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

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\begin{abstract}
Sustainably managed forests provide renewable raw material that 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 technologically improved value chains. This paper focuses 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 are provided. Using three different methods – Sustainability Impacts Assessment (SIA), Life Cycle Assessment (LCA), and Emission Saving Criteria (ESC) – we calculated current and innovative machine solutions in terms of fuel use, energy use, and greenhouse gas emissions, to quantify the impact of the technology choice and also the effect of the choice of 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. The ESC has been discussed for the recast of the Renewable Energy Directive. Potential EU-wide results are presented.
\end{abstract}

\section*{Introduction}

The energy market is changing substantially toward 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 (GHG) emissions. This tendency was manifested by European policymakers in Renewable Energy Directive (RED) 20–20 in the EU energy targets for 2020 climate and energy policy, including 20\% reduction of CO\textsubscript{2} emissions, 20\% of energy coming from renewables, and 20\% increase in energy efficiency by 2020 (European Parliament 2009). Its recast is currently under discussion at the 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 a program 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; Diaz-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 (Aguilar et al. 2014; Blennow 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 favorable conditions and vary in intensity and extent (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, recent changes in energy carriers and technologies for the use of wood could result in some currently neglected practices becoming sustainable and highly desirable in the near future (Walmsley & Golbold 2010; Anerud et al. 2011). 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-dimensional assortments of wood, such as thinnings. 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 in accessing remote places and/or rough terrain, as well as in obtaining enough bulk material of biomass as a side product of regular felling for roundwood (Díaz-Yáñez et al. 2013; Routa 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 to negotiate contracts with the forest industry (Díaz-Yáñez et al. 2013).
- Last but not least, forest wood chains (FWC) must be competitive in terms of economic and energy balance (Laitila and 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 the EY level. What are the impacts of the technology innovations on GHG emissions, energy use and energy savings, turnover (calculated as value added), and employment? How

![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.](image)

| Country group | Total potential volume [1000 m$^3$] | Pre-commercial [1000 m$^3$] | Stemwood [1000 m$^3$] (Harvestable) | Harvest residues [1000 m$^3$] | Stumps [1000 m$^3$] |
|---------------|----------------------------------|----------------------------|-----------------------------------|-----------------|-----------------|
| CEU           | 522,000                          | 3299                       | 201,905                           | 33,734          | 0               |
| EEU           | 146,693                          | 3054                       | 126,213                           | 17,426          | 0               |
| NEU           | 262,028                          | 4082                       | 215,016                           | 29,560          | 9398            |
| SEU           | 70,462                           | 928                        | 58,270                            | 11,264          | 0               |
| EU            | 1,001,183                        | 1,362                      | 601,404                           | 91,985          | 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 felling |
much can these improved technologies contribute toward 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, GHG 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).

Materials and methods

Current value chains and technical improvements

Typical value chains for harvesting primary domestic biomass (i.e. no import) have been modeled for four EU regions:

- Northern EU (NEU): Estonia, Finland, Ireland, Latvia, Lithuania, Sweden, UK
- Central EU (CEU): Austria, Benelux, Denmark, France, Germany
- Southern EU (SEU): Bulgaria, Italy, Portugal, Romania, Spain (no data available for Cyprus, Greece, Malta)
- Eastern EU (EEU): Czech Republic, Hungary, Poland, Slovak Republic, Slovenia

This study focuses on small-dimension timber (SDT) supply chains producing harvest residues (tops, branches, full trees below 8 cm diameter at breast height) 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 are also major differences in reporting practices among the various countries. The input information reflecting dominant forest biomass supply chains was collected from scientific literature (Szewczyk and Wojtala 2010; Kent et al. 2011; Diaz-Yáñez et al. 2013; Murphy et al. 2014; Asikainen et al. 2015), as well as from statistics (FAOSTAT, Finland, Lithuania, 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, for national percentage of predominant operation systems and Table 1 for potential volumes per assortment. Table 7 These are currently the best available characterization 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 (1) increased volumes of harvesting timber and resulting additional biomass (compare Annex 1 and 2), and (2) a shift in technology towards more mechanization and carefully selected technological innovations. These scenarios were compared to the baseline. Potentials and removals were calculated in pairs for all presented time steps. Only the following scenarios were presented in this paper:

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

Volumes of additional material supply (see next section and Figure 1) 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 technological improvements (see technological scenarios). All values are aggregated based on volume-weighted averages throughout Europe (for details, see Annex 2).

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, and 2030, and for potentials for the same years. 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 modeled 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 follows:

- 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 2 (3) for removal and potential volumes for 2010, 2015, 2020, 2030).
2010 reference
The basis for “2010 potential” is the “Real Forest B2 Reference potential” from EFSOS II (2010 constraints) see Table 1. 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 felling is included, but not advocated for use as bioenergy.

2010, 2015, 2020, 2030 B2 wood energy+ scenario for potential and removals
For modeling these years, the calculated “B2 Wood energy+ potentials” were based on the “B2 Promoting wood energy potential: High mobilization scenario” from EFSOS II with the adjustment to include pre-commercial volumes in the potential.

For the “B2 Wood energy+ removal,” only two-thirds 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.

Upon closer inspection, we determined the volumes (in $1000 \text{ m}^3$) that can be expected from European forests for 2010 and 2030 (see Figure 2).

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 toward increased mechanization (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 Transport (HCT) or the Antti Ranta trailers – due to their increased payload. On a similar note, enlarged-space forwarders

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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. Assumes that 2/3 of pre-commercial thinning can be harvested and extracted. These volumes are additional material for removal from thinning and final felling.
Economic, environmental and social impact evaluation

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

1. SIA using the ToSIA 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 proven to be open for including new indicators. It has also been applied to compare biomass value chains with fossil oil chains (den Herder et al. 2012; Tuomasjukka et al. 2017).

2. SIAs in ToSIA compare relative impacts (e.g. EUR/process unit) and absolute impacts (e.g. 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; Lindner et al. 2012; den Herder et al. 2012; Berg et al. 2014). The following indicators were calculated according to practices presented in Berg (2011): value added (EUR), energy use (kWh), GHG emissions (CO₂ equivalents), and employment (full-time 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 GHG emission indicators for LCA-based methods to be included in the comparison of impacts, as described in Tuomasjukka et al. (2017) and below.

3. 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 approach (Swedish Environmental Management Council 2000) was added to the ToSIA method in the form of energy use and GHG emission indicators, reflecting direct and indirect impacts. LCA is one of the oldest approaches for environmental assessments, and it is ISO standardized (ISO 14040).

4. An approach adopting European Sustainability Criteria for minimum GHG savings, the ESC as currently under discussion for the revision of the RED (European Commission 2016), was further added to ToSIA. ESC is an indicator comparing value chain impacts in terms of GHG 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 m³ and available 40.6 million m³ in 2010, to available 161.5 million m³ in 2020, and available 168.6 million m³ 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.

Turnover in feedstock supply

The volume-weighted average of forest biomass for energy is presented in Table 4.

Reduction in fuel consumption

Harvesting

The fuel reductions in harvesting were most pronounced for the following systems: most successful was the introduction of the NAARVA 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 m³/h and fuel consumption of 1.7 L/m³. The NAARVA multisystem head has reached a productivity of 7.4 m³/h and a fuel consumption of 1.5 L/m³ (12% reduction), and the MAMA felling head a productivity of 8.2 m³/h and a fuel consumption of 1.3 L/m³ (24% reduction).

The use of harvesters (6.5 m³/h at 1.7 L/m³) instead of chainsaw felling (0.7 m³/h at 0.8 L/m³) in pre-commercial thinning is less expensive, but (depending on productivity) more fuel intensive. At chainsaw productivity rates of up to 0.3 m³ per hour with a fuel consumption of 1.8 L/m³, fuel consumption is approximately the same as for mechanized felling systems. However, below this productivity rate, mechanized fellings is 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 m³/h and 1.15 L/m³ 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 37.5 (solid equivalent) m³/h (up to 46%) and fuel use dropping as low as 1.06 L/m³ (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 equaling 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 an average of 20 (solid equivalent) m³/h to 33.3 (solid equivalent) m³/h. This fuel reduction was up to 18% for mixed assortments from an average of 1.15 L/m³ (solid equivalent) to 0.94 L/m³ (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), HCT vehicles (74 t), and tilting container truck and megaliner for logs (90 t). A 74 t chip truck has a payload of 55 t 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 the conventional 0.023 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/t km to 0.012 L/t km. A 90 t timber truck has a payload of 66 t 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 optimization.

**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 L/m³ respectively, while the direct and indirect energy use were 1.96 and 1.33 L/m³ respectively. 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). Tables 6 and 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 NAARVA Grip EH28 head were used instead of a conventional head in harvesting operations.

**Calculation of RED greenhouse gas emission reductions**

The technical improvements decrease the fossil fuel consumption, which leads to reductions of GHG 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 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 GHG emissions associated with stemwood use as shown in Giuntoli et al. (2014). The selected technological innovations result in an emission reduction of 1–7% in the total supply chain.

Table 10 shows GHG emissions reductions calculated as ESC compared to a fixed FFC reflecting the emission of a standard fossil fuel value chain, as in discussion for the revision of the RED (European Commission 2016).

In Table 11, the supply chain emissions for residues have been calculated in a similar way as above for whole trees (undelimed 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.

In the context of the GHG emissions 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 0.04–0.06% in total GHG savings, simply because the fossil reference emissions are quite high (80 g CO₂/MJ) compared to the already very low emissions of the wood residue supply chain (1.32–1.37 g CO₂/MJ).

**Increase in manpower**

Relative additional employment for forest biomass for energy supply chains is 0.00097 FTE/m³ for pre-commercial thinning, 0.00069 FTE/m³ for harvest residue supply chains, and 0.00018 FTE/m³ for stump supply chains. “Additional” here means on top of the traditional roundwood forest wood chains: pre-commercial thinning by a harvester, forwarding of harvest residues, pre-commercial thinning of whole trees and stumps, chipping of these, and transport of chips to heat plant. These relative impacts of FTE/m³ are multiplied with the material passing through those chains (compare to Table 8, volumes in million m³ for forest biomass for energy). As a result, depending on the amount of additionally mobilized biomass modeled for 2010 to 2030, the increment in full-time workers for increased biomass harvesting could reach 10,054 FTE in 2010, 18,434 FTE in 2015, 23,230 FTE in 2020, and finally 23,266 FTE in 2030 (see Table 12).


**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?**

Modeled feedstock supply changes can vary greatly across the specific European countries included in this study, both in volume 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 increased transport costs. These constraints were not explicitly modeled in the construction of the supply scenarios. However, a 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 considerable 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 added value in the feedstock supply must be considered with caution, given the price that can be obtained for the feedstock itself (value of timber) as well as the income to supply chain operators for offering their work as a service (value of service). Economic feasibility differs strongly from country to country, based on local conditions.

The values calculated in this study indicate a potential hypothetical economic added value 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 modeled 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; they are based on a number of assumptions, so the results should be interpreted with caution.

It should be noted that there are cost differences within country groups. Especially within the Nordic country group, cost differences are large (Nordic versus 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 CEU and EEU.

The theoretical cost supply calculations presented here take new innovative machinery into account and are based on trials and prototype demonstrations 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 realized only in the case of widespread adoption, which is not the case yet, since sufficient machines and trained workers are not necessarily available on 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 (1) no statistics exist at all; (2) there is almost full coverage of data, but not exactly for the right parameters; or (3) data exists 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, 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 response 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 and Erler 2011). This especially applies for innovative machine systems, where only one or two studies of a completely new system were available. That impacts the accuracy and

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

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

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

| 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. Value of forest biomass for energy supply chains per scenario.

| 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. Energy use of selected innovations.

| Forest operation                          | Direct fuel consumption innovative solution (L/m$^3$) | Direct and indirect fuel consumption (LCA) (innovative solution) (L/m$^3$) |
|-------------------------------------------|--------------------------------------------------------|--------------------------------------------------------------------------|
| CEU Thinning with harvester with MAMA head in CTL system* | 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 harvesting method where trees are felled, delimbed, and cross-cut into various assortments directly at the felling site.

### Table 6. Direct and indirect energy use of selected supply systems.

| Forest operation          | Reference Direct Energy Use (reference case) | Reference 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. kgCO$_2$eq from direct and indirect energy use of selected supply systems.

| Forest operation          | Reference Emissions for reference case with only direct energy use | Reference 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. Fuel consumption reduction of selected innovations.

| Innovation                                  | Fuel consumption reference case (L/m$^3$) | Fuel consumption innovative solution (L/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                                                |
representativeness of the chosen systems and the accuracy of the attached data. Nevertheless, Annex 2 (1) currently represents the best (available) data for European bioenergy systems in use.

In summary, forest biomass from SDT assortments has a potential to contribute toward 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 owners in terms of sales of timber from tending operations that 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 (1)
how much fossil fuel can be replaced by renewables; (2) how much more efficient in terms of reduced emissions and energy use these bioenergy chains are in comparison with current ones (energy use versus energy generation); (3) if forest production remains sustainable; and (4) co-benefits of using low-quality wood assortments as the possibility in indirectly supporting forest management operations to improve forest stand quality.

Following the ESC, the emissions of the supply chain can be compared with the FFC that represents the average carbon emissions of the fossil supply chain that are replaced by bioenergy. According to the European Commission (2014), the FCC of fossil heat production is 80 g CO₂/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 the use of wood energy replacing wood energy for fossil fuels in heat generation.

In this study, ToSIA and LCA methods were used side by side to assess the energy use and GHG 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 CO₂ 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 GHG 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/m³ for direct impact to 254.9 MJ/m³ for the LCA-based 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 GHG emissions. A current limitation of the LCA method is that there are only indirect impacts for the procurement of fossil fuel to run the machine (Lindholm et al. 2010). However, data is missing on other parts of upstream chains – such as maintenance of the road network, production of machinery or resource extraction to machinery (Berg and Karjalainen 2003). Global Warming Potential (GWP) and GHG emission calculation are very similar, with the main difference that for GWP calculations not only the GWP of CO₂ is included (72 g MJ⁻¹) but also of N₂O and CH₄ with according lifetime factors, which account for an additional 1.098 g MJ⁻¹.

In order to get some comparison to the energy-saving potential with reference to fossil oil chains, the ESC method was applied. The emission reductions shown by using the method as presented by the 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 emissions calculation method, the FFC 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 (e.g. in Czech Republic) than if natural gas is replaced (e.g. 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 FFC; however, an average EU value is reflecting average EU-level emission savings. The emission value of natural gas, for instance, is 56 g CO₂/MJ, which is 30% below the fossil fuel comparator of 80 g CO₂/MJ; while the value of coal is 95 g CO₂/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 once they are established in the field (Lindholm 2005). Furthermore, other factors – such as transportation distance – play a role in the energy efficiency of forest wood supply chains. In this study, only rough average transport distances were used. With an increase in distance, CO₂ emissions also increase. Ranta et al (2006) mentioned the importance of the location of the comminution phase, as it defines the form of material for the next supply chain step: 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 525,000 (in EU28). Moreover, more than 2.8 million employees work in professions that are dependent on forest products – such as manufacture of furniture, paper, and other wood-based materials. Asikainen et al. (2011) estimated employment in forest harvesting operations for increased biomass for energy harvesting with a total of 40,000 persons.

This study contributes to workforce and work demand estimations at EU level. The modeled increase in the amount of bioenergy harvesting can create the opportunity (and probably even the need) to enlarge the number of employed persons in the field of forestry by up to 23,266 FTE persons by 2030 for the modeled value chains and harvesting volumes. As already mentioned, additional employment in forest biomass for energy supply chains comparing a traditional approach varies between 0.00018 and 0.00097 FTE/m³ depending on the harvesting technology. Expected increase in removals from current 27 million m³ to 169 million m³ in 2030 could provide from 25,500 to 137,700 new FTEs by 2030.
Depending on how quickly this increase in harvesting volume for bioenergy takes place, there will be also a demand for suitable workers. Whether, and how rapidly, markets can react to this demand in training skilled and qualified operators is outside the scope of this study. The possible deficit 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 contribute to the purchasing power of rural areas.

**Conclusion**

This paper takes into 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 most 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 GHG emissions – can be expected with better-mechanized tools. However, the practical applicability of different modern technologies is highly variable over Europe due to factors including forest stand structure, topography, and 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 likely result in adverse sustainability impacts and not be feasible to cover in terms of costs and energy use, or could simply be 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 GHG 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 separately and more transparently in the comparison. Absolute stand-alone values for environmental impacts – such as GHG emission, energy use, and energy saving – can be misleading. For this reason, a more holistic approach – on that explicitly quantifies direct impacts and clarifies the magnitude of direct plus indirect impacts – is recommended by the authors. In this study, SIA plus LCA extension as separate indicators revealed assumptions of indirect impacts included in LCA methods and the magnitude of those. The ESC-based method was a useful extension to the integrated SIA and LCA indicators, as here a renewable value chain was pitched against a standard FFC 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 also become a very relevant indicator for solid biomass applications. If the GHG reduction threshold is not met, the bioenergy does not count toward EU targets. Since 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 if it is to be successful on the EU market. This study highlighted the potential of the most promising technologies for EU-wide application.

**Notes**

1. In Tuomasjukka et al. (2017) the calculation of ESC is explained. In contrast to this paper, however, that paper refers to “European Sustainability Criteria,” as they were under discussion in that form at the time it was written. The calculation method has not changed, only the name.
2. 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.
3. 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 that are not connected to a district heating network (Den Herder et al. 2012). Tuomasjukka et al. (2017, p. 116) 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.”
4. “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” interpreted as the value (= price) of the service provided by an entrepreneur for forest operations.
5. Tuomasjukka et al. (2017, p. 116) 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.”

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Annex

Annex 1: Baseline of typical current (2010) forest wood chain (FWC) in Europe. The focus is on bioenergy supply chains. Gray 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 Table 3. Volumes per process are given as 1000 m³.
Annex 2: Forest operation systems in use across Europe

(1) 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.

(2) Potential 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, delimbed and cross-cut into various assortments directly at the felling site.

(3) Overview of potentials and removal volumes at EU level for study per assortment for 2010, 2015, 2020, and 2030.
| Country    | MIPS/SEA [2010] | MIPS/SEA [2010] | Harvest residues (ha/1000m³) | Biomass thin tree (ha/1000m³) | Biomass STL (%) | Biomass WTS (%) | Biomass STL (%) | Biomass WTS (%) | Transport (tonne) | Post-harvest (%) |
|------------|-----------------|-----------------|-------------------------------|-------------------------------|----------------|----------------|----------------|----------------|----------------|-----------------|
| Austria    | 322 958         | 278 382         | 43 775                        | 1 102                         | 0              | 0              | 0              | 0              | 0              | 0               |
| Bulgaria   | 8 128           | 6 409           | 1 590                         | 123                           | 0              | 0              | 0              | 0              | 0              | 0               |
| Czech      |                 |                 |                               |                               |                |                |                |                |                |                 |
| Republic   | 25 111          | 21 228          | 3 279                         | 604                           | 0              | 9              | 60             | 31             | 0              | 0               |
| Denmark    | 3 971           | 3 316           | 3 778                         | 77                            | 0              | 10             | 90             | 95             | 0              | 0               |
| Estonia    | 13 122          | 11 995          | 805                           | 821                           | 0              | 0              | 5              | 95             | 0              | 0               |
| Finland    | 85 508          | 70 810          | 9 491                         | 1 051                         | 3 556           | 0              | 0              | 100            | 0              | 0               |
| Germany    | 103 242         | 84 365          | 16 151                        | 2 727                         | 0              | 0              | 53             | 47             | 0              | 0               |
| Ireland    | 3 123           | 2 833           | 239                           | 51                            | 0              | 0              | 5              | 95             | 0              | 0               |
| Italy      | 26 742          | 23 179          | 3 526                         | 36                            | 0              | 0              | 85             | 15             | 0              | 0               |
| Latvia     | 18 390          | 15 742          | 2 427                         | 221                           | 0              | 0              | 25             | 75             | 0              | 0               |
| Lithuania  | 10 543          | 8 959           | 1 377                         | 208                           | 0              | 0              | 71             | 29             | 0              | 0               |
| Netherlands| 1 482           | 1 362           | 98                            | 23                            | 0              | 0              | 20             | 80             | 0              | 0               |
| Poland     | 58 414          | 50 529          | 6 973                         | 912                           | 0              | 0              | 95             | 5              | 0              | 0               |
| Portugal   | 10 802          | 8 760           | 1 843                         | 199                           | 0              | 0              | 90             | 0              | 10             | 0               |
| Romania    | 32 536          | 28 215          | 3 642                         | 678                           | 0              | 0              | 98             | 2              | 0              | 0               |
| Slovakia   | 11 384          | 9 368           | 1 557                         | 459                           | 0              | 0              | 100            | 0              | 0              | 0               |
| Slovenia   | 8 433           | 7 713           | 612                           | 108                           | 0              | 0              | 88             | 12             | 0              | 0               |
| Spain      | 24 791          | 19 923          | 4 299                         | 569                           | 0              | 0              | 65             | 35             | 0              | 0               |
| Sweden     | 111 915         | 91 456          | 13 573                        | 1 351                         | 5 535           | 5              | 0              | 95             | 0              | 0               |
| United Kingdom | 15 455      | 13 220          | 1 648                         | 279                           | 0              | 0              | 100            | 0              | 0              | 0               |
| EU 2010 Removal | 896 351 | 85 13 1 0 0 | 1 1 0 11 54 0 62 35 3 95 | |
| Volumes at EU level (1000 m³) | Pre-commercial | Harvest residues | Stumps | Stemwood | Total removal |
|-------------------------------|----------------|-----------------|--------|----------|---------------|
| 2010 B2 EFISCEN reference removal | 11,362 | 29,268 | 3775 | 515,693 | 548,735 |
| 2010 B2 potential | 11,362 | 29,268 | 3775 | 515,693 | 548,735 |
| 2010 B2 removal | 7575 | 29,268 | 3775 | 515,693 | 556,311 |
| 2015 B2 Promoting wood energy potential | 14,361 | 117,328 | 17,794 | 615,758 | 765,241 |
| 2015 B2 wood energy+ removal | 9574 | 88,781 | 16,262 | 544,598 | 649,641 |
| 2020 B2 Promoting wood energy potential | 15,539 | 138,026 | 25,254 | 610,420 | 789,239 |
| 2020 B2 wood energy+ removal | 10,359 | 126,310 | 24,843 | 562,471 | 713,624 |
| 2030 B2 Promoting wood energy potential | 14,586 | 141,832 | 22,986 | 617,965 | 797,368 |
| 2030 B2 wood energy+ removal | 9724 | 133,009 | 25,908 | 584,363 | 743,280 |
Annex 3:

Scenario of typical technologically improved forest wood chain (FWC) in comparison to baseline. Gray 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 mechanization 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 m³.