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Increased wood energy use: evaluation of resource availability and selected environmental impacts for the case study area Bavaria

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Abstract

This thesis deals with the analysis of wood energy availability and consumption in Bavaria as well as with the evaluation of selected environmental impacts due to increased wood energy use. *The key question of the study at hand is whether more wood energy can be used and how it can be consumed most efficiently in order to mitigate trade-offs arising from increased wood energy demand.* Wood energy consumption has been increasing in the past years entailing questions of sustainable harvest rates and leading to conflicts of interests, i.e. the increased use of renewable energies versus concerns about over-utilisation of domestic forest resources. Moreover, there are concerns about increased competition between the wood energy sector and the material-based wood sector for a renewable but yet limited resource. There are also data gaps regarding the environmental impact of a shift in resource allocation due to increased wood energy use. Furthermore, as a considerable share of wood energy is being burnt in low-efficient residential heating systems with low efficiency rates and without adequate filter technologies, there is a strong but yet unclear improvement potential in terms of resource use efficiency and emission load reduction for Bavaria.

In order to answer the above data gaps and research questions, the Bavarian wood energy sector is analysed from different contexts. Firstly, resource availability and potential for additional wood energy supply from the forest is evaluated, taking account of forest growth conditions, different forest management objectives and attitudes towards forestry via interviews of private forest owners in Southern Bavaria. This work shows that additional supply potential is available but mobilisation potential is small due to socio-economic restrictions such as forest owners' willingness to supply more wood. The study concludes that practically there is no additional supply potential for biomass from Bavarian forests. Additional energy production from woody biomass in Bavaria could come from e.g. improved energy use efficiency.

Secondly, the impact of increased wood energy use is analysed via a life-cycle assessment approach, applying the basket of benefit method to the Bavarian forestry and wood cluster, and taking account of correlated substitution effects. So far, life-cycle assessments mainly focused on individual wood products, neglecting interdependent effects and the impact of a shift in wood consumption on a regional scale. This work reveals that, due to competition and substitution effects in the Bavarian forestry and wood cluster, increased wood energy use potentially leads to minor increase in greenhouse gas emissions and to higher particulate matter emissions, but at the same time to lowered primary energy demand. Therefore, the basket of benefit method shows that a shift in wood consumption can entail Janus-faced environmental impact. In total, increased resource use efficiency is crucial for a sustainable wood energy use. The basket of benefit method was tested for the case study area Bavaria and for selected impact categories and should be applied to additional impact categories and study areas in order to further refine the methodology and reveal additional consequences of increased wood energy consumption.

Thirdly, the thesis analyses the impact of a new air emission control act on the development of $PM_{2.5}$ emission load for Bavaria. The results exhibit that there is a potential for additional wood availability, as well as for the reduction of dust emissions from residential wood combustion through technology development. According to the analysis, the law amendment could entail a reduction in particulate matter emissions by up to 50% until 2025 and thus strongly contribute to improved air quality and the fulfilment of political targets for clean air.

Fourthly, the thesis puts the overall situation in Bavaria into a context with other regions, unfolding characteristics of regional wood energy use patterns for Bavaria. The chapter illustrates that wood energy use is high compared to resource availability. Moreover, political incentives and high social acceptance for bioenergy were major contributors towards an increase in the use of wood energy in Bavaria.

This dissertation shows that the increased wood energy use can be environmentally beneficial and socially acceptable, but only if wood energy is used in an efficient and responsible manner and if technological development keeps up with an increasing resource demand.

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1 Introduction

1.1 Renewable energy use in Europe and the increase in wood consumption

One of the main challenges for today's forestry and wood cluster is the growing wood energy demand. The increasing production of fuel wood from the forest can have various implications on the forest environment and on forest-dependent industries, both negative and positive. It is a subject highly relevant to policy makers and to different stakeholders from the environmental and energy sector as well as the wood-based industry.

Against the background of climate change, European member states have agreed on ambitious targets for renewable energy. A set of legislative frameworks and promotional instruments on European, German and Bavarian level has been introduced by policy makers to support the proliferation of wood energy use. On European level, *Directive 2009/28/EC of the European Parliament and of the Council on the promotion of the use of energy from renewable sources* (EC 2009) sets the ground for future wood energy consumption in the European Union. Until 2020 more than 20% of final energy demand in the EU should be sourced from renewable energies. Each member state has to fulfil binding targets.

For example in Germany, the energy concept of the Federal government foresees that greenhouse gas (GHG) emissions will be reduced by 60% until 2020 in comparison to 1990, that the share of renewable energy will be increased to 18%, and that the share of biomass in thermal heating will be increased to 14% (Bundesregierung 2010). The concept also requires an increase in energy use efficiency and a reduction in primary energy demand. The Renewable Energies Act further aims at increasing the share of renewable electricity production to 35% by 2020 and includes a guaranteed feed-in remuneration for power producers. Renewable electricity generation in Germany is strongly supported through the feed-in tariff scheme and through other fiscal measures (Teckenburg et al. 2011); however, these support mechanisms are mainly directed to power generation. Most of the wood biomass burnt in Germany is being used for heating purposes (UBA 2014b).

In order to support the planned bioenergy expansion for heat production from 10% to 14%, the Market Incentive Program (MAP) has been introduced, comprising public subsidies in Bavaria of up to 0.76 billion € in 2013 (50 Hertz transmission GmbH 2013). Furthermore, the law EEWärmeG introduces a legal mandate on home owners to use renewable energies for heating and cooling purposes in new buildings (Teckenburg 2011). The Bavarian government implemented a renewable energy plan which targets at an increase in the share of renewable energy from 23% in 2008 to 54% in 2021. The share in bioenergy – a vast amount coming from woody biomass – shall be increased from 6% in 2009 to 10% in 2021 (Bayerische Staatsregierung 2011).

Fostered through above described governmental support mechanisms for renewable energy generation as well as due to volatile and rising fossil energy prices in the past decade, renewable energy is increasingly being used in Germany. Although energy prices are currently comparably low, a study by Härtl & Knoke (2014) revealed that most scientific scenarios assume a long-term price increase. Since half of all energy is used for heating purposes and since two thirds of renewable heat is generated from solid biomass, wood is currently the most important renewable energy in Germany (FNR 2013) and thus has a crucial role to play for the transition towards a renewable energy future.

From 2005 to 2010, the annual amount of wood energy use in Germany has increased by 20 hm^3, so that in 2010 fuel wood consumption (51%) was – for the first time in decades – higher than material-based wood use (Mantau 2012). According to Knauf (2014), who applied a different calculation methodology, the share in wood energy use would be more than 60% and the wood energy use as reported by Mantau would be underestimated due to double counting of industrial residues. While nationwide renewable energy consumption for household heating has grown by 57% between 2005 and 2012, the total energy consumption has declined by 8% (Destatis 2013). In Bavaria, wood energy use grew from von 3.7 in 2005 to 6.1 million tonnes (bone-dry) in 2013 (Gaggermeier et al. 2014).

The increased demand is positive for forest owners who can market their products more easily. Wood as a local resource can support the generation of regional value added and the creation of jobs in rural areas. Wood further exhibits lower greenhouse gas emissions in comparison to fossil resources (e.g. Bauer 2007, Jungbluth et al. 2007, Werner et al. 2007). However, as the production and use of forest energy wood also entail trade-offs, there are concerns about the increasing use of wood energy. Although a renewable resource, there are limits to fuel wood supply from the forest. The question arises to what extent additional material can be supplied from domestic forests without compromising the limits of sustainability. While in the second half of the 20th century annual harvest in Eastern and Western European countries was significantly below increment (Gold 2003), felling rate has been increasing steadily since 1990 (UNECE/FAO 2011). In Germany, overall felling rates have been considerably augmenting in the last decade, with rising wood energy consumption being a substantial driver. In Bavarian state forests, annual harvest meanwhile equals timber felling potential (BaySF 2012). Therefore, a further increase is no longer possible without violating sustainability.

On the contrary, some privately owned forests are still characterised by an underutilisation, in particular small-scale private forests. The recent national forest inventory BWI 3 (BMELV 2014) confirmed for small and medium size private forests that growing stock has been increasing, indicating an additional potential for wood supply.

This situation is not restricted to German private forests and applies to most countries in Europe (Schlüter 2008). As about half of European forests is privately owned (UNECE/FAO 2011), private forest owners play a crucial role in satisfying the needs of both the wood energy sector and the material-based wood industry. A further increase of domestic wood demand in Europe is predicted as a consequence of ambitious targets for renewable energy (UNECE/FAO 2011). However, there are concerns about an overexploitation of forests and about a strong competition between the material and energetic utilisation of wood from forests. Moreover, the question arises to what extent increased wood energy use adds to climate change mitigation and to other air emissions.

1.2 State of knowledge and need for research

1.2.1 Increased wood energy demand and potential sustainable wood supply

Comprehensive knowledge on the real wood supply potential is a prerequisite for sound political and forest management decisions. In recent years, wood supply calculations have been carried out at a global, European, national or province level (e.g. Kaltschmitt & Hartmann 2001, BMELV 2004, Parrika 2004, Dieter & Englert 2005, Hetsch et al. 2008, Hofer & Altweg 2008, Schadauer 2009, van den Berg et al. 2010, Mantau et al. 2010, UNECE/FAO 2011, Ferranti et al. 2014).

According to the latest national forest inventory BWI3, growing stock is at a historically high level and has been increasing in the past 10 years by another 7 %. The highest growing stock on average can be found in privately owned forests. According to BWI3, the overall harvest intensity in private forests was already at a high level; however, there are strong differences across forest ownership size classes and especially in smaller forests harvest rates are comparably low. Accordingly, the highest additional supply potential is situated in small-scale private forests. The reasons for this are diverse and inter alia relate to fragmentation of ownership or lack in interest in forestry (SFC 2010).

An intensification of harvest rates can influence forest ecosystems. Against this background, knowledge on sustainable harvest rates is all the more important. However, estimates like the national forest inventory are targeted at larger scales and an in-depth assessment of sustainable harvest rates at a local level is difficult. Moreover, the national forest inventory – like many other studies – mainly refer to the bio-technical supply potential, neglecting the influence of forest owners' behaviour on the real wood supply potential. The motivation and behaviour of forest owners are key to understanding local supply potentials for wood. Therefore, scientific uncertainties still exist at a sub-regional or local scale, especially for privately owned forests. Estimations based on mere inventory data are insufficient, especially when it comes to the real wood supply potential, i.e. the willingness of forest owners to supply wood but such information is crucial, e.g. for renewable energy concepts and investment decisions into woody biomass plants.

Further uncertainties complicate reliable estimates of potential sustainable wood supply. Amongst these are the effect of climate change on forest growth and on the forests' proneness to calamities, future implications of policy requirements, market effects or societal preferences with regard to forest management as well as competition of forest production goals with conservation or protection targets (overview see Ferranti et al. 2014). Additionally, there are scientific uncertainties on the demand side with regard to the real amount of fuel wood consumed in private households, which is often not recorded in official statistics (Ferranti et al. 2014), and which could comprise different sources of wood – from virgin fibre from the forest to post-consumer wood.

Forests fulfil various functions. Logically, the interests and stakeholders' expectations regarding forest management and wood energy use are manifold. Increased wood energy use can thus also lead to conflicts of interest (perceived, potential, real). Against the background of limited wood supply from forests due to various bio-technical and socio-economic constraints, a further increase in the demand for fuel wood from the forest will either trigger the need for innovative or intensified forest management or for improved resource use or will not be possible without compromising different interests. For example, forest biodiversity could be affected through increased fuel wood use, e.g. due to changes in tree species composition, as well as removal of forest residues or deadwood, and lead to trade-offs between wood energy extraction and forest biodiversity conservation (Ferranti et al. 2014).

From a forest ecology viewpoint, there are several constraints to increased fuel wood supply. For example, increased tree harvesting can negatively affect the forest soil nutrient stock. Moreover, dead wood stock and quality (e.g. degree of decomposition, standing or lying dead wood) can have a special value for species diversity. The latest national forest inventory BWI3 in Germany (BMELV 2014) revealed that forests contain on average 21 m^3 ha^{-1} deadwood. This amount has been considered low and increased harvesting to satisfy bioenergy demand could result in a reduction of deadwood by 5% (Verkerk et al. 2011). Dead wood is generally an important parameter for species richness in forests. Increased wood harvest may further influence age class distribution and tree species composition which could again entail an impact on e.g. the nutrient balance of forests.

Klein & Schulz (2012) and Härtl (2013) analysed the interrelations of harvest rate and carbon storage in forest ecosystems and wood products. The studies concluded that moderate increase in forest growing stock has higher climate protection effect than e.g. harvesting an increased amount of timber even if substitution effects are taken into account. Therefore, increased harvest rates as a consequence of increased wood energy use entail additional emissions of greenhouse gases. Similarly, Wibe (2012) showed that increased harvest of nutrient-rich forest residues may reduce forest productivity in the long term and thus entail lowered potential of forests to store carbon from the atmosphere.

On the other hand, there are also mutual implications from increased wood energy use. In light of climate change and due to ecological restructuring of forests, hard wood species are increasingly promoted in Central Europe. The increased wood energy use could support the transition towards more broad-leaved, close-to-nature forests as in Germany hard wood species on average (e.g. for beech: 558 bone-dry kg per cubic meter) have a higher density, respectively higher energy content than soft wood species (e.g. for spruce: 379 bone-dry kg per cubic meter) (LWF 2014) and are thus attractive for wood energy use. Moreover, there are fewer opportunities for material-based wood use due to more inhomogeneous plant growth of broad-leaved trees, and thus there is less competition for raw materials. For example in Bavaria in 2011, on average 47% of spruce logs were assorted as sawn timber or veneer while only 16% of oak logs were assorted accordingly (Rothe et al. 2015). This implies that the wood energy sector is a more attractive sales market for forest owners of mixed forests or hardwood dominated forests.

According to UNECE/FAO (2003) and EC (2015), the development of a market for wood energy represents an opportunity to raise the income and employment and to promote rural development. Moreover, the augmented demand and the increase in wood prices bring positive contribution margins for e.g. forest thinning operations in spruce stands. Therefore, increased wood harvest can also help prevent forest damage through calamities such as windthrow or pest infestation.

In summary, there is need for improved calculation of wood supply potential from the forest due to data gaps especially on the sub-regional and local scale. An in-depth review of all trade-offs and mutual implications on the forest resource level are outside the scope of this dissertation. Therefore, the subsequent document will focus on selected environmental indicators to assess the impact of increased wood energy use. In particular, the focus will be on sustainable timber harvest rates against the background of increased demand.

1.2.2 Increased wood energy consumption and the impact on selected environmental indicators

In addition to the forest resource level, there are implications of an increased wood energy demand on the overall resource availability for the wood-based industry and the wood energy sector. Wood is a renewable resource but the supply from domestic forests is limited due to various constraints. Therefore a consumption shift towards more wood energy use means that less domestic wood is available for other uses, entailing a competition between different industries, i.e. between the wood-based industry and the wood energy sector. “Missing” wood quantities either have to be imported or replaced with non-wood alternatives. For example, a lowered wood availability in the wood pellets industry would mean that more energy needs to be supplied from fossil sources such as oil or gas while a lowered wood availability in the construction sector would mean that sawn timber needs to be exchanged with construction material made from fossil sources such as steel or aluminium.

The question arises whether a shift in consumption has negative or positive impact on environmental indicators, e.g. global warming potential. A lack in knowledge exists with regard to the impact of increased wood energy use on environmental indicators, taking into account indirect effects on a regional scale, i.e. a decreased availability in the material sector and thus higher use of non-wood alternatives or import of timber products. Few scientific studies have assessed the environmental impact of material use versus energy use of wood. WI/RWI (2008) described advantages and disadvantages of wood energy use compared to wood material use. Carus et al. (2010) and Carus et al. (2014) evaluated the production of biomaterials with bioenergy, using a given area of agricultural land as a reference. Both studies concluded that cascaded material use is superior to the immediate combustion of resources. The aspect of cascaded use of wood is not included in this thesis, but recently Höglmeier et al. (2014) provided an overview on the utilisation of recovered wood in cascades versus utilisation of primary wood via a life cycle assessment and system expansion. Gärtner et al. (2013) compared different product life cycles of wood with fossil alternatives and found that direct combustion of wood instead of cascaded material use can entail, e.g. increased global warming potential.

However, these studies state individual comparisons of product alternatives. Due to different functional units (e.g. MJ, m^3, m^2, t) and end uses (electricity, heat, material use), study results and related products cannot be directly compared to each other. For example, wood pellets combustion for domestic heat generation is not directly comparable to combustion of wood chips for heat and power production. Moreover, when assessing the impact of a shift in material allocation over time, i.e. increased wood energy use and decreased resource availability in other sectors, it is indispensable to consider indirect effects on a regional scale. These include the consumption of imported timber or of alternative products, e.g. a building with brick walls instead of wooden walls in the material-based sector, or the consumption of imported wood pellets instead of fuel oil or natural gas. Lastly, effects of a consumption shift have only been assessed for defined units, e.g. for a hectare of land or a ton of biomass, and not on a regional scale. A comprehensive, regional impact assessment of a shift in consumption, taking into account both wood material use and wood energy use as well as associated indirect effects through alternative (fossil) usages, has not been conducted so far.

1.2.3 Increased wood energy consumption and the potential for particulate matter emission reduction

While wood energy use can contribute to greenhouse gas emission reduction, it also accounts for a considerable amount of emissions harmful to human health such as particulate matter ($PM_{2.5}$). Recent data showed that $PM_{2.5}$ emissions from fuel wood combustion have considerably increased in the past decades in Germany and that most of these emissions result from residential wood combustion for heating purposes (Ewens 2014).

The topic of increased dust emissions and its relevance for human health has been addressed in many scientific studies. Lim et al. (2012) revealed that worldwide particulate matter emissions are the main environmental root of ill health, and that air pollution causes about 7 million premature deaths per year. Recently, Kim et al. (2015) provided an overview on the health effects of particulate matter emissions, and Lu et al. (2015) conducted a systematic review and a meta-analysis of the adverse health effects of dust pollution in China. Song et al. (2015) reported on the health impacts of particulate matter, on increased mortality rates and on serious health threats such as respiratory diseases, cardiovascular diseases and chronic bronchitis. Pascal et al. (2014) revealed that particulate matter emissions have a significant short-term impact on mortality in France. Giuntoli et al. (2015) highlighted several environmental impacts associated with the use of wood energy, amongst them local air pollution through particulate matter emissions and pointed out that any action promoting wood energy use should consider whether proper actions for the management of adverse effects are in place. Caserini et al. (2010) showed that emissions from domestic devices correspond to almost one third of the total particulate emissions in Italy in 2005. Lamberg (2014) compared small-scale wood pellet boiler emissions in Finland with other combustion units as well as with non-wood energy sources and found that some biomass raw materials exhibit significant particle emissions.

In Germany, a vast share of dust emissions comes from old furnaces with a lack in modern filter technology and low energy use efficiency (Bundestag 2007). PM emissions from small combustion plants have increased by more than one fifth from 2005 till 2010 (Ewens 2014) while wood energy consumption in private households has grown in the same period by one third (Mantau 2012). According to research done by the World Health Organization (WHO 2006), particulate matter emissions entail an average reduction in human life expectancy of 10 months in Germany. However, the WHO data refer to the year 2000 and since then particulate matter emissions from residential heating with solid fuels have been increasing by more than 50%, according to data by UBA (2013).

Therefore, a potential for increased resource use efficiency, lowered emissions and improved health conditions exists for the wood energy sector. Recently, a law amendment has become effective in Germany, which sets stricter emission thresholds for wood energy combustion depending on the installation type. The impact of the law amendment could be strong; however, it is unclear to what extent the law amendment will be really implemented and monitored in practice and to what extent the increasing wood energy consumption counteracts the political targets. Moreover, scientific uncertainties relate to the number of installations affected by the law amendment, to the overall amount of wood combusted in residential heating system and to the impact of the law amendment on particulate matter emissions.

1.2.4 Wood energy use in Bavaria seen from a broader context - comparing Bavarian conditions with other regions

The situation in the case study area Bavaria with regard to an increase in wood consumption is similar for Germany – see e.g. Knauf (2014) who reported that meanwhile more than 60% of total wood consumption refers to wood energy use. Moreover, the German situation is comparable to other countries within the European Union for which an expansion of biomass use is targeted within the recent biomass action plans (EC 2015). The use of biomass for energy has significantly increased in Europe over the last twenty years (Ferranti et al. 2014). Sweden and Finland, two European countries with a large forest resource per capita, produce between 25 and 30% of their final energy consumption from (predominantly forest) biomass (AEBIOM 2012). Several wood supply estimates have been conducted producing a comprehensive view of the wood supply potential for bioenergy production at the European (overview see Ferranti et al. 2014), national and regional level (e.g. Hofer & Altweg 2008, Mantau et al. 2010, UNECE/FAO 2011, Mantau 2012).

However, not all European countries have a comparably high focus on bioenergy, partly due to differing natural conditions. Moreover, when comparing Bavaria with other regions in the world, it becomes evident that there are regions where biomass plays a much less important role and where much less wood is harvested and used for energy. For example Tasmania, Australia's southernmost state and a region comparable to Bavaria in terms of its forest area, has a much larger forest resource per capita but the use of forest biomass for energy is restricted to domestic firewood and only few industrial heating plants. Substantial uncertainties exist regarding the current use and the sustainable future supply of forest biomass feedstock for energy production in Tasmania. There is no reliable information on the potential Tasmanian forest biomass for energy feedstock originating from forest management covering both public and private land, mainly due to the insignificance of wood energy use in this region – in contrary to Bavaria.

2 Goal of the thesis and scientific objectives

2.1 Overall goal and research questions

Increased wood energy use can trigger several trade-offs. The overall evaluation of the impact of increased wood energy use is diverse and complex, and thus needs to be evaluated at different scales. The key question of the study at hand is *whether more wood energy can be used and how it can be consumed most efficiently in order to mitigate trade-offs arising from increased wood energy demand*. The main goal of the dissertation is to assess the impact of increased wood energy use on the availability of wood resources and to evaluate selected environmental impacts for the case study area Bavaria such as emissions to air. The overarching research topics and research questions for this dissertation are:

1. Sustainable supply potential from the forest (resource context, paper 1 extended)
    - Research question 1: How much wood can be sustainably supplied from domestic forests, taking into account nature conservation restrictions, nutrient sustainability, dead wood restrictions, technical constraints and forest owners attitudes towards harvesting and fuel wood mobilisation?
    - Research question 2: Given current wood energy demand and harvest levels, is there an additional supply potential in Bavaria?

2. Increased wood energy use and its impact on environmental indicators (emission load context, paper 2)
    - Research question 3: How will emissions relevant for climate and human health alter in the future following a shift in wood consumption towards more wood energy use?
    - Research question 4: Is it favourable to use wood in a certain manner and are there different trends according to the impact category chosen?

3. Reduction potential of emissions through increased resource use efficiency (emission reduction context, paper 3)
    - Research question 5: To what extent can future dust emission load from wood combustion be reduced?
    - Research question 6: How much additional wood energy could be gained through increased resource use efficiency?

4. Comparison of the situation in Bavaria with Tasmania, and other regions (comparative context, paper 4 extended)
    - Research question 7: What are similarities and differences with regard to wood energy use in Bavaria and other regions?

2.2 Outline of the thesis

Paper 1 presents the constraints to additional wood supply from private and communal forests in Bavaria and is extended for the whole forest area in Bavaria including the state forest in this dissertation. The challenges arising from an increased wood energy demand are outlined from a resource supply viewpoint. Paper 2 shows the consequences of increased wood energy consumption on resource allocation in the forestry and wood cluster Bavaria, as well as the impact on greenhouse gas, on particulate matter emission and on primary energy demand. Therefore the challenges arising from increased wood energy consumption are presented with regard to emission load and energy balance. Against the background of increasing wood energy consumption and increased emission load, Paper 3 presents the opportunities for higher resource use efficiency and for reduced particulate matter emission load. As a vast share of particulate matter originates from residential biomass combustion, the third section focuses on this market segment only. Finally, Paper 4 sets the case study area Bavaria into a broader context and compares the socio-economic and natural conditions to other regions, e.g. Tasmania – a state with a similar forest area but with contrary framework conditions in order to reveal specific patterns of the Bavarian wood energy sector.

Finally, the results are discussed in a broader context and a synthesis of the publications 1–4 is presented. Figure 1 provides an overview on the thesis at hand.

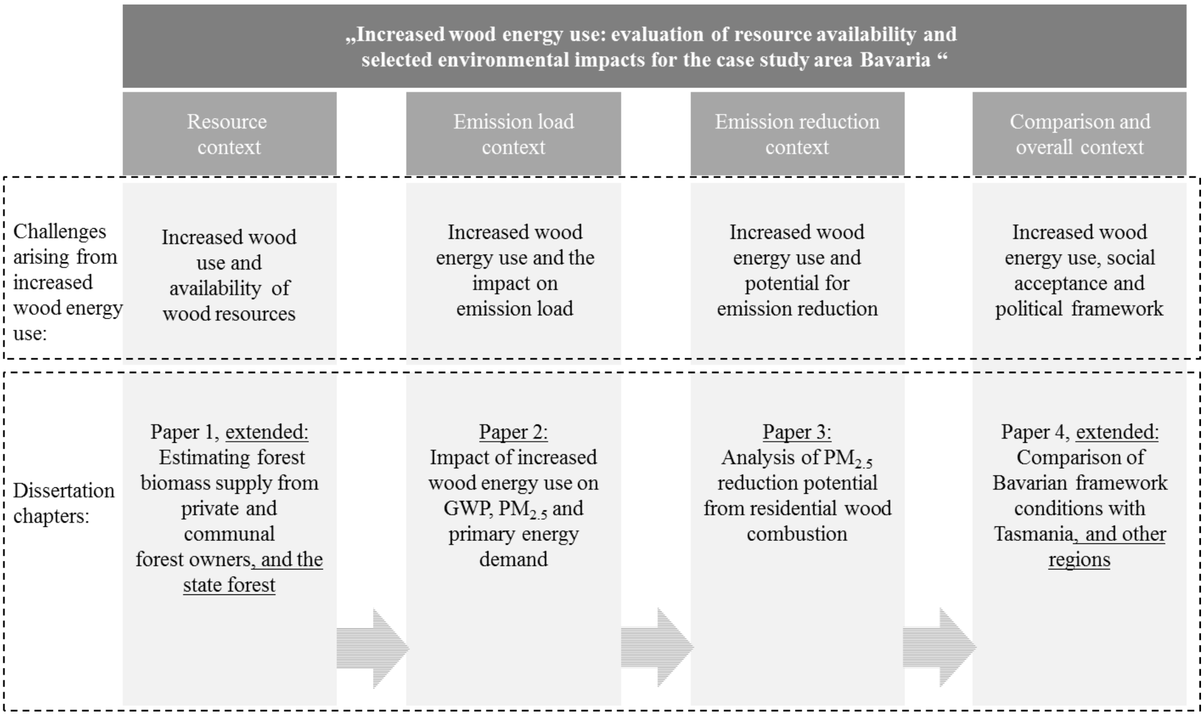


Figure 1 Outline of the thesis

3 Overview on scientific publications

3.1 Publication 1: *Estimating forest biomass supply from private forest owners - A case study from Southern Germany*

Wilnhammer M, Rothe A, Weis W, Wittkopf S.

Biomass and Bioenergy 47 (2012):177-87

Summary

In recent years, political stimuli for renewable energies in Europe and rising prices of fossil fuels entailed an increase in wood demand. Sound data on resource availability and forestry impacts are crucial for sustained wood production. However, in-depth data on the local and sub-regional scale were to date not available, in particular with regard to private forest owners who own a vast share of forest land in the study area.

Therefore, a methodology was developed to estimate the biomass supply potential from such forests. Most of the data was obtained via stratified random interviews with private forest owners. Bio-technical potential was derived via an analysis of theoretical supply potential, bio-technical constraints and of forest owners' forest management behaviour, deriving the additional supply potential for woody biomass. Results exhibit that despite considerable bio-technical restrictions the investigated small-scale private forests offer an additional potential for forest biomass harvest. However, strong further restrictions for wood mobilisation relate to the willingness of owners to harvest additional biomass.

Own contribution

Matthias Wilnhammer designed the methodology of the paper based on prior work done by Andreas Rothe (i.e. the distinction in theoretical, bio-technical and socio-economic potential), conducted the data gathering (supervision to interviews with forest owners), the statistical data analysis and calculations, and wrote the paper. The co-authors made suggestions to the paper methodology and design and revised the manuscript.

3.2 Publication 2: *Effects of increased wood energy consumption on global warming potential, primary energy demand and particulate matter emissions on regional level based on the case study area Bavaria (Southeast Germany)*

Wilnhammer M, Lubenau C, Wittkopf S, Richter K, Weber-Blaschke G

Biomass and Bioenergy 81 (2015):190-201

Summary

In this publication, a scenario analysis was applied to model a shift in wood consumption towards more wood energy use in Bavaria until 2035. Against the background of increased demand for wood energy, the question arose whether a shift in consumption has negative or positive impact on environmental indicators. A regional impact assessment of a shift in wood consumption for the Bavarian forestry and wood cluster, taking into account wood use patterns and associated indirect effects through fossil usages, has not been conducted so far.

Prevalent wood products, imported timber and conventional alternatives of use were assessed via a Life Cycle Assessment according to three environmental indicators: global warming potential, primary energy demand and particulate matter emissions. The basket of benefit method was used to evaluate the impact of increased wood energy use and decreased material-based wood use in the study area. LCA analysis was conducted on the basis of a comprehensive literature research and with the LCA software GaBi 6.0.

Results reveal that a shift towards more wood energy consumption can lead to a minor increase in global warming potential and to a reduction in primary energy demand. Particulate matter emissions from wood energy use increase strongly but definite conclusions cannot be drawn due to lack of data. More research is needed to fill data gaps but the basket of benefit approach is a valuable tool to crystallise effects of an increased wood energy use.

Own contribution

Matthias Wilnhammer contributed to the methodology. He conducted the LCA analysis, the scenario and sensitivity analyses as well as the literature review for all energy products. Consumption and demand patterns were co-developed with research colleagues. Mr. Wilnhammer wrote the paper and the co-authors supported in the manuscript revision.

3.3 Publication 3: *The impact of a new emission control act on $PM_{2.5}$ emissions from residential wood energy use in Bavaria, Germany*

Wilnhammer M, Richter K, Wittkopf S, Weber-Blaschke G

Journal of Cleaner Production 145 (2017):134-41

Summary

Residential biomass combustion is responsible for a large amount of particulate matter emissions which are harmful to human health. An emission control act has recently become effective in Germany aiming at heating system modernisation and emission load reduction. In light of an increasing wood energy consumption, there was need for research with regard to the impact of the air emission control act on the long-term development of $PM_{2.5}$ emissions.

This paper exhibits the development of $PM_{2.5}$ emission load from wood energy combustion for the case study area Bavaria and describes the impact of the law amendment. Emission factors of prevalent heating systems were calculated and the influence of the emission control act analysed, taking into account retro-fitting and replacement rates of old heating systems and different wood consumption developments. The results show that $PM_{2.5}$ emissions could be reduced considerably and that there is a strong potential for increased resource use efficiency in the domestic heating sector. Moreover, it becomes apparent that policy makers have a crucial role to play towards a responsible use of wood energy resources and that wood energy needs to be consumed in a most efficient way to mitigate adverse health effects.

Own contribution

Matthias Wilnhammer developed the paper methodology, conducted the data analysis and literature review as well as drafted the manuscript. The co-authors added to the study design and to the manuscript revision.

3.4 Publication 4: *Current and potential use of forest biomass for energy in Tasmania*

Rothe A, Moroni M, Neyland M, Wilnhammer M

Biomass and Bioenergy 80 (2015):162-72

Summary

In this scientific publication, the Bavarian wood energy sector was compared with other European countries and with Tasmania, an Australian state, which exhibits several contrary patterns to Bavaria in terms of biomass production and wood energy use. The antagonistic patterns entail that Bavaria and Tasmania are well suited for a comparative analysis in order to crystallise specific characteristics. The current use and the potential sustainable supply of forest biomass in Tasmania were quantified and compared to Bavaria, and the reasons for the strong differences in wood energy use were analysed, taking account of economic, legislative and social drivers.

The results show that forest bioenergy production in Bavaria as well as in European regions and countries, is strong relative to the available resource. There is a high social and political acceptance for this energy source and generally fuel wood consumption plays a strong role. In contrast, the resource availability in Tasmania is large but consumption is at a minimum and could be more than quadrupled from a resource availability perspective.

Social acceptance is a prerequisite for the success of initiatives or legislation to achieve an increase in wood energy use, as the case study for Tasmania shows.

Own contribution:

As a co-author, Matthias Wilnhammer contributed to the paper chapters on economic background, legislative framework and social drivers of the Bavarian wood energy sector.

4 Material and methods

4.1 Study area

For the papers 1, 2, and 3, Bavaria was chosen as a case study area and then compared to other regions in paper 4. For the State of Bavaria, Germany, a good database exists for the forestry and wood cluster, inter alia due to studies by Röder et al. (2008), Friedrich et al. (2012) and Gaggermeier et al. (2014). Bavaria is a state in Southern Germany where wood energy use is traditionally high and which is characterised by a rather high population density (175 people per km^2) leading to a strong domestic market for wood products and bioenergy. Almost one third of annual harvest in Germany comes from Bavaria (Destatis 2013). There are more than 1 000 sawmills and about 20 large plants for engineered wood products (veneer, plywood, particle boards, chemical pulp, mechanical pulp) processing annually about 4 hm^3 wood (Rothe et al. 2015). In general, the vast majority of wood energy is used for heat generation and 29% of heat is consumed in private households (BMWI 2014, FNR 2013).

Share of wood energy assortments in total harvest has increased from 23% in 2005 to 34% in 2010 (Friedrich et al. 2012). Overall wood consumption in 2010 was 26.7 hm^3, including post-consumer material, industry residues and wood from landscape management. Almost half was used for energy (12.8 hm^3), predominantly in private households (7.5 m^3) but also in heating plants (1.1 hm^3) and combined heat and power plants (4.2 hm^3). 10.6 hm^3 of sawn timber were consumed, as well as 1.6 h m^3 of paper and 2.1 hm^3 of wood-based panels (Friedrich et al. 2012).

According to the German forest inventory for the period 1987-2002 (BMELV 2004), regional fellings were considerably below annual increment (6 m^3 ha^{-1} a^{-1} compared to 14 m^3 ha^{-1} a^{-1}), resulting in an increase in growing stock. The underutilisation was especially pronounced in small-scale privately owned forests. The latest national forest inventory confirmed that growing stock in small and medium scale private forests remains at high levels (BMELV 2014), and that there is additional harvest potential.

The use of forest biomass for energy is widespread in Bavaria which is typical for many European countries where the share of energy derived from biomass is closely correlated with the available forest resource (Rothe et al. 2015). In the 27 member nations of the European Union biomass contributed 8.2% of total final energy consumption in 2010 or nearly 64% of European renewable energy (AEBIOM 2012). Two thirds of total biomass for energy production or about 50% of total renewable energy (Mantau 2010) was from forest biomass.

According to Friedrich et al. (2012), 28% of nationwide wood energy in 2010 was consumed in this study area and more than half of wood energy is used in private households for heating purposes. Split logs are the predominant source of heat energy in private households (79 %), wood pellets are being increasingly used and in 2012 accounted for 11 % (Gaggermeier et al. 2014). In total, wood consumption in private households in 2010 was 7.5 hm^3 a^{-1}, equivalent to 62 PJ a^{-1} (Friedrich et al. 2012). Wood consumption is steadily increasing in the study area and has already accounted for 8.1 hm^3 a^{-1} in 2012, equivalent to 66 PJ a^{-1} of energy (Gaggermeier et al. 2014). Domestic heating in 2012 thus accounted for 58% of overall wood energy consumption of 114 PJ a^{-1} (Gaggermeier et al. 2014). In order to derive the amount of wood consumption in private households, nationwide data from Struschka et al. (2003), Nussbaumer et al. (2008), Struschka et al. (2008), Rheinbraun (2011) and Ewens (2014) were analyzed and applied to the calculations for Bavaria.

For evaluating the supply potential for wood energy from forests (publication 1) the paper focuses on three southern German counties (Bad Tölz-Wolfratshausen, Miesbach, Rosenheim) due to its representativeness for rural regions in Southern Germany, the high conservation value of its mountainous regions and thus the potential threat to sustainability, and the accessibility to personal information such as addresses of potential interviewees due to good contacts with the forest owners associations. The methodology is then extended in this dissertation to all of Bavaria. With regard to the analysis of the impact of increased wood energy use on emissions relevant for climate change and human health, as well the emission reduction potential (publications 2 and 3) and the overall wood energy sector patterns (publication 4), the paper relates to all of Bavaria as well.

4.2 Applied scientific methodology

4.2.1 Estimating potential sustainable wood supply from forests for wood energy at a local and regional scale (paper 1 extended, resource availability)

Interview of private and communal forest owners

In order to obtain the necessary data regarding harvest rate and forest owners' log classification (i.e. wood energy use), private and communal forest owners organised in forest owners associations were interviewed via a stratified random sample, divided into six strata according to common size classes of forest holdings (Beck & Perschl 2006). Determination of minimum sample size per stratum was calculated according to Kauermann & Küchenhoff (2010) using the formula $N = 4\ S\ e^{-2}$, where N is the minimum sample size, S the standard deviation of interview responses to felling intensity in $m^3\ ha^{-1}\ a^{-1}$ and e the required accuracy. As it was not possible to draw upon previous knowledge on local felling intensity, a pilot sample N of ten interviews within each stratum was drawn in order to determine the standard deviation S. For e, a maximum deviation of 10% from the arithmetic average within each stratum was postulated. For example, e = 1 if arithmetic average of our pilot sample equalled a felling intensity of 10 $m^3\ ha^{-1}\ a^{-1}$ (Table 1).

Table 1 Number of interviewed owners and minimum sample size according to size class of forest holdings (Wilnhammer et al. 2012).

Size class (ha)	**Standard deviation (S)**	**Required accuracy (e)**	**Minimum sample size of interviews (N)**	**Number of interviewed owners (N)**
< 4.9	2.37	0.87	29	31
5 - 9.9	2.74	1.10	25	44
10 - 19.9	2.15	1.03	17	66
20 - 49.9	1.60	0.64	25	52
50 - 99.9	1.54	0.80	15	19
> 100	1.48	0.66	11	14
Total	-	-	122	226

Probands were selected with a random generator from a members list provided by the forest owners associations and interviewed personally or by phone. In case that an owner refused to participate, the following one on the list was contacted. The contents of the interview comprised questions concerning the forest estate, ownership situation, harvesting practices as well as log grading and marketing for the period 2006-2008.

Assessment of biomass potential in private, communal and state forests of Bavaria

The biomass potential according to publication 1 was calculated in three steps.

1) Theoretical potential was calculated as above ground forest biomass using local forest inventory data (data basis: BWI 2).
2) Technical-ecological potential was calculated by subtracting the following restrictions from above ground biomass (for a detailed overview please see publication 1):
   - Accessibility: constraints resulting from insufficient forest infrastructure (data basis: interview results).
   - Nature conservation: restrictions through protection of forest areas (data basis: GIS analysis, literature research).
   - Nutrient sustainability: constraints entailed by requirements of maintaining soil fertility (data basis: literature research).
   - Leaving coarse woody debris: limitations from minimum dead wood requirements (data basis: literature research).
   - Restrictions through harvest loss (data basis: interview results).
3) Socio-economic potential:
   - Annual harvesting rates and log grading are calculated per size class and per wood assortment (data basis: interview results).

Finally, the bio-technical potential was compared with utilisation patterns of owners, deriving the additional supply potential for the area under investigation.

This methodology was further extended to whole Bavaria, including state forests in order to fully estimate wood supply potential in the province. Moreover, interviews with forest owners were not conducted and harvest rates and log classification were determined via literature (BMELV 2014 and LWF 2015). According to BMELV (2014), the net annual increment is 11.9 m^3 ha^{-1} a^{-1}, respectively a gross annual increment of 13.3 m^3 ha^{-1} a^{-1}, using a biomass expansion factor of 1.16. The following constraints were calculated for whole Bavaria:

- Accessibility: According to BMELV (2014) 98 % of forest area is accessible, entailing a harvest constraint on 2% of the area, respectively 0.3 m^3 ha^{-1} a^{-1}.

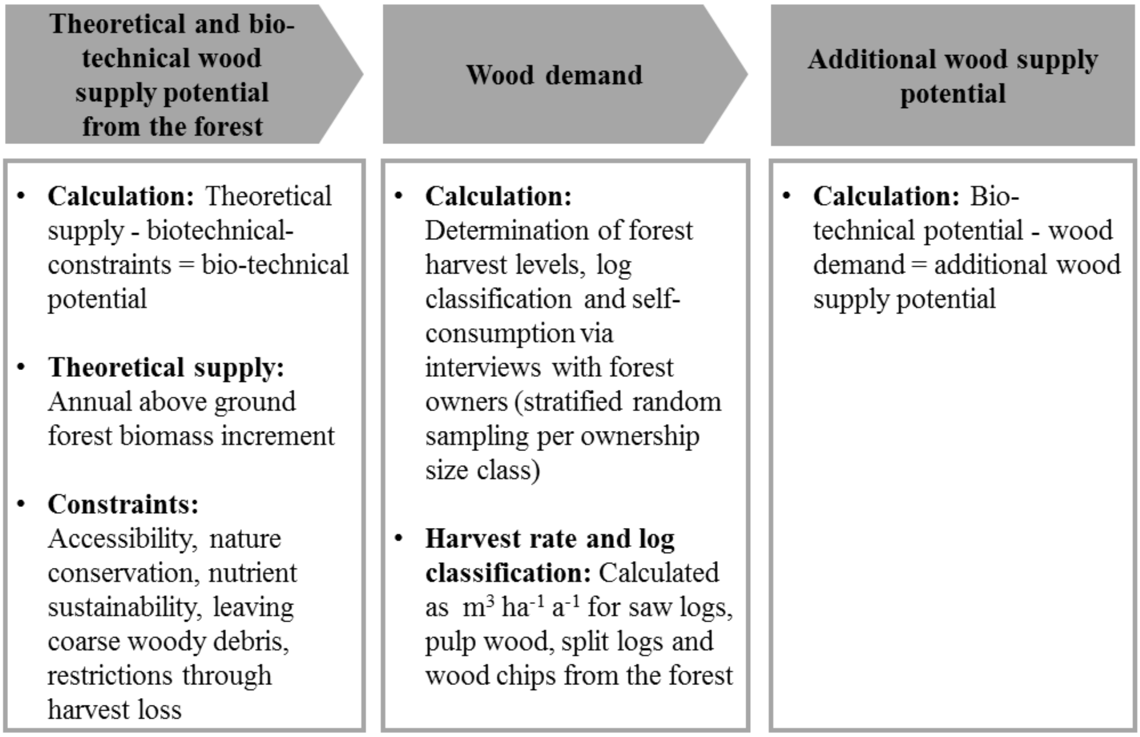
- Nature conservation: According to BMELV (2014), 6% of the forest area is protected through §30 BNatschG. On such areas, no harvest operations were considered. Further 3 % are nature conservation areas (StMELF 2015, BMELV 2014) for which harvesting limitations on 50% of the area are assumed. Accordingly, harvest restrictions of 1.2 m^3 ha^{-1} a^{-1} arise.

- Nutrient sustainability: Harvest restrictions are calculated for 34% of the area (nutrient-poor soils, substrate groups 4 and 5, see LWF 2010). For such areas a reduction in harvest of 15% (tree crown biomass) was assumed, resulting in a harvest restriction of 0.6 m^3 ha^{-1} a^{-1}.

- Leaving coarse woody debris: In Bavarian forests, the average amount in dead wood is 22 m^3 ha^{1} (BMELV 2014). Applying a weighted decomposition rate according to tree species of 0.06 (Rock et al. 2008) on average 0.7 m^3 ha^{-1} a^{-1} dead wood need to be left on site in order to keep dead wood stock in an equilibrium.

- Harvest loss: Applying a harvesting loss of 10% according to StMELF (1990), average harvesting loss equals 1.1 m^3 ha^{-1}.

Figure 2 summarizes the applied methodology for paper 1 and its further application to whole Bavaria.



- **Calculation:** Theoretical supply - biotechnical-constraints = bio-technical potential
- **Theoretical supply:** Annual above ground forest biomass increment
- **Constraints:** Accessibility, nature conservation, nutrient sustainability, leaving coarse woody debris, restrictions through harvest loss

- **Calculation:** Determination of forest harvest levels, log classification and self-consumption via interviews with forest owners (stratified random sampling per ownership size class)
- **Harvest rate and log classification:** Calculated as m^3 ha^{-1} a^{-1} for saw logs, pulp wood, split logs and wood chips from the forest

- **Calculation:** Bio-technical potential - wood demand = additional wood supply potential

Figure 2 Overview on applied methodology for paper 1 extended.

4.2.2 Assessing the impact of increased wood energy use on primary energy demand, global warming potential and particulate matter emissions (paper 2, emission load)

Scenario analysis

Two scenarios were defined to model a shift in consumption, i.e. less material-based wood use and more wood energy use, and to analyse the effect on environmental impact categories:

- a ”baseline scenario” which describes a constant wood consumption until 2035 for all material-based and energy-related wood products, and
- a “wood energy scenario” which refers to an increasing demand for wood energy.

While wood consumption data for the year 2010 by Friedrich et al. (2012) were used as a starting point for scenario modelling, the wood energy scenario was based on the “Reference scenario” of the European Forest Sector Outlook Study II (UNECE/FAO 2011). A consumption shift was calculated based on five-year periods. For the determination of wood energy consumption, woody biomass from the forest as well as woody biomass from outside the forest were considered, i.e. short rotation plantations, wood from landscape management, industry co-products and post-consumer wood.

The development of wood energy demand per product and period was defined based on studies about potential wood supply and forecasted wood energy demand (BMU 2010, UNECE/FAO 2011, Härtl 2013, Härtl & Knoke 2014, DEPI 2013). In case that the potential supply per product and period was below the wood energy demand, wood pellet imports were modelled. In order to exclude external effects, import, export and domestic trade of wood products were kept in balance. Furthermore, round wood imports were not considered. In the event of a lack in domestic raw materials for wood-based panels, wood imports were calculated. As regards graphical paper, it was assumed that electronic media will substitute wood-based paper products. Assumptions, based on expert interviews and expert panels in combination with statistics and outlook studies, were additionally made in case that no scientifically sound data were available. In order to ensure comparability, the overall demand for both energy and material purposes was set stable in both scenarios and in every period.

Furthermore, the study concentrated on the most relevant, i.e. most commonly used wood products in the study area according to Friedrich et al. (2012), i.e. split logs, a mix of wood chips as well as wood pellets. Split logs and wood pellets represented the production of heat, whereas wood chip mix stood for both production of thermal energy and electricity. As material-based products, sawn timber as well aswood-based panels and graphical paper were selected.

Because the wood energy scenario entails an increase in fuel wood consumption and a decrease in material-based wood use, those alternative products which are substituted by fuel wood or which are used instead of material-based wood products were identified. In the electricity sector, electricity generation from wood was compared with the future German power mix and heat generation from wood was compared with heat generation from natural gas. In the material-based sector, representative non-wood buildings in Bavaria were determined to be used instead of equal buildings constructed with sawn timber, respectively representative electronic media to be used instead of graphical paper products. Furthermore, imports of wood-based panels were calculated.

Life cycle assessment

The goal of the life cycle assessment presented in this study was to compare the impact of a shift in wood utilisation on environmental indicators and to derive recommendations for improved wood consumption. The LCA was designed as a cradle-to-grave analysis and conducted via the LCA software GaBi 6.0 (PE International 2012). The life cycles of the wood products for energy and material purposes were evaluated along common regional supply chains. The products were assessed according to three environmental impact categories, which are highly relevant for the study area against the background of current scientific and public discussions relating to wood energy usage, i.e. non-regenerative primary energy demand (net calorific value), global warming potential (GWP 100) without biogenic CO_2, and particulate matter emissions ($PM_{2.5}$). The consequences of altered wood consumption on environmental indicators were assessed over time.

Basket of benefit methodology and wood use balance

The basket of benefit approach according to Fleischer (1994) and Bystricky et al. (2010) was applied to analyse the impact of altered wood consumption in Bavaria. The methodology is a life-cycle assessment approach to compare emissions from diverse product pathways against each other and against alternative products. Comparability is warranted through system expansion which guarantees that different systems, e.g. energy use instead of material use, contain an equivalent amount of benefits and the same end uses (Fleischer et al. 2011).

In order to ensure a common basis for comparison of energy products, all fossil and wood energy-related data were converted into energy (MWh) and round wood equivalents (m^3). The functional unit in the material-based sector was harmonised via converting all units of material-based wood products and their product alternatives into round wood equivalents (m^3). Impact category results per cubic meter were multiplied with wood product amounts consumed in each of the five-year periods. Wood consumption per product in the baseline scenario was frozen over the reporting period. In the wood energy scenario, increased fuel wood consumption triggered the substitution of fossil energy and a lack of timber in the material-based sector which was equilibrated through the use of imported timber or of non-wood alternatives (Figure 3).

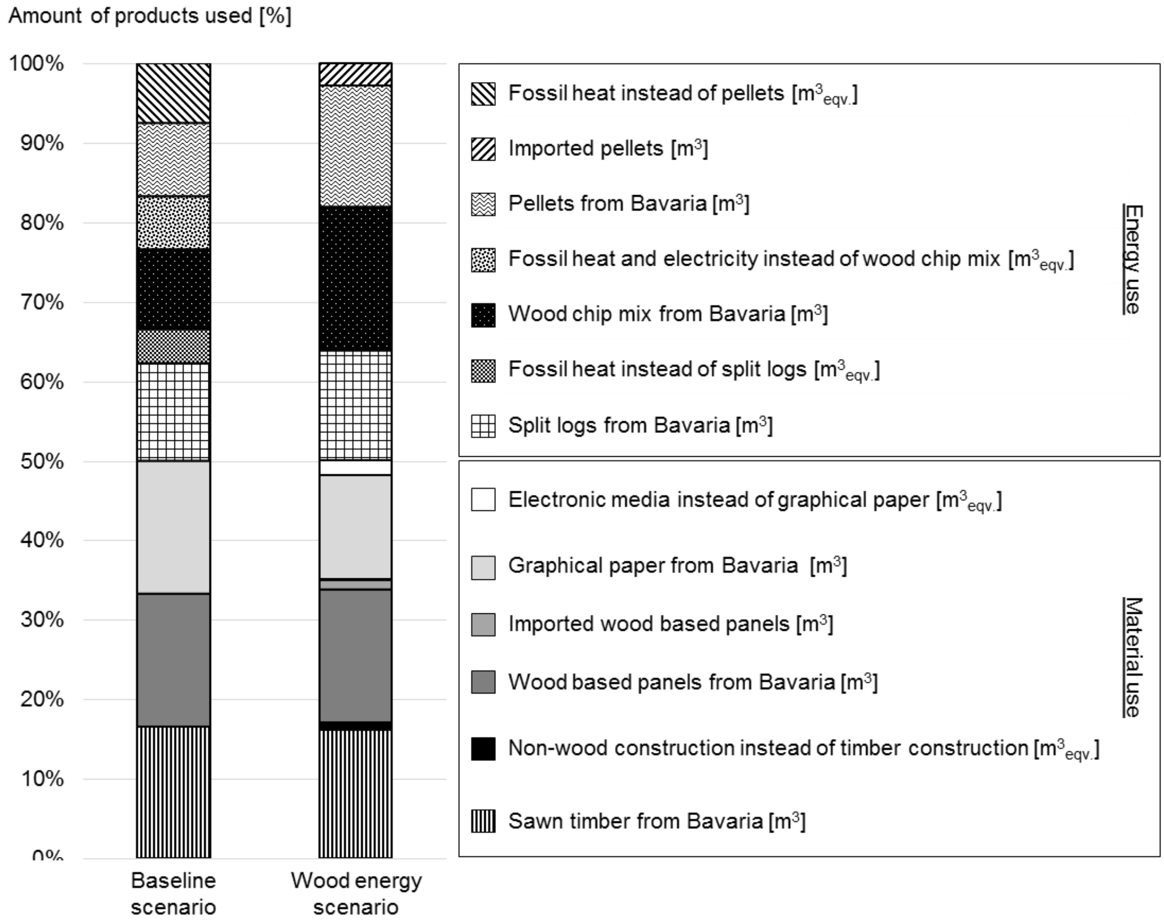


Figure 3 Illustration of the basket of benefit methodology and the products used to fulfil energy and material demand (Wilnhammer et al. 2015).

Note: The unit [m^3] refers to the amount of wood used to produce the respective products. The unit [m^3eqv] refers to the amount of wood which is substituted through the respective alternative product.

Through this approach, a comparative assessment of material and energy use at the regional level under different consumption scenarios was possible. The modelled consumption per wood assessment and over time was validated via interviews with scientists and industry representatives as well as through a literature review. Figure 4 summarizes the applied methodology for paper 2.

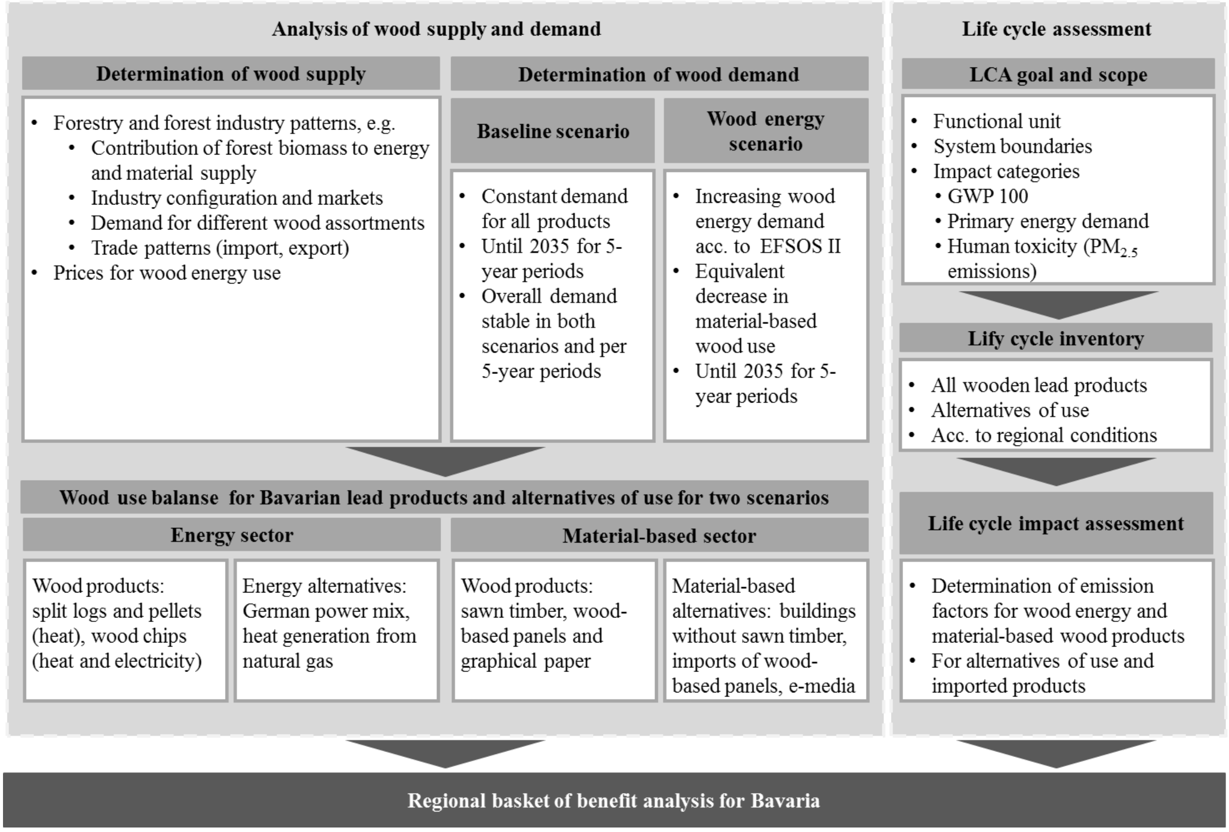


Figure 4 Overview on the applied methodology in paper 2.

4.2.3 Analysing the reduction potential of particulate matter emissions from residential wood combustion (paper 3, emission reduction potential)

Inventory of installed heating systems

The national inventory of residential and commercial combustion systems is heterogeneous with regard to heating system and age. Rheinbraun GmbH (2011) and UBA (2014a) the number of firing systems in private households in Germany was estimated at 14 million residential wood-burning furnaces and 0.7 million boilers. As 15 % of German households are situated in Bavaria (LfStaD 2015), and as 3% of these households have more than one heating system installed (Gaggermeier et al. 2014), it was estimated that overall 2.3 million wood combustion systems were installed in Bavarian households in 2010. Out of these, 1.8 million installations were single room furnaces and 0.5 million central heating systems. The share per installation type was derived based on the breakdown by Struschka et al. (2008) for Germany and the share of pellet boilers in central heating systems via data by DEPI (2013). Wood consumption volumes in private households were multiplied with emission values per heating system and thus overall emission load could be extrapolated to the case study area.

Introduction of a new imission control act (Bundesimmissionsschutzverordnung BImSchV) and calculation of modernisation rate

A law amendment of the German Federal Immission Control Act became effective at the beginning of 2015. The act sets limits for pollutant emissions as well as requirements for continuous monitoring of emission load and for retro-fitting or decommissioning of old installations. The impact of the law amendment was analyzed by determining the number of installations which will be affected by the amendment and the year of their retro-fitting or decommissioning. In particular, according to Bundestag (2007) and HDG Bavaria (2009), 13.9 million out of a total of 14.9 million (Rheinbraun 2011) installations will need to be replaced or retro-fitted, corresponding to a modernisation rate of 93% and this overall modernisation rate was applied to the case study area. Data by Struschka et al. (2008) on the age class distribution of installations was used to calculate the modernisation rate per installation type and cut-off year.

Emission factors per combustion systems and development of wood consumption

The calculation only considered the conversion phase of wood energy products, i.e. the wood combustion since the new legal act is concentrated on the conversion phase only. Emissions per installation types were calculated according to data by Struschka et al. (2003), Nussbaumer et al. (2008) and EEA (2013). The amount of wood used per combustion system was multiplied with the associated emission factors and the development of total $PM_{2.5}$ emission load in Bavaria was modelled until 2035. The overall development of $PM_{2.5}$ emissions was calculated as a result of the changing heating system infrastructure via multiplying installation-specific consumption data per period with installation-specific emission factors. Two scenarios for the development of wood energy consumption were calculated, equivalent to the methodology described under section 4.2.2 (paper 2), i.e. a stable wood consumption until 2035 and an increased wood energy scenario.

It was further assumed in this analysis that an additional consumption of wood is a consequence of a displacement of fossil sources such as heating oil and natural gas. In order to put the results into a context, the analysis further comprised a calculation of emission development without the impact of the law amendment. Based on the assumption that the average heating system is exchanged after 30 years, an annual exchange rate of old installations with new ones of 1/30 was applied. Moreover, it was assumed that the new installations comply with minimum emission limits set in the legal control act.

Figure 5 summarises the applied methodology for paper 3.

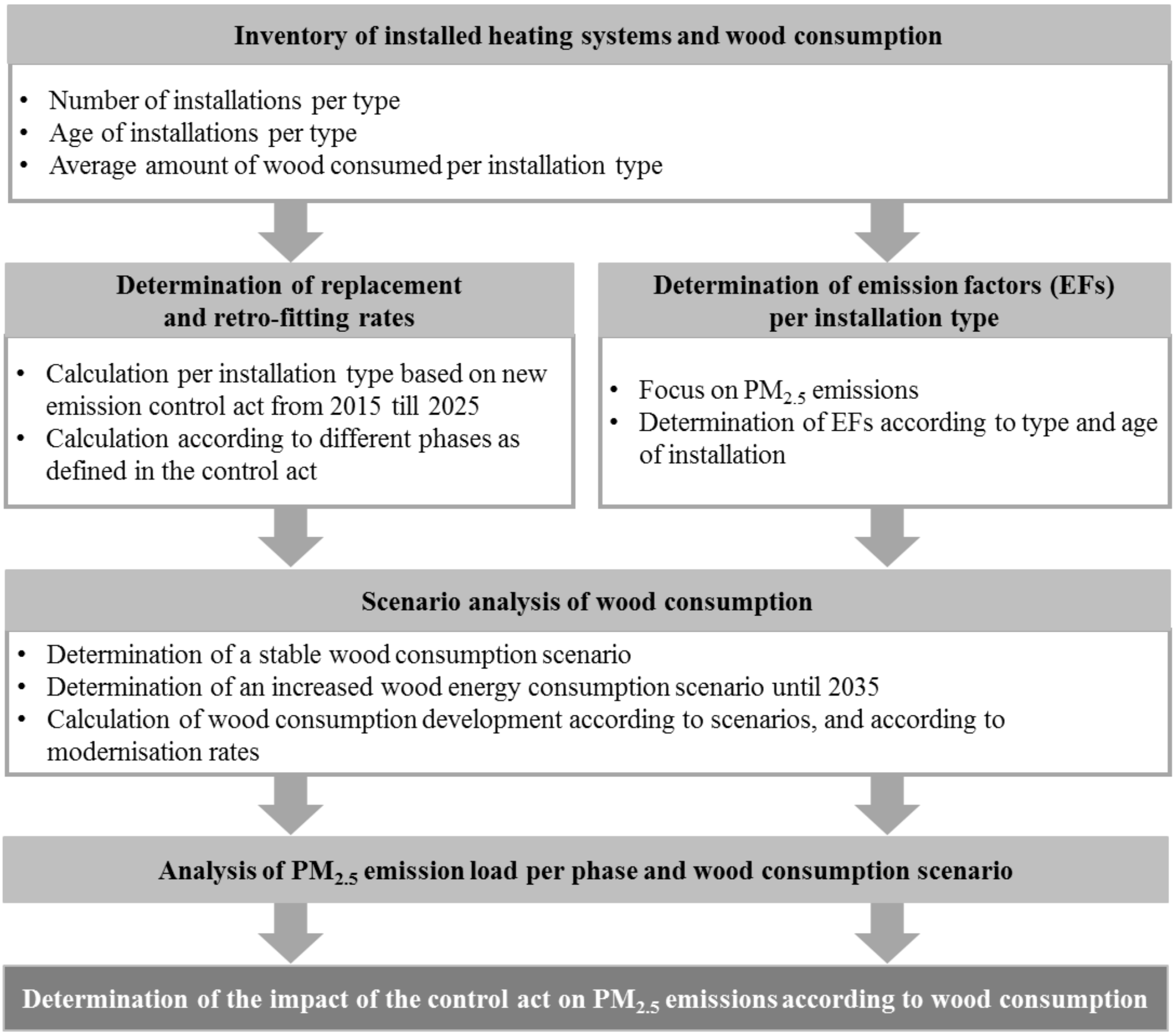


Figure 5 Overview on the applied methodology in paper 3.

4.2.4 Comparing wood energy use patterns in Bavaria with other regions (paper 4 extended, wood energy use patterns)

Case study – contrasting wood energy use in Bavaria with Tasmania and other regions

A case study comparison was conducted via contrasting Tasmanian results with data from Bavaria in order to interpret wood energy sector patterns from Bavaria. Despite Tasmania and Bavaria having a comparable forest area, there are significant differences between the two states in industry configuration and markets. In particular, the following differences were investigated via literature research and data comparison:

- Evaluation of forest biomass potential and resource utilisation. Estimates of the volumes of wood-processing residues used for energy were obtained via interviews with industry representatives (Rothe 2013), estimates for domestic firewood consumption were based on literature data (e.g. Driscoll et al. 2000). Firewood consumption was estimated by multiplying the number of households using firewood as a main heating source with average household consumption data (Rothe et al. 2015). The potential supply of forest biomass for energy was calculated separately for low quality logs and harvesting residues resulting from forest management of both native forest regrowth and plantations as well es from wood processing residues.

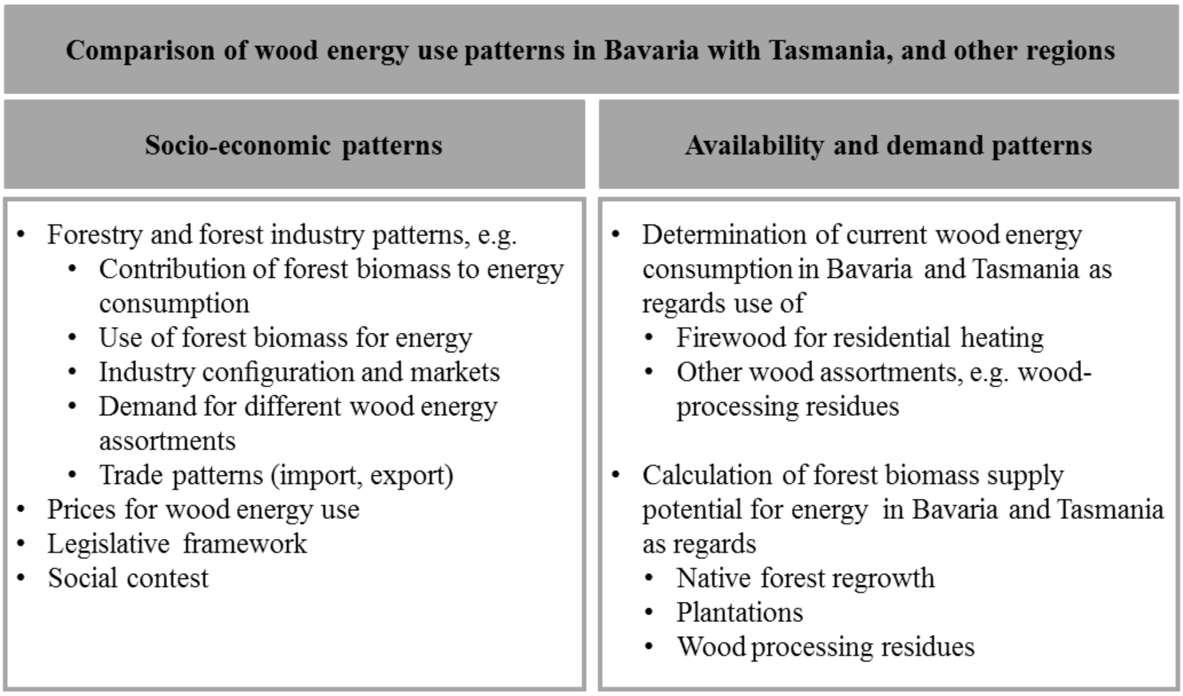
Literature review of economic, legislative and social drivers

A comparison of economic, legislative and social drivers for forest biomass utilisation for energy production was conducted via a literature review. In particular, prices for energy wood were determined and the socio-economic framework conditions as well as wood energy supply and demand patterns were analysed. Thus, an overview on the market situation in both Bavaria and Tasmania was possible and the reasons for different price structures could be determined.

The legislative framework was analysed based on a literature review and an overview on policy measures in the European, German and Bavarian level was elaborated. Moreover, the political incentives in Australia and Tasmania were analysed and a comparison between the Bavarian and the Tasmanian situation was thus possible.

With regard to the social context, a review of stakeholder comments and disputes in the bioenergy realm in Tasmania has been conducted. A literature review was undertaken to reveal the different interested parties, together with potential disputes surrounding wood energy use. A comparison of stakeholder patterns and disputes, respectively acceptance levels of wood energy use in Bavaria has been carried out in order to exhibit similarities and differences.

Figure 6 summarizes the applied methodology for paper 4 extended.



Comparison of wood energy use patterns in Bavaria with Tasmania, and other regions

Socio-economic patterns

- Forestry and forest industry patterns, e.g.
    - Contribution of forest biomass to energy consumption
    - Use of forest biomass for energy
    - Industry configuration and markets
    - Demand for different wood energy assortments
    - Trade patterns (import, export)
- Prices for wood energy use
- Legislative framework
- Social contest

Availability and demand patterns

- Determination of current wood energy consumption in Bavaria and Tasmania as regards use of
    - Firewood for residential heating
    - Other wood assortments, e.g. wood-processing residues

- Calculation of forest biomass supply potential for energy in Bavaria and Tasmania as regards
    - Native forest regrowth
    - Plantations
    - Wood processing residues

Figure 6 Overview on the applied methodology in paper 4 extended.

5 Results and discussion

5.1 Increased wood energy demand and resource availability

5.1.1 Potential sustainable wood supply – case study results from Bavaria (paper 1 extended)

In total, 226 organised forest owners were interviewed via a stratified random sample, divided into six strata according to common size classes of forest holdings (Beck & Perschl 2006) and according to a minimum sample size per stratum (Kauermann & Küchenhoff 2010). The interviews with forest owners revealed that average harvesting rate in private and communal forests in the past years (8.4 $m^3\ ha^{-1}\ a^{-1}$) was considerably lower than bio-technical potential (11.0 $m^3\ ha^{-1}\ a^{-1}$ (Figure 7). More than half of the wood was sorted for material use (saw logs, 55%). However, wood energy use is very important for forest owners as 42% of timber was graded as fuel wood and only 3% was graded as pulp wood. Self-consumption rate (28% of total harvest was used as fire wood and wood chips) was very high, too.

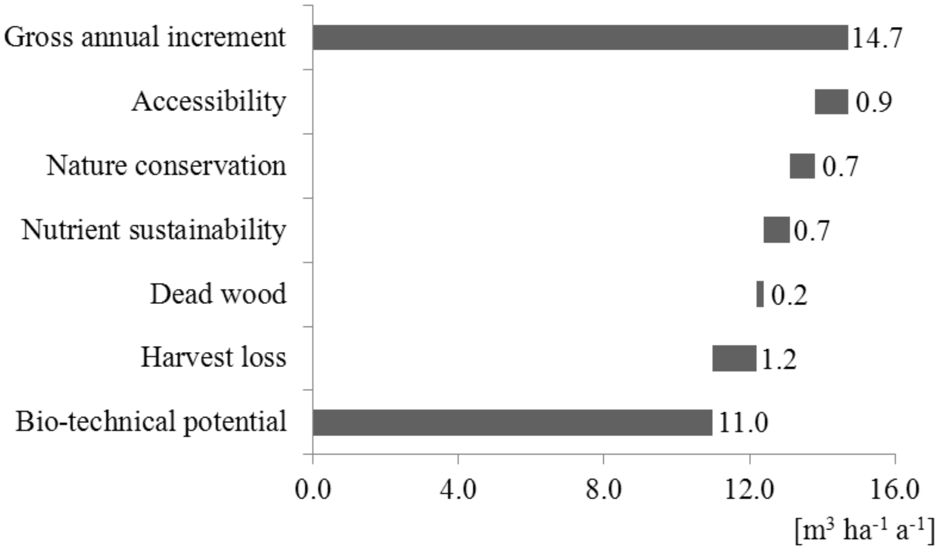


Figure 7 Theoretical potential, harvesting restrictions and technical-ecological potential in $m^3\ ha^{-1}\ a^{-1}$ *for the investigated forest area in Southern Bavaria) (Wilnhammer et al. 2012).*

Since harvest was below the technical-ecological potential, there was still an additional utilisation potential of 2.6 $m^3\ ha^{-1}\ a^{-1}$ (Figure 4). In contrast to literature, felling intensity was high in all size classes smaller than 100 ha. Importance of fuel wood and self-consumption declined with increasing holding size. In holdings smaller than 5 ha, more than 50% of the harvest was used as fuel wood and 80% of fuel wood was self-consumed.

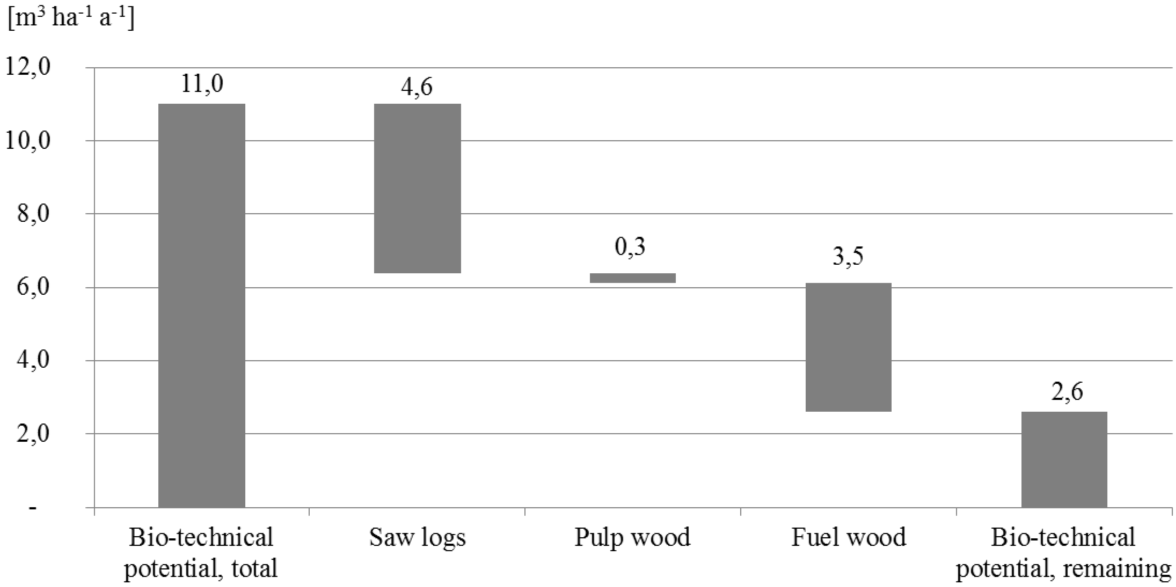


Figure 8 Felling intensity and log classification in m^3 ha^{-1} a^{-1} *in southern Bavaria (Wilnhammer et al. 2012).*

As up to 80 % of forest owners responded that they “do not know” whether they would supply additional wood in case of increasing demand or that they “are not willing to supply more wood”, the general mobilisation potential from such forests seems low. It is thus questionable to what extent additional supply potential can be really brought to the market. In contrast, it could also be that owners are even more hesitant to harvest timber in case of rising wood prices as they might hope for a further increase in financial value of their forest resources.

5.1.2 Potential sustainable wood supply – applying the methodology to Bavaria

In summary, bio-technical potential is 9.4 m^3 ha^{-1} a^{-1} (Figure 9). Overall harvest constraints are 3.9 m^3 ha^{-1} a^{-1} and therefore 71% of the theoretical potential can be harvested from a bio-technical viewpoint. According to BWI3 (BMELV 2014), the current harvest rate in Bavaria is 9.0 m^3 ha^{-1} a^{-1} entailing an additional supply potential of 0.4 m^3 ha^{-1} a^{-1}. According to LWF (2015), 55% of harvested timber in Germany was graded as saw log, 36% as fuel wood and 9 % as pulp wood (Figure 9).

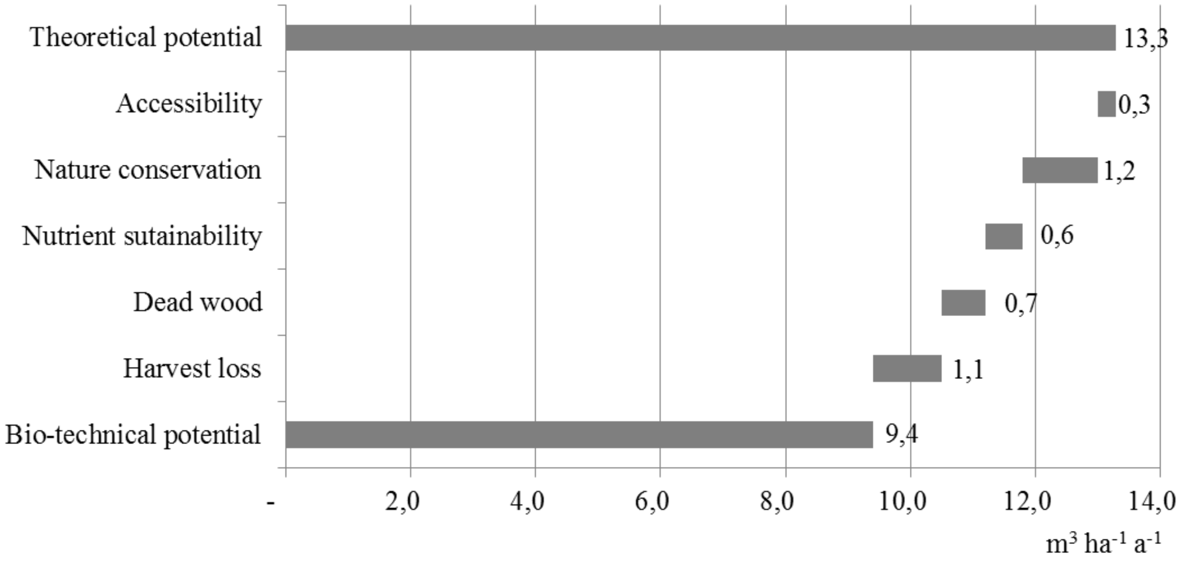


Figure 9 Increment of above-ground biomass (theoretical potential), harvesting restrictions and technical-ecological potential in m^3 ha^{-1} a^{-1} *in Bavarian forests (private, communal and state forests).*

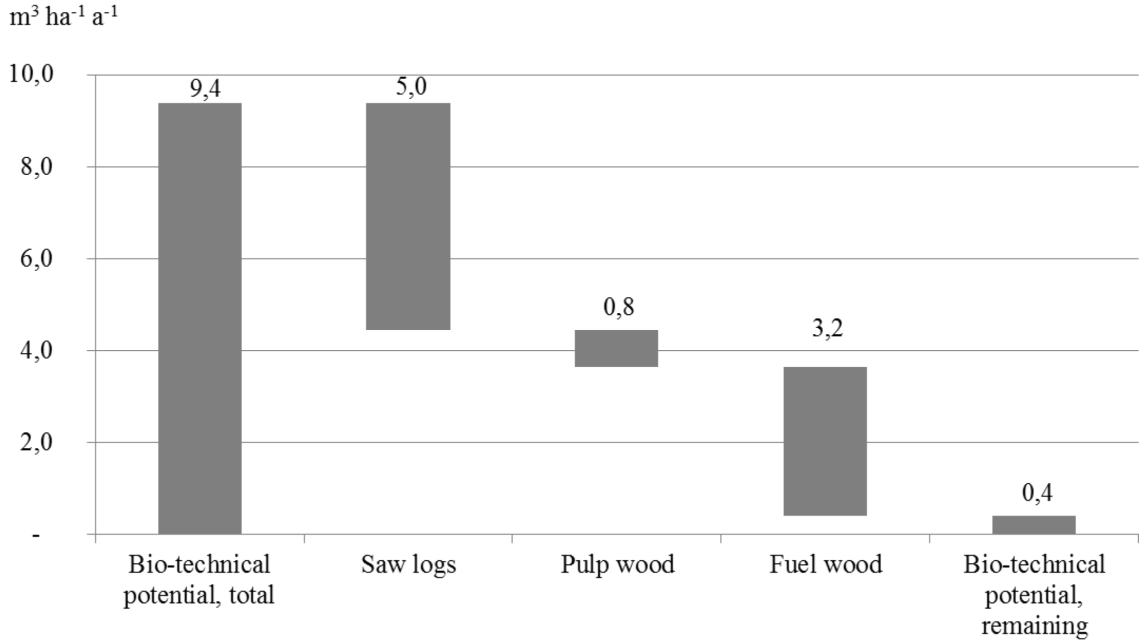


Figure 10 Average felling intensity and log classification in m^3 ha^{-1} a^{-1} *in Bavarian forests.*

An additional supply potential of 0.4 m^3 ha^{-1} a^{-1} can be considered as not relevant or not existent in order to avoid an overexploitation, i.e. when applying a precautionary approach. Moreover, the figures presented here for Bavaria are average numbers and should thus be considered with care. Therefore, one can conclude that on average there is no relevant additional supply potential for Bavaria. While in selected areas, i.e. small-scale private forests additional supply potential might exist in theory, it is still questionable if these resources can be mobilised in practice. However, in case that this amount of material would be mobilised, then the additional supply potential of 0.4 m^3 ha^{-1} a^{-1} for the total Bavarian forest area (25 000 km^2) would sum up to 1 hm^3 a^{-1} wood (550 000 m^3 a^{-1} sawn wood, 210 000 m^3 a^{-1} pulp wood and 190 000 m^3 a^{-1} fuel wood). Assuming unchanged log classification by owners, two third of the fuel wood would be used for private purposes and about 35 000 m^3 a^{-1} would be additionally available for the market. Figure 11 compares the results for the case study areas Southern Bavaria and Bavaria in total and reveals that both the theoretical and the bio-technical potential is higher for southern Bavaria thus resulting in more wood availability.

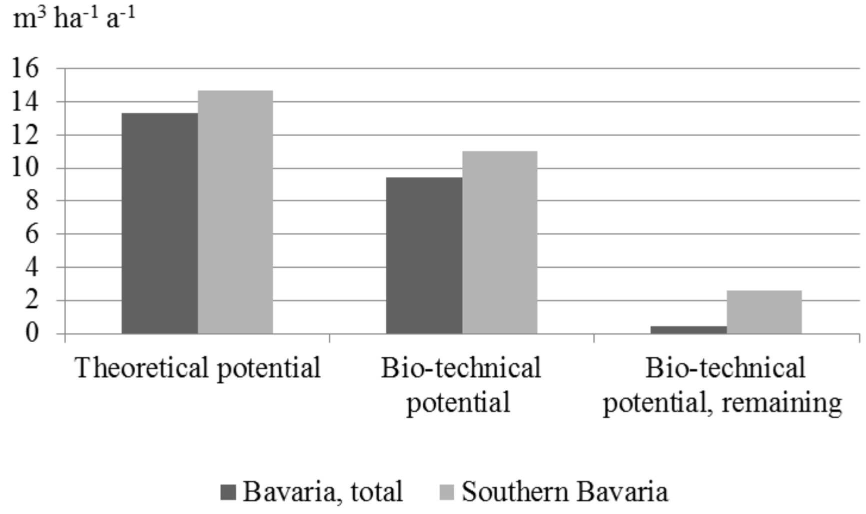


Figure 11 Comparison of theoretical potential, bio-technical potential and remaining bio-technical potential for the case study areas southern Bavaria and Bavaria, total.

A rough calculation based on wood prices (100 Euro/m^3 for spruce saw logs, 50 Euro/m^3 for spruce fire wood (split logs), and 35 Euro/m^3 for pulp wood) exhibits an unused forestry turnover of 74 million Euro annually. 190 000 m^3 ha^{-1} a^{-1} correspond to an annual wood energy potential of around 330 000 MWh (calculation basis: share of coniferous wood 77%, density of softwood (spruce) is 0.379 t/m^3, density of hardwood (beech) is 0.558 t/m^3, water content is 50%), respectively to approximately 33 million liter of heating oil. Against the background that fuel wood consumption on average entails a greenhouse gas (GHG) emission reduction of 600 kg CO_2-eq per cubic meter (Werner & Richter 2005), the additional consumption of fuel wood in the study area instead of fossil sources would entail annual savings in greenhouse gases of 114 000 tons. Assuming that average CO_2-eq emissions per inhabitant correspond to 11 t a^{-1}, this amount in GHG reduction corresponds to the emissions of 10 000 persons. However, in case that forest growing stock or the material-based sector is negatively affected, then the overall GHG emissions could increase (see paper 2). Moreover, in case that forest owners increasingly use material for wood energy self-consumption purposes, more fossil energy will be substituted. Here, the question arises what impact an increase in the use of wood energy has on e.g. GWP (paper 2) or particulate matter emissions (paper 2 and paper 3), especially in light of low-efficient household heating systems. Therefore, a consideration of additional effects within the whole forestry and wood cluster is necessary to reveal the real environmental impact of increased wood energy use more holistically.

This result underlines the importance of forestry for rural development and substitution of fossil fuel. However, this study also indicates that realising this potential is a challenge. The willingness of owners to sign long-term contracts with the forest owners associations is low. This result leads to other questions, e.g. what happens if harvest rate remains stable, but if more wood is consumed for energy and less for material-based purposes, and would such a development be positive or negative with regard to GHG emissions and other indicators for a responsible resource consumption.

5.1.3 Comparison of results to other studies on potential sustainable wood supply

The heterogeneous ownership structure of the investigation area (see 5.1.1), composed of many small-scale owners with less than 5 ha (often split up in several lots) and only few owners with properties >100 ha is typical for other European countries (Wild-Eck et al. 2006, Schmidthüsen & Hirsch 2010). In terms of numbers of private forest owners as well as distributions of size classes, small-scale land holdings prevail in Europe. 61% of all private forest holdings have an area of less than 1 ha and 86% of all holdings belong to the size class up to 5 ha (Schmithüsen & Hirsch 2010).

Harvest intensity in Southern Bavaria was nearly twice compared to the figures Schmithüsen & Hirsch (2010) reported for private forests in Austria, Germany and Switzerland. This reflects on the one hand the favourable site conditions with a high productivity in the investigation area. On the other hand, the extension service from the forest owners associations and from the State forest service as well as rising timber prices seemed having fostered the activity of owners. The high importance of fuel wood and of self-consumption in small forest holdings corresponds well with the findings of more recent studies for Bavaria and also for Austria (Hastreiter 2012, Schwarzbauer et al. 2009). In small forest holdings the amount of fuel wood harvest usually exceeds saw log harvest and most of the fuel wood is used for domestic heat production. Though price-related supply functions were not investigated, the result that most forest owners are hesitant to supply additional wood confirms the study by Blennow et al. (2014) who found that forest owners' harvest behaviour cannot be explained as direct responses to changes in prices and markets, and that European private forest owners cannot be expected to supply the requested amounts of woody biomass for energy to meet the EU 2020 renewable energy targets. Nevertheless, in a recent study for Bavaria, Härtl & Knoke (2013) developed oil price scenarios and connected them to timber price scenarios which then served to determine felling plans for forest enterprises. They found that rising oil and timber prices entailed significant changes in timber supply and grading ratios, tending towards an increase in wood energy use.

5.1.4 Applicability of the method for estimating potential sustainable wood supply

The study is mainly based on interviews with forest owners. Contrary to the outcomes of the national German forest inventory covering the period 1987-2002 (BMELV 2004), small owners even harvested more timber than owners of larger holdings. One reason might have been that fuel prices strongly increased since the turn of the century and therefore it was more attractive to use fuel wood. Price-related supply functions were not evaluated but it seems clear that increasing prices for fossil energy favour the use of fuel wood. Intensive utilisation by small owners has also been reported by Huber (2007) for Austria.

While the method proposed here could be applied to all private forest owners, the results are only valid for the members of the investigated forest owners associations. It seems likely that these owners are more interested in forestry and harvesting. The high harvesting intensity of 10 m^3 ha^{-1} a^{-1} in holdings smaller than 20 ha might thus be more a figure for active owners rather than an average for all private forests. In terms of interest in harvesting there are at least two other categories of owners, a) those who have some interest in harvesting but are not members in a forest owners association, and b) those who have other than economic interests. Therefore, the presented figures might overestimate average harvest intensity in private forests but further studies are necessary to analyse this aspect.

Another source of uncertainty originates from the fact that behaviour of owners changes with time. Especially harvesting intensity and log classification may vary in future according to individual attitudes, wood prices or financial support schemes by the government. Furthermore, the influence of timber prices on harvesting intensity was not investigated. The past two decades were characterised by strong fluctuations caused by e.g. wind throw events and volatile fossil energy prices. After 2005, timber prices significantly increased and it is likely that this contributed to the intensified harvesting.

5.2 Impact of increased wood energy use on GHG and $PM_{2.5}$ emissions as well as on primary energy demand (paper 2)

5.2.1 Development of wood use, shift in resource allocation and in substitution factors

The scenario analysis for the Bavarian cluster shows that increased wood energy consumption (wood energy scenario) results in a decline of material-based wood use due to increased competition of forest industries and due to a decrease in wood supply in some periods. While total energy demand is fulfilled with domestic wood or with imported pellets, wood resources need to be imported in the material-based sector, e.g. wood based panels, or otherwise the production capacity is reduced (e.g. printing sector or sawn industry) and alternative products have to fulfil the demand. The shift in consumption leads to the substitution of wood through fossil resources or imported wood in the material-based sector or to the substitution of fossil energy with fuel wood products respectively. Substitution factors for primary energy demand, global warming potential (in CO2eq) and particulate matter emissions of wood products and fossil alternatives were calculated. In order to take account of the range of emissions from wood energy use, minimum (worst case) and maximum (best case) efficiency rates of wood energy use were incorporated, too (Table 2).

Table 2 Substitution factors per indicator and product (Wilnhammer et al. 2015).

Sector	**Product substitution** [functional unit]	**End use**	**Substitution factor**	**Primary energy demand** [GJ/functional unit]	**GWP 100** [t/functional unit]	**PM$_{2.5}$** [g/functional unit]
Material	Non-wood construction instead of wood construction [building type]	Construction	Worst case	+1 050.0	+69.9	n.a.
			Ø	+639.7	+59.4	n.a.
			Best case	+227.7	+5.1	n.a.
	Imported wood-based panels instead of domestic wood-based panels [m^3_l]	Furniture	Worst case	n.a.	n.a.	n.a.
			Ø	+0.7	+0.01	n.a.
			Best case	n.a.	n.a.	n.a.
	Electronic media instead of graphical paper [t]	Media	Worst case	+223.1	+15	n.a.
			Ø	0	0	n.a.
			Best case	-58.4	-1.9	n.a.
Energy	Heat from split logs instead of natural gas [MWh]	Heat	Worst case	-3.8	-0.21	+1 600
			Ø	-4.1	-0.25	+548
			Best case	-4.1	-0.27	+436
	Heat from pellets instead of natural gas [MWh]		Worst case	-3.5	-0.22	+123
			Ø	-3.6	-0.23	+114
			Best case	-3.7	-0.23	+111
	Imported pellets instead of natural gas [MWh]		Worst case	-1.2	-0.19	+306
			Ø	-1.4	-0.20	+279
			Best case	-1.5	-0.21	+270
	Heat from wood chip-mix instead of natural gas [MWh]		Worst case	-3.6	-0.24	+271
			Ø	-3.7	-0.25	+253
			Best case	-3.7	-0.25	+237
	Electricity and heat from wood chip mix instead of electricity mix [MWh]	Heat and electricity	Worst case	-7.9	-0.57	+528
			Ø	-8.1	-0.58	+390
			Best case	-8.2	-0.59	+307

5.2.2 Basket of benefit evaluation per impact category

The basket of benefit analysis shows that, when extrapolating the average LCA results per product and period to the overall wood consumption, the enhanced wood energy use entails an increase in CO_2eq emissions by 140 kt a^{-1} in Bavaria (Figure 12). This amount corresponds to additional CO_2eq emissions of 0.11% in Bavaria, i.e. to an additional release by 13 000 persons (out of a total of 12 million inhabitants in Bavaria) per year. However, the results vary between -810 kt a^{-1} and +548 kt a^{-1} depending on the assumptions made so that the impact on global warming potential could be either negative or positive and no definite conclusion can be drawn. Therefore, the increase in wood energy use could also lead to GHG savings if bioenergy is used in a most efficient way and if, for example, the assumption is made that wood energy substitutes more carbon-intensive fossil fuels such as oil sands. Accordingly, resources in general need to be consumed in a most modern and efficient manner in both the material-based and energy sector.

While reduced wood availability in the material-based sector triggers an increase in GWP, increased combustion of wood instead of fossil energy leads to reduced emissions. The effect in the material sector exceeds the one in the energy sector. The evaluation shows that the substitution of sawn timber in the construction sector through non-wood constructions has strong negative impact on GWP. Importing wood-based panels has minor negative impact on CO_2eq emissions.

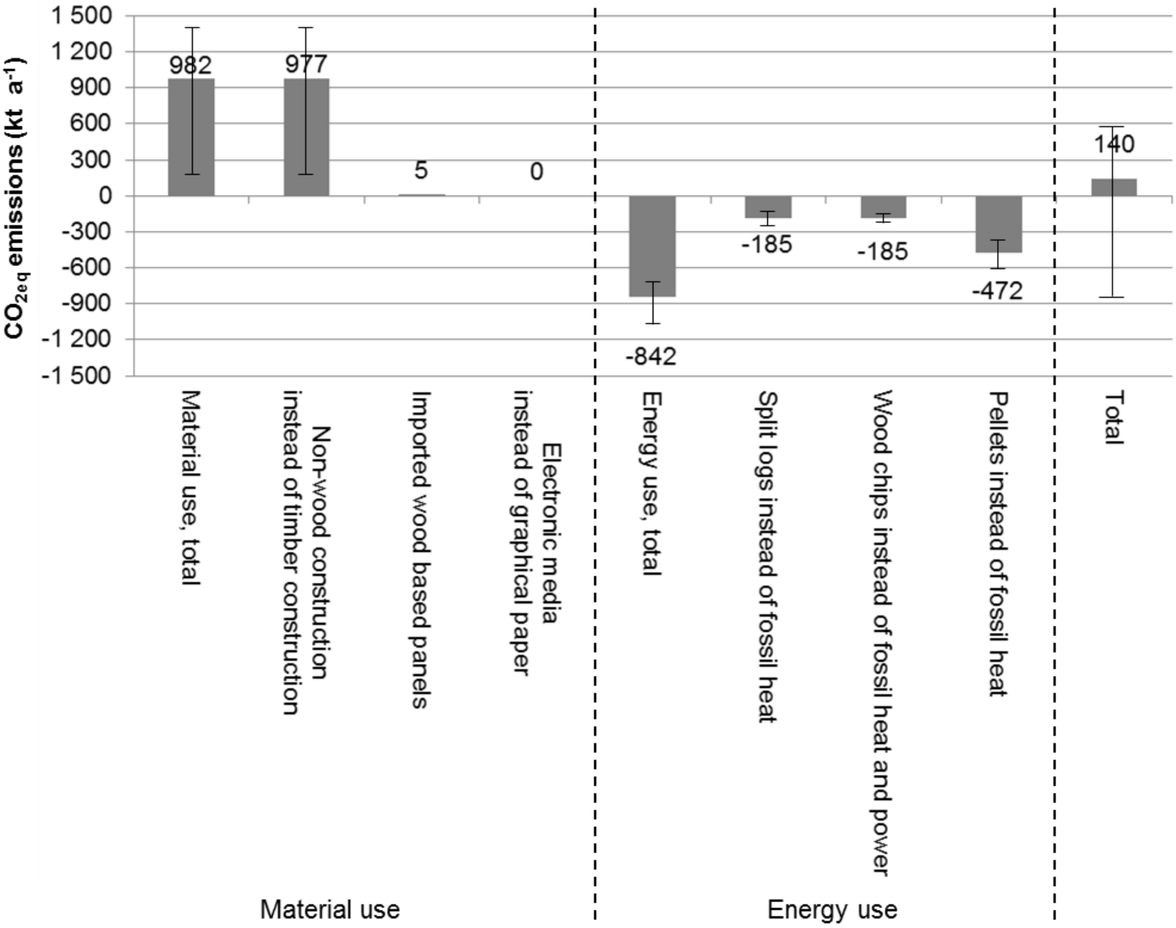


Figure 12 Increased wood energy use and the average impact on global warming potential (without biogenic CO_2) (Wilnhammer et al. 2015).

In the wood energy sector, the use of split logs and wood chips has similarly high effect on the reduction in CO_2eq emissions. The average amount of emissions saved through the increased wood energy use is -185 kt a^{-1} for both increased split log use and increased wood chips use. As a strong increase (+1.4 hm^3 a^{-1}) in wood pellets consumption was modelled in the wood energy scenario, more than half of the GHG emission reduction in the energy sector (-472 kt a^{-1}) comes from the substitution of fossil fuels through pellets.

Primary energy demand decreases by -1.6 PJ a^{-1} on average, corresponding to a demand of 10 000 inhabitants in the study area per year. Figure 13 shows that the substitution of sawn timber in the construction sector triggers considerably increased primary energy demand. The use of imported wood-based panels instead of domestic timber does not reveal an impact. As the substitution factors for the use of e-media instead of graphical media were set to zero due to data gaps, the basket of benefit shows no impact through a substitution of wood through e-media. In the energy sector, the use of split logs and wood chips instead of fossil energy contributes to a similar degree to the reduction in primary energy demand. The wood pellet consumption adds to even stronger reduction in primary energy demand. In total, the results vary between -9 PJ a^{-1} and +0.3 PJ a^{-1} depending on the assumptions made. Again, the impact on primary energy demand could thus be either negative or positive so that no definite conclusion can be drawn.

However, there is a high probability that overall primary energy demand will be lowered as a result of increased wood energy use. According to the paper results, enlarged wood energy use would only trigger an overall uptake in primary energy demand, if resource use in the material-based sector would be highly efficient (best case) and if efficiency rates in wood energy consumption would be low (worst case), e.g. if in the wood energy sector there would be no technological development (for further information see publication 2 in the annex).

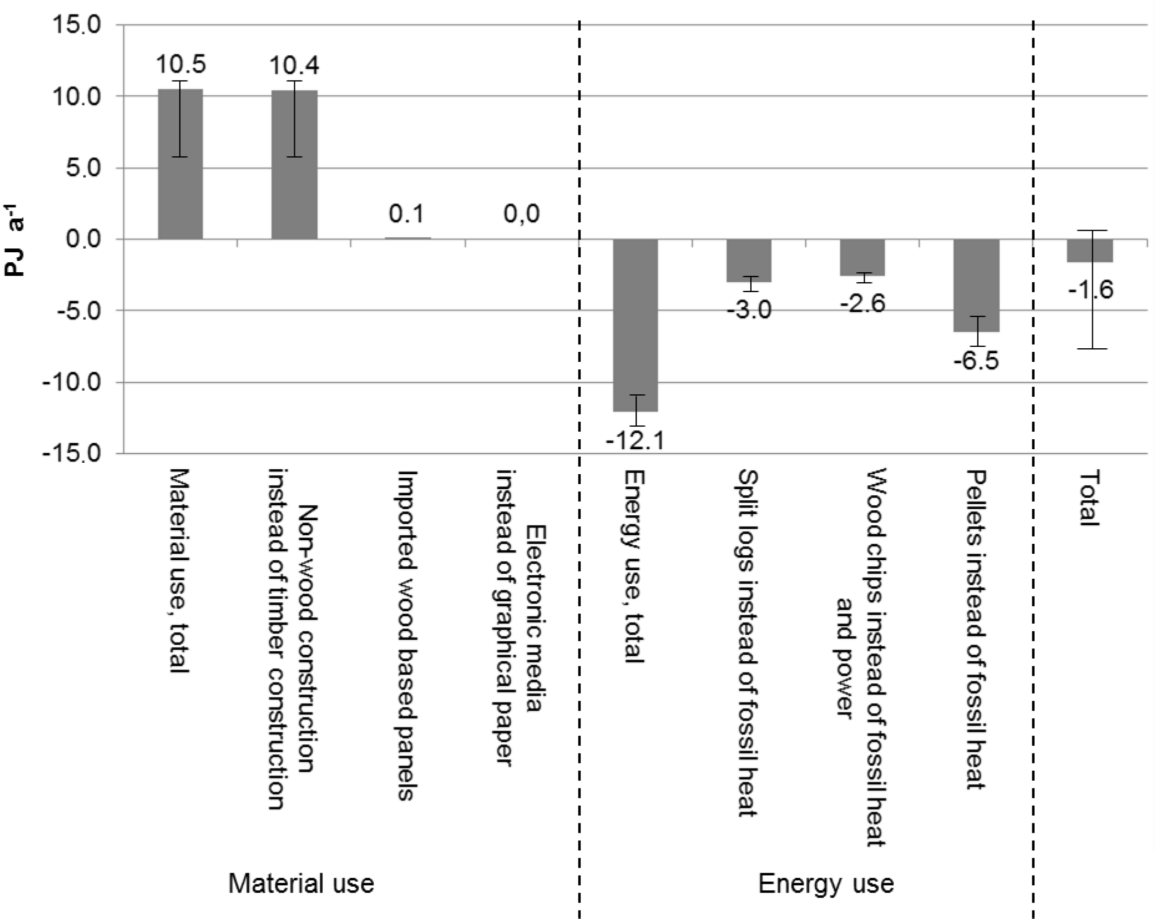


Figure 13 Increased wood energy use and the average impact on non-regenerative primary energy demand (net calorific value) (Wilnhammer et al. 2015).

With regard to particulate matter emissions, not enough data was available in the material-based sector because no comparative studies exist between wood-based products and alternatives of use. Thus, no statement can be made whether the substitution of wood in the material-based sector through product alternatives has positive or negative effects. Increased wood energy use leads to considerably higher particulate matter emissions. On average, 1.2 kt are additionally released per year (Figure 14). This increase represents a growth in total emission load from the wood energy sector in the study area by 25%, compared to 2010 values (Ewens 2014). More than half of these emissions (0.7 kt) originates from wood pellets use as in the wood energy scenario a strong increase in demand for this product was assumed. The share of imported pellets in particulate matter emission load is 0.4 kt. The particulate matter emissions from split log combustion increase by 0.4 kt whereas the consumption of this assortment rises by 0.6 hm^3 only. Compared to pellets, the increase in $PM_{2.5}$ emissions from split log combustion is thus disproportionally high. The total results vary between +1.1 and +1.4 kt a^{-1} for the whole study area.

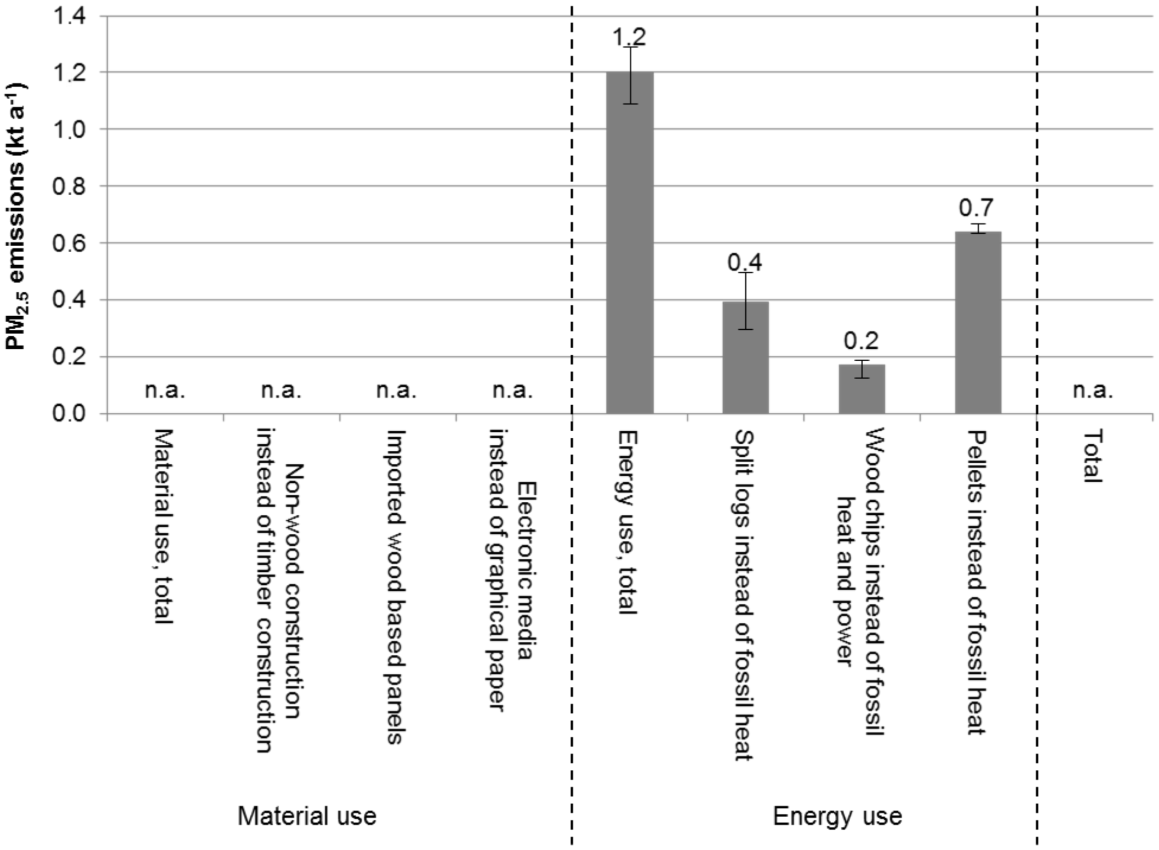


Figure 14 Increased wood energy use and the average impact on $PM_{2.5}$ emission load (Wilnhammer et al. 2015); Note: Due to rounding, not all numbers presented add up to the totals provided

The results of the basket of benefit analysis vary if wood energy use is compared with different fossil energy sources. For example, if wood energy is not only compared to natural gas but to a mix of natural gas and crude oil, and if electricity production from wood is not compared to the electricity mix but to those energy sources that are curtailed or squeezed out of the market according to the study by Nitsch et al. (2013), i.e. lignite, hard coal and nuclear power, then the basket of benefit analysis reveals an overall reduction in CO_2eq emissions by -15 000 t a^{-1} in the study area. Primary energy demand rises only by additional +0.02 PJ a^{-1} in this case. No conclusions can be drawn on the overall impact on $PM_{2.5}$ emission load through the sensitivity analysis due to lack in data in the material-based sector.

5.2.3 Applicability of the method for an environmental impact assessment of a shift in wood consumption on a regional scale

The study did not aim at developing an exact prognosis of future wood use. In contrast, a scenario analysis was applied in order to reveal the impact of different wood consumption patterns. A wood energy scenario was calculated, based on the study EFSOS II by UNECE/FAO (2011) in order to test the basket of benefit approach and identify the impact of a consumption shift on sustainability indicators.

Via the basket of benefit analysis the impact of a net change in demand was assessed, i.e. the increased product demand in the ”wood energy scenario” compared to the constant demand in the ”baseline scenario”. Therefore, only the net change in consumption from one scenario to the other was considered in this model. For the impact analysis prevalent combustion systems were chosen which represent a larger amount of combustion techniques and for which a good database exists. Average product life cycles were modelled via GaBi 6.0. In reality, a variety of chimneys, ovens, boilers, heating plants and combined heat and power plants exists and the results of the impact analysis strongly depend on the efficiency of the combustion systems and on the alternatives of use chosen in the basket of benefit.

Emissions from wood combustion can differ considerably, for example $PM_{2.5}$ emissions from non-automatic installations can be higher by the factor ten compared to automatic installations EEA 2013). LCA databases for split log ovens need to be improved (Steubing 2013, Gärtner et al. 2013). Especially in the field of wood energy use in households, an improved energy use efficiency and lowered emission load can be expected due to a recent law amendment aiming at the modernisation of these installations (BMU 2010, see publication 3).

Against the background that a scenario analysis was applied in order to crystallise the impact of a change in resource allocation on selected environmental indicators, the applied methodology delivered valuable results and revealed the impacts on a larger study area and over a longer time period. These long-time and large-scale estimates need to be seen as a "what if" scenario and as guidance for decision makers rather than as a prognosis.

5.2.4 Comparison of results

The presented results state average figures and there is a considerable variance in substitution factors. Thus, the results from the basket of benefit methodology strongly depend on the selected product life cycles. On the one hand, GHG emissions increased as a result of the shift towards more wood energy use. However, the effect is only small as the emissions correspond to an additional release of greenhouse gases by 13 000 persons per year. As more than 12 million people live in the study area, the increase in global warming potential is less than 0.3% compared to the number of residents. While the substitution of fossil fuels through wood energy had a decarbonisation effect, reduced wood availability in the material-based sector and the necessity to either import wood or to use non-wood alternatives entailed an opposite effect. Importing sustainably produced sawn timber has substantial advantages over substitution of sawn timber with non-wood construction materials. The results further exhibit a considerable increase in particulate matter emissions in the wood energy sector if no additional measures for emission reduction are introduced. The basket of benefit analysis demonstrates that larger amounts of $PM_{2.5}$ are released through split log use in private households. Nussbaumer et al. (2008) and Kelz et al. (2012) showed that a strong improvement potential through the application of filter systems exists for old and non-automatic split log installations. The introduction of a new legal act in Germany by the beginning of 2015, aiming at the retro-fitting or replacement of old wood energy installations might lead to a reduction in particulate matter emissions (see section 5.3).

Another uncertainty relates to the fact that particulate matter contains a considerable amount of black carbon which is formed from incomplete combustion of organic compounds (EEA 2013) and is even emitted from modern wood burning appliances (McFiggans 2015). On average 10% of $PM_{2.5}$ emission load from residential wood combustion belongs to the black carbon fraction (EEA 2013). The impact of black carbon on global warming potential is still subject to larger data gaps and intense scientific debate. The latest IPCC report (IPCC 2015) stated that aerosols, amongst them black carbon, continue to contribute the largest uncertainty to global warming estimates. Bond et al. (2013) gathered available model results and proposed an estimate for black carbon's global climate forcing resulting from biomass combustion (+1.1 W m^{-2}, with 90% uncertainty bounds of +0.17 to +2.1 W m^{-2}). The study concluded that the radiative forcing caused by black carbon is too low in many models and that black carbon would be the second most important human climate forcer after CO_2. While the radiative forcing of black carbon alone is strong, total aerosol radiative forcing is even negative (-0.35 W m^{-2}) according to IPCC (2015), thus leading to a cooling effect.

Due to data gaps, reliable information on the radiative forcing of black carbon and co-emitted aerosols was not available for the case study region. As such emissions are temporally and spatially variable (Bond et al. 2013) and due to complex interdependences (Rogelj et al. 2014), a reliable global characterisation factor for life cycle impact assessments has not yet been determined. More research is needed in order to include such effects into LCA studies and ensure a holistic assessment of the global warming potential of wood utilisation.

In summary, the basket of benefit analysis shows that, with the exception of particulate matter emissions for which no definite conclusions can be drawn, the use of wood instead of fossil resources has strong advantages in both the material-based sector and the energy sector but that wood needs to be used most efficiently in order to avoid negative effects.

Due to the complexity and variety of the topic, as well as due to the magnitude of research questions, some aspects could not be dealt with in this dissertation. These limitations relate to, inter alia an analysis of the impact of increased wood energy use on other sustainability indicators, such as forest soil and forest biodiversity, hemeroby, landscape level effects, or (de-) eutrophication. Further research is recommended here. Moreover, the impact of increased wood energy use on socio-economic indicators, such as employment, income or value-added, and the impact of increased use of wood energy in Bavaria on other regions or countries was outside the scope of this dissertation. However, linked research work (overview see Weber-Blaschke et al. 2014) addressed these crucial socio-economic aspects.

5.3 Reducing $PM_{2.5}$ emissions from residential wood energy use in the case study area Bavaria (paper 3)

5.3.1 Development of retro-fitting and replacement rate

As a consequence of the law amendment, 2.13 million out of 2.29 million installations will be modernised until 2025 in Bavaria, out of which 1.6 million will be single room furnaces and 0.5 million central heating systems. The predominant share of installations (70%) will be replaced or retro-fitted in 2021 and 2025. While some of the older single-room furnaces will not be replaced (161 000 installations respectively 9%, i.e. historic and discontinuously used installations), all central heating systems installed before 2010 will be affected until 2021 according to this projection.

5.3.2 Development of $PM_{2.5}$ emissions

The calculated emission load from heat generation in private households in 2010, taking into account the specific combustion systems installed in the case study region, is 4.5 kt a^{-1}. The predominant share of emissions comes from single room furnaces (3.9 kt a^{-1} respectively 87%). Their emissions are high relative to those of central heating systems and the retro-fitting and replacement of these old installations leads to continuously decreasing particulate matter emissions. Depending on the amount of new systems installed per period, there are slight differences per period, i.e. in 2021 and 2025 the emission reduction is stronger due to an enhanced modernisation rate. In total, the impact of the law amendment could be strong and emissions reduced from 4.5 kt a^{-1} in 2010 to 2.2 kt a^{-1} in 2025, respectively by 51% (Figure 11). In the baseline scenario, emission load remains stable after 2025 as neither a change in wood energy consumption nor a further impact of additional legal regulations or technological developments were considered.

Furthermore, the increased annual average efficiency from 2010 to 2035 according to Deischl (2013) entails increased resource availability of 0.4 hm^3 of wood. This amount of wood corresponds to an increased energy production from wood energy of 3.5 PJ a^{-1} in 2035, respectively to 970 000 MWh or 97 million liters of heating oil. Assuming that an average household consumes 2 000 liters of heating oil per year 48 500 households could be additionally supplied with heat through this additional amount of energy, potentially entailing the substitution of other energy sources such as heating oil and natural gas. As fuel wood consumption on average entails a GHG emission reduction of 600 kg CO_2-eq per cubic meter

(Werner & Richter 2005), the additional potential for energy production from fuel wood in the study area instead of fossil sources would entail annual savings in greenhouse gases of 240 kt CO_2-eq. Assuming that average CO_2-eq emissions per inhabitant correspond to 11 t a^{-1}, this amount in GHG reduction would correspond to the emissions of 22 000 persons.

Reduction potentials for other emissions have not been assessed in this study; however, it is recommended to address these in further research work, e.g. via a more in-depth analysis of technological developments in residential wood combustion on Global Warming Potential, other dust emissions (PM_{10}, PM_1, black carbon), or primary energy demand.

In case of an increased wood energy demand (see section 4.2.2), consumption of split logs and wood pellets rises from 6.7 hm^3 to 9.6 hm^3 until 2035. Consequently, emission load will also rise. However, the increase will not be proportional with the uptake in wood energy use as an above-average growth in wood pellet combustion dampens the effect. The increase in wood combustion in the wood energy scenario between 2010 and 2035 entails an increase in $PM_{2.5}$ emission load by 35% in comparison to the stable wood demand scenario, equivalent to an increase by 0.8 kt a^{-1} until 2035. However, total emissions will still decrease due to the law amendment. In the increased wood energy scenario, overall emission load will be 3.0 kt a^{-1} in 2035, out of which 2.6 kt a^{-1} will arise from split log use and 0.4 kt a^{-1} from wood pellets use. Moreover, as the last phase of the emission control act will become effective in 2025, $PM_{2.5}$ load would rise again from 2025 (2.6 kt a^{-1}) to 2035 in the increased wood energy demand scenario (Figure 15).

The figure also exhibits the development in emissions to air in case that the law amendment is not effective at all, i.e. that emission load will also decrease due to an automatic exchange of installations elder than 30 years. However, the reduction in emissions to air until 2035 is lower and in case of an increased wood energy demand scenario almost equals the level of 2010.

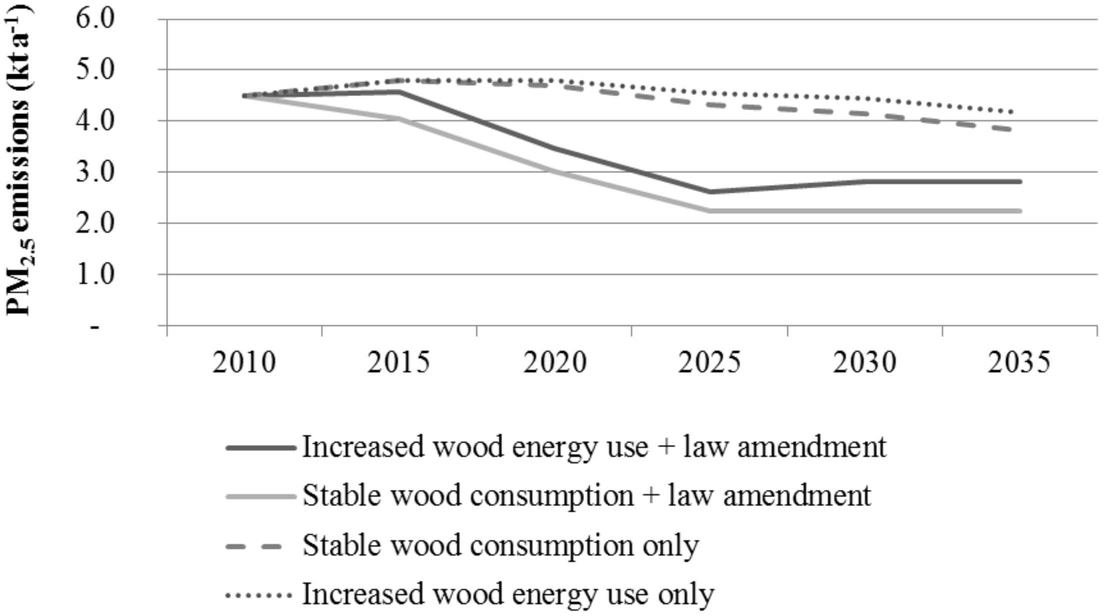


Figure 15 Impact of the law amendment and the development of PM$_{2.5}$ emissions. Values are shown for stable wood demand and an increasing wood use (Wilnhammer et al. 2017).

5.3.3 Uncertainties in calculations

There are some uncertainties in the presented calculations due to knowledge gaps on the real development of PM$_{2.5}$ emission load since 2010, the real number of household heating systems and the amount in wood consumed per installation together with associated emission factors. Moreover, the PM$_{2.5}$ values used in this study refer to minimum emission thresholds per installation type as regulated by the law amendment. The projection could therefore be considered as a conservative estimate of the impact of the law amendment as future technological innovations could further reduce average emission factors. In practice some of the automatically controlled installations could exhibit even lower emission factors if e.g. the heating material is of high quality (i.e. due to homogeneous firing behaviour, low humidity, no contamination, low bark content). In fact, some of the latest installation types are superior to legal requirements in terms of dust emissions (FNR 2014). For example, Hartmann (2014) showed that substituting a simple wood stove with a modern stove with a catalytic converter entails a dust emission reduction by 75%. Enke (2013) also reported on potential emission reductions by 72% through installations with modern filter techniques in comparison to old installations.

However, non-automatic heating systems exhibit higher emission levels. For example, in case that post-consumer wood is burnt in domestic households, dust emissions will presumably be higher due to impurities. In general, the emission factors for pellets used in households are more reliable as the material is more homogenous in terms of moisture content, and as pellets do not contain bark or impurities in contrast to wood chips and split logs. For example Karvosenoja et al. (2004) explored $PM_{2.5}$ emission reduction potential for Denmark, Finland, Norway and Sweden, and found that a fuel switch from logs to pellets leads to a strong reduction in $PM_{2.5}$ emissions. This result is in line with our finding that a growth in pellet consumption and a substitution of split logs diminish $PM_{2.5}$ emission load.

5.3.4 Comparison of results

According to Ewens (2014) the particulate matter emissions from wood energy combustion in Germany could be reduced from 30 kt in 2010 to less than 16 kt in 2025. This calculation, which shows a reduction in dust emissions by 50% until 2025, confirms the projection in paper 4. In the Gothenburg protocol, Germany committed to reducing its particulate matter emissions by 26% compared to 2005, respectively to 16.6 kt a^{-1} until 2020. The projection for Bavaria, if extrapolated to Germany, exhibits that this target could be reached – under a stable wood consumption scenario, if the law amendment is fully implemented in practice and if user behaviour conforms to best practice. According to the assumptions made in the increased wood energy scenario, $PM_{2.5}$ emissions will be 16% higher in 2020 compared to stable wood energy demand conditions. The fulfilment of the targets set in the Gothenborg protocol could then be questionable, especially if the law amendment implementation is not fully effective.

Bavaria and Germany are densely populated and the extent of wood energy use is high and therefore there is need to dampen $PM_{2.5}$ emissions. This applies to many European countries such as the UK, Denmark, Finland, Norway and Sweden. Other regions such as Tasmania (see paper 4) have lower population density and lower wood energy consumption. Consequently, the forestry and wood clusters in such regions face different challenges as regards wood energy consumption and environmental impacts.

In general, there is need to align research and environmental policies targeting at the reduction of dust emissions with e.g. climate change policies. Paper 3 focused on particulate matter emissions but further research on interdependent effects on other emissions is recommended. The effects of an integration of different environmental policies should be further evaluated. At the moment, e.g. greenhouse gas emissions are addressed under different policies and regulations than emissions relevant for health. Schmale et al. (2014) pointed out that e.g. energy ministries tend to focus on CO_2 reductions while environment ministries manage air quality, and because regulation of greenhouse gas emissions is subject to global agreements whereas air pollutants are limited locally by legislation. The 2015 Paris Agreement under the United Nations Framework Convention on Climate Change, thus is an opportunity for governments not only to reduce CO_2 emissions but also to include other climate forcers such as particulate matter emissions into climate-change mitigation policies, respectively to better coordinate research and action under different policy umbrellas. Further research is needed to crystallise the pros and cons of joint or separate air pollution and climate change mitigation policies (Schmale et al. 2014).

5.4 Wood energy use in Bavaria seen from a broader context - comparing Bavarian conditions with other regions, particularly Tasmania (paper 4 extended)

5.4.1 Forestry and forest industry in Bavaria

The comparison of patterns of the Bavarian wood energy sector with other regions reveals remarkable similarities and differences. The use of biomass for energy is widespread in Bavaria which is typical for many European countries (Figure 16) where the share of energy derived from biomass is closely correlated with the available forest resource. In the European Union biomass contributed 8.2% of total final energy consumption in 2010 or 64% of European renewable energy (AEBIOM 2012). Two third of total biomass for energy production or about 50% of total renewable energy (Mantau et al. 2010) was from forest biomass.

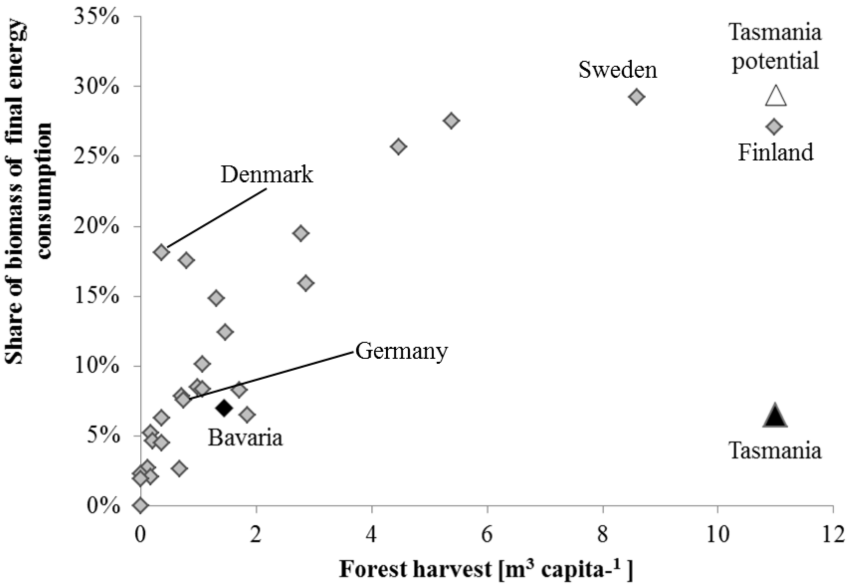


Figure 16 Share of bioenergy in final energy consumption per country (bold). Triangles show the current (filled) and potential (empty) use in Tasmania. (Rothe et al. 2015, edited).

In Bavaria, most fuel wood is used regionally due to the high residential demand. In contrast, all low quality hardwood logs in Tasmania are exported as chips into China and Japan. In Tasmania the fraction of total energy supply generated from forest biomass (6%) is only slightly higher than in Bavaria (5%) although the annual harvest per capita is about sevenfold higher in Tasmania. Only 14% of the annual Tasmanian harvest is used for generating energy. Although the relative firewood consumption in Tasmania (about 1 t y^{-1} $capita^{-1}$ of green wood) is more than double that of Bavaria (0.4 t y^{-1} $capita^{-1}$ of green wood), only 10% of the annual Tasmanian harvest is used as fuelwood for private households due to the low population density. In Bavaria one third of wood supply from the forest is used directly as energy wood, including post-consumer wood and other woody biomass outside the forest, overall share in wood energy consumption is above 50 %.

No data could be obtained as regards the GHG savings or $PM_{2.5}$ emission load from residential wood combustion in Tasmania. However, the fact that the relative firewood consumption per capita is considerably higher than in Bavaria, and that most wood is burnt in residential buildings for heating in likely old installations, it is assumed that the contribution of wood consumption per capita to GHG savings on the one hand and to $PM_{2.5}$ emission load on the other hand, is considerably higher than in Bavaria.

While the available resource of forest biomass for energy is extensively utilised in Bavaria forest biomass production could be more than quadrupled in Tasmania. The potential fraction of total energy production in Tasmania from forest biomass energy of 30%, as estimated in this study, is consistent with current conditions in European countries with a large forest resource per capita (Sweden, Finland, Baltics).

5.4.2 Comparison of economic, legislative and social drivers for forest biomass utilisation for energy production

There is currently no Tasmanian market for energy logs and the fraction of timber explicitly sold as energy wood is insignificant. Tasmanian prices for low grade pulp-logs and firewood are half Bavarian prices. In contrast to Tasmania there is a strong domestic demand for energy wood in Bavaria, especially from hardwood species. Since 2005 there has been a considerable increase in demand for energy wood and for example currently about 60% of the total beech harvest (2.5 hm^3 a^{-1}) is sold as fuel wood. The demand results predominantly from private households using fuelwood. In addition there are more than 600 biomass plants processing about 3 hm^3 a^{-1} (Friedrich et al. 2012). Due to the strong demand, wood energy prices have nearly doubled between 2005 and 2013 (CARMEN 2014). This has entailed an increase in industrial wood prices as e.g. particleboard plants or pulp mills compete for the same material. Figure 17 shows that the share in wood energy use is much higher in Bavaria.

Figure 17 Fraction of wood supply used for energy in Tasmania and Bavaria (Rothe et al. 2015).

Within the Renewable Energy Target (RET) scheme the Australian Government aims to ensure that 20 % of Australia's electricity comes from renewable sources by 2020. The RET scheme primarily focuses on solar and wind systems but electricity generated from biomass including wood residues has been recognised under the RET scheme. In 2012 wood residues originating from native forestry were excluded from the RET scheme due to concerns about native carbon effects after native forest harvesting. Since the origin of wood residues is often unclear this change had an important impact on forest biomass projects. Another major impediment is missing incentives within the RET scheme for other forms of energy such as thermal heat. In Tasmania government funding of forest biomass for energy has been negligible in the past and there is no operating biomass plant producing electricity or heat. All private stoves and furnaces are operating without public subsidies.

For Germany and Bavaria, a set of legislative frameworks and promotional instruments governs renewable energy development. The Renewable Energies Act includes a feed-in remuneration for power producers. The subsidies currently amount to 6.24 Cent kWh^{-1} (Statista 2014). In order to support the planned expansion of bioenergy use for heat production the Market Incentive Program (MAP) promotes biomass use, for example a new installation of a pellet boiler is subsidised with up to the 3 500 € (BAFA 2013). Exact data on the total amount of subsidies in Bavaria concerning biomass are not available, but a breakdown of nationwide subsidies (50 Hertz 2013) to Bavaria according to population equals 760 million € in 2013.

Disputes concerning harvesting in “native forests” have damaged the social acceptance of forest biomass and discredited bioenergy in Australia. According to Ulrik (2012) the lack of understanding and acceptance among important stakeholders is the main reason that implementation of forest biomass for energy in Australia is minimal compared to many European countries. In Bavaria the use of forest biomass currently has a strong social license, except from individual local protests following “not in my backyard” interests. There are many regional and community initiatives supporting biomass use within renewable energy targets. Domestic firewood has a centuries-long tradition and is an important part of the rural lifestyle especially in Central and Northern Europe. The strong emotional link of people with “their” firewood may explain why potential negative effects of intensive firewood harvest and combustion do not receive much attention from society.

The German Federal Ministry of Food and Agriculture promotes the use of bioenergy via “bioenergy villages” (Bioenergiedörfer) and “bioenergy regions” (Bioenergieregionen) which illustrate the benefits of bioenergy use (BMELV 2012). However, there is an increasing discussion about the optimal intensity of forest management (Suda & Schaffner 2013). Key areas of discussion are the preservation of minimum coarse woody debris amounts in the forest stand, maintenance of soil fertility and the percentage of forests without active management. Nevertheless environmental NGO's are not specifically addressing forest biomass use at present (Weich 2015). Main reasons may be the trade-off between promotion of renewable energies (a major goal of environmental NGO's) and a reduced harvesting intensity as well as the widespread use of fuelwood also by environmentalists.

6 Synthesis and Conclusions

In this work, additional supply potential for wood energy was assessed and the impact of increased wood energy consumption on selected environmental indicators was evaluated. Furthermore, the potential for emission reduction was estimated and a comparison made between the case study area and other regions.

Overall this work shows that additional forest biomass availability for energy in Bavaria is unlikely and that more wood energy can only be produced via improved resource use efficiency. Improved use of wood energy depends on various aspects, amongst them are inter alia the allocation of wood assortments to most efficient utilisation purposes, the combustion of wood in modern installations in order to ensure high energy outputs and low emission levels, the shift towards more heat production from pellets instead of split logs in private households, and the successful implementation of a law amendment to reduce dust emissions.

In this final section, the scientific papers will be summarised and conclusions will be drawn with regard to the research questions raised in chapter 2.

1. **How much wood can be sustainably supplied from domestic forests in Bavaria, taking into account nature conservation restrictions, nutrient sustainability, dead wood restrictions, technical constraints and forest owners' attitudes towards harvesting and fuel wood mobilisation?**

Bio-technical constraints on theoretical biomass potential are considerable. In the case of Bavaria, on average 30% of the theoretical biomass potential cannot be used due to constraints arising from e.g. restricted accessibility, nutrient sustainability prescriptions and harvest losses. Moreover, strong mobilisation restrictions relate to the willingness of owners to harvest additional wood. Increased wood mobilisation strongly depends on behaviour of owners. Since this behaviour varies in space and mere time literature values are not reliable. The presented method, which is mainly based on data obtained from interviews, allows a sound assessment of forest biomass supply for small-scale privately owned forests for a given period of time and for a defined area. For the total Bavarian forest area, on average 9.4 m^3 ha^{-1} a^{-1} can be sustainably supplied. In Southern Bavaria the supply potential is 11.0 m^3 ha^{-1} a^{-1} and is higher mainly due to better growth conditions. Moreover, due to the study design the data for Southern Bavaria refer to private and communal forests only and these forests exhibit higher share in soft wood species and thus higher increment values.

2. Given current wood energy demand and harvest levels, is there an additional supply potential?

Small-scale private forests offer a – mainly theoretical – potential for additional use of forest biomass. Harvest intensity in the study area was already high. Though in selected areas, i.e. small-scale private forests, additional supply potential might exist, it is questionable if these resources can be really mobilised. An additional supply potential of 0.4 m^3 ha^{-1} a^{-1} in whole Bavaria practically can be considered as not relevant or not existent in light of the low willingness of owners to supply more wood. Therefore, it is concluded that on average there is no realisable, additional supply potential for Bavaria. Self-consumption rate is high in domestic private forests, revealing a high relevance of the resource for forest owners.

Current knowledge on the biomass potential of private forests on a local scale is still insufficient. However, such information is needed for both renewable energy concepts and investment decisions. Since forest biomass is only a fraction of total woody biomass other sources like biomass from landscape management, waste wood, residues from forest industry and from biomass plantations should be included in such studies. In order to get a complete picture of private forests, further studies should comprise other ownership categories differentiated by the owner’s attitude towards their forest. Such studies would help to better understand the behaviour of forest owners, their knowledge of and attitude towards forestry. These forest owners presumably form a heterogeneous group of individuals, e.g. ‘non-traditional’, ‘urban’ and ‘absentee’ forest owners, or owners who have inherited their forest and thus do not automatically hold an intrinsic motivation to manage their property.

Therefore it can be concluded that on average there is no realistic, additional supply potential for biomass from Bavarian forests. Further energy production from woody biomass in Bavaria should come from increased resource use efficiency.

3. How will emissions relevant for climate and human health alter in the future following a shift in wood consumption towards more energy use?

The basket of benefit method was applied for a limited number of products and for selected impact categories. Only non-biogenic CO_2 emissions and non-regenerative primary energy demand were considered, as well as $PM_{2.5}$ emissions. The analysis of additional environmental indicators is recommended for further studies, e.g. the impact of increased wood energy use on soil conditions, emissions into water or hemeroby. The basket of benefit method also allows assessing economic or social indicators, e.g. the influence of a consumption shift on value-added or employment.

The analysis shows that a shift in wood consumption can entail a Janus-faced environmental impact. According to the scenario analysis, global warming potential will lightly deteriorate whereas primary energy demand will improve as a result of a shift in wood consumption towards more wood energy use. Additional greenhouse gas emissions, entailed by a reduced wood availability in the material-based sector, might not be fully compensated through the use of wood energy instead of conventional fuels. Particulate matter emissions will rise in case of increased wood energy consumption; however, because of insufficient data in the material-based sector, no definite conclusions can be drawn. In total, increased resource use efficiency is crucial for a sustainable wood energy use.

A lack in data exists for $PM_{2.5}$ emissions in the material-based sector, e.g. regarding the substitution of paper products through electronic products, so that additional research is recommended. Furthermore, energy demand for heating might decrease in the long-term due to demographic changes and increased thermal insulation of buildings. A knowledge deficit also exists with regard to the radiative forcing of black carbon and co-emitted aerosols originating from biomass combustion, as well as to what extent such effects can be analysed via LCA approaches.

The basket of benefit method was applied to compare material-based wood use with wood energy use in the case study area Bavaria. For the first time, ecological indicators have been analysed on a regional scale, i.e. for the Bavarian forestry and wood cluster. Through this approach the sector could be holistically assessed, taking into account e.g. interdependent substitution effects. The methodology proved to be suitable for this kind of comparative analysis and it is recommended for further testing and refinement in other sectors or regions.

4. Is it favourable to use wood in a certain manner and are there differences according to the impact category chosen?

While the substitution of fossil fuels through wood energy had a decarbonisation effect, reduced wood availability in the material-based sector and the necessity to either import wood or to use non-wood alternatives entailed an opposite effect. Importing sustainably produced sawn timber has substantial advantages over substitution of sawn timber with non-wood construction materials. Depending on the assumptions made in the basket of benefit analysis, the overall effect on GWP through an increased wood energy use in Bavaria could be either positive or negative. However, the increase in wood energy use could also lead to GHG savings if bioenergy is used in a most efficient way and if, for example, the assumption is made that wood energy substitutes more carbon-intensive fossil fuels such as oil sands or natural gas sourced via fracking methods. As a conclusion, resources need to be consumed in a most modern and efficient manner in both the material-based and energy sectors. Moreover, the impact categories primary energy demand and human toxicity (particulate matter emissions) have a counteracting effect. According to the basket of benefit analysis it appears that more wood energy consumption leads to more energy savings but also to higher dust emissions. Therefore, this is a trade-off and there is need to further support technological development of combustion systems.

More wood energy consumption apparently has a negative impact on human toxicity, particularly when timber is used as split logs. Wood pellet combustion exhibits comparably low $PM_{2.5}$ emissions due to the homogeneous material quality (no bark, dry) and the use in modern installation types. The results indicate that it would be advantageous to import wood instead of using conventional resources. However, the overall positive effect on the environment largely depends on the production conditions abroad as well as on the transport system and distances related to wood imports. The combustion in automatic, modern devices with homogenous wood material, e.g. certified wood pellets, strongly supports more responsible wood use. In general, increased resource use efficiency is crucial for a sustainable wood energy use. If wood combustion is conducted in an efficient and modern manner, more wood is available for all consumers and particularly $PM_{2.5}$ emissions from wood energy use can be lowered.

5. To what extent can future emission load from wood combustion be reduced?

The new law amendment in Germany can be a crucial measure to reduce future $PM_{2.5}$ emission load. According to the presented projection, current emission load from residential wood combustion can be reduced by 50%. In the baseline scenario, $PM_{2.5}$ could be reduced in the study area by 50% until 2025, and remain stable until 2035. In the increased wood energy scenario, overall $PM_{2.5}$ emissions can be also reduced; however, the emission load is higher than under stable consumption conditions and will rise again after 2025 so that additional measures would be necessary to achieve political targets for emission reduction. The successful modernisation of heating systems will also depend on the financial burden which arises for homeowners from the retro-fitting or exchanging of older installations.

Uncertainties relate to the real development of emissions, i.e. to the user behaviour which can strongly influence the emission load per installation and to the real amount of wood energy installations in the study area. Therefore, public information campaigns and effective oversight from chimney sweepers are important. Generally, fuel wood quality is a key lever for ensuring low emissions. The use of non-standardised fuels such as contaminated waste wood or material with high moisture or bark content will complicate compliance with emission limits.

Moreover, innovations may further help to reduce emissions in the long run and to use wood energy most efficiently, i.e. those targeting at enhanced standardisation of wood combustion in private households. Another lever could be bark-free split logs. For example, if bark was already removed from logs in the forest stands, then this would not only contribute to lowered dust emissions but also to enhanced forest management as this material is nutrient-rich and important for soil ecology. Therefore, research into the development of debarking methods in the forest stand would add value. It has to be considered though that bark constitutes an important source of thermal energy for drying of sawn wood in saw mills.

However, the successful modernisation of heating systems depends on various factors so that it is still questionable to what extent the law amendment will really be implemented in practice. For example, if wood energy combustion will constantly grow in the future then there will be a need for even stronger energy use efficiency, building insulation and emission controls. Decision makers should continuously support increased energy efficiency and building insulation, and promote modern wood combustion technologies.

6. How much additional wood energy could be gained through increased resource use efficiency?

The law amendment has furthermore a positive impact on resource use efficiency, entailing an additional potential for energy generation. For example in the baseline scenario up to 3.5 PJ a^{1} in 2035 can be additionally supplied from the same amount of wood in comparison to 2010. In other words, the increased resource use efficiency entails additional wood availability of 0.4 hm^3 a^{-1}. Through this additional amount of wood up to 970 000 MWh or 97 million liters of heating oil could be made available, and up to 48 500 households be additionally supplied with thermal energy per year. Alternatively, assuming a constant energy demand, this additional amount of wood could be available for other uses or annual harvest could be decreased in Bavaria by 0.4 hm^3.

7. What are similarities and differences as regards wood energy use in Bavaria compared to other regions?

The use of forest biomass for energy is widespread in Bavaria and Europe, and forest biomass is seen as a major component of renewable energies. Bavaria is characterised by a strong domestic market for wood products and bioenergy. While forest area is rather small, forest available for wood production is comparably high. Wood production in Bavaria plays a major role, particularly bioenergy production has been increasing in recent years. Fuel wood is consumed locally, indicating a high relevance for the well-being of particularly rural communities. However, as it is the case in other regions, too, there are scientific concerns about the trade-offs of biomass harvesting. Key areas of discussion are the preservation of minimum coarse woody debris amounts in the forest stand, or dust emissions from wood combustion.

In contrast to Bavaria and other countries in Europe, forest bioenergy production is small in e.g. Tasmania relative to the available resource. A weak domestic market for energy wood, the lack of political stimuli and a low social acceptance are likely key factors. Political incentives are key if the use of residues and low quality timber for energetic purposes should be increased. Besides small regional biomass projects, the export of processed material such as pellets may offer opportunities to better utilise the resource. Addressing social acceptance will be a prerequisite for the success of initiatives or legislation to achieve this potential.

Further comparative analysis of wood energy supply and demand patterns across regions and countries is recommended in order to conclude on strengths and weaknesses of forestry and wood clusters, as well as to reveal opportunities for and threats to more responsible use of forest biomass. As a conclusion, the analysis shows that the wood energy sector in Bavaria is comparably strong, i.e. that local supply and domestic demand are already at a high level, and that there is a strong support from society and political decision makers for sustained wood energy use.

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9 Publications

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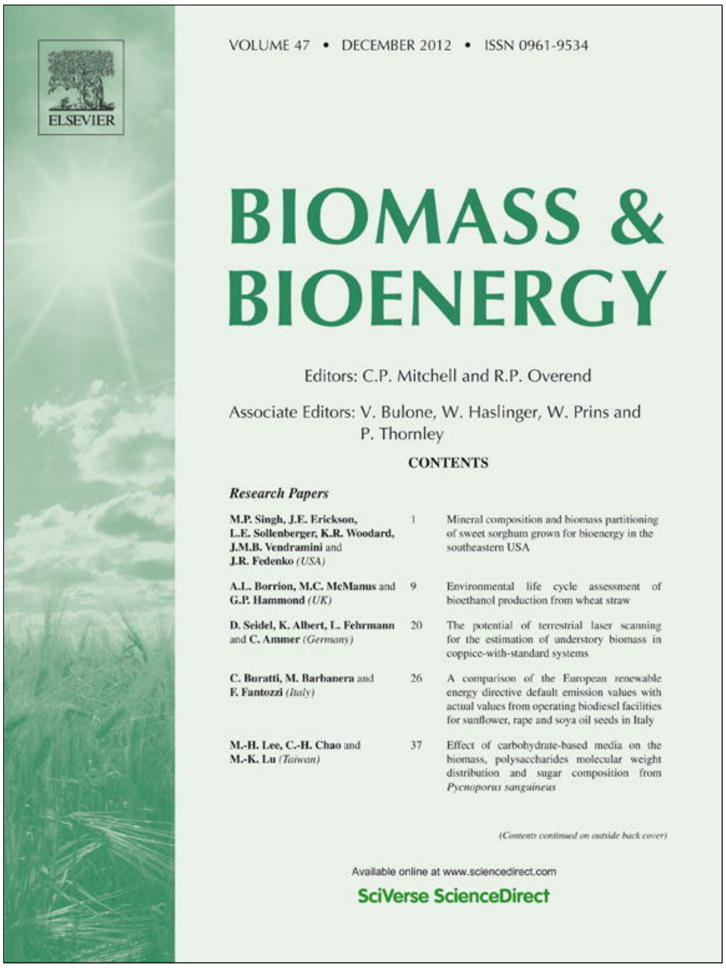

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Estimating forest biomass supply from private forest owners: A case study from Southern Germany

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ABSTRACT

In this article we developed a method to estimate forest biomass availability in a situation with small-scale privately owned forests and applied it to three administrative districts in Southern Germany where the majority of owners is organised in forest owners associations. Based on gross annual increment of regional forest resources we calculated a theoretical potential of above-ground biomass from which we subtracted technical and ecological constraints, e.g. restrictions resulting from conservation needs or nutrient removal. The resulting figure was the bio-technical potential of forest biomass. We then assessed the socio-economic potential of forest biomass by considering recent timber felling rates and log grading of owners. In order to determine market potential we differentiated between self-consumption and marketed timber. We compared the calculated potential and timber utilisation patterns of forest owners, deriving the additional supply potential of forest biomass. Most of the data were obtained by a stratified random interview of 226 private forest owners organised in forest owners associations. Although observed harvest intensity was high there was still a considerable potential for increased use of forest biomass. However, willingness of owners to intensify timber harvesting and to supply fuel wood on the basis of long-term contracts is a restriction to additional mobilisation of wood.

1. Introduction

In recent years, political stimuli for renewable energies in Europe and rising prices of fossil fuels entailed an increase in wood demand. In Germany, the market price for wood chips thus has almost doubled since 2005 [1]. Consequently, the marketing of fuel wood has become an important source of income for forest owners. According to the German wood energy and pellet association, currently 15 M households in Germany use wood for generating heat and the amount of private pellet heating systems has risen from 8000 in 2001 to 155,000 in 2011 [2]. Besides the prevalent fuel wood use in private households, wood energy is increasingly used in municipal or private biomass heating plants, wood chip or pellet heating systems.

While in the second half of the 20th century annual harvest in Eastern and Western European countries was significantly below increment [3], felling rate has been increasing since 1990 [4]. In Germany felling rates have been considerably increasing in the last decade, with rising

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wood energy consumption being a substantial driver. In Bavarian state forests annual harvest meanwhile equals timber felling potential [5]. A further increase is no longer possible here without violating sustainability. On the contrary privately owned forests are still characterised by a significant underutilisation, in particular small-scale private forests. This situation is not restricted to Germany but applies to most countries in Europe [6]. As about half of European forests is privately owned [4], private forest owners play a crucial role in satisfying the needs of both the wood energy sector and the forest-based industry.

A further increase of domestic wood demand is predicted as a consequence of ambitious targets for renewable energy, especially after Germany's decision to phase out nuclear power by 2020. As a consequence, public and scientists are increasingly concerned about an overexploitation of forests. In this situation, comprehensive knowledge on the real wood supply potential is an indispensable prerequisite for sound management decisions. While in recent years wood supply calculations have been carried out at global, European, national or province level [4,7–15], scientific uncertainties still exist at a sub-regional or local scale, especially for privately owned forests. Here behaviour of owners plays a crucial role and estimations based on mere inventory data are insufficient. However, information on the sustainable supply potential is crucial both for renewable energy concepts and investment decisions into woody biomass plants.

Therefore we performed a study to assess local biomass potential in privately owned forests with the following aims: (1) to develop a method for assessing biomass potential in a situation with small-scale ownership, (2) to assess sustainable biomass supply by considering technical and ecological restrictions, (3) to assess market potential of forest biomass by considering utilisation patterns of owners, and (4) to derive a regional market potential of forest biomass as a basis for renewable energy concepts and investment decisions. We only considered organised owners, since this study was funded by three local forest owners associations. These owners, who represent 75% of the total private forest owner area in the region, can be assumed to be quite interested in forest management.

2. Material and methods

2.1. Study area

We investigated three southern German counties (Bad Toelz Wolfratshausen, Miesbach, Rosenheim) with a total private and communal forest area of 96 000 hectares (ha). The reasons for selecting these counties were 1) its representativeness for rural regions in Southern Germany, 2) the high conservation value of its mountainous regions and thus the potential threat to sustainability, and 3) the accessibility to personal information such as addresses of potential interviewees due to good contacts with the forest owners associations. 59% of these forests are privately owned (44% organised, 15% not organised), 2% are owned by communities (all organised) and 39% are state owned. Tree species composition is dominated by conifers (77% of forest area) with Norway spruce being the prevalent species. The most important hardwood species is European beech.

According to the Bavarian forest ecological classification [16] the study area is mainly located in the zone 'Schwaebisch-Bayerische Jungmoraene und Molassevorberge', some parts in the North belong to 'Schwaebisch-Bayerische Schotterplatten und Altmoraenenlandschaft' and some parts in the South to 'Bavarian Alps' (predominantly flysch and limestone). The climate is pre-alpine, with an annual temperature between 4 °C and 7 °C and an annual precipitation between 1100 and 2000 mm, depending on elevation and microclimate [17].

According to the German forest inventory for the period 1987–2002 [8], regional fellings were only 6 $m^3\ ha^{-1}\ a^{-1}$ and far below the annual increment of 14 $m^3\ ha^{-1}\ a^{-1}$, resulting in an increase in growing stock. The underutilisation was especially pronounced in small-scale privately owned forests. However, since 2005 harvest intensity strongly increased and this was also reflected by our investigation covering the years 2006–2008.

2.2. Interview of forest owners

In order to obtain the necessary data we performed comprehensive interviews among private and communal forest owners organised in forest owners associations. Due to the low proportion of community forests in the investigated area we did not differentiate between the two ownership types.

We took a stratified random sample of 226 forest owners, divided into six strata according to common size classes of forest holdings [18]. Determination of minimum sample size per stratum was calculated according to Kauermann [19] using the formula $N = 4\ S/e^2$, where N is the minimum sample size, S the standard deviation of interview responses to felling intensity in $m^3\ ha^{-1}\ a^{-1}$ and e the required accuracy. As we could not draw upon previous knowledge on local felling intensity, we draw a pilot sample N of ten interviews within each stratum in order to determine the standard deviation S. For e we postulated a maximum deviation of 10% from the arithmetic average within each stratum. For example, $e = 1$ if arithmetic average of our pilot sample equalled a felling intensity of 10 $m^3\ ha^{-1}\ a^{-1}$ (Table 1).

Probands were selected with a random generator from a members list provided by the forest owners associations and interviewed personally or by phone. In case that an owner refused to participate we contacted the following one on the list. The contents of the interview comprised questions concerning the forest estate, ownership situation, harvesting practices as well as log grading and marketing for the period 2006–2008. The questionnaire template is attached in the Appendix.

2.3. Assessment of biomass potential

Biomass potential was calculated in three steps: 1. Calculation of above ground forest biomass (theoretical potential).

Table 1 – Number of interviewed owners and minimum sample size according to size class of forest holdings.

Size class (ha)	Standard deviation (*S*)	Required accuracy (*e*)	Minimum sample size of interviews (*N*)	Number of interviewed owners (*N*)
<4.9	2.37	0.87	29	31
5–9.9	2.74	1.10	25	44
10–19.9	2.15	1.03	17	66
20–49.9	1.60	0.64	25	52
50–99.9	1.54	0.80	15	19
>100	1.48	0.66	11	14
Total	–	–	122	226

2. Calculation of a technical–ecological potential by considering technical and ecological restrictions. 3. Calculation of socio-economic potential by considering log grading behaviour and self-consumption of forest owners. The resulting figure is the sustainable biomass potential distinguished between self-consumed biomass and marketable biomass.

2.3.1. *Above ground forest biomass (theoretical potential)*

We calculated gross annual increment of the investigated forest area by multiplying the regional increment values of the national forest inventory with the proportions of softwood and hardwood species derived from the interview results in order to render more precisely the tree species proportions. On the subregional scale, data accuracy of the national forest inventory is critical. According to the data available from the national forest inventory we used the unit $m^3\ ha^{-1}\ a^{-1}$ for all calculations and converted it into tonnes (t) (absolutely dry) in a final step. Since the inventory data only considered wood >7 cm diameter (in the following referred to as stem) and since published biomass extension factors only refer to growing stock of mature stands but not to increment, we used a biomass increment extension factor (ratio between the annual growth of above ground biomass and stem growth) of 1.16 for softwood (spruce) and 1.15 for hardwood (beech) to assess total increment of above ground biomass. The values are based on biomass investigations in three Norway spruce and three European beech stands located on different geological substrates in the investigation area (Table 2).

Diameter at breast height (DBH) was measured for all trees per plot. Biomass of stem wood, bark, branches, twigs and needles was investigated for seven trees differing in DBH. After felling, the length of the whole tree was determined and disks were taken from the stem at breast height in intervals of 4.1 m. Diameter and bark width were measured in order to calculate wood and bark volume and dry weight was derived from the disks. The total fresh weight of the crown (branches + twigs + needles) was measured using a sample of ten whole branches per tree. Fresh and dry weight of branches (diameter > 1 cm), twigs and needles was determined as well as the relation between these compartments along the crown. Biomass at stand level was derived by using simple power functions to describe the relationship between DBH and biomass of stem wood, bark, branches, twigs and needles (Table 3).

Biomass growth for a rotation period of 80 years (spruce) and 120 years (beech) was modelled using the growth simulator SILVA 2.3 (Fig. 1) [20].

2.3.2. *Technical–ecological potential*

The technical–ecological potential was calculated by subtracting the following restrictions (as percentage) from above ground biomass:

Table 2 – Stand characteristics of the spruce and beech stands used for calculation of the biomass increment extension factor.

Stand	Location	Altitude	Parent material	Tree species	Age [a]	Number of stems $[ha^{-1}]$	Basal area $[m^2\ ha^{-1}]$	Mean DBH [cm]	Biomass stem $[t\ ha^{-1}]$	Biomass crown $[t\ ha^{-1}]$
Schliersee	11° 48.84′ E 47° 43.38′ N	1070	Flysch	Spruce	65	853	67	31.6	343	58
Taubenberg	11° 46.32′ E 47° 50.38′ N	680	Upper freshwater molasse	Spruce	99	611	60	35.4	368	40
Gotzing	11° 48.96′ E 47° 49.3′ N	675	Periglacial gravel	Spruce	75	567	54	34.7	329	47
Schliersee	11° 48′54″ E 47° 43′20″ N	1080	Flysch	Beech	75	919	22	17.3	179	22
Taubenberg	11° 46′20″ E 47° 50′27″ N	710	Periglacial gravel	Beech	62	592	30	25.4	245	31
Gotzing	11° 48′11″ E 47° 49′53″ N	665	Periglacial gravel	Beech	77	498	27	26.4	228	59

Table 3 – Coefficients for the power function describing the relationship between DBH (diameter at breast height in m) and different biomass fractions for each investigation site.

Site	Spruce					Beech				
	Tree part	*a*	*b*	R^2	Sig.	Tree part	*a*	*b*	R^2	Sig.
Schliersee	Needles	544.3	2.880	0.81	0.0060	Twigs	457.9	2.815	3.78	0.0205
Gotzing		237.0	2.179	0.84	0.0039	(Ø < 1 cm)	81.72	1.599	2.16	0.0037
Taubenberg		186.5	2.428	0.91	0.0007		110.0	1.733	3.50	0.0001
Schliersee	Twigs	467.3	3.036	0.85	0.0032	Fine	169.5	1.800	2.19	0.0807
Gotzing	(Ø < 1 cm)	80.87	1.439	0.71	0.0178	Branches	156.0	1.726	2.45	0.0026
Taubenberg		77.71	1.741	0.81	0.0058	(Ø 1–2 cm)	410.8	2.125	5.28	0.0002
Schliersee	Branches	1861	3.782	0.92	0.0007	Coarse	1386	2.840	4.56	0.0456
Gotzing	(Ø > 1 cm)	328.3	2.020	0.87	0.0023	Branches	1197	2.705	5.72	0.0009
Taubenberg		511.6	2.556	0.94	0.0003	(Ø 2–7 cm)	1418	2.326	6.79	0.0014
Schliersee	Stem	175.7	1.661	0.91	0.0009	Stem	146.4	1.123	0.70	0.0437
Gotzing	Bark	240.2	1.652	0.94	0.0003	Bark	531.9	2.180	3.51	0.0001
Taubenberg		309.8	1.842	0.97	0.0000		316.6	1.893	4.30	0.0005
Schliersee	Stem	3639	1.982	0.93	0.0004	Stem	5152	1.918	1.34	0.0010
Gotzing	Wood	4765	2.117	0.97	0.0001	Wood	12 689	2.537	4.77	0.0001
Taubenberg		5706	2.257	0.98	0.0000		6676	2.141	5.16	0.0000

Biomass = $a^*\mathrm{DBH}^b$.

- Harvest restrictions resulting from insufficient forest infrastructure (slope steepness, opening up status): The percentage of area available for harvesting was assessed by interviewing forest owners to which extent their property is accessible to forest machinery.
- Harvest restrictions resulting from nature conservation issues: We conducted a GIS analysis in order to identify areas with special ecological values or areas protected by law (e.g. swamps, nature reserves). For areas with special ecological value (article 30 of the German Nature Conservation law) we assumed no harvest, for conservation areas with potential forest management we assumed harvesting limitations on 50% of the area.
- Harvest restriction resulting from leaving coarse woody debris: According to principles of the Bavarian State Forest Enterprise [21] which postulates an average of 7.0 m^3 ha^{-1} coarse woody debris for softwood dominated forests we assumed an average amount of coarse woody debris of 6.0 m^3 ha^{-1} for softwood (spruce) and 10 m^3 ha^{-1} for hardwood (beech) for private forests in our study area. For calculating the annual input of fresh wood to maintain this amount we used an average decomposition rate (DRC) of 0.05 for spruce and 0.07 for beech [22]. The annual input of fresh wood was then calculated by multiplying the amount of coarse woody debris with decomposition rate.

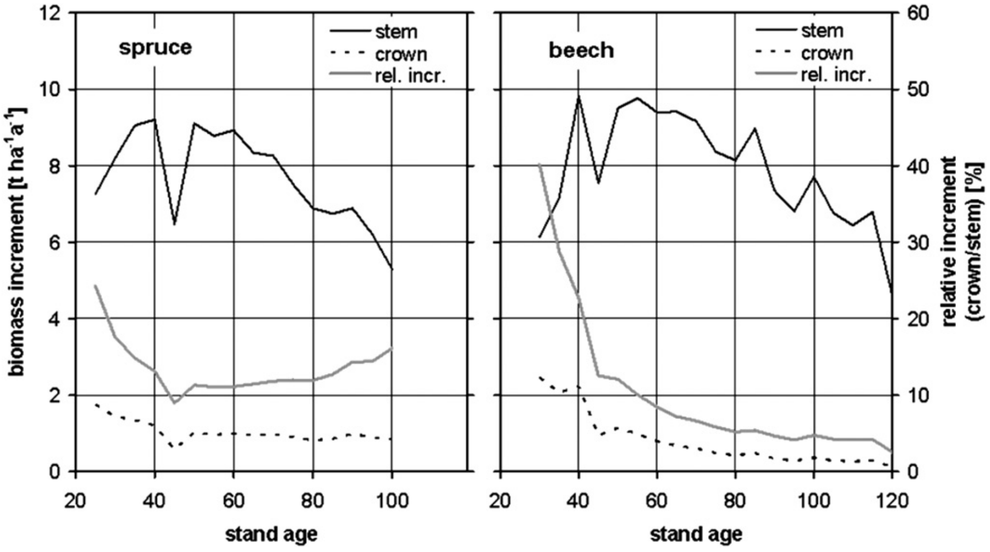

Fig. 1 – Biomass increment of stem [t ha^{-1} a^{-1}] and crown and increment ratio [%] (as average of three plots per species).

- Harvesting restrictions resulting from nutrient sustainability: For the five most widespread soil types in the area we calculated nutrient budgets for the base cations calcium, magnesium and potassium considering nutrient input via through fall and weathering as well as nutrient loss via seepage water output and full tree harvesting. The data were available from a previous study on nutrient budgets for the Bavarian State forest [23]. In case budgets were negative for either cation we assumed a reduction of potential harvest by 20% in order to maintain soil fertility.
- Harvesting loss: We assumed a harvesting loss of 10% according to conversion factors for forests in Bavaria [24]. This percentage figure takes account of the practice not to use the stump in the investigated area, of a top diameter of 7 cm, of remaining slash and of stripped off bark even during full-tree harvest.

2.3.3. *Socio-economic potential*

Annual harvesting rates as well as log grading (saw logs, pulp wood, and wood for energy use) were calculated per size class as a three year average for the period 2006–2008 using the results from the interviews. The wood for energy use was differentiated into fire wood and wood chips as well as into self-consumption and sales. The socio-economic potential of biomass was obtained by multiplying the technical–ecological potential ($m^3\ ha^{-1}\ a^{-1}$) with the proportion of each biomass fraction (wood assortments resulting from log grading behaviour of owners and self-consumption of fuel wood) for the period 2006–2008.

3. Results

Overall, we contacted 500 forest owners from a list provided by the forest owners associations and succeeded to interview 226 persons, representing 3.6% of all organised private and communal forest owners (226 out of 6300) and 11.8% of the organised private and communal forest area (8434 ha out of 71,400 ha). Forest owners were on average 48.9 years old, the share of female owners was 4%. 78% of owners were farmers, three forth of them full-time farmers.

Increment of above ground biomass (theoretical potential) was 14.7 $m^3\ ha^{-1}\ a^{-1}$, the bio-technical potential after consideration of all restrictions was 11.0 $m^3\ ha^{-1}\ a^{-1}$ (Fig. 2). Average harvesting in 2006–2008 amounted to 8.4 $m^3\ ha^{-1}\ a^{-1}$. Around 55% of the timber was used as saw logs, 42% as fuel wood and 3% as pulp wood. 28% of total harvest was self-consumption of fire wood and wood chips while only 14% of fuel wood (fire wood and wood chips) was marketed (Fig. 3).

Since harvest was well below the technical–ecological potential there was still a significant potential of additional utilisation of 2.6 $m^3\ ha^{-1}\ a^{-1}$. Assuming unchanged log classification behaviour of forest owners for the remaining potential this would mean an increase of fuel wood supply potential in a magnitude of 1.1 $m^3\ ha^{-1}\ a^{-1}$.

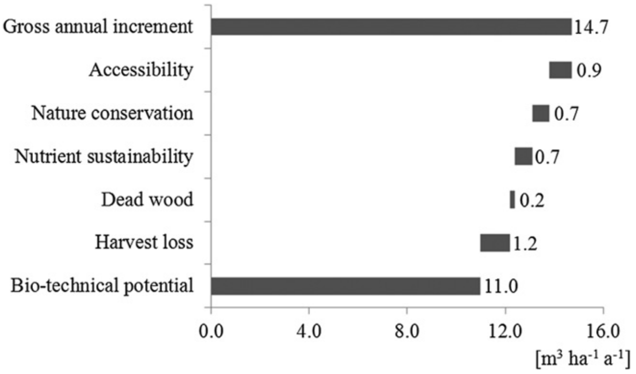

Fig. 2 – Increment of above-ground biomass (theoretical potential), harvesting restrictions and bio-technical potential in $m^3\ ha^{-1}\ a^{-1}$ (average of the years 2006–2008 for the investigated forest area owned by the 226 respondents).

Felling intensity was high in all size classes smaller than 100 ha, especially in those smaller than 20 ha (Fig. 4). Moreover, harvest rate was rather even within size classes (Fig. 5). Importance of fuel wood and self-consumption declined with increasing holding size. In holdings smaller than 5 ha, more than 50% of the harvest was used as fuel wood and 80% of fuel wood was self-consumed (Fig. 6).

While total harvest was similar, considerable differences occurred in log classification and self-consumption in the three counties (Fig. 7). In the county of Rosenheim harvest of fuel wood and self-consumption was nearly twice compared to the county of Miesbach. The majority of owners from neither county were willing to supply wood on the basis of long-term contracts with forest owners associations (Fig. 8).

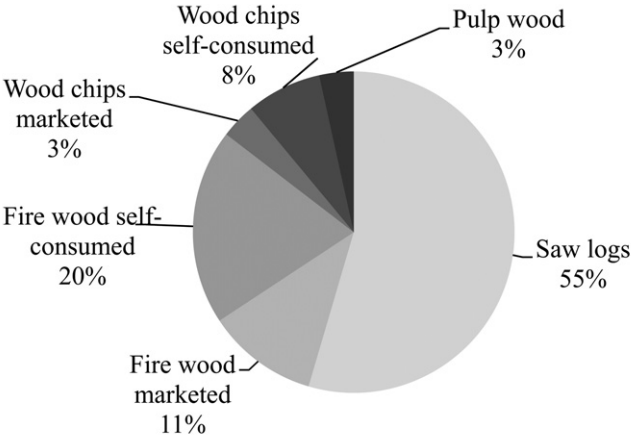

Fig. 3 – Log classification and self-consumption in % for fire wood and wood chips (average of the years 2006–2008 for the investigated forest area owned by the 226 respondents).

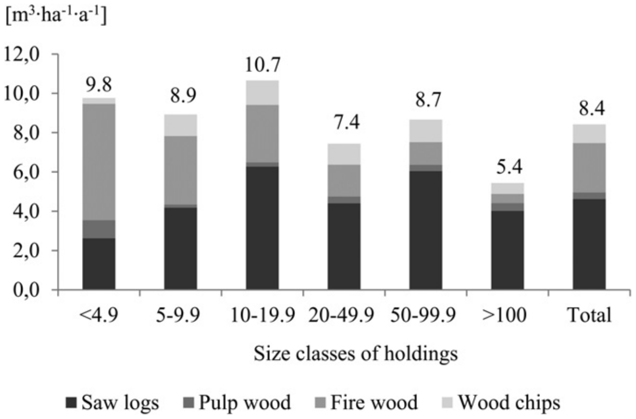

Fig. 4 – Felling intensity and log classification in $m^3\ ha^{-1}\ a^{-1}$ according to size class of forest holdings (average of the years 2006–2008 for the investigated forest area owned by the 226 respondents).

Fig. 6 – Fuel wood (fire wood and wood chips) harvest ($m^3\ ha^{-1}\ a^{-1}$) and self-consumption (%) according to size class of forest holdings.

4. Discussion

4.1. Method

Our study is mainly based on the interview of forest owners. The sample size covering 226 interviews represents 3.6% of all owners or 11.8% of the area of forest owners associations. Number of interviewed persons exceeded minimum sample size (accuracy of 10% concerning felling intensity) in all size classes and all parameters of the interviews ranged within a 95% interval of confidence. Willingness of owners to participate in the study was high (except owners >100 ha) and performing the interviews was more straightforward compared to other studies [25–27] since we could refer to the member lists of forest owners associations.

With guidance from the interviewer, all forest owners could quantify the amount of wood harvested by assortment, species and year, as well as tree species composition and diameter class distributions (>30 cm, 15–30 cm and 15 cm) of their forests. Due to data availability we could only validate some aspects of the answers against secondary data like the amount of marketed timber (data available from the forest owners associations) and forest composition (data for all private forest owners for the whole region known from the national forest inventory). We also validated the answers against the assessment of the managers of the forest owners associations for selected well-known owners. Since the responses corresponded well with the available secondary data we assumed a high validity of the whole interview. No correlation could be determined as regards the forest owners' answers to the interview and the manner in which the interviews were conducted (i.e. in person or by telephone).

Standard deviation of fellings diminished with increasing holding size indicating a more homogenous felling intensity in larger holdings. The majority of owners with holdings smaller than 10 ha did not regularly manage their forest. However, annual fluctuations were at least partly equilibrated through using a three year average in our study. Contrary to the outcomes of the national German forest inventory covering the period 1987–2002 [9] in our study small owners even harvested more timber than owners of larger holdings. One reason might have been that fuel prices strongly increased after the turn of the

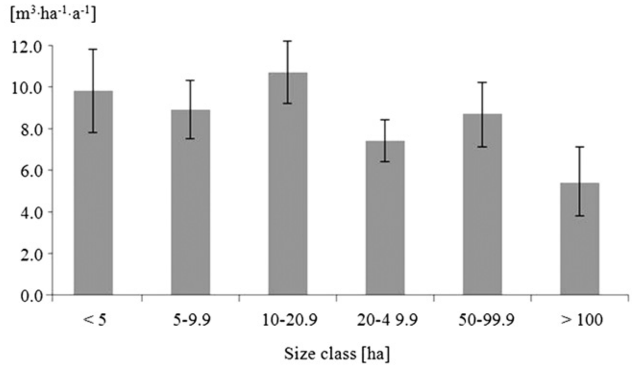

Fig. 5 – Confidence interval (t-distribution, confidence level 0.95) for felling intensity in $m^3\ ha^{-1}\ a^{-1}$.

Fig. 7 – Harvest, intensity, log classification and self-consumption ($m^3\ ha^{-1}\ a^{-1}$) according to county.

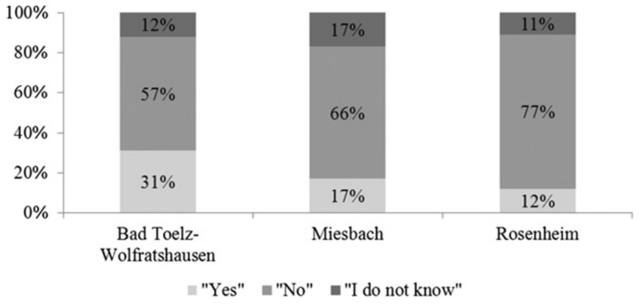

Fig. 8 – Willingness of owners to supply wood on the basis of long-term contracts with forest owners associations according to county (in %).

century and therefore it was more attractive to use fuel wood. We did not investigate price-related supply functions but it seems clear that increasing prices for energy favour the use of fuel wood. Intensive utilisation by small owners has also been reported by Huber for Austria [28] and informal markets (subsistence, supply to family members, neighbours, etc.) seem to be comparably constant [29]. Additionally it cannot be excluded, that we underestimated harvest in holdings >100 ha since nearly 50% of such owners were not willing to participate in the study.

While the method proposed here could be applied to all private forest owners, our results are only valid for the members of the investigated forest owners associations. It seems likely that these owners are more interested in forestry and harvesting. The high harvesting intensity of 10 m^3 ha^{-1} a^{-1} in holdings smaller than 20 ha might thus be more a figure for active owners rather than an average for all private forests. In terms of interest in harvesting there are at least two other categories of owners, a) those who have some interest in harvesting but are not members in a forest owners association, and b) those who have other than economic interests. Therefore we assume that our figures overestimate harvest intensity in all private forests but further studies are necessary to analyse this aspect.

Additionally some owners could have deliberately reported incorrect data for reasons of privacy or lack in forestry knowledge. The low harvesting intensity in holdings >100 ha points towards this direction. Another source of uncertainty originates from the fact that behaviour of owners changes with time. Strictly speaking our results are only valid for the years 2006–2008, a time period characterised by rising timber prices and a high wood demand. Harvesting intensity in these three years was nearly twice compared to the period 1987–2002 investigated in the German forest inventory. Especially harvesting intensity and log classification behaviour may also vary in future according to individual attitudes, wood (energy) prices or financial support schemes by the government.

In our study we did not investigate influence of timber prices on harvesting intensity. Our reference period from 1987 to 2002 (last National German Forest Inventory) was characterised by very strong fluctuations caused by big wind throw events. After 2005, timber prices significantly increased and it is likely that this contributed to the intensified harvesting. However, the set of our data was not suitable for investigating the reaction of harvest intensity to price changes.

Strength of our study certainly was that we investigated the behaviour of forest owners with a comprehensive interview. Nearly all studies on wood supply potential (overview see Hepperle [30]) are based on physical data from the inventories, and in addition to assumption on log classification and on different utilisation scenarios. While this approach may lead to reliable results for large areas such as industrial or state forests, our study indicates that behaviour of small owners may vary significantly even between adjacent counties. Therefore, in a situation of small private ownership information concerning harvest and log classification behaviour is an indispensable prerequisite for reliable estimates of biomass potential. Though in some studies, e.g. by Hofer [11] and by Schadauer [15], all bio-technical and socio-economic aspects were thoroughly considered, the harvest potential resulting from behaviour of forest owners was not calculated.

Our method to calculate restrictions as a percentage of gross annual increment presumably slightly underestimated the bio-technical potential due to a certain double consideration. For example restrictions resulting from accessibility or areas with special ecological values may have contributed to coarse woody debris. Also the fact that theoretical potential was calculated for volume instead of density of tree species slightly underestimated theoretical potential. Therefore, our biomass potential is a conservative estimate in the sense of a minimum sustainable utilisation option.

4.2. *Comparison of results to other studies*

The heterogeneous ownership structure of the investigation area, composed of many small-scale owners with less than 5 ha (often split up in several lots) and only few owners with properties >100 ha is typical for other European countries [27,31]. In terms of numbers of private forest owners as well as distributions of size classes, small-scale land holdings prevail in Europe. 61% of all private forest holdings have an area of less than 1 ha and 86% of all holdings belong to the size class up to 5 ha [31].

Harvest intensity in our study was nearly twice compared to the figures Schmithüsen [31] reported for private forests in Austria, Germany and Switzerland. This reflects on the one hand the favourable site conditions with a high productivity in our investigation area. On the other hand the extension service from the forest owners associations and from the State forest service as well as rising timber prices seemed having fostered the activity of owners. Also the fact, that 78% of owners are farmers contributed to the high harvest intensity. This figure is far above those from other German areas which range from 14 to 48% [32]. Farmers usually have a stronger affinity to land management than owners without a farming background. Such owners which strongly increased in the last decades are less represented in forest owners associations and tend to practise less intensive forest management [32].

The high importance of fuel wood and of self-consumption in small forest holdings corresponds well with the findings of more recent studies for Bavaria and also for Austria [33,34]. In small forest holdings the amount of fuel wood harvest usually exceeds saw log harvest and most of the fuel wood is used for domestic heat production.

4.3. *Potential for fuel wood*

Despite the relatively high harvest intensity in the years 2006–2008 we predicted an additional potential of 2.6 $m^3\ ha^{-1}\ a^{-1}$, 1.1 $m^3\ ha^{-1}\ a^{-1}$ being fuel wood (both fire wood and wood chips). For the total private and communal forest area of 96 000 ha this would sum up to 250 000 $m^3\ a^{-1}$ wood (138 000 $m^3\ a^{-1}$ sawn wood, 7000 $m^3\ a^{-1}$ pulp wood and 105 000 $m^3\ a^{-1}$ fuel wood). Assuming unchanged log classification by owners two third of the fuel wood would be used for private purposes and about 35 000 $m^3\ a^{-1}$ would be available for the market.

A rough calculation based on current wood prices (100 €/m^3 for spruce saw logs, 50 €/m^3 for spruce fire wood (split logs), 15 €/m^3 loose for wood chips logged to forest road and 35 €/m^3 for pulp wood) exhibits an unused forestry turnover of M 14.5 € annually. 105 000 $m^3\ ha^{-1}\ a^{-1}$ correspond to an annual wood energy potential of around 185 000 MWh (calculation basis: share of coniferous wood 77%, density of softwood (spruce) is 0.379 t/m^3, density of hardwood (beech) is 0.558 t/m^3, water content is 50%), respectively to approximately 18.5 M L of heating oil. This underlines the importance of forestry for rural development and substitution of fossil fuel with regard to climate change.

However, our study also indicates that realising this potential is a big challenge. Willingness of owners to sign long-term contracts with the forest owners associations is low. This corresponds with previous studies showing that private forest owners often do not regularly manage their forest [6,35]. For many farmers, forestry is only an addendum to their agricultural business and harvesting is performed in case of capital requirements, fuel wood demand or building construction [36]. According to Schwarzbauer et al. [34] owners react to increasing or decreasing timber prices and long-term contracts would hinder their flexibility. Other owners with a small property do not rely on forest income and are more interested in forest values like recreation, ecology or security of investment [6,37–39]. In such a case, commitment of owners to regular wood supply contracts with forest owners associations is naturally low. Several other reasons make it difficult to intensify harvest: a small size of private forest holdings with unknown boundaries, limited access, cost-effective harvesting technology, fragmentation of ownership, and the trend to larger sawmills which require high amounts of timber on a just-in-time and regular basis [6]. The application of modern, cost-effective harvest technology also is a matter of size. In our case fellings were predominantly performed by chain-saw (82%) und the percentage of harvester-based felling increased with size of the holding.

Efforts to increase wood supply from small-scale private forests have been conducted in many European countries. In recent publications [29,40,41] a set of measures to foster management activities were identified, amongst them information campaigns improving knowledge and forestry skills, enhanced accessibility to forests and wood transportation, and increased cooperation between private forest owners via forest owners associations. In general, strong owner associations with effective structures are considered to be a major factor for realising the supply potential of private forests.

5. Conclusions

Small-scale private forests offer a potential for additional use of forest biomass. Despite harvest intensity in our study was already high, sustainable harvest could be further increased by about 20% without violating sustainability. However, realising this potential is a big challenge since willingness even of the members of forest owners associations to sign long-term agreements with forest owners associations is low.

Biomass availability strongly depends on behaviour of owners concerning harvest intensity and log classification. Since this behaviour varies in space and time literature values are not reliable. The method, which is mainly based on input data obtained from interviews, allows a sound assessment of forest biomass supply for small-scale privately owned forests. Although we applied the method only to organised owners, it can be used to other ownership categories as well.

Further studies are needed to fill data gaps. Current knowledge on the biomass potential of private forests on a local scale is still insufficient [29,31]. However, such information is urgently needed for both renewable energy concepts and investment decisions. Due to a high variability in space and time more studies covering different areas and periods should be performed. Since forest biomass is only a fraction of total woody biomass other sources like biomass from landscape management, waste wood, residues from forest industry and from biomass plantations should be included in such studies. In order to get a complete picture of private forests, further studies should comprise other ownership categories differentiated by the owner's attitude towards their forest. Such studies would help to better understand the behaviour of forest owners, their knowledge of and attitude towards forestry. These forest owners presumably form a heterogeneous group of individuals, e.g. 'non-traditional', 'urban' and 'absentee' forest owners, or owners who have inherited their forest and thus do not automatically hold an intrinsic motivation to manage their property.

Acknowledgements

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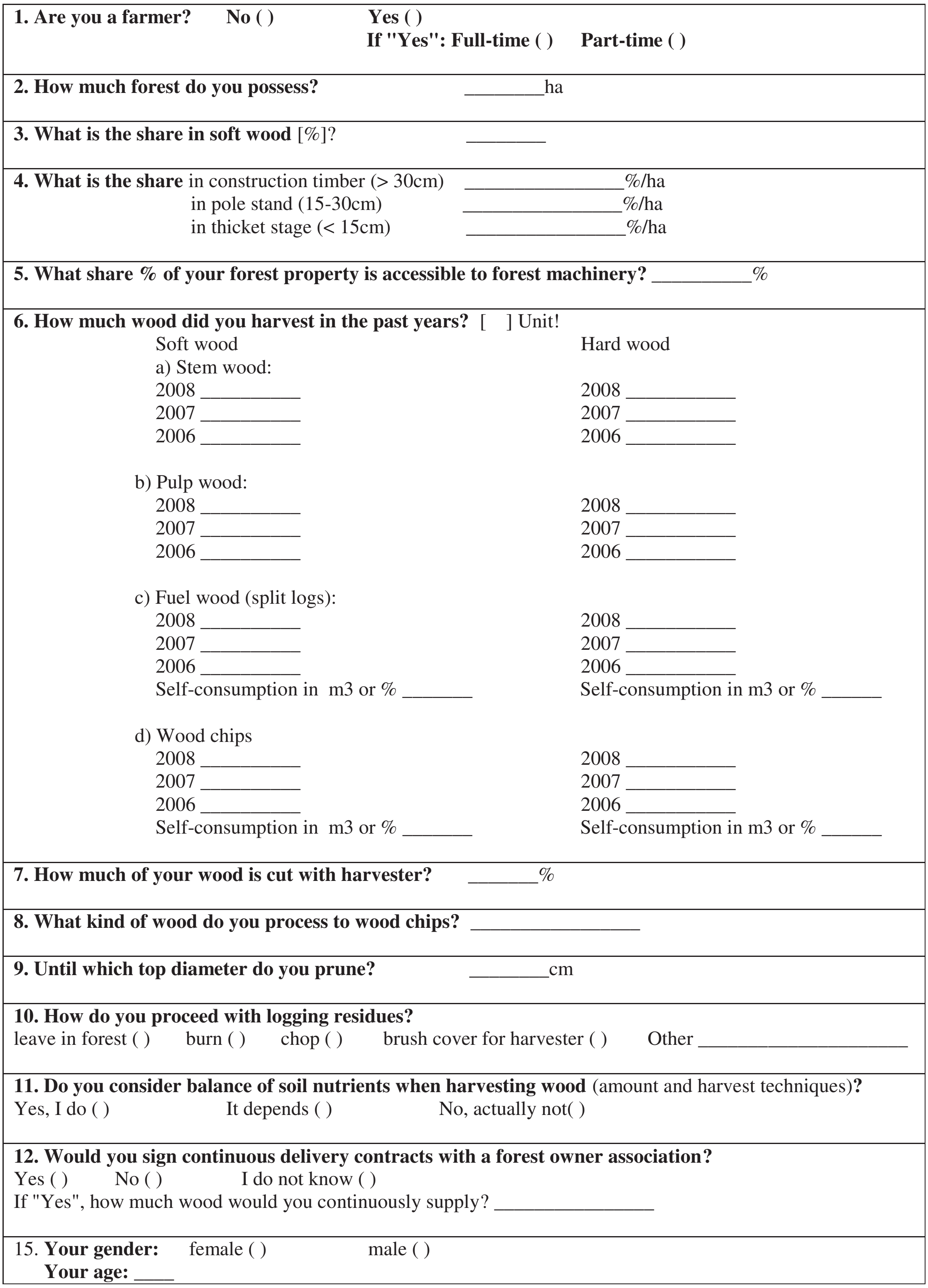
Appendix. Template of the questionnaire for interviewing private forest owners.



1. Are you a farmer? **No ( )** **Yes ( )**
If "Yes": Full-time ( ) **Part-time ( )**

2. How much forest do you possess? ________ha

3. What is the share in soft wood [%]? ________

4. What is the share in construction timber (> 30cm) ________________%/ha
in pole stand (15-30cm) ________________%/ha
in thicket stage (< 15cm) ________________%/ha

5. What share % of your forest property is accessible to forest machinery? __________%

6. How much wood did you harvest in the past years? [ ] Unit!

Soft wood	Hard wood
a) Stem wood:	
2008 __________	2008 ___________
2007 __________	2007 ___________
2006 __________	2006 ___________
b) Pulp wood:	
2008 __________	2008 ___________
2007 __________	2007 ___________
2006 __________	2006 ___________
c) Fuel wood (split logs):	
2008 __________	2008 ___________
2007 __________	2007 ___________
2006 __________	2006 ___________
Self-consumption in m3 or % _______	Self-consumption in m3 or % ______
d) Wood chips	
2008 __________	2008 ___________
2007 __________	2007 ___________
2006 __________	2006 ___________
Self-consumption in m3 or % _______	Self-consumption in m3 or % ______

7. How much of your wood is cut with harvester? _______%

8. What kind of wood do you process to wood chips? _________________

9. Until which top diameter do you prune? ________cm

10. How do you proceed with logging residues?
leave in forest ( ) burn ( ) chop ( ) brush cover for harvester ( ) Other _____________________

11. Do you consider balance of soil nutrients when harvesting wood (amount and harvest techniques)**?**
Yes, I do ( ) It depends ( ) No, actually not( )

12. Would you sign continuous delivery contracts with a forest owner association?
Yes ( ) No ( ) I do not know ( )
If "Yes", how much wood would you continuously supply? ________________

15. **Your gender:** female ( ) male ( )
Your age: ____

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Research paper

Effects of increased wood energy consumption on global warming potential, primary energy demand and particulate matter emissions on regional level based on the case study area Bavaria (Southeast Germany)

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ABSTRACT

Wood energy use has strongly increased in Europe in the last decade entailing enhanced resource competition between the wood energy sector and the material-based wood sector. We applied the basket of benefit method for the forestry and wood cluster of the study area Bavaria to evaluate the impact of increased wood energy use and decreased material-based wood use on global warming potential, primary energy demand and particulate matter emissions. A baseline and a wood energy scenario were developed until 2035 and wood utilization in both scenarios was assessed via a Life Cycle Assessment of prevalent wood products, imported timber and conventional alternatives of use. The study reveals that, according to the modelled scenarios and the average substitution factors used, a demand shift towards more wood energy leads to a minor increase in global warming potential and to a reduction in primary energy demand. Increase in particulate matter emissions from wood energy use is strong, but definite conclusions cannot be drawn due to lack in data for material-based wood use. Moreover, the study results vary strongly depending on the products used for the comparative analysis. Through our approach, the ecological impact of increased wood energy use becomes visible for a whole region, taking into account the effect of a demand shift and of interdependent substitution effects.

1. Introduction

Against the background of climate change, European member states have agreed on ambitious targets for renewable energy. For example in Germany, the energy concept of the government foresees that greenhouse gas (GHG) emissions will be reduced by 60% till 2020 in comparison to 1990, and that the share of biomass in thermal heating will increase to 14% [1,2]. Renewable energy is increasingly used in Germany, due to rising prices of fossil fuels and fostered through governmental subsidies for electricity generation from renewables. As half of total energy is used for heating purposes and as two third of renewable heat is generated from solid biomass, wood is currently the most important renewable energy in Germany [2]. From 2005 till 2010 the share in wood energy use has increased by 20 h m^3, so that in 2010 wood energy use (50.6%) for the first time since decades was higher than material-based wood use [3]. While the nationwide renewable energy consumption for household heating has grown by 56.7% between 2005 and 2012, the total energy consumption has declined by 8.4% [4]. The increased demand is positive for forest owners who can market their products more easily. While increased wood energy use adds to substituting CO_{2}- intensive fossil fuels, the consumption shift also means that less domestic wood is available for other uses, e.g. material-based wood products. Missing wood quantities either have to be imported or replaced with non-wood alternatives. The question arises whether a shift in consumption has negative or positive impact on environmental indicators, e.g. global warming potential, taking regional wood supply and demand into consideration.

Life cycle assessments (LCAs) are a common tool to analyse the

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environmental burden of product usage. LCAs of wood products have been conducted in various studies. For wood energy use in central Europe, e.g. Refs. [5–10] have provided comprehensive analyses. For material-based wood products, databases are available through research done by e.g. Refs. [7,8,11]. LCA calculations for specific products were conducted by e.g. Refs. [12–23] in the wood energy sector, as well as by e.g. Refs. [24–28] in the material-based sector. The studies, however, state individual evaluations of selected product life cycles and assessed either wood material or wood energy use. Due to different functional units (e.g. MJ, m^3, m^2, t) and end uses (electricity, heat, material use) study results and related products cannot be directly compared to each other. For example, wood pellets combustion for domestic heat generation is not directly comparable to combustion of wood chips for heat and power production. Moreover, when assessing the impact of a shift in material allocation over time, i.e. increased wood energy use and decreased resource availability in other sectors, it is indispensable to consider indirect effects. These include the consumption of imported timber or of alternative products, e.g. a building with brick walls instead of wooden walls in the material-based sector, or the consumption of imported wood pellets instead of fuel oil or natural gas.

Few scientific studies have assessed the environmental impact of material use versus energy use of wood. Ref. [29] described advantages and disadvantages of wood energy use compared to wood material use. Refs. [28] and [30] evaluated the production of biomaterials with bioenergy, using a given area of agricultural land as a reference. Both studies concluded that cascaded material use is superior to the immediate combustion of resources. Refs. [31] and [32] compared different product life cycles of wood with fossil alternatives and found that direct combustion of wood instead of cascaded material use can entail e.g. increased global warming potential. However, these studies state individual comparisons of product alternatives.

A lack in data still exists with regard to the impact of increased wood energy use on environmental indicators, taking also indirect effects into account, too, i.e. a decreased availability in the material sector and thus higher use of non-wood alternatives or import of timber products. Moreover, effects of a consumption shift have only been assessed for defined units, e.g. a hectare of land or a ton of biomass, and not on a regional scale. A comprehensive, regional impact assessment of a shift in consumption, taking into account both wood material use and wood energy use, as well as associated indirect effects through alternative (fossil) usages so far has not been conducted. Therefore, the purpose of this paper is to compare wood energy use with material-based wood use via applying the basket of benefit method and to crystallize the impact of increased wood energy use for a whole region. The study is designed to answer the following research questions:

- What are ecological consequences of a shift in consumption towards more wood energy use and less material-based wood use on a regional scale?
- Is it favourable to use wood in a certain manner and which recommendations can be derived for improved resource consumption?

In order to answer the research questions, wood consumption in the study area Bavaria, Southern Germany, is evaluated through a life cycle assessment (LCA) according to different impact categories. A shift in consumption from wood material use to wood energy use is modelled from 2010 till 2035, entailing decreased fossil energy use but increased non-wood material consumption. Finally, the basket of benefit method is tested to evaluate the shift in consumption and its overall effect on environmental indicators.

2. Material and methods

2.1. Study area

As case study area we chose the province of Bavaria, Germany, because a good database exists for the forestry and wood cluster due to studies by Refs. [33] and [34]. The study area is characterized by a strong forestry and wood cluster as almost one third of annual harvest in Germany comes from there [4]. Share of wood energy assortments in total harvest has increased from 23% in 2005 to 34% in 2010 [34]. Overall wood consumption in 2010 was 26.7 h m^3, including post-consumer material, industry residues and wood from landscape management. Almost half was used for energy (12.8 h m^3), predominantly in private households (7.5 m^3) but also in heating plants (1.1 h m^3) and combined heat and power plants (4.2 h m^3). 10.6 h m^3 of sawn timber were consumed, as well as 1.6 h m^3 of paper and 2.1 h m^3 of wood-based panels [34].

2.2. Scenario analysis to model changes in wood consumption till 2035

Wood consumption data for the year 2010 by Ref. [34] were used as a starting point for scenario modelling. Two scenarios were defined to model a shift in consumption. While the “baseline scenario” describes a constant wood consumption until 2035 for all material-based and energy-related wood products, the “wood energy scenario” refers to an increasing demand for wood energy. The wood energy scenario assumptions were based on the “Reference scenario” of the European Forest Sector Outlook Study II [35] in which an annual growth in wood energy use by 1.5% is assumed for Germany on the long run. We implied that this trend is applicable for our research area and that material-based wood use decreases by the same amount as wood energy use rises. The consumption shift was calculated for five-year periods. In order to determine wood supply from the forest, we used data from Ref. [36] who calculated management behaviour and felling rates of forest owners for our study area and for the same time span on the basis of increasing oil and wood prices.

For the determination of wood energy consumption we considered woody biomass from the forest, i.e. above-ground forest biomass, as well as woody biomass from outside the forest, i.e. short rotation plantations, wood from landscape management, industry co-products and post-consumer wood. The development of wood energy demand per product and period was defined according to [35], however, restrictions were set with regard to supply rates according to [36]. For split logs we assumed a lowered increase (growth rate 0.75% p.a.) in wood demand due to a law amendment which has come into effect by the beginning of 2015 [37]. The law sets stricter requirements for wood use, especially for split log combustion in private households. Furthermore data by Refs. [3,38–41] on minimum requirements for wood assortment composition of wood-based panels and graphical paper, as well as utilization capacity of paper mills and sawmills were used to determine a realistic supply per product in the study area over the reporting period.

In case that the supply per product and period was below the wood energy demand, we calculated wood pellet imports. The demand for this assortment has tripled since 2013 and a further increase is expected for the future [42]. In order to exclude external effects, we further assumed that import, export and domestic trade of wood products are in balance. Such a trend has emerged since 2010 in the Bavarian foreign trade statistics for round wood [43]. For domestic trade no statements can be made since such data are not included in official trade statistics. Furthermore, round wood imports were not considered due to an expected shortage of wood in European countries [44], respectively due to high costs for imports from overseas [45]. In the event of a lack in domestic raw materials for wood-based panels, we modelled wood imports. For graphical paper, we assumed that electronic media will substitute wood-based paper products. In order to ensure comparability, we postulated that the overall demand for both energy and material purposes is stable in both scenarios and in every period.

2.2.1. Determination of wood products and alternatives of use for the LCA analysis

A range of both wood energy and material-based wood products are consumed in the study area. For the LCA analysis we concentrated on the most relevant, i.e. most commonly used wood products in the study area according to [34]. As wood energy products we chose the assortments (1) split logs, (2) a mix of wood chips including forest chips, saw-mill co-products and post-consumer wood, as well as (3) wood pellets. Split logs and wood pellets represent the production of heat, whereas wood chip mix stands for both production of thermal energy and electricity. As material-based products we chose (4) sawn timber, (5) wood-based panels and (6) graphical paper.

Because the wood energy scenario entails an increase in fuel wood consumption and a decrease in material-based wood use, those alternative products which are substituted by fuel wood or which are used instead of material-based wood products were identified. In the electricity sector we compared electricity generation from wood with the future German power mix according to [46], respectively heat generation from wood with heat generation from natural gas. For a subsequent sensitivity analysis, we calculated substitution factors for those energy sources that are squeezed out of the market according to [46], i.e. lignite, hard coal and nuclear power in the electricity sector, as well as a mix of natural gas and crude oil in the heating sector. In the material-based sector, we determined representative non-wood buildings in Bavaria (residential, industrial and farm buildings) to be used instead of equal buildings constructed with sawn timber, respectively representative electronic media (books for education or entertainment, flyers, catalogues) to be used instead of graphical paper products. Furthermore, imports of wood-based panels were calculated.

2.2.2. LCA analysis and impact categories

The goal of the life cycle assessment was to compare the impact of a shift in wood utilization on environmental indicators and to derive recommendations for improved wood consumption. The LCA was designed as a cradle-to-grave analysis and thus comprised the assessment of wood production in the forest including cultivation, wood harvest and transport, manufacturing and distribution to customers, as well as wood use and combustion including ash disposal. Re-usage and final combustion were additionally considered for material-based products. LCA analysis was conducted via the LCA software GaBi 6.0 by Ref. [8]. The life cycles of the wood products for energy and material purposes were evaluated along common supply chains in the study area (Table 1).

The products were assessed according to three environmental impact categories, which in our viewpoint are highly relevant with regard to current scientific and public discussions relating to wood energy usage:

1. non-regenerative primary energy demand (net calorific value),
2. global warming potential (GWP 100) without biogenic CO_2, calculated in carbon dioxide equivalent (CO_2eq) emissions, and
3. particulate matter emissions ($PM_{2.5}$).

As we assessed the consequences of altered wood consumption over time on environmental indicators rather than concentrating on physical flows from or to a product, our analysis states a consequential LCA in contrast to an attributional LCA [47]. The LCA was designed according to ISO 14040/44 [48,49] and the ILCD handbook [50].

LCA analysis of wood energy products was based on data by Refs. [5] and [8]. LCA of material-based wood use was designed according to data by Refs. [8,16,27,40,51–53]. Data by Refs. [8] and [16] were used for the impact assessment of pellet imports. We modelled that the pellets are transported via ship from Quebec to the port of Hamburg (6590 km), from there with a train (600 km) to the geographical centre of Bavaria from where the pellets are distributed to the end consumer per truck (100 km). Imports from Canada were chosen as exemplary product because 38% of imported pellets in the EU in 2010 came from Canada [54]. Data for LCA analysis of different energy alternatives in the heat (natural gas, crude oil) and power (electricity mix, lignite, hard coal, nuclear power) sectors were taken from Ref. [8]. There is a strong variance in net efficiencies of wood energy installations [14,55]. We therefore calculated average values for wood energy use in the study area. In order to take account of the range of emissions from wood energy use, we also calculated minimum (worst case) and maximum (best case) efficiency rates of wood energy use.

For LCA analysis of a representative non-wood building used instead of a wooden building, we used data by Refs. [56–61]. Data by Ref. [62] were used to assess representative electronic media consumed instead of print media. Imports of wood-based panels were determined according to [8]. Transport distances of wood products were derived according to data by Refs. [5,8,11,27,33].

2.2.3. Basket of benefit method and wood use balance

As the products are not directly comparable due to diverse end uses and different functional units, the basket of benefit approach according to [63] and [64] was applied to compare different systems and to analyse the impact of altered wood consumption in the study area. The method was originally developed to compare different recycling pathways of recycled plastic bottles [63–66]. The methodology is a special life-cycle assessment approach to compare emissions from diverse product pathways against each other and against alternative products. Comparability is warranted through system expansion which guarantees that different systems, such as energy use instead of material use, contain an equivalent amount of goods produced, as well as fulfil the same end uses and benefits [67]. The benefits generated in the wood energy scenario were equated to those in the baseline scenario by substituting wood-based material consumption with synthetic or fossil alternatives by the same amount as fuel wood consumption increases. As the basket of benefit approach is used in our analysis as a tool to analyse the impact of a change in product consumption on environmental impact categories, a constant demand was modelled in the baseline scenario and an increased demand in the wood energy scenario.

In order to ensure a common basis for comparison of energy products, we converted all fossil and wood energy-related data into both energy equivalents (MWh) and round wood equivalents (m^3). The functional unit in the material-based sector was also harmonized via converting all units of material-based wood products and their product alternatives into round wood equivalents (m^3). Impact category results per cubic meter were multiplied with wood product amounts consumed in each of the five-year periods in both scenarios. Wood consumption per product in the baseline scenario was freezed over the reporting period. In the wood energy scenario, increased fuel wood consumption triggered substitution of fossil energy and a lack of timber in the material-based sector which was equilibrated through the use of imported timber or of non-wood

Table 1
Adaptation of GaBi datasets to Bavarian conditions.

Assessed wood product	Product specification	Tree species composition acc. to Haertl & Knoke 2013	Transport distance [km]$^{2)}$	Efficiency rates[a]
Split logs (heat)	Split logs from the forest, burnt in 6 kW stove, domestic heating	Spruce 52%, pine 22%, beech 21%, oak 5%)	15 km	60 (20–80)
Wood chip mix (heat and electricity)	Wood chips from the forest, saw mill co-products, post-consumer wood	Wood chips from the forest 40% (spruce), saw mill co-products 20% and post-consumer wood 20% (Bavarian mix according to Friedrich et al., 2012 ([34])) Products burnt in 1 MW heating plant, 1.4 MW combined heat and power plant (CHP), as well as 6.4 MW CHP	50 km (wood chips from the forest und saw mill co-products), 100 km (post-consumer wood)	70 (40–80)
Wood pellets (heat)	Saw mill co-products, burnt in 15 kW stove, domestic heating	Spruce 100%	100 km	80 (70–85)
Sawn timber	91% sawn soft wood, 9% sawn hard wood	Soft wood: spruce 100%, hard wood: beech 100%	50 km	n/a
Wood-based panels	100% Particle Board	Industrial soft wood: spruce 100%; Industrial hard wood: beech 100% Saw mill co-products and industrial rest wood: 100% spruce Post-consumer wood: no tree species defined as no ecological backpack is accounted for recycled material	74 km industrial wood, 90 km saw mill co-products, 117 km post-consumer wood	n/a
Pulp and paper	100% Paper mix (German average)	Industrial soft wood: spruce 100%; Industrial hard wood: beech 100% Saw mill co-products: spruce 100%	154 km industrial wood, 220 km saw mill co-products	n/a

[a] Figures show average values used for calculation in GaBi 6.0, in brackets are minimum and maximum ranges of efficiency rates used for the sensitivity analysis.

alternatives (Fig. 1). Through this approach, a comparative assessment of material and energy use at the regional level under different consumption scenarios was possible.

3. Results

3.1. Development of wood consumption and shift in resource allocation

The wood energy scenario results in a growth of fuel wood consumption by 2.5 h m^3 till 2035, respectively an equivalent

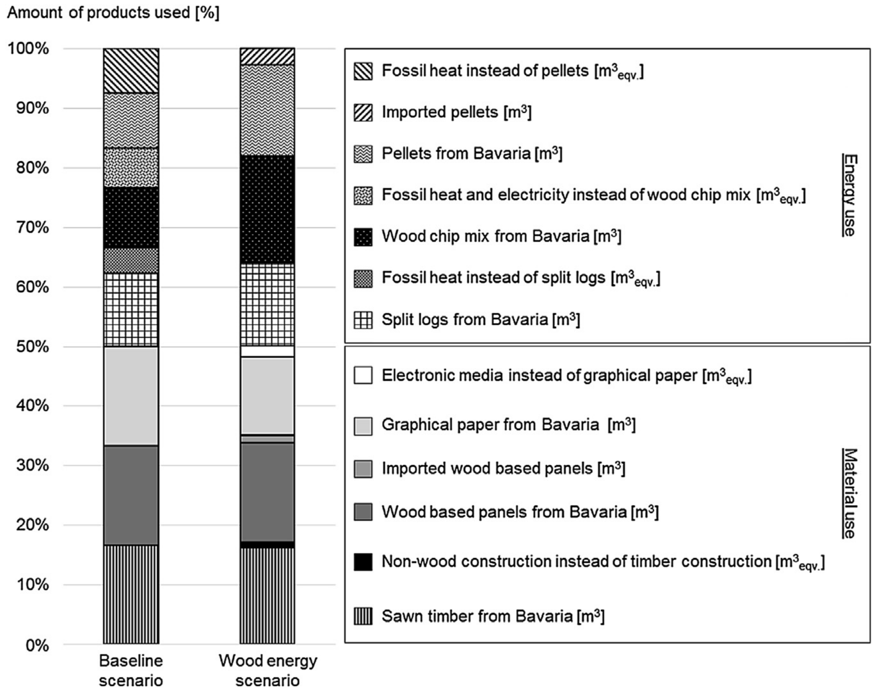

Fig. 1. Illustration of the basket of benefit methodology and the products used to fulfil energy and material demand. While in the baseline scenario fossil energy is still used in the basket of benefit, fossil energy is substituted in the wood energy scenario and overall wood energy use increases. In contrast, material-based wood use decreases in the wood energy scenario and non-wood construction materials are consumed instead of timber.

decrease of material use and substitution through alternatives of use. Material-based wood use declines by 31% while wood energy use rises by 35% till 2035 compared to 2010 levels. The average share of energy use in total wood consumption rises from nearly 50% in 2010 to 63% in 2035. The total material demand is 14.5 h m^3 in both scenarios, however, only 13.4 h m^3 are fulfilled through domestic wood sources. In the baseline scenario the wood-based material demand is fully satisfied with wood from the study area. The energy demand is 14.7 h m^3 of wood equivalents in both scenarios. In the wood energy scenario, total energy demand is fulfilled with domestic wood or with imported pellets. In the baseline scenario, 12.2 h m^3 are fulfilled with domestic biomass, the remaining energy equivalents with fossil sources (Table 2). The average overall wood consumption per period was equilibrated in both scenarios (26.7 h m^3) in order to allow a comparison.

3.2. Average LCA results for wood products and alternatives of use

Split log consumption on average exhibits lower CO_2eq emissions (23 kg MWh^{-1}) and less non-regenerative primary energy demand (143 MJ MWh^{-1}) compared to the use of pellets (51 kg MWh^{-1}, respectively 607 MJ MWh^{-1}). However, average $PM_{2.5}$ emissions are considerably higher when split logs (556 g MWh^{-1}) are used instead of pellets (120 g MWh^{-1}). The reasons are that the supply chain for the production of split logs is shorter but that less homogenous material is burnt in non-automatic installations. Imported pellets exhibit higher CO_2eq emissions (74 kg MWh^{-1}) and higher $PM_{2.5}$ emissions (287 g MWh^{-1}), as well as higher primary energy demand (2830 MJ MWh^{-1}) than locally produced pellets due to the different production conditions and long overseas transport. Heat production with wood chip mix leads to CO_2eq emissions of 32 kg MWh^{-1}, primary energy demand of 50 MJ MWh^{-1} and $PM_{2.5}$ load of 261 g MWh^{-1}. Using natural gas results in much higher CO_2eq emissions (280 kg MWh^{-1}) and non-regenerative primary energy demand (4240 MJ MWh^{-1}), but in considerably lower $PM_{2.5}$ emissions (7 g MWh^{-1}) compared to biogenic peers. The results for heat production are not yet comparable to electricity production due to different functional units and end uses. While the production of electricity from wood chips compared to average electricity mix on average exhibits positive effects for CO_2eq emissions (24 kg MWh^{-1} compared to 603 kg MWh^{-1}) and non-regenerative primary energy demand (503 MJ MWh^{-1} compared to 8560 MJ MWh^{-1}), $PM_{2.5}$ emissions are much higher (414 g MWh^{-1} compared to 23 g MWh^{-1}).

Different net efficiency rates of wood energy installations were calculated. Table 3 shows that these have a considerable impact on our analysis. For example, $PM_{2.5}$ substitution factors for heat generation with split logs instead of natural gas vary between +436 and +1660 g MWh^{-1}. The variance is smaller for pellets and wood chips used instead of fossil alternatives, as these wood energy assortments are burnt more homogenously in modern, automatic installations.

In the material sector, the consumption of sawn timber leads to non-regenerative primary energy demand of 1984 MJ m^{-3}, CO_2eq emissions of 65 kg m^{-3} and $PM_{2.5}$ emissions of 16 g m^{-3}. The consumption of imported sawn timber exhibits higher ecological burden for all three impact categories (primary energy demand of 2165 MJ m^{-3}, CO_2eq emissions of 73 kg m^{-3}, $PM_{2.5}$ load of 21 g m^{-3}). When an average non-wood construction is produced instead of a wooden building, primary energy demand increases by 640 GJ per building and CO_2eq emissions rise by 59 tonnes per building (Table 3). $PM_{2.5}$ emissions of wood and non-wood constructions could not be determined due to lack in data. Imported wood-based panels reveal higher CO_2eq emissions (247 kg m^{-3}), higher $PM_{2.5}$ emissions (74 g m^{-3}) and increased primary energy demand

Table 2
Average annual production quantities of wood products made in Bavaria, imported wood products and alternatives of use for the baseline scenario and the wood energy scenario in round wood equivalents.

Sector	Wood products, imported wood products and alternatives of use	Scenario [functional unit/a] in millions	
		Baseline	Wood energy
Energy use	Split logs [m^3]	5.6	6.2
	Fossil heat instead of split logs [$m^3_{eqv.}$]	0.6	–
	Subtotal split logs (producers in study area) and alternatives [$m^3_{eqv.}$]	6.2	6.2
	Wood chip mix [m^3]	5.5	6.0
	Fossil heat and power instead of wood chip mix [$m^3_{eqv.}$]	0.5	–
	Subtotal Wood chip mix (producers in study area) and alternatives [$m^3_{eqv.}$]	6.0	6.0
	Wood pellets [m^3]	1.1	2.0
	Fossil heat instead of wood pellets [$m^3_{eqv.}$]	1.4	–
	Imported wood pellets [m^3]	–	0.5
	Subtotal wood pellets (producers in study area) and alternatives [$m^3_{eqv.}$]	2.5	2.5
	Total energy demand of domestic wood [m^3]	12.2	14.2
	Total alternative energy demand [$m^3_{eqv.}$]	2.5	0.5
	Total energy demand [$m^3_{eqv.}$]	14.7	14.7
Material use	Sawn timber [m^3]	10.9	9.7
	Non-wood construction material instead of wood construction [$m^3_{eqv.}$]	–	1.2
	Subtotal sawn timber (producers in study area) and alternatives [$m^3_{eqv.}$]	10.9	10.9
	Wood-based panels [m^3]	2.0	1.9
	Wood-based panel imports [m^3]	–	0.1
	Subtotal Wood-based panels (producers in study area) and alternatives [$m^3_{eqv.}$]	2.0	2.0
	Graphical paper [m^3]	1.6	0.8
	Electronic media instead of graphical paper [$m^3_{eqv.}$]	–	0.8
	Subtotal graphical paper (producers in study area) and alternatives [$m^3_{eqv.}$]	1.6	1.6
	Total demand of domestic wood	14.5	12.4
	Total alternative material demand	–	2.1
	Total material demand [$m^3_{eqv.}$]	14.5	14.5
Total demand of domestic wood [m^3]		26.7	26.7
Total demand of alternative products and imports [$m^3_{eqv.}$]		2.5	2.5
Total demand [$m^3_{eqv.}$]		29.2	29.2

Note: Due to rounding, not all numbers presented add up to the totals provided.

Table 3
Substitution factors for non-renewable primary energy demand, global warming potential (in CO_{2eq}) and particulate matter emissions of wood products and fossil alternatives.

Sector	Product substitution [functional unit]	End use	Substitution factor	Primary energy demand [GJ/functional unit]	GWP 100 [t/functional unit]	$PM_{2.5}$ [g/functional unit]
Material	Non-wood construction instead of wood construction [building type]	Construction	Worst case	+1050.0	+69.9	n.a.
			Ø	+639.7	+59.4	n.a.
			Best case	+227.7	+5.1	n.a.
	Imported wood-based panels instead of domestic wood-based panels [m^3]	Furniture	Worst case	n.a.	n.a.	n.a.
			Ø	+0.7	+0.01	n.a.
			Best case	n.a.	n.a.	n.a.
	Electronic media instead of graphical paper [t]	Media	Worst case	+223.1	+15	n.a.
			Ø	0	0	n.a.
			Best case	−58.4	−1.9	n.a.
Energy	Heat from split logs instead of natural gas [MWh]	Heat	Worst case	−3.8	−0.21	+1600
			Ø	−4.1	−0.25	+548
			Best case	−4.1	−0.27	+436
	Heat from pellets instead of natural gas [MWh]		Worst case	−3.5	−0.22	+123
			Ø	−3.6	−0.23	+114
			Best case	−3.7	−0.23	+111
	Imported pellets instead of natural gas [MWh]		Worst case	−1.2	−0.19	+306
			Ø	−1.4	−0.20	+279
			Best case	−1.5	−0.21	+270
	Heat from wood chip-mix instead of natural gas [MWh]		Worst case	−3.6	−0.24	+271
			Ø	−3.7	−0.25	+253
			Best case	−3.7	−0.25	+237
	Electricity and heat from wood chip mix instead of electricity mix [MWh]	Heat and electricity	Worst case	−7.9	−0.57	+528
			Ø	−8.1	−0.58	+390
			Best case	−8.2	−0.59	+307

Note: The products are not yet comparable due to different functional units and end uses.

(4382 MJ MWh^{-1}) than locally produced goods because of the larger transport distances (198 kg m^{-3}, 54 g $PM_{2.5}$ m^{-3}, 3681 MJ MWh^{-1}). The comparative analysis of print media and electronic media leads to indifferent results, because GHG emissions and primary energy demand are closely linked to the user behaviour, the length of the life cycle and recycling characteristics of the electronic device. Our calculations according to [62] show that using electronic media instead of graphical media could lead to both a reduction (−1.9 tonnes per tonne paper) and an increase in CO_2eq emissions (+15 tonnes per tonne paper). Moreover, the analysis of primary energy demand exhibited that substitution factors vary between −58 and +223 GJ per tonne paper. As no definite conclusions can be drawn on the impact of substituting graphical media with electronic media, we set the values for primary energy demand and GWP to zero, i.e. in our calculations the substitution of wood-containing paper through synthetic materials does not have an impact on primary energy demand and GWP. The determination of $PM_{2.5}$ emissions from print media and electronic media was not possible due to lack in data. The choice of products in the construction sector has only a minor influence on the GWP result.

Substitution factors shown in Table 3 for the use of wood energy products instead of fossil energy are closely related to the efficiency rates of installations and to user behaviour in case of non-automatic installations (Table 1).

3.3. Basket of benefit evaluation per impact category

The basket of benefit analysis shows that, when extrapolating the average LCA results per product and period to the overall wood consumption, the enhanced wood energy use entails an increase in CO_2eq emissions by 140 000 t a^{-1} in the study area (Fig. 2). This amount corresponds to additional CO_2eq emissions of 0.11% in Bavaria, i.e. to an additional release by 13 000 persons (out of a total of 12 million inhabitants in Bavaria) per year, given that on average 11.2 t a^{-1} are emitted per capita [68]. While reduced wood availability in the material-based sector triggers an increase in GWP, increased combustion of wood instead of fossil energy leads to reduced emissions. The effect in the material sector exceeds the one in the energy sector. The evaluation shows that the substitution of sawn timber in the construction sector through non-wood constructions has strong negative impact on GWP. This result is based on the analysis that an average wooden building in the study area additionally contains 48.5 m^3 of sawn timber compared to non-wooden buildings [59,61,69]. Importing wood-based panels has minor negative impact on CO_2eq emissions. As explained in chapter 3.2, the value for the use of e-media instead of graphical media was set to zero due to the strong variations in CO_2eq emissions (between +13 600 kt a^{-1} and −53 kt a^{-1}). In fact, the impact of a substitution in the material-based sector could be both negative and positive, depending on the assessed product life cycles in the basket of benefit. The GWP results for the substitution of timber constructions with non-wood construction vary between +130 and +1300 kt a^{-1} and the results for imported wood panels alter between +3 and +5 kt a^{-1}.

In the wood energy sector, the use of split logs and wood chips has similarly high effect on the reduction in CO_2eq emissions. The average amount of greenhouse gases saved through the increased wood energy use is −185 kt a^{-1} for both increased split log use and increased wood chips use. As we modelled a strong increase (+1.4 hm^3 a^{-1}) in wood pellets consumption in the wood energy scenario, more than half of the GHG emission reduction in the energy sector (−472 kt a^{-1}) comes from the substitution of fossil fuels through pellets. The figures in the wood energy sector fluctuate between −944 and −757 kt a^{-1}. In total, the average impact on global warming potential through the shift in wood consumption entails an increase in CO_2eq emissions by 140 kt a^{-1} in the study area. The results vary, however, between −810 kt a^{-1} and +548 kt a^{-1}, depending on the assumptions made. Thus, the impact on global warming potential could be either negative or positive so that no definite conclusion can be drawn.

While a negative impact on GHG emissions resulted from the consumption shift, primary energy demand decreases by +1.6 PJ a^{-1} on average, corresponding to the demand of 10 000 inhabitants

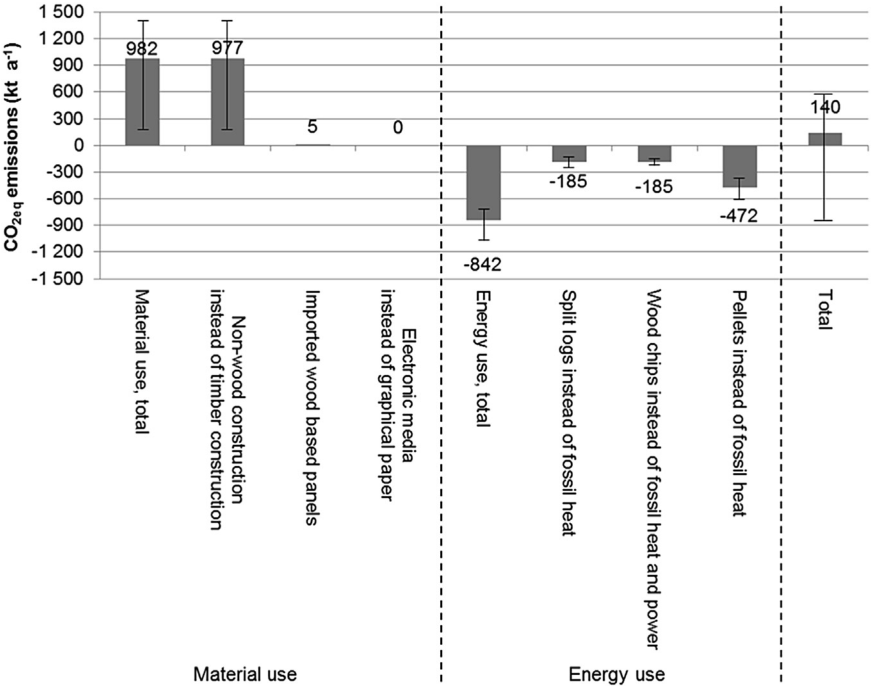

Fig. 2. Increased wood energy use and the average impact on global warming potential (without biogenic CO_2) for wood products, imported wood and alternatives of use. Data are only shown for the shift in consumption, i.e. refer to quantitative consumption differences between the baseline and the wood energy scenario.

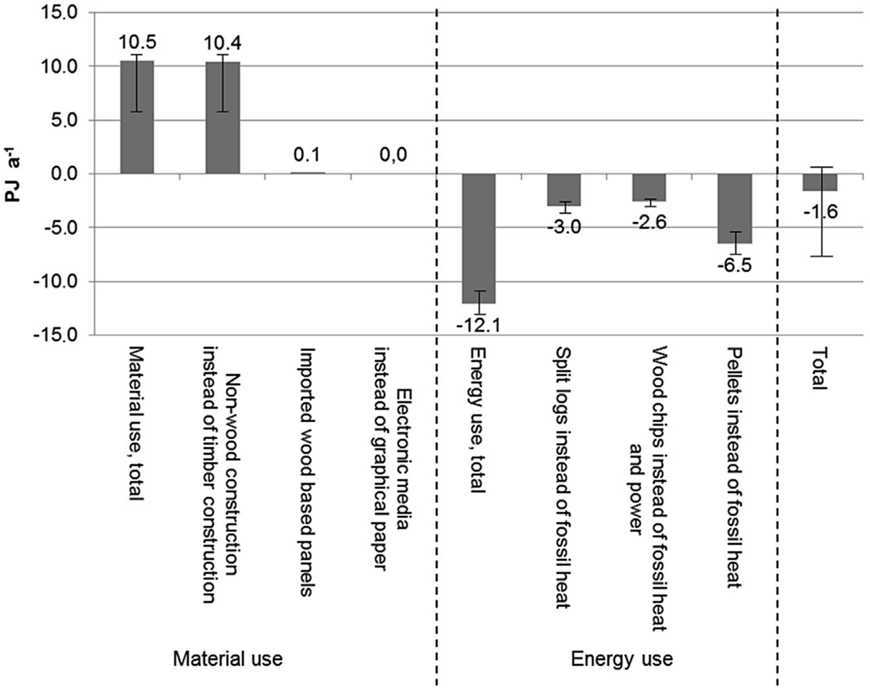

Fig. 3. Increased wood energy use and the average impact on non-regenerative primary energy demand (net calorific value) for wood products, imported wood and alternatives of use. Data are only shown for the shift in consumption, i.e. refer to quantitative consumption differences between the baseline and the wood energy scenario.

in the study area per year [70,71]. Fig. 3 shows that the substitution of sawn timber in the construction sector triggers considerably increased primary energy demand. The use of imported wood-based panels instead of domestic timber does not reveal an impact. As the substitution factors for the use of e-media instead of graphical media were set to zero, the basket of benefit shows no impact through a substitution of wood through e-media. However, as explained above, the actual emissions can vary strongly (between −58 and +223 GJ t_{paper}^{-1}). The impact of a shift in wood consumption on primary energy demand in the material-based sector varies between 5 and 11.6 PJ a^{-1} for the whole study area. In the energy sector, the use of split logs and wood chips instead of fossil energy contributes to a similar degree to the reduction in primary energy demand. The wood pellet consumption adds to

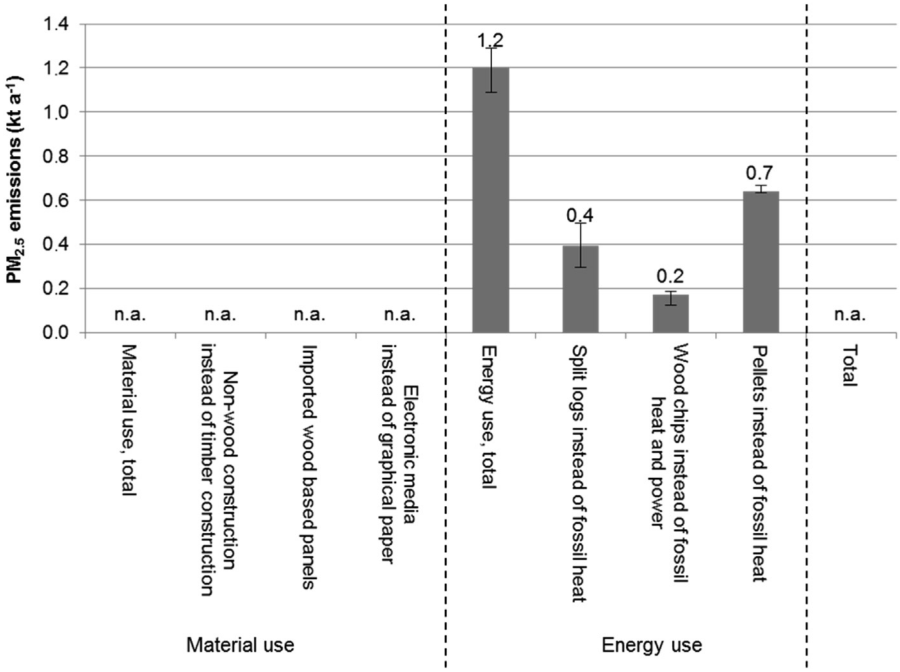

Fig. 4. Increased wood energy use and the average impact on $PM_{2.5}$ emission load for wood products, imported wood and alternatives of use. Data are only shown for the shift in consumption, i.e. refer to quantitative consumption differences between the baseline and the wood energy scenario. Note: Due to rounding, not all numbers presented add up to the totals provided.

even stronger reduction in primary energy demand. In total, the results vary between -9 PJ a^{-1} and $+0.3$ PJ a^{-1}, depending on the assumptions made. Again, the impact on primary energy demand could thus be either negative or positive so that no definite conclusion can be drawn.

With regard to particulate matter emissions, not enough data were available in the material-based sector. Thus, no statement can be made whether the substitution of sawn timber, wood-based panels and graphical paper through product alternatives has positive or negative effects. Increased wood energy use, however, leads to considerably higher particulate matter emissions. On average, 1.2 kt are additionally released per year (Fig. 4). This increase represents a growth in total emission load from the wood energy sector in the study area by 25%, compared to 2010 values [72]. More than half of these emissions (0.7 kt) originate from wood pellets use. The share of imported pellets in particulate matter emission load is 0.4 kt. The particulate matter emissions from split log combustion increase by 0.4 kt whereas the consumption of this assortment rises by 0.6 h m^3 only. Compared to pellets, the increase in $PM_{2.5}$ emissions from split log combustion is thus disproportionally high. The total results vary between $+1.1$ and $+1.4$ kt a^{-1} for the whole study area, as a result of the change in wood consumption.

A sensitivity analysis further revealed that if missing wood volumes in the material sector, particularly sawn timber, are substituted with sustainably produced imported wood, a shift in consumption towards wood energy use entails an overall reduction in CO_2eq emissions by $-349\,000$ t a^{-1} and increased savings in primary energy demand by -6.8 PJ a^{-1}. Thus, the use of wood in the construction sector has a key influence on our analysis. Moreover, the results of the basket of benefit analysis vary, if wood energy use is compared with different fossil energy sources. For example, if wood energy is not only compared to natural gas but to a mix of natural gas and crude oil, and if electricity production from wood is not compared to the electricity mix but to those energy sources that are curtailed or squeezed out of the market according to the study by Ref. [46], i.e. lignite, hard coal and nuclear power, then the basket of benefit analysis reveals an overall reduction in CO_2eq emissions by $-15\,000$ t a^{-1} in the study area. Primary energy demand rises only marginally ($+0.02$ PJ a^{-1}). No conclusions can be drawn on the overall impact on $PM_{2.5}$ emission load through the sensitivity analysis due to lack in data in the material-based sector. According to [73] the sector "commercial, institutional and household fuel combustion" contributes most to $PM_{2.5}$ emissions in the European Union (33% share in 2011).

The sensitivity analysis reveals that, depending on the analysed product life cycles, the enlarged wood energy use can lead to both a reduction and an increase in global warming potential and that no definite conclusions can be drawn. The selection of wood products, imported timber and alternative materials assessed in the basket of benefit thus plays a key role for the results of the basket of benefit analysis.

4. Discussion

4.1. Method

A scenario analysis was conducted to crystallize the impact of a potential future shift in wood consumption. We did not aim at developing an exact prognosis of future wood use, thus applied a simplified approach and calculated our scenarios on the basis of the study EFSOS II by Ref. [35]. The reasons for applying the EFSOS II "Reference scenario" were that it states a recent and comprehensive estimate of future wood use in European countries. Furthermore, the study refers to the present policy framework in Europe and to current trends in the forestry sector [35]. For our study objectives, i.e. testing the basket of benefit approach and identifying the impact of a consumption shift on sustainability indicators, a simplified application of an existing scenario was considered sufficient.

Via the basket of benefit analysis we assessed the impact of a net change in demand, i.e. the increased product demand in the “wood energy scenario” compared to the constant demand in the “baseline scenario”. Therefore, only the net change in consumption from one scenario to the other was considered in our model.

For the impact analysis we chose prevalent combustion systems which represent a larger amount of combustion techniques and for which a good database exists. Average product life cycles were modelled via GaBi 6.0. In reality, a variety of chimneys, ovens, boilers, heating plants and combined heat and power plants exists and the results of the impact analysis strongly depend on the efficiency of the combustion systems and on the alternatives of use chosen in the basket of benefit. Emissions from wood combustion can differ considerably, for example $PM_{2.5}$ emissions from non-automatic installations can be higher by the factor ten compared to automatic installations [74]. LCA databases for split log ovens need to be improved [23,31]. Especially in the field of wood energy use in households, an improved energy use efficiency and lowered emission load can be expected due to a recent law amendment aiming at the modernization of these installations [37].

According to [8] the 6 kW boiler, which was chosen for our analysis, is representative for small-scale installations of up to 20 kW and the pellet boiler is representative for installations of up to 30 kW. Furthermore, the modelled 1 MW heating plant also represents plants from 700 kW to some MW [46]. In the case of larger combined heat and power (CHP) plants, no comprehensive datasets were available for the study area. In order to take account of combustion conditions in larger CHP plants, we thus applied a weighted resource use efficiency factor of 40% for the modelled ORC and CHP plants [9,34]. The combustion of biomass in large CHP plants plays a considerable role in the research area as two third of wood energy burnt in CHP plants in the study area is consumed in plants with thermal capacity above 15 MW [34]. Overall, 94% of all wood burnt in the study area [34] was represented through the wood products.

As only a shift in consumption was assessed, and as the overall wood harvest rate from the forest was stable in our model, forest growing stock and forest carbon stock were not considered as further influencing factors on GWP. In the event that increased wood energy use influences harvest rate and entails decreased forest growing stock, carbon storage in the forest is reduced. Refs. [75,76] analysed the interrelations of harvest rate and carbon storage in forest ecosystems and wood products. They found that moderate increase in forest growing stock combined with cascaded use of wood products has higher climate protection effect than setting aside forest land or than harvesting an increased amount of timber.

We modelled only natural gas as alternative product in the heating sector. The sensitivity analysis showed that the basket of benefit method would exhibit different results if further fossil sources were assessed. For example, heating with crude oil is more carbon-intensive and energy-intensive, respectively releases more particulate matter than heating with natural gas [8]. Moreover, electricity production with those sources that are curtailed or squeezed out of the market according to the study by Ref. [46] due to increased renewable energy use, i.e. lignite, hard coal and nuclear energy, is marginally more carbon-intensive, more energy-intensive and entails more particulate matter emissions than the modelled electricity mix.

The import of paper products was neglected in our scenarios due to a lack in data and in light of an increasing demand for electronic media. Therefore, electronic media were used as a substitute product for graphical paper in the wood energy scenario.

4.2. Comparison of results

The presented results state average figures and there is a considerable variance in substitution factors. Thus, the results from the basket of benefit methodology strongly depend on the selected product life cycles. On the one hand, GHG emissions increased as a result of the shift in wood for energy use. However, the effect is only small as the emissions correspond to an additional release of greenhouse gases by 13 000 persons per year. As more than 12 million people live in the study area, the increase in global warming potential is less than 0.3% compared to the number of residents. While the substitution of fossil fuels through wood energy had a decarbonization effect, reduced wood availability in the material-based sector and the necessity to either import wood or to use non-wood alternatives entailed an opposite effect. Importing sustainably produced sawn timber has substantial advantages over substitution of sawn timber with non-wood construction materials. This finding confirms the results by Ref. [31] who showed a similar consequence of substituting sawn timber. They also found that direct combustion of wood instead of cascaded material use has negative impact on e.g. global warming potential and human toxicity, particularly when timber is used as split logs rather than as sawn timber. The results are also in line with the study by Ref. [76] who found that prior material use of wood is favourable compared to direct combustion of wood with regard to greenhouse gas emissions. Furthermore, studies by Refs. [7] and [27] revealed that wood products with shorter life span, e.g. wood chips, have a lower climate change mitigation potential than those with a long life span such as construction timber.

Our study exhibits a considerable increase in particulate matter emissions in the wood energy sector if no additional measures for emission reduction are introduced. In the wood energy scenario, 1.2 kt particulate matter are additionally emitted in the study area per year. Compared to 2010 values, this implies an increase in particulate matter emissions by 25% until 2035. The basket of benefit analysis demonstrates that larger amounts of $PM_{2.5}$ are released through split log use in private households. Refs. [12] and [77] showed that a strong improvement potential through the application of filter systems exists for old and non-automatic split log installations. The introduction of a new legal act in Germany by the beginning of 2015, aiming at the retro-fitting or replacement of old wood energy installations might lead to a reduction in particulate matter emissions load. However, more research is needed to determine the exact impact of the law amendment on the development of emission load.

Particulate matter contains a considerable amount of black carbon which is formed from incomplete combustion of organic compounds [74] and is even emitted from modern wood burning appliances [78]. On average 10% of $PM_{2.5}$ emission load from residential wood combustion belongs to the black carbon fraction [74]. The impact of black carbon on global warming potential is still subject to larger data gaps and intense scientific debate. The latest IPCC report [79] stated that aerosols, amongst them black carbon, continue to contribute the largest uncertainty to global warming estimates. Bond et al. [80] gathered available model results and proposed an estimate for black carbon's global climate forcing resulting from biomass combustion ($+1.1\ \mathrm{W\ m^{-2}}$, with 90% uncertainty bounds of $+0.17$ to $+2.1\ \mathrm{W\ m^{-2}}$). The study concluded that the radiative forcing caused by black carbon is too low in many models and that black carbon would be the second most important human climate forcer after CO_2. While the radiative forcing of black carbon alone is strong, total aerosol radiative forcing is even negative ($-0.35\ \mathrm{W\ m^{-2}}$) according to [79], thus leading to a cooling effect.

Due to data gaps, reliable information on the radiative forcing of black carbon and co-emitted aerosols was not available for our case study region. As such emissions are temporally and spatially variable [80] and due to complex interdependences [81], a reliable global characterization factor for life cycle impact assessments has not yet been determined. The comprehensive quantification of the global warming potential, including the effect of black carbon and co-emitted aerosols, was unfortunately beyond the scope of our LCA study. More research is needed in order to include such effects into LCA studies and ensure a holistic assessment of the radiative forcing resulting from wood utilization.

In summary, the basket of benefit analysis shows that, with the exception of particulate matter emissions for which no definite conclusions can be drawn, the use of wood instead of fossil resources has strong advantages in both the material-based sector and the energy sector.

4.3. Innovation

The basket of benefit method was tested as a tool to visualize the ecological impact of demand shifts and interdependent substitution effects. So far, wood energy and material-based wood use have been compared directly to each other, neglecting further indirect and interdependent effects in the forestry and wood sector. The applied method states a comparative analysis of different wood utilization forms for the forestry and wood cluster of a larger study area. To the authors' knowledge, the impact of a shift in wood consumption on ecological sustainability aspects has been evaluated for the first time on regional scale. Furthermore, the applied method can be transferred to other regions and allows assessing additional impact categories or products. Through our analysis, data gaps became evident, in particular relating to $PM_{2.5}$ emissions from material-based wood use and with regard to wood energy emission factors. Further research is recommended in this regard to draw a complete picture.

5. Conclusions

The basket of benefit method shows that a shift in wood consumption entails Janus-faced environmental impact. According to our scenario analysis and to the average substitution factors applied, global warming potential lightly deteriorates whereas primary energy demand improves as a result of a shift in wood consumption towards more wood energy use. Additional greenhouse gas emissions, entailed by a reduced wood availability in the material-based sector, are not fully compensated through the use of wood energy instead of conventional fuels. It is advantageous to import wood instead of using conventional resources. Particulate matter emissions rise due to increased wood energy consumption; however, because of insufficient data in the material-based sector, no definite conclusions can be drawn. In total, increased resource use efficiency is crucial for a sustainable wood energy use. If wood combustion is conducted in an efficient and modern manner, more wood is available for all consumers and particularly $PM_{2.5}$ emissions from wood energy use can be lowered.

More research is needed to fill data gaps. The basket of benefit method was applied for a limited number of products and for selected impact categories. Data were calculated for average product life cycles and the variance of results was calculated for a worst and a best case scenario. However, due to the lack in data and the strong variance of results depending on the products analysed via the basket of benefit method, no definite conclusions could be drawn on the impact of increased wood energy use on the assessed impact categories. We only considered non-biogenic CO_2 emissions and non-regenerative primary energy demand, as well as $PM_{2.5}$ emissions. The analysis of additional environmental indicators is recommended for further studies, e.g. the impact of increased wood energy use on soil conditions, emissions into water or hemeroby. The basket of benefit method also allows assessing economic or social indicators, e.g. the influence of a consumption shift on value-added or employment. A lack in data exists for $PM_{2.5}$ emissions in the material-based sector, e.g. regarding the substitution of paper products through electronic products, so that additional research is recommended. In the wood energy sector, it is expected that a law amendment which regulates the retro-fitting or replacement of old wood stoves since the beginning of 2015, will have a dampening effect on future split log use. Furthermore, we expect that energy demand for heating will decrease in the long-term due to demographic changes and increased thermal insulation of buildings. It is still unclear, however, to what extent this will influence future emission load. A knowledge deficit also exists with regard to the radiative forcing of black carbon and co-emitted aerosols originating from biomass combustion, as well as to what extent such effects can be analysed via LCA approaches.

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The impact of a new emission control act on particulate matter emissions from residential wood energy use in Bavaria, Germany

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ABSTRACT

The use of wood energy for renewable heat production in private households has grown considerably in central Europe in the past years. Residential wood combustion is Janus-faced with regard to air emissions. Besides yielding lower greenhouse gas emissions than the combustion of fossil fuels, wood combustion is associated with pollutant emissions that are harmful to human health. The heating systems have great potential for emission reduction due to the widespread combustion of wood in installations that are often overage. An emission control act aimed at heating system modernisation and emission load reduction has recently taken effect in Germany. This paper analyses the development of the particulate matter emission load from wood energy combustion in the case study area of Bavaria until 2035. It also evaluates the impact of the legal amendment. The emission load of prevalent heating systems is calculated based on two wood consumption scenarios, and the influence of the emission control act is analysed, taking into account retro-fitting and the replacement rates of old heating systems. The results show that particulate matter emissions could be reduced considerably and there is potential for an increase in the efficiency of resource use in the domestic heating sector.

1. Introduction

1.1. Problem statement

The European Union has set ambitious targets for renewable energies and greenhouse gas emission (GHG) reduction. The political goals, together with rising prices for fossil fuels, have entailed an increasing demand in renewable energy. Wood combustion is Janus-faced with regard to emissions to air (Wilnhammer et al., 2015). On the one hand, the rising substitution of fossil fuels through wood energy can have positive impact on greenhouse gas emissions. However, according to Agostini et al. (2014) it is important to note that in order to assess the climate change mitigation potential of forest bioenergy pathways, the assumption of biogenic carbon neutrality is generally not valid if carbon stock changes in the forest are not accounted for. For example, Giuntoli et al. (2015) pointed at the importance of protecting long-term forest productivity for climate change mitigation and Holtsmark (2015) concluded that bioenergy from slow-growing forests usually has a larger climate impact in a 100-year timeframe than fossil oil and gas. On the other hand, there are rising concerns about harmful dust emissions, i.e. particulate matter (PM), carbon monoxide and hydrocarbons (UBA, 2007). Increasing dust emissions from wood energy use in the last years in Germany were predominantly caused by the rising combustion in residential heating systems (UBA, 2014a). PM emissions from small combustion plants have increased by more than one fifth from 2005 till 2010 (Ewens, 2014). According to research done by the World Health Organization (WHO, 2006), particulate matter emissions entail an average reduction in human life expectancy of 10 months in Germany. However, the WHO data refer to the year 2000 and since then particulate matter emissions from residential heating with solid fuels have been increasing by more than 50%, according to data by UBA (2013).

The challenge to lower emission load has been acknowledged by policy makers in a set of protocols and legal acts. For example, the Gothenburg protocol, commits European countries to reduce particulate matter emissions by 26% until 2020 in comparison to 2005 (UBA, 2013). In Germany, the Federal Emissions Control Act (BImSchV) was adopted to facilitate the implementation of the Gothenburg protocol, and to conform to the EU Ambient Air Quality

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Directive 2008/50/EC (European Commission, 2008). The act aims at reducing pollutant emissions via more efficient wood energy use in residential heating systems and sets emission limits depending on the material burnt. According to BMU (2014), the act would help to reduce nationwide emission load from small heating systems from 24,000 to 16,000 tons in 2025, and thus add to fulfilling the targets set in the Gothenburg protocol.

This paper builds on the work presented in Wilnhammer et al. (2015) but the novelty is that it introduces an analysis of the impact of the new emission control act on emission load and on resource use efficiency.

1.2. State of knowledge and need for research

Lim et al. (2012) revealed that worldwide particulate matter emissions are the main environmental root of ill health, and that air pollution causes about 7 million premature deaths per year. Kim et al. (2015) provided an overview on the adverse health effects of particulate matter emissions. Lu et al. (2015) conducted a systematic review and a meta-analysis of the adverse health effects of dust pollution in China. Song et al. (2016) reported on the health impacts of particulate matter, on increased mortality rates and on serious health threats such as respiratory diseases, cardiovascular diseases and chronic bronchitis. Pascal et al. (2014) revealed that particulate matter emissions have a significant short-term impact on mortality in France. Giuntoli et al. (2015) highlighted several environmental impacts associated with the use of wood energy, amongst them local air pollution through particulate matter emissions, and pointed out that any action promoting wood energy use should consider whether proper actions for the management of adverse effects are in place. Caserini et al. (2010) showed that emissions from domestic devices correspond to almost one third of the total particulate emissions in Italy in 2005. Lamberg (2014) compared small-scale wood pellet boiler emissions in Finland with other combustion units as well as with non-wood energy sources, and found that different biomass raw materials exhibit significant particle emissions. Nussbaumer et al. (2008) provided an overview on particulate emission factors from biomass combustion from different European countries. They found a wide range of emission factors and showed that automatic combustion plants are strongly related to particle removal, and that optimal operation is a major contributor to reduce PM emissions.

In the UK, the contribution of emissions from domestic wood combustion to total $PM_{2.5}$ has increased over recent years while overall emissions of $PM_{2.5}$ have strongly fallen in the past decades (UK National Statistics, 2015). McFiggans (2015) showed that through the governmental incentives in the UK that aim at increased heat production via biomass, -only boilers and pellet stoves could have further unwanted consequences for air quality in the future. In northern Europe residential wood combustion is relatively common and has been considered as a potential way to reduce GHG emissions (Karvosenoja et al., 2004). Molnar and Sallsten (2013) revealed that particulate matter emissions in northern Scandinavia were much higher in 2001–2010 than in 1990–2000 which might have been caused by the increased use of wood for heating in Sweden. However, air pollution and particulate matter emissions levels in Scandinavia are generally lower than in other European countries, and in recent years there has even been a slight decline in emissions e.g. in Norway (Norwegian Institute of Public Health, 2014).

In Germany, overall dust emissions from wood combustion have been increasing considerably from 20,000 tons in 2000 (UBA, 2007) to 30,000 tons in 2010 (Ewens, 2014), corresponding to an increase in the $PM_{2.5}$ fraction from 19,600 tons to 29,400 tons (EEA, 2013). Given the high amount of wood energy consumption, it is unclear whether the political targets for emission reduction can be met by 2025. Wood-fired residential heating systems contribute significantly to particulate matter emissions, especially non-automatic furnaces. About half of these systems is older than 20 years and is responsible for about two third of the total dust load (BMU, 2014). Moreover, increased resource use efficiency offers a potential for lowering greenhouse gas emissions and for increasing energy use efficiency.

The modernisation of these installations thus creates an opportunity for meeting the political targets with regard to both efficient bioenergy expansion and emissions reduction. The retrofitting of old installations also facilitates a more efficient consumption of the renewable yet limited resource wood.

However, data availability is low as regards the present amount of wood consumed per appliance. Due to recent publications by Friedrich et al. (2012) and Gaggermeier et al. (2014), data availability for the province of Bavaria is comparably high. Besides mere consumption, emission load depends on the combustion technology of installed heating systems. However, the results of residential heating system statistics vary according to different data sources and data collection methods (Joa et al., 2015). Additionally, there is a wide variety of $PM_{2.5}$ emission factors, as these are closely linked to the age of an appliance and associated technology (Kelz et al., 2012) and to the wood assortments used (Nussbaumer, 2003).

As the new emission control act sets legally binding minimum requirements regarding emission factors per installation, low-performing appliances will be forced out of the market and replaced with modern systems, or be retro-fitted with new filter technology. For reliable projections on future emission load, it is thus essential to assess the retro-fitting and decommissioning rate of existing appliances, as well as which new types of heating systems will be used and how much wood will be burnt per appliance. In light of the increase in emissions harmful to human health, there is need for research on how emission load will develop in the future and whether the targets for PM emission reduction can be achieved as a result of the introduction of the law amendment.

1.3. Objectives and research questions

The presented study aims at evaluating the impact of the law amendment on $PM_{2.5}$ emission load and at exhibiting the impact of policy measures and technological development on emission reduction against the background of increasing wood consumption and augmenting $PM_{2.5}$ emissions in the case study area Bavaria. We concentrate on the predominant use of wood for thermal energy production in private households, i.e. heat production from solid wood and pellets. The study strives to answer the following research questions:

- What is the current emission load from wood energy use for heat generation in private households, considering the specific combustion systems installed in Bavaria?
- How will PM emissions evolve until 2035, taking account of the law amendment and the replacement of old technologies?

The paper will describe the development in wood energy consumption in the study area, provide an inventory of installed heating systems, and exhibit its future development, Moreover, the impact of the law amendment on the modernisation rate of heating system stock will be analysed and conclusions will be drawn on the development of the associated $PM_{2.5}$ emission load in the study area.

2. Material and methods

2.1. Study area and wood consumption

Bavaria is a province in southern Germany where wood energy use is traditionally high. The study area is characterised by a strong forestry and wood cluster (Rothe et al., 2015). According to Friedrich et al. (2012), 28% of nationwide wood energy in 2010 was consumed in this study area. More than half of wood energy in private households is used for heating purposes (Friedrich et al., 2012).

Split logs are the predominant source of thermal energy from wood in private households (79%), wood pellets are being increasingly used and in 2012 accounted for 11% (Gaggermeier et al., 2014). Wood chips play only a marginal role in household heating (<1%) and the database for post-consumer wood burnt in private households is weak. These latter two assortments are therefore neglected in our study. In total, wood consumption in private households in 2010 was 7.4 $hm^3\ a^{-1}$, equivalent to 62 PJ a^{-1} (Gaggermeier et al., 2014). Wood energy consumption is steadily increasing in the study area and has already increased to 8.1 $hm^3\ a^{-1}$ in 2012, equivalent to 66 PJ a^{-1} of energy (Gaggermeier et al., 2014). Domestic heating in 2012 thus accounted for 58% of overall wood energy consumption (114 PJ a^{-1}, see Gaggermeier et al., 2014). In order to derive the amount of wood consumption in private households, nationwide data from Struschka et al. (2003, 2008), Nussbaumer et al. (2008), GmbH (2011) and Ewens (2014) were applied to our calculations for Bavaria.

2.2. Inventory of installed heating systems

The national inventory of residential and commercial combustion systems is heterogeneous with regard to heating system and age. The latest comprehensive study for Germany that revealed data per installation type dates back to Struschka et al. (2008). A more comprehensive, up-to-date and public database is currently not available. More recent but non-explicit data on the amount of installed heating systems in private households were published by UBA (2014b) which estimated that firing systems for solid fuels account for 14 million residential wood-burning furnaces and 0.7 million boilers. In another study, the number of installations in Germany in the year 2010 was derived via a consumer survey among 14,000 households (GmbH 2011). Though this study allows an estimation of residential wood energy consumption for 2010, a detailed breakdown of consumption per appliance type is not possible.

Since 15.3% of German households are situated in Bavaria (LfStaD, 2011), and since 3% of these households have more than one heating system installed (Gaggermeier et al., 2014), we calculated that overall 2.3 million wood combustion systems were installed in Bavarian households in 2010, of which 1.8 million installations were single room furnaces and 0.5 million were central heating systems. The share per installation type was derived based on the breakdown by Struschka et al. (2008) for Germany, assuming that the share per installation type in Bavaria is equivalent to Germany and that there was no change in the relative share of heating systems from 2008 to 2010. The share of pellet boilers in central heating systems was calculated via data by DEPV (2014) as for this dynamic market segment up-to-date information had to be obtained. The amount of wood consumed in private households was calculated via applying consumption values per heating system according to Struschka et al. (2008) and extrapolating these to the total wood combustion in Bavaria according to data from Gaggermeier et al. (2014) (Table 1).

2.3. Transition periods for retrofitting and decommissioning set by the new emission control act (Bundesimmissionsschutzverordnung BImSchV)

The law amendment of the Federal Immission Control Act of Germany was introduced in March 2010. The control act inter alia regulates wood combustion in small and medium-sized single-room furnaces and heating boilers in private households. The act sets limits for pollutant emissions, as well as requirements for continuous monitoring of emission load and for retro-fitting or decommissioning of old installations (UBA, 2010). Emission limits and minimum efficiency rates are set per combustion system, depending on age and type of the installations. Transitional periods are defined per age and type of installation (see Table 2). Excluded from the new legal act are only a few installation types, e.g. furnaces which were installed before 1950 and open fireplaces. Since March 2010, newly purchased installations already have to conform to minimum emission limits. Since January 2015, enhanced emissions limits are effective which also have an impact on already installed furnaces and boilers, i.e. old installations need to be replaced or retro-fitted.

2.4. Development of modernisation rate

The data availability regarding the amount of installations that need to be retrofitted in Germany as a result of the law amendment is fragmentary as no scientifically resilient data are available. However, a report to the German parliament (Bundestag, 2007) reveals the rough number of installations affected by the new legal act. The overall number of installations that will be replaced per period is determined based on this report and on data by HDG Bavaria (2009), who calculated the annual replacement rate for installations in Bavaria based on Bundestag (2007). These data can be considered as a best estimate on the number of installations that will be affected by the law amendment in Germany. According to

Table 1
Number of solid fuel heating systems and amount of wood consumed in private households in Bavaria in 2010 (based on Struschka et al., 2008; Rheinbraun GmbH 2011, DEPV, 2014; Gaggermeier et al., 2014).

Installations	Number of installations [million]	Total wood consumption [hm^3]
Single room furnaces, total	1.78	4.17
Tiled stove	0.58	2.01
Chimney stove	0.54	1.38
Wood stove	0.16	0.11
Open and closed fireplaces	0.49	0.62
Pellets stove	0.02	0.05
Central heating systems, total	0.51	3.20
Wood boilers	0.32	2.57
Pellet boilers	0.19	0.63
Total	2.29	7.37

Table 2
Transition periods for existing single room furnaces and central heating systems (UBA, 2010).

Installation type	Time of type test or time of installation	Date of retrofitting or decommissioning
Single room furnaces	Before 01.01.1975	31.12.2014
	01.01.1975 to 31.12.1984	31.12.2017
	01.01.1985 to 31.12.1994	31.12.2020
	01.01.1995 to 22.03.2010	31.12.2024
Central heating systems	Before 31.12.1994	01.01.2015
	01.01.1995 to 31.12.2004	01.01.2019
	01.01.2005 to 31.12.2010	01.01.2025

Bundestag (2007) and HDG Bavaria (2009), 13.9 million out of a total of 14.9 million (GmbH, 2011) installations will need to be replaced or retro-fitted, corresponding to an overall modernisation rate of 93%. We applied this overall modernisation rate to the case study area and further used data from Struschka et al. (2008) on the age class distribution of installations in order to calculate the modernisation rate per type and cut-off year.

2.5. $PM_{2.5}$ emission factors per combustion systems and $PM_{2.5}$ emission load per installation type

We only considered the use phase of the wood energy products, i.e. wood combustion, as the new legal act is concentrated on the use phase only. Emissions from old appliances were calculated according to data by Struschka et al. (2003) who identified average emission factors for appliances from earlier than 1990 until 2001. Emission factors for installations from 2001 until 2015 were calculated according to Nussbaumer et al. (2008) and EEA (2013) (see Table 3).

Some of these data are published as PM_{10} and therefore an average factor of 0.98 was applied according to EEA (2013) in order to convert from PM_{10} to $PM_{2.5}$. Furthermore, some emission factors are given in mass per standard cubic meter (mg $Nm^{3\ -1}$) while others are given in mass per energy unit (mg MJ^{-1}) so that unit conversion was conducted according to Bauer et al. (2007). Open and closed fireplaces were jointly considered, since data on the amount of wood consumed was only available for fireplaces in general.

Finally, the amount of wood used per combustion system was multiplied with the associated emission factors per period, and the development of total $PM_{2.5}$ emission load in Bavaria was calculated until 2035. The new law amendment defines maximum emission values per installations type and stage. Stage 1 applies to systems installed until the end of 2014 and stage 2 applies to systems installed from the beginning of 2015. We considered that the influence of the law amendment will only last until 01.01.2025 (see Table 2) and therefore applied stable emission factors and a stable wood consumption from 2025 onwards.

We calculated the overall development of $PM_{2.5}$ emissions as a result of the changing heating system infrastructure via multiplying installation-specific consumption data per period (Table 1) with installation-specific emission factors (Table 3). For the consumption data we also considered the changing annual average efficiency use efficiency rates per installation type until 2035 according to Deischl (2013) (Table 3).

2.6. Scenarios regarding wood development, retrofitting rates and emission factors

There are various factors that may influence the results of the development of the $PM_{2.5}$ emissions, such as the development in the use of wood energy, retrofitting rates, as well as heating systems emission factors. In order to gain a better understanding about the variable influences, different scenarios are developed and analysed.

For the development of wood consumption, we used real consumption data for 2010 until 2012 according to Gaggermeier et al. (2014) and then calculated a stable overall wood consumption until 2035. Due to the increased resource use efficiency, more energy will be produced from the same amount of wood in the future.

In addition, a scenario for an unstable wood consumption, i.e. a growing demand of 1.5% per year (UNECE/FAO, 2011) was calculated for the case study area until 2035. In the growing demand scenario, a constant increase in wood energy consumption was calculated, taking into account supply and demand patterns, wood imports and exports, as well as interdependent supply as well as demand structures in the forestry and wood cluster in Bavaria (see Wilnhammer et al., 2015). In this scenario total wood consumption will raise between 2010 and 2035, and wood pellets demand will grow disproportionally strong. The increase in demand will further

Table 3
Average emission factors for solid wood heating systems in Germany (Sources: Struschka et al., 2003 1), Nussbaumer et al., 2008 2), UBA 2010 3), Deischl 2013 4)).

Heating system	$PM_{2.5}$ emissions (g kWh^{-1})[a]			Annual average energy use efficiency in 2010 (%) 4)	Annual average energy use efficiency in 2035 (%) 4) [c]
	Old 1)	New (stage 1) 3)	New (stage 2) 3)		
Tiled stove	0.37	0.17	0.09	60	65
Chimney stove	0.38	0.17	0.09	65	65
Open fireplace[b]	0.54	0.17	0.09	50	65
Closed fireplace	0.22 2)	0.17	0.09	50	65
Wood stove	0.38	0.17	0.09	60	65
Pellet stove	0.07	0.07	0.07	65	65
Wood boiler	0.07	0.04	0.04	74	76
Pellet boiler	0.07	0.04	0.04	78	82

[a] As regulated in the emission control act.

[b] Open fireplaces do not need to be replaced according to the law amendment and therefore we applied the old emission factor until 2035 for this installation type. The "new" limit values for open fireplaces reveal the emission values for newly installed fireplaces. However, in terms of a conservative estimate and as there is no binding requirement to exchange such installations we did not consider a reduction in these emissions.

[c] Defined as theoretical net energy demand minus the losses during heat generation (e.g. thermal efficiency factor, degree of utilisation, user behaviour, or losses in the buffer or distribution system).

be different according to wood assortment (see Wilnhammer et al., 2015); however, the relative demand per installation type will be stable, regardless whether the installation is old or new. Through the growing demand scenario, potentially rising wood energy consumption and an impact on emission load shall be crystallised. We further assume in this analysis that an additional consumption of wood is a consequence of a displacement of fossil sources such as heating oil and natural gas.

In order to put the results into context, the analysis further comprises a calculation of emission development without the impact of the law amendment. Based on the assumption that the average heating system is exchanged after 30 years, the annual exchange rate of old installations with new ones is 3.3%. The new installations will comply with minimum emission limits set in the legal control act.

3. Results

3.1. Development of retro-fitting and replacement rate

In total, 2.13 million out of 2.29 million installations will be modernised until 2025 in Bavaria according to our projection, out of which 1.6 million will be single room furnaces and 0.5 million central heating systems. The predominant share of installations (70%) will be replaced or retro-fitted in 2021 and 2025 (Tables 4 and 5). While some of the older single-room furnaces will not be replaced (161,000 installations respectively 9%, i.e. historic and discontinuously used installations), all central heating systems installed before 2010 will be affected until 2021 according to our projection.

3.2. Development of $PM_{2.5}$ emissions under stable wood consumption conditions

The calculated emission load from heat generation in private households in 2010, taking into account the specific combustion systems installed in the case study region, is 4.5 kt a^{-1} (Table 6). The predominant share of emissions comes from single room furnaces (3.9 kt a^{-1} respectively 87%). Their emissions are high relative to those from central heating systems (Table 6).

The retro-fitting and replacement of old installations leads to continuously decreasing particulate matter emissions. Depending on the amount of new systems installed per period, there are slight differences per period, i.e. in 2021 and 2025 the emission reduction is stronger due to an enhanced modernisation rate. In total, the calculation shows that the impact of the law amendment could be strong and that emissions could be reduced from 4.5 kt a^{-1} in 2010 to 2.2 kt a^{-1} in 2025, respectively by 51% (Fig. 1). In our projections the emission load remains stable after 2025 as we did not calculate a change in wood energy consumption and as no further impact of additional legal regulations or technological developments was considered.

Furthermore, the increased annual average efficiency of on average 6% from 2010 to 2035 according to Deischl (2013) entails

Table 4
Development of retro-fitting and replacement rate for single room furnaces (based on data by Bundestag, 2007; HDG Bavaria, 2009).

Installations	Amount of installations in 2010 (in 1000)	Amount of replaced or retro-fitted installations per cut-off year (in 1000)				
		2015	2019	2021	2025	Total
Tiled stove	575	94	84	139	218	535 (93%)
Chimney stove	535	87	78	129	202	496 (93%)
Wood stove	160	26	23	39	61	149 (93%)
Open and closed fireplaces	486	53	68	123	172	416 (86%)
Pellets stove	23	4	3	6	9	22 (96%)
Single room furnaces, total	1779	264	256	436	662	1618 (91%)

Table 5
Development of retro-fitting and replacement rate for central heating systems (based on data by Bundestag, 2007; HDG Bavaria, 2009).

Installations	Amount of installations in 2010 (in 1000)	Amount of replaced or retro-fitted installations at cut-off date (in 1000)			
		31.12.2014	31.12.2017	31.12.2020	Total
Wood boiler	319	–	113	206	319 (100%)
Pellets boiler	191	–	6	185	191 (100%)
Central heating systems, total	510	–	119	391	510 (100%)

Table 6
Development of $PM_{2.5}$ emissions in kt a^{-1} from single room furnaces and central heating systems.

	Installations	Year								
		Start	Retrofitted/new				Remaining/old			
		2010	2015	2019	2021	2025	2015	2019	2021	2025
Single room furnaces	Tiled stove	1.9	0.1	0.1	0.2	0.3	1.7	1.4	0.9	0.3
	Chimney stove	1.3	0.0	0.1	0.1	0.2	1.2	1.0	0.6	0.2
	Wood stove	0.1	0.0	0.0	0.0	0.1	0.1	0.1	0.1	0.0
	Open and closed fireplace	0.6	0.0	0.1	0.2	0.4	0.6	0.5	0.3	0.2
	Pellets stove	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Subtotal	3.9	0.1	0.3	0.6	1.0	3.6	3.0	1.9	0.7
Central heating systems	Wood boiler	0.5	–	0.1	0.4	0.4	0.3	0.2	–	–
	Pellets boiler	0.1	–	0.0	0.1	0.1	0.1	0.1	–	–
	Subtotal	0.6	–	0.1	0,.5	0.5	0.3	0.2	–	–
Emissions, total		4.5	0.1	0.4	1.1	1.5	3.9	3.2	1.9	0.7

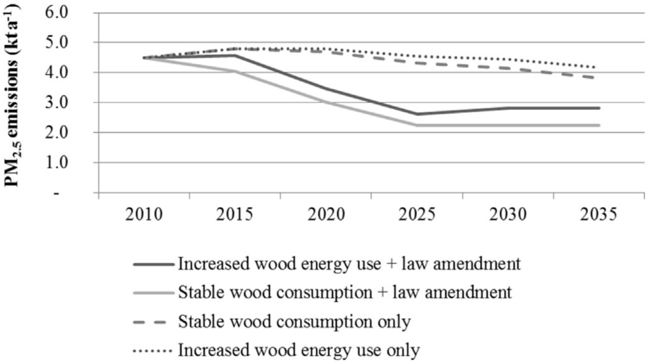

Fig. 1. Impact of the law amendment and the development of PM2.5 emissions from all installations and per period between 2010 and 2035 based on the assumptions for installation numbers and retrofitting/replacement rates. Values are shown for stable wood demand and an increasing wood use.

increased resource availability of 0.4 hm^3 of wood. This additional amount of wood corresponds to an increased energy production from wood energy of 3.5 PJ a^{-1} in 2035, respectively to 970,000 MWh or 97 million liters of heating oil. Assuming that an average household consumes 2000 L of heating oil per year, 48,500 households could be additionally supplied with heat through this additional amount of energy, potentially entailing the substitution of other energy sources such as heating oil and natural gas.

3.3. *Development of emissions in case of growing wood demand*

According to the increased wood energy scenario by Wilnhammer et al. (2015), consumption of split logs and wood pellets rises from 6.7 hm^3 to 9.6 hm^3 until 2035. In a scenario of increased wood use, emission load will also rise. However, the increase will not be proportional with the uptake in wood energy use as an above-average growth in wood pellet combustion dampens the effect. According to our projection, the increase in wood combustion by 43% between 2010 and 2035 entails an increase in PM$_{2.5}$ emission load by 35% in comparison to the stable wood demand scenario, equivalent to an increase by 0.8 kt a^{-1} until 2035. However, total emissions will still decrease due to the law amendment. In the increased wood energy scenario, the overall emission load will be 3.0 kt a^{-1} in 2035, out of which 2.6 kt a^{-1} will arise from split log use and 0.4 kt a^{-1} from wood pellets use, compared to an overall emission load of 2.2 kt a^{-1} in the stable wood demand scenario. Moreover, as the last phase of the emission control act will become effective in 2025, PM$_{2.5}$ load would rise again from 2025 (2.6 kt a^{-1}) to 2035 in the increased wood energy demand scenario (Fig. 1).

The figure also exhibits the development in emissions to air in case that the law amendment is not effective at all, i.e. that emission load will also decrease due to an exchange of installations elder than 30 years. However, the reduction in emissions to air until 2035 is much lower and in case of increased wood energy demand scenario almost equals the level of 2010.

4. Discussion

4.1. *Uncertainties in calculations*

There are some uncertainties in our calculations, mainly due to knowledge gaps on the real development of PM$_{2.5}$ emission load in recent years, the real number of household heating system and the amount in wood consumed per installation together with associated emission factors. Moreover, there are differing literature values for the number of household heating systems in the case study area due to different data sources and data collection methods. According to Joa, 2014 the amount of single room furnaces for the case study area is 2.36 single room furnaces while according to Gaggermeier et al. (2014) there are only 1.77 million furnaces. Moreover, according to Joa, 2014, the overall dust emission load was 5.4 kt a^{-1} in 2013, equivalent to 5.0 kt a^{-1} for PM$_{2.5}$. This value is 7% higher than our projection due to different methodological approaches and data sources.

Moreover, the PM$_{2.5}$ values used in this study refer to minimum emission thresholds per installation type as regulated by the law amendment. Our projection could therefore be considered as a conservative estimate of the impact of the law amendment as future technological innovations could further reduce average emission factors. However, if compliance with new emission limits is not effectively monitored and old installations are not retro-fitted or exchanged, or if consumer behaviour is not optimal then the impact of the emission control act will be lower than projected in this paper.

Several studies investigated the age of installations and associated emissions (BUWAL, 2001; Winiwarter et al., 2001; Struschka et al., 2003; Johansson et al., 2004; Kunde et al., 2007; Obernberger et al., 2008; Schmidl et al., 2008; Struschka et al., 2008; Nussbaumer and Boogen, 2010; Schmidl et al., 2011). The studies reveal a wide range of emission factors per installation depending on the operating conditions, wood materials used and heating systems. In practice some of the automatically controlled installations could exhibit even lower emission factors if e.g. the heating material is of high quality (i.e. due to homogeneous firing behaviour, low humidity, no contamination, low bark content). In fact, some of the latest installation types are superior to legal requirements in terms of dust emissions (FNR, 2014).

However, it could also be that particularly non-automatic heating systems exhibit higher emission levels. For example, contamination with non-wood materials in e.g. post-consumer products can play a role. Gaggermeier et al. (2014) found that 169,000 households in the study area burn post-consumer wood. We could not calculate the impact of post-consumer wood combustion in households as no scientific data on PM$_{2.5}$ emission factors are available. However, in case that post-consumer wood is burnt in domestic households, dust emissions will presumably be much higher due to impurities. In general, the emission factors for pellets used in households are more reliable as the material is more homogenous in terms of moisture content, and as pellets do not contain bark or impurities. Another uncertainty is whether the old installations that need to be replaced or retro-fitted will really be exchanged with modern wood energy installations. The monitoring through chimney sweepers will therefore be crucial for the implementation of the law amendment in practice and for its effectiveness.

4.2. *Comparison of results*

According to Ewens (2014), the particulate matter emissions from wood energy combustion in Germany could be reduced from 30 kt in 2010 to less than 16 kt in 2025. Our calculation, which shows a reduction in dust emissions by 50% until 2025, confirms this projection. In the Gothenburg protocol, Germany committed to reducing its particulate matter emissions by 26% compared to 2005, respectively to 16.6 kt a^{-1} until 2020. The projection for Bavaria, if extrapolated to Germany, exhibits that this target could be reached – under a stable wood consumption scenario, if the law amendment is fully implemented in practice and if user behaviour conforms to best practice. According to the assumptions made in the increased wood energy scenario, $PM_{2.5}$ emissions will be 16% higher in 2020 compared to stable wood energy demand conditions. The fulfilment of the targets set in the Gothenburg protocol could then be questionable.

The emission control act has a clear dampening effect in both scenarios while the impact is less strong in the increased wood energy scenario. If the newly installed heating systems go beyond legal requirements in terms of emission factors, then the dust emissions could be even further reduced. For example, Hartmann (2014) showed that substituting a simple wood stove by a modern stove with a catalytic converter entails a dust emissions reduction by 75%. Enke (2013) also reported on potential emission reductions by 72% through installations with modern filter techniques in comparison to old installations. Karvosenoja et al. (2004) explored $PM_{2.5}$ emission reduction potential for Denmark, Finland, Norway and Sweden. They found that a fuel switch from logs to pellets leads to a strong reduction in $PM_{2.5}$ emissions. Furthermore, this result is in line with our finding that a stronger growth in wood pellet consumption and a substitution of split logs diminish the overall $PM_{2.5}$ emission load.

The increase in wood energy demand in the second scenario is based on the projections by UNECE/FAO (2011). Since then, energy prices have been fluctuating (DESTATIS, 2015). It is unclear how prices for fossil and renewable energies will develop in the future and therefore the calculations given here need to be seen as scenarios, not as forecasts.

UNEP and WHO (2011) also projected that in e.g. European countries black carbon emissions, amongst them $PM_{2.5}$, will be reduced in the upcoming years. However, on a global scale they predicted only a minor change in emissions until 2030, because reductions in North America, Europe and parts of Asia will be offset by increases in other regions. According to Schmale et al. (2014), international air quality control and political incentives are not coordinated and controlled, i.e. unregulated residential emissions from biomass heating are rising and will account for 80% of black-carbon emissions in Europe in 2025. Moreover, they revealed that the annual EU limit for $PM_{2.5}$ that is binding by 2015 is 2.5 times higher than that recommended by the World Health Organization. Thus, even if the estimated emission reduction for Bavaria, respectively Germany, would suffice to achieve the political targets, much more efforts need to be taken to reduce global $PM_{2.5}$ emission load.

5. Conclusions

The emission control act is crucial for future emission reduction and has a positive impact on resource use efficiency. Large centralised combustion plants and new district heating systems could further support the implementation of the law amendment in case that user behaviour cannot be controlled sufficiently. The successful modernisation of heating systems will also depend on the financial burden which arises for homeowners from the retro-fitting or exchanging of older installations.

Uncertainties relate to the real development of emissions, i.e. to the user behaviour that can strongly influence the emission load per installation and to the real amount of wood energy installations in the study area. Therefore, public information campaigns and effective oversight from chimney sweepers are important. Fuel wood quality is a key lever for ensuring low emissions. The use of non-standardised fuels such as contaminated waste wood or material with high moisture or bark content will complicate compliance with emission limits. Thus, enhanced quality control or enhanced standardisation via e.g. wood energy certification could be valuable.

There is further need to align environmental policies targeting at the reduction of dust emissions and with e.g. climate change policies. According to Schmale et al. (2014) e.g. energy ministries tend to focus on CO_2 reductions while environment ministries manage air quality, and regulation of greenhouse gas emissions is subject to global agreements whereas air pollutants are limited locally by legislation. The 2015 Paris Agreement under the United Nations Framework Convention on Climate Change thus states an opportunity for governments not only to reduce CO_2 emissions but also to include other climate forcers such as particulate matter emissions into climate-change mitigation policies, and to better coordinate action under different policy umbrellas.

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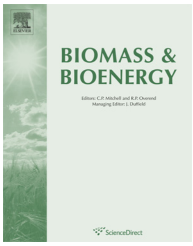

Research Paper

Current and potential use of forest biomass for energy in Tasmania

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ABSTRACT

Although Tasmania, Australia's southernmost state, has a large forest resource per capita there is no reliable information on the potential use of harvest residues, low quality logs or processing residues for energy production. In order to address the current knowledge gap we: i) quantified the current use and the potential sustainable supply of forest biomass in Tasmania, ii) compared those results with the use of forest biomass in Bavaria, a comparable state in Southeast Germany, and iii) analysed the low Tasmanian production of energy from forest biomass considering economic, legislative and social drivers. The current use of forest biomass for energy (400 kt y^{-1} of bone dry material) represents about 6% of Tasmania's total annual energy supply. The potential supply of forest biomass for energy production is estimated at 1800 kt y^{-1} of bone dry material equivalent to about 30% of Tasmania‘s current total annual energy supply. In contrast to Bavaria and other European countries, forest bioenergy production is small in Tasmania relative to the available resource and could be more than quadrupled from a resource availability perspective. A weak domestic market for energy wood leading to low prices, the lack of political stimuli and a low social acceptance are likely key factors. As a strong increase in market prices for forest biomass is unlikely, political incentives are necessary in order to increase the use of forest biomass. Addressing social acceptance will be a prerequisite for the success of initiatives or legislation to achieve this potential.

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1. Introduction

Tasmania, Australia's southernmost state, has a large forest resource per capita. Although about half of the 33 000 km^2 total forest area is reserved the total annual harvest is still at about 5 hm^3 (1 $hm^3 = 1\,000\,000\ m^3$) of timber corresponding to 10 m^3 $capita^{-1}$ [21]. In the past the majority of this harvest has been from native forests but in the future plantations will become the main source of timber. The bulk of the plantation estate in Tasmania and in fact throughout south-eastern Australia has been planted over the last 15 years, and whether it is managed for pulpwood or solid wood products this estate is currently some years from maturity. As the plantation estate matures, the potential harvest may increase [19].

The use of forest biomass for energy is comparatively small in Tasmania and restricted to domestic firewood and some industrial heating plants. Substantial uncertainties exist regarding the current use and the sustainable future supply of forest biomass feedstock for energy production in Tasmania. The last officially published figures on firewood use date back over 14 years [16] and a comprehensive study on industrial biomass use for energy production is not available. Several recent studies have investigated the potential use of biomass for energy in Australia. These studies were either relatively rough estimates covering large areas (whole of Australia), long timeframes (>20 years) and a wide range of possible feedstocks (e.g. Refs. [14,19]) or detailed estimates for a potential consumer considering the area and feedstock for a special purpose (e.g. Refs. [23,63]). There is no reliable information on the potential Tasmanian forest biomass for energy feedstock originating from forest management covering both public and private land.

In contrast to the situation in Tasmania, the use of biomass for energy has significantly increased in Europe over the last twenty years [20]. Sweden and Finland, two European countries with a large forest resource per capita, currently produce between 25 and 30% of their final energy consumption from (predominantly forest) biomass [4]. The increasing use of forest biomass for energy was stimulated by rising prices of fossil fuels and political support for renewable energy. As a consequence, the public and scientists are increasingly concerned about overexploitation of forests and strong competition between the material and energetic utilisation of wood from forests. Therefore several wood supply estimates have been conducted producing a comprehensive view of the wood supply potential for bioenergy production at the European (overview see Ref. [20]), individual nation and region within nation level (e.g. Refs. [30,32,62]).

In order to address the current knowledge gap about forest biomass for energy in Tasmania we undertook a study that:

i) quantified the current use and the sustainable potential supply of forest biomass for energy production in Tasmania,
ii) interpreted those results in comparison to Bavaria (a comparable state in Germany) and
iii) analysed the differences considering economic, legislative and social drivers.

In this study the term “forest biomass” refers to all woody biomass generated directly by forest management (split logs, other low quality logs, harvesting residues) and wood processing (e.g. shavings, sawdust, woodchips).

Tasmania can be seen as a case study for a region, where the use of forest biomass is marginal compared to the available forest resource. The results are intended to foster a better future utilization of forest biomass and wood in general, and to inform forest policy development and public discussions.

2. Material and methods

2.1. *Current use of forest biomass for energy*

Estimates of the volumes of wood-processing residues used for energy were based on oral or written interviews undertaken with representatives of the wood processing industry during May/June 2013 [44]. Between them, the participating companies were responsible for processing more than 90% of the total harvest in Tasmania at that time. The estimates for domestic firewood consumption were based on data from Driscoll et al. [16]; which were updated by Todd [56] and on unpublished data from a wood-heater survey performed by the Tasmanian Environment Protection Authority during the winter of 2011. Firewood consumption was estimated by multiplying the number of households using firewood as a main heating source with an average household consumption of 4.8 t y^{-1} of air dry material and by multiplying the number of households using firewood as a secondary heating source (where firewood is used as a supplement to a different primary heating source) of 2.2 t y^{-1} of air dry material.

2.2. *Potential supply of forest biomass for energy*

The potential supply of forest biomass for energy in the short term (over the next three years) was calculated separately for low quality logs and harvesting residues resulting from forest management of both native forest regrowth and plantations, and from wood processing residues (woodchips, shavings, sawdust). Material from oldgrowth harvesting was not included due to the low public acceptance of such harvesting and since oldgrowth harvesting is a very small proportion of the total harvest following signing of the Tasmanian Forests Agreement Act in 2013.

2.2.1. *Native forest regrowth*

For State forests the potential supply of low quality (pulpgrade) logs and harvesting residues from native forest regrowth was calculated for two main forest groups ‘Tall Native Eucalypt Forest’ and ‘Low Native Eucalypt Forest’ based on harvest areas and volumes per area. ‘Tall’ forests are defined as those over 34 m in height whilst ‘low’ forests are those from 8 to 34 m tall, in accordance with past practice [36,52]. Non–eucalypt species were not considered since they comprise <5% of the annual harvest. Future rates of harvest were based on the area of native forest regrowth harvested during the 2009/10, 2010/11, and 2011/12 Australian financial years (1 July – 30 June) derived from Forestry Tasmania's operational database. Forestry Tasmania is a government business enterprise charged with managing the production of timber from the State controlled production forests.

Oldgrowth areas were subtracted from total harvested areas and a further 20% reduction was assumed in line with the Tasmanian Forests Agreement Act 2013 which included a significant increase to the reserve area. Volumes per hectare were calculated using Forestry Tasmania's inventory database. Bark, branches and leaves were considered most likely to remain on site and were not included in the biomass for energy estimates. Biomass of stems and coarse woody debris for 56 forest classes and 21 inventory areas were averaged for the two forest groups ‘Tall Eucalypt Forest’ and ‘Low Eucalypt Forest’ (see Ref. [44] for further details). Harvest residues available for energy production were assumed to be 15% of total solid forest biomass, which includes live standing volume, dead standing volume and downed dead wood decay class 1 and 2 [28]. The 15% fraction has also been used by Ref. [19] and is based on the assumption that all <20 cm diameter solid forest biomass is left on site to maintain site nutrient levels and a significant fraction of >20 cm living biomass and 85% of dead solid biomass is retained on site in order to provide enough material for continuity of coarse woody debris formation. Recovery of 15% of harvest residue volumes is consistent with field trials where 13–17 % of total solid forest biomass was removed [5,41]. These trials assessed the economic recovery of fuelwood, and generally only pieces that were large enough to be collected using a forwarder were included; this varied with distance from landing, with a higher proportion of material collected close to the landing, and less from further away. In addition to harvest residues we considered 50% of pulpgrade logs to be available for energy production, based on current practices in Germany concerning hardwood utilisation [51].

For private forests the potential supply of low quality (pulpgrade) logs was calculated using published harvest rates for pulpwood for the 2009/10, 2010/11 and 2011/12 financial years [39]. Again 50% of pulpgrade logs were considered to be available for energy production. Available biomass from harvesting residues was assumed to be 45% of pulpwood harvest using the same relationship between harvesting residues and pulpwood as for State forests.

2.2.2. *Plantations*

For hardwood plantations under public management only thinnings and clearfells before mean rotation age were considered since there will be little mean rotation age clearfelling (<3% of harvesting volume) in coming years. Thinning and early clearfell areas and the corresponding harvesting volumes were available from internal planning processes of Forestry Tasmania.

Private hardwood plantations are managed almost entirely for pulpgrade material using short rotations (mostly 12–18 years). Since significant areas of these plantations are mature, the potential harvest was estimated by multiplying average annual clearfell area with estimated harvest volume per hectare. We conservatively assumed an 18 year rotation age and a stemwood volume of 250 m^3 ha^{-1} [12]. Aboveground residues (bark, branches, leaves) account for about 25–30 % of total biomass in eucalypt plantations [38]. Only one third of these residues (corresponding to about 10% of standing biomass) were considered to be available for biomass energy production due to economic and ecological restrictions ([26]; personal communication from forest growers). As for the assumptions for native forest regrowth, we considered that 50% of plantation hardwood pulpgrade logs could be available for biomass energy production.

Future harvest rates for softwood plantations were based on average harvest volumes for the period 2002–2011 during which time harvesting rates have been relatively constant [2]. In contrast to the assumption for hardwood material we assumed that pulpgrade softwood is only used for industrial purposes (current practice) and would not be available for energy. Available harvest residues for energy were assumed to be 7% of the merchantable volume of sawlog and pulp logs ([25]; personnel communication from forest growers). All small slash (<8–10 cm) was assumed to be left on site for economic and ecological reasons.

In many regions worldwide an important fraction of wood is salvage harvested following natural disturbances like fire, windthrow, snow or pathogens, especially in conifer forests [47,49]. Salvage cutting of timber can make a significant contribution to biomass for energy because this material is often not suitable for alternative uses. Fire is the dominant natural disturbance in Tasmania's eucalypt forests. However, few fires have occurred at a landscape scale since the 1930s and trees and burned forests contain large quantities of charcoal that makes them unattractive to harvest and process, particularly for paper making. Furthermore most native eucalyptus forests readily recover following wildfire. Hence, salvage operations in Tasmania are minimal and were not specifically included in our calculation.

2.2.3. *Wood processing residues*

The potential volumes of wood processing residues were estimated based on oral or written interviews undertaken with representatives of the wood processing industry (see 2.1). Interviews gathered data on the amount of timber processed, the amount of residues generated, the current use of residues and anticipated changes in future residue use. The percentage of residues generated during processing as well as the percentage potentially available for energy use was calculated separately for the four categories: softwood sawmilling, softwood chipping, hardwood sawmilling/peeling and hardwood chipping. These percentages were then applied to the potential Tasmanian harvest volumes expected in the next 3 years using the same four categories.

2.2.4. *Conversion factors*

The estimates for the current and potential use of forest biomass for energy are in part based on volumes and in part on mass where different materials have different water contents. We used the following conversion factors to allow estimated energy content to be presented using the common units of energy per kg of bone dry wood:

1 m^3 wood = 0.50 t of dry mass (softwood),
1 m^3 wood = 0.55 t of dry mass (eucalypt),
1 m^3 wood = 1 t wood (green),
Water mass fraction of green wood: 45%,
Water mass fraction of dry wood: 15%,
Water mass fraction of bone dry wood: 0%,
Energy content: 1 kg of bone dry wood = 18 MJ (5 kWh).

Table 1 – Forest biomass used for energy in Tasmania.

	kt y^{-1}	kt y^{-1}	Energy equivalent
	(green)	(bone dry)	PJ
domestic firewood	490	270	4.9
wood processing residues	220	120	2.2
total	710	390	7.0

3. Results

3.1. *Current use of forest biomass for energy*

Currently about 400 kt y^{-1} of bone dry forest biomass are used for producing energy in Tasmania (Table 1). This is equivalent to about 6% of Tasmania's total primary energy supply (110 PJ in 2012/13, [10]). All of the biomass is used for generating thermal energy; there are no facilities for producing electricity from biomass. Domestic firewood for heat production is the dominant use of forest biomass for energy, accounting for about two thirds of the total amount. Nearly one third of the total amount is derived from wood processing and is used for non-domestic heating, predominantly for kiln-drying of processed timber. Smaller amounts are used for other industrial heating, particularly during brick manufacturing, food processing or heating greenhouses. The production of wood pellets is negligible in Tasmania. About two thirds of processing residues are used for industrial (woodchips) or landscaping purposes (mostly bark). A significant quantity of processing residues (>20 kt y^{-1} of bone dry material) is currently not used for energy production or industrial/landscaping purposes and is placed into landfills or left on site.

3.2. *Potential supply of forest biomass for energy*

The potential supply of forest biomass for energy production in Tasmania is estimated at 1800 kt y^{-1} of bone dry material (Table 2). About 40% of this material (700 kt y^{-1} of bone dry material) is derived from harvest and processing residues. Using only these residues, bioenergy production could be nearly doubled from the current 400 kt y^{-1} of bone dry material. The residues originate in nearly equal quantities from plantations and native forests regrowth. 1100 kt y^{-1} of bone dry material (corresponding to about 60% of the potential energy wood) is pulpgrade material which is currently chipped and exported. At present an important fraction of the pulpgrade material is not used due to logistical and/or economic restrictions. About three quarters of total pulpgrade material originates from plantations, and one quarter from native forest regrowth.

The potential supply of 1800 kt y^{-1} of bone dry material corresponds to an energy equivalent of 33 PJ or approximately 30% of Tasmania's current energy demand (110 PJ in 2012/13, [10]). Residues currently left in the landscape to decompose or burnt in the open and low quality logs currently exported as woodchips have the potential to make a significant contribution to renewable energy production in Tasmania. The above estimates are conservative and can be regarded as a minimum potential since all underlying assumptions (e.g. conversion factors) are conservative and other forms of woody biomass (landscaping, waste wood) are not considered here. In addition we assume higher standards for retention of slash to maintain soil fertility and retention of dead wood for biodiversity than required by best management guidelines in Europe or North America (for an overview see Ref. [59]). The above estimates of potential energy production are expected to remain relevant for several years until 2020. The potential supply of forest biomass for energy is expected to increase in the medium and long term due to a significant increase in hardwood plantation production. Long term supply from softwood plantations is expected to remain constant, while long term supply from native forest regrowth is expected to decrease slightly.

4. Comparing Tasmania with Bavaria

4.1. *Forestry and forest industry in Bavaria and Tasmania*

This section presents a case study comparison by contrasting Tasmanian results with data from Bavaria, a southeast German state. The comparison allows an accurate interpretation of our results and an in-depth analysis of relevant drivers. Bavaria was selected due to similarities in Tasmania in area, contribution of forest biomass to total energy consumption and the proportion of forest management between

Table 2 – Potential supply of forest biomass for energy in Tasmania.

	Pulpgrade total	Pulpgrade for energy[a]	Residues for energy	Total energy wood		Energy equivalent
	kt (green)	kt (green)	kt (green)	kt (green)	kt (bone dry)	PJ
Native forests	1050	500	450	950	500	9
Plantation hardwood	3050	1500	350	1850	1000	18
Plantation softwood	700	0	100	100	50	1
wood processing			400	400	200	4
total	**4800**	**2000**	**1300**	**3300**	**1800**	**33**

[a] 50% of hardwood pulpgrade was assumed to be available for energy use, softwood pulpgrade was assumed to be used for processing only. Figures rounded to 50 kt.

Table 3 – Comparisons between Bavaria (Germany) and Tasmania (Australia). Sources [7,21].

	Bavaria	Tasmania
People (million)	12.5	0.5
Latitude of capital city	48° N (Munich)	42° S (Hobart)
Land (km^2)	71 000	68 000
Forest area (km^2)	25 000	34 000
Forest available for wood production (km^2)	24 000	12 000
Main forest type	Semi-natural spruce-beech forest	Natural and modified natural eucalypt forest
Wood production (hm^3 y^{-1})	15–20	5–6
Wood production (m^3 y^{-1} capita^{-1})	1.2–1.6	10–12
Forest biomass used for energy (hm^3 y^{-1})	10	0.7
Fraction of total energy supply generated from forest biomass (%)	5	6

the public and private sectors (Table 3). Additionally, recent comprehensive data is available on the domestic market for biomass used for energy in Bavaria [24]. The use of forest biomass for energy is widespread in Bavaria which is typical for many European countries (Fig. 1) where the share of energy derived from biomass is closely correlated with the available forest resource. In the 27 member nations of the European Union biomass contributed 8.2% of total final energy consumption in 2010 or nearly 64% of European renewable energy [4]. Two thirds of total biomass for energy production or about 50% of total renewable energy [33] was from forest biomass.

Despite Tasmania and Bavaria having a comparable forest area, there are significant differences between the two states in industry configuration and markets. Bavaria is located in the heart of Central Europe and is characterized by a high population density (175 people km^{-2}) leading to a strong domestic market for wood products and bioenergy. There are more than 1000 sawmills processing annually 11.5 hm^3 wood and about 20 plants for engineered wood products (veneer, plywood, particle boards, chemical pulp, mechanical pulp) processing annually about 4 hm^3 wood. The current revenue of the wood processing industry is estimated at 13.2 billion € [43]. Transport distances are usually below 100 km and most of the timber produced in Bavaria is locally processed. About one third of the raw timber is exported to neighbouring states of Germany or other countries, the import of raw timber from other states or countries is about half of the exported amount. In summary the calculated fraction of timber processed in Bavaria relative to the harvest from Bavaria's forests is between 80 and 90%.

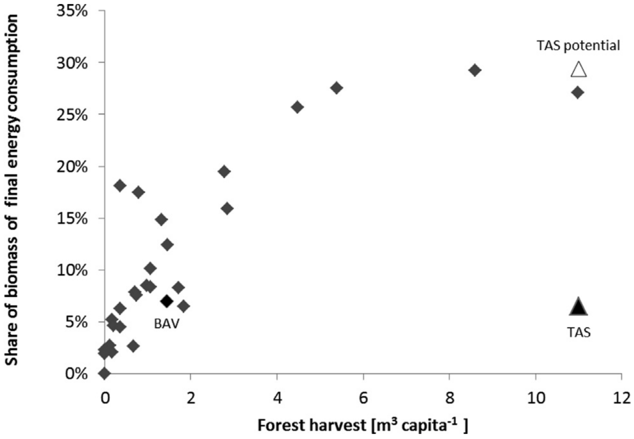

Fig. 1 – Share of biomass energy of final energy consumption in the 27 countries of the European Union (EU27) and the German state Bavaria (bold). Triangles show the current (filled) and potential (empty) use in Tasmania as estimated in this study. Data Source [4].

Tasmania is an island located off the south east coast of the Australian mainland with a low population density (7 people km^{-2}). Market countries with a high population density and wood demand such as Indonesia, China or Japan are about 8000 km from Tasmania. There are 61 individual forest processing businesses in Tasmania, most of them very small operations. The four largest volume businesses processed almost 90% of Tasmania's forest harvest [48]. Transport distances are generally <100 km, except for low quality logs from southern Tasmania that must be transported closer to 200 km to northern Tasmania following the recent closure of the southern port facility. The majority of sawlogs enter the domestic market (>90%) but their fraction of total harvest is less than 20%. The majority of the wood produced is low quality hardwood nowadays mostly originating from plantations. Currently almost all low quality hardwood logs are exported as chips into China and Japan, where the main processing takes place.

4.2. *Comparison of forest biomass resource utilization*

In Tasmania the fraction of total energy supply generated from forest biomass (6%) is only slightly higher than in Bavaria (5%) although the annual harvest per capita is about sevenfold higher in Tasmania (Table 3). Only 14% of the annual Tasmanian harvest is used for generating energy. Biomass for energy is dominated by domestic space heating with firewood and a smaller fraction is used by industrial boilers producing heat (Fig. 2). However, there is no biomass plant in Tasmania and pellet production is only just beginning. Quantities are small and the production of pellets from sawdust which commenced in 2014 is expected to expand to produce 800–900 t y^{-1} of pellets in 2015/2016. Although the

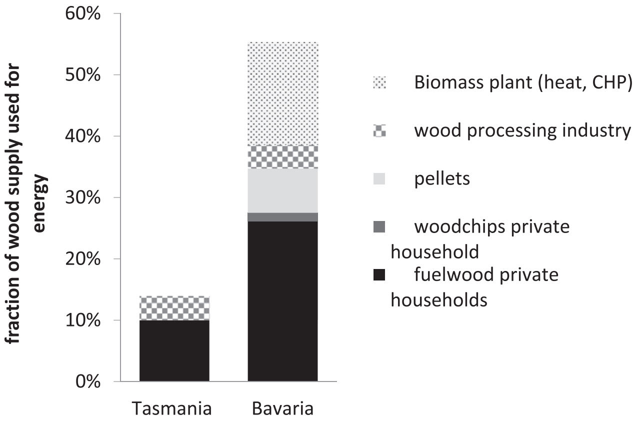

Fig. 2 – **Fraction of wood supply used for energy in Tasmania and Bavaria. Data for Bavaria from [24]; data for Tasmania as estimated in this study.**

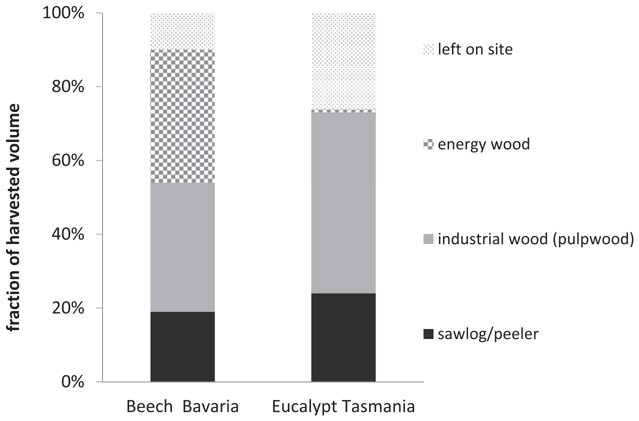

Fig. 3 – **Beech and eucalypt log grades in the State Forests of Bavaria (2011) and Tasmania (2010/11). Total volume: beech 0.8 hm^3, eucalypt: 3.3 hm^3.**

relative firewood consumption in Tasmania (about 1 $t\ y^{-1}$ $capita^{-1}$ of green wood) is more than double that of Bavaria (0.4 $t\ y^{-1}$ $capita^{-1}$ of green wood), only 10% of the annual Tasmanian harvest is used as fuelwood for private households due to the low population density. In Bavaria 55% of the annual harvest (18 $hm^3\ y^{-1}$ over the last 5 years) was used to generate energy. 27% of the wood supply was used directly as energy wood (i.e. without further processing), largely as domestic firewood with a small proportion of woodchips. Nearly the same amount of energy wood originated from processing residues and waste wood from used wood products. Significant amounts of pellets are produced from processing residues and are mostly used for heating private households. The 680 biomass plants in Bavaria (mostly between 0.5 and 2 MW in size) use 17% of the available wood supply with waste wood being the dominant feedstock. The harvesting of log grades explicitly referred to as energy wood in Tasmania is insignificant compared to Bavaria even when taking into account considerable illegal harvesting [35]. Only 1% of total harvest from State forests in Tasmania is firewood sold through firewood collecting permits and commercial firewood sales compared with 36% of beech harvest from State forests sold directly as energy wood in Bavaria (Fig. 3). In Tasmania the total demand for firewood is small and about 25% of the harvested tree remains on site. Most of this material is burnt in the open during regeneration burns that are undertaken to prepare a seedbed for the next crop [22]. In Bavaria only 10% of the harvested tree is left on site to decompose. While the available resource of forest biomass for energy is extensively utilised in Bavaria our estimates indicate that forest biomass production could be more than quadrupled in Tasmania from a resource availability perspective. The potential fraction of total energy production in Tasmania from forest biomass energy of 30%, as estimated in this study, is consistent with current circumstances in European countries with a large forest resource per capita (Sweden, Finland, Latvia, Lithuania and Estonia) indicating this potential is realistic (Fig. 1).

4.3. *Comparison of economic, legislative and social drivers for forest biomass utilization for energy production*

4.3.1. *Prices for energy wood*

There is currently no Tasmanian market for energy logs and the fraction of timber explicitly sold as energy wood is insignificant. Tasmanian prices for low grade pulp-logs and firewood are ≤ half Bavarian prices, and Tasmanian prices for woodchips from processing are below Bavarian prices (Table 4). In contrast prices for wood pellets are significantly higher in Tasmania than in Bavaria. This is due to the small volume of the pellet market in Tasmania (<10 $kt\ y^{-1}$) and the lack of a large scale pellet production facility in Tasmania. The Tasmanian demand for firewood is small relative to the annual harvest and firewood collecting permits for private use are priced close to zero. Due to the low demand, firewood prices are determined by transport and labour costs for preparation with the price of the raw material itself being low

Table 4 – **Comparison of prices (€ t^{-1}) for forest biomass used for energy between Bavaria and Tasmania.**

	Bavaria	Tasmania
Hardwood energy logs (roadside)	65	[a]
Hardwood collecting permit (private use)	30	3
Hardwood pulplogs (roadside)	65	25[b]
Firewood air dry (delivered)	200	120
Forest woodchips	80	[a]
Woodchips from processing (mill door)	110	80
Wood pellets (retail)	300	430

Prices for logs sold in the forest refer to 1 t green material (first three rows), all other prices to 1 t dry material. Prices without VAT, conversion: 1$AUD = 0.80 €.

[a] Currently there is no market for energy logs/forest woodchips in Tasmania, energy logs/forest woodchips would be priced as for pulplogs/processed woodchips.

[b] 15 Euro has been added to stumpage prices for Tasmania to cover felling, snigging and stacking at roadside.

and having little effect on price. Due to the low Tasmanian population density a significant rise in local firewood prices is unlikely. The theoretical maximum consumption of domestic firewood - assuming that all 200 000 Tasmanian households [3] use fuelwood as a primary heating source and consume 5 t y^{-1} equals, at most, 20% of the annual harvest. In addition there are few industrial heating plants and no biomass plants generating municipal heat in Tasmania which would increase the demand for, and hence potentially the price of, firewood, low quality logs and woodchips. Furthermore, there is no domestic demand for hardwood chips from an industry such as pulp and paper making. As a consequence prices of low quality pulpgrade logs, firewood, and woodchips are determined by their industrial use on the world market.

In contrast to Tasmania there is a strong domestic demand for energy wood in Bavaria, especially from hardwood species. Since 2005 there has been a strong increase in demand for energy wood and currently about 60% of the total beech harvest (2.5 hm^3 y^{-1}) is explicitly sold as energy wood. The demand results predominantly from private households using fuelwood. In addition there are more than 600 biomass plants processing about 3 hm^3 y^{-1} [24]. Due to the strong demand, prices for energy wood have nearly doubled in the last 10 years [13]. This has also entailed a significant increase in prices for industrial wood, since industrial users such as particleboard plants or pulpmills compete for the same resource. Only a low proportion of low quality logs is exported to other countries, and between 2010 and 2013 Bavarian roundwood imports and exports were about the same. As a consequence prices for low quality industrial logs and energy wood (firewood, woodchips) are dominated by the domestic market rather than the world market. Even within Bavaria there are strong differences with firewood prices next to urban agglomerations about one third higher compared to rural areas [55].

4.3.2. *Legislative framework*

Within the Renewable Energy Target (RET) scheme the Australian Government aims to ensure that 20 per cent of Australia's electricity comes from renewable sources by 2020. The RET scheme primarily focuses on solar and wind systems but electricity generated from biomass including wood residues has been recognised under the RET scheme. In 2012 wood residues originating from native forestry were excluded from the RET scheme by the former Socialist-Green coalition due to concerns concerning native carbon effects after native forest harvesting, a position the current conservative federal government plans to reverse. Since the origin of wood residues is often unclear this change had an important impact on forest biomass projects. Another major impediment concerning forest biomass for energy is missing incentives within the RET scheme for other forms of energy such as thermal heat, since electricity usually is not the most efficient use of forest biomass [59]. In Tasmania government funding of forest biomass for energy has been negligible in the past and there is no operating biomass plant producing electricity or heat. All private stoves and furnaces are also operating without public subsidies.

For Germany, an increase in the share of renewable energy to 18% is foreseen by 2020 [11]. A set of legislative frameworks and promotional instruments governs renewable energy development [9]. The Renewable Energies Act aims to increase the share of renewable electricity production to 35% of total production by 2020 and includes a guaranteed feed-in remuneration for power producers. The subsidies are collected via a nationwide, standardized apportionment which currently amounts to 6.24 € kWh^{-1} consumed [50]. In order to support the planned expansion of the use of bioenergy for heat production from 10% to 14% the Market Incentive Program for renewable energies also promotes biomass use. For example, a new installation of a pellet boiler, wood chip or split log boiler is subsidized up to the value of 3500 € [6]. Exact data on the total amount of subsidies in Bavaria concerning biomass are not available, but a breakdown of nationwide subsidies [1] to Bavaria according to population equals 760 million € of public subsidies in 2013.

4.3.3. *Social context*

The social context of the use of forest biomass for energy in Australia has been investigated in detail by Ref. [58]. Disputes concerning harvesting in “native forests” have damaged the social acceptance of forest biomass and discredited bioenergy in Australia. According to [58] the lack of understanding and acceptance among important stakeholders is the main reason that implementation of forest biomass for energy in Australia is minimal compared to many European countries. It may also explain why forest biomass from native forests is not promoted in Australian renewable energy programs. The controversy surrounding native forest harvesting has been especially intense and long-lasting in Tasmania [31,45]. Environmental NGO's such as the “Wilderness Society” or “Markets for Change” fear that the use of forest biomass for energy will increase native forest harvesting and therefore fiercely oppose the promotion of this energy source. Even government agencies are quite critical about the intensive use of fuelwood [18]. Currently there are signs that environmental groups may support regional biomass projects with a strong community engagement. Although this may help to develop a better understanding of the possibilities of forest biomass use, such regional projects can only process small quantities due to the small Tasmanian population.

In Bavaria and the rest of Germany the use of forest biomass currently has a strong social license, except from individual local protests following “not in my backyard” interests. There are many regional and community initiatives supporting biomass use within renewable energy targets. The German Federal Ministry of Food and Agriculture promotes the use of bioenergy via so-called bioenergy villages and bioenergy regions which illustrate the benefits of bioenergy use, particularly biogas and wood [8]. However, there are signs that scientific concerns about the trade-offs of biomass harvesting (overview see Ref. [20]) are gaining in importance and there is an increasing discussion about the optimal intensity of forest management also in Bavaria [53]. Key areas of discussion are the preservation of minimum coarse woody debris amounts, maintenance of soil fertility and the percentage of forests without active management. Nevertheless environmental NGO's are not specifically addressing forest biomass use at present [60]. Main reasons may be the trade-off between promotion of renewable energies (a major goal of environmental NGO's) and a reduced harvesting intensity as well as the widespread use of fuelwood also by environmentalists.

5. Discussion

In contrast to Bavaria and elsewhere in Europe, the use of forest biomass for energy is low in Tasmania and could be more than quadrupled from a resource availability perspective. Domestic demand for forest biomass for energy is low in Tasmania and the bulk of the forest harvest is exported as pulpwood to other countries. Thus prices for low quality logs are dominated by international pulpwood prices. In contrast to the Tasmanian situation, bioenergy use significantly influences prices for low quality timber in many regions worldwide [29,42]. Due to the increasing demand for forest biomass feedstock for energy production prices for energy wood reached or surpassed prices for industrial wood in many parts of Europe leading to strong competition between both uses. While for the European market a further uptake in fuel wood demand and therefore increasing prices is expected [20] a significant domestic increase for Tasmania is unlikely. Therefore larger quantities of forest biomass could only be sold on the world market, e.g. as pellets. In this case prices for forest biomass for energy must be equal or higher compared to pulpgrade material in order to make it an attractive alternative for forest owners. In the past world market prices for energy wood (pellets, woodchips) were not high enough to absorb significant quantities of Tasmanian timber and up to now no investor has been willing to invest in bigger bioenergy projects.

Public subsidies would be an option to foster the use of forest biomass for energy under marginal economic conditions. In the European Union the increasing supply of renewable energies is a major political goal and the aim is that by 2020, more than 20% of final energy consumption shall be supplied by renewable energies according to the Renewable Energy Directive 2009/28/EC. The use of (forest) biomass is considered a major component of renewable energies especially for producing thermal energy or combined thermal and electrical energy. As a consequence European countries have been supporting the use of (forest) biomass though the intensity varies across the European Union. Beside different renewable energy targets and minimum obligations for bioenergy per country, European member states have introduced different tax exemptions, investment grants and feed-in tariffs [54]. In the last few years the intensive system of public support in the European Union has experienced increasing criticism for economic (financial burden, too much wood directed at bioenergy instead of solid wood), ecological (environmental trade-offs) and social (competition with food production) reasons [20] and this may influence the corresponding policy. The increase of renewable energies is also a major political goal in Australia. However, the Renewable Energy Target (RET) scheme of the Australian Government with a 20% target for renewable sources for Australia's electricity by 2020 primarily focuses on solar and wind systems. Concerning forest biomass for energy Australia is much more conservative than Europe and corresponding public subsidies have been insignificant up to now. One reason is that the demand for heat (the main application for biomass) is much lower in Australia due to a low population density and a warmer climate. Furthermore there is an intensive discussion about potential negative ecological effects connected with an increased use of forest biomass, e.g. concerning carbon effects of biomass use [15,34] or potential tradeoffs concerning water quality or biodiversity [40]. Similar discussions are reported from other continents [57,59] and it seems clear that this has an impact on the social license of forest biomass for energy and as a consequence on public subsidies.

The relatively low social license of forest biomass for energy is certainly a major impediment to more intensified use of forest biomass for energy in Tasmania. Even the domestic use of firewood has been under debate because of potential adverse effects on coarse woody debris [27]. Nevertheless the use of domestic firewood still has a positive reputation and is an important part of the Tasmanian lifestyle. However, all ideas concerning an intensified use of forest biomass (biomass plants, export) are facing intensive opposition, since there is a strong fear that intensified use of forest biomass might intensify native forest harvesting. Here the long-lasting Australian conflict on native forest harvesting seems to influence even the use of forest residues for energy [58]. In Europe the use of forest biomass for heating has a strong social license. Domestic firewood has a centuries-long tradition and is an important part of the rural lifestyle especially in Central and Northern Europe. The strong emotional link of people with “their” firewood may explain why potential negative effects of intensive firewood use do not receive attention from environmentalists. Also small/medium sized biomass plants are usually supported by communities and in many cases by environmental stakeholders. The bigger the biomass-for-energy plants the more they tend to be challenged. Especially large-scale electricity generation is often criticised by the public, especially when there is no combined use of heat and power and energy efficiency is low. Apart from the opposition against individual big biomass plants practical conflicts concerning the use of forest biomass are rare, although there is increasing scientific discussion on this topic [17,37,46].

Tasmania has a significant forest resource which is currently not fully utilized. Lacking domestic processing facilities, all woodchips must be exported, creating small incomes per ton of wood processed and few jobs [61]. Initiatives to improve this situation should consider better wood utilization in general rather than focusing only on forest biomass for energy. In the last 10 years several so called “cluster-initiatives” were started in different German states aimed at fostering value adding for the whole forest sector. Also in Tasmania several attempts were made to improve wood utilization from native forests, including peeling for export and the production of Laminated Veneer Lumber. However, all further attempts must consider the specific properties of eucalypt timber as a hardwood species. The fraction of high quality log grades is inherently lower in hardwood species than in softwood species, where sawlog recovery may be as high as 80% of the tree volume (Fig. 4). The comparison with oak forestry in Bavaria may give an indication of realistic recovery rates. Oak is one of the most valuable German timbers

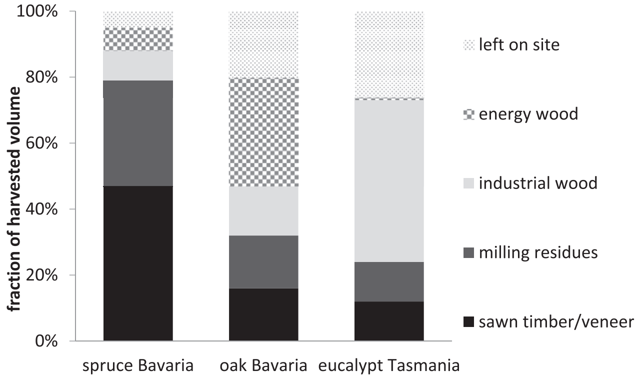

Fig. 4 – Log grades in the State Forests of Bavaria (2011) and Tasmania (2010/11).Total volume: spruce 3.5 hm^3, oak 0.1 hm^3, eucalypt: 3.3 hm^3 Fraction of residues during sawmilling/veneer production was assumed to be 50% for hardwood species and 40% for softwood species.

and high quality sawlogs are sold up to more than 1000 € m^{-3}. A high recovery of sawlogs and veneer logs has been the main target of forest management for more than 200 years. The recovery of high quality sawlogs and veneer logs from oak trees in the State forest of Bavaria is about 10%, total sawlog recovery is about 30%. Hence only about 15% of the tree volume finally ends up as sawn timber/veneer when losses during wood processing are considered (Fig. 4). The comparison with Tasmania indicates some potential for better recovery of more valuable eucalypt log grades. However, a sawlog/peeler recovery above 35% is not realistic for eucalypt forestry (plantation and native) in the foreseeable future. Even under an optimistic scenario, more than 80% of tree volume will end up as low quality products. A Tasmanian future forest industry must therefore – besides trying to increase the yield of high quality products – work towards better use of woodchips that are currently exported and on a better use of residues that are not used at all. According to European experiences the better use of forest biomass for energy could make an important contribution to the value of the whole forestry sector.

6. Conclusions

In contrast to Bavaria and other countries in Europe, forest bioenergy production is small in Tasmania relative to the available resource. A weak domestic market for energy wood, the lack of political stimuli and a low social acceptance are likely key factors. Due to the low population density in Tasmania, a strong increase in market prices for forest biomass is unlikely in the near future. Therefore political incentives are necessary in order to increase the use of residues and low quality timber for energetic purposes. Besides small regional biomass projects, the export of processed material such as pellets or torrefied wood may offer opportunities to better utilize the resource. Addressing social acceptance will be a prerequisite for the success of initiatives or legislation to achieve this potential.

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Eidesstattliche Erklärung

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

Increased wood energy use: evaluation of resource availability and selected environmental impacts for the case study area Bavaria

am Lehrstuhl für Holzwissenschaft unter der Anleitung und Betreuung durch Apl. Prof. Dr. rer. silv. Gabriele Weber-Blaschke ohne sonstige Hilfe erstellt und bei der Abfassung nur die gemäß § 6 Abs. 6 und 7 Satz 2 angegebenen Hilfsmittel benutzt habe.

Ich habe keine Organisation eingeschaltet, die gegen Entgelt Betreuerinnen und Betreuer für die Anfertigung von Dissertationen sucht, oder die mir obliegenden Pflichten hinsichtlich der Prüfungsleistungen für mich ganz oder teilweise erledigt.
Ich habe die Dissertation in dieser oder ähnlicher Form in keinem anderen Prüfungsverfahren als Prüfungsleistung vorgelegt.
Ich habe den angestrebten Doktorgrad noch nicht erworben und bin nicht in einem früheren Promotionsverfahren für den angestrebten Doktorgrad endgültig gescheitert.

Die öffentlich zugängliche Promotionsordnung der TUM ist mir bekannt, insbesondere habe ich die Bedeutung von § 28 (Nichtigkeit der Promotion) und § 29 (Entzug des Doktorgrades) zur Kenntnis genommen.

Ich bin mir der Konsequenzen einer falschen Eidesstattlichen Erklärung bewusst.

München, den 23.04.2016

Matthias Wiln

Matthias Wilnhammer