# Sustainability impacts of increased forest biomass feedstock supply – a comparative assessment of technological solutions

Diana Tuomasjukka[1i], Salvatore Martire[1ii], Marcus Lindner[1], Dimitris Athanassiadis[2], Martin Kühmaier[3], Jan Tumajer[4], Martijn Vis[5], Raffaele Spinelli[6], Matthias Dees[7], Robert Prinz[8], Johanna Routa[8], Antti Asikainen[8]

[1]Diana Tuomasjukka[1], Salvatore Martire[2], Marcus Lindner, European Forest Institute (EFI), Yliopistokatu 6, 80100 Joensuu, Finland; +358-50-7734320; diana.tuomasjukka@efi.int. marcus.lindner@efi.int

[2]Dimitris Athanasiadis, Swedish University of Agricultural Sciences (SLU), 901 83 Umeå, Sweden; +46-90-7868304; dimitris.athanassiadis@slu.se

[3]Martin Kühmaier, University of Natural Resources and Life Sciences (BOKU), Peter-Jordan-Straße 82, 1190 Wien, Austria; +43-1-47654-91518; martin.kuehmaier@boku.ac.at

[4]Jan Tumajer, Institute of Forest Ecosystem Research (IFER), Czech Republic, +420-2-4195 0607; jan.tumajer@ifer.cz

[5]Martijn Vis, Biomass Technology Group (BTG), Postbus 835, 7500 AV Enschede, Netherlands; +31-53-4861186; vis@btgworld.com

[6]Raffaele Spinelli, National Research Council of Italy (IVALSA), Via Madonna del Piano 10, 50019 Sesto Fiorentino, Italy; +39-55-522564; spinelli@ivalsa.cnr.it.

[7]Matthias Dees, FELIS, Albert-Ludwigs-Universität Freiburg, Tennenbacherstr. 4, 79106 Freiburg; Germany; +49-761-203-3697; matthias.dees@felis.uni-freiburg.de

[8]Robert Prinz, Johanna Routa, Antti Asikainen, Natural Resources Institute Finland (Luke), Yliopistokatu 6, 80100 Joensuu, Finland; robert.prinz@luke.fi, johanna.routa@luke.fi; antti.asikainen@luke.fi

[1] corresponding author
[2] Independent researcher: salvo.martire@gmail.com

***Acknowledgements:***

This work was supported by research of the INFRES project (www.infres.eu) which received funding from the European Union Seventh Framework Programme (FP7/2012-2015) under grant agreement n°311881, and from S2Biom project which is co-funded by the European Commission in the Seventh Framework Programme (Project No. FP7-608622), as well as from the Bio Based Industries Joint Undertaking under the European Union's Horizon 2020 research and innovation programme under grant agreement No 20757 "TECH4EFFECT". Special thanks to Olalla Díaz-Yáñez for providing the background data of her paper and Hans Verkerk for EFISCEN runs.

# Sustainability impacts of increased forest biomass feedstock supply – a comparative assessment of technological solutions

Sustainably managed forests provide renewable raw material, which can be used for primary/secondary conversion products and as biomass for energy generation. The potentially available amounts of timber, which are still lower than annual increments, have been published earlier. Access to this timber can be challenging for small-dimensioned assortments, however, technologically improved value chains can make them accessible while fulfilling economic and environment criteria. This paper evaluates the economic, environmental and social sustainability impacts of making the potentially available timber available with current and with technologically improved value chains. This paper focusses on increasing the biomass feedstock supply for energy generation. Quantified impact assessments show which improvements in terms of costs, employment, fuel and energy use, and reduced greenhouse gas emissions can be expected if better mechanized machines than before are provided. Comparative results for current and innovative machine solutions in terms of fuel use, energy use, and greenhouse gas emissions have been calculated using three different methods. This was done in order to quantify not only the impact of the technology choice but also the effect of the choice of the assessment method. Absolute stand-alone values can be misleading in analyses and the use of different impact calculation approaches in parallel is clarifying the limits of using LCA-based approaches. Impacts are calculated using three methods: Sustainability Impacts Assessment (SIA), Life Cycle Assessment (LCA) and Emission Saving Criteria (ESC). The ESC has been discussed for the recast of the Renewable Energy Directive. Potential EU-wide results are presented.

Keywords: bioenergy, technological innovations, value chains, sustainability, Renewable Energy Directive targets

## Introduction

The energy market is changing substantially towards renewable materials and energy. Securing reliable domestic energy supply sources, maintaining economic growth and addressing environmental concerns have led to EU policies that place increasing reliance on renewable energy while striving to reduce greenhouse gas emissions. This tendency was manifested by European policy makers in Renewable Energy Directive (RED) 20-20-20 in the EU energy targets for 2020 climate and energy policy, including 20 % reduction of $CO_2$ emissions, 20 % of energy coming from renewables and 20 % increase in energy efficiency till 2020 (European Parliament 2009). Its recast is currently under discussion at EU level as a part of the EU Climate and Energy framework 2030. This leads to a policy-driven trend of increasing biomass use from forests, to national and regional policy goals and programmes to increase the share and amount of renewable energy in an effort to combat climate change (Gerssen-Gondelach et al. 2014) as well as ensuring energy security and supporting rural development through the efficient use of availability of local resources. In Europe, wood is a major renewable resource with still underused potential (UNECE and FAO 2011; Díaz-Yanez et al. 2013). Its use for energy does not conflict with ethical issues of competition in land use for food production (Harvey and Pilgrim 2011).

The future market for forest bioenergy is expected to grow steadily. The willingness of (private) forest owners to produce and deliver wood for energy depends on the market conditions (Blennow et al. 2014; Aguilar et al. 2014). The return on investment is therefore largely influenced by market prices, but also the costs and energy efficiency of harvesting bioenergy. Harvest residues are harvested usually as part of silvicultural tending measures or as part of harvesting operations. The extraction of harvest residues is practiced in European countries under very favourable conditions and vary in intensity and extend (Díaz-Yáñez et al. 2013; Walsh & Strandgard 2014), as biomass harvest operations are expensive and energy consuming. In many cases, the combined cost of logistics will exceed the delivered value of the resource by a substantial margin (Keefe et al. 2014).

However, the recent changes of energy carriers and technologies for the use of wood can make some currently neglected practices sustainable and highly desirable in the near future (Anerud et al. 2011, Walmsley & Golbold 2010). For example, the use of wood for combined heat and power, for co-firing and in modern direct heating stoves are all already substantially increasing. This allows the use of low-quality and small-dimensioned assortments of wood, such as from thinnings. As a result, an increase of the demand for wood in form of woodchips and pellets on the EU market, particularly from European sources, is to be expected.

Theoretically available biomass volumes (UNECE and FAO 2011; Vis and Dees 2011; Lindner et al. (2017)) do not guarantee practical availability, even if the market demand exists or is increasing. Biomass availability is limited by technological and economic factors such as:

- Technical feasibility and capacity of existing harvesting and transport technologies suitable for forest biomass assortments of small dimensions (Lindroos, 2010)
- Difficulties to access remote places and/or rough terrain, as well as to obtain enough bulk material of biomass as a side product of regular fellings for roundwood (Routa et al., 2013, Díaz-Yáñez et al., 2013).
- Sustainability considerations such as nutrient depletion and soil protection (Routa et al., 2013),
- Small-sized, fragmented forests in private ownership that fail to produce significant volumes or tonegotiate contracts with forest industry, (Díaz-Yáñez et al., 2013)
- Furthermore, forest wood chains (FWC) need to be competitive in terms of economic and energy balance (Laitila & Väätäinen 2012).

The objective of this study is to assess the efficiency and sustainability impacts of selected innovative technology solutions as suggested by Alakangas et al. (2015) for biomass harvesting for energy at EU level: What are the impacts of the technology innovations on greenhouse gas emissions, energy use and energy savings, turnover (=calculated as value added) and employment? How much can these improved technologies contribute towards the EU energy targets in comparison with current mechanization choices?

To do this, material flows related to biomass harvesting and processing chains were designed for four distinct European regions. Moreover, the potential impact of modern technologies was compared. For better transparency, three impact assessment methods were used in comparison to calculate energy use, greenhouse gas emissions and savings as explained as a method in Tuomasjukka et al. (2017): Sustainability Impact Assessment (SIA) (Lindner et al. 2012), Life Cycle Assessment (LCA) (International Organization for Standardization 2006) and Emission Saving Criteria (ESC)[3].

## Material and Methods

### *Current value chains and Technical improvements*

Typical value chains for harvesting primary domestic biomass (i.e. no import) have been modelled for four EU regions, and namely: Northern EU (NEU), Central EU (CEU), Southern EU (SEU) and Eastern EU (EEU).

- NEU: Sweden, Finland, UK, Ireland, Estonia, Latvia, Lithuania
- CEU: Austria, Benelux, Denmark, France, Germany

[3] In Tuomasjukka et al (2017) the calculation of ESC is explained. In difference to this paper however, it is referred to in that paper as "European Sustainability Criteria" as they where under discussion in that form at the time of the paper. The calculation method has not changed , only the name .

- SEU: Bulgaria, Romania, Italy, Portugal, Spain, (no data available for Cyprus, Greece, Malta)
- EEU: Czech Republic, Hungary, Poland, Slovak Republic, Slovenia

This study focuses on small-dimension timber (SDT[4]) supply chains producing harvest residues (tops, branches, full-trees below 8cm diameter at breast height (DBH)) and forest chips from pre-commercial thinnings, commercial thinnings, final harvests and stump extraction. The basic "business as usual" forest bioenergy supply chains were calculated based on volume weighted average chains. The input data was difficult to get as the used systems and the respective shares of the used systems are not necessarily part of the national reporting. There arealso major differences in reporting practices between different countries. The input information reflecting dominant forest biomass supply chains was collected from scientific literature (Díaz-Yáñez et al. 2013; Asikainen et al. 2015; Szewczyk and Wojtala 2010; Kent et al. 2011; Murphy et al. 2014), as well as from statistics (FAOSTAT, Lithuania, Finland, Sweden). In addition, information from a joint questionnaire of the INFRES and S2Biom projects to the leading experts in forest operations throughout Europe was used. The harmonized results are presented in Annex 2, Table 17, and are the currently best available characterisation of typical national value chains.

### *Choice of scenarios*

All scenarios on potential harvests and removals are based on "Baseline 2010" which compiles the felling and potential volumes of 2010. The scenarios were investigated with focus on: a) increased volumes of harvesting timber and resulting additional biomass

[4] The authors are aware that stumps are not necessarily small. However, as they get processed to chips in the end, they were included under SDT assortments.

(compare Annex 1 and 2), and b) a shift in technology towards more mechanisation and carefully selected technological innovations. These scenarios were compared to the baseline. The following scenarios were all calculated but only the ones in black are presented in this paper:

- B2 reference 2010 (removal) – this is the baseline.
- B2 Wood energy 2010 (potential)
- B2 Wood energy potential (2015)
- B2 Wood energy+ removal (2015)
- B2 Wood energy potential (2020)
- B2 Wood energy+ removal (2020)
- B2 Wood energy potential (2025)
- B2 Wood energy+ removal (2025)
- B2 Wood energy potential (2030)
- B2 Wood energy+ removal (2030)

Volumes of additional material supply (see next section) as well as economic, environmental and social indicators were calculated for the most common value chains per country and for selected new value chains with technologial improvements (see technological scenarios). All values are aggregated based on volume-weighted averages throughout Europe (for details see Annex 2).

*a) Increased biomass material flow and assumptions*

The potential for available biomass, i.e. maximum which can be harvested in a given year without exceeding annual increments, was obtained from the European Forest Information SCENario Model (EFISCEN) results for the European Forest Sector Outlook Study II (EFSOS II) (UNECE and FAO 2011) for removals in 2010, 2015, 2020, 2030 and for potentials for the same years (however only values for 2010 and 2030 are presented in this paper. In the raw data, for 2010 EFSOS II “B2 reference removals” and “B2 reference potentials”, for potentials 2015 to 2030 “B2 Promoting wood energy potential” and for removals 2015 to 2030 “B2 wood energy removal” were used with the following adjustments:

- *EFSOS II EFISCEN data for potentials* has modeled volumes for: stemwood and biomass from pre-commercial thinning, stemwood, residues and stumps from thinning, and stemwood, residues and stumps from final harvest.
- *EFSOS II EFISCEN data for removals* has modelled volumes for: stemwood, residues and stumps from thinning, and stemwood, residues and stumps from final harvest.

As this paper focuses on SDT, the raw data mentioned above was adjusted as follws:

- *Potentials* include pre-commercial materials (i.e. stemwood and biomass from pre-commercial thinning), residues from thinning and final felling, stumps (only from final felling and for coniferous trees in Finland, Sweden, UK), and stemwood from thinnings and final harvest.
- *Removals* include residues from thinning and final felling, stumps (only from final felling and for coniferous trees in Finland, Sweden, UK), and stemwood from thinnings and final harvest, plus 66.6% of the potential volume resulting from pre-commercial thinnings (see Annex 2c for removal and potential volumes for 2010, 2015, 2020, 2030).

*2010 Reference:*

Basis for "2010 potential" is the "Real Forest B2 Reference potential" from EFSOS II (2010 constraints). It includes the harvestable amount of material based on constraints in 2010, such as the exclusion of protected areas, peatlands and poor sites, and technical constraints such as max. 66% of available harvest residues. Stemwood from thinning and final fellings is included, but not advocated to be used for bioenergy.

Table 1: Biomass potentials according to EFSOS-II (B2 Reference 2010) per assortment, aggregated per country group and for EU, with comments on current utilization and assumptions.

*2010, 2015, 2020, 2030 B2 Wood energy+ scenario for potential and removals:*

For modelling these years, the calculated "B2 Wood energy+ potentials" were based on the "B2 Promoting wood energy potential: High mobilisation scenario" from EFSOS II with the adjustment to include pre-commercial volumes in the potential.

For the "B2 Wood energy+ removal" only 2/3 of potential volumes from pre-commercial thinning were added. This amount reflects the technical harvestable amount of slash, and is the same share as for harvest residues.

Figure 1: Comparison of 2010 reference and 2030 Wood energy forest potential (pale bars), against B2 reference 2010 removal (solid bar) as well as B2 Wood Energy removals for 2010, 2015, 2020, 2030 (solid bars).

Upon closer inspection, the following volumes [in 1000 $m^3$] can be expected from European forests for 2010 and 2030 (see Fig 2):

Figure 2: Overview of potential and removal from 2010 to 2030: a) Forest harvestable potential by assortments; b) 2010 B2 removal reference+ and B2 removal Wood energy+:

Removal Wood energy by compartment, assuming that 2/3 of pre-commercial thinning can be harvested and extracted. These volumes are additional material for removal from thinning and final fellings.

*Technological innovations*

In addition to increasing harvesting volumes (within sustainable limits) with a focus on biomass from SDT, changes in scenarios focus on a shift in technology towards increased mechanisation (Annex 3) and carefully selected technological innovations (Table 3) from time studies which were conducted within the INFRES project (Asikainen et al. 2015; Spinelli [ed] 2015).

In particular, changing from chainsaws to harvesters would allow a significant increase in operator productivity, as well as a dramatic improvement in operator safety. Furthermore, forwarder extraction is faster and safer. With boogie bands and higher number of axels it is lighter on the soil than extraction performed with a skidder or with adapted farming equipment due to better load distribution. Forwarder extraction is also less expensive than cable extraction, when new technology, like winch-assist harvesters and forwarders, allow implementing mechanized cut-to-length harvesting on steep terrain. Finally, chipping at roadside allows accruing the benefits of size reduction (e.g. lower transport costs) earlier on along the supply chain.

Higher transportation efficiency is expected from larger trucks – such as the Swedish High Capacity Vehicle (HCV) or the Antti Ranta trailers – due to their increased payload. On a similar note, enlarged-space forwarders may offer increased extraction efficiency, due to their larger payload. Feller-bunchers (Naarva) and harvesters (MAMA) with multi-tree handling capability allow a substantial increase of felling productivity when engaged with small-trees. The use of a hybrid chipper results in significant diesel fuel savings, whereas resorting to a high-mobility mountain chipper (Pezzolato) allows overcoming access constraints and taking size reduction as close to the forest as possible, with significant benefits on subsequent handling and transportation.

Table 2: Final selection of machine innovations and their potential for application across EU.

### *Economic, environmental and social impact evaluation*

In this study we used three relevant methods to calculate and comparie economic, environmental and social impacts of alternative bioenergy chains in an extension of indicators for the ToSIA method (Lindner et al. 2012) as described in Tuomasjukka et al. (2017). The methods were:

- Sustainability Impact Assessment (SIA) using ToSIA (Tool for Sustainability Impact Assessment) method (Lindner et al. 2012). ToSIA was used because it allows a comparative and quantitative assessment of economic, environmental and social impacts. This method is well suited to assess impacts of changes in biomass value chains (Martire et al. 2015) such as in this case driven by machine innovations. It is data driven and proved to be open for including new indicators. It has been applied also to compare biomass value chains with fossil oil chains[5] (den Herder et al. 2012,

[5] Fossil oil chain: This chain includes extraction, transportation and refining of crude oil to heavy fuel oil and light heating oil. Heavy fuel oil is used for heat and electricity production in district heating and power plants and light heating oil is generally used to heat residential homes, farms, schools and other private and public buildings which are not connected to a district heating network (den Herder et al. 2012).
Tuomasjukka et al. (2017) explains in detail a method of comparing renewable value chains to a standard fossil chain in energy savings: "The Commission staff working document SWD(2014)259 (European Commission 2014) provides updated fossil fuel comparator data that are needed to calculate the GHG savings of a biomass conversion chain compared to the fossil fuel alternative. The recent proposal (European Commission 2016) contains obligatory sustainability criteria for solid biomass combustion plants with an input capacity of more than 20 MW. These criteria also provide a relevant framework for voluntary, and possibly future obligatory sustainability certification of bioenergy plants with lower input capacities. As the ESC method (over)simplifies the emission reduction calculation, this method was also compared with a SIA- and a LCA-based method. Relevant ESC have been identified and expressed as indicators used in ToSIA."

Tuomasjukka et al. 2017).

Sustainability Impact assessments in ToSIA compare relative impacts (eg EUR/process unit) and absolute impacts (eg relative impacts per process multiplied with the material flow in that process, and summed up for all processes within the chain) between alternative value chains. Most studies so far have only calculated direct impacts of each process (Lindner et al., 2010; Berg et al., 2014; den Herder et al., 2012; Lindner et al., 2012). The following indicators were calculated according to practices laid down in Berg (2011): value added in EUR[6], energy use in kWh, greenhouse gas emission in $CO_2$ equivalents, and employment in fulltime equivalents (FTE). Details on economic calculations are detailed explicitly for all value chains in Prinz et al (2015) and for economic, environmental and social impacts for all value chains in Tuomasjukka et al (2015).

In addition to direct impacts, in this study we successfully investigated the possibility to expand the method to also develop greenhouse gas emission indicators for LCA-based methods to be included in the comparison of impacts as described in Tuomasjukka et al (2017) and below.

- Life cycle assessment (LCA) is a tool to evaluate the environmental aspects of a product or service through all stages of its life cycle. LCA has been standardized through ISO 14040 and 14044. An LCA-based (Life Cycle Assessment) approach (Swedish Environmental Management Council 2000) was added to the ToSIA method in form of energy use and greenhouse gas emission indicators reflecting direct and

[6] "Value added" in calculated as the "Value (=price) of timber raw material at road site" plus the "Value of services". The latter is calculated based on the indicator "Wages and salaries" and interpreted as the value (=price) of the service provided by an entrepreneur for forest operations.

indirect impacts. LCA is one of the oldest approaches for environmental assessments and it is ISO standardized (ISO 14040).

- An approach adopting European Sustainability Criteria for minimum greenhouse gas savings, here called Emission Saving Criteria (ESC) as in discussion for the revision of the Renewable Energy Directive (European Commission 2017) was further added to ToSIA. ESC is an indicator comparing value chain impacts in terms of greenhouse gas emissions to a fixed fossil-fuel comparator (FFC) reflecting the emission of a standard fossil fuel value chain (Tuomasjukka et al. 2017).

## Results

### *Annual supply of forest biomass:*

The amount and share of forest biomass assortments normally used for energy purposes such as materials from pre-commercial thinning, harvest residues and stumps, could be considerably increased from the currently used 25-30 million $m^3$ and available 40.6 million $m^3$ in 2010, to available 161.5 million $m^3$ in 2020, and available 168.6 million $m^3$ in 2030 (see Table 3). The increase in forest biomass for energy is due to better residue recovery and increasing stemwood harvesting. Even if stemwood is not used for bioenergy purposes in our calculations, it is a source for further forest biomass assortments.

Table 3: Improving harvesting technologies, as well as storage and mill operations: increased supply of forest biomass.

### ***Turnover in feedstock supply***

Volume weighted average of forest biomass for energy is presented in Table 4.

Table 4: Value of forest biomass for energy supply chains per scenario

### ***Reduction in fuel consumption***

*Harvesting:*

The fuel reductions in harvesting were most pronounced for the following systems: most successful was the introduction of the NARVA and the MAMA harvesting system in pre-commercial and commercial thinning operations. They replaced the conventional single-grip harvester, with its productivity of 6.5 $m^3/h$ and fuel consumption of 1.7 $l/m^3$. The NARVA multistem-head has reached a productivity of 7.4 $m^3/h$ and a fuel consumption of 1.5 $l/m^3$ (12% reduction), and the MAMA felling head a productivity of 8.2 $m^3/h$ and a fuel consumption of 1.3 $l/m^3$ (24% reduction).

The use of harvesters (6.5 $m^3/h$ at 1.7 $l/m^3$) instead of chainsaw fellings (0.7 $m^3/h$ at 0.8 $l/m^3$) in pre-commercial thinning is less expensive but (depending on productivity) more fuel intensive. At chainsaw productivity rates of up to 0.3 $m^3$ per hour with a fuel consumption of 1.8 $l/m^3$, fuel consumption is approximately the same as for mechanised felling systems. However, below this productivity rate, mechanised fellings are superior in terms of fuel consumption. Motor-manual operations are very widely spread in CEU, SEU and especially EEU.

Therefore, the calculated potential fuel reductions for the suggested innovations in the field of harvesting range from 12 % to 24 %.

*Chipping*

A mixture of harvest residues, logs and tops was the basis for conventional chipping (average productivity of 20 $m^3$/h and 1.15 l/$m^3$ fuel use) and for chipping with the new Pezzolato chipper and Kesla hybrid chipper. Chipping trials with the Pezzolato chipper were successful, with productivity reaching to 37.5 (solid equivalent) $m^3$/h (up to 46%) and fuel use dropping as low as 1.06 l/$m^3$ (solid equivalent) (up to 8 %). These fuel use reductions have the same trend in reducing GHG emissions.

Initial results of the Kesla Hybrid chipper are an exception to the rule of increasing productivity equalling a decrease in fuel consumption, as in this case a completely new technology (hybrid engine) was used. In this case, the productivity increase of the prototype machine was 39 % from average 20 (solid equivalent) $m^3$/h to 33.3 (solid equivalent) $m^3$/h. This fuel reduction was up to 18 % for mixed assortments from average 1.15 l/$m^3$ (solid equivalent) to 0.94 l/ $m^3$ (solid equivalent). The very initial results of the prototype hybrid chipper are promising, and further improvements are to be expected as the technology and operation matures.

*Transportation*

Improvements in transportation were mainly tested for Finland and Sweden with special permits of exceeding the legal maximum load of 60 t with the following trucks: Antti Ranta truck with optimized load volume (69 t), High Capacity Transport (HCT) vehicles (74 t), and tilting container truck and megaliner for logs (90 t). A 74 t chip truck has a payload of 55t compared with a conventional payload of 44 t (for a 60 t truck, used as the representative basis for the Finnish trials; see Laitila et al. 2016). This reduces energy consumption by about

15 % from conventional 0.023 l/t km to 0.020 l/t km. A 69 t chip truck has a payload of 44.5 t compared with a conventional payload of 39.8 t (for a 60 t truck, used as the representative basis for the Swedish trials). Reductions in fuel consumption were about 12 % from the conventional 0.013 l/tkm to 0.012 l/tkm.A 90 t timber truck has a payload of 66t compared with a conventional payload of ca 38 t. Fuel reductions of about 19% from the conventional 0.019 l/t km to 0.016 l/t km have been shown in earlier studies (Löfroth and Svenson, 2012).

Productivities are expected to improve with longer distances for the chip trucks, than shown for the 22 km (for 74 t) and 40 km (for 69 t) distances in the trials. In general, current reduction in fuel use was between 12 % and 19 %, with potential for further optimisation.

*Calculation of direct and indirect Impacts (LCA)*

Table 5 shows the direct and indirect energy use when selected, innovative technical solutions are used in the harvesting and chipping of the feedstock. The direct energy use for the reference cases (conventional harvester and chipper) were 1.69 and 1.15 liters/m$^3$ respectively (grey), while the direct and indirect energy use were 1.96 and 1.33 liters/m$^3$ respectively (black). The calculation method is detailed in Tuomasjukka (2017), supply costs are presented in Prinz et al (2015) and impacts for value chains in Tuomasjukka et al (2015).

Table 5: Energy use of selected innovations

Table 6 and Table 7 reveal the contribution of each operation in the direct and indirect energy use and resulting emissions of GHG for the whole supply chain. The results show that the most energy consuming (and thus higher emissions of GHG) phases are within the harvesting and transport chain. A decrease in energy use and emissions is observed when the innovative technical solutions are utilized. The highest effect (decrease of energy use and emissions) was observed when the MAMA or the NaarvaGrip EH28 head were used instead of a conventional head in harvesting operations.

Table 6: Direct and Indirect energy use of selected supply systems

Table 7: kg$CO_2$eq from Direct and Indirect energy use of selected supply systems

*Calculation of RED greenhouse gas emission reduction*

The technical improvements decrease the fossil fuel consumption, which leads to reductions of greenhouse gas emission in the supply chain. Table 8 shows the reduction in energy consumption of selected technological innovations, leading to a similar emission reduction compared with standard equipment.

Table 8: Fuel consumption reduction of selected innovations

Table 9 shows the emissions of the technological improvements on the total supply chain. Data on the reference supply chain was obtained from ToSIA. The ToSIA reference emissions of the supply chain are roughly in line with the standard greenhouse gas emissions associated with stemwood use as shown in JRC (2014). The selected technological innovations result in an emission reduction in the total supply chain by 1-7 %.

Table 9: GHG emissions in the wood supply chain (g $CO_2$-eq/MJ wood)

Table 10 GHG emission reduction calculated as ESC compared to a fixed fossil-fuel comparator (FFC) reflecting the emission of a standard fossil fuel value chain, as in discussion for the revision of the Renewable Energy Directive (European Commission 2017)

In Table 11 the supply chain emissions for residues have been calculated in a similar way as above for whole trees (undelimbed small trees). Hybrid chippers and Pezzolato chippers have emission reductions of 10 and 8 %, respectively, compared with the reference chipper, making the whole residue to chips supply chain 2-3 % more carbon efficient.

Table 11: GHG emission reduction calculated according to COM(2010)11 and SWD(2014)259

In the context of the GHG emission reduction calculation, in which the emissions of the wood supply chain are compared with a fossil reference, these innovations result in only a minor improvement of total greenhouse gas savings of 0.04-0.06 %, simply because the fossil reference emissions are quite high (80 g$CO_2$/MJ) compared to the already very low emissions of the wood residue supply chain (1.32-1.37 g $CO_2$/MJ).

***Increase in manpower***

Relative additional employment for forest biomass for energy supply chains, measured as futt-time employment (FTE) per $m^3$, is 0.00097 FTE/$m^3$ for pre-commercial thinning, 0.00069 FTE/$m^3$ for harvest residue supply chains, and 0.00018 FTE/$m^3$ for stump supply chains. "Additional" here means on top of the traditional roundwood forest wood chains: pre-commercial thinning by harvester, forwarding of harvest residues, pre-commercial thinning whole trees and stumps, chipping of the same assortments, and transport of chips to heat plant. These relative impacts of FTE per $m^3$ are multiplied with the material passing through those chains (compare to Table 8, volumes in million $m^3$ for forest biomass for energy). As a result, depending on the amount of additionally mobilized biomass modelled for 2010 to 2030, the increment in full-time workers for increased biomass harvesting could reach 10054 FTE in 2010, 18434 FTE in 2015, 23230 FTE in 2020 and finally 23266 FTE in 2030 (see Table 12).Table 12: Increase in manpower needs in EU for increased biomass harvesting (potential)

**Discussion:**

***What additional feedstock supply for forest biomass for energy can be mobilized through innovative technology and what is the additional economic***

***value added of those supply chains?***

Modelled feedstock supply changes can vary greatly across the specific European countries included in this study, both in volumes of biomass and in economic value. There are several reasons for that. The development of the annual supply volumes can be restricted by several socio-economic constraints such as forest ownership structure and market development including the demand and price of energy biomass (Orazio et al 2017). In addition, the physical location of biomass sources in relation to the demand points can reduce sourcing due to increasing transport costs. These constraints were not explicitly modelled in the construction of the supply scenarios. However, large part of the theoretical supply volumes was not included in the potential supply to reflect the impact of these potential barriers on wood mobilization.

There are great regional differences across European countries and regions, not only in the economic, but also in natural conditions, which limits the use of certain technologies. The presented average data about economic profitability and value added in feedstock supply must be considered with caution both for the price that can be obtained for the feedstock itself (=value of timber) as well as for the income to supply chain operators for offering their work as a service (=value of service). Economic feasibility differs strongly from country by to country, based on local conditions.

The values calculated in this study indicate a potential hypothtical economic value added of up to 5731 million EUR. This value reflects the hypothetical increase in biomass supply as value of the additional timber based on timber price and the hypothetical broad application of the modelled technological innovations for most common supply chains per country, which leads to additional entrepreneurial activity with the subsequent economic turnover of providing harvesting operations as a service. The additional feedstock supply and connected turnover from the value chains were aggregated based on volume-weighted averages for four major European regions. Therefore, these values do give a theoretical average indication, but as explained, the variations are quite wide.

As a limitation of this study, the calculated costs and value added should be seen as estimates with some uncertainties which are based on a number of assumptions, when using the results from this study.

It should be noted, that there are cost differences within country groups. Especially within the Nordic country group, cost differences are large (Nordic vs Baltic countries) and therefore the results concerning country groups are only suitable for drawing a general picture of supply costs in the EU. Similar observations can be made for the differences between Central and Eastern Europe.

The presented theoretical cost supply calculations take new innovative machinery into account and are based on trials and prototype demonstrations presented and documented within the INFRES project (compare INFRES Demo reports 1-23, Alakangas et al. 2015). As these machines were mainly prototypes or new systems, the values should be understood as estimates. These estimates will be reach only in the case of widespread adoption, which is not the case yet, as this amount of machines or trained workers are not necessarily available at a large scale. Furthermore, investments into building and further developing these innovative machine systems are not included in the calculation.

The main challenge of this study lies in the data availability and data input. Ideally, the input data for the estimation of supply costs should come from statistics, or from earlier studies (Díaz-Yáñez et al. 2013). Unfortunately, many of the parameters are such that i) no statistics exist at all, ii) there is almost full coverage of data but not exactly for the right parameters, or iii) data exists of for the right parameters, but not for all the countries. Therefore, the authors conducted a survey among leading European experts in the field of forest bioenergy supply chains, in order to determine dominant supply chains per country, and estimates of supply costs per operation. This survey approach has its own limitations, which include a typically low reply rate and the fact that the answers can include “educated guesses” by the experts. The “educated guesses/expert opinions” were further aggregated to the most dominant forest biomass supply chain per country with average productivity. It should be noted however that productivity varies largely between and within countries. This effect is well known as the effect of an operator on productivity and it is large (e.g. Purfürst & Erler 2011). This especially applies for innovative machine systems where only one or two studies of a completely new system where available. That impacts the accuracy and representativeness of the chosen systems and the accuracy of the attached data. We can however state that Table 2 represents the currently best (available) data for European bioenergy systems in use.

In summary, forest biomass from STD assortments has a potential to contribute towards the RED targets, and technological solutions can make the harvest and hauling cost accessible. Even more, the potential economic value of supplying SDT biomass for energy has a considerable economic value for forest operation entrepreneurs to provide as a service, as well as for forest owner in terms of sales of timber from tending operations which mainly serve silvicultural goals.

### ***Can innovative supply chains reduce environmental impacts in comparison with current ones?***

Increased production generally means increased impacts in absolute terms for the same value chain. However, when looking at the larger picture, what counts with respect to sustainability risks is a) how much fossil fuel can be replaced by renewables, b) how much more efficient in terms of reduced emissions and energy use these bioenergy chains are in comparison with current ones (energy use vs energy generation), and c) if forest production remains sustainable, and d) co-benefits of using low-quality wood assortments as the possibility in indirectly supporting forest management operations to improve forest stand quality.

Following the Emission Saving Criteria (ESC), the emissions of the supply chain can be compared with the Fossil Fuel Comparator (FFC) that represents the average carbon emissions of the fossil supply chain that are replaced by bioenergy. According to European Commission (2014) the FCC of fossil heat production is 80 $gCO_2$/MJ. Table 11 shows that the reference supply chain already results in an emission reduction of 98.3% compared with the fossil reference situation. The selected technological innovations result in an additional emission reduction of 0.04-0.06%. This means that the above described innovations have a limited role in achieving the total emission reductions derived from by the use of wood energy replacing wood energy for fossil fuels forin heat generation.

In this study ToSIA and LCA methods were used side by side to assess the energy use and greenhouse gas emissions of a conventional forest harvesting, system as well as of harvesting systems that include technological innovations. The results showed that systems that included technological innovations had lower energy use and consequently lower $CO_2$ emissions than conventional systems. The calculations were based on average fuel consumption and productivity values of the involved machinery and could show some variation depending mainly on stand conditions and operator experience.

To answer the questions on if and how much more efficient the new harvesting technologies are in terms of energy use and greenhouse gas emission in comparison to the current value chains and in comparison to fossil supply chains, the authors expanded on the restrictions of sustainable harvesting levels (harvesting less than the annual increment per country with consideration to site productivity), to include a comparison of direct impacts of replacing current machines with recommended innovations and to calculate direct plus indirect impacts.

The results for direct impacts showed a difference between 219.7 MJ/m$^3$ for direct impact to 254.9 MJ/m$^3$ for LCA-approach. As indirect impacts are connected to the direct impacts, a similar trend can be observed between direct impacts versus direct plus indirect impacts for the scenario options. This comparison works very well for energy use and for greenhouse gas emissions. A current limitation of the LCA-method is that only indirect impacts for the procurement of fossil fuel to run the machine exists (Lindholm et al. 2010). However, data on other parts of upstream chains such as maintenance of road network, production of machinery or resource extraction to machinery is missing (Berg & Karjalainen 2003). GWP and GHG emission calculation are very similar, with the main difference that for GWP calculations not only the GWP of $CO_2$ is included (72 g/MJ) but also of N2O and CH4 with according lifetime factors, which account for an additional 1.098 g/MJ.

In order to get some comparison to the energy saving potential with reference to fossil oil chains[7], the ESC method was applied. The emission reductions shown by using the method

[7] Tuomasjukka et al. (2017) explains in detail a method of comparing renewable value chains to a standard fossil chain in energy savings: "The Commission staff working document SWD(2014)259 (European Commission 2014) provides updated fossil fuel comparator data that are needed to calculate the GHG savings of a biomass conversion chain compared to the fossil fuel alternative. The recent proposal (European Commission 2016) contains obligatory sustainability criteria for solid biomass combustion plants with an input capacity of more than 20 MW. These criteria also provide a relevant framework for voluntary, and possibly future obligatory sustainability certification of bioenergy plants with lower input capacities. As the ESC method (over)simplifies the emission reduction calculation, this method was also compared with a SIA- and a LCA-based method. Relevant ESC have been identified and expressed as indicators used in ToSIA."

as presented by European Commission (2010) depend on (1) the emissions of the supply chain (nominator) and (2) the fossil fuel comparator that represents the supply chain for fossil heat and or electricity production. The emissions of the supply chains have been calculated with a reasonable degree of accuracy, although actual supply chains will vary from case to case. In case of the European GHG emission calculation method, the fossil fuel comparator is a fixed reference value that can be used throughout the EU. This makes the calculation method transparent and easy to use. However, in reality the use of biomass leads to higher emission reductions if coal is replaced (for instance in Czech Republic) than if natural gas is replaced (for example in the Netherlands). The use of site-specific emission factors for the fossil fuel emissions can therefore show a substantially different emission reduction than when using the fixed fossil fuel comparator:, however an average EU value is reflecting average EU level emission savings. The emission value of natural gas for instance is 56 g$CO_2$/MJ, which is 30% below the fossil fuel comparator of 80 g $CO_2$/MJ; while the value of coal is 95 g $CO_2$/MJ, which is 19% higher than the fossil fuel comparator.

As a disclaimer for all three methods used, most of the machine innovations tested within this study are in the "introduction to the market" phase, and it is expected that their environmental performance will improve even more when they are established in the field (Lindholm 2005). Furthermore, other factors play a role in the energy efficiency of forest wood supply chains such as transportation distance. In this study only rough average transport distances were used. With an increase in distance also $CO_2$ emissions increase. Ranta et al (2006) mentioned the importance of the location of the comminution phase as it defines the form of material for the following supply chain step, i.e. transportation. Depending on the end-using facilities there are varying roadside costs and transportation costs as a consequence of their locations and the effects on transportation distances.

***What does increased bioenergy harvest mean in terms of employment and regional development in Europe?***

Based on EUROSTAT data, there has been a continuous increase in the number of employees in the field of forestry and logging since 2009. In 2014, the estimated number of people working in these professions exceeded 525 thousands (in EU28). Moreover, more than 2.8 million of employees work in professions which are dependent on forest products – e.g. manufacture of furniture, paper and other wood-based materials. Asikainen et al (2011) estimated employment in forest harvesting operation  for increased biomass for energy harvesting with a total of 40 000 persons.

This study contributes to the work force and work demand estimation at EU level. The modelled increase in the amount of bioenergy harvesting can bring on the opportunity (and probably even the need) to enlarge the number of employed persons in the field of forestry by up to 23266 fulltime employed persons by 2030 for the modelled value chains and harvesting volumes. As already mentioned above, additional employment in forest biomass for energy supply chains comparing traditional approach varies between 0.00018 and 0.00097 FTE/$m^3$ depending on the harvesting technology. Expected increase in removals from current 27 million $m^3$ to 169 million $m^3$ in 2030 can provide from 25500 to 137700 new FTEs till by 2030.

Depending on how fast the increase in harvesting volume for bioenergy actuallywill be happening, there will be also a demand for suitable workers. If and how fast markets can react to this demand in training skilled and qualified operators is outside the scope of this study. The possible bottleneck of skilled workers to meet the market demands of biomass production was already highlighted by Routa et al (2013).

A significant part of the operation costs are salaries and social costs. With an increase of work and thus employment in forest operations, rural areas are strengthened with work opportunities. The salaries obtained from these operations contributes to the purchasing power of rural areas.

## Conclusion

This paper takesinto account a variety of geographic and operational conditions of wood harvesting scenarios throughout Europe to suggest a full range of innovative solutions that can be adapted to the majority of EU countries. The assessed technology innovations are mostly prototypes or early machine systems, but still within the reach of most logging contractors and biomass supply companies in Europe. They are neither more complicated nor significantly more costly than the current technology options they are meant to replace.

This paper provides the quantified impact assessment on which improvements in terms of costs, employment, fuel and energy use, and reduced Greenhouse gas emission can be expected with better-mechanized tools than were available before. However, the practical applicability of different modern technologies is highly variable over Europe due to factors including forest stand structure, topography, economic, environmental and legislative constraints. It would be desirable to investigate, which are the optimal solutions for each region/operating environment. The most ambitious improvement is to replace motor-manual felling with mechanized multi-tree felling. This technology shift results in very large benefits in terms of productivity, cost and safety. For this reason it is already taking place throughout most of Europe, in locations where motor-manual felling is still popular.

Expanding biomass use without improved technologies would be likely to result in adverse sustainability impacts and not be feasible to cover in terms of costs, energy use or would be simply technologically impossible. The suggested technological improvements can help to mitigate those adverse impacts as presented in the paper.

Comparative results for the current and innovative machine solutions in terms of fuel use, energy use, and greenhouse gas emissions were calculated by means of three different methods integrated into one as explained in Tuomasjukka et al. (2017). As a result the effect of choosing an impact assessment method over another was quantified and reported as part of the environmental impact calculation. The effect of different machine choices becomes obvious seperately and mor etransparently in the comparison, Absolute stand-alone values for environmental impacts, such as greenhouse gas emission, energy use and energy saving, can be misleading. For this reason a more holisitc approach which explicitly quantifies direct impacts and the magnitude of direct plus indirect impacts is clarifying and recommended by the authors. In this study, SIA plus LCA extension as separate indicators, shone a light on assumptions of indirect impacts included in LCA methods and the magnitude of those. The ESC based method ws a useful extension to the integrated SIA and LCA indicators, as here a renewable value chain was pitched against a standard Fossil Fuel Comparison factor, and thus highlights estimated saving potentials against a benchmark. If the ESC method will be introduced in the recast of the RED, it will become a very relevant indicator for solid biomass applications too. If the GHG reduction threshold it not met, the bioenergy does not count to the EU targets. As one of the main purposes of increasing bioenergy is to provide competitive and renewable energy, cost- and energy efficiency are crucial to any new technological development to be successful on the EU market. This study highlighted to potential of the most promising technologies for EU-wide application.

## References


Anerud E, Jirjis R.2011. Fuel quality of Norway spruce stumps - influence of harvesting technique and storage method. Scand J Forest Res, 26:257–266.

EUROSTAT Database (2015). European Commission. available at http://ec.europa.eu/eurostat/web/main/home

Aguilar F X, Ca, Z, D'Amato A.W, 2014. Non-industrial private forest owner's willingness-to-harvest: How higher timber prices influence woody biomass supply. Biomass and Bioenergy, 71, pp.202–215. Available at: http://linkinghub.elsevier.com/retrieve/pii/S0961953414004589.

Alakangas E, Routa J, Asikainen A, Nordfjell T (Ed.) 2015. Innovative, effective and sustainable technology and logistics for forest residual biomass. Natural Resources Institute Finland, Joensuu, Finland. 40 p.

Asikainen A, Routa J., Laitila J., Riala M., Prinz R, Stampfer K,  Holzleitner F, Kanzian C, Erber G, Dees M, Spinelli R, Tuomasjukka D, Athanasiadis D, Bergstrom D, Rodriguez J. 2015. Innovative, effective and sustainable technology and logistics for residual forest biomass: summary of the INFRES project results. Jyväskylä, Finland. 40 p.

Asikainen A, Anttila P, Verkerk H, Diaz O, Röser D. Development of forest machinery and labour in the EU in 2010-2030. Formec Austria 2011, Pushing the Boundaries with Research and Innovation in Forest Engineering. Conference proceedings in cd, 2011.

Asikainen A, Ilvesniemi H, Sievänen R, Vapaavuori E, Muhonen T, editors. 2012. Bioenergia, ilmastonmuutos ja Suomen metsät. Metlan työraportteja / Working Papers of the Finnish Forest Research Institute 240. 211 p. ISBN 978-951-40-2378-1 (PDF). SaatavissaAvailable at: http://www.metla.fi/julkaisut/workingpapers/2012/mwp240.htm.

Berg S [ed]. 2011. Tools for Sustainability Impact Assessment Manual for data collection for Regional and European cases. EFI Technical Report. Joensuu. 36. pp113

Berg S, Schweier J, Brüchert F, Lindner M, Valinger E. 2014. Economic, environmental and social impact of alternative forest management in Baden-Württemberg (Germany) and Västerbotten (Sweden). Scandinavian Journal of Forest Research, (June), pp.1–14. Available at: http://www.tandfonline.com/doi/abs/10.1080/02827581.2014.927913.

Berg S, Karjalainen T, 2003. Comparison of greenhouse gas emissions from forest operations in Finland and Sweden. Forestry, 76(3), pp.271–284.

Blennow K, Persson E, Lindner M, Faias S P, Hanewinkel M, 2014. Forest owner motivations and attitudes towards supplying biomass for energy in Europe. Biomass and Bioenergy, 67, pp.223–230.

Den Herder M, Kolström M, Lidner M, Suominen, T, Tuomasjukka D, Pekkanen M, 2012. Energies 2012, 5(11), 4870-4891

Díaz-Yáñez O, Mola-Yudego B, Anttila P, Röser D, Asikainen A, 2013. Forest chips for energy in Europe: Current procurement methods and potentials. Renewable and Sustainable Energy Reviews, 21, pp.562–571.

European Commission. 2010. Report from the Commission to the council and the European Parliament on sustainability requirements for the use of solid and gaseous biomass sources inelectricity, heating and cooling. COM(2010)11 final. Brussels

European Commission. 2014. Commission staff working document: State of play on the sustainability of solid and gaseous biomass used for electricity, heating and cooling in the EU. SWD(2014) 259. Brussels

European Commission. 2017. Proposal for a DIRECTIVE OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL on the promotion of the use of energy from renewable sources (recast). Brussels. 116p.

European Parliament, 2009. Directive 2009/28/EC of the European Parliament and of the Council of 23 April 2009. Official Journal of the European Union, 140(16), pp.16–62.

Gerssen-Gondelach S, Saygin D, Wicke B, Faaij A, 2014. Competing uses of biomass - Assessment and comparison of the performance of bio-based heat, power, fuels and materials. Renewable and Sustainable Energy Reviews, 40(April), pp.964–998. Available at: http://dx.doi.org/10.1016/j.rser.2014.07.197.

Harvey M, Pilgrim S, 2011. The new competition for land: Food, energy, and climate change. Food Policy, 36(SUPPL. 1), pp.S40–S51. Available at: http://dx.doi.org/10.1016/j.foodpol.2010.11.009.

den Herder M, Kolström M, Lindner M, Suominen T, Tuomasjukka D, Pekkanen M. 2012. Sustainability impact assessment on the production and use of different wood and fossil fuels employed for energy production in North Karelia, Finland. Energies.

5:4870–4891. http://dx.doi.org/10.3390/en5114870
International Organization for Standardization. 2006. ISO 14040 Environmental management – life cycle assessment – principles and framework. Geneva. p. 20.
Keefe R, Anderson N, Hogland J, Muhlenfeld K, 2014. Woody Biomass Logistics. In D. Karlen, ed. Cellulosic Energy Cropping Systems. John Wiley & Sons, Ltd., p. 398.
Kent T, Kofman P D, Coates E, 2011. Harvesting wood for energy. Cost-effective woodfuel supply chains in Irish forestry,
Laitila J, Väätäinen K., 2012. Truck Transportation and Chipping Productivity of Whole Trees and Delimbed Energy Wood in Finland. Croatian Journal of Forest Engineering, 33(2), pp.199–210.
Laitila J, Asikainen A, Ranta T. 2016. Cost analysis of transporting forest chips and forest industry by-products with large truck-trailers in Finland. Biomass and Bioenergy. 90:252–261. Available from: http://dx.doi.org/10.1016/j.biombioe.2016.04.011
Lindholm E., 2005. Virkesfordonens bränsleförbrukning kan minskas. (23).
Lindholm E, Berg S, Hansson P, 2010. Energy efficiency and the environmental impact of harvesting stumps and logging residues. European Journal of Forest Research, 129(6), pp.1223–1235.
Lindner M, Werhahn-Mees W, Suominen T, Vötter D, Zudin S, Pekkanen M, Päivinen R, Roubalova M, Kneblik P, Brüchert F, et al. 2012. Conducting sustainability impact assessments of forestry-wood chains: Examples of ToSIA applications. Eur J For Res. 131:21–34. http://dx.doi.org/10.1007/s10342-011-0483-7
Lindner M, Werhahn-Mees W, Suominen T, Vötter D, Zudin S, Pekkanen M, Päivinen R, Roubalova M, Kneblik P, Brüchert F, et al. 2012. Conducting sustainability impact assessments of forestry-wood chains: Examples of ToSIA applications. European Journal of Forest Research. 131:21–34.
Lindner M, Suominen T, Palosuo T, Garcia-Gonzalo J, Verweij P, Zudin S, Päivinen R. 2010. ToSIA-A tool for sustainability impact assessment of forest-wood-chains. Ecol Modell. 221:2197–2205. http://dx.doi.org/10.1016/j.ecolmodel.2009.08.006
Lindner, M., Dees, M.G., Anttila, P., Verkerk, P.J., Fitzgerald, J., Datta, P., Glavonjic, B., Prinz, R., Zudin, S., 2017. Assessing Lignocellulosic Biomass Potentials from Forests and Industry. In: Panoutsou, C. (Ed.), Modeling and Optimization of Biomass Supply

Chains. 1st Edition. Top-Down and Bottom-up Assessment for Agricultural, Forest and Waste Feedstock. Academic Press, pp. 127-167.

Lindroos O, 2010. Scrutinizing the Theory of Comparative Time Studies with Operator as a Block Effect. International Journal of Forest Engineering, 21(1), pp.20–30.

Löfroth C, Svenson G. 2012. ETT - Modulsystem för skogtransporter - En Trave Till (ETT) och Större Travar (ST). Skogforsk Arbetsrapport. 758: 2012, Uppsala. p 152.

Martire S, Tuomasjukka D, Lindner M, Fitzgerald J, Castellani V, 2015. Biomass and Bioenergy Sustainability impact assessment for local energy supplies' development: The case of the alpine area of Lake Como , Italy. Biomass and Bioenergy, 83, pp.60–76. Available at: http://dx.doi.org/10.1016/j.biombioe.2015.08.020.

Murphy F, Devlin G, McDonnell K, 2014. Forest biomass supply chains in Ireland: A life cycle assessment of GHG emissions and primary energy balances. Applied Energy, 116, pp.1–8. Available at: http://dx.doi.org/10.1016/j.apenergy.2013.11.041.

Orazio, C., Kies, U., & Edwards. D. 2017. Handbook for wood mobilization in Europe. Measures for increasing wood supply from sustainably managed forests. European Forest Institute. 112 p.

Prinz R, Anttila P, Asikainen A. 2015. Biomass from forests - cost estimation of complete supply chains [Internet]. Joensuu. Available from: http://forestenergy.org/observer:get_page/observer/action/details/itemid/689

Ranta T., Rinne S., 2006. The profitability of transporting uncomminuted raw materials in Finland. Biomass and Bioenergy 30(3): 231–237. http://dx.doi.org/10.1016/j.biombioe.2005.11.012.

Routa J, Asikainen A, Björheden R, Laitila J, Röser D, 2013. Forest energy procurement: State of the art in Finland and Sweden. Wiley Interdisciplinary Reviews: Energy and Environment, 2(6), pp.602–613.

Swedish Environmental Management Council, 2000. Requirements for Environmental products declarations, EPD.

Szewczyk G, Wojtala L, 2010. The cost of timber harvesting with a harvester in stands under rebuilding with the use of partial cutting. In: FORMEC 2010.

Tuomasjukka D, Fitzgerald J, Simunovic N, Lind T, Athanassiadis D, Kühmaier M, Tumajer J, Vis M, Prinz R, Asikainen A. 2015. Report documenting sustainability impacts of scenarios for different fuel sources and procurement [Internet]. Joensuu. Available from: http://forestenergy.org/observer:get_page/observer/action/details/itemid/689

Tuomasjukka D, Athanassiadis D, Vis M. 2017. Threefold Sustainability Impact Assessment method comparison for renewable energy value chains. International Journal of Forest Engineering. 28:116–122.

UNECE, FAO (Eds.), 2011. The European Forest Sector Outlook Study II. 2010-2030,

Vis, M., Dees, M. (Eds.), 2011. Biomass Resource Assessment Handbook: Harmonisation of Biomass Resource Assessments, Best Practices and Methods Handbook. VDM Verlag Dr. Müller, Saarbrücken.

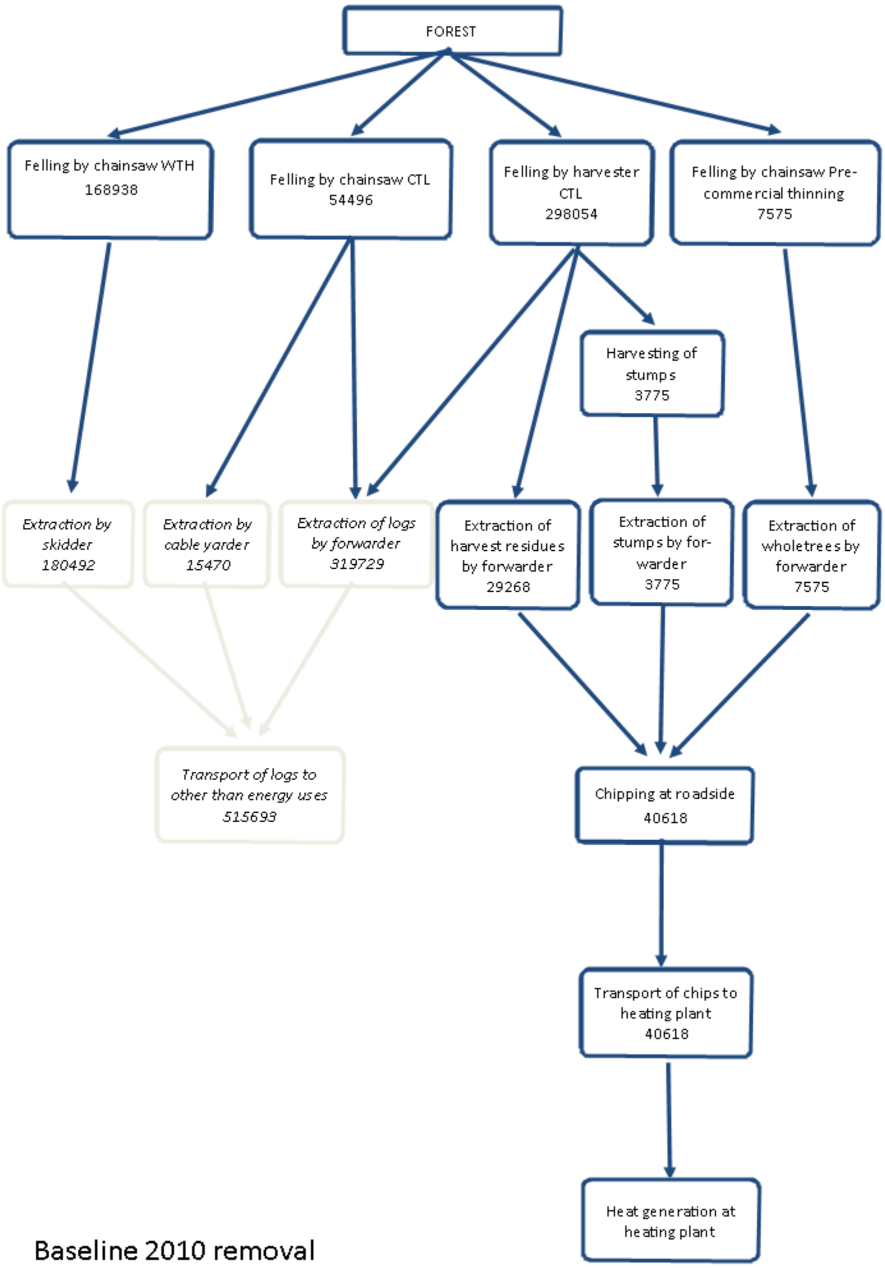
Walsh D, Strandgard M, 2014. Productivity and cost of harvesting a stemwood biomass product from integrated cut-to-length harvest operations in Australian Pinus radiata plantations. Biomass and Bioenergy, (66), pp.93–102.

Walmsley J , Godbold D L, 2010. Stump harvesting for Bioenergy—a review of the environmental impacts. Forestry, 83:17–38.

Walsh D, Strandgard M. 2014. Productivity and cost of harvesting a stemwood biomass product from integrated cut-to-length harvest operations in Australian Pinus radiata plantations. Biomass and Bioenergy 66:93-102.

**Annex:**

Annex 1: Baseline of typical current (2010) forest wood chain (FWC) in Europe. The focus is on bioenergy supply chains. Grey process (*italic font*) were not further followed as they are outside the field of interest. Blue processes (plain font) where calculated. WTS is a harvesting method where trees are felled with a cut at the base. CTL is a harvesting method where trees are felled, delimbed and cross-cut into various assortments directly at the felling site. This baseline is the basis for comparison with scenarios described in Figure 5 and in Table 3. Volumes per process are given as 1000 $m^3$



## Annex 2: Forest operation systems in use across Europe

a) Removal 2010 (EFISCEN)

Forest operation systems in use across Europe per country (harvesting – blue and marked with *, extraction – green and marked with #, transport distance – red and marked with ~), and EFISCEN 2010 removal per assortment (yellow and marked with ^) excluding pre commercial thinning. This percentage per operation type reflects the current situation of harvesting operations in the EU. WTS is a harvesting method where trees are felled with a cut at the base. CTL is a harvesting method where trees are felled, delimbed and cross-cut into various assortments directly at the felling site.

| Country | ^EFISCEN [2010] [1000m3] | ^roundwood [2010] [1000m3] | ^harvest residues [2010] [1000m3] | ^precom thin tree [2010] [1000m3] | ^stumps [2010] [1000m3] | *motorsaw CTL [%] | *motorsaw WTS [%] | *harvester CTL [%] | *harvester WTS [%] | #forwarder CTL [%] | #skidding WTS [%] | #cableyarding [%] | ~Transport distance to incineration [km] |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Austria | 28 850 | 27 065 | 1 785 | | 0 | 26 | 56 | 18 | 0 | 33 | 45 | 22 | 60 |
| Bulgaria | 6 925 | 6 405 | 521 | | 0 | 0 | 100 | 0 | 0 | 0 | 100 | 0 | 20 |
| Czech Republic | 19 967 | 18 728 | 1 238 | | 0 | 9 | 60 | 31 | 0 | 31 | 68 | 1 | 25 |
| Denmark | 3 042 | 2 778 | 264 | | 0 | 0 | 10 | 90 | 0 | 95 | 5 | 0 | 150 |
| Estonia | 8 902 | 8 729 | 173 | | 0 | 0 | 5 | 95 | 0 | 100 | 0 | 0 | 100 |
| Finland | 72 054 | 67 464 | 3 281 | | 1 309 | 0 | 0 | 100 | 0 | 100 | 0 | 0 | |
| Germany | 78 245 | 72 255 | 5 990 | | 0 | 0 | 53 | 47 | 0 | 47 | 50 | 3 | |
| Ireland | 2 330 | 2 289 | 42 | | 0 | 0 | 5 | 95 | 0 | 95 | 5 | 0 | 58 |
| Italy | 10 194 | 9 770 | 425 | | 0 | 85 | 0 | 15 | 0 | 40 | 45 | 15 | 100 |
| Latvia | 8 566 | 8 057 | 510 | | 0 | 0 | 25 | 75 | 0 | 100 | 0 | 0 | |
| Lithuania | 15 520 | 14 864 | 656 | | 0 | 71 | 0 | 29 | 0 | 100 | 0 | 0 | |
| Netherlands | 1 397 | 1 361 | 35 | | 0 | 0 | 20 | 80 | 0 | 80 | 20 | | |
| Poland | 47 456 | 44 686 | 2 771 | | 0 | 0 | 95 | 5 | 0 | 15 | 85 | 0 | 250 |
| Portugal | 9 262 | 8 689 | 573 | | 0 | 90 | 0 | 10 | 0 | 80 | 20 | 0 | 25 |
| Romania | 20 666 | 19 855 | 811 | | 0 | 0 | 98 | 2 | 0 | | 99 | 1 | 30 |
| Slovakia | 10 083 | 9 369 | 714 | | 0 | 100 | 0 | 0 | 0 | 0 | 100 | 0 | 0 |
| Slovenia | 4 304 | 4 159 | 145 | | 0 | 88 | 0 | 12 | 0 | 12 | 68 | 20 | 100 |
| Spain | 21 235 | 19 923 | 1 312 | | 0 | 0 | 65 | 35 | 0 | 30 | 60 | 10 | 60 |
| Sweden | 96 933 | 89 335 | 5 246 | | 2 352 | 5 | 0 | 95 | 0 | 100 | 0 | 0 | 93 |
| United Kingdom | 10 735 | 10 277 | 343 | | 114 | 0 | 0 | 100 | 0 | 100 | 0 | 0 | |
| **EU 2010 Removal Total** | **476 667** | **94** | **6** | **0** | **1** | **10** | **31** | **54** | **0** | **62** | **35** | **3** | **95** |
| CEU | 111 533 | 93 | 7 | 0 | 0 | 7 | 52 | 41 | 0 | 45 | 47 | 8 | 69 |
| SEU | 47 617 | 94 | 6 | 0 | 0 | 15 | 19 | 9 | 0 | 38 | 55 | 8 | 56 |
| EEU | 102 476 | 94 | 6 | 0 | 0 | 15 | 75 | 9 | 0 | 13 | 85 | 1 | 145 |
| NEU | 215 041 | 93 | 5 | 0 | 2 | 7 | 1 | 91 | 0 | 100 | 0 | 0 | 93 |

b) Potenial 2010 (EFISCEN)

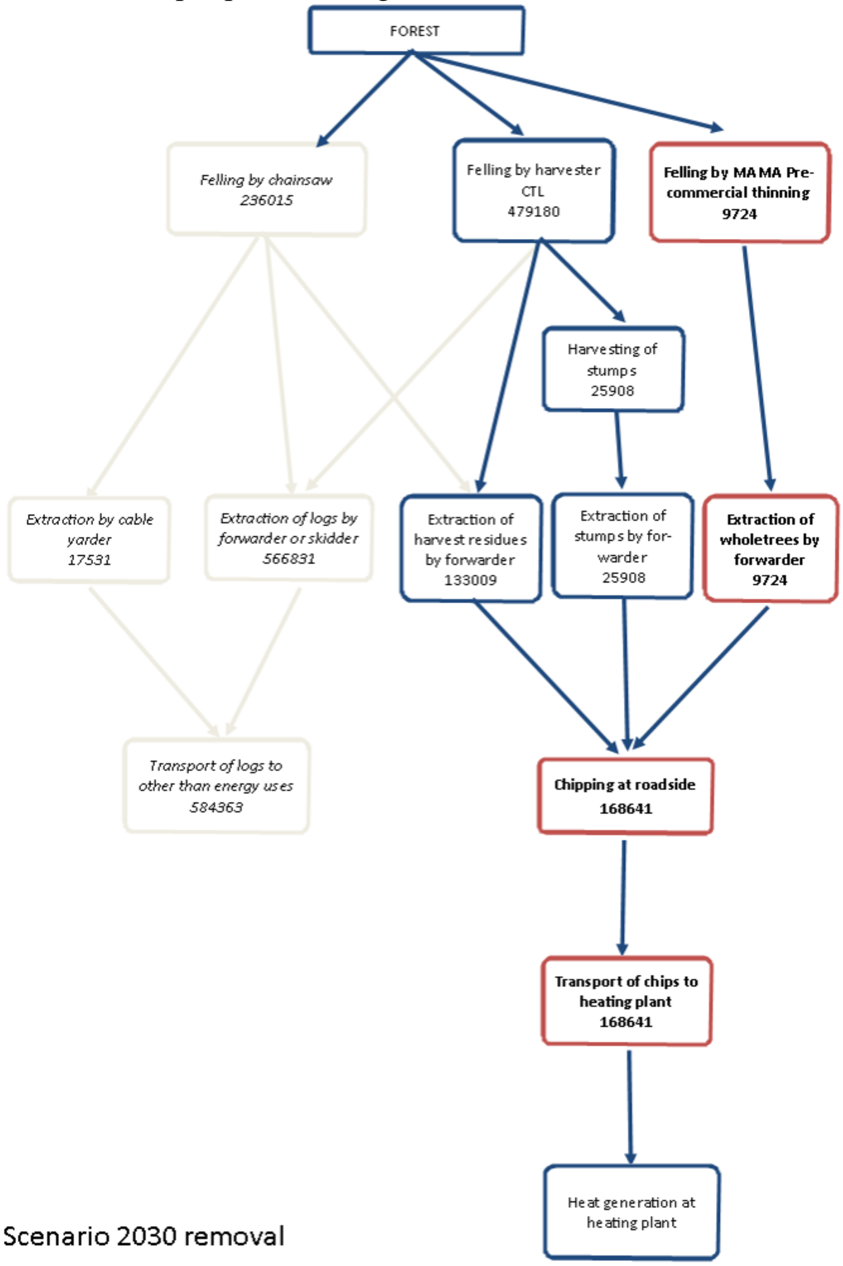
Forest operation systems in use across Europe per country (harvesting – blue and marked with *, extraction – green and marked with #, transport distance – red and marked with ~), and EFISCEN 2010 B2 Potential per assortment (yellow and marked with ^). This percentage per operation type reflects the current situation of harvesting operations in the EU. WTS is a harvesting method where trees are felled with a cut at the base. CTL is a harvesting method where trees are felled, delimbed and cross-cut into various assortments directly at the felling site.

| Country | ^EFISCEN [2010] [1000 m3] | ^roundwood [2010] [1000 m3] | ^harvest residues [2010] [1000 m3] | ^precom thin tree [2010] [1000 m3] | ^stumps [2010] [1000 m3] | * motorsaw CTL [%] | * motorsaw WTS [%] | * harvester CTL [%] | * harvester WTS [%] | #forwarder CTL [%] | #skidding WTS [%] | #cableyarding [%] | ~Transport distance to incineration [km] |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Austria | 322 958 | 278 382 | 43 475 | 1 102 | 0 | 26 | 56 | 18 | 0 | 33 | 45 | 22 | 60 |
| Bulgaria | 8 128 | 6 409 | 1 596 | 123 | 0 | 0 | 100 | 0 | 0 | 0 | 100 | 0 | 20 |
| Czech Republic | 25 111 | 21 228 | 3 279 | 604 | 0 | 9 | 60 | 31 | 0 | 31 | 68 | 1 | 25 |
| Denmark | 3 971 | 3 316 | 578 | 77 | 0 | 0 | 10 | 90 | 0 | 95 | 5 | 0 | 150 |
| Estonia | 13 122 | 11 995 | 805 | 321 | 0 | 0 | 5 | 95 | 0 | 100 | 0 | 0 | 100 |
| Finland | 85 508 | 70 810 | 9 491 | 1 651 | 3 556 | 0 | 0 | 100 | 0 | 100 | 0 | 0 | |
| Germany | 103 242 | 84 365 | 16 151 | 2 727 | 0 | 0 | 53 | 47 | 0 | 47 | 50 | 3 | |
| Ireland | 3 123 | 2 833 | 239 | 51 | 0 | 0 | 5 | 95 | 0 | 95 | 5 | 0 | 58 |
| Italy | 26 742 | 23 179 | 3 526 | 36 | 0 | 85 | 0 | 15 | 0 | 40 | 45 | 15 | 100 |
| Latvia | 18 390 | 15 742 | 2 427 | 221 | 0 | 0 | 25 | 75 | 0 | 100 | 0 | 0 | |
| Lithuania | 10 543 | 8 959 | 1 377 | 208 | 0 | 71 | 0 | 29 | 0 | 100 | 0 | 0 | |
| Netherlands | 1 482 | 1 362 | 98 | 23 | 0 | 0 | 20 | 80 | 0 | 80 | 20 | 0 | |
| Poland | 58 414 | 50 529 | 6 973 | 912 | 0 | 0 | 95 | 5 | 0 | 15 | 85 | 0 | 250 |
| Portugal | 10 802 | 8 760 | 1 843 | 199 | 0 | 90 | 0 | 10 | 0 | 80 | 20 | 0 | 25 |
| Romania | 32 536 | 28 215 | 3 642 | 678 | 0 | 0 | 98 | 2 | 0 | 0 | 99 | 1 | 30 |
| Slovakia | 11 384 | 9 368 | 1 557 | 459 | 0 | 100 | 0 | 0 | 0 | 0 | 100 | 0 | |
| Slovenia | 8 433 | 7 713 | 612 | 108 | 0 | 88 | 0 | 12 | 0 | 12 | 68 | 20 | 100 |
| Spain | 24 791 | 19 923 | 4 299 | 569 | 0 | 0 | 65 | 35 | 0 | 30 | 60 | 10 | 60 |
| Sweden | 111 915 | 91 456 | 13 573 | 1 351 | 5 535 | 5 | 0 | 95 | 0 | 100 | 0 | 0 | 93 |
| United Kingdom | 15 455 | 13 220 | 1 648 | 279 | 308 | 0 | 0 | 100 | 0 | 100 | 0 | 0 | |
| **EU 2010 Removal Total** | **896 051** | **85** | **13** | **1** | **1** | **10** | **31** | **54** | **0** | **62** | **35** | **3** | **95** |
| CEU | 427 683 | 93 | 7 | 0 | 0 | 7 | 52 | 41 | 0 | 45 | 47 | 8 | 69 |
| SEU | 70 462 | 94 | 6 | 0 | 0 | 15 | 19 | 9 | 0 | 38 | 55 | 8 | 56 |
| EEU | 135 878 | 94 | 6 | 0 | 0 | 15 | 75 | 9 | 0 | 13 | 85 | 1 | 145 |
| NEU | 262 028 | 93 | 5 | 0 | 2 | 7 | 1 | 91 | 0 | 100 | 0 | 0 | 93 |

c) Overview of potentials and removal volumes at EU level for study per assortment for 2010, 2015, 2020, 2030 in $1000m^3$

| Volumes at EU level [1000 m3] | Pre-commercial | Harvest Residues | Stumps | Stemwood | Total removal |
|---|---|---|---|---|---|
| 2010 B2 EFISCEN reference removal | | 29268 | 3775 | 515693 | 548735 |
| **2010 B2 potential** | 11362 | 91985 | 9398 | 601404 | 714150 |
| **2010 B2 removal** | 7575 | 29268 | 3775 | 515693 | 556311 |
| **2015 B2 Promoting wood energy potential** | 14361 | 117328 | 17794 | 615758 | 765241 |
| **2015 B2 wood energy+ removal** | 9574 | 88781 | 16262 | 544598 | 649641 |
| **2020 B2 Promoting wood energy potential** | 15539 | 138026 | 25254 | 610420 | 789239 |
| **2020 B2 wood energy+ removal** | 10359 | 126310 | 24843 | 562471 | 713624 |
| **2030 B2 Promoting wood energy potential** | 14586 | 141832 | 22986 | 617965 | 797368 |
| **2030 B2 wood energy+ removal** | 9724 | 133009 | 25908 | 584363 | 743280 |

Annex 3: Scenario of typical technologically improved forest wood chain (FWC) in comparison to baseline. Grey process (*italic font*) were not further followed as they are outside the field of interest. Blue processes (plain font) were calculated with increased volumes (**bold font**) and a shift to more mechanisation for harvesting bioenergy assortments. Red processes were in additionally compared on replacing current with technological innovations as explained in Table 3. WTS is a harvesting method where trees are felled with a cut at the base. CTL is a harvesting method where trees are felled, delimbed and cross-cut into various assortments directly at the felling site.Volumes per process are given as 1000 $m^3$.



**TABLES**

Table 1:

| Country group | Total potential volume [1000 m³] | Pre-commercial [1000 m³] | Stemwood [1000 m³] | (Harvestable) Harvest Residues [1000 m³] | Stumps [1000 m³] |
|---|---|---|---|---|---|
| **CEU** | ***522000*** | 3299 | 201905 | 33734 | 0 |
| **EEU** | ***146693*** | 3054 | 126213 | 17426 | 0 |
| **NEU** | ***262028*** | 4082 | 215016 | 29560 | 9398 |
| **SEU** | ***70462*** | 928 | 58270 | 11264 | 0 |
| ***EU*** | ***1001183*** | ***11362*** | ***601404*** | ***91985*** | ***9398*** |
| **Comments** | | **Currently not/ little utilized** | **This equals 97% of annual increment** | **66% of all tops and branches were considered technically harvestable. Currently partially utilized** | **Only Finland, Sweden and UK were considered to harvest stumps in final fellings** |

Table 2:

| Scenarios/machines | NEU | CEU | SEU | EEU |
|---|---|---|---|---|
| Antti Ranta, enlarged truck space (69t) | x | | | |
| Swedish HCV (74t and 90t) (Skogforsk) | x (Swe, Fin) | | | |
| Pezzolato (chipper) | x | x | x | x |
| Narva EF28 multitree harvester head | x | x | x | x |
| Press-collector: extended space forwarder | x | x | x | x |
| MAMA felling head | x | x | x | x |
| Kesla hybrid chipper | x | x | x | x |

Table 3:

| Forest biomass for energy assortments [million $m^3$] | Stemwood for other uses [million $m^3$] | Total [million $m^3$] | Scenario |
|---|---|---|---|
| 41 | 516 | **557** | **B2 reference 2010 (removal)** |
| 115 | 545 | **660** | **B2 Wood energy+ 2015 (removal) EU** |
| 162 | 563 | **724** | **B2 wood energy+ 2020 (removal)** |
| 169 | 585 | **753** | **B2 wood energy+ 2030 (removal)** |

Table 4:

| Scenario | Forest biomass for energy [million m$^3$] | Value of raw material [million EUR] | Value of services [million EUR] | Total value [million EUR] |
|---|---|---|---|---|
| **B2 reference 2010 (removal)** | 40.6 | 1379 | 0.9 | 1380 |
| **B2 Wood energy+ 2015 (removal)** | 114.6 | 3892 | 2.5 | 3895 |
| **B2 wood energy+ 2020 (removal)** | 161.5 | 5485 | 3.4 | 5488 |
| **B2 wood energy+ 2030 (removal)** | 168.6 | 5727 | 3.6 | 5731 |

Table 5:

| Forest operation | Direct fuel consumption innovative solution (litres/m³) | Direct and Indirect fuel consumption (LCA) (innovative solution (litres/m³) |
|---|---|---|
| CEU Thinning with harvester with MAMA head in CTL system[a] | 1.30 | 1.51 |
| CEU Clearcutting with harvester with NaarvaGrip EH28 head in CTL system | 1.50 | 1.74 |
| Chipping with Hybrid chipper | 1.02 | 1.18 |
| Chipping with Pezzolato chipper | 1.06 | 1.23 |

[a] A harvesting method where trees are felled, delimbed and cross-cut into various assortments directly at the felling site

Table 6:

| **Forest operation** | **Reference** | | **Direct and Indirect Energy use of Scenarios with innovations** | | | |
|---|---|---|---|---|---|---|
| | **Direct Energy Use (reference case)** | **Direct and Indirect Energy use (LCA) (reference case)** | **CEU Thinning with harvester with MAMA head in CTL system** | **CEU Clearcutting with harvester with NaarvaGrip EH28 head in CTL system** | **Chipping with Hybrid chipper** | **Chipping with Pezzolato chipper** |
| Harvesting | 60.4 | 70.1 | 53.8 | 53.6 | 70.1 | 70.1 |
| Forwarding | 27.2 | 31.6 | 31.6 | 31.6 | 31.6 | 31.6 |
| Chipping | 41.1 | 47.6 | 47.6 | 47.6 | 42.2 | 43.9 |
| Transportation of whole tree | 54.1 | 62.8 | 62.8 | 62.8 | 62.8 | 62.8 |
| Transportation of chips | 36.9 | 42.8 | 42.8 | 42.8 | 42.8 | 42.8 |
| Sum | 219.7 | 254.9 | 238.6 | 238.4 | 249.5 | 251.2 |

Table 7:

| Forest operation | Reference | | Emissions from Direct and Indirect Energy use of Scenarios with innovations | | | |
|---|---|---|---|---|---|---|
| | Emissions for Reference case with only direct Energy use | Emissions for Direct and Indirect Energy use (LCA) (reference case) | CEU Thinning with harvester with MAMA head in CTL system | CEU Clearcutting with harvester with NaarvaGrip EH28 head in CTL system | Chipping with Hybrid chipper | Chipping with Pezzolato chipper |
| Harvesting | 4.4 | 5.1 | 3.9 | 3.9 | 5.1 | 5.1 |
| Forwarding | 2.0 | 2.3 | 2.3 | 2.3 | 2.3 | 2.3 |
| Chipping | 3.0 | 3.5 | 3.5 | 3.5 | 3.1 | 3.2 |
| Transportation of whole tree | 4.0 | 4.6 | 4.6 | 4.6 | 4.6 | 4.6 |
| Transportation of chips | 2.7 | 3.1 | 3.1 | 3.1 | 3.1 | 3.1 |
| Sum | 16.1 | 18.6 | 17.4 | 17.4 | 18.2 | 18.4 |

Table 8:

| Innovation | Fuel consumption reference case (litres/$m^3$) | Fuel consumption innovative solution (litres/$m^3$) | Fuel consumption reduction, emission reduction (%) |
|---|---|---|---|
| CEU Thinning with harvester with MAMA head in CTL system | 1.69 | 1.30 | 23 |
| CEU Clearcutting with harvester with NaarvaGrip EH28 head in CTL system | 1.69 | 1.50 | 11 |
| Chipping with Hybrid chipper | 1.15 | 1.02 | 11 |
| Chipping with Pezzolato chipper | 1.15 | 1.06 | 8 |

Table 9:

| Forest operation | Reference | Scenarios with technological innovations | | | | |
|---|---|---|---|---|---|---|
| | Whole tree | CEU Thinning with harvester with MAMA head in CTL system | CEU Clearcutting with harvester with NaarvaGrip EH28 head in CTL system | Chipping with Hybrid chipper | Chipping with Pezzolato chipper | Average improvement combi harvester and chipper |
| Harvesting | 0.59 | 0.45 | 0.52 | 0.59 | 0.59 | 0.49 |
| Forwarding | 0.27 | 0.27 | 0.27 | 0.27 | 0.27 | 0.27 |
| Chipping | 0.40 | 0.40 | 0.40 | 0.36 | 0.37 | 0.36 |
| Transport whole tree | 0.53 | 0.53 | 0.53 | 0.53 | 0.53 | 0.53 |
| Transport chips | 0.36 | 0.36 | 0.36 | 0.36 | 0.36 | 0.36 |
| Sum | 2.15 | 2.01 | 2.08 | 2.10 | 2.12 | 2.01 |
| Emission reduction compared to baseline | | 6% | 3% | 2% | 1% | 7% |

Table 10:

| Impacts | Reference | Scenarios with innovations | | | | |
|---|---|---|---|---|---|---|
| | Whole tree | CEU Thinning with harvester with MAMA head in CTL system | CEU Clearcutting with harvester with NaarvaGrip EH28 head in CTL system | Chipping with Hybrid chipper | Chipping with Pezzolato chipper | Average improvement combi harvester and chipper |
| Emissions supply chain ($gCO_2/MJ$)[a)] | 2.15 | 2.01 | 2.08 | 2.10 | 2.12 | 2.01 |
| Fossil fuel comp. heat ($gCO_2/MJ$) | 80.0 | 80.0 | 80.0 | 80.0 | 80.0 | 80.0 |
| Emission reduction supply chain | 97.31% | 97.48% | 97.40% | 97.37% | 97.35% | 97.49% |
| Improvement compared to baseline | | 0.15% | 0.08% | 0.05% | 0.04% | 0.16% |

Table 11:

| Impacts | | Residues – baseline | Scenario - chipping with Hybrid chipper | Scenario - chipping with Pezzolato chipper |
|---|---|---|---|---|
| **Impacts per process [in $gCO_2eq/MJ$]** | Forwarding | 0.33 | 0.33 | 0.33 |
| | Chipping | 0.40 | 0.36 | 0.37 |
| | Transportation residues | 0.64 | 0.64 | 0.64 |
| | Transport chips | 0.00 | 0.00 | 0.00 |
| **Impacts for whole chain (aggregation of the processes above)** | Total emission | 1.37 | 1.32 | 1.34 |
| | Reduction compared to baseline | | 3% | 2% |
| | **GHG emission reduction calculation** | | | |
| | Emissions supply chain | 1.37 | 1.32 | 1.34 |
| | Fossil fuel comparator (heat) | 80 | 80 | 80 |
| | Emission reduction supply chain | 98.29% | 98.35% | 98.33% |
| | Improvement compared to baseline | | 0.06% | 0.04% |

Table 12:

| | 2010 | 2015 | 2020 | 2030 |
|---|---|---|---|---|
| **Increased manpower from additional volumes and improved harvesting technology** | 10054 FTE | +184340 FTE | +23230 FTE | +23266 FTE |

**FIGURE Captions**

Figure 1: Comparison of 2010 reference and 2030 Wood energy forest potential (pale bars), against B2 reference 2010 removal (solid bar) as well as B2 Wood Energy removals for 2010, 2015, 2020, 2030 (solid bars). The removals do not include volumes from pre-commercial thinning. Potentials do include volumes from pre-commercial thinning.

Figure 2: Overview of potential and removal of volumes from 2010 to 2030: a) Forest harvestable potential by assortments; b) B2 removal reference+ and B2 removal Wood energy+: Removal Wood energy by compartment. Assuming that 2/3 of pre-commercial thinning can be harvested and extracted. These volumes are additional material for removal from thinning and final fellings

Figure 1

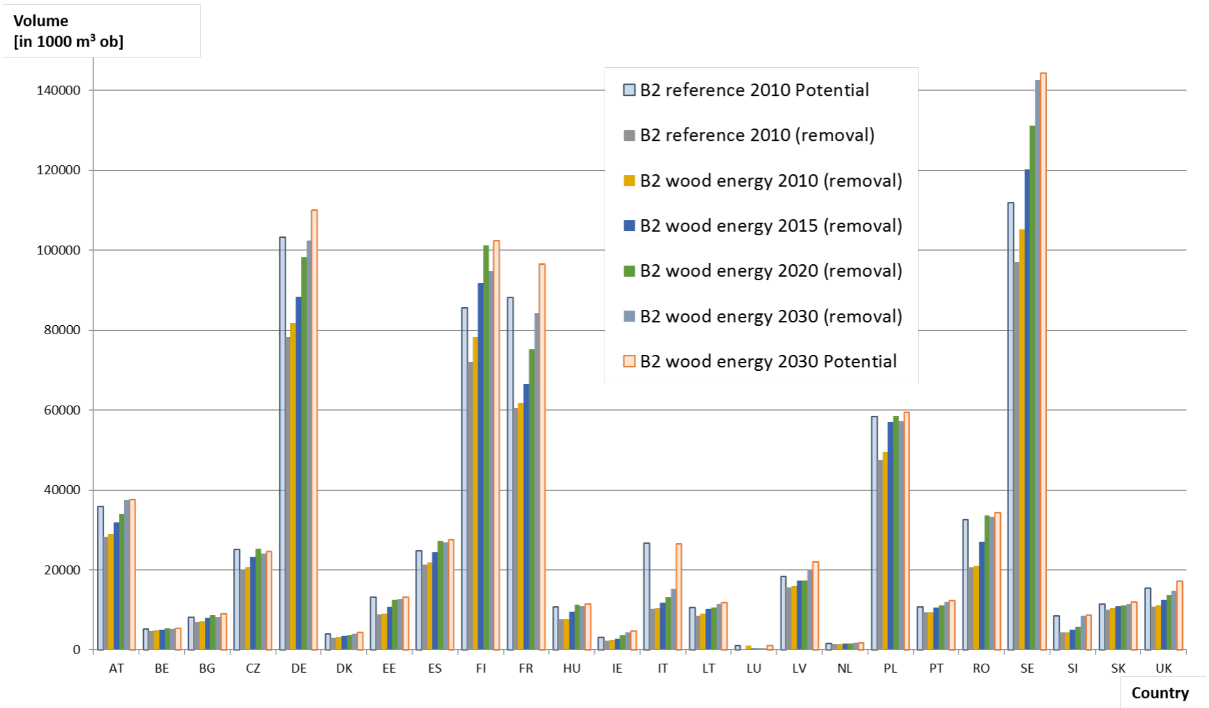



Figure 2a

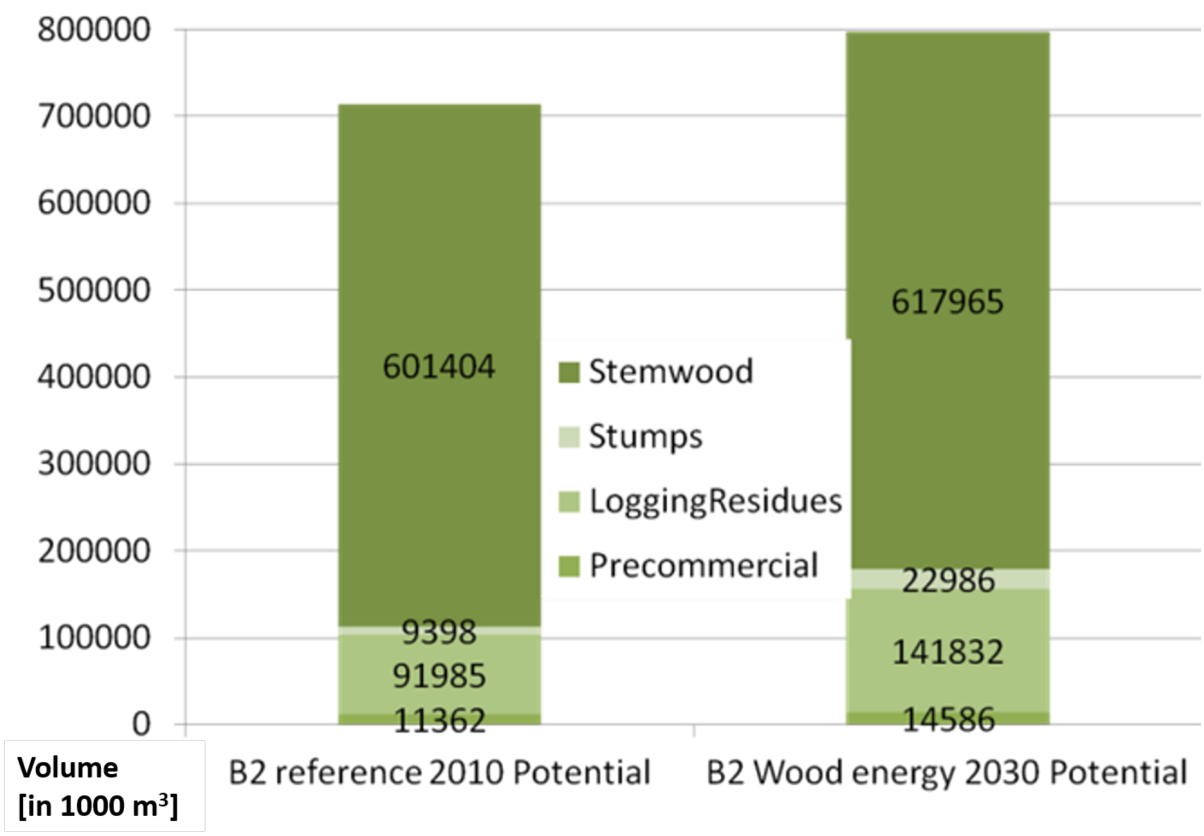
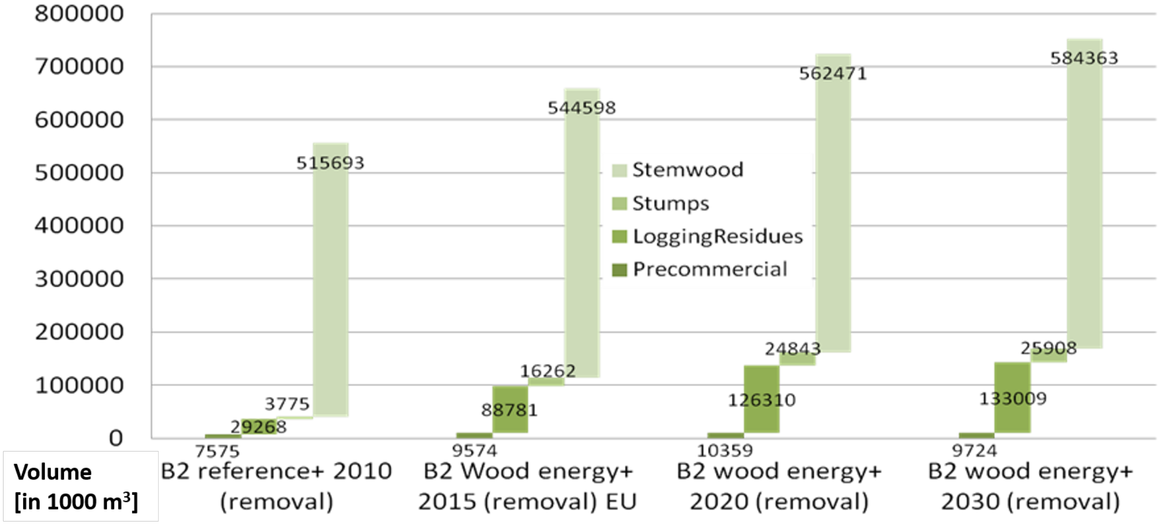


Figure 2b


800000
700000
600000
500000
400000
300000
200000
100000
0
515693
544598
562471
584363
Stemwood
Stumps
LoggingResidues
Precommercial
3775
29268
7575
16262
88781
9574
24843
126310
10359
25908
133009
9724
Volume
[in 1000 m³]
B2 reference+ 2010 (removal)
B2 Wood energy+ 2015 (removal) EU
B2 wood energy+ 2020 (removal)
B2 wood energy+ 2030 (removal)