0.9	45	0.2	0.0	0.0	941	1.1
	Other Renew.	0.46	1.0	8390	1.3	236	1.0	449.7	37.4	2786	3.3
	Other	0.43	1.0	5661	0.9	346	1.4	26.0	2.2	1298	1.5
	Hard Coal	0.00	0.0	0	0.0	0	0.0	0.0	0.0	0	0.0
	Σ	**44.04**		**639,857**		**24,488**		**1203.8**		**85,422**	
0% Energetic Use	Natural Gas	20.51	36.6	333,137	40.8	491	14.9	0.7	0.1	19,816	25.0
	LFO	15.86	28.3	219,104	26.8	670	20.3	2.6	0.5	22,143	27.9
	Power	11.93	21.3	161,567	19.8	1115	33.8	22.8	4.5	23,254	29.3
	District Heat	4.49	8.0	62,128	7.6	266	8.1	0.4	0.1	6607	8.3
	LPG	1.10	2.0	15,308	1.9	84	2.5	0.4	0.1	1541	1.9
	Lignite	1.10	2.0	9697	1.2	74	2.2	0.0	0.0	1544	1.9
	Other Renew.	0.46	0.8	8390	1.0	236	7.1	449.7	89.5	2786	3.5
	Other	0.43	0.8	5661	0.7	346	10.5	26.0	5.2	1298	1.6
	Hard Coal	0.15	0.3	1516	0.2	16	0.5	0.0	0.0	297	0.4
	Solid Biofuels	0.00	0.0	0	0.0	0	0.0	0.0	0.0	0	0.0
	Σ	**56.05**		**816,509**		**3298**		**502.6**		**79,284**	

Scenario S2 – wood mobilization from private forests, represents the scientific approach to the determination of solid biofuels potentials in the state based on Wilnhammer et al. (2012), where energy wood mobilization potential from private forests were assessed. Results for this scenario are very similar to S1 while being more conservative in the estimation of available solid biofuels. As such, total emissions in the impact category of GW of 48.88 Mt CO_2-eq. * yr^{-1} were calculated, which correspond to savings of 0.73 Mt CO_2-eq. * yr^{-1} (approx. 1.5% compared to baseline conditions). Developments in other impact categories follow the patterns of S1 (Fig. 6).

Scenario S3 – 100% energetic wood use is intended to display the limits of wood energy potentials from Bavarian forests. The scenario shows that, even though 100% of the available wood in the state (approx. 20.2 M m^3 under bark, see Table 4) would be used for energetic purposes, the share of energy from solid biofuels in the heating mix cannot surpass 25%. Of course, this is under the assumption of a sustainable forest management. Accordingly, the maximum additional GHG savings of wood from Bavarian forests are approx. 5.6 Mt CO_2-eq. * yr^{-1} compared to baseline conditions for the reference year 2011 leading to maximum GHG-savings of 11%. The trade-off is an increase of PM emissions of 68% and of ET emission of 37%. The share of natural gas and LFO for S3 decreases to 38.9% and 16.2% respectively (Fig. 4). We underline that a 100% energetic use of wood is not realistic or useful, since the material use of wood is inhibited, but it clearly indicates that using wood for energetic purposes is in fact a key to fulfilling climate change mitigation goals in Bavaria and Germany. However, since the mitigation effects are limited it cannot be classified as the singular solution.

In the absence of the utilization of wood for the provision of heat (as it is depicted in Scenario S4 – 0% energetic wood use), the share of natural gas and LFO increases to 46.6% and 28.0% respectively, entailing increased impacts on GW of 6.4 Mt CO_2-eq. * yr^{-1}. This represents an increase of 13% (Fig. 6) in total GHG-emissions to 56.05 Mt CO_2-eq. * yr^{-1}. Similar to S3, S4 is not a realistic scenario as wood is a well-established part of the heating mix in Bavaria and changes in this regard are not expected. Nevertheless, the comparison of the baseline and the S4 heating mix scenario without energetic wood use shows the climate change mitigation performance of the **current** share of wood. GHG-emissions would be 13% higher without the energetic use of wood. Of course, under the assumption, that other renewables are still limited and mainly natural gas and LFO are displaced.

Using a specific wood energy mix and specific LCA calculations for the different systems helps to avoid the use of generalized displacement factors as employed in similar studies (e.g. Klein et al., 2013). This leads to more realistic and detailed results. Furthermore, our calculations allow for new specified displacement factors through energy substitution, based on the current wood energy mix for Bavarian conditions. These displacement factors are currently under preparation.

4. Conclusions

This study for the first time provides the distribution of energy carriers for the provision of heat, i.e. the current and potential future structures of the heating mix, and their consequential environmental effects in the study region. The study chose the region of Bavaria, due to the availability of data for the research group. Of course, the tools and assessment methodology can be implemented for any other region for which the required data can be obtained. Emission factors for individual heating systems, weighted emission factors and total environmental effects for the region are provided, which can be utilized for future assessments. Additionally, the assessment of different solid biofuels utilization

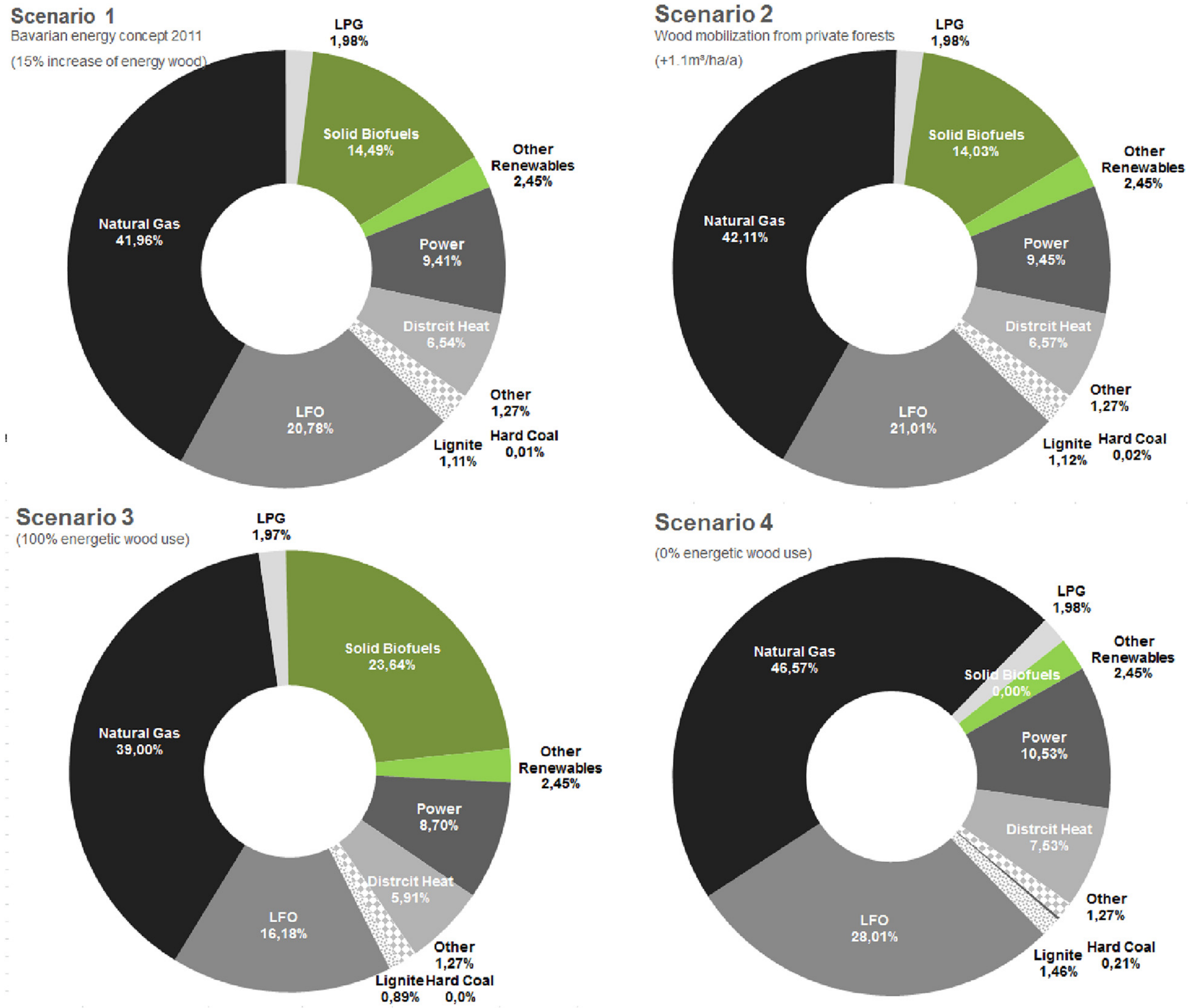

Fig. 4. Shares of heating mix per final energy carrier for the four scenarios. Scenario 1: Bavarian energy concept 2011; Scenario 2: Wood mobilization from private forests; Scenario 3: 100% energetic use of wood; Scenario 4: 0% energetic use of wood. LFO = light fuel oil; LPG = liquid propane gas.

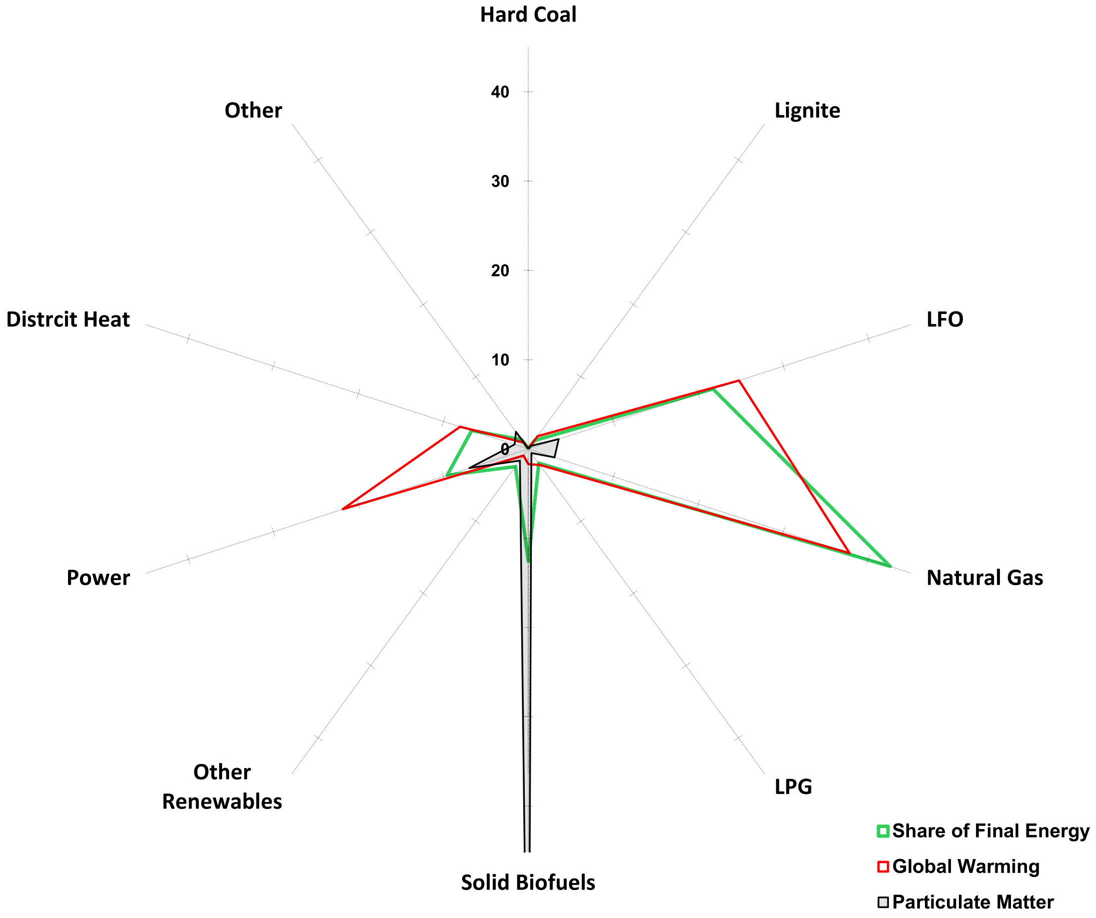

Fig. 5. Shares [%] per energy carrier of the final energy (Fig. 3) mix and the impact on Global Warming and Particulate Matter emissions (Table 7). LFO = light fuel oil; LPG = liquid propane gas.

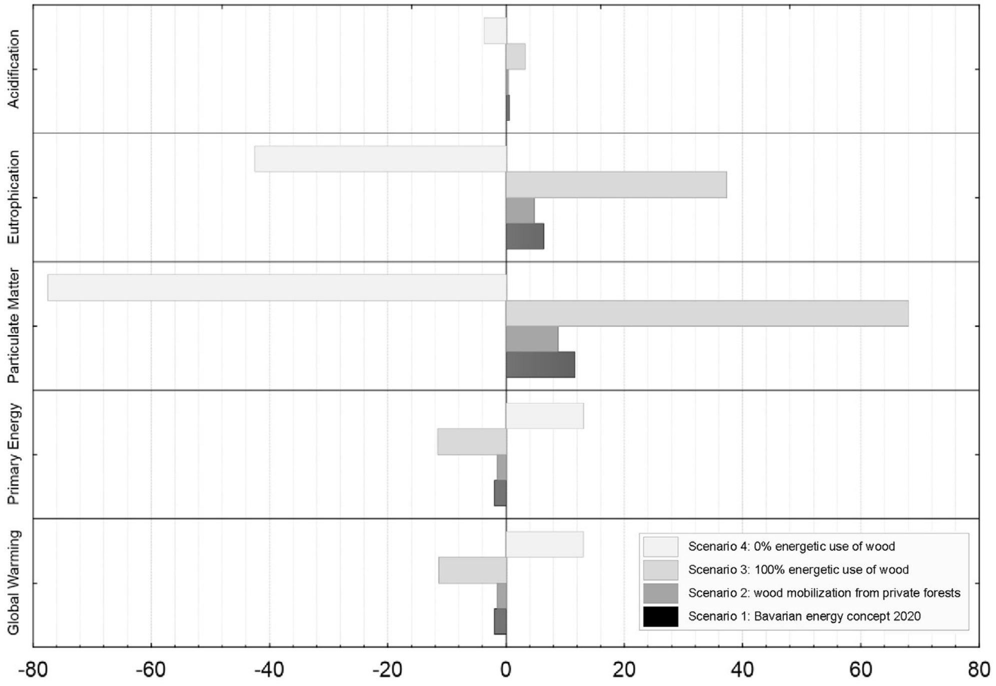

Fig. 6. Relative changes in the analyzed environmental impact categories in comparison to baseline conditions (heating mix 2011). S1 = Scenario 1: Bavarian energy concept 2011; S2 = Scenario 2: Wood mobilization from private forests; S3 = Scenario 3: 100% energetic use of wood; S4 = Scenario 4: 0% energetic use of wood.

pathways does not necessarily have to be the main focus for this type of assessment. Any other resource or technology, depending on the focus of the study, may be focused on, such as other renewable or conventional energy carriers or final energy provided by these technologies. On the basis of our research, the following conclusions can be drawn:

(1) In 2011 a total amount of 663.715 TJ of final energy was used for the provision of heat in the state of Bavaria. The heating mix is dominated by natural gas (42.6%) and light fuel oil (21.7%). Solid biofuels exhibit the third largest share with 12.6%.

(2) A regionalized and weighted emission factor for heat from solid biofuels of 0.0028 kg CO_2-eq. * MJ_{th}^{-1} could be identified. An emission factor for the complete heating mix of 0.075 kg CO_2-eq. * MJ_{th}^{-1}, and of 0.086 kg CO_2-eq. * MJ_{th}^{-1} for the mix without the influence of renewable energies was deduced. For the impact on GW, important parameters are the transportation distance, auxiliary energy inputs, the biomass water content and the combustion efficiency. Particulate matter emissions are strongly influenced by the combustion technology and the water content of the wood. High water contents entail low heating values, which necessitates the combustion of additional wood in order to obtain the same amount of final energy. Freshwater Eutrophication is most influenced by choices pertaining the amount and treatment of the wood ash, while acidification is influence by the combustion and filter technologies.

(3) The heating mix in Bavaria (Baseline) causes emissions of 49.6 Mt CO_2-eq. * yr^{-1}, 14.580 t of $PM_{2.5}$-eq. * yr^{-1}, 876.1 t P-eq. * yr^{-1} and 82.468 kmol H+ eq. * yr^{-1}, for which 721,787 TJ of primary energy were expended.

(4) Emissions for Scenario 1 – "Bavarian energy concept" show a potential reduction of GHG-emissions of approximately 1 Mt CO_2-eq. * yr^{-1}, an increase in particulate matter emissions of 1690 t of $PM_{2.5}$-eq. * yr^{-1}, and an increase in freshwater eutrophication of 56 t P-eq. * yr^{-1}. Scenario 2 – "wood mobilization from private forests" exhibits slightly more moderate changes. Scenario 3 – "100% energetic wood use" demonstrates that the maximum share of solid biofuels of the heating mix cannot surpass 25% under the current sustainable forest management practices. Scenario 4 – "0% energetic wood use" shows the climate change mitigation performance of the current use of solid biofuels. GHG-emissions would be 13% higher without this energetic use of wood, of course, entailing considerable emissions through the use of alternative fuels in order to satisfy the demand for heat. It was additionally demonstrated that solid biofuels exhibit favorable climate change mitigation properties. Nevertheless, they also entail considerable problems in other environmental impact categories, which can only partially be mitigated by technology- or life cycle design.

We recommend the expansion of this assessment to other areas of biomass utilization, such as the generation of power of transport services, in order to obtain the total performance and contribution of the use of biomass towards climate change mitigation and other important environmental impacts. Additionally, leakage effects, such as the import of biomass, are also critical factors for the assessment of environmental sustainability and climate change mitigation potentials and should be integrated in further assessments.

For the assessment of the reduction of environmental effects, in comparison to other energy carriers such as fossil fuels, generalized and often arbitrary displacement factors were employed in the past. This research lays the foundation for more specialized and accurate displacement factors for individual technologies and mixes, which will be expanded upon in subsequent research.

Acknowledgements

This study was part of the project "Experts Group Resource Management Bio-energy in Bavaria" ("ExpRessBio- Expertengruppe Ressourcenmanagement Bioenergie Bayern"). The authors thank the Bavarian State Ministry of Food, Agriculture and Forestry for funding.

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IV

Science of the Total Environment 569–570 (2016) 395–403

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Mitigating environmental impacts through the energetic use of wood: Regional displacement factors generated by means of substituting non-wood heating systems

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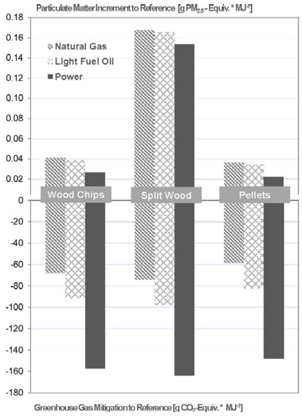
HIGHLIGHTS

- Stratified displacement factors through wood heating in Bavaria were developed.
- A method for creating displacement factors in other regions is suggested.
- Wood heating entails substantial GHG mitigation effects but increased PM emissions.
- Wood heat displaces -90.3 g CO_2-eq.$*$MJ^{-1} compared to the fossil heating mix.
- The reference system has the biggest impact on the magnitude of GHG mitigation.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 14 April 2016
Received in revised form 25 May 2016
Accepted 4 June 2016
Available online xxxx

Keywords:
LCA
Heat
Displacement
Regional
Energy
Substitution

ABSTRACT

Wood biomass, especially when applied for heating, plays an important role for mitigating environmental impacts such as climate change and the transition towards higher shares of renewable energy in today's energy mix. However, the magnitude of mitigation benefits and burdens associated with wood use can vary greatly depending on regional parameters such as the displaced fossil reference or heating mix. Therefore, regionalized displacement factors, considering region-specific production conditions and substituted products are required when assessing the precise contribution of wood biomass towards the mitigation of environmental impacts. We carried out Life Cycle Assessments of wood heating systems for typical Bavarian conditions and substitute energy carriers with a focus on climate change and particulate matter emissions. In order to showcase regional effects, we created weighted displacement factors for the region of Bavaria, based on installed capacities of individual wood heating systems and the harvested tree species distribution. The study reveals that GHG displacements between -57 g CO_2-eq.$*$MJ^{-1} of useful energy through the substitution of natural gas with a 15 kW spruce pellets heating system and -165 g CO_2-eq.$*$MJ^{-1} through the substitution of power utilized for heating with a modern 6 kW beech split log heating system can be achieved. It was shown that the GHG mitigation potentials of wood utilization are overestimated through the common use of light fuel oil as the only reference system. We further propose a methodology for the calculation of displacement factors which is adaptable to

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http://dx.doi.org/10.1016/j.scitotenv.2016.06.021

other regions worldwide. Based on our approach it is possible to generate displacement factors for wood heating systems which enable accurate decision-making for project planning in households, heating plants, communities and also for entire regions.

1. Introduction

Environmental effects of wood biomass through a material or energetic application can entail benefits associated with the displacement of other, often times more harmful, building materials or energy carriers (Sathre and O'Connor, 2010). Existing European and German policies consider the use of biomass to entail GHG reductions and subsequently aim to promote bioenergy (EC, 2009; Bundesregierung, 2011). Not all uses however, are equally suitable for a renewable, but not infinite resource such as wood which offers a wide array of potential applications, not only as an energy carrier, but also as a building material or as raw material for the chemical industry (BMU, 2014).

One application which has historically been well suited and important for wood, both in developed and developing countries, is the provision of heat which is even more evident in the structure of today's heating mixes, where e.g. in Bavaria approximately 80% of renewable heat is provided by solid biomass (solid biomass is the term used in the official statistics published by the Bavarian State Institute for Statistics and Data Processing for a group of energy carriers which consists to more than 95% of wood) (Wolf et al., 2016). Especially, if an increase in the supply of sustainably produced wood is not to be expected in the future, the most efficient technology for the consumption of wood should be prioritized. Due to high efficiencies when compared to other applications, such as the generation of power or transportation fuels, the conversion of wood to heat can fulfill this condition (Cherubini and Strømman, 2011). Of course, an efficient resource use can also be obtained by increasing the lifetime of products and through the cascading of its resources, followed by a final thermal use of the wood (Höglmeier et al., 2015).

Hence, the total benefit or burden of the wood utilization system is quantified as the sum of environmental effects, typically identified through life cycle assessments (LCA), associated with the production of the wood product in comparison to the environmental effects associated with the production of one or more reference products which are displaced by the wood product.

For the wood in building products, a variety of studies assess the displacement of conventional building materials with wood and provide conferrable displacement factors which can be utilized for any sufficiently equal building product (Taverna et al., 2007; Sathre and O'Connor, 2010; Suter et al., 2016). For energy systems the regional displacement is determined by a national mix or supplier mix of energy carriers, and therefore no general and conferrable displacement factors can be disclosed. Identifying the mix of energy carriers for the provision of power is rather trivial, whereas this does not hold true for the provision of heat. Its decentralized structure and lacking obligations to report fuel consumptions and emissions pose a challenge when determining the heating mix and subsequent displacements. For this reason, typically a mix of light fuel oil (LFO) and natural gas, or only one of them is used when assessing the GHG mitigation potentials of a heating system (Jäppinen et al., 2014; Felder and Dones, 2007; Ghafghazi et al., 2011; Esteban et al., 2014; Katers et al., 2012; Knauf et al., 2015). This can, due to the aforementioned importance of the reference system, lead to skewed results and flawed interpretations and the actual GHG mitigation through using wood for heating is not depicted. This is why the utilization of stratified emission factors is practiced by the annual national Greenhouse Gas inventory report under the UNFCCC, where actual GHG emissions of the energy mix, also for heat, are reported (Umweltbundesamt, 2014). Since the choice of reference system consequently is of great impact towards the interpretation of the LCA, it should be carefully chosen in order to reflect the actual displacement occurring. Finally, actual GHG mitigation effects are a matter of scaling and differ for systems like a household, a community, a region or a country. It is therefore the aim of this study to provide GHG mitigation factors for the displacement of energy carriers through various wood heating systems in Bavaria, southern Germany. In our research we addressed the following research questions:

1. What methodical steps are required in order to depict the environmental effects of the displacement of various energy carriers with wood used for heating on a household and on a regional level and how can these methods be transferred to other countries or regions?
2. On the example of Bavaria, what is the magnitude of GHG mitigation of the most frequent wood heating systems when displacing individual non-wood energy carriers or a weighted heating mix currently used for the provision of heat in the study region of Bavaria?
3. What are environmental tradeoffs, e.g. in the form of emissions of particulate matter, associated with the GHG mitigation of wood heating systems?

2. Material and methods

Determining the magnitude of a displacement, i.e. the amount of environmental effects caused by a system in comparison to a reference system requires the examination of both systems' life cycles. In the case of this study, the displacement effect (further described as "displacement factor") is the difference between the non-wood and the wood system, where a system can be a single heating appliance, a heating plant or an entire region.

$$\begin{aligned}&\text{Displacement effect}\\&\quad=\text{Environmental Burden}_{\text{wood}}-\text{Environmental Burden}_{\text{non wood}}\end{aligned}$$

For this study, environmental effects, with a focus on GHG emissions, of wood heating systems and their reference systems, both fossil and renewable, were analyzed through LCA in accordance to DIN EN ISO 14044 (DIN, 2006). The selection of assessed wood heating systems in the case study area is based on Joa et al. (2015), which, by means of expert interviews and literature, represents the installed capacities and location of wood heating systems in Bavaria in the year 2012, while the modeling of the wood heating systems (i.e. the employed emission factors) follows the assumptions of Wolf et al. (2016). A system description and the applied modeling parameters for the wood heating systems can be found in Fig. 1.

The life cycle of each heating system starts with the raw material acquisition phase which is the provision of wood [A]. Due to similarities in wood properties of native softwoods, heating systems utilizing softwood were modeled as if spruce was employed. The same applies for native hardwoods, which were modeled as beech. In the subsequent transformation phase [B], three assortments of wood energy carriers, split wood, wood chips and wood pellets are produced, transported [T] and converted into final energy [C] through a variety of energy carrier specific heating systems (Fig. 1). All systems were modeled from cradle to grave with the omission of the waste treatment phase [E], which is of very minor impact for most heating systems and is cut off following the <1%/95% cut-off rule in the global warming impact category (Wolf et al., 2016).

Impact assessment, with a focus on GHG emissions, was conducted in accordance to the ILCD Handbook (European Commission, 2010).

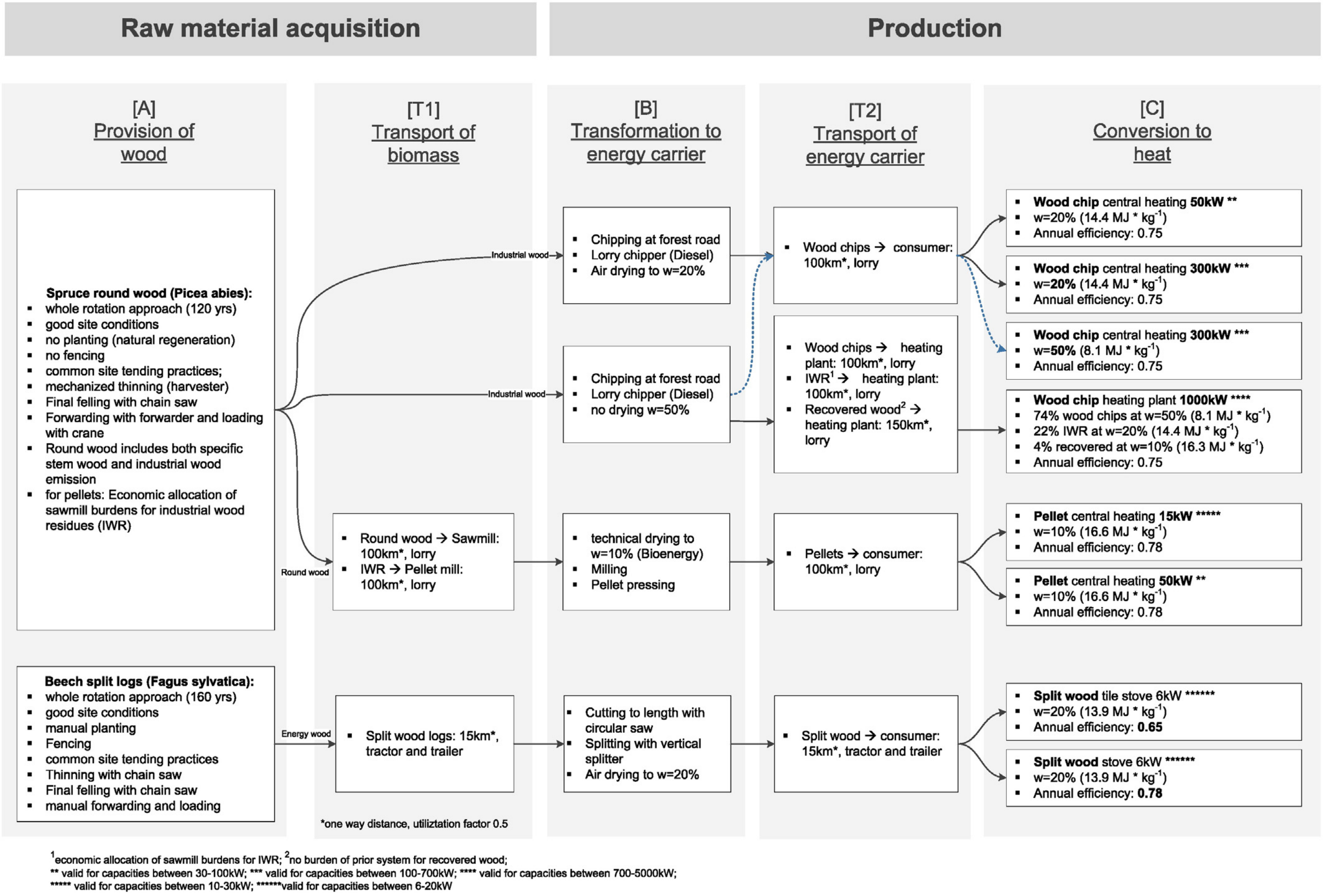

Fig. 1. Description of life cycle stages, system assumptions and parameters in the modeling of the wood heating systems.

IPCC GHG emissions, without biogenic CO_2, in kg CO_2-eq. (Intergovernmental Panel on Climate Change, 2007) was chosen as an appropriate indicator, since it was assumed that wood combusted under Bavarian conditions originates from sustainably managed forests and long-term carbon regrowth in forest biomass can be expected. In order to assess tradeoffs associated with GHG mitigation through wood heating systems, the emissions of particulate matter (PM), following the RiskPoll method (Rabl and Spadaro, 2012) in kg $PM_{2.5}$-eq. were assessed. Additionally, the calculations of GHG emissions for heating mixes are based on heating mixes outlined in Stenull (2010) for Germany and Wolf et al. (2016) for Bavaria. For Bavarian conditions the GHG emissions are weighted according to the share of final energy of individual energy carriers in the heating mix (natural gas: 42.56%; LFO: 21.72%, solid biofuels (i.e. wood): 12.6%, power: 9.56%, district heat: 6.67%, other renewables: 2.45%, LPG: 1.98%, other: 1.27%, lignite: 1.15%, hard coal: 0.04%), finally leading to a specific weighted emission factor for 1 MJ of heat for Germany and Bavaria, respectively. The deduction of the heating mix was carried out by analyzing statistics concerning the use of final energy in the study region of Bavaria in the year 2011 (the most up to date statistic available), which are provided by the Bavarian State Institute for Statistics and Data Processing (BayLAStDV, 2014).

Furthermore, for situations where no individual wood heating technology is displacing an individual energy carrier or a mix of energy carriers, a weighted wood heating technology mix can be employed. For the case study area, this mix is weighted by the installed capacities (Joa et al., 2015) of individual wood heating systems (Table 1) and the harvested tree species and wood assortment distribution in Bavaria, derived by the national forest inventory (Klemmt et al., 2014) and annual timber statistics. Results are depicted on the basis of 1 MJ of useful energy and the potential energy from 1 m^3 of wood (beech or spruce, depending on the system). For the conversion of emissions and subsequent displacements factors on the basis of 1 MJ to m^3, the emission factors were coupled with the lower heating value (LHV) of the respective wood species (spruce: $w = 50\%$, 6167 $MJ*m^{-3}$; $w = 20\%$, 6862 $MJ*m^{-3}$; beech: $w = 20\%$, 9702 $MJ*m^{-3}$) and the annual efficiency of the respective heating.

3. Results and discussion

3.1. Range of displacement factors on the basis of 1 MJ

The GHG displacement factors of solid (wood) biofuel heating systems (in g CO_2-eq.) displacing different energy carriers utilized for the

Table 1
Distribution of installed capacities of wood heating systems based on Joa et al. (2015) for Bavaria (reference year: 2013).

	Installed capacity [MW_{th}]	Share [%]
Single room heating systems		
Split wood tile stove	6866	31.0
Split wood modern stove	9679	43.7
Central heating systems		
Pellet 15 kW	975	4.4
Pellet 50 kW	975	4.4
Wood chips 50 kW	262	1.2
Wood chips 300 kW – w = 20%	262	1.2
Wood chips 300 kW – w = 50%	262	1.2
Split wood modern stove	1685	7.6
Heating plants	1165	5.3
Σ	22,130	100

provision of useful energy for heat on the basis of 1 MJ thermal energy are shown in Table 2. GHG displacement factors exhibit a range between -3.1 g CO_2-eq.∗MJ^{-1} for the displacement of the group of other renewable energy carriers with a 15 kW pellet central heating system and -165 g CO_2-eq.∗MJ^{-1} for the displacement of power (employed for heating) by a modern 6 kW split wood stove. It can be observed that split wood systems have the lowest associated GHG emissions and consecutively show the highest displacement factors followed by wood chip and pellet systems. Split wood systems exhibit a high mitigation potential due to the low degree of mechanization in the production process. Pellets on the other hand show higher emissions due to a more technical production process involving power for the grinding and pressing of pellets. Wood chips occupy a middle ground between split wood and pellet heating systems in terms of environmental performance and mechanization. Split wood systems exhibit the greatest share of GHG emissions in the phase of converting the energy carrier to final energy. Even when discounting for biogenic CO_2, methane and nitrous oxide from combustion alone are responsible for the majority of impacts associated with the systems. However, for wood chips and pellets systems the greatest share of GHG emissions in the phase of transforming the raw wood into the energy carrier, due to a higher degree of energy related emissions during that phase. For the conventional energy carriers with the highest share in the heating mix according to Wolf et al. (2016) (natural gas and LFO), a spread between -57.6 g CO_2-eq.∗MJ^{-1}, for the displacement of natural gas by a 15 kW pellet central heating system, and -99.1 g CO_2-eq.∗MJ^{-1}, for the substitution of LFO by a 6 kW modern split wood stove, could be observed.

When combusting spruce split wood instead of beech split wood the displacement factor would be reduced by approximately 2% (due to a higher specific LHV of spruce) displacing natural gas, 1.5% displacing LFO and 0.9% displacing power. Combusting beech wood chips instead of spruce wood chips, the displacement factor would be increased by approximately 5.4% for the displacement of natural gas, 4% for the displacement of LFO and 2.4% for the displacement of power. These variations again demonstrate the importance of the choice of reference system as they have the biggest impact on the magnitude of displacement effects and can overshadow individual decisions on the product LCA level (e.g. variation in combusted wood species or transport distances). It is therefore imperative to be certain which reference systems are displaced by the product system instead of an arbitrary decision concerning the reference system.

Weighted displacement factors (weighted by installed capacity of wood heating systems and harvested tree species and wood assortments based on Bavarian conditions) for the displacement of natural gas, LFO and power are -71.5 g CO_2-eq.∗MJ^{-1}, -95.2 g CO_2-eq.∗MJ^{-1} and -161 g CO_2-eq.∗MJ^{-1} respectively. For all systems, the magnitude of displacement factors is strongly influenced by the size of combustion system, i.e. higher combustion capacities lead to higher displacement factors. Also of strong influence is the efficiency of the combustion process as well as the water content of the biomass. These factors directly influence the amount of biomass, and associated emissions, required for the production of heat. Therefore, a higher water content leads to an overall lower displacement factor. In addition to the displacement factors of individual heating systems, it is convenient to disclose factors applicable for the assessment of GHG reductions on a regional level, i.e. for a town, region, state or country. These displacement factors can be utilized if not one system is replacing another specific system directly, but the impact of a number of different systems being exchanged by a respective wood heating technology or by a weighted mix of wood heating technologies is to be assessed. Due to the high share of installed capacity of split wood systems in Bavaria, they also strongly influence the magnitude of the displacement factors for the mix of wood heating technologies. The GHG mitigation effect of displacing the current heating mix including renewables could be shown to be -77.5 g CO_2-eq.∗MJ^{-1}, while the displacement of the heating mix excluding renewables is -90.3 g CO_2-eq.∗MJ^{-1}. This displacement factor of -90.3 g CO_2-eq.∗MJ^{-1} is recommended by the authors when assessing the potential performance of planned wood energy systems outside of a homeowner's context for areas similar to the study region of Bavaria.

Even though the data foundation for the calculation of displacement factors are Bavarian statistics for final energy used for heat, displacement factors are comparable, and can be scaled to overall German conditions. In comparison to Bavarian conditions, a heating mix for Germany, based on Stenull (2010) exhibits 12% lower emissions, due to higher shares of natural gas in the German heating mix. Consequently, a displacement through wood energy for overall German conditions, weighted by share of final energy in the German heating mix, exhibits a displacement factor of -101.1 g CO_2-eq.∗MJ^{-1} (excluding other renewables).

3.2. Range of displacement factors on the basis of 1 m^3

The GHG displacement factors of solid biofuel heating systems (in kg CO_2-eq.) displacing different energy carriers utilized for the provision of useful energy for heat on the basis of the potential energy obtainable from 1 m^3 of solid wood is shown in Table 3. GHG displacement factors

Table 2
GHG displacement factors (g CO_2-eq.∗MJ^{-1}) of heat provided by wood heating systems in Bavaria. S = spruce, B = beech, w = water content. Negative values represent reduction of GHG emissions.

	Natural gas	Light fuel oil	Power	District heat	Other[a] renewables	Heating mix[b] incl. renewables	Heating mix[b] excl. renewables
	g CO_2-eq.∗MJ^{-1}						
Wood chips, central heating, 50 kW (S, w = 20%)	−66.7	−90.4	−156.2	−75.6	−12.2	−72.2	−85.4
Wood chips, central heating, 300 kW (S, w = 20%)	−67.6	−91.3	−157.2	−76.5	−13.1	−73.1	−86.4
Wood chips, central heating, 300 kW (S, w = 50%)	−65.4	−89.1	−155.0	−74.3	−10.9	−70.9	−84.2
Wood chips, heating plant, 1000 kW (wood mix)	−66.8	−90.5	−156.4	−75.7	−12.3	−72.3	−85.6
Split wood, tile stove, 6 kW (B, w = 20%)	−73.2	−96.9	−162.7	−82.1	−18.7	−78.7	−91.9
Split wood, modern stove, 6 kW (B, w = 20%)	−75.4	−99.1	−165.0	−84.3	−20.9	−80.9	−94.2
Pellet, central heating, 15 kW (S, w = 10%)	−57.6	−81.3	−147.1	−66.4	−3.1	−63.1	−76.3
Pellet, central heating, 50 kW (S, w = 10%)	−59.1	−82.8	−148.7	−68.0	−4.6	−64.6	−77.9
Mix of wood heating technologies[c]	−71.5	−95.2	−161.0	−80.4	−17.0	−77.0	−90.3

[a] Mix between solar thermal, geothermal, biogas and the biogenic share of waste burned in a waste incineration plant.
[b] Mix weighted by share of final energy for heat in Bavaria (2011).
[c] Mix weighted by installed capacities of individual heating systems and volumes of harvested tree species.

Table 3
GHG displacement factors (kg CO_2-eq.∗m^{-3}) of heat provided by wood heating systems in Bavaria. S = spruce, B = beech, w = water content. Negative values represent reduction of GHG emissions.

	Natural gas	Light fuel oil	Power	District heat	Other[a] renewables	Heating mix[b] incl. renewables	Heating mix[b] excl. renewables
	kg CO_2-eq.∗m^{-3}						
Wood chips, central heating, 50 kW (S, w = 20%)	−343	−465	−804	−389	−63	−372	−440
Wood chips, central heating, 300 kW (S, w = 20%)	−348	−470	−809	−394	−67	−376	−444
Wood chips, central heating, 300 kW (S, w = 50%)	−303	−412	−717	−344	−50	−328	−389
Wood chips, heating plant, 1000 kW (wood mix)	−334	−452	−781	−378	−61	−361	−427
Split wood, tile stove, 6 kW (B, w = 20%)	−462	−611	−1026	−518	−118	−496	−580
Split wood, modern stove, 6 kW (B, w = 20%)	−571	−750	−1248	−638	−158	−612	−713
Pellet, central heating, 15 kW (S, w = 10%)	−314	−443	−802	−362	−17	−344	−416
Pellet, central heating, 50 kW (S, w = 10%)	−322	−452	−811	−371	−25	−352	−425
Mix of wood heating technologies[c]	−410	−546	−923	−461	−97	−442	−518

[a] Mix between solar thermal, geothermal, biogas and the biogenic share of waste burned in a waste incineration plant.

[b] Mix weighted by share of final energy for heat in Bavaria (2011).

[c] Mix weighted by installed capacities of individual heating systems and volumes of harvested tree species.

exhibit a range between −17 kg CO_2-eq.∗m^{-3} for the displacement of the group of other renewable energy carriers with a 15 kW pellet central heating system and −1248 kg CO_2-eq.∗m^{-3} for the displacement of power (employed for heating) by a modern 6 kW split wood stove. Weighted displacement factors (weighted by installed capacity of wood heating systems and harvested tree species and wood assortments) for the displacement of natural gas, LFO and power are −410 kg CO_2-eq.∗m^{-3}, −546 kg CO_2-eq.∗m^{-3} and −923 kg CO_2-eq.∗m^{-3} respectively. The GHG mitigation effect of displacing the current heating mix including renewables could be shown to be −442 kg CO_2-eq.∗m^{-3}, while the displacement of the heating mix excluding renewables is −518 kg CO_2-eq.∗m^{-3}.

Results on the basis of m^3 show a much larger spread of results, e.g. the displacement of power through pellets achieves 89% of the GHG mitigation in comparison to the split wood system when calculated to the MJ of final energy in comparison to only 64% when results are compared based on 1 m^3 of fresh wood. This effect can be explained by the different wood densities and corresponding masses of absolute dry wood per m^3 of spruce and beech. Additionally, 1 m^3 of beech wood contains more energy (9700 MJ [LHV], w = 20%) compared to spruce (6900 MJ [LHV], w = 15%) and thereby, more fossil energy can be displaced with 1 m^3 of beech wood. While results based on the MJ of final energy reflect the ratios of the lower heating values based on 1 kg of beech and spruce, results on the basis of the m^3 reflect the ratios of energy content of 1 m^3 between spruce and beech.

In order to relate the results on the basis of 1 m^3 of solid wood to other units such as 1 kg or 1 t, the density of the respective wood species can be used for conversion. In the case of spruce a density of 377 kg∗m^{-3} and for beech a density of 588 kg∗m^{-3} should be employed as the divisor.

3.3. Selection of appropriate reference systems

Recognized literature on the energetic substitution of wood depicts displacement factors of −440 kg CO_2-eq.∗m^{-3} (Suter et al., 2016), −600 kg CO_2-eq.∗m^{-3} (Taverna et al., 2007) and −675 kg CO_2-eq.∗m^{-3} (Köhl et al., 2009). For Suter et al. (2016) and Taverna et al. (2007) a mix of LFO and natural gas is used as a reference system. In contrast, the calculations of Köhl et al. (2009) are based on the displacement of LFO. However, the composition of heating mixes dictates, for an in depth assessment of the displacement of heat provided by conventional energy carriers through wood, to also incorporate other, major energy carriers, such as power, in order to achieve sufficiently accurate displacement factors. Especially for heat, due to the decentralized provision structure, displacement factors shall not be based on an arbitrary mix of heating systems or energy carriers but should represent a realistic displacement of individual heating systems, e.g. the individual displacement of natural gas, LFO, power and also other renewable heating systems. Only with these individual displacements, homeowners, which are faced with a decision of modernization or the new installation of a heating system, can assess true potential GHG mitigations caused by the shift or renovation of their heating systems.

Utilizing standard displacement approaches commonly found in literature, where a reference system consisting of only one energy carrier (e.g. LFO, natural gas, or an arbitrary mix of LFO and natural gas) is used, can lead to over- or underestimations of the displacement effect. On the example of Bavaria, taking only into account the displacement of natural gas, as opposed to the actual mix of energy carriers in the heating mix, leads to a decrease of the effect of displacement of approximately 7% (Fig. 2). Taking only into account the displacement of LFO increases the effect of substitution by 20%. This simplification is mostly due to the previous lack of a defined heating mix for a region or a country. To put the importance of sound displacement factors further into perspective, we calculated the different magnitudes of displacement when displacing purely LFO with the weighted wood heating mix and when displacing the emissions associated with the Bavarian heating mix with the weighted wood heating mix for the current amount of final energy provided through wood in Bavaria based on Wolf et al. (2016). If only LFO would be used as a reference instead of a weighted mix of different energy carriers used for heat in Bavaria in the year 2011, mitigation effects (in CO_2-equivalents) would be overestimated by 1.4 M t∗yr^{-1}. On the other hand, utilizing natural gas instead of LFO leads to an underestimation of 0.45 M t∗yr^{-1}. As such, a total GHG mitigation effect through wood energy, utilizing our weighted displacement factors for wood heat (88.6 PJ∗yr^{-1} according to Wolf et al. (2016)), representing displacement of −6.4 M t∗yr^{-1} (Fig. 2). Adding the effects of the displacement of grid power through wood power (4.8 PJ∗yr^{-1} according to Gaggermeier et al. (2014)), a GHG mitigation of −7.2 M t∗yr^{-1} could be shown. Considering that the provision of heat has the highest share of the total final energy in comparison to power or transportation, the calculation of the displacement should also reflect this importance.

3.4. Tradeoffs encountered through the mitigation of GHG caused by the displacement of non-wood energy

In order to assess the environmental effects of products it is not sufficient to identify only GHG emissions associated with the life cycle of

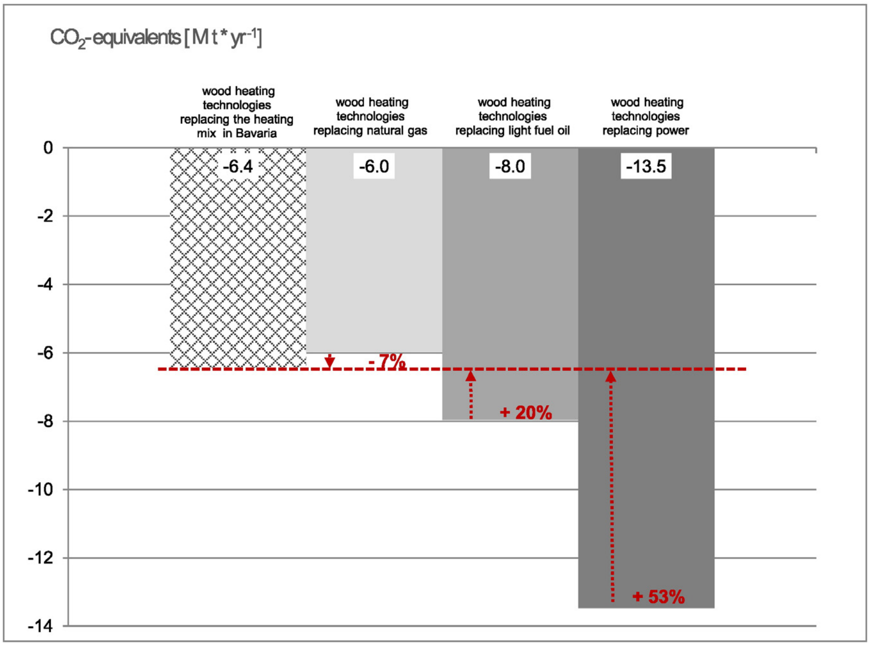

Fig. 2. Displacement of GHG emissions (M t$*$yr^{-1}) caused by Bavarian wood heating technologies in comparison to the Bavarian heating mix and other selected individual energy carriers as a reference system.

the product. Goods and services can be linked to several environmental impacts, e.g. agricultural good or some forms of plantation forestry, are associated with fertilization and possible eutrophication of water and ground, which should be accounted for when assessing environmental impacts in a more comprehensive fashion. For wood energy systems, besides global warming impacts, emissions of particulate matter play an important role (Nussbaumer et al., 2008) and are linked to health issues and loss of lifetime (Cohen et al., 2004). Of course, there are various other environmental impacts of energy systems, but it should at least be considered to depict the most important ones. Not always do environmental effects correlate positively. This can be shown by the tradeoffs of environmental benefits and burdens associated with the provision of wood energy, where on the one hand considerable GHG mitigation potentials can be identified, which, on the other hand, entail an increase in particulate matter emissions (Fig. 3). Nevertheless, distinct differences between technologies for the provision of heat from wood can be identified and are in accordance to Kelz et al. (2012), wherein emissions of particulate matter of old split wood systems are 20 to 60% above those of modern stoves and pellet heating systems exhibit only 6% of the particulate matter emissions of old split wood systems. Additionally, a strong improvement of the application of filter systems could be identified (Kelz et al., 2012). Results for the mitigation of $\mathrm{PM}_{2.5}$ emissions (a positive value is an increase in $\mathrm{PM}_{2.5}$ emissions) show that wood chip heating systems (on the example of the system: wood chips, central heating, 300 kW; spruce, w = 20%), while providing average GHG mitigation, exhibit an increase of particulate matter emissions between 26.5 mg $\mathrm{PM}_{2.5}$-eq.$*$MJ^{-1} when displacing power and 40.8 mg $\mathrm{PM}_{2.5}$-eq.$*$MJ^{-1} when displacing natural gas (Fig. 3). Split wood systems exhibit the highest emissions (15.4 mg $\mathrm{PM}_{2.5}$-eq.$*$MJ^{-1} when displacing power and 16.8 mg $\mathrm{PM}_{2.5}$-eq.$*$MJ^{-1} when displacing natural gas), while pellet heating systems provide the lowest increments of all wood heating systems (22 mg $\mathrm{PM}_{2.5}$-eq.$*$MJ^{-1} when displacing power and 36 mg $\mathrm{PM}_{2.5}$-eq.$*$MJ^{-1} when displacing natural gas), while showing the lowest GHG displacement factors of all wood heating technologies. The complete list of particulate matter displacement factors for wood energy can be found in Table 4 for the displacement per MJ final energy and in Table 5 for the displacement per potential energy obtainable from 1 m^3 of solid wood. For this case, additional emissions of 776 g$*$m^{-3} caused by the weighted wood heating technology mix could be shown.

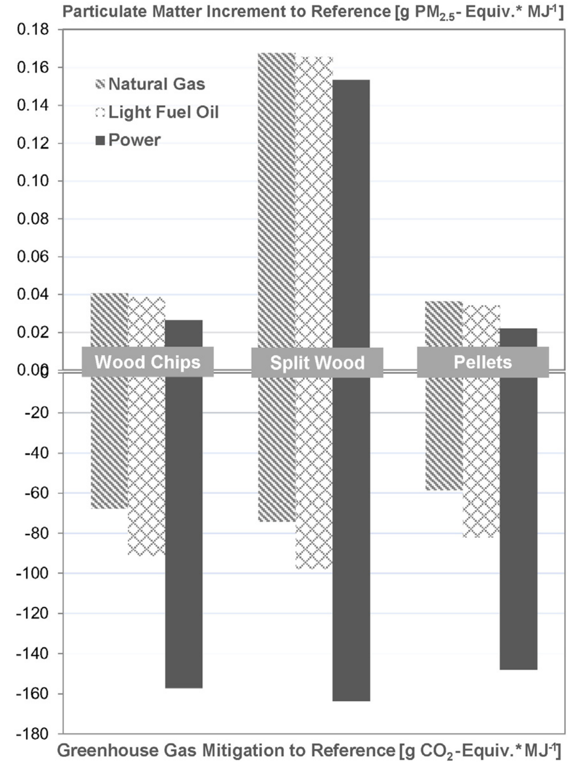

Fig. 3. Displacement of particulate matter emissions (g $\mathrm{PM}_{2.5}$–eq.$*$MJ^{-1}) and greenhouse gases (g CO_2-eq.$*$MJ^{-1}) through wood chip, split wood, and pellet heating systems in Bavaria (reference year: 2011).

The results are also in line with Wilnhammer et al. (2015) showing similar results for a more limited selection of wood energy systems and reference systems (only natural gas) (split wood: 152 mg $\mathrm{PM}_{2.5}$-eq.$*$MJ^{-1}; pellets: 32 mg $\mathrm{PM}_{2.5}$-eq.$*$MJ^{-1}; wood chips: 70 mg $\mathrm{PM}_{2.5}$-eq.$*$MJ^{-1}). The combined consideration of GHG and particulate matter has the results that for pellets, which are associated with a relatively

Table 4
Particulate matter displacement factors (mg $PM_{2.5}$-eq.*MJ^{-1}) of heat provided by wood heating systems in Bavaria. S = spruce, B = beech, w = water content. Positive values represent increments of particulate matter emissions.

	Natural gas	Light fuel oil	Power	District heat	Other[a] renewables	Heating mix[b] incl. renewables	Heating mix[b] excl. renewables
	mg $PM_{2.5}$-eq.*MJ^{-1}						
Wood chips, central heating, 50 kW (S, w = 20%)	31.1	29.1	16.8	27.4	18.2	10.6	27.9
Wood chips, central heating, 300 kW (S, w = 20%)	40.8	38.8	26.5	37.1	27.9	20.3	37.6
Wood chips, central heating, 300 kW (S, w = 50%)	62.9	60.9	48.5	59.1	50.0	42.4	59.7
Wood chips, heating plant, 1000 kW (wood mix)	63.2	61.2	48.8	59.5	50.3	42.7	60.0
Split wood, tile stove, 6 kW (B, w = 20%)	167.8	165.7	153.4	164.0	154.9	147.2	164.5
Split wood, modern stove, 6 kW (B, w = 20%)	146.6	144.6	132.3	142.9	133.7	126.1	143.4
Pellet, central heating, 15 kW (S, w = 10%)	45.8	43.8	31.5	42.1	32.9	25.3	42.6
Pellet, central heating, 50 kW (S, w = 10%)	36.3	34.3	22.0	32.6	23.4	15.8	33.1
Mix of wood heating technologies[c]	138.6	136.6	124.2	134.8	125.7	118.1	135.4

[a] Mix between solar thermal, geothermal, biogas and the biogenic share of waste burned in a waste incineration plant.
[b] Mix weighted by share of final energy for heat in Bavaria (2011).
[c] Mix weighted by installed capacities of individual heating systems and volumes of harvested tree species.

high demand of power in the production process, the GHG mitigation improves with the share of renewable energies in the power grid mix, while still maintaining the most favorable $PM_{2.5}$ emissions properties when compared to wood chips or split wood systems.

In conclusion, the magnitude of $PM_{2.5}$-eq. emissions through wood heating has to be critically discussed since the adequacy of flows associated with $PM_{2.5}$-eq. emissions for German conditions (due to the amendment of the 1. federal emissions protection regulation (BImSchV) in the current version of the ecoinvent database) might not be given. The reduction of particulate matter emissions caused by wood heating systems has been furthered in Germany in the form of the amendment of the 1. federal emissions protection regulation (BImSchV) (BMU, 2010), which will have a substantial impact on the emissions of particulate matter from split wood and wood chips heating systems. Modernization or decommissioning of inefficient wood heating systems could therefore lead to a potential future reduction of particulate matter emissions of up to 50% (Wilnhammer et al., 2016). As such, it would be desirable, for a future in depth assessment of $PM_{2.5}$-eq. mitigations associated with wood heating, to update these flows to represent also the current best available technology.

4. Conclusions

Our study shows that there are substantial GHG mitigation effects through the use of wood for heating, although they are not without tradeoffs for other environmental impacts, such as particulate matter emissions. The magnitude of the mitigation is strongly dependent on the choice of reference system. It is proposed, if GHG mitigation potentials of wood energy for individual communities, regions or countries are to be analyzed, to not rely the interpretation of LCA results on the comparison on only one reference system, but to carry out comparisons to the most prominent heating sources in the heating mix. In this study, we showed the importance for a concise definition of reference system and provided, for the first time, regional displacement factors for wood heating systems for a case study area. Through the large share of wood used for heating, it is now possible to assess the environmental effects of wood heating and associated GHG mitigation for Bavaria accurately and without having to make use of the more general displacement factors of the past. It could also be shown why it is necessary to focus on regional aspects when assessing environmental impacts of the provision of heat and why heat should be analyzed in a different manner than other energetic wood uses, such as power. On the basis of this study, the following conclusions can be drawn:

Table 5
Particulate matter displacement factors (g $PM_{2.5}$-eq.*m^{-3}) of heat provided by wood heating systems in Bavaria. S = spruce, B = beech, w = water content. Positive values represent increments of particulate matter emissions.

	Natural gas	Light fuel oil	Power	District heat	Other[a] renewables	Heating mix[b] incl. renewables	Heating mix[b] excl. renewables
	g $PM_{2.5}$-eq.*m^{-3}						
Wood chips, central heating, 50 kW (S, w = 20%)	160	150	86	141	94	55	144
Wood chips, central heating, 300 kW (S, w = 20%)	210	200	136	191	144	105	194
Wood chips, central heating, 300 kW (S, w = 50%)	291	282	224	274	231	196	276
Wood chips, heating plant, 1000 kW (wood mix)	316	306	244	297	251	213	300
Split wood, tile stove, 6 kW (B, w = 20%)	1058	1045	967	1034	977	929	1038
Split wood, modern stove, 6 kW (B, w = 20%)	1110	1094	1001	1081	1012	954	1085
Pellet, central heating, 15 kW (S, w = 10%)	250	239	172	230	180	138	232
Pellet, central heating, 50 kW (S, w = 10%)	198	187	120	178	128	86	181
Mix of wood heating technologies[c]	795	783	712	773	721	677	776

[a] Mix between solar thermal, geothermal, biogas and the biogenic share of waste burned in a waste incineration plant.
[b] Mix weighted by share of final energy for heat in Bavaria (2011).
[c] Mix weighted by installed capacities of individual heating systems and volumes of harvested tree species.

(1) In order to avoid over- or underestimations of GHG mitigation and other environmental effects of wood heating systems for a specific region (or other larger units), we suggest developing individual displacement factors using the following approach:

a. Estimation of the specific wood heating technology mix e.g. by using statistics or estimations concerning installed capacities of wood heating systems in a region
b. Estimation of the specific heating mix of the respective region by means of final energy statistics
c. Calculation of GHG and/or other emissions of all relevant heating systems and a subsequent calculation of a mass weighted mean GHG emission factor based 1 MJ of thermal energy
d. Estimation of specific displacement factors by comparing GHG and/or other emissions of the heating mix (without the share of solid biofuels) and the heating mix including the wood heating mix.

This method enables the estimation of GHG and other environmental mitigation effects at a certain time and allows for conclusions towards the effects of shifts in the regional heating mix.

Mitigation benefits can only be claimed for a product if an actual mitigation is occurring; therefore, it is recommended to carry out any calculation of displacement with a reference system that represents the energy carrier that is truly displaced in the geographical system boundary. If it is unclear which energy carrier this is, a weighted mix (e.g. weighted by share of final energy used for heating) can be employed.

Due to the rather slowly changing nature of most regional heating mixes, in comparison to the power mix, it is considered valuable by the authors to make the effort of calculating these stratified displacement factors as they are bound to be of merit for a much longer time than factors in the power sector.

(2) The GHG displacement of conventional energy carriers displays a range between -57.6 g CO_2-eq.$*MJ^{-1}$ (314 kg CO_2-eq.$*m^{-3}$), for the displacement of natural gas by a 15 kW pellet central heating system, and -165 g CO_2-eq.$*MJ^{-1}$ (1248 kg CO_2-eq.$*m^{-3}$), for the displacement of power by a 6 kW modern split wood stove.

The GHG reduction effect of displacing the current heating mix including renewables could be shown to be -77.5 g CO_2-eq.$*MJ^{-1}$, while the displacement of the heating mix excluding renewables is -90.3 g CO_2-eq.$*MJ^{-1}$, which is also the displacement recommended by the authors when assessing the potential performance of wood heating on a regional scale comparable to Bavaria.

(3) This approach is also valid for discerning displacement factors for other environmental effects, both negative (= reduction of environmental effects) and positive (= increment of environmental effects). In this study, displacement factors for particulate matter emissions were additionally incorporated. Results thus show the tradeoffs of wood energy. Wood heating systems, while providing GHG mitigation, exhibit a positive displacement, which mean additional emissions, of $PM_{2.5}$. The displacement exhibits a range between 0.036 g $PM_{2.5}$-eq.$*MJ^{-1}$ when pellets displace natural gas and 0.168 g $PM_{2.5}$-eq.$*MJ^{-1}$ when split wood displaces natural gas.

Acknowledgements

This study was part of the project “Experts Group Resource Management Bio-energy in Bavaria” (“ExpRessBio- Expertengruppe Ressourcenmanagement Bioenergie Bayern”). The authors thank the Bavarian State Ministry of Food, Agriculture and Forestry for funding.

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