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Sustainability Assessment of current and recommended methods

TECH4EFFECT project report

Diana Tuomasjukka, Michael den Herder, Janni Kunttu, Hernán Serrano León, Christophe Orazio, Venla Wallius, Mercedes Rois, Robert Prinz and Johanna Routa

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Summary

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The TECH4EFFECT project (http://www.tech4effect.eu/), funded by the "Bio Based Industries Joint Undertaking under the European Union's Horizon 2020 research and innovation program", is an international research collaboration of 20 partners from science and industry. The objective of the project is to enhance efficient wood production, by adapting the management of European forests to the requirements of a modern bioeconomy, and to meet new challenges such as climate change. Data and knowledge- based management will enable more efficient silviculture and harvesting, but also reduction of soil and environmental impact from forest operations with the TECH4EFFECT benchmarking system.

Within the Tech4Effect project, the baseline reference of current and most common wood value chain practices in major EU regions (Northern, Central, Southern, Eastern EU) from stand regeneration to timber at road side was defined, building on the processes and supply chains gathered in Work Package (WP)5.This was done in a process-based approach, integrating the silvicultural and operational practices with current volumes of growing stock and fellings, calculating material flows along those wood value chains and quantifying via a set of indicators their environmental, social and economic performance. In a second step, the TECH4EFFECT scenarios of increased wood mobilization (link to WP2) and improved efficiency (link to WP3) was compared against the baseline. The analysis focused on the study cases analysed in WP2, WP3 & WP4, using the Tool for Sustainability Impact Assessment ToSIA (Lindner et al., 2010). The analysis of the environmental wood chain performance considered greenhouse gas emissions (consistent with LCA methodology), energy use, and soil impact indicators. Social impacts were studied in terms of employment effects and occupational safety. The economic performance of the alternative wood value chains was analysed with cost-benefit analysis. Indicators as well as data needs for calculating these pan-European indicator values was harmonised in close cooperation with WP5.

This deliverable report consists of bottom-up upscaling from work studies and case studies to national level for selected representative countries, as well as top-down assessments at EU level and disaggregated impacts for four regions: Northern EU (NEU), Southern EU (SEU), Eastern EU (EEU) and Central EU (CEU). These impacts have been cross referenced to the Tech4Effect goals:

Efficiency goals of 20% reduced production costs, 15% reductions in fuel consumptions, less environmental impacts (soil damage) and 2% increased forest (yield) productivity.

These goals are discussed per impact category and technological solution. In addition, digitalisation and biofuels are assessed and discussed as options to mobilise timber at reduced environmental impact.

Keywords: Scenario, value-chain, material flow, wood harvesting, wood operations, digitalization

Tiivistelmä

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TECH4EFFECT (http://www.tech4effect.eu/ on kansainvälinen tutkimusyhteistyöhanke, johon osallistuu 20 partneria sekä tutkimuslaitoksia että käytännön toimijoita. Hanketta rahoittaa Bio-based Industries Joint Undertaking (BBI JU). Hankkeen tavoitteena on tehostaa puuntuotantoa mukauttamalla Euroopan metsien hoito nykyaikaisen biotalouden vaatimuksiin ja vastaamaan uusiin haasteisiin, kuten ilmastomuutokseen. Tietoon ja tiedonsiirtoon perustuva metsänkäsittely mahdollistaa tehokkaammat metsänhoidon ja puunkorjuun menetelmät, mutta vähentää myös metsänhoitotoimien maaperä- ja ympäristövaikutuksia.

TECH4EFFECT-hankkeessa määritettiin ensin nykyisten, yleisimpien hankintaketjujen nykytila keskeisillä EU-alueilla (Pohjois-, Keski-, Etelä- ja Itä-EU) metsänuudistamisesta tienvarteen korjattuun puuhun asti. Tämä tehtiin työpaketti 5:ssa kerättyjen prosessien ja arvoketjujen pohjalta hyödyntäen prosessikeskeistä lähestymistapaa, jossa metsänhoito- ja metsänkäsittelymenetelmät yhdistetään nykyisiin puusto- ja hakkuumääriin. Näiden hankintaketjujen materiaalivirrat laskettiin ja niiden sosiaaliset sekä ympäristö- ja talousvaikutukset määritettiin valittujen indikaattorien avulla. Seuraavassa vaiheessa TECH4EFFECT:ssä luotuja skenaarioita puun mobilisoinnin lisäämisestä (Työpaketti 2 ja tehokkuuden kasvattamisesta (Työpaketti 3) verrattiin nykytilaan. Analyysi keskittyi työpaketeissa 2, 3 ja 4 tehtyihin case-tutkimuksiin ja siinä hyödynnettiin ToSIA-työkalua (Tool for Sustainability Impact Assessment, Lindner et al. 2010). Puuarvoketjujen ympäristövaikutusten analyysi huomioi kasvihuonekaasupäästöt (LCA-metodologian mukaisesti), energiankulutuksen ja maaperävaikutukset. Sosiaalisten vaikutusten arvioinnissa analysoitiin työllisyysvaikutuksia ja työturvallisuutta. Vaihtoehtoisten arvoketjujen taloudellisia vaikutuksia selvitettiin kustannus-hyötyanalyysin avulla. Näiden paneurooppalaisten indikaattorien laskentaan tarvittava data ja indikaattorit yhdenmukaistettiin yhteistyössä työpaketti 5:n kanssa.

Tämä raportti koostuu tapaustutkimusten skaalaamisesta kansalliselle tasolle valituissa maissa sekä EU-tason vaikutusten eriyttämisestä neljälle EU-alueelle: Pohjois-, Keski-, Etelä- ja Itä-EU. Vaikutuksia on peilattu TECH4EFFECT-projektin tavoitteisiin: 20 % alhaisemmat tuotantokustannukset, 15 % vähennys polttoaineen kulutuksessa, pienemmät ympäristövaikutukset (maaperän vahingoittuminen) ja 2 % suurempi metsän tuottavuus (saanto). Tavoitteita pohditaan jokaisen vaikutusluokan ja teknologisen ratkaisun osalta. Raportissa käsitellään lisäksi digitalisaation ja biopolttoaineiden mahdollisuuksia puumateriaalin mobilisoimiseksi pienemmillä ympäristövaikutuksilla.

Avainsanat: skenaario, arvoketju, materiaalivirta, puunkorjuu, metsänkäsittelymenetelmä, digitalisaatio

Contents

1. Introduction

The current society is strongly based on non-renewable fossil resources and materials. The extensive use of fossil resources has led and contributed to many complex and global environmental issues. These include environmental degradation, resource scarcity leading to e.g. problems in food and energy security, the loss of biodiversity, and climate change. Thus, finding better and more sustainable alternatives for fossil materials and products based on them is crucial in combating climate change as well as other major environmental issues.

The concept of bioeconomy is seen as a potential solution to these issues. Bioeconomy refers to moving on from our current economy based on fossil materials and resources into an economy where renewable biomass is utilized for bio-based materials, products, energy and chemicals (McCormick & Kautto 2013). Bioeconomy increases the sustainability of society, creates jobs, and enhances food and energy security as well as decreases the dependency on finite fossil fuels (McCormick & Kautto 2013). The transition towards bioeconomy requires multidisciplinary efforts from numerous sectors and actors (Bugge et al. 2016).

Bioeconomy can utilize biomasses derived from multiple sources. With new technologies and innovations, wood has proven to be an especially versatile material that can substitute fossil-based resources (e.g. Näyhä 2019). Currently, a great number of different products and materials can be derived from wood. The benefits of forest biomass include sequestering a significant amount of carbon dioxide and not competing with food production to the same extent as agricultural biomass (Ministry of Economic Affairs and Employment of Finland 2017). On the other hand, the increased use of forest resources for wood-based bioeconomy can have negative environmental impacts, too, and in recent years there has been a lot of discussion about the optimization of carbon stocks in forests and the trade-off between the increase in forest biomass utilization and biodiversity conservation (Johansson 2018). One key issue to be tackled is the availability of forest biomass; for example, not every private forest owner might be interested in harvesting trees from their forests (Kraxner et al. 2017). Depending on the site characteristics, harvesting can be expensive and sometimes inefficient. Thus, it is increasingly important to optimize and enhance the forest biomass availability with new, innovative forest management and operations practices, including digital solutions and management software. However, changes in practices aiming at increased wood mobilization and enhanced efficiency have economic, environmental and social impacts that need to be taken into account in policymaking. Moreover, it is also in the operators' and forest owners' interests to increase the efficiency and economic feasibility of their activities.

This report focuses on the sustainability impacts of selected innovative forest management and operations practices using seven European countries as case examples. The aim is to examine the impacts on the environmental and socio-economic performance of the forest value chain. The sustainability indicators used in this study include employment (social sustainability), production costs (economic sustainability), and greenhouse gas emissions (environmental sustainability). Different scenarios for forest management and operations are analyzed using ToSIA, the Tool for Sustainability Impact Assessment (Lindner et al. 2010). Focus is on finding innovations that can maintain or improve forest yield while having less environmental impacts.

2. Material and Methods

2.1. Bottom-up: Representative case studies integrated into national generic chains

2.1.1. Geographic representation and upscaling

This report combines individual case studies from seven European countries: Finland, Norway, Denmark, Poland, France, Austria, and Italy (Figure 1). The availability of data for the creation of sensible scenarios affected the choice of countries included in this study. Furthermore, the countries for case studies were chosen to represent the multiple biogeographical regions (so-called ecoregions) in Europe as well as the main EU regions (Northern, Central, Eastern, Southern) (Table 1), so that the variety of geographical conditions, tree species, and the most common forest management and operations practices in Europe were taken into consideration. Some countries included in the case studies represent more than one biogeographical region.

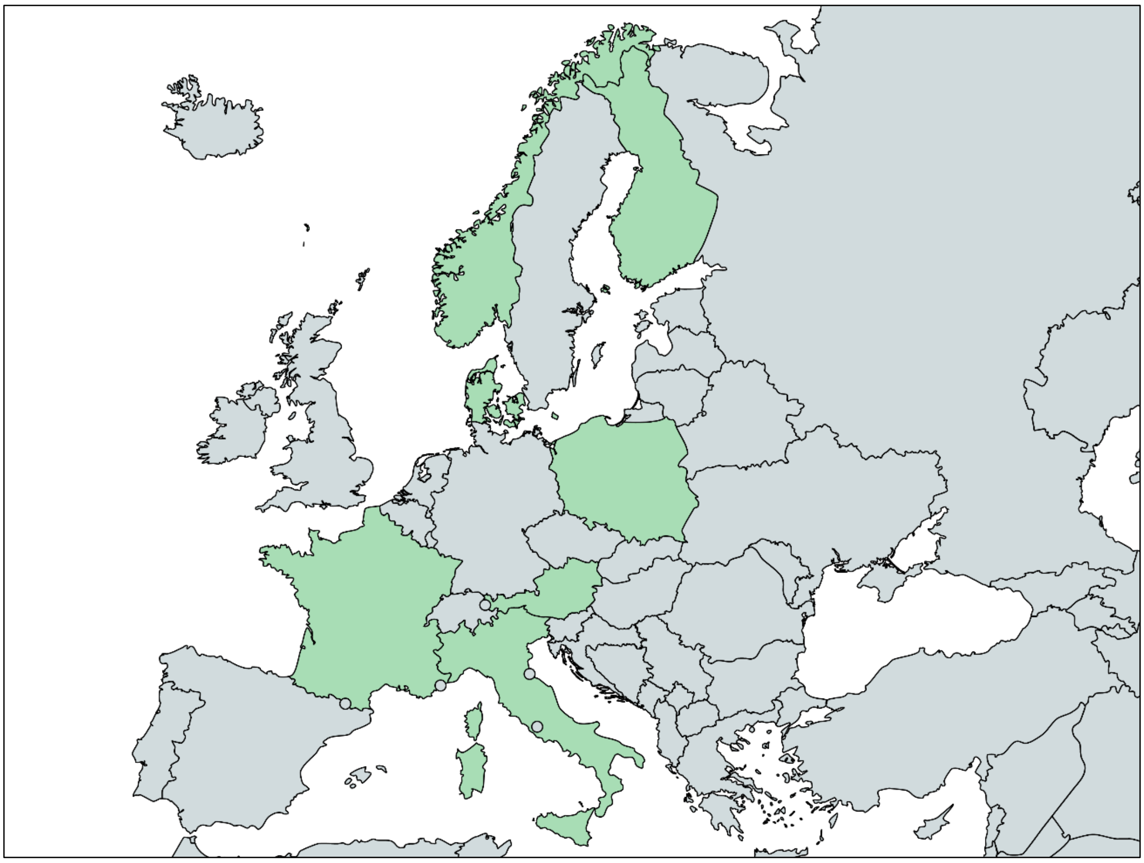

Figure 1. Countries selected for case studies. Map created with mapchart.net.

Table 1. Case studies and the ecoregions that the countries represent (dominant ecoregion bolded).

Country	Ecoregion(s)	Area
Finland	Boreal	NEU (Northern Europe)
Norway	**Boreal**, Alpine	NEU
Denmark	**Continental**, Atlantic	CEU (Central Europe)
Poland	Continental	EEU (Eastern Europe)
France	**Atlantic,** Continental	CEU
Austria	Alpine	CEU
Italy	**Mediterranean,** Alpine, Continental	SEU (Southern Europe)

2.1.2. ToSIA Method: Comparative value chains with indicators, material flow, baselines and scenarios per each country

The Tool for Sustainability Impact Assessment (ToSIA) was developed to assess the sustainability of forest-wood chains (Figure 2). Forest-wood chains consist of processes that are needed in order to convert forest biomass into products or services (Päivinen et al. 2012). Process is the element during which "the wood material changes its appearance and/or moves to another location" as stated by Päivinen et al. (2012). With the help of ToSIA, it is possible to evaluate selected sustainability impacts of changes occurring in the forest-wood chains and their operational processes (e.g. harvesting, transport, industrial processing) (Lindner et al. 2010). In ToSIA, indicators for sustainability impacts can be chosen freely. ToSIA then calculates the absolute indicator values based on the volume of material flowing to the system and its processes, making it possible to evaluate and compare sustainability impacts under different conditions in a consistent and transparent manner (Lindner et al. 2010).

In this study, forest-wood value chains were created with ToSIA for each country included. Baselines were structured according to the current forest operations and management practices. Then, indicators and scenarios were added for each country-specific value chain separately. Impacts are only direct impacts of the specific process.

It should be noticed that the 'baseline' value chains are generalized to represent certain forest types, and depending on the country, there might be several different 'current practice' value chains depending on the climate and surface conditions, tree species, and soil types, for instance. For the same reason, the baseline indicator values in the forest-wood value chains should only be used for scenario comparison in a relative scale. The indicator values in each country may vary heavily depending on the regional factors, thus they should not be considered accurate statistical representatives. The aim of the ToSIA analysis is to show the relative impact of the scenario, meaning changing a process, its indicator value, or material flow in the baseline selected to represent the reference situation.

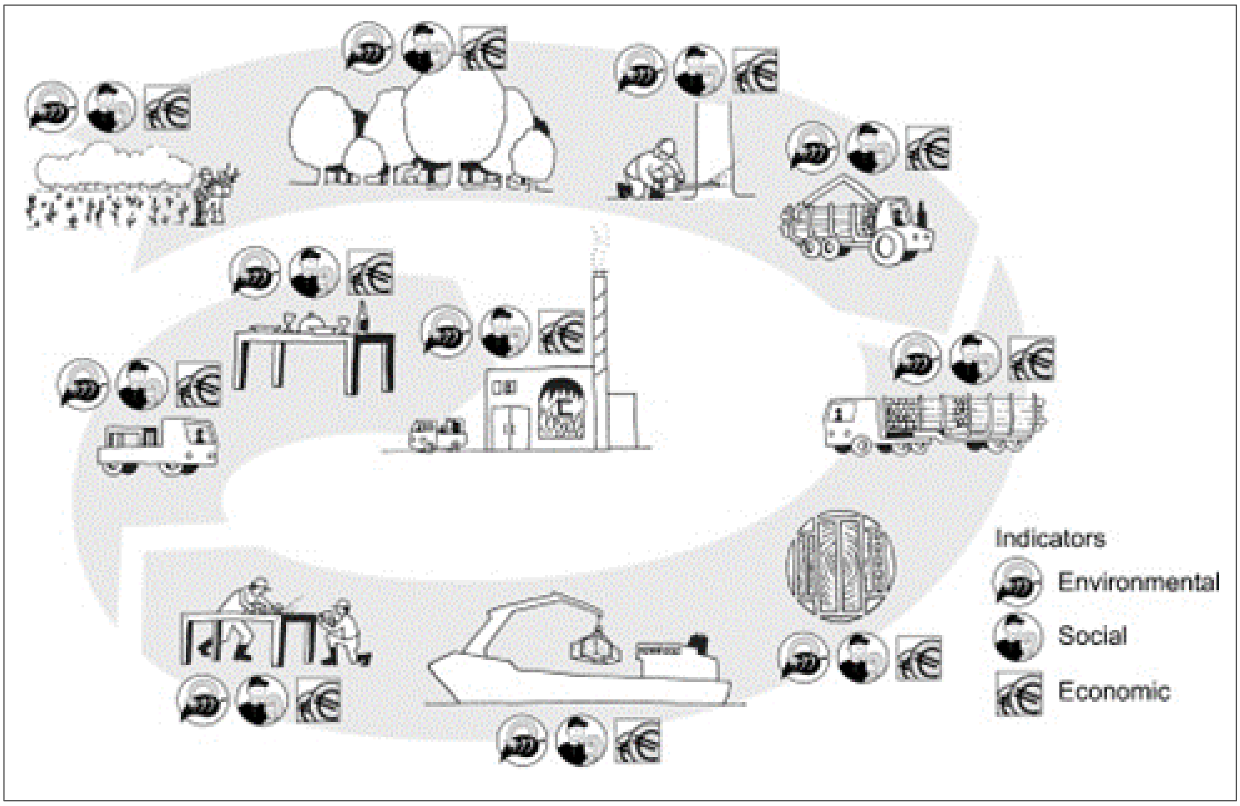

Figure 2. ToSIA analyses sustainability impacts of forest-wood-chains using economic, social and environmental indicators (Lindner et al. 2010).

2.1.3. Scenarios

Scenarios were chosen separately for each country-specific case study. Relevant literature including experimental studies as well as expert opinions were used as a reference. Scenarios included different changes in forest management and operations practices that could increase the wood biomass availability in the area. The number of scenarios per country varied from 1 to 3 depending on the availability of data for suitable scenarios (Table 2). A list of rejected scenarios can be found in Annex III.

Table 2. Scenarios included in the study.

Country	Scenario	Reference
Finland, Norway	Adjusting harvester settings	Prinz et al. 2018
Finland, Norway	Corridor thinning	Nuutinen 2017
Finland	N fertilization combined with improved breeding material	Routa et al. 2013
Norway	N and nutrient mix fertilization combined with early thinning	Holt Hanssen & Kvaalen 2018
Austria	Tree selection by harvester	Eberhard 2019
Austria	Traction winch-supported harvesting and forwarding in steep terrain	Holzfeind et al. 2018
Poland	Increase mechanical harvesting	Gruchała et al. 2019; Karol Bronisz (pers. comm.)
Denmark	Filling in empty space: Planting spruce on skidding trails	Strange & Raae 2019
Denmark	Filling in empty space: Planting fast growing hybrid larch on skidding trails	Strange & Raae 2019
France	Stump harvesting for combined risk control and bioenergy recovery.	Serrano-León et al. (unpublished)a
France	Improved breeding regeneration material	Serrano-León et al. (unpublished)b
Italy	Increase mechanical harvesting	Spinelli et al. 2020 (under preparation)

2.1.4. Volumes and indicators

For each case, a baseline was created to describe the business as usual system for forest management and operations in each country. Typically, the baseline was created for one forest stand the size of one hectare and upscaled to national level after finishing the baseline. Literature review (using scientific studies, reports, official statistics etc.) was conducted in order to determine the average volumes of material flowing into and out of the system, e.g. the share of trees to be removed in thinnings. The volumes were then modified according to the scenarios to examine the impacts of chosen scenarios.

The impacts were examined by using sustainability indicators to present the three pillars of sustainability: social, economic, and environmental. The indicators were the same for all country specific case studies and are presented in Table 3.

Table 3. Sustainability indicators used for the country case studies.

Aspect of sustainability	Indicator	Unit
Social	Employment	Full-time equivalent FTE
	Occupational accidents (only in Poland, Austria, Italy)	Number of non-fatal and fatal accidents
Economic	Operational costs	€
Environmental	Greenhouse gas emissions	CO2 equivalent
	Energy use	MJ

2.2. Top-down: EU level current and increased mobilisation volumes calculated for predominant and potential volumes and changes in technology

The European Union (EU) accounts for approximately 5% of the world's forests, and contrary to what is happening in many other parts of the world, the forested area of the EU is slowly increasing. The concept of forest used here is as defined in Eurostat (2018a), 'land with tree crown cover or equivalent stocking level, of more than 10% and with an area of more than 0.5 hectares (ha). The trees should be able to reach a minimum height of 5 meters at maturity in situ'.

For commercial timber production strict guidelines, certification and legislation exists to ensure sustainable and legal forest management, while maintaining diverse ecosystem service and natural capital functions (CICES).

Forests are one of the major natural resources in Europe, covering about 42% of the land area. With an active forest industry, most forests in the EU are managed according to principles of sustainability (Forest Europe 2015). Felling rates are at 66% of the increment and forest areas are increasing by 44000 km2 per year (Forest Europe 2015). 44% of EU territory is under Natura 2000 protection (EEA 2016), more than 60% of forests are certified. Forests and wood products – both from virgin and recycled uses – feature heavily in the circular Bioeconomy strategy (2018). To be sustainable, this demands resilient management of the European forests, while increasing material supply.

The overall level of EU-28 roundwood production reached an estimated 458 million m^3 in 2016. Among the EU Member States, Sweden produced the most roundwood (81 million m^3) in 2016, followed by Finland, Germany and France (each producing between 51 and 61 million m^3). Slightly more than one fifth (21.6%) of the EU-28's roundwood production in 2016 was used as fuelwood, while the remainder was industrial roundwood used for sawn wood and veneers, or for pulp and paper production. The total output of sawn wood across the EU-28 was approximately 100 (106 in 2016) million m^3 per year from 2010 to 2016 (Forest Europe 2015, Eurostat 2018b).

These actual fellings are contrasted by the sustainable potential of wood supply. The potential to increase wood supply is given according to calculations by Verkerk et al. 2019: forests in 39 European countries could currently provide 401 million tonnes dry matter yr^{-1} of biomass. The total potential availability of woody biomass for all uses from forest resources in the 28 EU member states is estimated at 335 million tonnes dry matter yr^{-1} overbark in 2020 and 319 million tonnes dry matter yr^{-1} overbark in 2050. By 2050, this potential could increase to 321 and 406 million tonnes dry matter yr^{-1} overbark for the Enhanced production and Improved supply scenarios, respectively. The minimum basis for these scenario calculations stipulates that the felling levels never exceed the annual increment and excludes environmentally fragile areas.

2.2.1. Geographic representation and upscaling

Typical value chains for harvesting primary domestic biomass production have been modelled for four EU regions:

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

2.2.2. Method: Comparative value chains with indicators, material flow, baselines and scenarios per each country top level figure

Basic value chains (processes):

The most common harvesting identified in this study systems were based on earlier work, such as INFRES project and improved for TECH4EFFECT:

1. Harvester and forwarder in cut-to-length method (CTL): This fully mechanized harvesting system originates from Scandinavia and represents the currently highest level of mechanization. Today, it is used across the whole Europe mainly in coniferous forests and on flat or slightly sloping terrain.
2. Recent advances in mechanization, led to winch-supported fully mechanized harvesting operations (both for harvester and forwarder). Primarily to reduce slip and associated soil disturbance by attaching a traction aid winch to fully mechanized harvesting and to increase safety during timber harvesting on slopes by mechanization. From early on, it has been used on slopes not traversable with standard harvester and forwarders without excessive soil disturbance. The number of machines in operation has increased exponentially in recent years and is expected to increase even more.
3. Chainsaw and cable yarder: This highly mechanized harvesting system is considered the most efficient system for timber harvesting on steep terrain not traversable by ground-based machinery, not even for winch-supported systems. Furthermore, it is regarded superior to ground-based harvesting systems as regards to soil disturbance. In our calculations we assumed 50:50 split between WTS and CTL system.
   For the scenario only CTL system was considered.
4. Chainsaw and skidder in whole-tree system (WTS): This partially mechanized harvesting system has been widespread in Central, Eastern and Southern Europe in the past and continues to do so especially in Eastern and Southern Europe. Further, it is a very common harvesting system in management of forest owned by farmers, where a winch is attached to a tractor primarily used for agricultural purposes. While harvesting by chainsaw can be either done in a whole-tree or cut-to-length system, we assumed a combination of chainsaw + skidding in WTS, while chainsaw CTL is combined with extraction by forwarder or cable yarder.
   For the scenario all motor manual WTS were considered to be replaced by CTL systems, and high levels of mechanization.

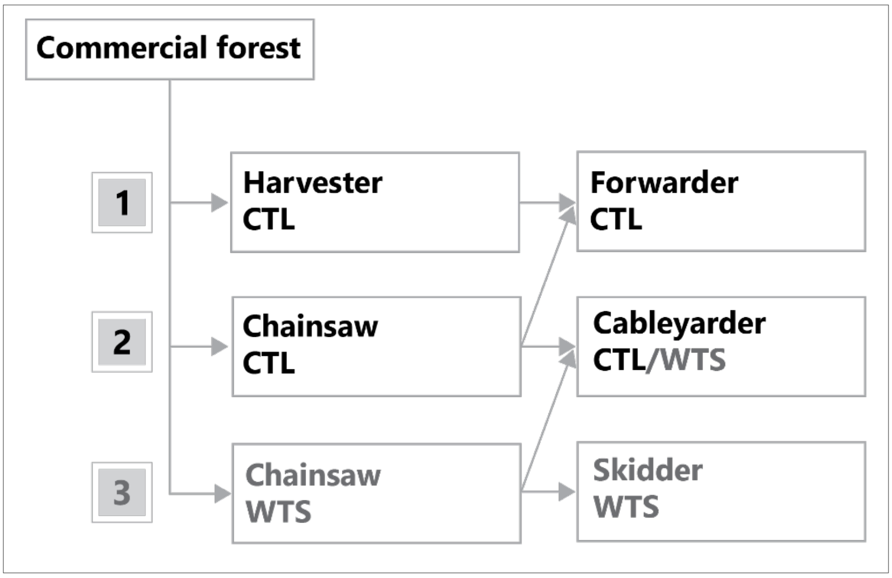

Figure 3. Baseline (black and grey processes) and scenario (black processes only) value chains assessed in this report.

3. Results

3.1. Upscaling bottom-up: baseline versus innovations per country and elaboration of importance as representative of a specific ecoregion or management system

3.1.1. Norway

Bioeconomy in Norway and role of forestry

Norway has signed and ratified the Paris Agreement in 2016 and is aiming at reducing greenhouse gas emissions 40% below 1990 levels by 2030 (Norway in the UN 2019). The target is to transform to a low-emission society by 2050. To support this, the Government of Norway has created a National Bioeconomy Strategy that was first published in 2016.

The Government's Bioeconomy Strategy of Norway has three overarching objectives: increased value creation and employment, reduction in greenhouse gas emissions, and more efficient and sustainable use of resources. Consequently, four focus areas are discussed in the strategy: i) supporting cross-cutting cooperation across sectors, ii) promoting the markets for renewable bio-based products, iii) using and processing biological resources in an efficient and profitable manner, and iv) producing and extracting bioresources sustainably (Norwegian Ministry of Agriculture and Food 2018). The strategy highlights the importance of education, research, and industry involvement. It focuses also on enabling new technologies, such as nanotechnology and ICT, to boost the modern bioeconomy.

The natural resources of Norway are extensive. During the last century, Norway has made efforts to improve the state of its forest resources after intensive logging in the 19th Century. Currently, approximately 37% of land in Norway has forest cover, with a total volume of 960 million m^3 and productive forests covering 8,144,200 hectares (Statistics Norway 2018). Norway has strong aquaculture and large fisheries. Moreover, it has relevant knowledge to support the research and development of various bioeconomy opportunities. Norway has numerous national institutes with expertise in bioeconomy, such as multiple universities, Norwegian Institute for Nature Research, and Norwegian Institute of Bioeconomy Research established in 2015 (Norwegian Ministry of Agriculture and Food 2018). Norway has stable funding programmes for bio-based industrial sector alongside with bioeconomy research and innovations (Norwegian Ministry of Agriculture and Food 2018).

The turnover of Norwegian bioeconomy is approximately 5% of total economy turnover and equals to about 36 billion Euros or 350 billion NOK (Norwegian Ministry of Agriculture and Food 2018). Food industry has the biggest value creation, followed by aquaculture and fisheries, agriculture and forestry, and the wood products industry. Traditional bio-based industries (including agriculture, forestry, fisheries and aquaculture) employ 5% of total labour force in Norway. However, this does not include the labour force working with bioeconomy in the smaller sectors of e.g. construction, textiles, and chemicals (Norwegian Ministry of Agriculture and Food 2018).

Baseline with processes, volumes and indicators

The baseline value chain is built to represent average Norwegian coniferous growth conditions. The baseline consists of full rotation of around 85 years for even-aged Norway spruce *(Picea abies*) stand and 100 years for Scots pine (*Pinus sylvestris*) stand, sized one hectare each. The site is assumed to be locating in the southern part of Norway where most of the productive forests in Norway are located. Norway uses the so-called H40 system to indicate the quality of site. In this study, the site quality is assumed to be 14, indicating that the largest trees in the site are 14m high DBH at the age of 40 years. This is categorized to represent the average, good quality stand in Norway (Statistics Norway 2018).

The forest management practices (Table 4), timing, and intensity are based on official statistics as well as guidelines for forest operators, mainly by Skogbrukets Kursinstitutt, and simulation data by Cardellini et al. (2018). Value chains for both spruce and pine start from scarification to improve seeding conditions. For pine, the typical regeneration method is seed tree regeneration where high-quality pines (on average, 60 trees per hectare) are left to grow and regenerate the area naturally. For spruce, planting is preferred. Approximately 2,000 seedlings are planted per one hectare.

Pre-commercial thinning is conducted approximately 10 years after regeneration. This is done to avoid unwanted tree species and vegetation and leave room for growth for the trees that are not thinned. Approximately 50% of the growing stock is removed in pre-commercial thinning, thus, around 2,000 trees/ha for spruce and 2,500 trees/ha for pine are left to grow. The first commercial thinning is performed when the mean height of trees is around 14m. Second thinning takes place when the mean height is around 17m. Around 32–35% of growing stock is removed in both thinnings.

The baseline is presented in Table 4 on a hectare level and then upscaled to Norwegian level. Total productive forest area in Norway is 8,144,200 hectares, however, in this study, the regions of Nordland, Troms and Finnmark in northern Norway are excluded due to their deviant topography. Protected forests were also excluded. Hence, the total productive forest area used in further calculations is 6,691,000 hectares of which 1,949,800 hectares are spruce dominant forests and 1,685,700 hectares are pine dominant forests. The rest is mixed or broadleaf dominant forests, thus excluded from scenario analysis.

Table 4. Baseline including processes and their hour productivity. The outflows are presented in a hectare level and scaled up to represent spruce and pine dominated forests in Norway.

Unit	Process	Productivity (process units/hour)	Outflow per one hectare (Norway spruce)	Outflow per one hectare (Scots pine)	Outflow for Norway spruce stands in Norway (ha)	Outflow for Scots pine stands in Norway (ha)
ha	Scarification (forwarder and ripper)	0.5	1	1	1.949.800	1.685.700
ha	Planting	0.06	1	n/a	1.949.800	n/a
ha	Pre-commercial thinning (brush saw)	0.1	1	1	1.949.800	1.685.700
m^3	Thinning 1 (harvester)	5.8	71	56	138.435.800	94.399.200
m^3	Thinning 2 (harvester)	7.3	85	75	165.733.000	126.427.500
m^3	Final felling (harvester)	20.5	260	199	506.948.000	335.454.300
m^3	Seed tree felling (chain saw)	10	n/a	11	n/a	18.542,700

The sustainability indicator values used in the baseline scenario are presented in Table 5. The employment is estimated using annual full-time employment of 1,630 hours and process-based hour productivities according to Cardellini et al. (2018). Fuel consumption of the machinery was taken from the data by Cardellini et al. (2018) and the CO_2 equivalent of machinery from Finnish statistics database Lipasto (VTT 2016).

Table 5. Baseline indicator values per process unit.

Unit	Process	Employment (FTE/process unit)	Greenhouse gas emissions from machinery (kg CO2-e/process unit)	Energy use (kWh/process unit)	Production costs (€/process unit)
ha	Scarification (forwarder and ripper)	0.00116	389	476	340
ha	Planting	0.00982	n/a	n/a	1100
ha	Pre-commercial thinning (brush saw)	0.00577	162	99.2	430
m^3	Thinning 1 (harvester)	0.000108	12.6	15.7	24.2
m^3	Thinning 2 (harvester)	0.0000847	9.9	12.3	21.3
m^3	Final felling (harvester)	0.0000299	3.5	4.35	13.1
m^3	Seed tree felling (chain saw)	0.000112	26	16.2	13.6

Scenarios with processes, volumes and indicators

The alternative scenarios are formed by applying innovative forest management methods to the baseline. The scenarios aim at either i) increasing the growth of forests and biomass production (N and nutrient mix fertilization; increased thinnings), ii) increasing the production efficiency (corridor thinning) or iii) decreasing GHG emissions from machinery (harvester settings). The alternative scenarios are based on data available from experimental studies conducted preferably in Norway, but in case the data was lacking, studies conducted in other Nordic countries (Sweden, Finland) were used. The differences in location, soil type, and other geographical restriction could not, however, be taken into account.

N and nutrient mix fertilization

Repeated (3 times) fertilization of spruce stands was used together with early, so-called bio thinning carried out when trees are 9–13 meters high. Fertilization was carried out by spreading either only nitrogen (150 kg/ha) or a mixture of nitrogen (150 kg/ha) and other nutrients (K, Ca, Mg, P, S, Cl, B, Mn, Cu). The first fertilization and thinning took place when the average height of trees was between 8 and 12 m, second fertilization after (on average) 8 years, and third one from 8 to 14 years after the second. The trees were measures 8–14 years after the third fertilization. Second, ordinary thinning was carried when the top height reached 16 m (together with third fertilization in most test sites). Third thinning was not carried out. The increase in biomass production compared to no fertilization but thinnings according to above description was 13% when using only N fertilization, and 23% when N and nutrient mix fertilization was used (Holt Hanssen & Kvaalen 2018). As the yield increases due to fertilization in the mechanized processes (thinning 1 + 2 + final felling), the average processing efficiency per unit over the whole rotation time (m^3-yr^1) increases. In the motor manual processes it remains the same.

Corridor thinning

Instead of selective harvesting, thinning using 1–2m wide corridors is adopted as a method for first thinning in pine stands (Bergström 2009). Corridors used in this scenario were assumed to be perpendicular, even though fan-shaped corridors could also be used (Figure 4). Otherwise the value chains (spruce and pine) and the volumes are the same as in the baseline. Based on a Finnish field study, hour productivity in the first thinning in pine stands increased 31.6% compared to the baseline (Nuutinen et al. 2017).

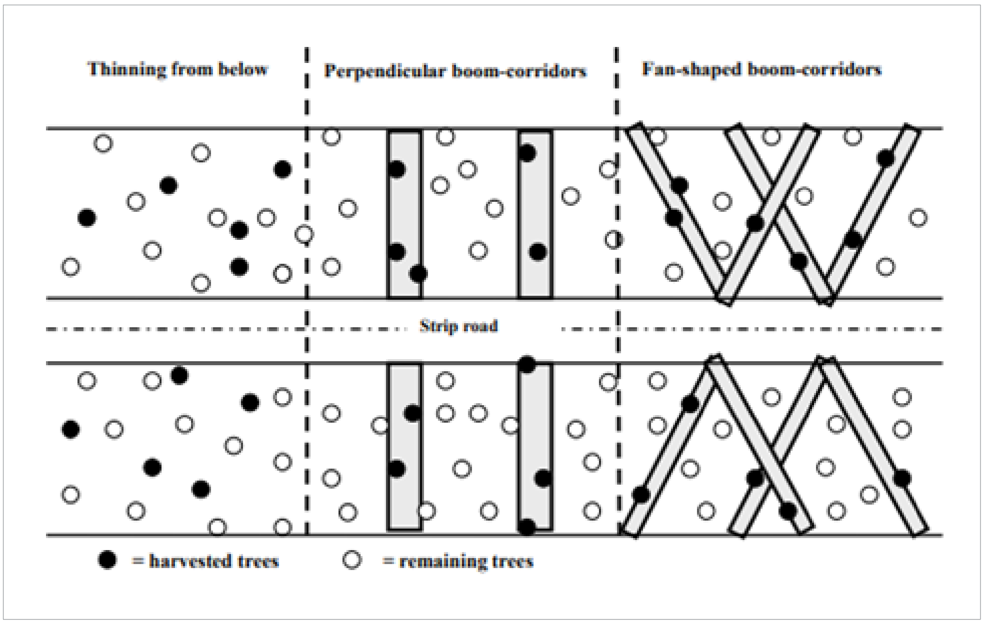

Figure 4. Corridor thinning methods (Bergström, 2009).

Harvester settings

In the mechanical thinnings (1st and 2nd thinnings) and final felling, forest harvester machine settings were switched from business-as-usual to ECO-mode. The ECO-mode was used in both spruce and pine stands. Based on a Finnish case study by Prinz et al. (2018), ECO-mode decreased hour productivity by 5.5%, but still reduced the total GHG emissions and the energy consumption on average by 1%. The volumes are the same as in the baseline.

The impact of scenarios on indicators were upscaled to country level. Annual averages are over rotations (85 years for spruce, 100 years for pine) are presented.

'Harvester settings' scenario increased production costs by 2.4%. Corridor thinning decreased costs by 2.5% and fertilization scenario increased them by 7.8% (Figure 5). However, fertilization also increases the production volumes. Employment decreased by 2.7% in corridor thinning scenario but increased by 3% in harvester settings scenario and by 8% in fertilization scenario (Figure 8). Fertilization scenario did not take the actual fertilization work into account as fertilization is typically done by forest-owners themselves and the increase is mainly from the harvesting of increased biomass, thus, the actual increase in employment might be even higher.

Annual average energy use decreased by 0.4% in 'harvester settings' scenario and by 3.7% in corridor thinning (due to increased efficiency) (Figure 6). On the other hand, fertilization scenario increased annual energy use by 10%, however, fertilization also increases production volumes significantly. The relative energy use per cubic meter decreased by 3.4% in fertilization scenario. Subsequently, GHG emissions decreased by 3.5% in corridor thinning scenario and 0.4% in 'harvester settings' scenario. Fertilization scenario increased absolute emissions by 10% compared to the baseline (Figure 7).

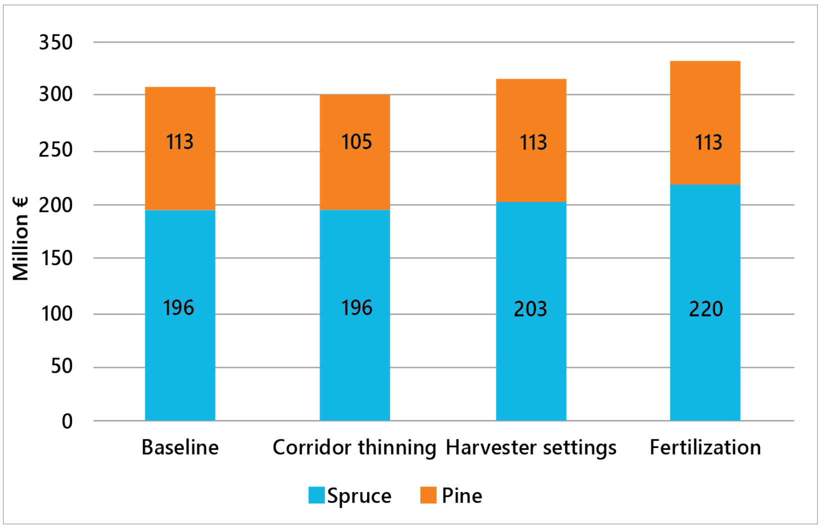

Figure 5. Annual average production costs over rotations in coniferous forests in Norway.

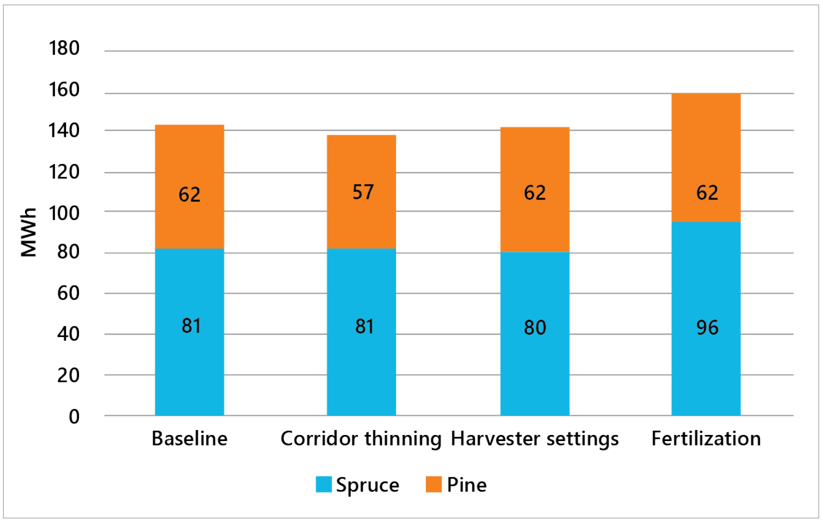

Figure 6. Annual average energy use over rotations in coniferous forests in Norway.

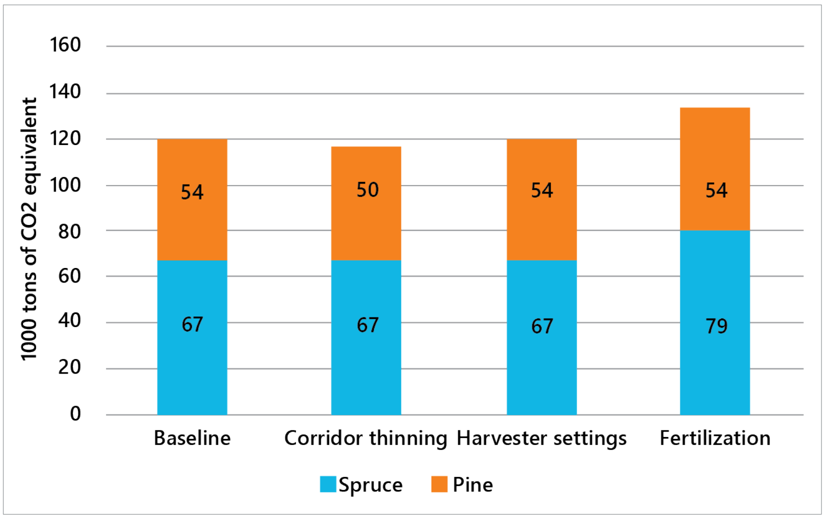

Figure 7. Annual average greenhouse gas emissions over rotations in coniferous forests in Norway.

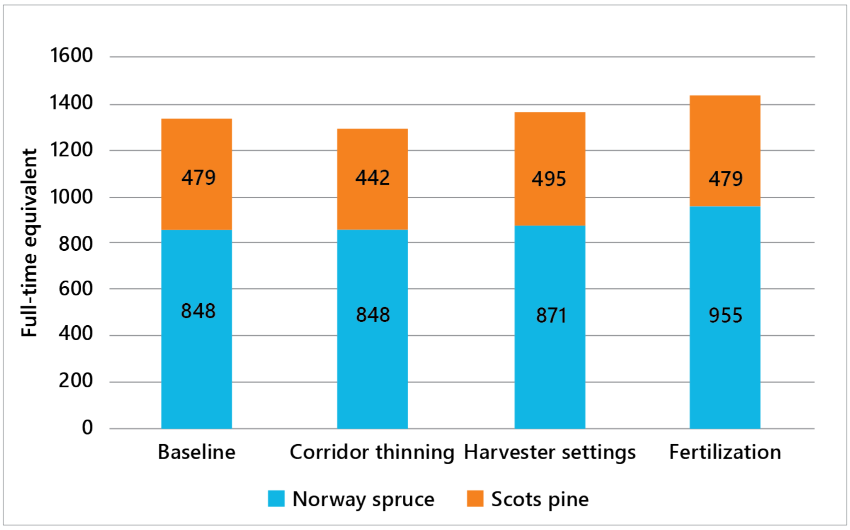

Figure 8. Annual average employment over rotation in coniferous forests in Norway.

When comparing scenario performances in relation to objectives for TECH4EFFECT project, fertilization scenario seems to have the biggest potential (Table 6), decreasing both production costs and fuel consumption (when calculated as relative values per cubic meter) while increasing forest yield. Corridor thinning and adjusting harvester settings have no impact on forest yield but can have minor reductions in both production costs and fuel consumption.

Table 6. T4E goals and achievements in the Norwegian scenarios (in relation to production volumes) in country level (in spruce and pine dominated forest areas).

T4E goal / Scenario	Corridor thinning	Harvester settings	Fertilization
20% decrease in production costs	Decreased by 2.5%	Increased by 2.4%	Decreased by 7.2%
15% decrease in fuel consumption	Energy use decreased by 3.7%	Energy use decreased by 0.4%	Energy use decreased by 3.4%
2% in forest (yield) productivity	No impact	No impact	Increased yield by 12%

3.1.2. Finland

Bioeconomy in Finland and role of forestry

The forests cover 86% of the total land area in Finland, in which 77% are forestry lands (areas preserved for forest management) (Vaahtera et al. 2018). Only 7.6% of the land area are agricultural lands (Ministry of Agriculture and Forestry, 2014). As Finland is located in boreal conditions, around half of the growing stock is pine (*Pinus sylvestris*), 30% spruce (*Picea abies*), and the rest is mainly birch (*Betula pendula or Betula pubescens*) (Vaahtera et al. 2018). The soil is mainly mineral and around 33% is peat (Vaahtera et al. 2018). Forests are in the centre of the Finnish bioeconomy, as they are the biggest renewable resource in the country.

The total domestic turnover of the forest industries was nearly 30 billion euros in 2017, representing 22% of the total Finnish industrial turnover (Vaahtera et al. 2018). The pulp and paper industry is the biggest industry in Finland and contributed nearly 80% of the whole sector's turnover (Vaahtera et al. 2018). Another major industry is sawmilling industry and continuing growing due to increasing Asian sawn wood demand. Whereas the turnover and overall profitability of forest industries continues increasing, forest sector's employment has decreased since 2015 (Natural Resources Institute 2017a). In 2018 forest sector employed in total 63,000 persons, whereas in 2015 total employment was 65,000. However, in general the employment of forest industries has increased, and the decrease is mainly in forest management operations. Digitalization and mechanization generally improve the productivities; therefore, it is natural that the nature of jobs may change. In addition, mechanization and digitalization related service-based job classification is still difficult, therefore official statistics may not offer the full picture.

It is estimated that the Finnish bioeconomy could grow to contribute in total of 100 billion euros by 2025 (Ministry of Employment and the Economy, 2014). The objective of the Finnish Bioeconomy Strategy is to ”generate new economic growth and new jobs from an increase in the bioeconomy business and from high added value products and services while securing the operating conditions for the nature's ecosystems” (Ministry of Employment and the Economy, 2014). The strategy focuses on the diversification of wood-based products and new uses of wood, and forest resource mobilization and management technologies in that sense. One of the objectives is to create new business and employment through mechanical engineering sector and equipment manufacture and increase the expertise and digital solutions in forest management technologies (Ministry of Employment and the Economy, 2014). The harvest level was nearly 80 million cubic meters in 2018 and planned new pulp factory investments may increase the wood use even more if actualized (Natural Resources Institute Finland, 2018a). Thus, it is even more important to improve wood mobilization and resource efficiency and develop low-carbon solutions for forest sector in the future.

Baseline with processes, volumes and indicators

The baseline value chain is built to represent typical Finnish coniferous growth conditions and forest management. The baseline represents even-aged Norway spruce (*Picea abies)* and Scots pine (*Pinus sylvestris*) full rotation periods of around 80 years, starting from soil scarification and planting (spruce) or sowing (pine), and ending to final felling. The site is assumed to be medium fertile locating in middle boreal conditions in Finland. The forest management practices (Table 7), timing, and intensity is based on Tapio's "Best Practice Guidelines for Sustainable Forest Management", which is an official Finnish guideline for forest management (Äijälä et al. 2014), and INFRES simulation data (Cardellini et al. 2018).

Both value chains (spruce and pine) start from scarification to improve seeding conditions. Usually in medium fertile soil types moulding is commonly used (Vaahtera et al. 2018; Äijälä et al., 2014), and forest owner can use for example excavator to implement the practise. Natural regeneration by using seed trees could be used for pine, but for spruce it is not recommended due to uncertain regeneration success (Äijälä et al. 2014). However, in this case manual sowing is used for pine, and planting for spruce with a manual tool called 'pottiputki'. In normal environmental circumstances the recommendation for pine sowing is 250–300 g seeds/ ha (Äijälä et al. 2014). To date, mechanized sowing is used in large regeneration areas, whereas planting is still carried out by hand (Vaahtera et al. 2018). However, in this case we choose manual sowing so that the differences in costs between spruce and pine value chains are less radical and therefore will not distort the analysis. For spruce, around 2,000 seedlings per ha are planted (Äijälä et al. 2014).

The tending of stand is performed to avoid unwanted tree species and vegetation, control the number of seedlings, and prevent plant pathogens such as twist rust (*Melampsora pinitorqua*) spreading to pines through aspen (*Populus tremula*). Based on recommendations, 2,000 trees/ha for pine stands and around 1,800 trees/ha for spruce stands are left to grow (Äijälä et al., 2014). Tending is traditionally made by using brush saw, although some piloting studies have already implemented on mechanized tending (e.g. Routa et al. 2020). Currently, mechanized tending still requires more piloting and development to achieve higher hour productivity. The pre-commercial harvesting is also traditionally carried out motor-manually (Vaahtera et al. 2018). In the baseline, pre-commercial harvesting is implemented, when the volume is around 20 m^3, based on Finnish recommendations on pre-commercial harvesting limit, and the estimated removal of trees is around 25% of the growing stock (Äijälä et al. 2014).

The first commercial thinning is performed when the mean height of trees is around 12m. The share of removals is calculated based on recommendations to leave 87m^3 ha^{-1} for pine and spruce stands (Äijälä et al. 2014). The second thinning is performed, when the stock exceeds 210–240 m^3/m^2 depending on the species (adjusted estimate based on INFRES results and recommendations (Äijälä et al. 2014). Trees left to grow is 167 m^3 ha^{-1} for pine and spruce stands. The final felling is performed when the pre-intervention volume is around 243 m^3 based on INFRES results and recommendations (Äijälä et al. 2014). The total timber yield in the final felling is around 220 m^3 (Table 7). The total yield of saw log and pulp wood over the whole rotation period for spruce is 332 m^3, and for pine 314 m^3, respectively.

The results are upscaled to spruce-dominated and pine-dominated areas in Finland (Natural Resources Institute 2017b), when the annual yields (total yield divided by the rotation time of 80 years) would be 21 million m^3 for spruce and 51 million m^3 for pine, respectively (Table 7).

Table 7. Baseline hour productivities and material outflows based on a process in Norway spruce and Scots pine stands. The outflows are presented in a hectare level and scaled up to represent spruce- and pine dominated forests in Finland.

Unit	Process	Hour productivity (process unit/hour)	Outflow per one hectare (Spruce)	Outflow per one hectare (Spruce)	Outflow per one hectare (Spruce)	Outflow pine forests in Finland (ha)
ha	Scarification	1	1	1	5,062,000	12,973,000
ha	Planting/sowing	0.06	1	1	5,062,000	12,973,000
ha	Tending with brushsaw	0.11	1	1	5,062,000	12,973,000
ha	Precommercial harvesting (motor manual)	0.08	1	1	5,062,000	12,973,000
m^3	Thinning 1 with harvester	5	50	40	253,100,000	518,920,000
m^3	Thinning 2 with harvester	8	65	56	329,030,000	726,488,000
m^3	Final felling with harvester	20.5	217	218	1,097,361,784	2,829,748,394

The sustainability indicator values used in the baseline scenario are presented in Table 8. The harvesting costs are based on official statistics of mechanical harvesting in Finland (Natural Resources Institute Finland 2018b). In Finland, regeneration and young forest management are traditionally non-commercial and profitless operations, and there is national funding available (KEMERA) for these activities (the Finnish Forest Centre 2019). Thus, private forest owners often implement these operations by themselves. The costs for these processes are estimated by using several sources: pre-commercial thinning based on available funding per one hectare (the Finnish Forest Centre 2019), pine sowing based on seed price (Suomen 4H-liitto 2007), spruce planting based on seedling price (Fin Forelia Oy 2019), and scarification based on unit cost presented in the study of Routa et al. (2013). The employment is simply estimated by using annual full-time employment 1,732 hours and process-based hour productivities which are estimated based on INFRES data, and the energy consumption and GHG emissions (Co2, N2O,CH4) are taken from statistic database Lipasto (VTT 2016).

Table 8. Baseline indicator values per unit.

Unit	Process	Employment FTE/unit	Greenhouse gas emissions from machinery CO2 kg equiv./unit	Energy use - Direct fossil fuel use kWh/unit	Production costs €/unit
ha	Scarification (Spruce, Pine) (Excavator/ Forest machine)	0.000577	183.70	218.17	264
ha	Planting (Spruce)	-	-	-	720
ha	Sowing (Pine)	-	-	-	140
ha	Cleaning with brushsaw	6.42E-05	1310.90	803.25	-
ha	Pre-commercial thinning (motor manual)	4.62E-05	1820.70	1115.63	160
m^3	Thinning 1 with harvester	0.000115	12.74	15.87	16.71
m^3	Thinning 2 with harvester	7.22E-05	9.95	12.40	13.91
m^3	Final felling with harvester	2.82E-05	5.24	6.53	8.18

Scenarios with processes, volumes and indicators

The alternative scenarios are formed by applying innovative forest management methods to the baseline, which aim at either i) increasing the growth of forests (N fertilization and clone trees), ii) increasing the production efficiency (Corridor thinning), or decrease GHG emissions from machinery (Harvester settings ECO-mode). The alternative scenarios utilize WP2 data gathered from field- and simulation studies. To assess the potential total impact of alternative management scenarios, the value chains are the same as in the baseline. It should also be noticed that the findings from original field- and simulation studies are generalized to a country level (spruce- and pine dominated areas), and no restrictions e.g. soil type, geographical location, etc. are considered. The differences between the alternative scenarios and baseline are presented in the below descriptions.

Corridor thinning

instead of selective harvesting a straight corridor thinning was adopted as a method for first thinning in pine stands. Otherwise the value chains (spruce and pine) and the volumes are the same as in the baseline. Based on field results, hour productivity in the first thinning in pine stands increased 31.6% compared to the baseline (Nuutinen 2017).

Harvester settings ECO-mode

In the mechanical thinnings, meaning 1st and 2nd thinnings, and final felling, forest harvester machine settings were switched from BaU to ECO-mode. The ECO-mode was used in both, spruce and pine stands. Based on the study of Prinz et al. (2018), ECO-mode decreased the GHG emissions and the energy use on average by 1%. At the same time, the study indicated that ECO-mode may decrease the hour productivity by 5.5%, but as the empirical study settings varied (tree size etc.), this was not included to country level scenario. Therefore, also impact on production costs is left out (assumed the same as in the baseline). The volumes are the same as in the baseline.

N fertilization and clone trees

Traditional Norway spruce seedlings were replaced with cloned ones, and Nitrogen fertilization (150 kg/ha) was applied after first and second thinning on spruce stands in a rotation time of 80 years. The cost of clone trees was 1,5-fold compared to traditional ones, and the cost N fertilization was 124€/ha. The annual timber yield (from the 1st, 2nd, and final felling) increased by 34%. The data was based on a simulation study of Routa et al. (2013). *Note: The yield increases due to fertilization in the mechanized processes Thinning 1 + 2 + Final Felling, the average processing efficiency per unit over the whole rotation time (m^3 yr^{-1}) increases. In the motor manual processes it remains the same.

The annual average production volume in coniferous areas in Finland, meaning the total timber yield from commercial harvesting, increased by 10% in the 'N fertilization and clone trees' scenario compared to the baseline. The spruce timber yield per year was around 28 million m^3, whereas in the baseline it was 21 million m^3. In other scenarios the production volumes remained the same, but the economic, social, and environmental sustainability impacts varied.

The annual average production costs were the highest in the 'N fertilization and clone trees', and 13.7% higher compared to the baseline (Figure 9). However, in relation to the production volumes, the unit costs per harvested cubic meter were 14% lower in the 'N fertilization and clone trees' compared to the baseline, indicating higher economic profitability. In the 'Corridor thinning' scenario the annual average production costs decreased 6.2% compared to the baseline, whereas the 'Harvester settings ECO-mode' did not have an impact at all. Similarly, in the 'Harvester settings ECO-mode' the employment impacts remained the same as in the baseline (Figure 10). Corridor thinning decreased the annual average of full-time employment by 5.1%, whereas 'N fertilization and clone trees' increased it by 9.9%. Even though in this case, the unit level employment was again lower compared to the baseline, the impacts are still positive as the total employment rate still increases due to higher production volumes. Should also be noticed that the employment of fertilization is not included to the assessment, thus the actual rate can be slightly higher.

The annual average energy use and GHG emissions increased 5.8% and 5.2% in the 'N fertilization and clone trees' compared to the baseline (Figure 11, Figure 12). However, the energy use and GHG emissions per harvested cubic meter were again approximately 21% lower due to higher average processing efficiency, compared to the baseline. The N fertilization could affect the soil emissions, but they are not included to this assessment as we are focusing on the management operations. The 'Corridor thinning' decreased both annual average energy use and GHG emissions approximately by 2%, and 'Harvester settings ECO-mode' by approximately 0.5%, respectively.

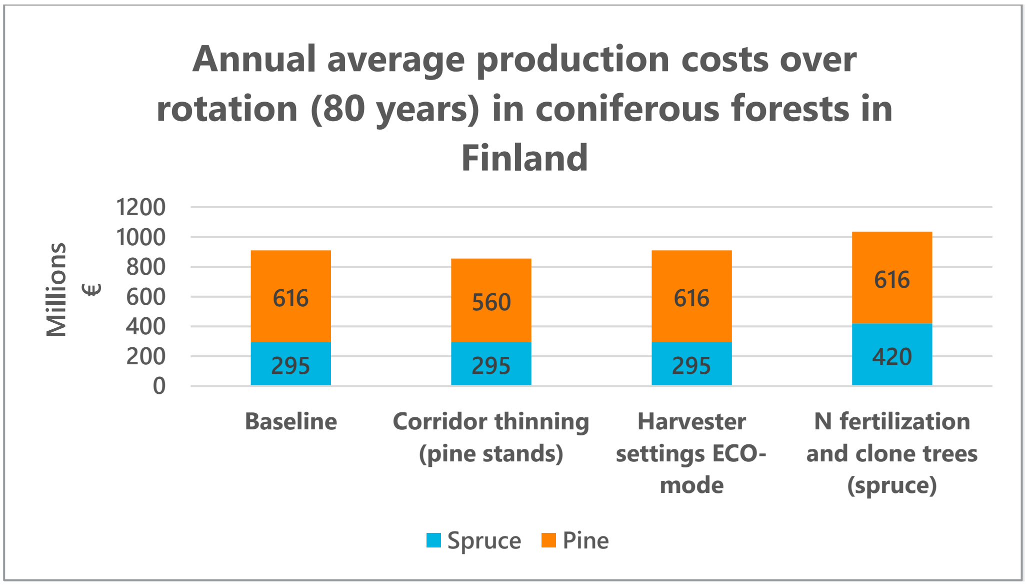

Figure 9. The average production costs per year over total rotation time (80 years) in Finland.

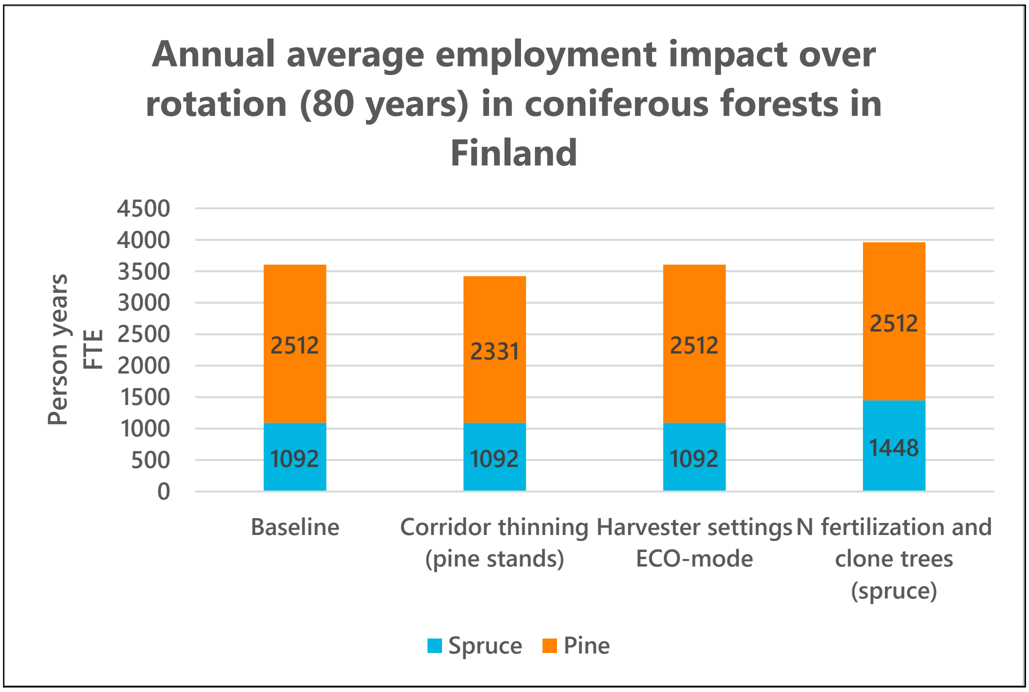

Figure 10. The average employment impact in FTEs per year over total rotation time (80 years) in Finland.

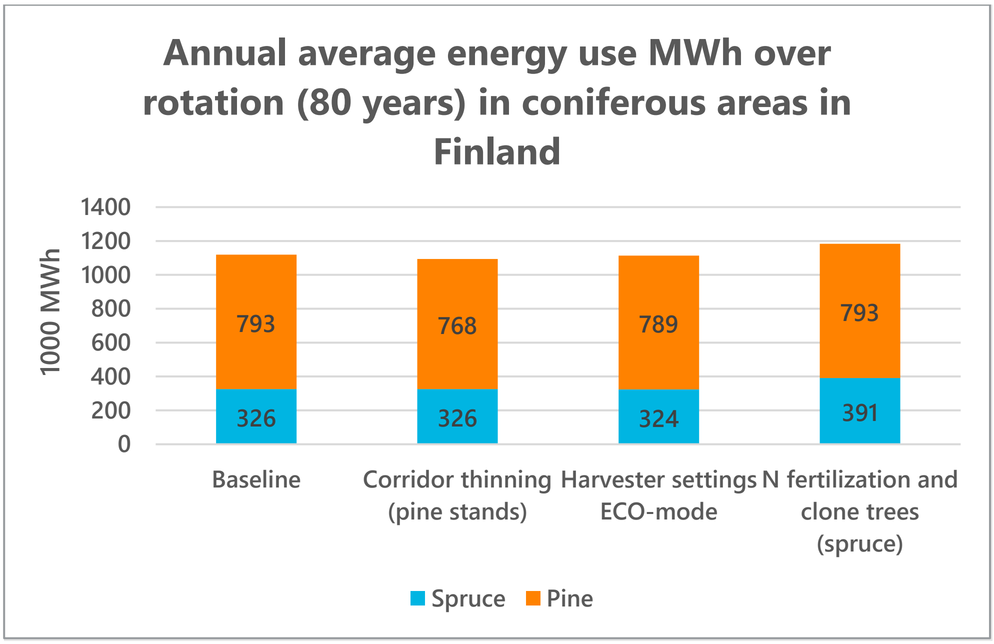

Figure 11. The average energy use (MWh) per year over total rotation time (80 years) in Finland.

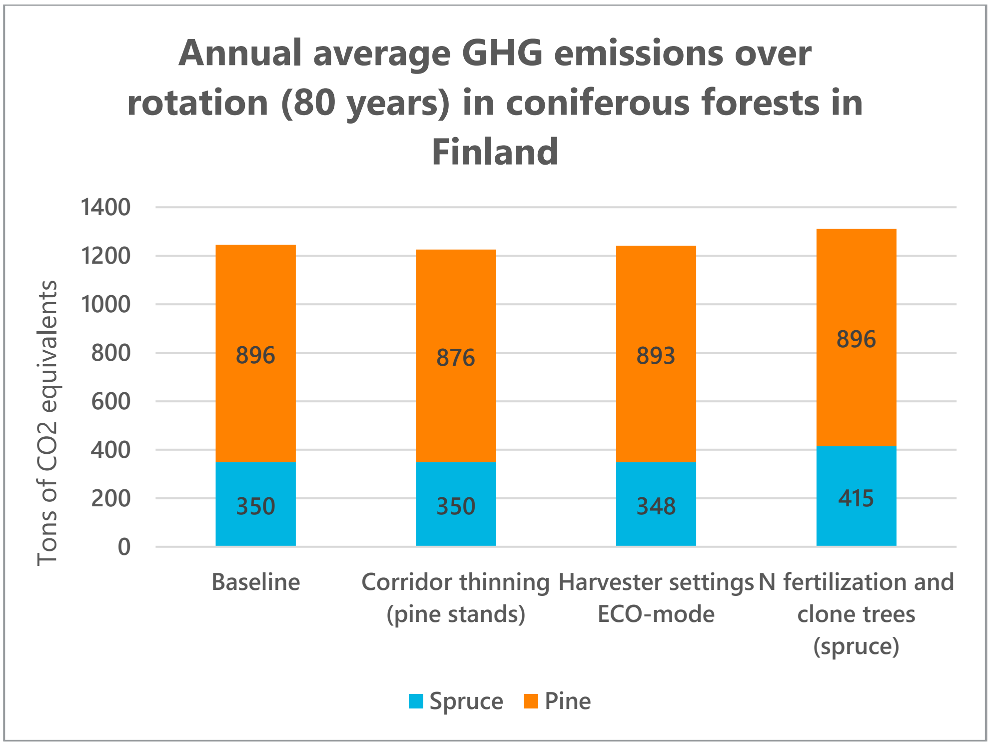

Figure 12. The average GHG emissions per year over total rotation time (80 years) in Finland.

Table 9. T4E goals and achievements in the Finnish scenarios (in relation to production volumes) in a country-level (in spruce and pine dominated forest areas). The unit-level impacts can be found in the original studies.

T4E goal / Scenario	Corridor thinning	Harvester settings ECO-mode	N fertilization and clone trees
20% decrease in production costs	Decreased by 6.2%	No impact	Decreased by 14%
15% decrease is fuel consumption	Decreased by 2%	Decreased by 0.5%	Decreased by 21%
2% increase in forest (yield) productivity	No impact	No impact	Increased by 10%

3.1.3. France

Bioeconomy in France and role of forestry

France endorsed its National Bioeconomy Strategy in 2017 as an official framework for the production and valorization of renewable resources (MAAF 2016). The priority of this strategy will focus on: i) an increased and sustainable mobilization of local biomass, which preserves the ecosystems producing raw materials (respect for biodiversity, landscapes, soil organic matter), and ii) optimizing the use and valorization of biomass produced to ensure capacity to meet food and non-food needs. This strategy aims at strengthening all value chains from multiple sectors: agriculture, forest, marine biomass, new materials, biofuels, biomolecules, bio-based materials, bioenergy, etc. It aims to raise social awareness about bioeconomy to make consumers and users more aware of these products. Their quality must be guaranteed through certification and normative standards, and their positive externalities highlighted, especially for the environment.

The National Bioeconomy Strategy is complemented by the Action Plan 2018-2020 outlining the concrete actions to be implemented (MAAF 2018). The Action Plan represents the outcome of strategic committee – the Bioeconomy Council – and a broad-based consultation process bringing together public authorities, industries, NGOs, academics and research institutes as well as local, regional and national decision makers. The Action Plan is focused on the national framework and tools likely to encourage the deployment of the bioeconomy in the regions.

The French National Bioeconomy Strategy is also consistent with the objectives of the National Forest and Wood Programme (PNFB) envisaged for the period 2016–2026, which considers the forest-wood sector as one of the bioeconomy pillars as provider of materials, chemicals, and energy derived from biological renewable resources (MAAF 2017). In addition, an ambitious National Forest-Wood Plan: Research, Development and Innovation 2025 (FBRI) aims at promoting new products and processes valorizing the French forest resource with priorities to put in place the future industry (chemicals, green industry, digital) in the context of the bio-economy (Amecourt et al. 2016).

The total turnover of the bioeconomy in France in 2015 summed up to 333 billion € (representing 15% of the total EU28 bioeconomy) and 1.56 million employed in bioeconomy (9% of the total EU28) (Ronzon and M'Barek 2018). The bioeconomy profile of France is leaded by the agriculture and food industry sectors, which generate more than the three quarters of their bioeconomy turnover. The contribution of the entire forest sector accounts for 11.8% of the total French bioeconomy turnover and 11.1% of the bioeconomy employment in 2015. The forestry sector contributes with 6.8 million € (2.1%) and 31,900 employees (2%), while the wood industry generates 14.2 million € (4.2%) and 78,400 employees (5%), and pulp-paper industry 18.17 million € (5.5%) and 54,700 employees (4.1%) (JRC-EC 2018; Ronzon and M'Barek 2018).

The forest contribution to bioeconomy is supported by the 16.9 million ha of forest covering more than 29% of the metropolitan France territory (ADEME 2018; MAAF 2016). The forest area of France includes 15.5 million ha forests for wood production, with 10.4 million ha of private forests supporting economically more than 3.3 million forest owners (MAAF-IGN 2016). Nearly half of the harvested volume is subject to sustainable management certification. From 62 million m^3 of harvested wood in 2014, 38 million m^3 were marketed for a value of 1.8 billion euros; while the energy wood consumed as solid biocombustible generated nearly 10 megatonnes of oil equivalent consumed (MAAF, 2016). Nevertheless, the felling rate in France is only around 50% of the biological production due to several factors limiting or discouraging logging of the available resource, such as forest fragmentation, growing stock in less accessible areas, increase of logging costs, and international market competition (MAAF-IGN 2016). As a result, the harvest pressure is increased on the most productive areas and conifer stands for which the removal rate is close to 100%.

The most representative of these productive areas where the processing capacity is high compared with the available resource is the Landes Massif forest in the Nouvelle-Aquitaine region. The Landes Massif consists of a large forest area of approximately 1 million ha dominated by maritime pine plantations that produces 7.6 million m^3 harvested annually, representing 24% of the national wood harvest (MAAF-IGN 2016). This large afforestation effort was originally planted in previously low productive marshes since 18th century. Decades of continuous intensification of silviculture and progress of breeding programmes has resulted on an increase of the average productivity up to 11 m^3/ha/year (Arbez et al. 2017; Bouffier et al. 2013; Mullin et al. 2011).

Despite the large area and productivity, the available resource supply is under high pressure as a result of the large catastrophic windthrows from the storms “Martin” in 1999 and “Klaus” in 2009, which cleared more than 100,000 ha and 223,000 ha respectively. In a post-storm context of limited wood production, the pressure on the wood resource is exacerbated by an increasing local demand of wood biomass for energy from 0.5 to 2 M m^3 in just 10 years (Brahic and Deuffic 2017; Emeyriat 2016; Landmann and Nivet 2014). Concretely, the wood energy demand has radically changed the industrial fabric organized around the forest of the Landes with the establishment of new players on the energy wood market, with a strong stake in structuring the players among themselves and promoting co-products in a circular logic. For example, the Regional Energy Commission (CRE) in Aquitaine have concluded contracts with almost all the paper mills and bio-refineries located in the region to develop high-power cogeneration plants, aiming to support their competitiveness with the bio-economy and energy transition.

To diversify the mobilization of the wood resource and reduce the wood-energy tension on the Landes forests, different initiatives aim to valorize underused wood resources (broadleaves, harvest residues, stump biomass) contributing to the supply of bioresources to the bio-economy sectors (Colin et al. 2009). Given the large biomass demand of these high-power cogeneration plants (consuming more than 500,000 t of biomass per year), up to 250,000 t of biomass could be covered from stumps and forest residues (Demolis and Roman-Amat 2016). As a result, the wood energy sector has found on the stump biomass a high-quality fuel resource at competitive price that is not in conflict with other uses of wood (timber, pulp), thus allowing to reduce the pressure on the wood resources for energy use while boosting the maritime pine silviculture (Demolis and Roman-Amat 2016). This extractive practice is a territorial innovation in a context of intensive forestry in large-scale planted forests with favorable conditions for stump extraction (flat terrain and sandy soils that limit the risk of erosion) (Banos and Dehez 2015; Landmann and Nivet 2014).

Baseline with processes, volumes and indicators

The baseline value chain was built to represent the standard forest management in maritime pine plantations in the Atlantic region of France, by focusing on the example of the Landes Massif. Stand-level development, harvest volumes and biomass were modelled using the forest growth model PP3 integrated in the simulation platform CAPSIS (Lemoine 1991; Meredieu 2002). The model allows analyzing the effects of alternative silvicultural scenarios on stand growth for pure even-aged stands of maritime pine depending on the site index and planting density (Salas-González et al. 2001). Growth simulations were conducted for an average fertility stand (dry mesophilic, site index 23.5m at 40 years) regenerated by seedling planting.

The standard silvicultural itinerary was simulated according to the recommended site-specific management guidelines (Sardin and Canteloup 2003). Standard silviculture consists on manual planting with a density of 1,250 seedlings/ha and four thinning operations from above with machine harvester, leading the stand to a final density of 300 trees/ha for final harvest at 45 years. Conventional practice between clearcut and stand preparation consist on leaving the stand for a fallow period of 2–3 years before reforestation. This fallow period aims to reduce the risk and damage rates of pest (*Hylobius abietis*) and root rot pathogens (*Heterobasidion annosum and Armillaria ostoyae*) that develops on stump, by taking advantage of progressive decomposition of the stump substrate (Brunette and Caurla 2016; Jactel et al. 2009).

The baseline productivity and outflow units by silvicultural process are presented in Table 10 on a hectare level and upscaled to the total productive area of maritime pine in the Atlantic regions of France. Baseline process-based hour productivities were taken from the average productivities of silvicultural regimes from the largest forest cooperative group of France (Alliance Forêts Bois, expert communication). Total productive area was estimated 943,000 ha, calculated as the total area from the large ecological regions of the National Forest Inventory (GRECO A - Grand Ouest, GRECO B – CentreNord, GRECO F – SudOuest) where maritime pine is the main species (IGN 2014). It should be noticed that the results from the growth simulation studies were generalized to extrapolate at a country level, and no restrictions nor stand variability (e.g. soil type, fertility, geographical location, climate, etc.) were considered.

Table 10. Baseline process hour productivities and material outflows in maritime pine stands in French Landes. The outflows are presented in a hectare level and scaled up to represent maritime pine dominated forests in Atlantic France (IGN 2014).

Unit	Process	Hour productivity (process unit/hour)	Outflow (process units / ha)	Outflow Maritime pine in France (process units)
ha	Site preparation after fallow period (Mechanical brushing, Full ploughing + Fertilization)	0.25	1	943,000
ha	Seedling planting	0.21	1	943,000
ha	Mechanical clearing (1,3 years)	0.06	1	943,000
m^3	Thinning 1 with harvester (including clearing of interlines)	5.39	24.8	23,358,110
m^3	Thinning 2 with harvester (including clearing of interlines)	7.90	42.0	39,643,720
m^3	Thinning 3 with harvester (including clearing of interlines)	9.70	47.4	44,735,920
m^3	Thinning 4 with harvester (including clearing of interlines)	11.18	65.9	62,181,420
m^3	Final felling with harvester	25.00	393.4	370,929,050

The sustainability indicator values used in the baseline scenario are presented in Table 11. The employment is estimated from the process-based hour productivities by considering an annual full-time employment of 1690 hours for France (INSEE 2018). Fuel consumption and costs of each silvicultural process were taken as average values per process unit from the largest forest cooperative group of France (Alliance Forêts Bois, expert communication). The energy consumption and GHG emissions were based on the average fuel consumption by machinery. Energy use of machinery was calculated from the fuel use in diesel liters per process unit, considering 35.7 MJ per liter of direct fuel use and an equivalence of 1 kWh per 3.6 MJ (Berg 2011). GHG emissions from machinery were calculated considering 73.01 g CO2-equivalent per liter of direct used diesel fuel (Myhre et al. 2013, Tuomasjukka et al. 2017).

Table 11. Baseline indicator values per unit.

Unit	Process	Employment FTE/unit	Greenhouse gas emissions from machinery kg CO2 equiv./unit	Energy use - Direct fossil fuel use kWh/unit	Production costs €/unit
ha	Site preparation after fallow period (Mechanical brushing, Full ploughing + Fertilization)	0.002367	199.39	758.63	532.5
ha	Seedling planting	0.002774	0.00	0.00	275.0
ha	Mechanical clearing	0.009231	31.58	120.14	650.0
m^3	Thinning 1 with harvester	0.000110	6.68	25.41	13.8
m^3	Thinning 2 with harvester	0.000075	4.52	17.21	10.3
m^3	Thinning 3 with harvester	0.000061	4.44	16.91	8.2
m^3	Thinning 4 with harvester	0.000053	4.05	15.40	7.2
m^3	Final felling with harvester	0.000024	2.09	7.93	4.5

Scenarios with processes, volumes and indicators

The alternative scenarios are formed by applying innovative forest management methods to the baseline. The alternative scenarios aim at either: i) increasing the production efficiency for early treatment and stand establishment (Stump extraction), or ii) increasing the growth of forests and biomass production (Improved breeding regeneration material). The alternative scenarios are based on data available from literature and simulations of silvicultural management. It should be noticed that the results from the growth simulation studies were generalized to extrapolate at a country level, and no restrictions nor stand variability (e.g. soil type, fertility, geographical location, climate, etc.) were considered.

Stump harvesting for combined risk control and bioenergy recovery

The standard practice of a fallow period between final felling and reforestation delays the reforestation actions and its effectiveness for control is limited, given that significant infestation from stumps may still occur years after felling and root rots can be maintained in the post-harvest stumps for several decades (Heritage and Moore 2001). A promising technique for effective risk prevention consists on the extraction of the stumps and coarse roots from the clearcut after final felling (Augusto et al. 2018; Cleary et al. 2013; Landmann and Nivet 2014; Vasaitis et al. 2008). In addition to its application as a management tool for health risk control, stump extraction has further technical-economic benefits in terms of forest management. It allows for faster regeneration actions, reduces the reforestation cost due to work productivity improvement and efficiency gains in site preparation operations, and allows to recover the stump biomass as a new woodfuel resource for fossil fuel substitution (Colin et al. 2009; Walmsley and Godbold 2010).

Total stump biomass was calculated from the simulated stand characteristics at rotation age using the allometric relationships estimated by Bert and Danjon (2006). Mobilizable stump biomass was assumed as 50% of available underground biomass (Colin et al. 2009) and was added to the total scenario production outflow in m^3 ha^{-1}. For the costs of stump extraction, two scenarios were considered: average direct extraction costs assumed by the forest owner (Alliance Forêts Bois, expert communication); or assuming free-of-charge stump extraction covered by the stump market contractors as a transaction for the stump biomass recovery for the energy wood industry (Banos and Dehez 2017). Both stump cost scenarios considered the cost reduction compared to the baseline as the opportunity cost from the fallow period. This opportunity cost was calculated as the difference in NPV (€/ha) between the baseline scenario considering the 2-year fallow period and the scenario with free-of-charge stump extraction.

The subsequent facilitation of soil preparation operations after stump extraction was considered as a reduction of 5% of site preparation ploughing costs corresponding to the efficiency gains estimations (GIS GPMF 2013). Control effectivity against Heterobasidion annosum and Hylobes sp. risk was considered comparable to the standard fallow practice, assuming no damage levels or mortality due to future infestation during the rotation in both baseline and stump extraction scenario. Other processes and harvest volumes of the stump extraction value chains were considered the same as in the baseline.

Improved breeding regeneration material

The maritime pine French breeding programme is one of the most advanced European programmes of tree genetic improvement, with three generations of genetically improved seed orchards based on the local Landes provenance population that provide all the currently available regeneration material in the French market (Bouffier et al. 2013; Mullin et al. 2011). While currently most of the harvested stands correspond to regeneration material from the first generation of seed orchards Landes Vigor-Forme VF1, a second generation VF2 with greater genetic gain have been recently used for large regeneration areas, especially since the massive windthrown damages caused by the storms “Martin” in 1999 and “Klaus” in 2009 (Mullin et al. 2011). The genetic gains in volume (estimated from realized gains in progeny trials at age 13 years) are expected to be 30% higher for VF2 orchards compared to the standard VF1 regeneration material (GIS PMF 2014; Mullin et al. 2011).

We considered an alternative genetic material scenario that represented the expected gains reported for the developing maritime pine breeding programme in the Landes region. The development of improved stands was simulated in PP3 by modifying the site index corresponding to the expected 30% genetic gain in mean annual increment (MAI) at the end of rotation, while applying the same timing of thinnings and rotation age as in the reference scenario. Process-based hour productivities, fuel consumption and costs for the breeding scenario were estimated as a logarithmic extrapolation of the baseline average values per process unit as a function of each process outflow in m^3 ha^{-1}.

The figures (Figures 13, 14, 15, 16) show the scenario results comparison of the sustainable indicators values per production volume unit (m^3). Employment in FTE/m^3 was only slightly increased (+0.3%) in the stump extraction scenario compared to the baseline, given the slight changes in hourly productivity (-0.3%). In contrast, the large increase in stand volume productivity per ha in the breeding scenario, which lead to a notably higher hourly productivity (+25.4%), resulted in a large reduction of the employment per volume unit (-20.3%).

Energy use and GHG emissions per volume unit were considerably reduced in the breeding scenario (-13.3%), while these indicators were slightly higher (+1.2%) in the stump extraction scenario. However, the stump harvesting scenario did not consider the fossil fuel substitution effects from the use of stump biomass energy.

Production costs per m^3 was also reduced in the breeding scenario (-13.1%), while they varied in the stump extraction scenarios depending on the assumptions. Considering that the extraction costs are covered by the forest owner, the extra unitary production costs will be compensated with the opportunity cost from reduced silvicultural rotation without fallow period, resulting on a limited change of the unitary production costs (+0.1%). In contrast, if the extraction costs are not assumed by the forest owner, the unitary production costs are lower (-1.7%) than in the baseline scenario due to the opportunity costs of the fallow period. Nevertheless, it is important to note that none of the scenarios considered the additional costs (hourly, fuel, €) from timber and stump forwarding and loading onto trucks after harvest.

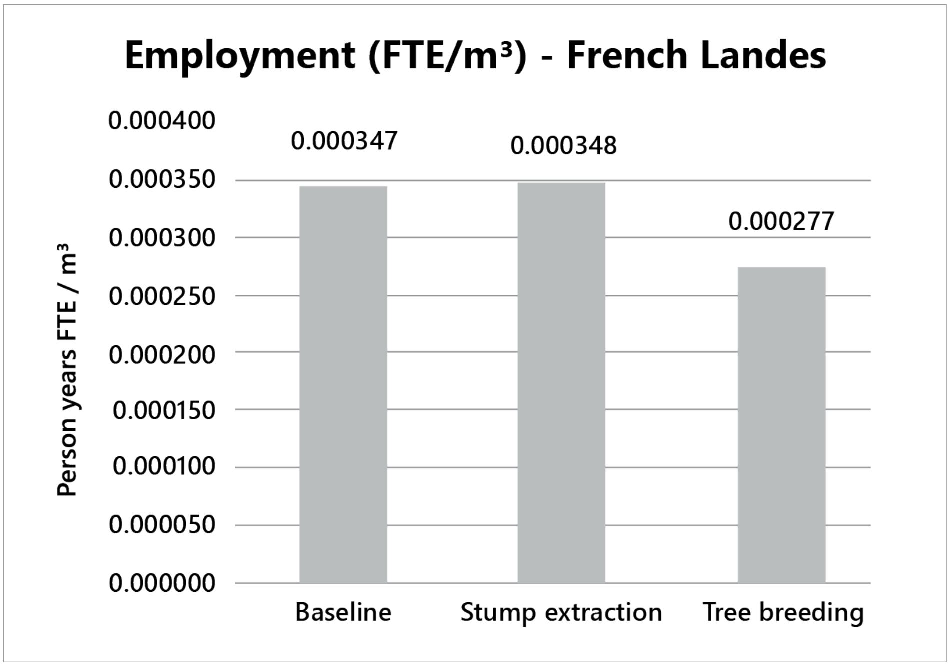

Figure 13. Full-time employment per unit of production volume (person year FTE / m^3) for different maritime pine silviculture scenarios in the French Landes.

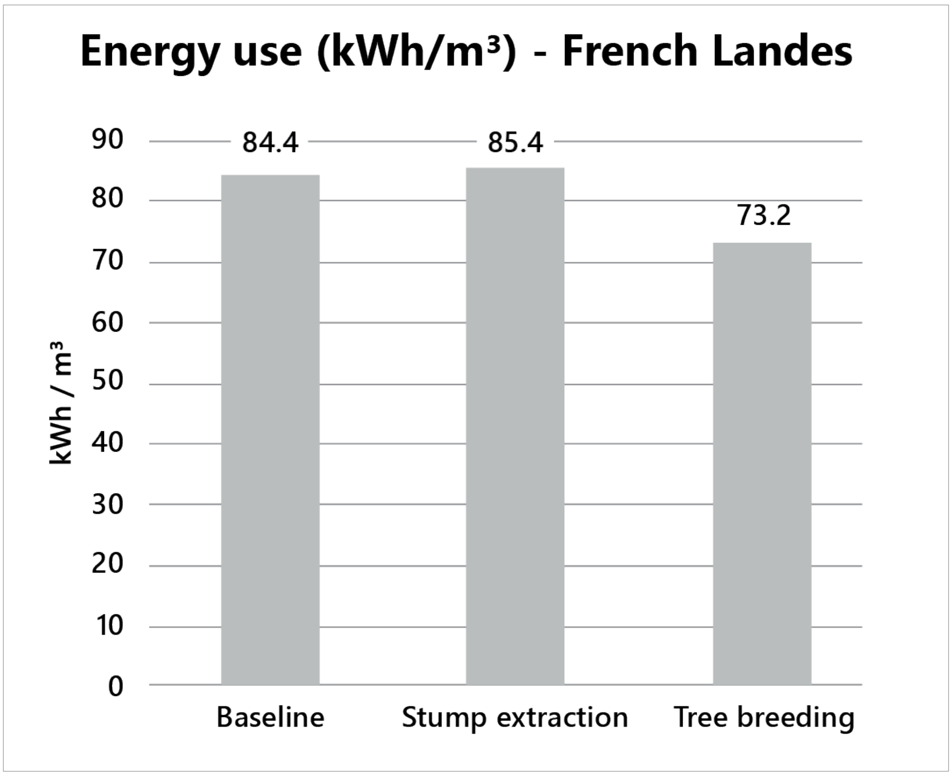

Figure 14. Energy use per unit of production volume (kWh / m^3) for different maritime pine silviculture scenarios in the French Landes.

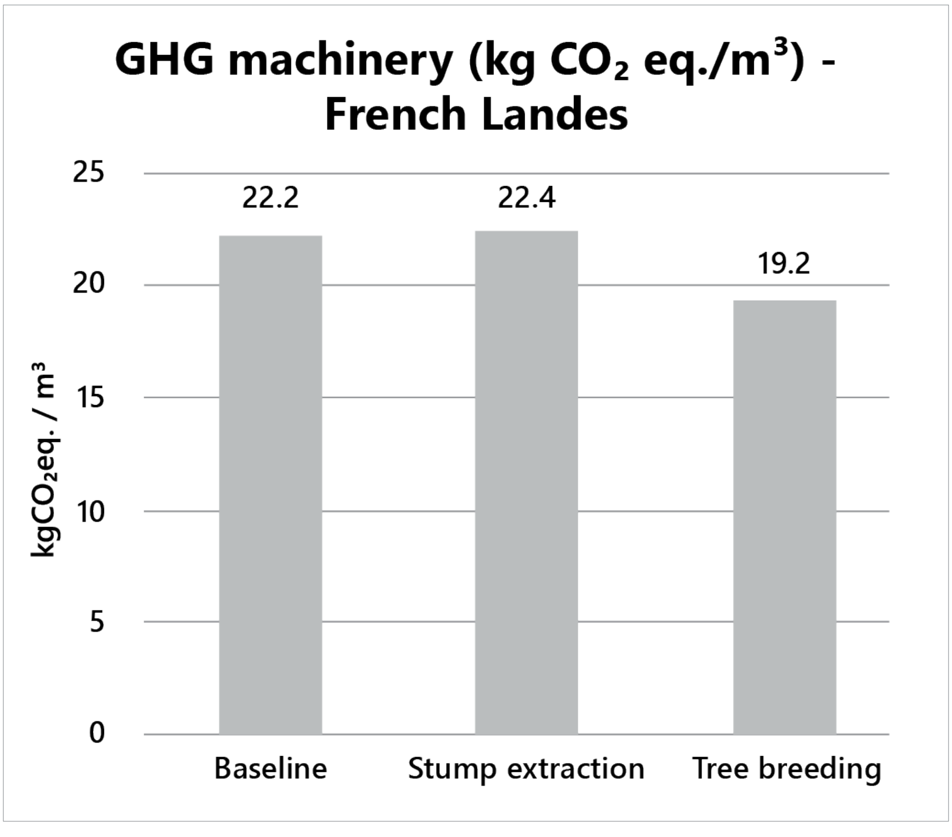

Figure 15. GHG emissions from machinery per unit of production volume (kg of CO2 equivalents / m^3) for different maritime pine silviculture scenarios in the French Landes.

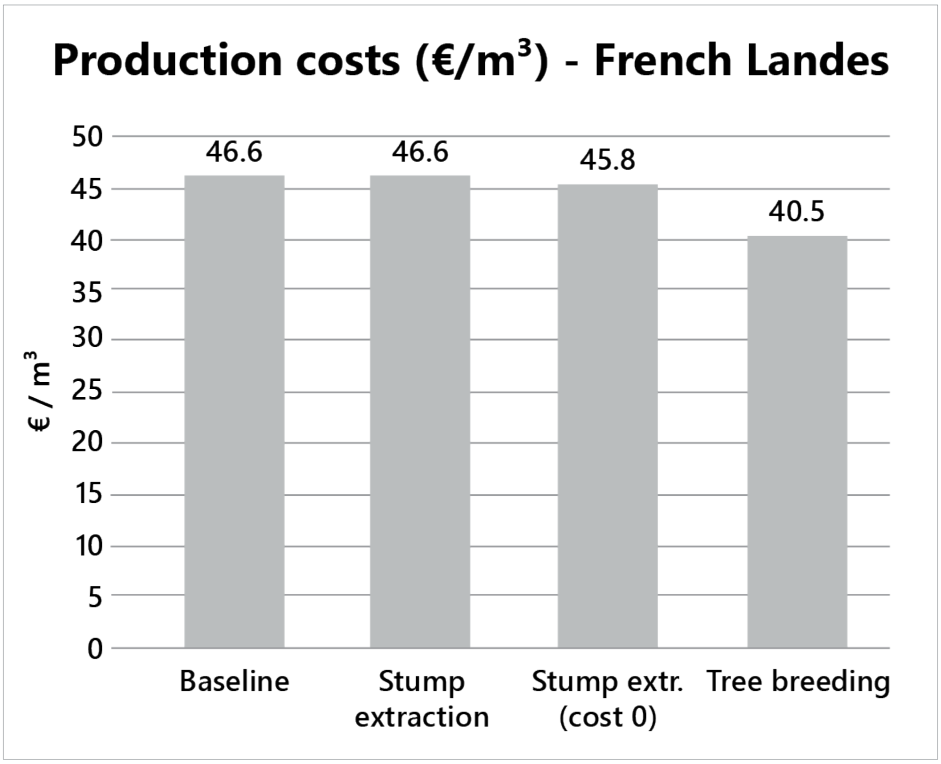

Figure 16. Production costs per unit of production volume (€ / m^3) for different maritime pine silviculture scenarios in the French Landes.

Figures 17, 18, 19 and 20 show the scenario comparison of the annual average indicators over rotation extrapolated to country level. Annual average indicators were calculated from the unitary indicator multiplied by the total scenario outflow per ha (573.5 m^3 ha^{-1} in the baseline scenario, 663.4 m^3 ha^{-1} including the stump extraction, and 745.4 m^3/ha for breeding scenario) and the total forest area of maritime pine in the Atlantic regions of France (943 000 ha), and divided by the rotation years (47 years for baseline and breeding scenarios, 45 year for stump harvest scenario).

Compared to the baseline scenario, annual average employment extrapolated to country level was considerable increased (+21.2%) for the stump scenario, compared with a moderate increase (+3.6%) in the breeding scenario. The higher indicator values resulted from the higher volume outflows of the alternative scenarios, which augmented the slight employment difference in volume units for the stump scenario and compensated the large reduction of unitary employment values for the most efficient breeding scenario.

Annual average energy use and GHG emissions were considerably higher (+22.3%) in the stump scenario (without considering the fossil fuel substitution from the use of stump biomass energy), while these indicators were also increased in the breeding scenario (+12.7%) due to the higher annual average productions.

Annual average production costs were also increased compared with the baseline for the breeding (+12.7%) and for the stump extraction scenarios, for which total production costs differed between +20.9% when the stump extraction costs are covered by the forest owner and +18.7% if they are free-of-charge to the forest owner and covered by the stump market contractors.

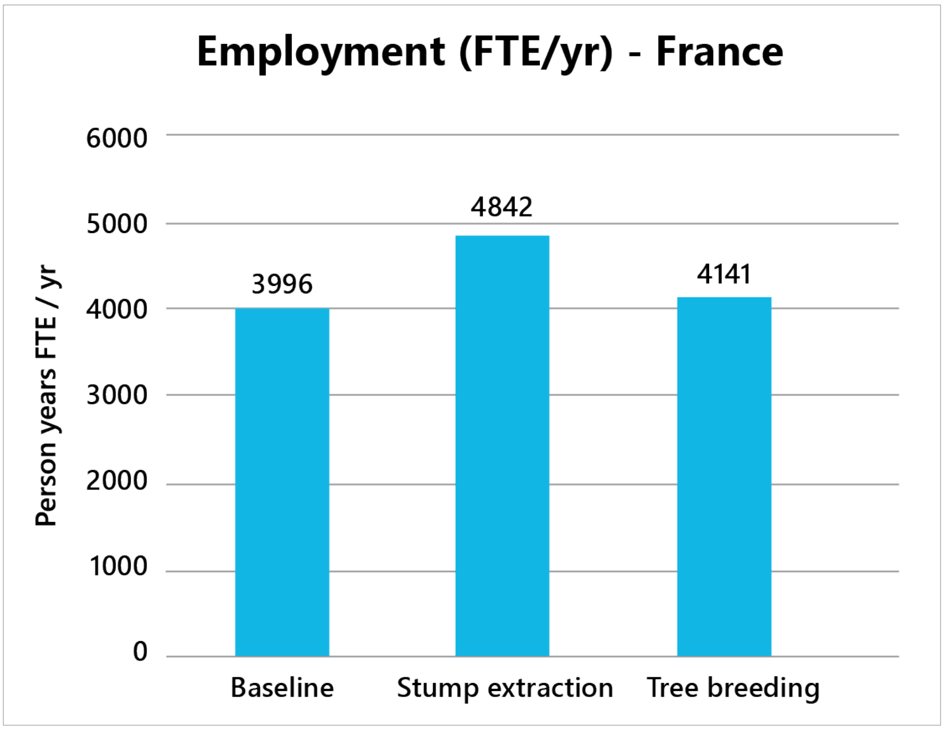

Figure 17. Annual average full-time employment (person year FTE / yr) over rotation time for different maritime pine silviculture scenarios extrapolated to France.

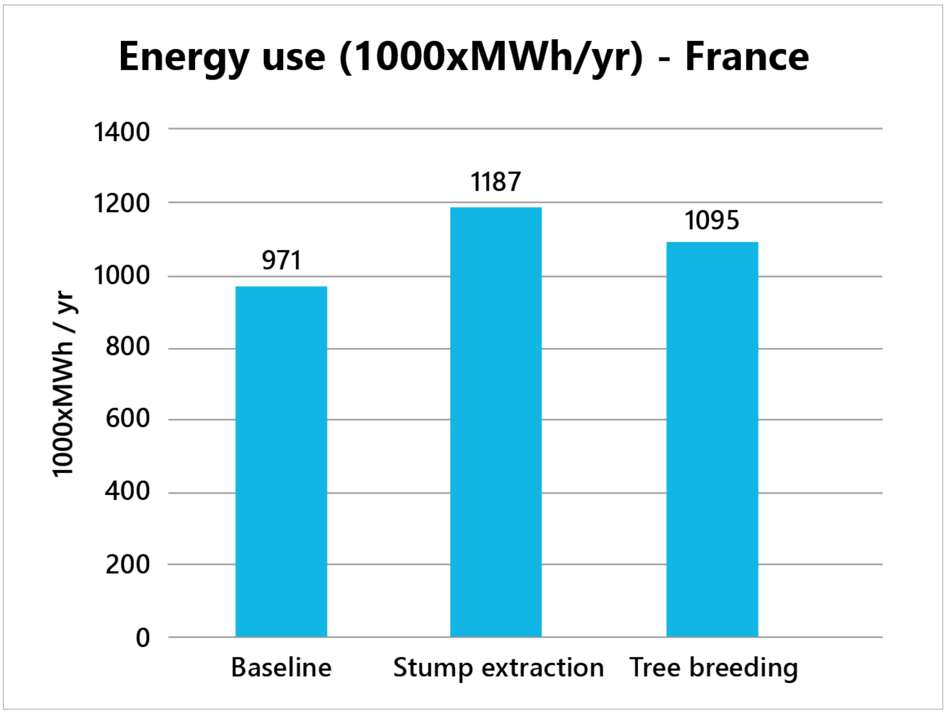

Figure 18. Annual average energy use (MWh / yr) over rotation time for different maritime pine silviculture scenarios extrapolated to France.

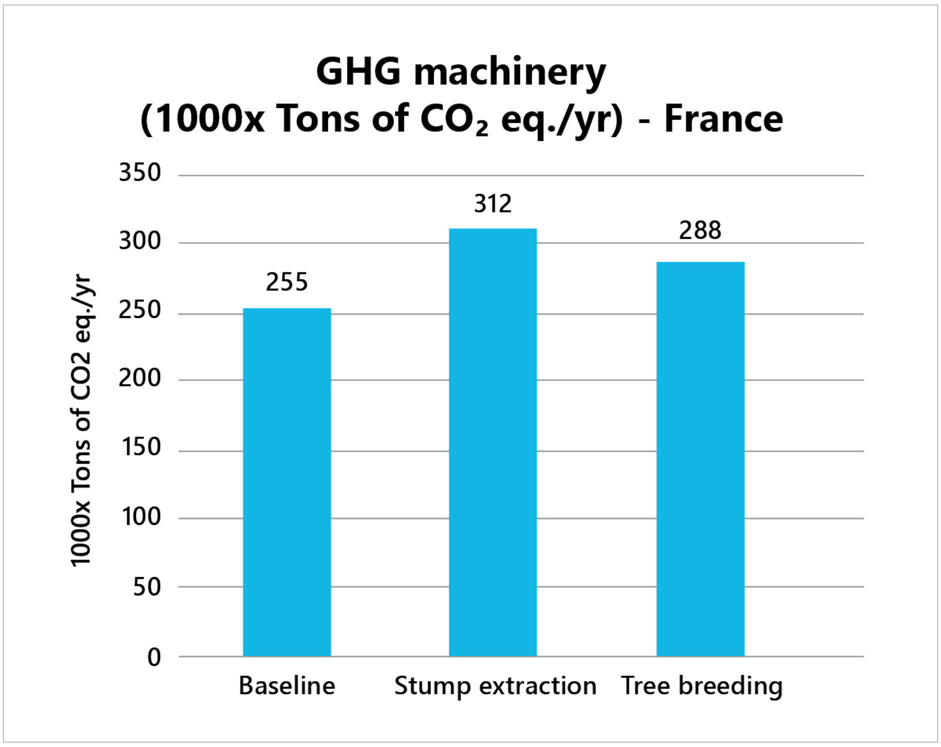

Figure 19. Annual average GHG emissions from machinery (tons of CO2 equivalents / yr) over rotation time for different maritime pine silviculture scenarios extrapolated to France.

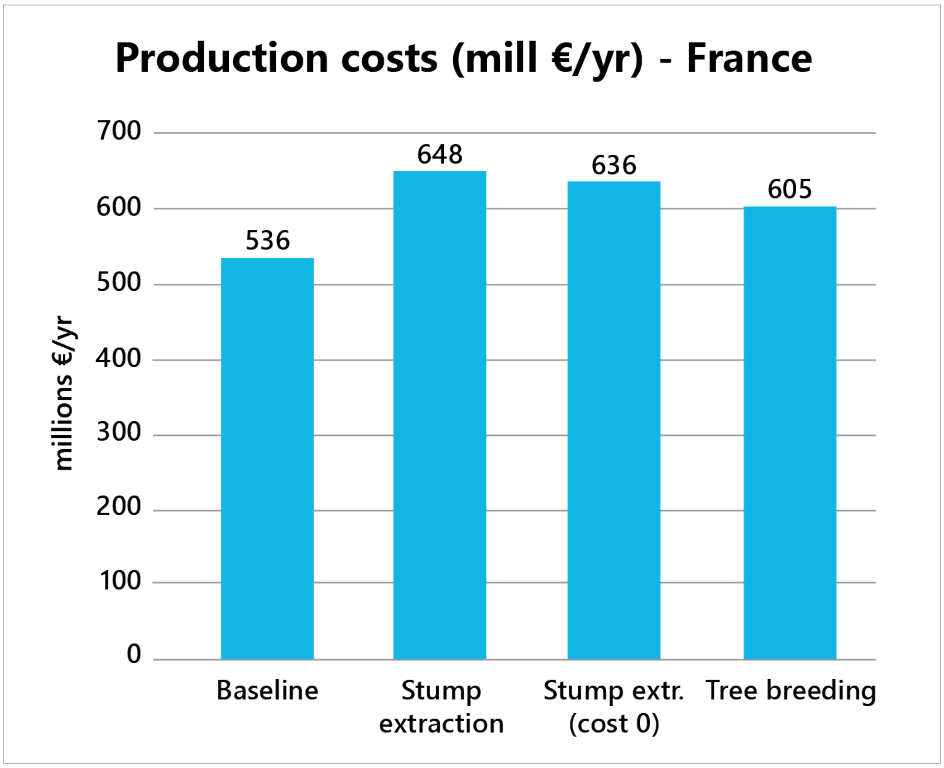

Figure 20. Annual average production costs (€/yr) over rotation time for different maritime pine silviculture scenarios extrapolated to France.

The extrapolation of the indicators resulted on higher values for the baseline scenario than those reported in national statistics. For example, the extrapolation of the baseline scenario of maritime pine silviculture to the entire species areas in the Atlantic regions of France was estimated to provide employment for 3996 FTE person year. These values will result from an estimated annual average production of 11.5 M m^3 yr^{-1}, of which 9.9 M m^3 yr^{-1} will correspond to the 813 000 ha of the Nouvelle Aquitaine region. This result is larger than the reported statistics for the Nouvelle Aquitaine region, which generates 2813 FTE of forest work for an average annual production of 5.4 M m^3 yr^{-1} (IGN 2014, Agreste 2017). However, the lower production values in the statistics compared to the baseline can be related to the post-storm context of limited wood production.

In addition, the sustainable indicators were calculated on the base of volume production extrapolated from a virtual stand hectare, as well as optimized hour productivities and costs estimated from process productivities on the stand without considering machinery transport between stands. The extrapolation of the theoretical stand to the total forest area does not consider the reduction in available productive stand area dedicated to, e.g., forest roads, wildfire breaks, ditches, etc. In real forest conditions, this will result in reduced volume production per stand surface, reduced machinery hour productivity and higher costs from increasing machinery distances. Finally, the stand-level indicators for the maritime pine silvicultural chain were based on the favorable conditions of the Landes region, with high stand productivity, easy forest accessibility and a strong forest sector structure. The extrapolation to the national level does not consider the differences in stand conditions, structure or access that would impact on the total indicator values.

Nevertheless, the estimated figures allow us to compare the potential impact of the different scenarios in relation to the baseline reference. When comparing scenario performances in relation to the goals aimed by the TECH4EFFECT project (Table 12), the breeding scenario seems to have the biggest potential, decreasing both production costs (-13.1%) and fuel consumption (-13.3%) relative per cubic meter while increasing forest yield (+30.0%).

Stump extraction had a positive impact in the forest yield (+15.7%) when considering the additional stump harvest on the total stand production. In contrast, the stump extraction slightly increased the unitary fuel consumption (+1.2%) over the rotation production. Regarding the unitary production costs, stump extraction has a minor impact (+0.1%) when the stump extraction costs are considered in the silvicultural operations by the forest owner, although they can be considerably reduced (-1.7%) if they are covered by the stump market contractors.

Table 12. T4E goals and achievements in the French scenarios in relation to production unit (m^3).

T4E goal / Scenario	Stump harvesting	Improved breeding regeneration material
20% decrease in production costs	Increased by +0.1% / Decreased by -1.7% if extraction costs covered by stump market	Decreased by -13.1%
15% decrease in fuel consumption	Increased by 1.2%	Decreased by -13.3%
2% in forest (yield) productivity	Increased by +15.7%	Increased by +30.0%

3.1.4. Austria

Bioeconomy in Austria and role of forestry

The Austrian Bioeconomy Strategy was launched in 2019 and provides guidance for all bioeconomy-relevant fields of action until 2030. It is complementary to the Integrated Climate and Energy Strategy on the decarbonisation efforts. The aim of the national bioeconomy strategy is to identify concrete measures for the further establishment of the bioeconomy in Austria in order to generate sustained growth spurts for bio-based products, bioenergy and related technologies and services. It aims at providing a framework for: i) increasing efficiency at all levels, ii) promoting conscious consumer behaviour and sustainable product range, iii) exploitation of all renewable sources of raw materials by using residues, by-products, waste and the production of novel raw materials, and iv) using opportunities from innovation for the transformation in business and society (BMNT 2019).

Agriculture, forestry and aquaculture are key sectors. Aquaculture becomes very relevant as it does not compete on the land use and offers a wide range of possibilities for the bioeconomy (BMNT et al. 2019). Also residuals, by-products, and waste are crucial resources for the Austrian bioeconomy (Gaugitsch 2019). As main products of the bioeconomy are highlighted: food and animal feed, materials (pulp and paper, fibres, chemicals, construction sector), and bioenergy (solid, liquid, gaseous) (Gaugitsch 2019).

The strategy identifies the action fields to be translated into a National Action Plan, with responsibilities, timeframe and budgetary requirements. A Center of Bioeconomy and a Bioeconomy cluster will be created (Gaugitsch 2019).

The operational goals according to BMNT et al. (2019) are: a) achieving the climate goals, b) reduction of dependence on non-renewable resources. This can be done by strengthening existing sectors of the economy, by supporting innovative technologies and services, by better networking of knowledge, by raising awareness and by creating acceptance for bio-based products and services, c) promotion of innovation, increasing scientific publications, transdisciplinary projects and patents in the field of bioeconomy, d) promoting economic development, e) securing and creating jobs, and f) promoting sustainable social transformation.

The strategy identifies an urgent need for behavioural and value changes, both by producers and consumers, to achieve all the goals of the bioeconomy strategy. Consumers decide on the choice of products and define the market demands, having a significant impact on the environmental impact of the Austrian economy (BMNT et al. 2019).

Baseline with processes, volumes and indicators

The baseline value chain represents average Austrian coniferous growth conditions. The baseline consists of a rotation of around 90 years for one hectare even-aged Norway spruce (*Picea abies*) stand. The forest management practices (Table 13), timing, and intensity are based on data by Cardellini et al. (2018). The value chain for Norway spruce starts from planting seedlings (about 2500 seedlings per hectare) and ends with final felling, cable yarding, debranching and cut-to-length at the roadside. In the baseline, the stand is thinned two times in year 40 and 55 followed by a final felling in year 90 (Cardellini et al. 2018).

On steep slopes in the alpine areas in Austria, manual harvesting and hauling of the felled trees by cable yarding is a very common method, although winch-supported harvesting/forwarding is increasing in popularity mainly because of labour safety aspects. However, chainsaw and cable yarder in whole tree method is considered the most efficient system for timber harvesting on steep terrain not accessible by ground-based machinery. In addition, it is regarded superior to ground-based harvesting systems when minimizing soil disturbance. Current field tests have shown that apart from improved occupational safety, winch-supported harvesting/forwarding systems can also be an economically feasible alternative compared to the more commonly used cable yarding system.

The baseline is presented in Table 13 on a hectare level and then upscaled to whole Austria. Almost half of the land area, 3.991 million ha, is covered with forest and this makes Austria one of the Central European countries with the highest share of forest (47,6%). About 60% of the country consists of mountainous areas (Quadt et al. 2013). According to the Austrian Forest Inventory 2007/09 (Austrian Forest Report 2015), coniferous forests cover 2.14 million hectares of land in Austria. This corresponds to 64% of the total forested area. In coniferous forests, spruce accounts for 81% of the trees. It covers 1.7 million hectares of land and thus 51% of the productive forest area in Austria.

Table 13. Baseline including processes and their hour productivity. The outflows are presented per hectare and scaled-up to represent spruce-dominated forests in Austria.

Unit	Process	Productivity (process units/hour)	Outflow per one hectare	Outflow for Norway spruce stands in Austria
ha	Planting	0.02	1	1,700,000
m^3	Tree marking by forester	18.75	36/148	1,700,000
m^3	Thinning 1 (chainsaw)	3	36	61,200,000
m^3	Thinning 2 (chainsaw)	3	148	251,600,000
m^3	Final harvest (chainsaw)	3	578	982,600,000
m^3	Cable yarding whole trees to the roadside	3	578	982,600,000
m^3	Debranching and cut to length by cable-yarding processing unit	10	578	982,600,000

Table 14. Baseline (motor-manual harvesting/cable yarding) indicator values per process unit.

Unit	Process	Employment (FTE/process unit)	Emissions from machinery (kg CO2-eq./process unit)	Energy use (kWh/ process unit)	Production costs (€/process unit)	Occupational accidents (non-fatal) per unit	Occupational accidents (fatal) per unit
ha	Planting	0.03	-	-	3150	-	-
m^3	Tree marking by forester	0.00003	-	-	0.91	-	-
m^3	Thinning 1 (chainsaw)	0.0002	1.31	0.83	23.67	0.000112	0.00000116
m^3	Thinning 2 (chainsaw)	0.0002	1.31	0.83	23.67	0.000112	0.00000116
m^3	Final harvest (chainsaw)	0.0002	1.31	0.83	23.67	0.000112	0.00000116
m^3	Cable yarding whole trees to the roadside	0.0002	27.32	33	24.17	0.0000356	0.00000037
m^3	Debranching and cut to length by cable-yarding processing unit	0.00006	8.2	9.9	11	0.00000594	0.00000006

Scenarios with processes, volumes and indicators

Winch-supported harvester / forwarder

Since mechanized harvesting using harvester / forwarder is in general safer compared to motor-manual harvesting followed by cable yarding, it is interesting to evaluate the implications on a national scale if motor-manual harvesting / cable yarding would be replaced with mechanical harvesting using winch-supported harvester / forwarder combination. In this scenario, we replaced motor-manual harvesting processes using chainsaw (2.5 kW) by harvesting with a winch-supported harvester (149 kW). Cable yarding (99 kW) was replaced by a winch-supported forwarder (136 kW). Forest management practices, timing of thinning and final harvest, and amount of wood harvested remained the same as in the baseline.

The modified indicator values used in the mechanization scenario are presented in Table 15. Employment is estimated based on the process-based hour productivities according to Tuomasjukka et al. (2015) and Holzfeind et al. (2018). Fuel consumption and related emissions of the machinery were taken from Finnish statistics database Lipasto (VTT 2016). Productions costs were taken from Tuomasjukka et al. (2015) and Holzfeind et al. (2018), and occupational accidents from Jänich (2009).

Table 15. Winch-supported harvesting scenario - indicator values per process unit.

Unit	Process	Employment (FTE/process unit)	Emissions from machinery (kg CO2-eq./process unit)	Energy use (kWh /process unit)	Production costs (€/process unit)	Occupational accidents (non-fatal) per unit	Occupational accidents (fatal) per unit
ha	Planting	0.03	-	-	3150	-	-
m^3	Tree marking by forester	0.0000329	-	-	0.91	-	-
m^3	Thinning 1 (winch-supported harvester)	0.0000685	13.29	16.56	12.75	0.00000594	0.00000006
m^3	Thinning 2 (winch-supported harvester)	0.0000685	13.29	16.56	12.75	0.00000594	0.00000006
m^3	Final harvest (winch-supported harvester)	0.0000685	13.29	16.56	12.75	0.00000594	0.00000006
m^3	Forwarding (winch-supported) to the roadside	0.0000449	8.1	9.91	9.1	0.00000594	0.00000006

Tree selection by harvester

In Austria, trees to be felled in thinnings are usually marked by a forester before the harvesting takes place (Eberhard 2019). The general opinion in Austria is that tree marking by a forester is essential in managing forest stands. However, it is time and money consuming. For this reason, forest owners concentrate mainly on good stands and on older stands to make thinning operations profitable. As a result, many stands where thinning is needed remain un-thinned, and the number of small dimension trees increases. According to Eberhard (2018), it would be possible to harvest a considerable larger amount of wood in Austrian forests in thinning operations. Therefore, Eberhard (2018) tested if tree marking by a forester was necessary at all.

According to Eberhard (2018), the amount of wood removed during first thinning and second thinning together was almost equal when he compared the removal by a forester (206 m^3) with the removal by a harvester (201 m^3). The result in productivity after 50 years was also quite equal for forester (1004 m^3) and harvester (1018 m^3). The most significant result was a reduction in production costs. Eberhard estimated that without tree marking, about 17,300 workdays per year would be saved which corresponds to approximately 2,350,000 € per year.

In this scenario we compare tree selection by forester and harvester using our sustainability indicators. We used the costs of tree marking and the effect on wood production based on data by Eberhard 2018 and calculated the impact on a whole rotation cycle.

In our analysis, replacing motor-manual harvesting (chainsaw-cable yarding) with winch-supported mechanical harvesting (winch-supported harvester-forwarder) reduced production costs by 58% (Figures 21 and 22). Compared to the winch-supported harvesting scenario, tree selection by the harvester him/herself only led to a further cost reduction of 11 cents (0.2%) per harvested cubic meter. Changing from motor-manual/cable yarding to winch-supported harvesting mechanical harvesting would reduce energy use by 40% (Figures 23 and 24) and the emissions from the machinery decreased by 42% (Figures 25 and 26). Tree marking had no significant impact on energy use and emissions. Changing from motor-manual/cable yarding to winch-supported mechanical harvesting reduced employment by 69% because of its improved efficiency. Because of a small increase in forest yield if we would omit tree marking by a forester and tree selection is done by the harvester, employment increased by about 3% (Figure 27). However, the biggest advantage of changing to winch-supported mechanical harvesting is in improving occupational safety, mainly because workers are now protected by the harvester/forwarder cabin and do not need to work with handheld chainsaws and cables used in cable yarding. Changing to mechanical harvesting systems would reduce the risk for both fatal and non-fatal accidents by about 92% (Figures 28 and 29).

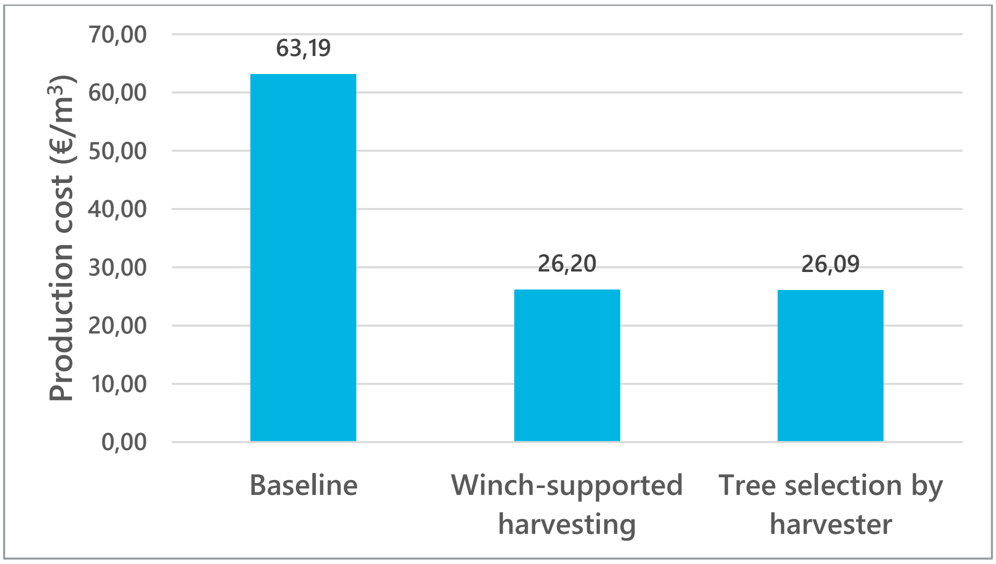

Figure 21. Production costs (€ m^{-3}) estimated over a full rotation in spruce forests in Austria.

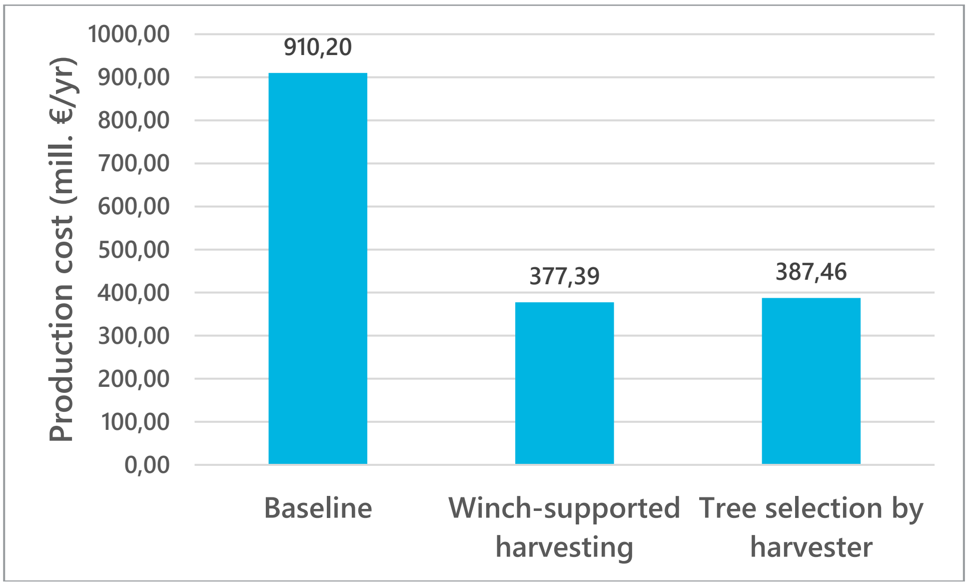

Figure 22. Mean annual production costs (mill. € yr^{-1}) estimated over a full rotation in spruce forests in Austria.

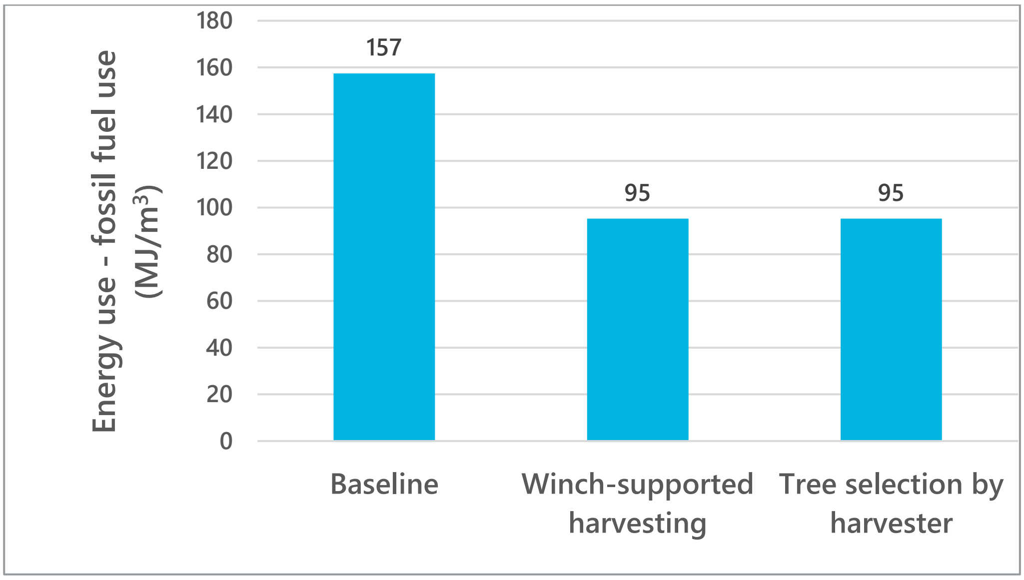

Figure 23. Energy use (MJ m^{-3}) by machinery used in forest operations estimated over a full rotation in spruce forests in Austria.

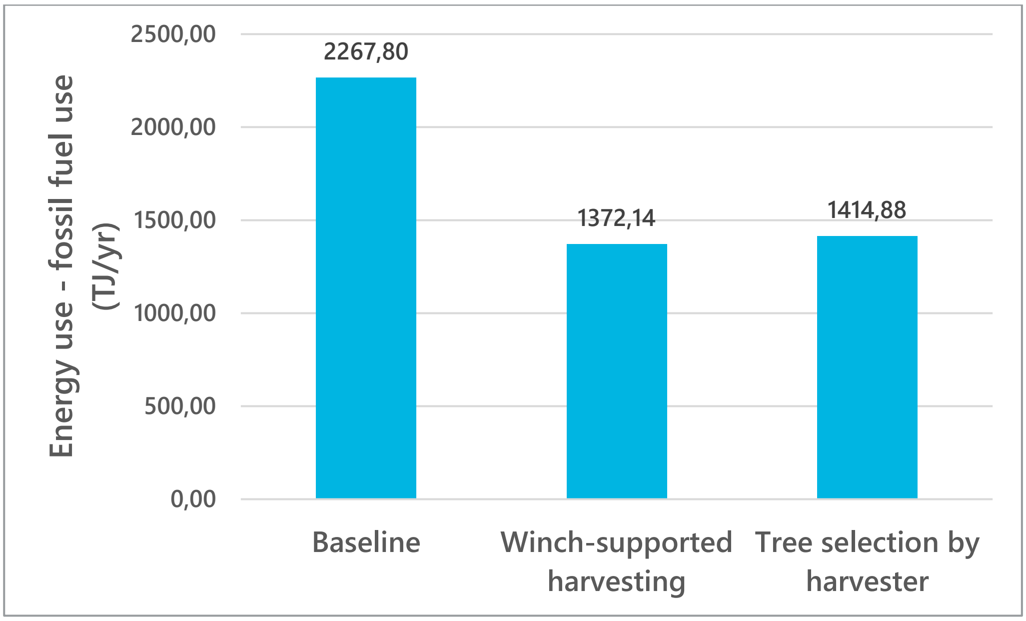

Figure 24. Mean annual energy use (PJ yr^{-1}) by machinery used in forest operations estimated over a full rotation in spruce forests in Austria.

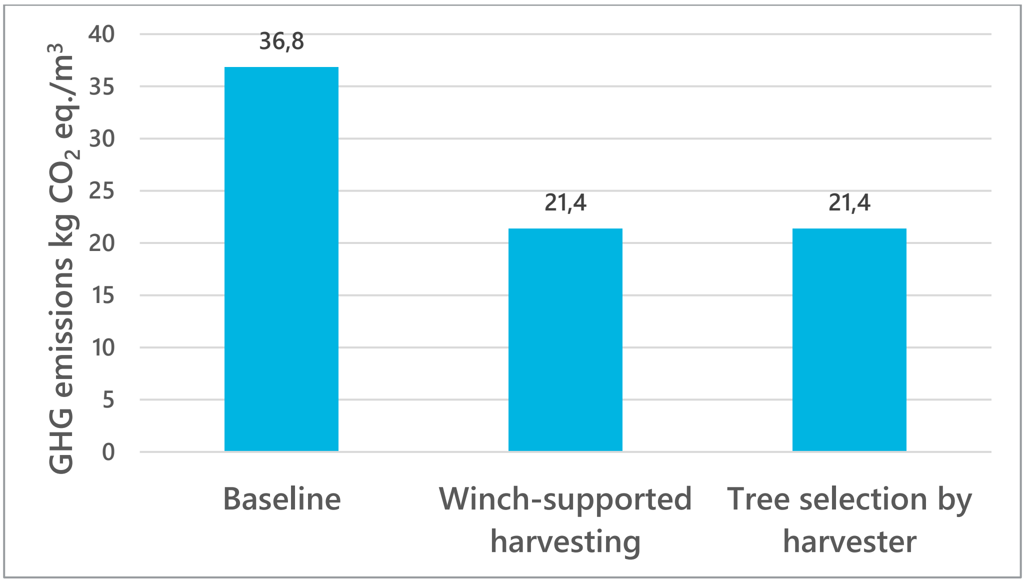

Figure 25. Greenhouse gas emissions (kg CO2 eq. m^{-3}) from machinery used in forest operations estimated over a full rotation in spruce forests in Austria.

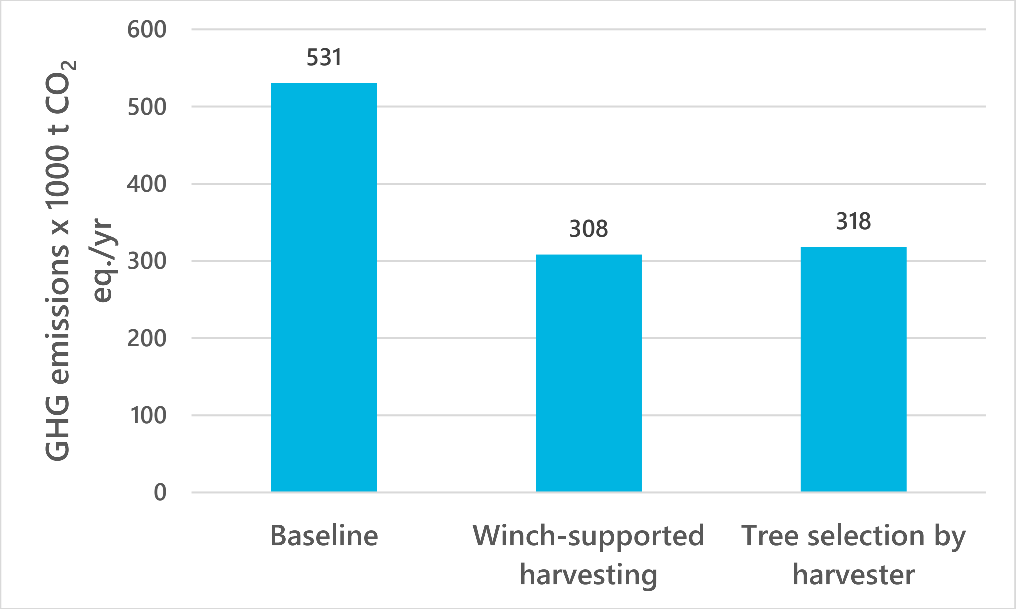

Figure 26. Mean annual greenhouse gas emissions (x 1000 t CO2 eq. yr^{-1}) from machinery used in forest operations estimated over a full rotation in spruce forests in Austria.

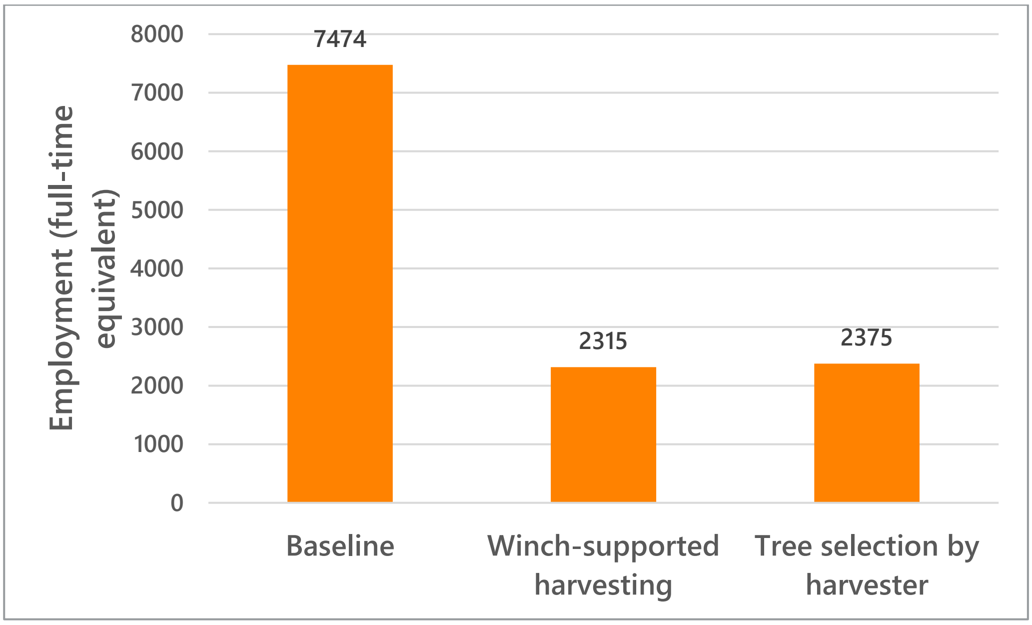

Figure 27. Mean annual employment (full-time equivalents) estimated over a full rotation in spruce forests in Austria.

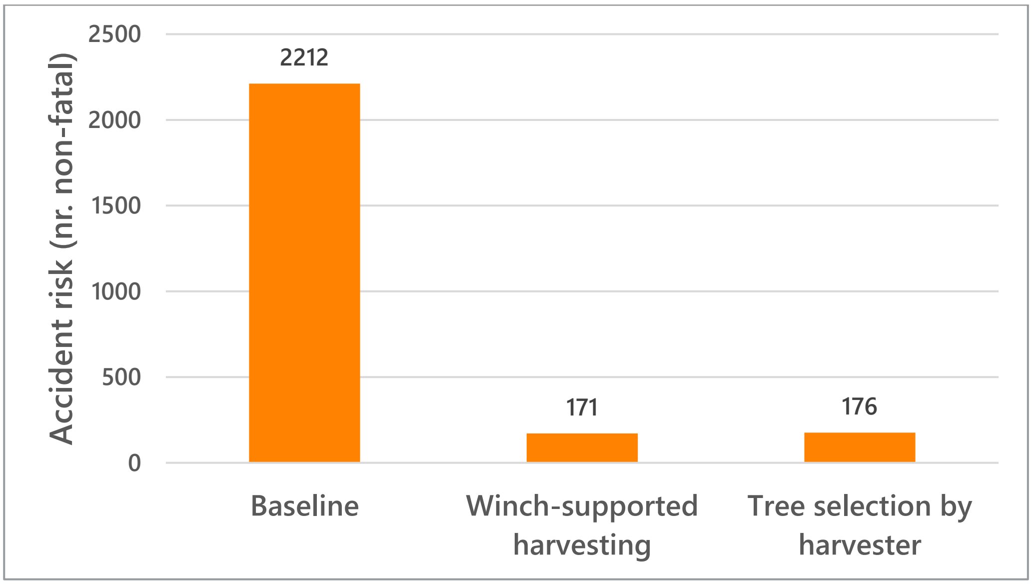

Figure 28. Risk for non-fatal accidents per year in forest operations estimated over a full rotation in spruce forests in Austria.

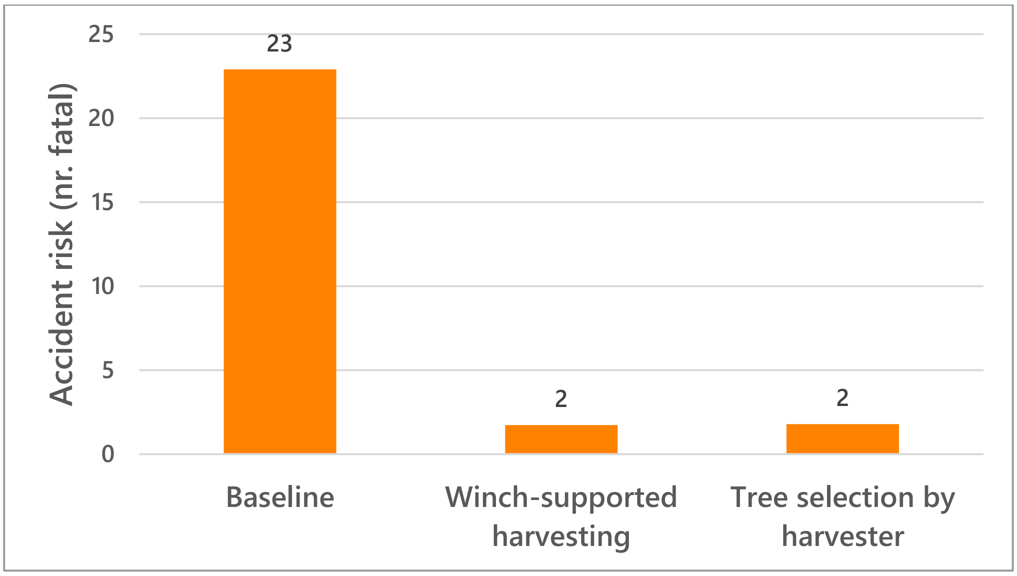

Figure 29. Risk for fatal accidents per year in forest operations estimated over a full rotation in spruce forests in Austria.

When comparing the selected management alternatives to the objectives of the TECH4EFFECT project, we can conclude that changing from motor-manual harvesting to winch-supported mechanical harvesting would reach the objective as production costs are markedly reduced (Table 16). More important, the risk for occupational accidents was greatly reduced. Another advantage was that fuel consumption and greenhouse gas emissions were reduced. Tree selection by the harvester instead of marking trees by a forester only had a very minor or no impact on costs and energy use but it did increase forest yield by about 3%.

Table 16. T4E goals and achievements in the Austrian scenarios at country level in spruce dominated forest areas.

T4E goal / Scenario	Winch-supported harvesting/forwarding	Tree selection by harvester
20% decrease in production costs	Production costs decreased by 58% Accident risk (non-fatal and fatal) decreased by 92%	Production costs decreased by 0.2% Accident risk remained the same
15% decrease in fuel consumption	Decreased by 40%	No impact
2% in forest (yield) productivity	No impact	Increased by 3%

3.1.5. Poland

Bioeconomy in Poland and role of forestry

Poland does not have a dedicated national bioeconomy strategy yet. Nevertheless, bio-based industry elements feature prominently in the country’s Smart Specialization Strategy (2016) (EC 2015, BBIC 2018), which is built along five axes: i) healthy society, ii) agro-food, forestry-timber and environmental bioeconomy, iii) sustainable energy, iv) natural resources and waste management, and v) innovative technologies and industrial processes.

Other strategies related to bioeconomy are the Strategy for Innovation and Efficiency of the Economy, the Strategy of Energy Safety and Environment, and the Strategy for Sustainable Development of Agriculture, Rural Areas and Fisheries (EC 2015). Another relevant links are the National Programme for the Development of a Low Emission Economy (2015), and the Strategy for Development of the country 2020, which defines developmental goals for Poland up to 2020 (2012) (BBIC 2018), and the BIOSTRATEG Strategic and Research program 'Environment, Agriculture and Forestry' (2013) (EC 2018a). Poland is also developing a roadmap towards Circular Economy, where bioeconomy has an own dedicated chapter.

Poland's bioeconomy sector is focused on agriculture, forestry and food processing, areas which are already central to the country's economy (Woźniaka and Twardowski 2018). Other sectors with relevance for the bioeconomy are fisheries, chemical, biotechnology and energy industries.

In addition to national efforts to develop the bioeconomy there are also efforts taking place at the regional level (Winther 2016). The Lodzkie Region was established as the first Bioregion in Republic of Poland, aiming at converting the Lodzkie Region into one of the most innovative regions in Europe and Poland in the area of sustainable bioeconomy. There are several other regional bioeconomy strategies as part of the RIS (2014) (EC 2018a).

Poland participates in the Central-Eastern European Initiative for Knowledge-based Agriculture, Aquaculture and Forestry in the Bioeconomy (BIOEAST), a macro-regional bioeconomy initiative, developed by Central and Eastern European countries, aiming at establishing a common strategy on bioeconomy and at strengthening the links between the involved sectors across the borders (EC 2018a; BBIC 2018). It envisions: i) sustainable increase of biomass production, ii) the need for circular ("zero waste") processing of available biomass, iii) the viability of rural areas (EC 2015).

Baseline with processes, volumes and indicators

The baseline value chain is built to represent average Polish coniferous growth conditions. The baseline consists of a rotation of around 100 years for one hectare even-aged Scots (*Pinus sylvestris)* stand. Rotation start from soil scarification and natural regeneration and ends with final felling.

The forest management practices (Table 17) timing, and intensity are based on data by Cardellini et al. (2018). Value chains for Scots pine start from scarification to improve seedling establishment. For Scots pine, both planting and natural regeneration can be applied. In the baseline scenario, we assumed that natural regeneration is successful with about 10,000 naturally regenerating seedlings per hectare.

Although mechanical harvesting is becoming more popular in Poland since the last decades, the use of less productive and less effective manual harvesting is still very common. According to previous published material, around the year 2010 only about 5% of the total volume was harvested mechanically while about 95% of the volume was still harvested manually by chainsaw (Szewczyk and Wojtala 2010; Kingsbury and Zochowska 2011). More recent estimates on the level of mechanized harvesting in Poland were lacking at the time of this assessment. Skidding and forwarding are the most common ways of timber extraction to the roadside (Tuomasjukka et al. 2015).

In the baseline, tending of the stand is carried out in year 12 followed by pre-commercial thinning in year 17. Hereafter, the stand is thinned six times in year 25, 32, 40, 50, 65 and 80 followed by a final felling in year 100 (Cardellini et al. 2018).

The baseline is presented in Table 17 on a hectare level and then upscaled to whole Poland. In Poland, forest land covers 9.3 million hectares and stocked forest land covers 9.1 million hectares (Gerasimov 2013). About 71% of the stocked forest area is covered by coniferous species such as pine (60%, 5,476,000 ha), spruce (6%) and fir (3%). A substantial area is covered by deciduous species such as birch (7%), alder (5%), aspen and poplar. The share of broadleaved species such as oak, beech and hornbeam is about 13% of the stocked forest area (Gerasimov 2013).

Table 17. Baseline including processes and their hour productivity. The outflows are presented in a hectare level and scaled-up to represent pine-dominated forests in Poland.

Unit	Process	Productivity (process units/hour)	Outflow per one hectare	Outflow for Scots pine stands in Poland
ha	Site preparation (scarification)	0.19	1	5,476,000
ha	Tending (brush saw)	0.05	1	5,476,000
ha	Precommercial thinning (chainsaw)	1	1	5,476,000
m^3	Thinning 1 (chainsaw)	0.96	17	93,092,000
m^3	Thinning 2 (chainsaw)	0.96	19	104,044,000
m^3	Thinning 3 (chainsaw)	0.96	23	125,948,000
m^3	Thinning 4 (chainsaw)	0.96	45	246,420,000
m^3	Thinning 5 (chainsaw)	0.96	47	257,372,000
m^3	Thinning 6 (chainsaw)	0.96	52	284,752,000
m^3	Final harvest (chainsaw)	0.96	470	2,573,720,000

The sustainability indicator values used in the baseline scenario are presented in Table 18. The employment is estimated using annual full-time employment of 1,776 hours and process-based hour productivities according to Cardellini et al. (2018). Fuel consumption and related emissions of the machinery were taken from Finnish statistics database Lipasto (VTT 2016). Productions costs were taken from Tuomasjukka et al. (2015) and occupational accidents from Jänich (2009).

Table 18. Baseline indicator values per process unit.

Unit	Process	Employment (FTE/process unit)	Emissions from machinery (kg CO2-eq./process unit)	Energy use (kWh/process unit)	Production costs (€/process unit)	Occupational accidents (non-fatal) per unit	Occupational accidents (fatal) per unit
ha	Site preparation (scarification)	0.00302	352	413	317	-	-
ha	Tending (brush saw)	0.0113	65	40	246	-	-
ha	Precommercial thinning (chainsaw)	0.000563	3.92	2.5	12.29	-	-
m^3	Thinning 1 (chainsaw)	0.000587	4.09	2.6	11.80	0.000112	0.00000116
m^3	Thinning 2 (chainsaw)	0.000587	4.09	2.6	11.80	0.000112	0.00000116
m^3	Thinning 3 (chainsaw)	0.000587	4.09	2.6	11.80	0.000112	0.00000116
m^3	Thinning 4 (chainsaw)	0.000587	4.09	2.6	11.80	0.000112	0.00000116
m^3	Thinning 5 (chainsaw)	0.000587	4.09	2.6	11.80	0.000112	0.00000116
m^3	Thinning 6 (chainsaw)	0.000587	4.09	2.6	11.80	0.000112	0.00000116
m^3	Forwarding (skidder or tractor)	0.000587	6.72	7.89	3.10	0.0000119	0.00000012
m^3	Final harvest (chainsaw)	0.000587	4.09	2.6	11.80	0.000112	0.00000116

Scenarios with processes, volumes and indicators

Mechanization of harvesting in coniferous forests

Since mechanized harvesting is in general safer and more efficient, it is interesting to evaluate the implications on a national scale if motor-manual harvesting would be replaced with mechanical harvesting. In this assessment, we replaced motor-manual harvesting processes using chainsaw (2.5 kW) by harvesting with a medium harvester (149 kW). Forwarding processes with a skidder or tractor (77 kW) were replaced by a forwarder (105 kW). Forest management practices, timing of thinning and final harvest, and amount of wood harvested remained the same as in the baseline.

The modified indicator values used in the mechanization scenario are presented in Table 19. Employment is estimated based on the process-based hour productivities according to Tuomasjukka et al. (2015). Fuel consumption and related emissions of the machinery were taken from Finnish statistics database Lipasto (VTT 2016). Productions costs were taken from Tuomasjukka et al. (2015) and occupational accidents from Jänich (2009).

Table 19. Mechanized harvesting scenario - indicator values per process unit.

Unit	Process	Employment (FTE/process unit)	Emissions from machinery (kg CO2-eq./process unit)	Energy use (kWh/process unit)	Production costs (€/process unit)	Occupational accidents (non-fatal) per unit	Occupational accidents (fatal) per unit
ha	Precommercial thinning (harvester)	0.000563	119	149	70.40	-	-
m^3	Thinning 1–6(harvester)	0.0000647	13.75	17.13	6.8	0.00000594	0.00000006
m^3	Forwarding (forwarder)	0.000144	22.02	26.92	5.5	0.00000594	0.00000006
m^3	Final harvest (harvester)	0.0000557	11.85	14.75	4	0.00000594	0.00000006

In our theoretical scenario, replacing motor-manual harvesting (chainsaw-skidder) with mechanical harvesting (harvester-forwarder) would results in a 31% production costs reduction (Figure 31). Changing to mechanical harvesting would increase energy use by machinery used in forest operations by 286% (Figures 32 and 33) and the emissions from the machinery used increases by 207% (Figures 34 and 35). Because of increased productivity, employment in forest operations would decrease by 66% if motor-manual harvesting is replaced with mechanical harvesting (Figure 36). The biggest advantage of changing to a higher level of mechanical harvesting is in improving occupational safety. Changing to mechanical harvesting systems would reduce the number of both fatal and non-fatal accidents by 90% (Figures 37 and 38).

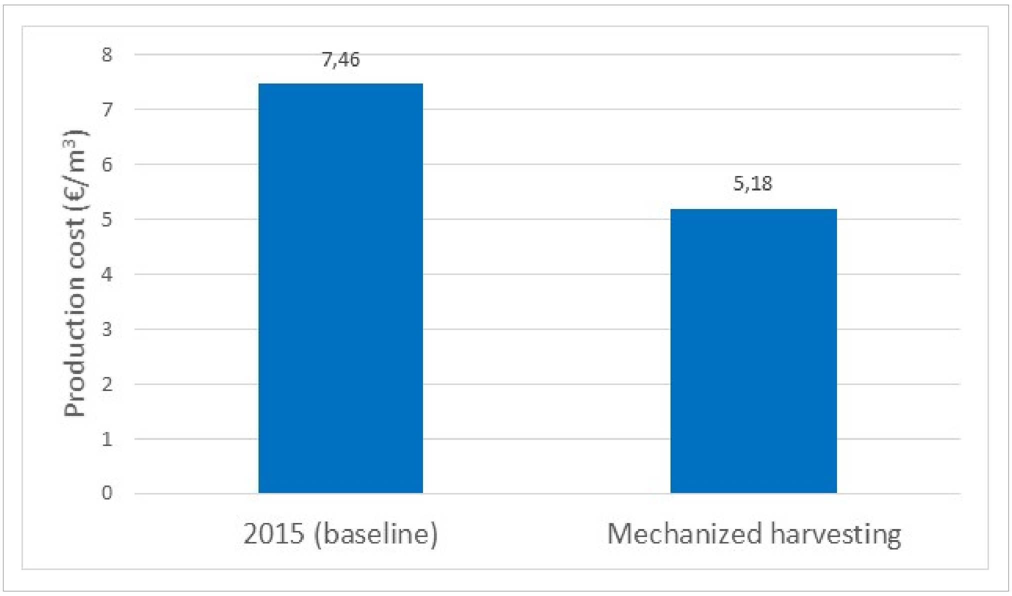

Figure 30. Mean production costs (€ m^{-3}) estimated over a full rotation in pine forests in Poland.

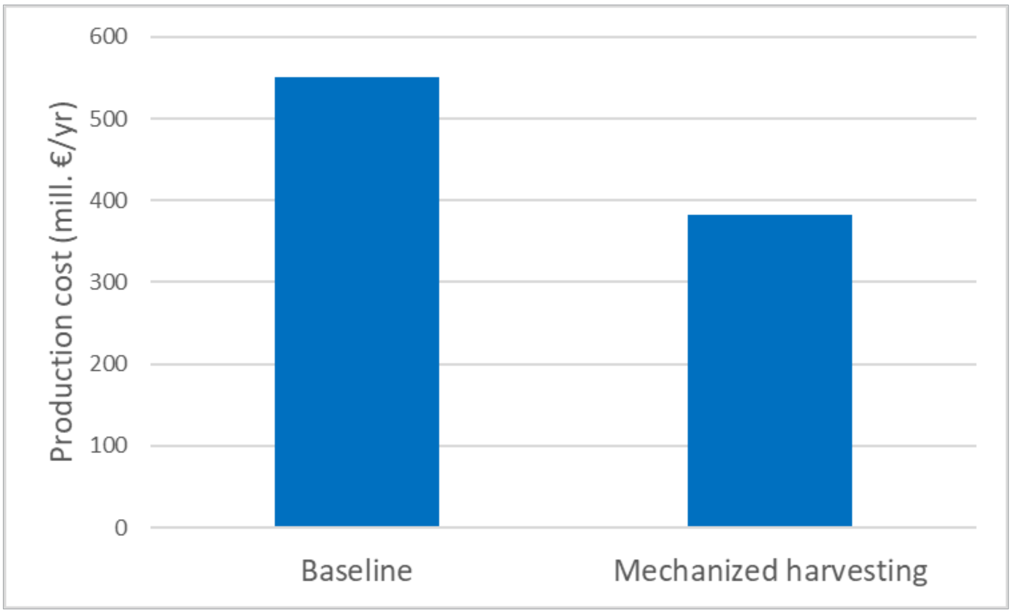

Figure 31. Mean annual production costs (mill. € yr^{-1}) estimated over a full rotation in pine forests in Poland.

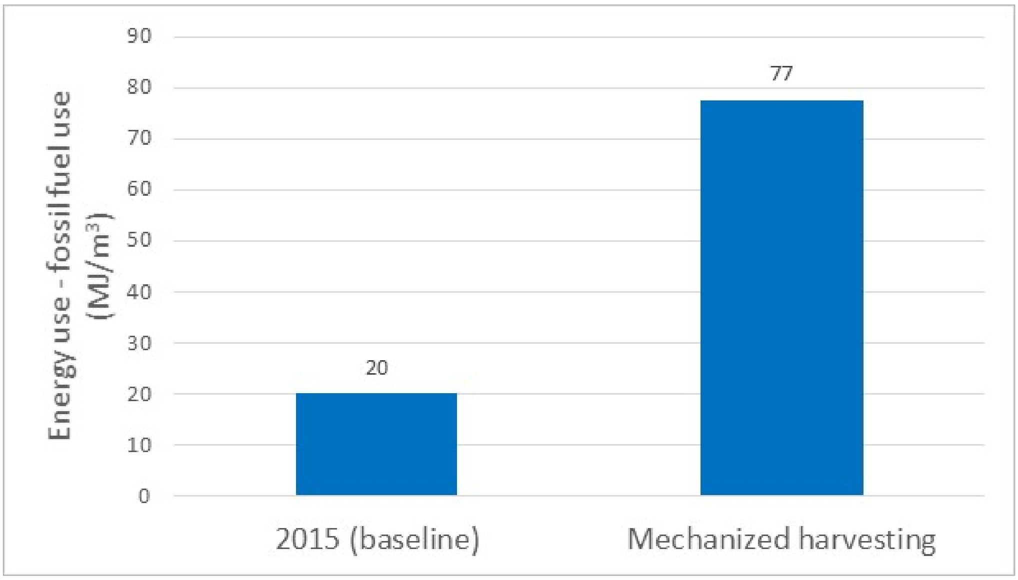

Figure 32. Mean energy use (MJ m^{-3}) by machinery used in forest operations estimated over a full rotation in pine forests in Poland.

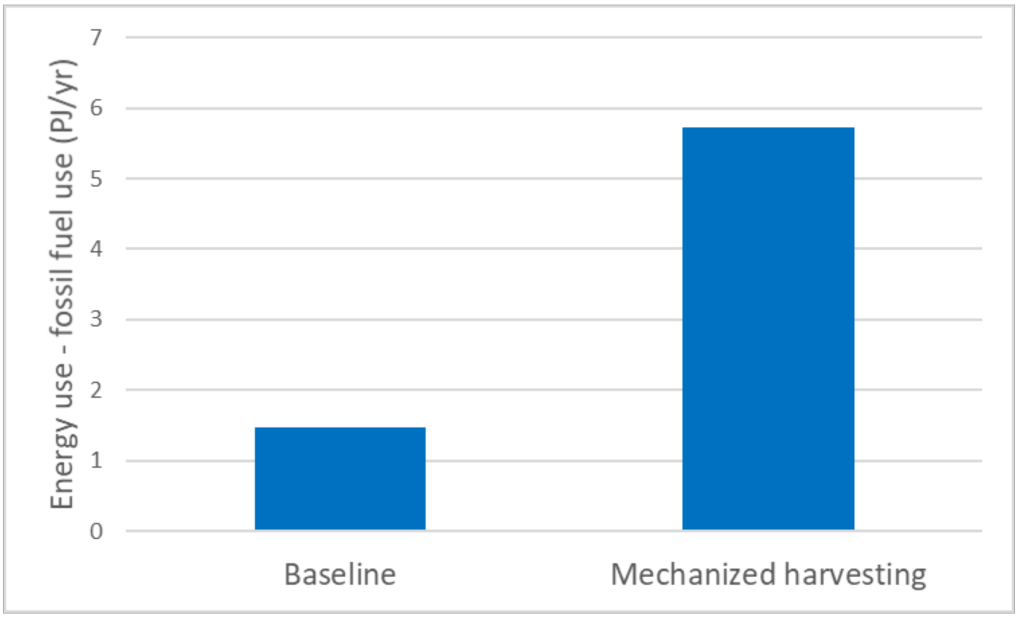

Figure 33. Mean annual energy use (PJ yr^{-1}) by machinery used in forest operations estimated over a full rotation in pine forests in Poland.

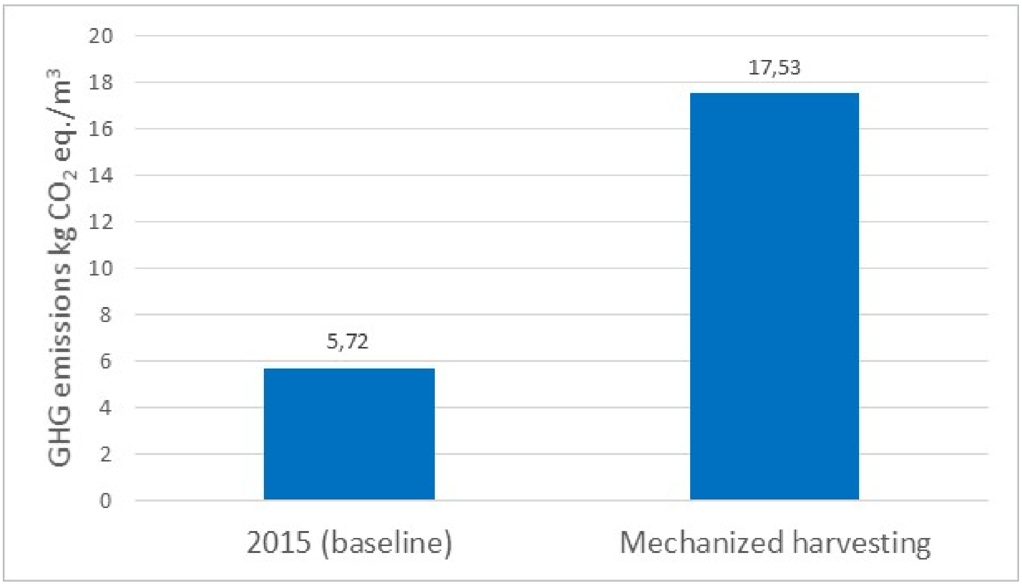

Figure 34. Mean greenhouse gas emissions (kg CO_2 eq. m^{-3}) from machinery used in forest operations estimated over a full rotation in pine forests in Poland.

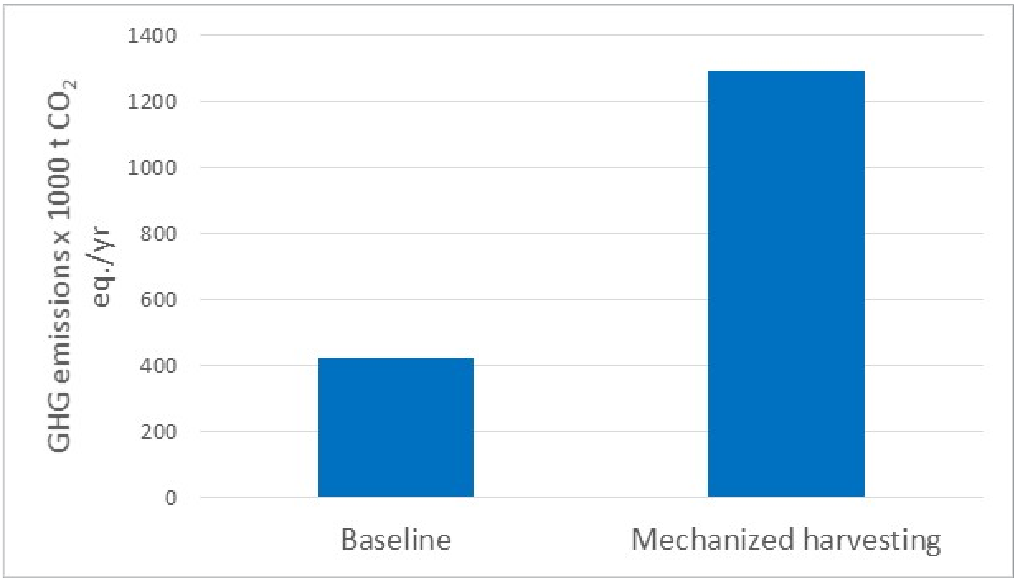

Figure 35. Mean annual greenhouse gas emissions (x 1000 t CO2 eq. yr^{-1}) from machinery used in forest operations estimated over a full rotation in pine forests in Poland.

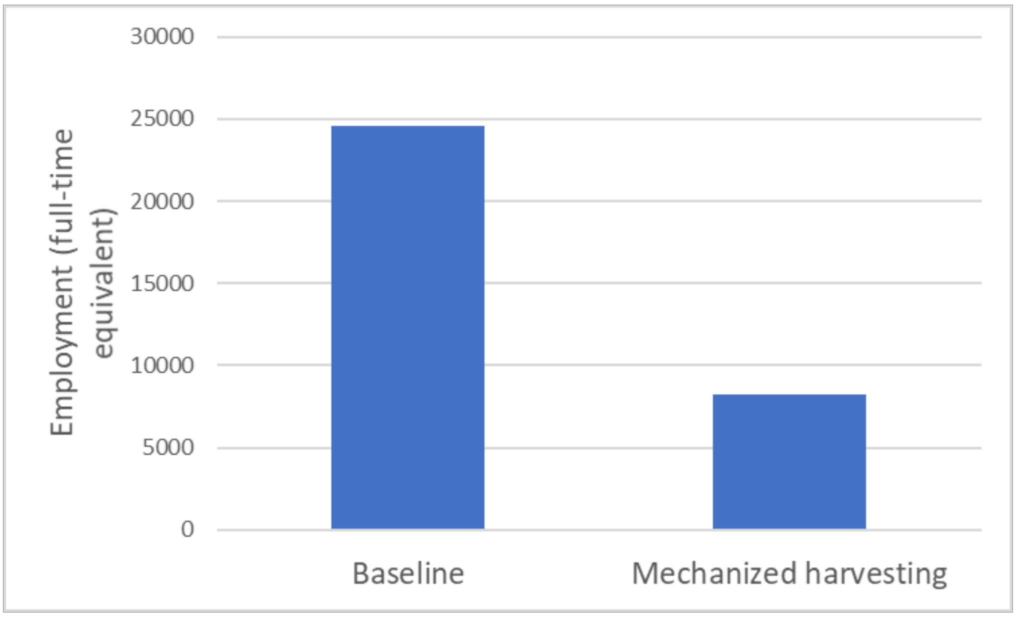

Figure 36. Mean annual employment (full-time equivalents) estimated over a full rotation in pine forests in Poland.

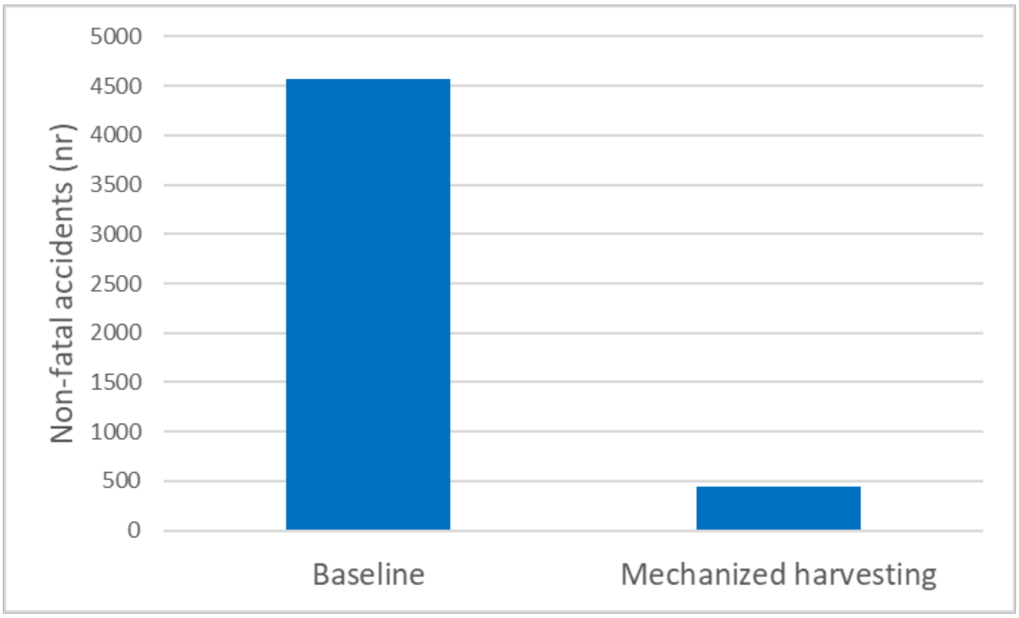

Figure 37. Risk for non-fatal accidents per year in forest operations estimated over a full rotation in pine forests in Poland.

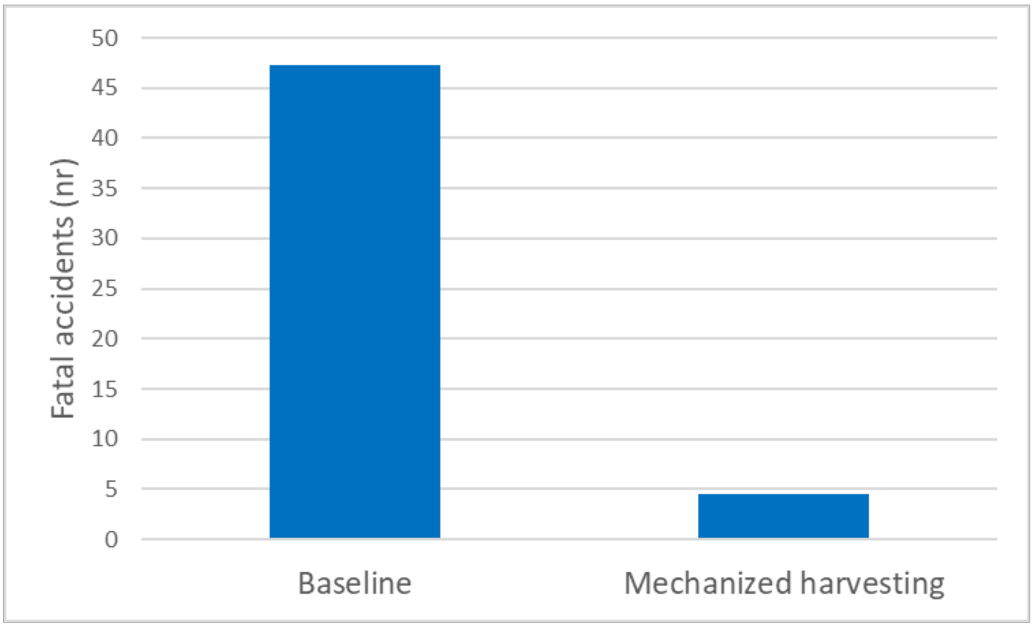

Figure 38. Risk for fatal accidents per year in forest operations estimated over a full rotation in pine forests in Poland.

When comparing scenario performances in relation to objectives for TECH4EFFECT project, it is clear that changing from motor-manual harvesting to mechanical harvesting would mean an increase in fuel use and related emissions (Table 20). However, changing to more mechanized harvesting has also some very important advantages. It has a large potential in reducing production costs and most of all it can create a very large improvement in occupational safety.

Table 20. T4E goals and achievements in the Polish scenario at country level in pine-dominated forest areas.

T4E goal / Scenario	Mechanized harvesting
20% decrease in production costs	Production costs decreased by 31%. Both fatal and non-fatal accidents decreased by 90%
15% decrease in fuel consumption	Energy use increased by 286%
2% in forest (yield) productivity	No impact

3.1.6. Italy

Bioeconomy in Italy and role of forestry

The Italian Strategy for Bioeconomy has been launched in 2017, as part of the implementation process of the National Smart Specialization Strategy, in synergy with the Italian Strategy for Sustainable Development (APRE 2019; Il Bioeconomista 2019). The Bioeconomy Strategy in Italy (BIT) has been updated in 2019. The strategy aims at interconnecting the main bioeconomy sectors, creating longer, more sustainable and locally routed value chains. It promotes the integration of research and innovation needs and opportunities, policy, business, and cultural attitude into a single systemic vision for the bioeconomy in line with the development model of the circular economy (CNBBSV 2019). It is envisioned as: i) moving from sectors to systems, ii) creating value from local biodiversity and circularity, iii) moving from economy to sustainable bioeconomy, iv) promoting the bioeconomy in the Mediterranean area, and v) moving from concept into reality.

The bioeconomy refers to the set of economic activities relating to the invention, development, production and use of biological products, services and processes across four macro-sectors: agrifood, forestry, biobased industry, and marine bioeconomy. It is important to remark that marine bioeconomy has a strong relevance in the Italian bioeconomy, the second biggest European fish industry (CNBBSV 2019). The Action Plan identifies the most significant challenges and research priorities.

In Italy, the entire bioeconomy sector (including agriculture, forestry, fisheries, food and beverages production, paper and pulp industries, textiles from natural fibers, leather, bio-pharmaceuticals, green chemistry, biochemicals and bioenergy) accounted for a total turnover of EUR 330 billion in 2017, and around 2 million employees. The main objective of the Strategy is to increase the current turnover and jobs by 15% by 2030, while increasing the level of circularity in the economy (Gyekye 2019; CNBBSV 2019). This will be done by:

a) improving the sustainable production and quality of products in each of the sectors and interconnecting and leveraging the sectors more efficiently; allowing an effective valorization of national terrestrial/marine biodiversity, ecosystem services and circularity by creating longer and more locally routed value chains, where the actions of public and private stakeholders integrate across the board at the regional, national and EU level; regenerating abandoned/marginal lands and former industrial sites;

b) creating: i) more investments in R&I, spin offs/ start-ups, education, training, and communication, ii) better coordination between regional, national and EU stakeholders/policies, iii) better engagement with the public, and iv) tailored market development actions.

The availability of local competitive biological feedstocks is an important requirement for bioeconomy industries. Italian regions, at an individual level, have a high level of agricultural and natural landscape specificity linked to the biodiversity of cultivated plants, animals, related ecosystem services and their diverse cultural heritage. Each territory, with its own specificity, can play an important role in the national bioeconomy, due to the different geographical allocation of biological resources, technologies, skills and expertises (CNBBSV 2019).

Baseline with processes, volumes and indicators

Coppice management is a widespread forestry practice whereby stand regeneration is obtained from the re-sprouting of cut stumps, rather than from the establishment of new trees from seed. For this reason, coppice management is only suited to tree species that can sprout new shoots from their stumps after cutting, that is true for most hardwoods, especially if the interval between cuts does not exceed 50 or 60 years. Coppice management offers the benefits of simplified care, prompt regeneration and short waiting time; its main drawback is in offering relatively small trees, which are only suitable for the production of pulpwood, fencing assortments and energy wood (Buckley 1992). As a main source of firewood, coppice stands were very common in the European countryside until the advent of fossil fuels (Hédl et al. 2010). After that, interest in coppice management has faced a steady decline, leading to abandonment and conversion into high forest. Nevertheless, coppice management still persists on large forest areas: estimates range from over 26 million hectares in the EU and its neighbours in the Balkans and in the Anatolian plateau (Nicolescu et al. 2015) to ca 16% of all productive forests in Europe, covering a total area of ca. 23 million ha (see COST FP1301). These are mainly located in the far west, south and south-eastern parts of the continent. Over half of European coppice forests are situated in industrialized countries, such as France, Italy and Spain.

Coppice management is the most common silvicultural system in Italy. Within the approximately 8,500,000 ha of Italian forests, the forest land classified as coppice currently includes almost 35% of the national forest cover (approximately 3,663,100 ha) (INFC 2007), yet its distribution varies between administrative units (INFC 2007). The most important species traditionally managed as coppice are deciduous oaks (*Quercus spp*., 33%), European hop hornbeam (*Ostrya carpinifolia Scop*., 17%), beech (*Fagus sylvatica L*., 13%), sweet chestnut (*Castanea sativa Miller*, 16%), which are usually grown as pure stands, and the evergreen holly oak (*Quercus ilex* L., 10%), which frequently grows in mixed stands (Nicolescu et al. 2015).

Coppice forests are normally harvested for firewood, using manual methods. Unfortunately, the mechanization of coppice harvesting is especially challenging, because coppice forests produce relatively small trees, which grow in clumps and have a marked basal sweep (Cacot 2015). That hinders mechanical felling and may result in increased time consumption and occasional stump damage (McEwan et al. 2016). On top of that, broadleaf trees often present heavy branching, which makes mechanized delimbing and bucking especially difficult (Suchomel et al. 2012) . Taken together, the characteristics of coppice trees severely restrict harvester productivity, compared with the levels achieved in softwood stands (Labelle et al. 2018).

The strongest limitation to the mechanization of coppice harvesting operations is in the relatively poor quality of the cut surface. In order to assure prompt regeneration, forest regulations prescribe that cuts must be as clean as possible and cut height may not exceed 10 cm from the ground surface. Since mechanical felling cannot guarantee that these requirements are met, forest managers often forbid mechanized felling in their coppice forests and accept the higher cost of motor-manual felling. However, a proper estimate of the regeneration deficit possibly caused by mechanized felling, which is far from ascertained. the association between cut quality and stump resprouting is part of traditional knowledge, which has been questioned in several scientific studies. It is therefore quite possible that mechanical cutting has no significant effect on stump regeneration, or that such effect is minimal. This issue is the subject of a separate line of experiments, still in progress and soon to offer objective evidence of one or the other outcomes (Spinelli et al. 2017).

Systems and system boundaries

The study (Spinelli et al. 2020; in preparation) considered two alternative coppice-based supply chains, and namely: 1) a traditional supply chain, using semi-mechanized work systems to produce split firewood for residential stoves and 2) an innovative supply chain, using fully-mechanized work systems to produce chips for a modern district-heating network. the transport, chipping and heating processes were excluded to only focus on the harvesting operation as done in other countries in this deliverable.

Stand characteristics were taken from the study by Schweier et al. (2015), and represented stand 1, i.e. a Mediterranean mixwood coppice with Turkey oak (*Quercus cerris L*.), downy oak (*Quercus pubescens L*.), common maple (Acer campestris L.) and small-leaf ash *(Fraxinus oxyphillus L.)* as the main species. This stand was selected because it represents well the hillside coppice stands that are most easily accessible to modern machinery, due to their relatively flat, even and firm soil conditions. Beech and chestnut coppice often grow on steep terrain (mini-yarders), where the introduction of mechanical felling is technically more difficult to achieve and may only be considered when cable-assist machine technology will become widespread in these regions (Visser and Stampfer 2015). Stands of this type are harvested at the age of 20, leaving behind ca. 100 standards per hectare, or 20% of the standing mass. Total harvest was estimated at 120 m^3 ha^{-1} for the traditional system and 150 m^3 ha^{-1} for the innovative one.

The traditional supply chain represented the case described by Picchio et al. (2009) and included the following steps: motor-manual felling and processing into 1-m logs with chainsaws; forwarding by farm tractors with front and rear boxes on a mean distance of 400 m.

Table 21. Baseline including processes and their hour productivity. The outflows are presented in a hectare level and scaled-up to represent coppice systems with beech and chestnut forests in Italy.

Unit	Process	Productivity (process units/hour)	Outflow per one hectare	Outflow for coppice stands in Italy
ha	Stumps after coppicing	1	1	3663100
m^3	Felling (Motorsaw)	1.3	120	439572000
m^3	Extraction (mechanised)	3	120	439572000

The productivity, production cost and fuel consumption of felling and extraction were obtained from a large review study recently published by Spinelli et al. (2016a). Fuel use was calculated as 0.8 l/m^3 for felling, 2.7 l/m^3 for extraction as input to Energy use and greenhouse gas emission calculation. Average annual employment for a fulltime equivalent (FTE) was 1608 h (EUSTAT, 2016).

Table 22. Baseline indicator values per process unit.

Unit	Process	Employment (FTE/process unit)	Greenhouse gas emissions from machinery (kg CO2 eq./process unit)	Energy use (MJ/process unit)	Production costs (€/process unit)
ha	Stumps after coppicing	-	-	-	-
m^3	Felling (Motorsaw)	0.000478	2.034	27	11.5
m^3	Extraction (mechanised)	0.000207	7.050	95	15.0
m^3	Total	0.000686	9.084	123	26.5

Scenarios with processes, volumes and indicators

Innovation could target harvesting productivity and work safety, as well as assortments with a shift from firewood to chips, and from manual shortwood harvesting to mechanized whole tree harvesting. While the demand in bioenergy for energy generation is increasing and coppice forest could satisfy this demand very well in producing bulk material without form requirements fast, also other product categories with similar requirements emerge in the wake of the EU Circular Bioeconomy strategy (2018), namely as raw material for chemicals, pharmaceuticals, textiles, even fuels. Coppice forests are ideally suited for supplying this market with significant amounts of wood, if production can be achieved at competitive conditions (Jansen and Kuiper 2004). In particular, harvesting cost must be reduced, while increasing operator safety and comfort (Picchio et al. 2009). A dramatic improvement in this direction is only obtained through mechanization, which has a multiplier effect on operator productivity and offers a much safer and comfortable workstation than can ever be found for the motor-manual work techniques that characterize traditional coppice harvesting (Spinelli et al. 2016).

The innovative supply chain included the following steps: mechanical felling and bunching with excavator-mounted feller shears; extraction by purpose-built forwarder, on a mean distance of 400 m.

Table 23. Baseline including processes and their hour productivity. The outflows are presented in a hectare level and scaled-up to represent coppice systems with beech and chestnut forests in Italy.

Unit	Process	Productivity (process units/hour)	Outflow per one hectare	Outflow for coppice stands in Italy
ha	Stumps after coppicing	1	1	3,663,100
m^3	Felling (mechanised)	7	150	549,465,000
m^3	Extraction (mechanised)	11	150	549,465,000

As to the 120 m^3 ha^{-1} vs. 150 m^3 ha^{-1} that is because the conventional system produces traditional firewood and thus limits the use wood to a minimum diameter of 5–6 cm, whereas the chipping of whole trees allows to recover smaller branches as well. Fuel use was calculated as 1.7 l/m^3 for felling, 1.1 l/m^3 for extraction.

Table 24. Scenario indicator values per process unit

Unit	Process	Employment (FTE/process unit)	Greenhouse gas emissions from machinery (kg CO_2 eq./process unit)	Energy use (MJ/process unit)	Production costs (€/process unit)
ha	Stumps after coppicing	-	-	-	-
m^3	Felling (mechanised)	0.000089	4.532	61	9.3
m^3	Extraction (mechanised)	0.000057	2.884	39	7.7
m^3	Total	0.000145	7.050	100	17.0

Environmental indicators

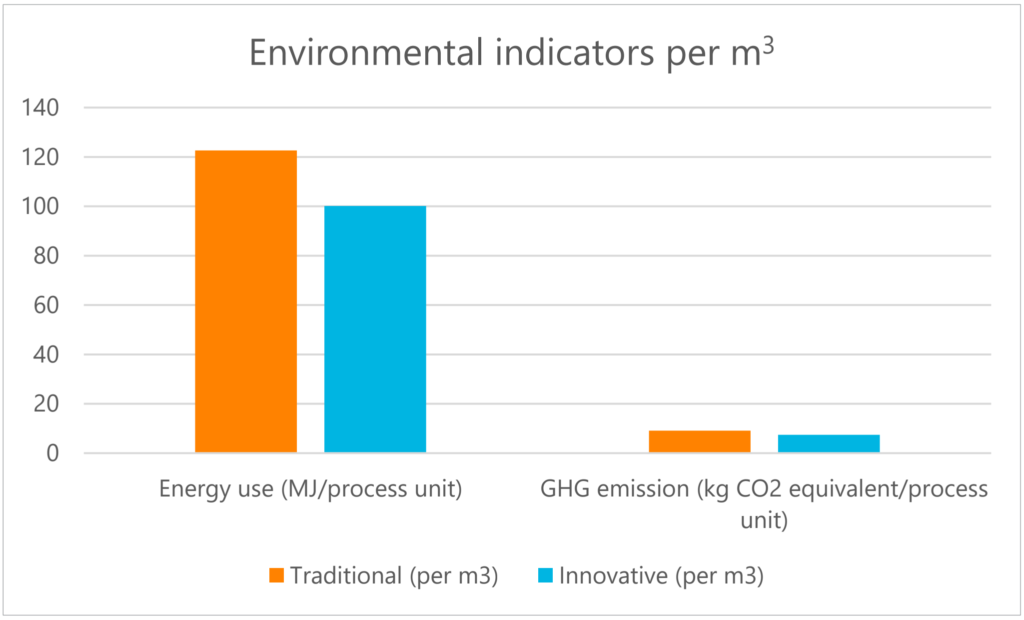

Figure 39. Environmental indicators. Energy use and GHG emission per m^3.

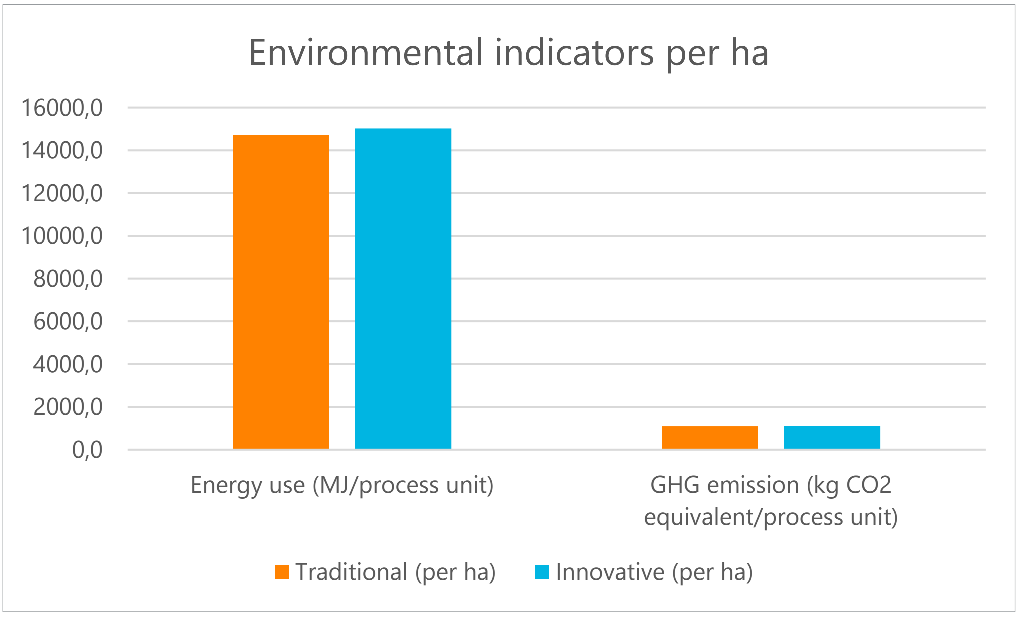

Figure 40. Environmental indicators. Energy use and GHG emission per ha.

Clear reduction in Energy use and Greenhouse gas emission of 18% per m^3, and slight increase of 2% per ha. Note that in the comparison per ha the extraction rate is higher 150 m^3 ha^{-1} instead of 120 m^3 ha^{-1}.

Social indicators

Employment numbers decline from 0.000686 FTE/m^3 to 0.000145 FTE/m^3 due to mechanization. While – particularly in rural areas – a decrease in employment potential is negative, the work itself becomes a lot safer and thus attractive. Simultaneously, as harvesting potentials and volumes are expected to increase, and increase in efficiency and decrease in workload will potentially reduce pressure on the workforce and make it possible to meet the demands.

Multiplied with the potential extraction of 120 m^3 ha^{-1} for the traditional system on all of Italy's coppice forests would require 10051 FTE of workers, assuming 30-year rotation periods. For the innovative system, extracting 150 m^3 ha^{-1} 2656 FTE would be required annually, again assuming 30-year rotation periods. The reduction in needed, qualified workers – while still considerable – makes it more feasible that timber is mobilized from these coppice stands.

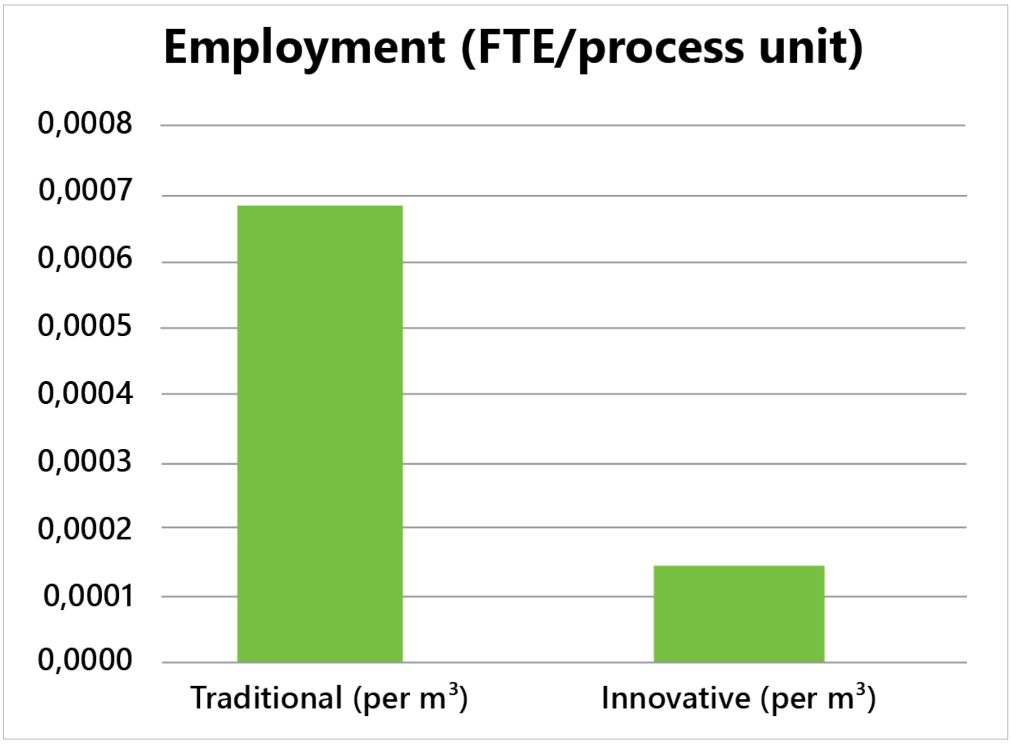

Figure 41. Social indicator employment per m^3.

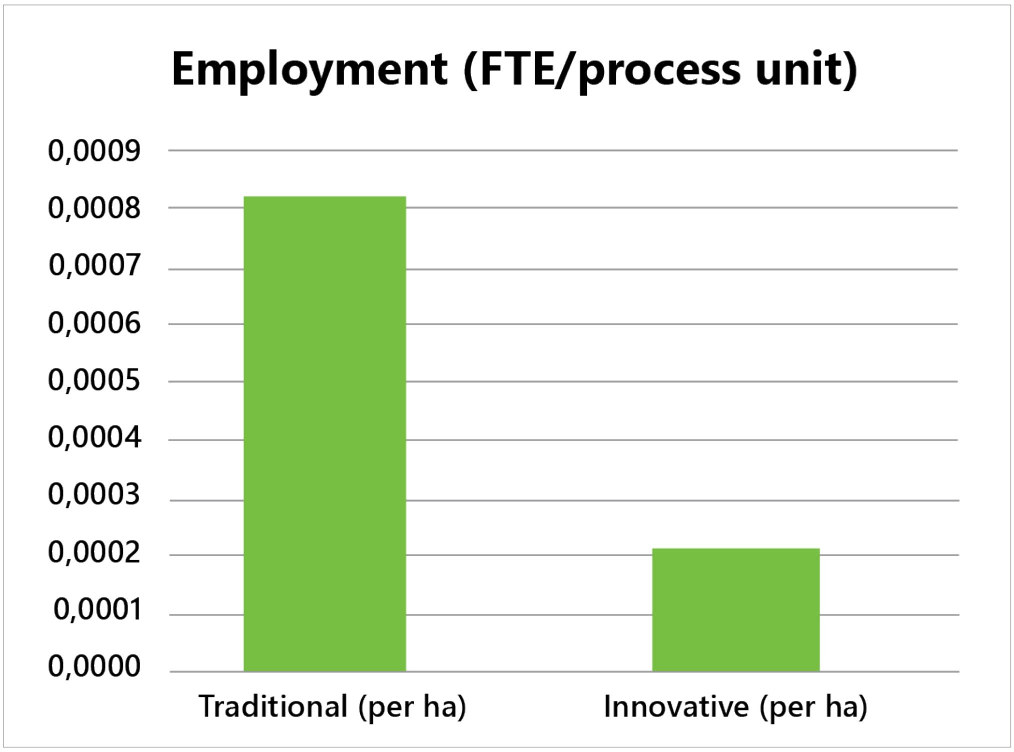

Figure 42. Social indicator employment per ha.

The study also considered two main types of social impacts: 1) employment potential and related potential for wages and salaries, and 2) work safety. The former was estimated by inverting worker productivity for each work step: this was especially easy because operators were considered to work independently from each other, even when multiple operators were engaged on the same worksite, as it is common with motor-manual felling and processing. The latter was estimated using existing scientific literature on the subject. In particular, it was assumed that mechanization would allow reducing non-fatal accident by a factor 3, that is from 15 to 5 claims per 100 workers (Bell 2002, Laflamme and Cloutier 1998), and fatal accidents by a factor 5, from 0.5 to 0.1 fatalities per million m^3 (Klun and Medved 2007).

Economic indicators

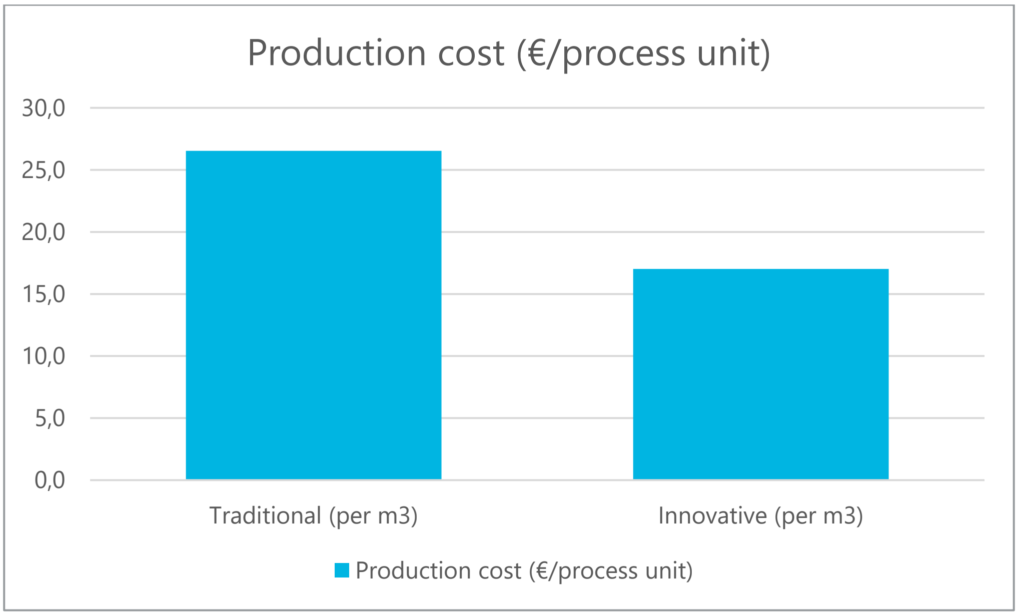

Figure 43. Economic indicator. Production cost per m^3.

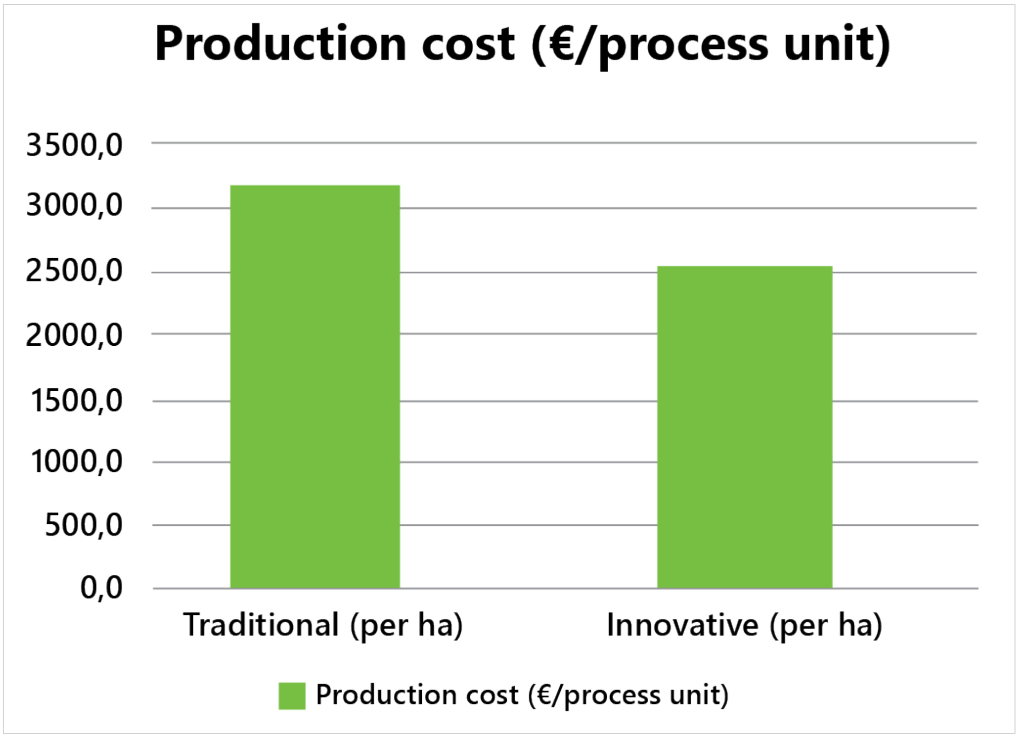

Figure 44. Economic indicator. Production cost per ha.

Lower costs of 36% per m^3 for innovation, and 20% per ha despite increased volume per ha. Quantified T4E goals and achieved results with these scenarios are reflected in Table 25.

Table 25. T4E goals and achievements in the Italian scenario in coppice stands.

T4E goal / Scenario	Mechanized harvesting
20% decrease in production costs	Production costs decreased by 36%. Fatal accidents decreased by 80% and non-fatal by 66%.
15% decrease is fuel consumption	Energy use and Greenhouse gas emission decreased by 18%.
2% in forest (yield) productivity	There are no results on the de facto sump regeneration available yet (Ongoing study), however, from initial observations it seems that stumps are healthy and no loss in growth potential is expected. Thus, the forest productivity is likely to be maintained (0%), while at the same time increasing the outtake of materials by 25%.

3.1.7. Denmark

Bioeconomy in Denmark and role of forestry

Denmark does not yet have a dedicated national bioeconomy strategy. However, the government's commitment to bioeconomy is framed by the "Growth Plan for Foods" and the "Growth Plan for Water, Bio and Environmental Solutions" (2013). In addition, Denmark has appointed a National Bioeconomy Panel, composed of experts from universities, industry and non-governmental organisations as well as policymakers. In the meantime, there are strategical papers for almost all industrial sectors stressing the meaning of a sustainable economy and encouraging respective developments. This concerns not only agriculture and forestry, but also the aquaculture, food and energy sector (German Bioeconomy Council 2015).

Denmark joined the European Union Strategy for the Baltic Sea Region (EUSBSR), which is the first Macro-regional Strategy in Europe. The Strategy is divided into three objectives, representing the three key challenges of the Strategy: saving the sea, connecting the region and increasing prosperity. Each objective relates to a wide range of policies and has an impact on the other objectives. Bioeconomy is one of 13 Policy Areas of the EUSBSR Action Plan (EUSBSR 2019; Nordic Council of Ministers 2019a).

Baseline with processes, volumes and indicators

The baseline value chain is built to represent average Danish coniferous growth conditions. The baseline consists of a rotation of around 50 years for one hectare even-aged Norway spruce (*Picea abies*) stand. Rotation starts from soil scarification and planting and ends with final felling.

The forest management practices (Table 26), timing, and intensity are based on simulation data by Cardellini et al. (2018) and a report by Raae & Strange (In Routa et al. 2020b). Value chains for spruce start from scarification to improve seedling establishment. For spruce, planting is the preferred regeneration method. In the baseline scenario, Norway spruce is planted in the whole area of a hectare except on those areas where skidding roads are planned. Skidding roads take up about 20% of the area. Planting distance is 1.5 x 1.65m which results in about 3,200 seedlings per hectare.

In year 23, when the mean tree height is about 9.4m, a first thinning of the stand takes place removing approximately 20% of the standing volume. In year 25, a second thinning takes place removing approximately 25% of the standing volume.

To estimate biomass production for Norway spruce, we applied modelled results by Raae & Strange (In Routa et al. 2020b) from planting experiments at four different locations in Denmark: Løvenholm, Store Hareskov, Harager Hegn and Nørlund. Raae and Strange assumed a yield class 16.4 m^3 ha^{-1} yr^{-1} for Norway spruce at a planting distance of 1.75 x 1.75 m (initial planting density of 3,265 plants per ha) and a dbh of 10.6 cm at age 23 and simulated the dbh of various planting distances. To estimate biomass production for Norway spruce after year 23, we used the modelled results from even-aged uniform spruce clear-cut systems in Denmark from Cardellini et al. (2018).

The baseline is presented in Table 26 on a hectare level and then upscaled to whole Denmark. Total productive forest area in Denmark is 625,603 hectares of which 38% is dominated by coniferous forests (Nord-Larsen et al. 2018). Norway spruce (*Picea abies*) is the most common species and covers 17.1% of the forest area (about 106,978 ha), followed by beech (Fagus sylvatica, 12.9%), pine (*Pinus ssp*, 12%), oak (*Quercus robur*, 9.6%), Sitka spruce (*Picea sitchensis,* 6.1%), abies (*Abies normania* 4.5%), maple (*Acer pseudoplatanus*, 3.5%), and ash (*Fraxinus excelsior,* 3.4%).

Table 26. Baseline including processes and their hour productivity. The outflows are presented in a hectare level and scaled-up to represent spruce-dominated forests in Denmark.

Unit	Process	Productivity (process units/hour)	Outflow per one hectare	Outflow for Norway spruce stands in Denmark
ha	Site preparation (removals of residuals, chipping, scarification)	1	1	106,978
ha	Planting	0.08	1	106,978
m^3	Thinning 1 (harvester)	6.5	20	2,139,560
m^3	Thinning 2 (harvester)	6.5	37.5	4,011,675
m^3	Final felling (harvester)	19	215	23,000,270

The sustainability indicator values used in the baseline scenario are presented in Table 26. The employment is estimated using annual full-time employment of 1,411 hours and process-based hour productivities according to Cardellini et al. (2018), Tuomasjukka et al. (2015) and Laine et al. (2016). Fuel consumption and related emissions of the machinery were taken from Finnish statistics database Lipasto (VTT 2016). Productions costs were taken from Aaronen (2011), Tuomasjukka et al. (2015) and Routa et al. (2019).

Table 27. Baseline indicator values per process unit.

Unit	Process	Employment (FTE/process unit)	Greenhouse gas emissions from machinery (kg CO_2 eq./process unit)	Energy use (kWh/ process unit)	Production costs (€/process unit)
ha	Site preparation (removals of residuals, chipping, scarification)	0.000709	66	77	264
ha	Planting	0.00845	-	-	384.12
m^3	Thinning 1 (harvester)	0.000109	18.4	22.9	6
m^3	Thinning 2 (harvester)	0.000109	18.4	22.9	6
m^3	Forwarding (forwarder)	0.0000601	7.3	8.9	3.16
m^3	Final felling (harvester)	0.0000373	6.3	7.8	7.09

Scenarios with processes, volumes and indicators

A considerable share of green energy production in Denmark relies on wood energy. A large part of the energy wood used in Denmark is imported. It has been debated if these imports are sustainable and should be restricted. This would imply an increased demand for energy wood from Danish forests. Although, the forest area has increased and still is increasing, the supply would in the long run be insufficient under the present conditions. It has been suggested to increase forest production in existing forests by silvicultural measures. One option is to replace trees with faster growing tree species.

This assessment evaluates the implications for biomass production if a fast-growing species, in this case hybrid larch, is mixed when establishing stands of Norway spruce. The impacts for biomass production are simulated if hybrid larch is planted on skidding roads.

Increasing production using ”power-cultures”

The term “power culture” reflects regeneration systems which make use of fast-growing tree species mixed with a main species, for instance Norway spruce. The main species is meant for high quality timber production. It is the idea that the fast-growing species both supports the main species in the stand during the first years and after 10–25 years it delivers a profitable output in terms of biomass (Figure 39). The power culture model can in principle be applied in any planted forest stand following a final felling. The fast-growing tree species can be planted in rows, equally distributed over the whole area or in rows or where future skidding roads are planned. In this case study, quality timber production of Norway spruce is assessed in combination with hybrid larch as the fast-growing supportive species.

For Norway spruce, a yield class 16.4 (m^3 ha^{-1} yr^{-1}) was assumed (Raae & Strange *In* Routa et al. 2020b). Growth and yield of Norway spruce in Danish forests is very well documented. Less documentation is found for hybrid larch. Lately, a number of yield tables for hybrid larch have been elaborated in Denmark and Southern Sweden. The first 35–40 years of growth is relatively well supported by measurements in existing stands of hybrid larch. Inventories of older stands are much less documented. However, in a Danish context the growth of hybrid Larch seems to be relatively unaffected by soil conditions. For the simulations presented in this study, a yield class of 17 m^3 ha^{-1} yr^{-1} was assumed (Raae & Strange *In* Routa et al. 2020b). In their study, Raae and Strange were interested in modelling the growth of the first 23 year of the growth of the hybrid larch. At this point the increment of the larch peaks and it is at the same time important to have the larch removed in order not to reduce production of quality timber of Norway spruce.

In the assessment, two scenarios were compared with the baseline. In the baseline, as stated above, Norway spruce is planted in the whole area of a hectare except in those areas where skidding roads are planned (Figure 45).

In the second scenario – Norway spruce on skidding roads, Norway spruce is planted over the whole area of a hectare, including the skidding roads. Spacing is 1.5 x 1.65 m which results in approximately 4,000 seedlings per hectare.

In the third scenario – Hybrid larch on skidding roads, Norway spruce is planted over the whole area of a hectare except where skidding roads are planned. Hybrid larch is planted on the skidding roads. Skidding roads take up about 20% of the area. Spacing is 1.5 x 1.65 m resulting in approximately 3,200 Norway spruce and 220 hybrid larch seedlings per hectare (spacing 3 x 3 m).

In the second and third scenario, spruce or hybrid large are harvested in year 23 in order to establish skidding roads and about 20% of the standing volume will be removed in thinning. Hybrid larch is estimated to have reached a total production usable for wood chips after 23 years at a height of 16,7m. After the first thinning in year 23, stands are managed the same way and develop along the same pattern in all three scenarios. In year 25, a second thinning of the stand takes place removing about 25% of the standing volume.

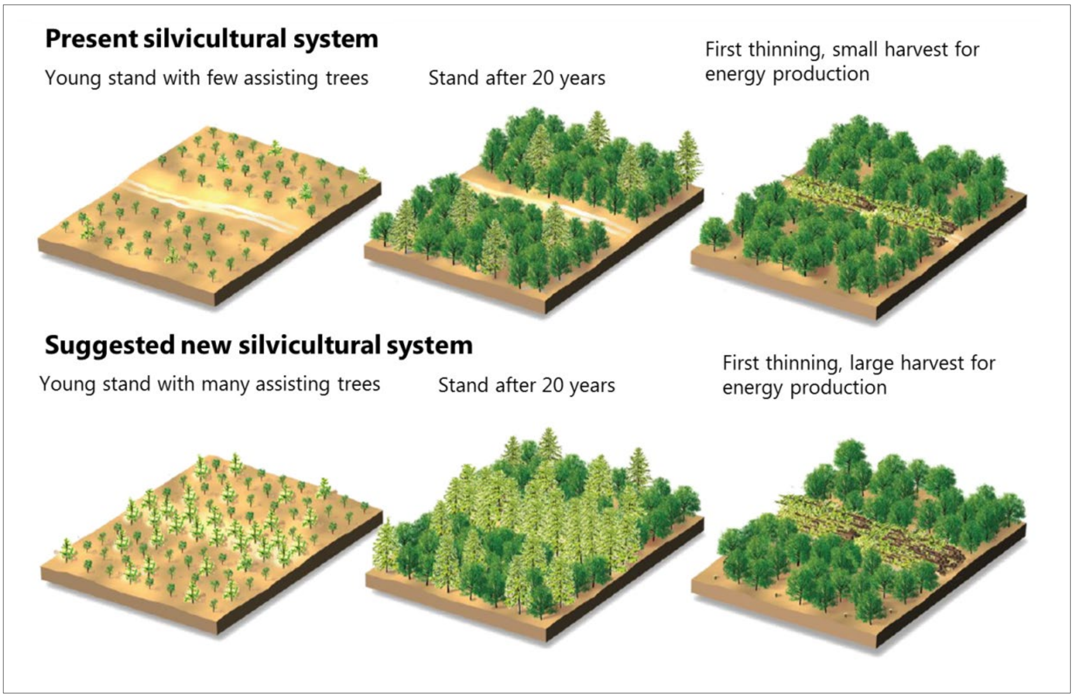

Figure 45. Power cultures for increased biomass and energy production.

Planting spruce on skidding roads resulted in a 3.3% production costs reduction (Figure 46. Planting fast growing hybrid larch on the same skidding roads resulted in a 19.6% cost reduction. However, energy use and its related greenhouse gas emissions from machinery increased by 6.4% for planting spruce and 20.9% and for planting hybrid larch (Figure 47, Figure 48, Figure 49, Figure 50). This increase in energy use and emissions was mainly due to that harvesting small-diameter trees requires more energy and consequently also causes more emissions compared to harvesting larger diameter wood in final felling. Since both planting spruce and larch on skidding roads improves forest yield (by about respectively 10% or 44%), employment increased by 12% for planting spruce and by 50% for planting hybrid larch. For the whole country this would mean annually the creation of 11 additional jobs for planting spruce and 44 additional jobs for planting hybrid larch (Figure 51).

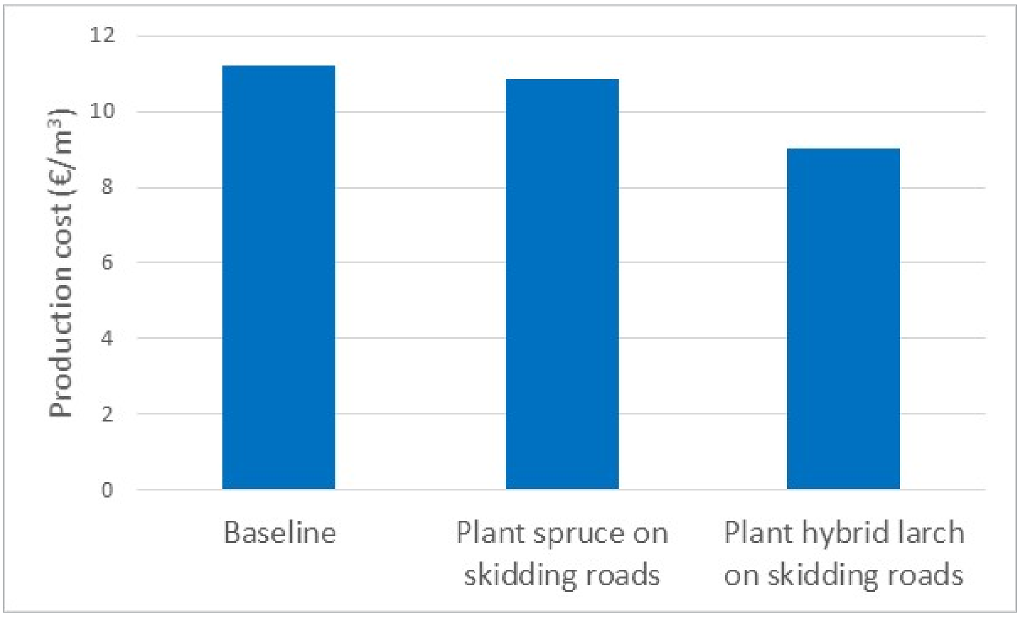

Figure 46. Production costs (€/m^3) estimated over a full rotation in spruce forests in Denmark.

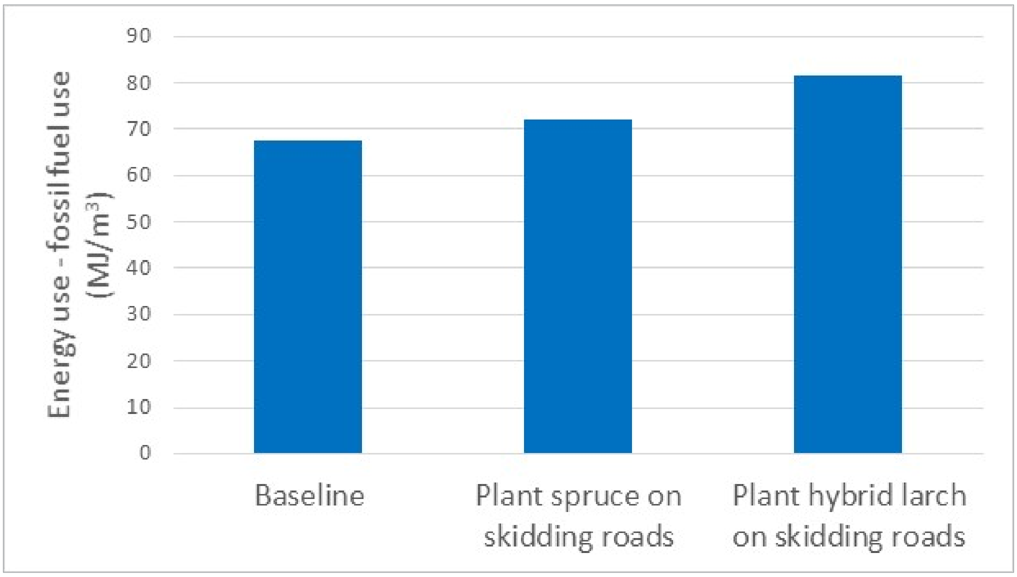

Figure 47. Mean energy use (MJ m^{-3}) by machinery used in forest operations estimated over a full rotation in spruce forests in Denmark.

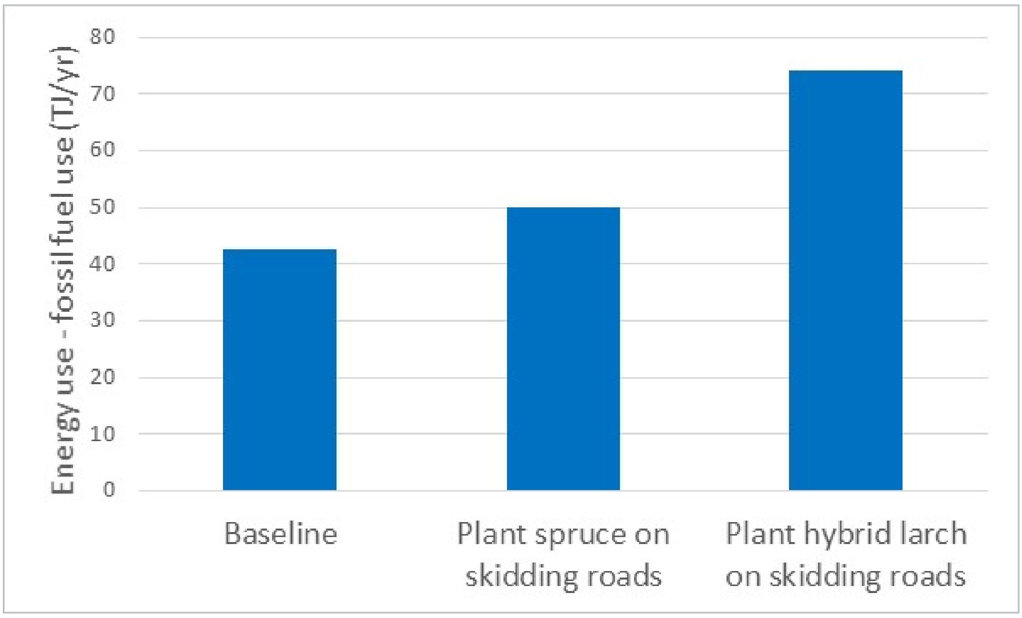

Figure 48. Mean annual energy use (TJ yr^{-1}) by machinery used in forest operations estimated over a full rotation in spruce forests in Denmark.

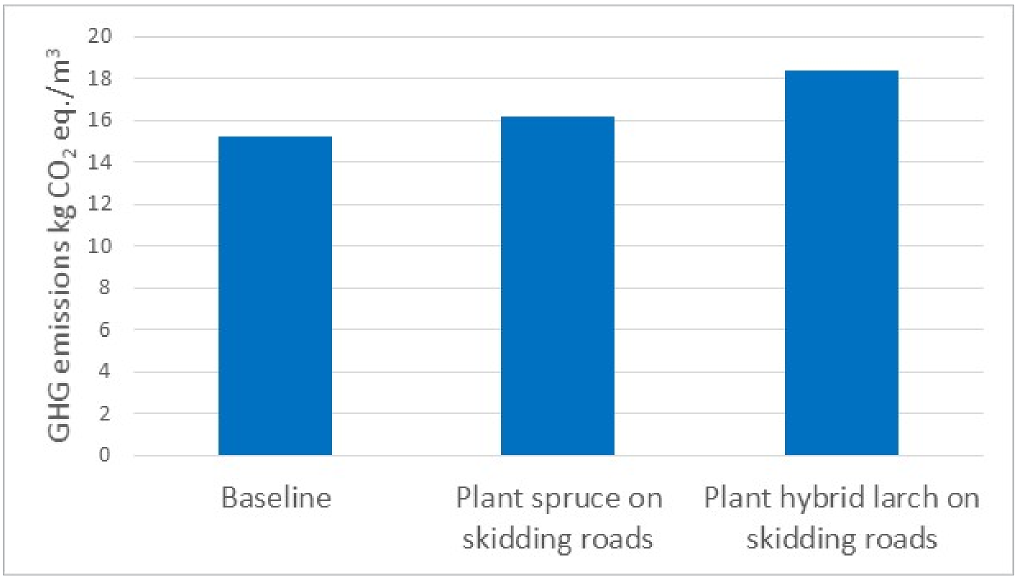

Figure 49. Mean greenhouse gas emissions (kg CO_2 eq. m^{-3}) from machinery used in forest operations estimated over a full rotation in spruce forests in Denmark.

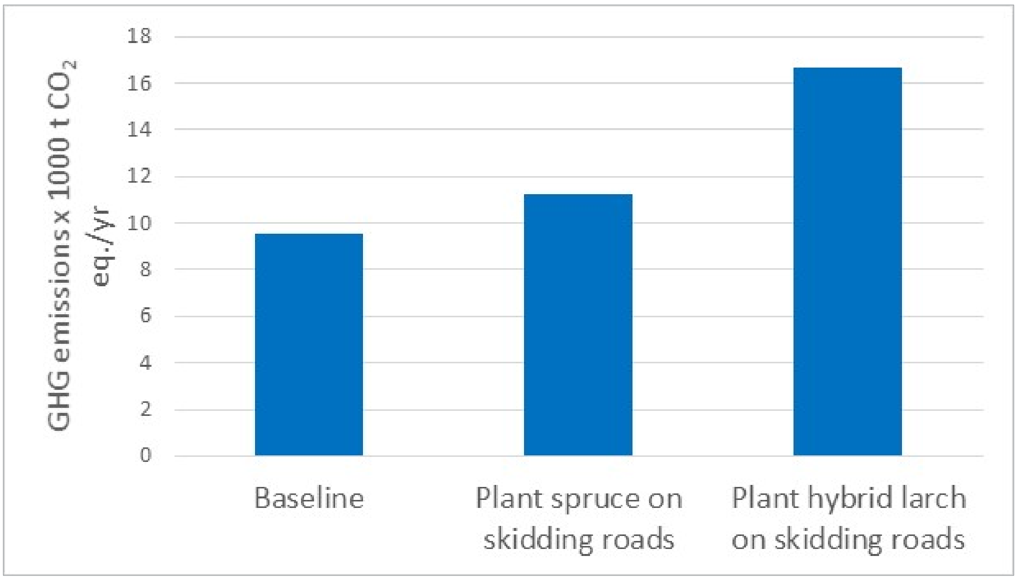

Figure 50. Mean annual greenhouse gas emissions (x 1000 t CO_2 eq. yr^{-1}) from machinery used in forest operations estimated over a full rotation in spruce forests in Denmark.

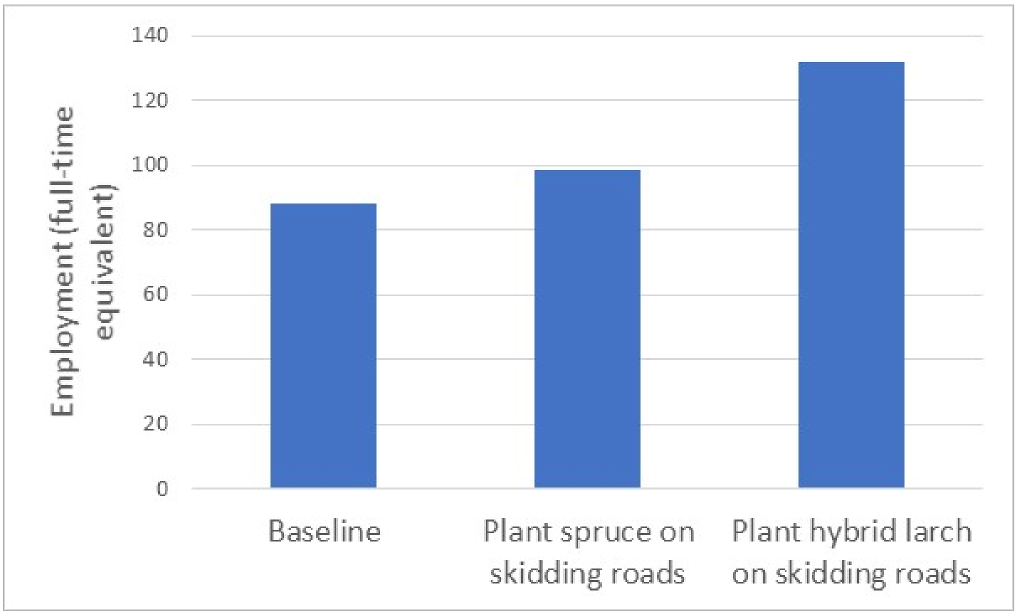

Figure 51. Mean annual employment (full-time equivalents) estimated over a full rotation in spruce forests in Denmark.

When comparing scenario performances in relation to objectives for TECH4EFFECT project, it is obvious that planting spruce on skidding roads would result in a small cost reduction, but planting hybrid larch would reach the T4E goal of reducing production costs by the target of 20%. However, both management options would at the same time result in an increase in fuel use and related emissions (Table 28). Nevertheless, another advantage was that forest yield increased as previously unused skidding roads are now also used for wood production, leading to a more efficient use of land, which is a scarce resource.

Table 28. T4E goals and achievements in the Danish scenarios at country level in spruce dominated forest areas.

T4E goal / Scenario	Plant spruce on skidding roads	Plant hybrid larch on skidding roads
20% decrease in production costs	Decreased by 3.3%	Decreased by 19.6%
15% decrease in fuel consumption	Increases by 6.4%	Increases by 20.9%
2% in forest (yield) productivity	Increased by 10%	Increased by 44%

3.2. Upscaling top-down: based on D7.2 volumes and D3.4 top performance figures for all of Europe

3.2.1. Bioeconomy in Europe and role of forestry

The EU Bioeconomy Strategy was launched back in 2012, addressing the production of renewable biological resources and their conversion into bio-products and bioenergy. The 2018 update aims for the deployment of a sustainable European bioeconomy to maximize its contribution towards the 2030 Agenda and its Sustainable Development Goals (SDGs), as well as the Paris Agreement (EC 2019). The renewed bioeconomy strategy supports the transition to a sustainable and circular bioeconomy, fitting wider EU priorities and policies (climate, circular, innovation, food, energy, trade, industry, agriculture, fisheries and marine, etc.). The purpose of the updated European Bioeconomy Strategy is therefore to further develop a bioeconomy that valorizes and preserves ecosystems and biological resources, drives the renewal of our industries and the modernization of our primary production systems through bio-based innovation, involves local stakeholders, protects the environment and enhances biodiversity (EC 2018b).

The objectives of the Bioeconomy Strategy (EC 2018c) are:

1. Ensuring food and nutrition security
2. Managing natural resources sustainably
3. Reducing dependence on non-renewable resources
4. Mitigating and adapting to climate change
5. Strengthening European competitiveness and creating jobs

The action plan focuses on: (i) strengthening and scaling up the bio-based sectors, unlocking investments and markets; (ii) deployment of local bioeconomies rapidly across the whole of Europe; and (iii) understanding the ecological limitations of the bioeconomy (EC 2018d, EC 2019).

The European bioeconomy is one of the EU’s largest and most important sectors encompassing agriculture, forestry, fisheries, food, bioenergy and bio-based products with an annual turnover of around 2.3 trillion euro and employing around 18 million people (EC 2018d). It is estimated that bio-based industries could create up to one million green jobs by 2030, especially in rural and coastal areas (ENRD, 2019). Currently, bioeconomy accounts for 7% of the European economy.

The bioeconomy, while it benefits the whole society, has a special resonance for rural areas, were most of the biological resources (plants, animals, micro-organisms and derived biomass, including organic waste) are produced. The mainstreaming of the bioeconomy is being accelerated by Rural Development Programmes (RDPs) around Europe, leading to the production of sustainable food and feed, innovative bio-based products, renewable energy and other services. The processing and distribution of bio-based products – from food and feed to fuels and materials – creates new opportunities for processors, retailers and consumers particularly in rural areas, but also beyond (ENRD 2019).

Apart from the forests' ecological value and impact on the EU landscape, the forest sector is also an economic resource. The overall level of EU-28 roundwood production reached an estimated 458 million m^3 in 2016. Among the EU Member States, Sweden produced the most roundwood (81 million m^3) in 2016, followed by Finland, Germany and France (each producing between 51 and 61 million m^3). Figure 52 shows the forest share of the land area in Europe.

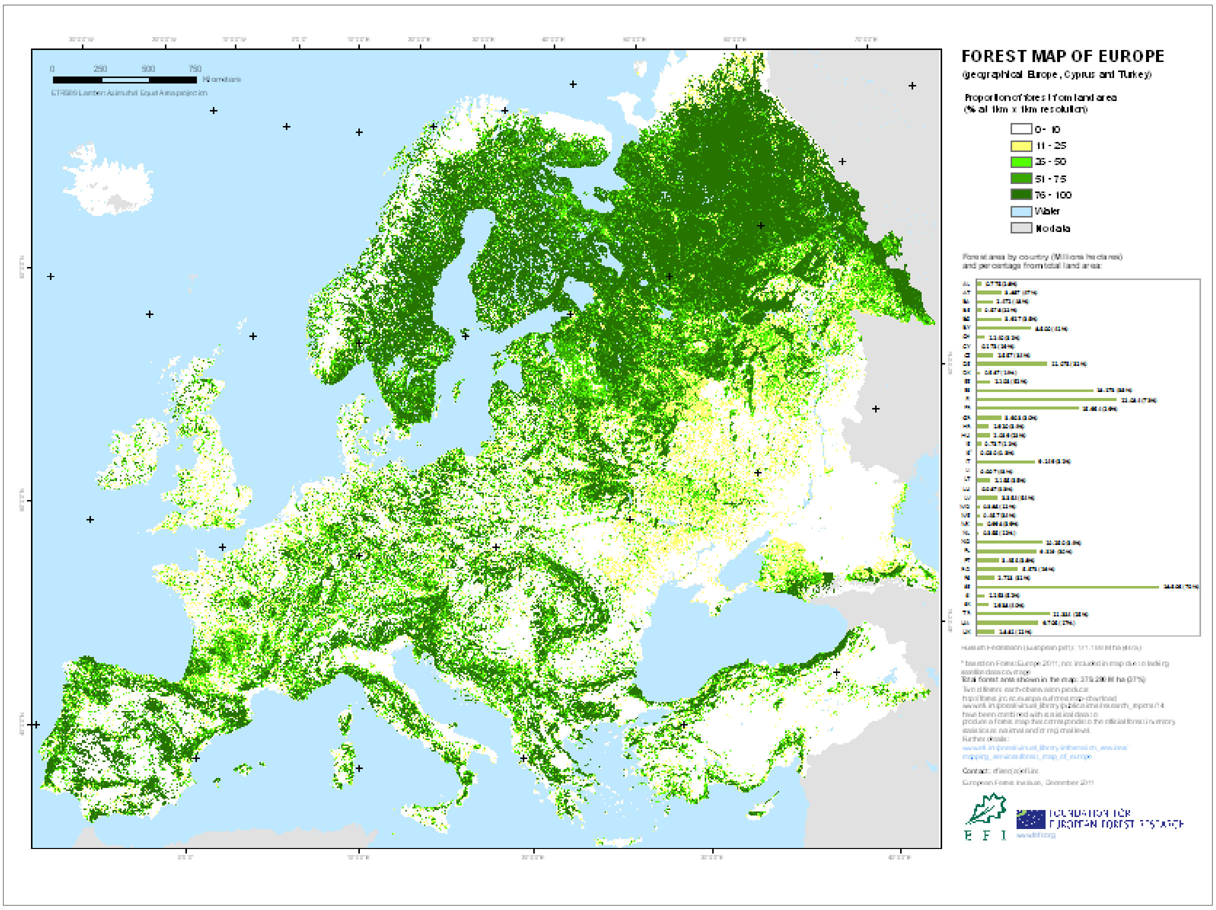

Figure 52. Forest map of Europe (Gunia et al. 2011).

The EU's wood-based industries cover a range of downstream activities, including woodworking industries, large parts of the furniture industry, pulp and paper manufacturing and converting industries, and the printing industry. Together, some 420,000 enterprises were active in wood-based industries across the EU-28; they represented one in five (20) manufacturing enterprises across the EU-28, highlighting that - with the exception of pulp and paper manufacturing that is characterized by economies of scale - many wood-based industries had a relatively high number of small or medium-sized enterprises.

The economic weight of the wood-based industries in the EU-28 as measured by gross value added was equivalent to EUR 139 billion or 7.3% of the manufacturing total in 2015. Within the EU-28's wood-based industries, the highest share was recorded for pulp, paper and paper products manufacturing (32.9% or EUR 46 billion), while the other three sectors had nearly equal shares - printing and service activities related to printing and the manufacture of furniture each amounted to 21–22% of the gross value added of wood based industries, while the manufacturing of wood and wood products made up 24%. The wood-based industries employed 3.3 million persons across the EU-28 in 2015 or 11% of the manufacturing total. There were 2 million persons employed within both the manufacture of wood and wood products and the manufacture of furniture, 644,000 persons were recorded for the activity of pulp, paper and paper products manufacturing, the lowest employment of the four activities (Eurostat 2018b).

Bio-Innovation in forest sector

The EU supports the bioeconomy with research and innovation funding. It has already invested €3.85 billion under Horizon 2020 (2014–2020) and proposed €10 billion for food and natural resources, including the bioeconomy, under Horizon Europe (2021–2027) (EC 2018b, EC 2018c).

Forests provide biomass that can have a wide range of uses as recent advances have demonstrated. Basically any item made from fossil fuels can be made out of trees, ranging from energy production, construction material, furniture, paper and many different bio-based products, such as wood-based textiles, packaging material, carbon fibre, bio-based plastics and composites, etc.

Figure 53 shows the EU Member States and regions having research and innovation priorities in the field of forest-based bioeconomy for the 2014–2020 period.

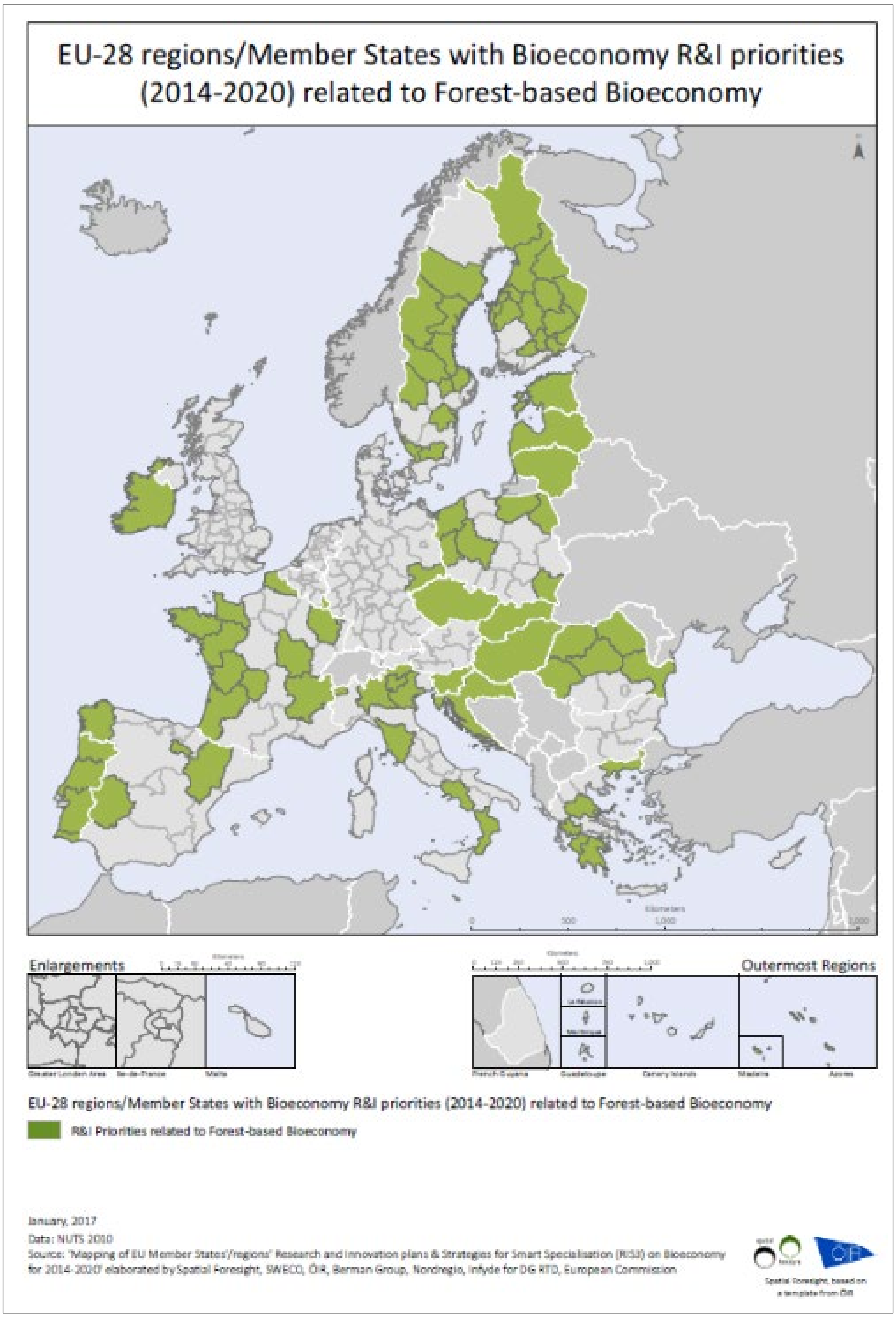

Figure 53. EU-28 regions/Member States with Bioeconomy Research & Innovation priorities (2014–2020) related to forest-based bioeconomy. Source: Spatial Foresight et al. 2017.

3.2.2. Material flow results for Baseline and Scenarios

Tree harvesting systems are either motor-manual, often with tree-length method, or fully mechanized, with cut-to-length method. In Europe these are the most common systems:

1. Harvester and forwarder in cut-to-length method (CTL)
2. Chainsaw and cable yarder (WTS/CTL)
3. Chainsaw and skidder in whole-tree system (WTS)

For the scenario, all motormanual WTS were considered to be replaced by CTL systems, and high levels of mechanization. The baseline data of shares for most common harvesting operation systems was based on Tuomasjukka et al. (2018) and WP2-4 communication, and thus adjusting for Tech4Effect scenario calculations to reflect all harvesting while excluding stump harvesting. Stump harvesting is practiced only in selected areas in Europe (mainly Sweden, Finland) and highly controversial while yielding only low volumes under high energy input. For this reason, they were excluded from the calculations in this study, while still using Verkerk et al. 2019 as input to the calculation.

Table 29. Percentage volumes and operational scenarios.

	Country	*chain-saw CTL [%]	*chain-saw WTS [%]	*har-vester CTL [%]	#for-warder CTL [%]	#skid-ding WTS [%]	#ca-bleyard-ing [%]
BASELINE	EU 28 2020	12	32	55	62	35	3
	CEU	7	52	41	45	47	8
	SEU	42	34	24	38	55	8
	EEU	15	75	9	13	85	1
	NEU	7	1	91	100	0	0
SCENARIO	EU 2050 Removal	46		54	97		3
	CEU	59		41	92		8
	SEU	91		9	92		8
	EEU	91		9	99		1
	NEU	9		91	100		0

Verkerk et al. 2019 estimated the potential availability of forest biomass. According to the calculations, forests in 39 European countries could currently provide 401 million tonnes dry matter yr^{-1} of biomass. The potential availability of woody biomass in the 28 investigated countries in 2020 is estimated at 335 million tonnes dry matter yr^{-1} overbark (or 732 million m^3 yr^{-1} overbark), or 330 million tonnes dry matter yr^{-1} overbark (or 722 million m^3 yr^{-1} overbark) excluding stumps for T4E impact upscaling calculations, according to the Base scenario.

The potential was projected to decrease to 319 million tonnes dry matter yr^{-1} overbark by 2050, but in general, the potential was rather stable over time. This is mainly because the potential for each year is based on the average maximum harvest level that can be maintained throughout the next 50-year period. By 2050, this potential could increase to 409 million tonnes dry matter yr^{-1} overbark for the combined scenario of Enhanced production and Improved supply; without stumps this potential is 365 million tonnes dry matter yr^{-1} overbark (or 797 million m^3 yr^{-1} overbark) as used for the T4E impact upscaling calculations.

The potential removal volumes used for the material flow and indicator calculation for the Baseline per country group and total, as well as for the combined scenario, were based on adjusted volumes Verkerk et al. 2019.

Table 30. The potential removal volumes for the Baseline 2020 per country group and total, as well as for the combined scenario 2050. Adapted from Verkerk et al 2019.

Mio m^3	NEU	CEU	EEU	SEU	EU28	
BASE 2020	252.2	232.4	141.6	96.2	722.4	BASE 2020: Potential availability of woody biomass (Mio m^3 yr^{-1} overbark) for the Base scenario in 2020 (excluding stumps)
Combined 2050	299.6	252.1	143.7	101.9	797.3	Combined 2050: Potential availability of woody biomass (Mio m^3 yr^{-1} overbark) for the Combined scenario in 2020 (excluding stumps). Combined = enhanced productivity and improved mechanization based on Verkerk et al. 2019

[%]	Country	*chainsaw CTL [%]	*chainsaw WTS [%]	*harvester CTL [%]	#forwarder CTL [%]	#skidding WTS [%]	#cableyarding [%]
BASELINE	EU 28 2020	12	32	55	62	35	3
	CEU	7	52	41	45	47	8
	SEU	42	34	24	38	55	8
	EEU	15	75	9	13	85	1
	NEU	7	1	91	100	0	0
SCENARIO	EU 2050 Removal	46		54	97		3
	CEU	59		41	92		8
	SEU	91		9	92		8
	EEU	91		9	99		1
	NEU	9		91	100		0

[Mio m^3]	Country	*chainsaw CTL	*chainsaw WTS	*harvester CTL	#forwarder CTL	#skidding WTS	#cableyarding
BASELINE	**EU 28 2020**	**86,7**	**231,2**	**397,3**	**450,0**	**251,8**	**20,6**
	CEU	15,6	121,3	95,5	104,8	109,5	18,1
	SEU	40,4	32,7	23,1	36,1	52,7	7,4
	EEU	21,7	106,9	13,1	19,1	120,8	1,8
	NEU	18,6	3,2	230,5	252,1	0,1	0,0
SCENARIO	**EU 2050 Removal**	**366,8**	**0**	**430,5**	**773,4**	**0**	**23,9**
	CEU	148,7		103,4	231,9		20,2
	SEU	92,7		9,2	93,8		8,2
	EEU	130,7		12,9	142,2		1,4
	NEU	27,0		272,6	299,6		0,0

The potential volumes per operation, following Table 30, are shown in Figure 54 for the Baseline and in Figure 55 for the Combined scenario at EU28 level. These shares and volumes have been used for upscaling the impacts calculated by indicators (see Chapter 3.2.2).

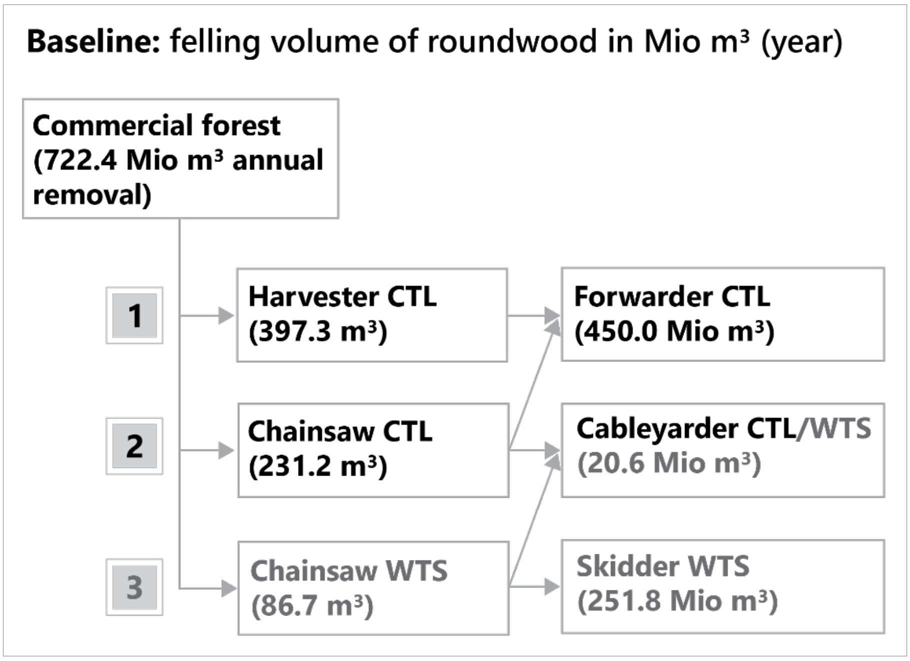

Figure 54. Baseline.

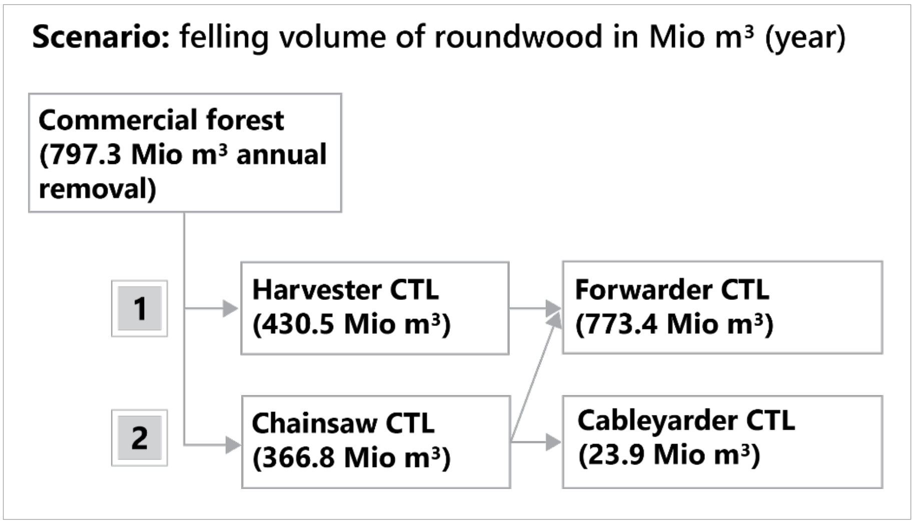

Figure 55. Scenario.

3.2.3. Indicators for baseline and scenario

Indicators used were in line with the country-specific case studies: employment (FTE), production costs (€), energy use (MJ) and consequent greenhouse gas emissions (CO2e). Indicator values were calculated for each process per one cubic metre of harvested forest biomass (Table 31) based on average productivities and fuel uses presented in Annex IV. Indicator calculations were conducted using values from INFRES D5.3 with small adjustments. Indicator values were then extrapolated to each EU region separately (Table 32, Table 33, Table 34, Table 35) and finally to EU level (Table 36).

Table 31. Indicator values per m^3 for all regions and operations.

Region	Process	Employment (FTE/m^3)	Greenhouse gas emissions from machinery (kg CO2-e/m^3)	Energy use (MJ/m^3)	Production costs (€/m^3)
NEU	Harvester CTL	0.00011	5.29	71.40	7.09
	Motorsaw CTL	0.00040	0.88	11.90	20.89
	Motorsaw WTS	0.00040	0.88	11.90	20.89
	Forwarder CTL	0.00005	1.83	24.72	2.52
SEU	Motorsaw CTL	0.00039	0.88	11.90	13.47
	Motorsaw WTS	0.00039	0.88	11.90	13.47
	Harvester CTL	0.00011	5.23	71.40	5.11
	Forwarder CTL	0,00004	1.83	24.70	1.95
	Skidding WTS	0.00014	0.84	11.32	4.76
	Cable yarding	0.00012	2.25	30.38	4.59
CEU	Motorsaw CTL	0.00046	0.93	12.00	23.67
	Motorsaw WTS	0.00046	0.46	6.43	23.67
	Harvester CTL	0.00008	4.73	63.00	11.72
	Forwarder CTL	0.00006	2.74	36.00	7.20
	Skidding WTS	0.00007	1.93	26.00	7.80
	Cable yarding	0.00011	7.05	95.20	24.17
EEU	Motorsaw CTL	0.00052	1.29	17.41	11.80
	Motorsaw WTS	0.00052	1.29	17.41	11.80
	Harvester CTL	0.00006	4.11	55.49	4.00
	Forwarder CTL	0.00015	7.52	101.61	5.50
	Skidding WTS	0.00009	2.97	40.09	3.10
	Cable yarding	0.00010	7.05	95.20	4.30

Table 32. Indicator values for NEU, presented in millions.

Indicator	Baseline	2050
Energy use MJ	22949.032	27191.052
GHG emissions kg CO2e	1699.872	2014.082
Employment FTE	0.045145852	0.053941723
Production costs €	2724.939	3251.756

Table 33. Indicator values for SEU, presented in millions.

Indicator	Baseline	2050
Energy use MJ	4.232.276	4.325.986
GHG emissions kg CO2e	312.122	319.796
Employment FTE	0.040909007	0.042247246
Production costs €	1.457.911	1.516.229

Table 34. Indicator values for CEU, presented in millions.

Indicator	Baseline	2050
Energy use MJ	15.326.579	18.570.04
GHG emissions kg CO2e	1.148.113	1.405.189
Employment FTE	0.086558	0.09281
Production costs €	6.405.82	6.889.491

Table 35. Indicator values for EEU, presented in millions.

Indicator	Baseline	2050
Energy use MJ	9.920.828	17.573.53
GHG emissions kg CO2e	734.833	1.300.836
Employment FTE	0.080951087	0.089390146
Production costs €	2.057.15	2.381.98

The results show that due to increased forest biomass availability and mechanization of operations, energy use and subsequent greenhouse gas emissions increase. Total production costs increase as the forest yield increases; however, in central and southern Europe, costs per cubic metre of harvested forest biomass decreases with mechanization. Employment increases all over Europe with increased forest biomass available for harvesting, creating jobs and improving well-being. In order to further reduce costs, energy use and emissions, the possibilities offered by new digital solutions should be considered (see chapter 3.2.2.3).

Table 36. Indicator values for the whole EU in baseline and scenario, presented in millions.

Indicator	Baseline	2050
Energy use MJ	52.428.715	67.660.608
GHG emissions kg CO2e	3.894.94	5.039.903
Employment FTE	0.253563947	0.278389115
Production costs €	12.645.82	14.039.456

A closer look at hotspots

According to the assessment by Verkerk et al. (2019), the forest biomass availability per unit of land is the highest in northern Europe (southern Finland and Sweden, Estonia and Latvia), central Europe (Austria, Czech Republic, and southern Germany), Slovenia, southwest France and Portugal. Some of these areas are, however, already strongly utilized and the availability of unused forest biomass is limited (Figure 56). Areas that have three hotspots (high forest biomass availability, high availability of unused forest biomass, and high proportion of forest biomass in total lignocellulosic biomass potential) include central Sweden, Estonia, Latvia, central Europe (central Germany, Austria, Czech Republic, Slovenia) as well as central Portugal. Improving forest management practices and operations in these areas could have a significant effect on the total biomass availability in Europe.

Fertilization in boreal forest hotspots (Sweden, Estonia, Latvia) would be effective in order to increase the availability and attractiveness of unused forest biomasses in these areas. In central European hotspots representing the alpine ecoregion, winch-supported harvesting could be beneficial. Central European hotspots representing continental ecoregions could explore the option of planting fast-growing tree species on skidding roads (so-called power cultures). In Portugal, coppice management could be a great option to improve forest productivity and reduce environmental impacts per harvested cubic metre.

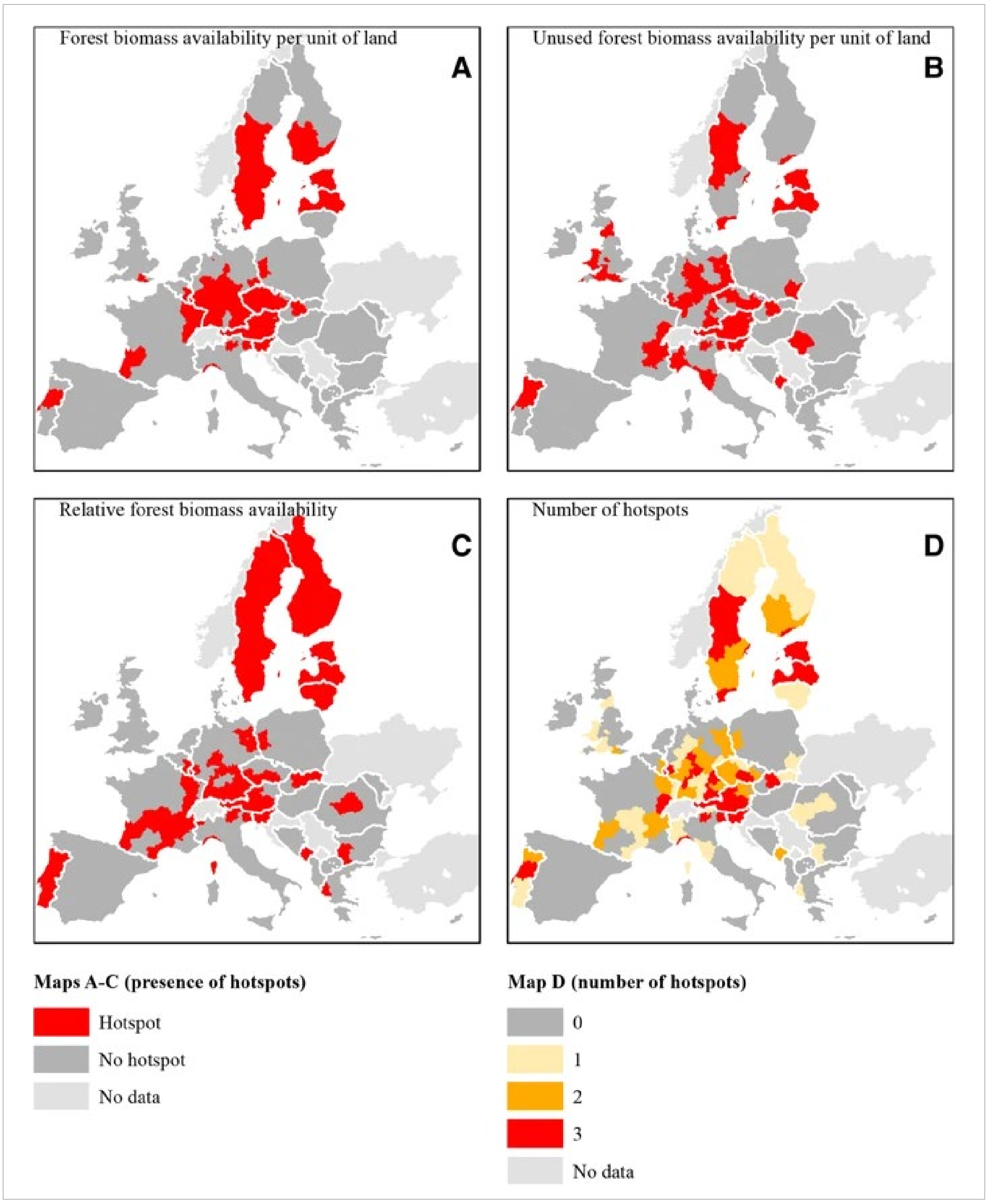

Figure 56. Hotspots in forest biomass availability by Verkerk et al. (2019).

A closer look at digitalisation

Digital technology was once seen as a threat to the forestry sector, but now its integration into daily forest practices is helping to cut costs and emissions and enable smarter, more responsible forestry. Technologies such as cloud computing, mobile devices, IoT (Internet of Things) platforms, remote sensing, laser scanning, smart sensors, drones and big data analysis and algorithms are just a few examples, increasingly in use (UNAC 2018a). Forestry 4.0, or precision forestry, accounts for the digitalization to obtain as much information as possible to support monitoring and decision-taking. It is of special relevance e.g. in forest inventories, increasing efficiency and the accuracy of e.g. tree height measurements (Liang et al. 2016). Nevertheless, digital technology can be used across the whole value-chain, from forest inventory, timber stock management, forestry operations, traceability and digital certification to e-marketplace for timber trade (UNAC 2018b). See Table 37 for examples of digital tool across the value-chain in the forest sector.

As digital tools vastly improve efficiency of forestry work, it is estimated that 10% of operating costs can be reduced – savings that can bring down the cost of wooden construction materials in the future. Forestry 4.0 will lead to significant changes and value-adds in harvest planning, harvest organization and control, operations, transport and logistics as well as timber sales (Müller et al. 2019). Digitalization can be implemented along the main processes in the wood supply chain, ranging from computer DSS in harvest planning, harvesting operations, machine-to-machine communication, machine vision to automation and post-harvest management systems for quality control (Muller et al 2019). However, to implement I 4.0 in wood supply, technical and socio-economic challenges have to be considered as well, such as the willingness of cooperation, questions of data autonomy and changing working environments (Muller et al. 2019).

Currently, modern forestry machines are already able to collect data on logs and site during harvesting (length, diameter, species, quality, remaining tree species, size and spatial distribution). However, these data collected by machines are not yet used to a great extent. This 'big data’ can in the near future be better used for forest management plans without extra data collection cost or by the industries receiving the wood, e.g. delivery of the “right raw material to the right industry” in case data can also include wood chemical parameters (Eriksson et al. 2011, Nordfjell et al. 2018). Transforming the ‘big data’ into ‘valuable data’ for better decision making will be one of the most relevant issues in the digitalization (Kaufmann and Forstner, 2014).

Lower costs would also be achieved when aggregating harvesting sites within a short distance, reducing the number or distance of machines’ relocations. This becomes of special relevance when using higher level of mechanization in the operations (Nordfjell et al. 2018). Digitalization in harvesting and positioning, with wireless communication between machines allows that localization data collected by the harvester can be used by the forwarder to locate the log piles along the skid trails. This application would help the forwarder operator choosing the optimal route to the piles and if needed, selectively collect the logs assortment by assortment. Furthermore, the forwarder could automatically record the locations of the log piles along the forest road or landing, directly transmitting these locations to the truck drivers. Real-time data about the infrastructure’s condition within the forest stand and machine generated data about slippage and motor performance could help decreasing soil rutting (Salmivaara et al., 2018). Radio-frequency identification (RFID) could be used for tagging logs (Björk et al., 2011; Häkli et al., 2013; Jung et al., 2009) by the harvester head once they are bucked (Pichler et al., 2017), with information about the tree and log (e.g. name of the assortment, the location of the stand or even the tree itself (Pichler et al.,2017). The advantages of individual log identification and traceability can be of relevant in the context of illegal logging control based on a transparent chain of custody (Athanasiadis et al. (2013). However, RFID technology is seldomly used yet in commercial forestry (Muller et al. 2019).

Digitalization can also increase the sustainability of forest operations. A Swedish case study by Mohtashami et al. (2012) showed that using digital maps and GIS-based models can decrease environmental impacts by pre-planning off-road transport routes for forest machines. This decreases soil and water damages but also increases efficiency by promoting shorter and better routes (Mohtashami et al. 2012). Modern sensors and modern control technology can be developed to reduce the damage to trees in thinning operations, minimizing e.g. the frequency that the crane on a machine hits a tree that shall remain in the stand. In that way it will be possible to use a long boom reach, and longer booms than today and still avoid collisions of the boom with trees in thinning operations (Nordfjell et al. 2018).

In the future, forest industry could explore the possibilities of automation. For example, remotely controlled harvesters and unmanned trucks could be used in the future (Kies and Kleinschmit 2018). This would reduce employment costs and in many remote and rural areas it would also solve the problem of a lack of skilled workers. Robotics are currently more commonly usedin agriculture than in forestry. Currently the main advances in forest robotics relate to pruning or collecting biomass. Autonomous, unmanned robots or tractors with or without human direction might play a bigger role in the near future. Alternatively, remote operated machines offer improved ergonomic and safety to the workers (Hellström et al. 2009), reducing the body vibrations to which the operator would be exposed to while sitting in the machine, or reducing the risk of accident while working in a very steep terrain. The automation and robotization of forest machines can reduce the stress on the operator and decrease the learning time an operator needs to reach full productivity (Ringdahl 2011; Westerberg 2014, Nordfjell et al. 2018).

Working with modern high-tech forest machinery requires special education and experience, and ability to work with several IT-software, thus it will require needs for educational organizations and well-trained operators (Nordfjell et al. 2018). Given the varying forest ecosystems, soil types and site conditions, as well as the varied structure of forest industries and the effect this has on demand for forest biomass across Europe, there is no single solution to the challenges of making forest harvesting and transportation technologies more efficient and economically viable as well as environment and climate sustainable (EIP-AGRI 2018). The term techno-diversity means searching for a variety of technological solutions, which are ecologically as well as socially adapted to the local conditions and needs, since they consider economical capacities of the forest stakeholders (Nordfjell et al. 2018).

Table 37. Examples of digital applications for forest management and operations control across the value-chain in Europe.

Application by sectors	Name	Aim	Link	Country
Forest inventory	MOTI	Designed for forestry professionals to capture in an easy, cost effective and reliable manner the key dendrometric variables such as basal area, number of trees per ha, tree height and stock, as a single measurement combined in a sample plot, or at the level of a stand inventory with automatic calculation of the error range of the estimations, through the use of a smartphone.	http://www.moti.ch/drupal/?q=en/node/31	CH
Forest inventory	Emonte-cubicar	It calculates the timber volume for the several forest species in the Galician region, based on a few dendrometric variables measured in the forest stand.	https://emonte.es/cubica/	ES
Forest inventory	Relasphone	Mobile application for collecting in situ forest measurements and estimating biomass	http://www.relasphone.com/	FI
Forest inventory	Trestima	Measure forest and roundwood piles by taking pictures.	https://www.trestima.com/w/en/	FI
Forest planning	Wuudis	Forest information and planning, storing and sharing information. Customer specific.	https://www.wuudis.com/	FI
Forest planning	sIMfLOR	Platform for Portuguese forest simulators	http://revistas.inia.es/index.php/fs/article/view/2951	PT
Forest planning	Metsään.fi	The platform provides an overview of the forest assets and up-to-date forest resource information, and treatment and harvesting suggestions for the next five years. Owners can notify the forest intervention performed. Users are forest owners and forest industry operators.	www.metsaan.fi	FI
Forest planning	Smartwood (in progress)	Decision Support System for planting forest species. Adapted for Galician region.	https://smartwood.app/	ES
Forest planning	KILDEN	Resources, georeferenced data, soil, biomass, cross-land uses, forest inventory (NIBIO)	https://kilden.nibio.no/	NO
Forest planning	KW-PLAN	Private forest owners, inventory, planning, harvesting, services	http://www.kwplan.dk/forside.aspx	DK
Forest planning	HEUREKA	Forest growth simulator, economic optimisation	https://pub.epsilon.slu.se/9358/	SE
Timber sale	Legno Trentino	Service matching in Northern Italy. The service is made available to forest owners and economic operators, to support the marketing of wood, firewood and wood chips from the forests of the province of Trento.	https://www.legnotrentino.it/asteonline/	IT
Timber sale	Legno Piemonte	LegnoPiemonte is an information service on the availability of wooded lots, arboriculture (including poplar cultivation) and finished woody assortments of Piedmontese origin.	https://www.legnopiemonte.eu/	IT
Timber sale	Emonte	Marketplace for timber lots in Galicia	https://emonte.es/	ES

Timber sale	KUUTIO	KUUTIO® is an open and independent marketplace for forest owners, wood buyers, brokers such as forest management associations and other forest service providers.	https://kuutio.fi/	FI
Biodiversity	Marteloscope	Marteloscope is a permanent plot within the forest in which tree measurements and associated software are linked to provide a framework for in-forest training in selection and marking. Trade-offs between ecological and economic criteria imposed on management treatments can be simulated and visualized using the software Smartelo.	https://informar.eu/marteloscopes	FR
Forest operations	WoodForce	Planning and control system for harvesting, selviculture and forest improvement that streamlines the forest supply chain.	https://www.woodforce.fi/	FI
Forest operations	Bucking App	When timber is harvested, trees are felled and cut (“bucked”) into pieces (so called “assortments”) of different length. The app can aid the user in separating the tree into the most suitable combination of assortments to obtain the highest value that can be gained from a tree.	http://www.tech4effect.eu/results/bucking-app/	AT
Forest operations	Ponsse Manager	PONSSE Manager allows you to easily monitor and control your company’s daily operations.	https://ponssemanager.com/	FI
Volume stock	Polterluchs	This system enables data on wood piles to be recorded very quickly, direct from the vehicle, simply by positioning the view-frame at the beginning of the wood stack and then driving past it. The recorded data is available on site immediately after being recorded and can be forwarded and processed using a variety of EDP systems.	https://www.emva.org/news/polterluchs-a-permanent-eye-on-the-timber/	DE
Volume stock	Timbeter	It counts the logs, measure diameters and density in less than 3 minutes.	https://www.iforest.es/servicios.php?ver=medicion	ES
Volume stock	Forest HQ	It is a cloud-based forest management platform, empowering data-based decisions to improve the sustainability and profitablity of a forest. From forest inventory, simulation and real time harvest information	http://www.treemetrics.com/	IE
Volume stock	Timberlog	It calculates timber volume from a diameter or circumferences and length. It creates a wood log that it is easily imported into spreadsheets and easy to share.	https://apkgk.com/timber.volume.calculator.timbervolumecalculator	SI
Volume stock	Bitterlich relascope	The software helps you to estimate the basal area of forest stands with a mobile phone.	https://apkgk.com/ee.deskis.adnroid.relascope	EE
Planning and control	IPTIM	Integrated Planning and Timberland Management. Several interconnected applications for storing data, communicate with crews, track machineries and transportation, monitoring logs, road planning, etc.: Manager, Mobile, Tracker, LogCount, Teams, Operations, Roadplan, Assets, and Options	https://www.simosol.fi/iptim	FI

Sensors in piles	RuuviTag	It is a Bluetooth® sensor that sends temperature, relative air humidity, air pressure and motion information directly to your mobile phone.	https://shop.ruuvi.com/product/ruuvitag-1-pack/	FI
Service providers contacts	MojGozdar	Portal for finding a forestry service provider across all the regions in Slovenia	https://www.mojgozdar.si/	SI

Some of the tools mentioned in Table 37 will be assessed in further detail within the TECH4EFFECT task 2.4. The respective report will present results with a particular focus on IT-tools, internet-based applications and other interfaces that enable both the requisition and marketing of silvicultural and harvesting services in three Nordic countries. Research has shown that considerable efficiency differences can exist between apparently similar supply chains, therefore, the task 2.4 focused on selected business processes between forest administrators, service providers, and local Forest Based Industries in Denmark, Finland and Norway.

4. Discussion

4.1. What is the potential in environmental and socio-economic impacts for the suggested systems?

In order to reach the different TECH4EFFECT goals and scenarios (20% decrease in production costs, 15% decrease in fuel consumption, 2% increase of forest yield), different scenarios were defined for the different case studies, based on the regular practices and the potential alternatives that would be feasible in those conditions.

In Norway, the fertilization scenario showed the biggest potential, decreasing both production costs (7.2%) and fuel consumption (3.4%), at the same time as increasing substantially the forest yield (16%) compared to the baseline. Corridor thinning and eco-harvester settings led only to minor reductions in costs and energy use without increasing forest yield. In Finland, the fertilization together with the use of clone trees had the most significant potential, decreasing costs (14%) and fuel consumption (21%) in a higher rate than in Norway. It also increased forest yield but in a lower percentage than in Norway (10%). Corridor thinning decreased up to 6.2% the production costs, while eco-harvesting had basically no impact towards any of the goals. The fertilization scenario increased the average of full-time employment due to higher production volumes.

In the case of France, the improved breeding regeneration material scenario provided the best results in terms of the TECH4EFFECT goals, as it decreased the production costs and the fuel consumption (13.1 and 13.3 respectively), while increasing the forest yield by 30%. The stump harvesting scenario, although increasing the forest yield productivity in 15.7%, it only decreased by 1.7% the production costs if extraction is covered by stump market, and even increased fuel consumption in 1.2%.

The winch-supported harvesting/forwarding scenario in Austria reduced the costs and fuel consumption substantially (58% and 40% respectively), having no impact on the forest yield. Changing from motor-manual harvesting/cable yarding to winch-supported harvesting greatly improved occupational safety as the risk for bot fatal and non-fatal accidents was reduced by more than 90%. The scenario of tree selection by harvester, although increasing the yield in 3%, there was no impact on fuel consumption and very minor decrease in production costs.

In Poland, the only scenario proposed was moving from motor-manual harvesting into mechanical harvesting. This would contribute to reducing the production costs by 31% and the employment needed (66%), while eliminating the occupational accidents to a high extent. While the yield would remain the same, the energy use would increase significantly (286%). Similarly, to Poland, the scenario proposed in Italy is the mechanized harvesting, providing similar results as for decreasing the production costs (36%) and improving occupational safety. The difference however is in the type of machine and accessibility for cutting the stump-sprouted bunch of trees. The yield productivity increased in this case up to 25%, and contrary to Poland, the energy use and greenhouse gas emissions decreased around 18% due to a different harvesting system.

In Denmark the two scenarios considered as alternative to the baseline scenario were planting spruce, or hybrid larch, on the skidding roads. Both scenarios contributed to decreasing the production costs, having the hybrid larch scenario a more significant impact (19.6%) than the spruce (3.3%). The fuel or energy consumption increased in both scenarios (6.4% with spruce and 20.9% with hybrid larch), and the forest yield increased largely by 10% with spruce and 44% with hybrid larch.

In summary, the scenarios that met the TECH4EFFECT goals were:

- Norway, increasing the forest yield through fertilization.
- Finland, increasing forest yield, decreasing production costs and decreasing fuel consumption through fertilization and clone trees.
- Poland, reducing the production costs through mechanized harvesting.
- Italy, decreasing production costs, decreasing energy use and increasing forest yield through mechanized harvesting.
- Denmark, decreasing production costs and increasing forest yield through hybrid larch planting in skidding roads, and increasing forest yield though spruce planting in skidding roads.
- France, increasing forest yield through stump harvesting and improved breeding material.
- Austria, decreasing production costs and fuel consumption through winch-supported harvesting and increasing forest yield through tree selection by harvester.

In general terms, mechanized harvesting and harvesting machinery is very advanced in terms of productivity, efficiency, costs, operator safety and reduced soil disturbance. At a machine operational level, technological improvements are very small. At an organizational level and value chain integration level, however, major improvements can be made to reduce management, communication and supervision between different operators. Digitalization is a low-energy and low carbon solution to avoid loss of harvested roundwood and to reduce driving to follow crews and operators. Unfortunately, there are no studies available to quantify those reductions in costs and emissions, as most operational studies are work studies of singular machines. Chapter 3.2.2.3 “A closer look at digitalization” elaborated on existing systems and their impacts.

Another field for large scale reduction of greenhouse gas emission, could be a systematic switch from fossil to biofuels to run harvesting machinery. According to the revised renewable energy directive 2018/2001/EU, REDII (Official Journal of the European Union 2018), the following calculatory emission reductions are accepted for replacing fossil diesel with rapeseed oil-based biodiesel:

> TYPICAL AND DEFAULT VALUES FOR BIOFUELS IF PRODUCED WITH NO NET CARBON EMISSIONS FROM LAND-USE CHANGE (Annex V):
>
> Greenhouse gas emissions saving – typical value: 52%
>
> Greenhouse gas emissions saving – default value: 47%
>
> Greenhouse gas emissions – typical value (g CO2eq/MJ) typical value: 32
>
> Greenhouse gas emissions – typical value (g CO2eq/MJ) typical value: 32

While these values show great potential of cutting greenhouse gas emission into half, an extensive study on the large scale availability of biofuels for harvesting operations and consequences on the competition with other sectors was outside the scope of this project.

4.2. What practices promote or maintain forest yield while having less environmental impact?

Based on our country-specific case studies, a few scenarios are promoting forest yield while having less environmental impacts. Corridor thinning maintains forest yield with less environmental impacts (energy use and GHG emissions) due to more efficient process compared to baseline and could therefore be a viable mainstreaming option for thinnings. Modern and improved harvest machinery can decrease fuel use and subsequent GHG emissions while having no effect on forest yield, however, mechanization taking place across Europe is naturally increasing both biomass availability and environmental impacts.

Mechanization is indirectly the key influencer also in the fertilization scenarios. The unit-level emissions and energy use are lower in the mechanized processes compared to motor manual ones. N Fertilization and improved seedling material increases the timber yield specifically in the late thinnings, which are usually fully mechanized processes in e.g. Finland and Norway. If higher timber yield is gained from mechanized processes and not from motor manual ones, the average processing energy use and GHG emissions for the total rotation decreases.

It is important to distinguish between relative effects per cubic metre and absolute effects. For example, fertilization can significantly increase forest productivity and typically decreases relative fuel consumption over rotation per cubic meter, despite the fact that absolute amount of fuel used will increase. This applies to most enhanced production scenarios, such as the use of improved breeding material and new, more productive varieties of tree species.

Mechanised harvesting in coppice system seems to also be very promising. With the rise of the bioeconomy increased amounts of biomass are needed. These volumes however, do not necessarily need to be long, straight, high-quality construction timber. For more pulp-based products (chemicals, textiles, packaging, paper, etc) coppice products may be very relevant. Then safe and efficient harvesting, which is gentle to soil and stumps as key, as showcased in the Italian study.

4.3. Which regions have the highest innovation potential in wood harvesting operations?

In general, Eastern and Central EU have the greatest innovation potential in shifting from motor-manual to mechanized harvesting systems. This change will be necessary to be able to mobilize increased volumes with higher efficiency and worker safety. The availability of a qualified and well-trained workforce, as well the necessary companies with adequate machines is crucial. Looking forward this would require support and financing to forest operation companies and training of workers to meet these increased demands. On the other side, the willingness of (private) forest owners to cut (thinnings and final fellings) is a prerequisite. Forest owner associations and competitive timber prices help to increase the private mobilization. At the same time, climate change related hazards (storm throw, biotic pests, fire) may increase and thus "provide" large timber volumes in an unplanned manner.

Rugged terrain is the next area to be mechanized, and technological solutions are developing rapidly, also in practice as was shown by the Austrian case study with the winch-supported machines.

4.4. What is the potential role and impact of digitalisation?

Digital technology has a huge development potential for forest management and production. Forestry 4.0 or precision forestry accounts for the digitalization to obtain as much information as possible to support monitoring and decision-taking across the whole value-chain, from forest inventory, timber stock management, forestry operations, traceability, digital certification and to e-marketplace for timber trade.

Digitalization can contribute to reducing costs (e.g. time invested in the forest measurements, operations, flow of information, efficiency of logistics) and increase the sustainability of forest operations (e.g. reducing tree, soil and water damages), improving at the same time data accuracy and thus enabling a smarter and more responsibly forestry.

5. Conclusions

European forests have the potential to provide more raw material at a sustainable level than current practices. To mobilize and supply the increased amounts of forest-based feedstock, a massive change from motor-manual to fully mechanized harvesting operations is needed, particularly in Eastern, Central and Southern EU. Coppice is a viable alternative to forest management for new wood assortments that do not require structural wood (e.g. chemicals). For boreal forests fertilization has the potential for higher yields. In high-intensity forest management power cultures provide a viable alternative to stump harvesting: more volume at reduced soil disturbance. Winch-supported systems revolutionize steep-terrain harvesting both in accessibility and in safety.

Digitalization is the next big field of improvement at value chain and company level, as forest operations are already very optimized at a technological machine level. To reduce emissions, both digitalization and wide use of bio-based fuels to run the operations are promising.

References

Aaronen, T. 2011. Vegetative propagation of conifers. Metsätieteen aikakauskirja, 1: 53–59.

ADEME. 2018. Stratégie de l'ADEME pour une bioéconomie durable - 2017–2022. ADEME, Angers.

Agreste. 2017. Mémento Emploi agricole, forestier et agroalimentaire. Nouvelle-Aquitaine. Édition 2017. Direction Régionale de l'Alimentation, de l'Agriculture et de la Forêt.

Äijälä, O., Koistinen, A., Sved, J., Vanhatalo, K., & Väisänen, P. 2014. Metsänhoidon suositukset [Best Practice Guidelines for Sustainable Forest Management]. Metsätalouden kehittämiskeskus Tapion julkaisuja. Tapio.

Amecourt, A. d', Houllier, F., Lemas, P.-R. & Sève, J.-C. 2016. Plan recherche-innovation 2025 filière forêt-bois. FBRI2025. Ministère de l'Agriculture, de l`'Agroalimentaire et de la Foret (MAAF).

APRE. 2019. Presentation of the Italian Strategy for Bioeconomy. Retrieved from https://www.researchitaly.it/en/events/presentation-of-the-italian-strategy-for-bioeconomy/

Arbez, M., Carnus, J.-M., Kremer, A., Augusto, L., Banos, V., Belouard, T., Bosc, A., Brunet, Y., Charier, B., Colin, A., Dehez, J., Demanet, A., Deuffic, P., Filliatre, C., Gardiner, B., Grelier, S., Guyon, D., Jactel, H., Kranodebski, M., Lesgourgues, Y., Lung, B., Malfait, J.-J., Maugé, J.-P., Meredieu, C., Morlier, P., Pastuszka, P., Orazio, C., Piou, D., Plomion, C., Raffin, A., Timbal, J. & Trichet, P. 2017. Forêts d'hier et de demain, 50 ans de recherche en aquitaine, LGPA-Editions. ed. Presses Universtaires de Bordeaux, Pessac.

Augusto, L., Pousse, N., Legout, A., Seynave, I., Jabiol, B. & Levillain, J. 2018. INSENSE : Indicateurs de SENSibilité des Ecosystèmes forestiers soumis à une récolte accrue de biomasse. Angers.

Austrian Forest Report. 2015. Sustainable Forest management in Austria. Austrian Forest Report 2015. Republic of Austria, Federal Ministry of Agriculture, Forestry, Environment and Water Management, Vienna, 157pp.

Banos, V. & Dehez, J. 2015. Les trajectoires du bois-énergie en Aquitaine : du développement local aux territoires de l'énergie ? geocarrefour 90: 329–338.

Banos, V. & Dehez, J. 2017. Le bois-énergie dans la tempête, entre innovation et captation ? Les nouvelles ressources de la forêt landaise. Nat. Sci. Soc. 25: 122–133.

BBIC. 2018. Mapping the potential of Poland for the bio-based industry. Country report. Retrieved from https://biconsortium.eu/sites/biconsortium.eu/files/downloads/Country-Report-Poland.pdf.

Berg, S. 2011. Manual for data collection for Regional and European cases. EFORWOOD – Tools for Sustainability Impact Assessment of the Forestry-Wood Chain. No. 36. EFI Technical Report, 2011.

Bergström, D. 2009. Techniques and systems for boom-corridor thinning in young dense forests, Acta Universitatis Agriculturae Sueciae.

Bert, D. & Danjon, F. 2006. Carbon concentration variations in the roots, stem and crown of mature Pinus pinaster (Ait.). Forest Ecology and Management 222: 279–295.

BMNT. 2019. Austria's Bioeconomy Strategy. Bundesministerium Nachhaltigkeit und Turismus. Retrieved from https://www.bmnt.gv.at/english/environment/Climateprotect/Austria-s-Bioeconomy-Strategy.html.

BMNT, BMBWF, BMVIT. 2019. Bioökonomie Eine Strategie für Österreich. Bioeconomy Strategy for Austria. Retrieved from https://www.bioeconomy-austria.at/cms/media/190313_Boes_Online_04x.pdf.

Bouffier, L., Raffin, A. & Alía, R. 2013. Maritime pine – Pinus pinaster Ait.. In: Mullin, T., Lee, S.J. (Eds.), Best Practice for Tree Breeding in Europe. Skogforsk, Uppsala, pp. 65–76.

Brahic, É. & Deuffic, P. 2017. Comportement des propriétaires forestiers landais vis-à-vis du bois énergie: Une analyse micro-économique. economierurale 7–25.

Brunette, M. & Caurla, S. 2016. An economic comparison of risk handling measures against Hylobius abietis and Heterobasidion annosum in the Landes de Gascogne Forest. Annals of Forest Science 73: 777–787.

Buckley, G.P. 1992. Ecology and management of coppice woodlands. Chapman & Hall, London.

Bugge, M., Hansen, T., & Klitkou, A., 2016. What is the bioeconomy? A review of the literature. Sustainability 8: 691.

Cacot E., Maire L., Chakroun M., Peuch D., Montagny X., Perrinot C. % Bonnemazou, M. 2015. La mécanisation du bûcheronnage dans les peuplements feuillus - Synthèse opérationnelle. Institut Téchnologique FCBA, Champs-sur-Marne, France. 38 p.

Cardellini, G., Valada, T., Cornillier, C., Vial, E., Dragoi, M., Goudiaby, V., Mues, V., Lasserre, B., Gruchala, A., Rørstad, P.K., Neumann, M., Svoboda, M., Sirgmets, R., Näsärö, O.-P., Mohren, F., Achten, W.M.J., Vranken, L. & Muys, B. 2018. EFO-LCI: A New Life Cycle Inventory Database of Forestry Operations in Europe. Environmental Management 61: 1031–1047.

Cleary, M.R., Arhipova, N., Morrison, D.J., Thomsen, I.M., Sturrock, R.N., Vasaitis, R., Gaitnieks, T. & Stenlid, J. 2013. Stump removal to control root disease in Canada and Scandinavia: A synthesis of results from long-term trials. Forest Ecology and Management 290: 5–14.

CNBBSV. 2019. Italian Bioeconomy Strategy. Retrieved from http://cnbbsv.palazzochigi.it/media/1719/bit_en_2019_web.pdf.

Colin, A., Barnérias, C., Salis, M., Coulon, F., Couturier, C., Thivolle-Cazat, A. & Rantien, C. 2009. Biomasse forestière, populicole et bocagère disponible pour l'énergie à l'horizon 2020. Rapport final. ADEME, Angers.

Demolis, C. & Roman-Amat, B. 2016. La filière forêt bois en Aquitaine six ans après la tempête KLAUS: Situation et perspectives (No. 15100). CGAAER.

Eberhard, B. 2019. Case study Austria - Effects of thinning by tree marking vs harvester selection. In: Eberhard, B. & Routa, J. (eds.). Report on Potential for Efficiency Increase in Silviculture. Deliverable 2.2. of the TECH4EFFECT project, Horizon 2020 Grant Agreement No. 720757.

EC. 2015. New Strategies on Bio-Economy in Poland. Retrieved from https://cordis.europa.eu/project/rcn/197325/factsheet/en.

EC. 2018a. Knowledge for policy. The bioeconomy in different countries. Poland. Retrieved from https://ec.europa.eu/knowledge4policy/bioeconomy/country/poland_en.

EC. 2018b. A sustainable Bioeconomy for Europe: strengthening the connection between economy, society and the environment. Updated Bioeconomy Strategy.

EC, 2018c. Bioeconomy: the European way to use our natural resources. Action plan 2018. Directorate-General for Research and Innovation.

EC, 2018d. A new bioeconomy strategy for a sustainable Europe. Factsheet.

EC. 2019. The Bioeconomy Strategy.

EIP-AGRI. 2018. Sustainable Mobilisation of forest biomass. Final report. EIP AGRI Focus Group on Sustainable Mobilisation of forest biomass.

Emeyriat, R. 2016. Diagnostic territorial des besoins en investissements matériels du projet FOREDAVENIR. Rapport final de l'etude. ADEME.

ENRD. 2019. Bioeconomy. Projects Brochure. Retrieved from https://enrd.ec.europa.eu/sites/enrd/files/enrd_publications/publi-eafrd-brochure-09-en_2019.pdf.

EUROSTAT. 2018a. Glossary: Forest.

EUROSTAT. 2018b. Agriculture, forestry and fishery statistics, Statistical books edition 2018. 200 p.

EUSBSR. 2019. EUSBSR in a nutshell. Retrieved from https://www.balticsea-region-strategy.eu/about/about.

Fin Forelia Oy. 2019. Cultivating seeds for sale | Fin Forelia Oy. Retrieved July 25, 2019, from https://www.finforelia.fi/en-gb/sales.

The Finnish Forest Centre. 2019. Tuki taimikon varhaishoitoon. Metsäkeskus.

Forest Europe. 2015. State of Europe's Forests 2015, Madrid. 312 pp.

Gaugitsch, H. 2019. Targets for the bioeconomy strategy in Austria. Workshop "Facilitating development of bioeconomy policy – needs and gaps". Retrieved from https://www.scar-swg-sbgb.eu/lw_resource/datapool/_items/item_41/country_overview_austria.pdf.

Gerasimov, Y. 2013. Atlas of the forest sector in Poland. Working Papers of the Finnish Forest Research Institute 268. Retrieved from http://www.metla.fi/julkaisut/workingpapers/2013/mwp268.htm.

German Bioeconomy Council. 2015. Bioeconomy in Denmark. Bioeconomy Policy (Part II) – Synopsis of National Strategies around the World. Retrieved from https://biooekonomie.de/sites/default/files/danemark.pdf.

GIS GPMF. 2013. Les cahiers de la reconstitution. Installation des peuplements (No. 3). Groupe Pin Maritime du Futur.

GIS PMF. 2014. GIS Groupe Pin maritime du futur. Les cahiers de la reconstitution n°4: matériel végétal de reboisement.

Gruchała, A., Bronis, K. & Zasada, M. 2019. Case study Poland - Mechanization of thinnings in conifer forests. In: Eberhard, B. & Routa, J. (eds.). Report on Potential for Efficiency Increase in Silviculture. Deliverable 2.2. of the TECH4EFFECT project, Horizon 2020 Grant Agreement No. 720757.

Gunia, K., Van Brusselen, J., Päivinen, R., Zudin, S &, Zudina, E. 2011. Forest map of Europe. Retrieved from: https://www.efi.int/knowledge/maps/forest.

Gyekye, L. 2019. Canada and Italy promote national bioeconomy strategies. BioMarket Insights. Retrieved from https://biomarketinsights.com/canada-and-italy-promote-national-bioeconomy-strategies/.

Hédl, R., Kopecky, M. & Komàrek, J. 2010. Half a century of succession in a temperate oakwood: from species-rich community to mesic forest. Divers Distrib16: 267–276.

Hellström, T., Lärkeryd., P., Nordfjell, T & Ringdahl, O. 2009. Autonomous Forest Vehicles – historic, envisioned and State-of-the-art. International Journal of Forest Engineering. 20(1): 31–38.

Heritage, S. & Moore, R. 2001. The assessment of site characteristics as part of a management strategy to reduce damage by Hylobius. (No. 38). Forestry Commission Information Note.

Holt Hanssen, K. & Kvaalen, H. 2018. Effects of repeated fertilization in young Norway spruce forests. Scand. J. For. Res. 33: 633–640.

Holzfeind, T., Stampfer, K. & Holzleitner, F. 2018. Productivity, setup time and costs of a winch-assisted forwarder. Journal of Forest Research 23: 196–203.

IGN. 2014. Résultats d'Inventaire Forestier – Résultats Standards (campagnes 2009 à 2013). Tome par Zonage Écoforestier. Institut National de l'Information Géographique et Forestière (IGN).

Il Bioeconomista. 2019. Italy updates its National Bioeconomy Strategy. Retrieved from http://news.bio-based.eu/italy-updates-its-national-bioeconomy-strategy/.

INFC. 2007. Le stime di superficie 2005 – Prima parte" Authors: Tabacchi G, De Natale F, Di Cosmo L, Floris A, Gagliano C, Gasparini P, Genchi L, Scrinzi G, Tosi V. Inventario Nazionale delle Foreste e dei Serbatoi Forestali di Carbonio [National Inventory of Forests and of Forest Carbon Pools]. MiPAF - Corpo Forestale dello Stato - Ispettorato Generale, CRA - ISAFA, Trento, Italy, 409 pp. Retrieved from http://www.sian.it/inventario-forestale/caricaDocumento?idAlle=496.

INSEE. 2018. Insee Références, édition 2018 - Fiches - Temps et conditions de travail.

Jactel, H., Nicoll, B.C., Branco, M., Gonzalez-Olabarria, J.R., Grodzki, W., Långström, B., Moreira, F., Netherer, S., Orazio, C., Piou, D., Santos, H., Schelhaas, M.J., Tojic, K. & Vodde, F. 2009. The influences of forest stand management on biotic and abiotic risks of damage. Annals of Forest Science 66: 701–701.

Jansen, P. & Kuiper, L. 2004. Double green energy from traditional coppice stands in the Netherlands. Biomass Bioen 26: 401–402.

Jänich, K. 2009. Unfallbericht 2008. Niedersächsisches Forstliches Bildungszentrum (Hrsg.), 28 S.

Johansson, J. 2018. Collaborative governance for sustainable forestry in the emerging bio-based economy in Europe. Current Opinion in Environmental Sustainability 32: 9–16.

JRC-EC. 2018. Data portal of agro-economics research - DataM. Jobs and Wealth in the European Union Bioeconomy. Retrieved from https://datam.jrc.ec.europa.eu/datam/mashup/BIOECONOMICS/index.html.

Kaufmann, T. & Forstner, L. 2014. Die horizontale Integration der Wertschöpfungskette in der Halbleiterindustrie - Chancen und Herausforderungen. In: Bauernhansl, T., ten Hompel, M., Vogel-Heuser, B. (Eds.), Industrie 4.0 in Produktion, Automatisierung und Logistik: Anwendung, Migration. Springer-Verlag, Wiesbaden, pp. 359–367.

Kies, U. & Kleinschmit von Lengefeld, A. 2018. Digitisation in the forest-based sector: State of technology and opportunities for innovation. Online presentation. Retrieved from https://www.researchgate.net/profile/Uwe_Kies/publication/322385958_Digitisation_in_the_forest-based_sector_State_of_technology_and_opportunities_for_innovation/links/5a5fb428458515b43779f4c1/Digitisation-in-the-forest-based-sector-State-of-technology-and-opportunities-for-innovation.pdf.

Kingsbury & Zochowska. 2011. Forestry situation and solid wood products in Poland. Report of Global Agricultural Information Network. Retrieved from: https://apps.fas.usda.gov/newgainapi/api/report/downloadreportbyfilename?filename=Forestry%20situation%20and%20solid%20wood%20products%20in%20Poland_Warsaw_Poland_10-12-2011.pdf.

Kraxner, F., Fuss, S. & Verkerk, P. J. 2017. Is there enough forest biomass available to meet the demands of the forest-based bioeconomy? In: Winkel, G. (Ed.): Towards a sustainable European forest-based bioeconomy – assessment and the way forward. What Science Can Tell Us 8, European Forest Institute.

Labelle, E. & Huss, L. 2018. Creation of value through a harvester on-board bucking optimization system operated in a spruce stand, Silva Fennica 52, 3.

Laine, T., Kärhä, K. & Hynönen, A. 2016. A survey of the Finnish mechanized tree-planting industry in 2013 and its success factors. Silva Fennica 50, 2.

Landmann, G. & Nivet, C. 2014. Projet Resobio. Gestion des rémanents forestiers : préservation des sols et de la biodiversité. Rapport final. ADEME. Ministère de l'agriculture, de l'agroalimentaire et de la forêt - GIP Ecofor., Angers, Paris.

Lemoine, B. 1991. Growth and yield of maritime pine (Pinus pinaster Ait): the average dominant tree of the stand. Annales des Sciences Forestières 48: 593–611.

Liang, X., Kankare, V., Hyyppä, J., Wang, Y., Kukko, A., Haggrén, H., Yu, X., Kaartinen, H., Jaakkola, A., Guan, F., Holopainen, M. & Vastaranta, M. 2016. Terrestrial laser scanning in forest inventories. ISPRS J. Photogramm. Remote Sens. 115: 63–77.

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.

MAAF. 2016. Une stratégie bioéconomie pour la France. Enjeux et vision. Ministère de l'Agriculture, de l`'Agroalimentaire et de la Foret (MAAF).

MAAF. 2017. The National Forest and Wood Programme (PNFB) 2016-2026. Ministère de l'Agriculture, de l`'Agroalimentaire et de la Foret (MAAF).

MAAF. 2018. A bioeconomy strategy for France 2018-2020. Action plan. Ministère de l'Agriculture, de l`'Agroalimentaire et de la Foret (MAAF).

MAAF-IGN. 2016. Indicateurs de gestion durable des forêts françaises métropolitaines, édition 2015, Résultats . Ministère de l'Agriculture, de l'Agroalimentaire et de la Forêt. IGN, Paris.

McCormick, K., & Kautto, N. 2013. The Bioeconomy in Europe: An Overview. Sustainability 5: 2589-2608.

McEwan, A., Magagnotti, N. & Spinelli, R. 2016. The effects of number of stems per stool on cutting productivity in coppiced Eucalyptus plantations. Silva Fennica, 50, 2.

Meredieu, C. 2002. Intégration dans Capsis d'un modèle de croissance du Pin maritime développé par l'INRA, in: Auclair, D. (Ed.), Modélisation et Intégration Logicielle : Croissance, Branchaison, Qualité Des Bois. Aide à La Décision Pour La Sylviculture et l'utilisation Du Bois Des Essences Forestières Françaises, Convention N° 61.45.47/01, MAPADERF/INRA. pp. 3–6.

Metsä Group. 2019. Virtual forests are coming: Forest management takes a leap into the digital age. Web article. Retrieved from https://www.metsagroup.com/en/Campaigns/IntelligentMetsa/intelligentforest/Virtual-forests-are-coming/Pages/default.aspx.

Ministry of Economic Affairs and Employment of Finland. 2017. Wood-based Bioeconomy Solving Global Challenges. MEAE guidelines and other publications 2/2017.

Ministry of Employment and the Economy. 2014. The Finnish Bioeconomy Strategy. Helsinki.

Mohtashami, S., Bergkvist, I., Löfgren, B. & Berg, S. 2012. A GIS approach to analyzing off-road transportation: A case study in Sweden. Croat. J. For. Eng. 33: 275–284.

Müller, F., Jaeger, D. & Hanewinkel, M. 2019. Digitization in wood supply – A review on how Industry 4.0 will change the forest value chain. Computers and Electronics in Agriculture 162 (2019) 206–218.

Mullin, T.J., Andersson, B., Bastien, J.C., Beaulieu, J., Burdon, R.D., Dvorak, W.S., King, J.N., Kondo, T., Krakowski, J. & Lee, S.J. 2011. Economic importance, breeding objectives and achievements, in: Genetics, Genomics and Breeding of Conifers. Skogforsk, Uppsala, pp. 40–127.

Myhre, G., Shindell, D., Bréon, F.-M., Collins, W., Fuglestvedt, J., Huang, J., Koch, D., Lamarque, J.F., Lee, D., Mendoza, B., et al. 2013. Anthropogenic and natural radiative forcing. In: Stocker, T.F., Qin, D., Plattner, G.K., Tignor, M., Allen, S.K., Boschung, J., Nauels, A., Xia, Y., Bex, V., Midgley, P.M. (ed). Climate change 2013: the physical science basis. Contribution of working group I to the fifth assessment report of the intergovernmental panel on climate change. Cambridge (UK) and New York (NY): Cambridge University Press; p. 659–740.

Natural Resources Institute. 2017a. Official Statistics Finland: Labour force in the forest sector by industry.

Natural Resources Institute. 2017b. Official Statistics Finland: Forest resources, tree species dominance NFI 11/12.

Natural Resources Institute Finland. 2018a. Total roundwood removals by Year.

Natural Resources Institute Finland. 2018b. Official Statistics Finland: Unit costs in mechanised harvesting of roundwood by felling method (Source Metsäteho Oy).

Näyhä, A. 2019. Transition in the Finnish forest-based sector: Company perspectives on the bioeconomy, circular economy and sustainability. Journal of Cleaner Production 209: 1294-1306.

Nicolescu, V., Pyttel, P. & Bartlett, D. (Eds.) 2015: Evolution and perspectives of coppice forests in European countries and South Africa. University of Transilvania, Braşov, Romania. 57 p.

Nordfjell, T., Borz, S., Krajnc, N. & Toivonen, R. 2018. Harvesting and transportation technologies. Minipaper 5. EIP AGRI Focus Group Sustainable mobilisation of forest biomass. Retrieved from https://ec.europa.eu/eip/agriculture/sites/agri-eip/files/fg20_mp5_harvesting_tech_2018_en_0.pdf.

Nordic Council of Ministers. 2019a. Bioeconomy in the Baltic Sea Region. Retrieved from http://www.bsrbioeconomy.net/about.html

Nordic Council of Ministers. 2019b. Wood in Construction. 25 cases of Nordic Good Practice. ISBN 978-92-893-6072-2. Retrieved from http://norden.diva-portal.org/smash/get/diva2:1297443/FULLTEXT03.pdf.

Nord-Larsen, T., Johannsen, V.K., Riis-Nielsen, T., Thomsen, I.M., Bentsen, N.S., Gundersen, P. & Jørgensen, B.B. 2018. Skove og plantager 2017: Forest statistics 2017.

Norway in the UN. 2019. Permanent Mission of Norway to the United Nations. Website. Cited June 3, 2019.

Norwegian Ministry of Agriculture and Food. 2018. Familiar resources – undreamt of possibilities. The Government’s Bioeconomy Strategy.

Nuutinen, Y. 2017. Presentation: Käytäväharvennus - Menetelmä nuorten metsien ensimmäiseen koneelliseen harvennukseen [Corridor thinning - a method for first mechanical thinning in young forests]. Retrieved August 7, 2019, from https://www.metsakeskus.fi/uutiset/kaytavaharvennus-tehokas-menetelma-nuorten-metsien-ensimmaiseen-koneelliseen-harvennukseen.

Official Journal of the European Union. 2018. Directive (EU) 2018/2001 of the European Parliament and of the Council of 11 December 2018 on the promotion of the use of energy from renewable sources (recast) (21/12/2018). Retrieved from: https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:32018L2001&from=EN.

Päivinen, R., Lindner, M., Rosén, K. & Lexer, M.J. 2012. A concept for assessing sustainability impacts of forestry-wood chains. Eur. J. For. Res. 131: 7–19.

Picchio, R., Maesano, M., Savelli, S. & Marchi, E. 2009. Productivity and Energy balance in conversion of a Quercus cerris L. coppice stand into high forest in central Italy. Croat J For Eng 30: 15–26.

Prinz, R., Spinelli, R., Magagnotti, N., Routa, J., & Asikainen, A. 2018. Modifying the settings of CTL timber harvesting machines to reduce fuel consumption and CO2 emissions. Journal of Cleaner Production, 197: 208–217.

Quadt, V., van der Maaten-Theunissen, M., Frank, G. 2013. Integration of Nature Protection in Austrian Forest Policy. INTEGRATE Country Report for Austria. EFICENT-OEF, Freiburg. 35pp.

Ringdahl, O. 2011. Automation in forestry – development of unmanned forwarders. Department of computing science, Umeå university. PhD thesis.

Ronzon, T. & M'Barek, R. 2018. Socioeconomic Indicators to Monitor the EU's Bioeconomy in Transition. Sustainability 10, 1745.

Routa, J., Kellomäki, S., Strandman, H., Bergh, J., Pulkkinen, P., & Peltola, H. 2013. The timber and energy biomass potential of intensively managed cloned Norway spruce stands. GCB Bioenergy, 5(1): 43–52.

Routa, J., Kilpeläinen, A., Ikonen, V.-P., Asikainen, A., Venäläinen, A., & Peltola, H. 2019. Effects of intensified silviculture on timber production and its economic profitability in boreal Norway spruce and Scots pine stands under changing climatic conditions. Forestry: An International Journal of Forest Research, 1–11.

Routa, J., Nuutinen, Y., & Asikainen, A. 2020. Productivity in Mechanizing Early Tending in Spruce Seedling Stands. Croatian Journal of Forest Engineering, 41(1).

Routa, J., Prinz, R. & Eberhard, B. (editors). 2020b. Increasing access to wood resources: Tech4effect Project Report. Natural resources and bioeconomy studies 86/2020. Natural Resources Institute Finland. Helsinki. 104 s.

Salas-González, R., Houllier, F., Lemoine, B. & Pignard, G. 2001. Forecasting wood resources on the basis of national forest inventory data. Application to Pinus pinaster Ait. in southwestern France. Annals of Forest Science 58: 785–802.

Salmivaara, A., Miettinen, M., Finér, L., Launiainen, S., Korpunen, H.,Tuominen, S., Heikkonen, J., Nevalainen, P., Sirén, M. & Ala-Ilomäki, J. 2018. Wheel rut measurements by forest machine-mounted LiDAR sensors–accuracy and potential for operational applications? Int. J. Forest Eng., pp. 1–12.

Sardin, T. & Canteloup, D. 2003. Guide de sylviculture du pin maritime de Lande. ONF. Office National des Forêts, Direction Territorial Sud-Ouest, Paris.

Serrano-León, H. & Orazio, C. Stump harvesting for combined risk control and bioenergy recovery. In: Potential for efficiency increase in silviculture. Case study France - Stump removal in maritime pine plantations. Deliverable D2.2 Tech4Effect project. Unpublished.

Serrano-León, H., Orazio, C. Ahtikoski, A., Sonesson, J., Perot, T., Perret, S. & Hubert, A. Improved breeding regeneration material. In: Economic effects of including innovative forest genetic resources' management options from a forest-owner's perspective. Deliverable D5.2 GenTree Project. Unpublished.

Spatial Foresight, SWECO, ÖIR, t33, Nordregio, Berman Group, Infyde. 2017. Bioeconomy development in EU regions. Mapping of EU Member States'/regions' Research and

Innovation plans & Strategies for Smart Specialisation (RIS3) on Bioeconomy for 2014-2020. Retrieved from https://ec.europa.eu/research/bioeconomy/pdf/publications/bioeconomy_development_in_eu_regions.pdf.

Spinelli, R., Cacot, E., Mihelic, M., Nestorovski, L., Mederski, P. & Tolosana, E. 2016. Techniques and productivity of coppice harvesting operations in Europe: a meta-analysis of available data. Annals of Forest Science 73, pp. 1125–139.

Spinelli, R., Pari, L., Aminti, G., Magagnotti, N. & Giovannelli A. 2017. Mortality, re-sprouting vigor and physiology of coppice stumps after mechanized cutting. Annals of Forest Science 74: 5. DOI: 10.1007/s13595-016-0604-z.

Spinelli, R., Magagnotti, N. & Tuomasjukka, D. 2020. Rationalization of coppice management in Mediterranean Europe: the sustainability effects of changing product strategy and technology level (under preparation).

Statistics Norway. 2018. The National Forest Inventory.

Strange, N. & Raae, K. 2019. Case study Denmark - Power cultures; fast growing species on skid roads. In: Eberhard, B. & Routa, J. (eds.). Report on Potential for Efficiency Increase in Silviculture. Deliverable 2.2. of the TECH4EFFECT project, Horizon 2020 Grant Agreement No. 720757.

Suchomel, C., Spinelli, R. & Magagnotti, N. 2012. Productivity of processing hardwood from coppice forests. Croat J For Eng 33:39–47.

Suomen 4H-liitto. 2007. Metsänviljelyopas [Handbook for Forest Regeneration]. Retrieved from http://docplayer.fi/6790082-Metsanviljelyopas-suomen-4h-liitto.html.

Szewczyk, G. & Wojtala, L. 2010. The cost of timber harvesting with timber harvester in stands under rebuilding with a use of particullar cutting. FORMEC. Padova. Retrieved from https://www.formec.org/images/proceedings/2010/Ab061.pdf

Tuomasjukka, D. et al. 2015. Sustainability impacts of scenarios for different fuel sources and procurement technologies. Deliverable 5.3 report for the INFRES project – Innovative and effective technology and logistics for forest residual biomass supply in the EU (311881). Retrieved from https://www.researchgate.net/publication/328192334_INFRES-Innovative_and_effective_technology_and_logistics_for_forest_residual_biomass_supply_in_the_EU_311881_D53-REPORT_DOCUMENTING_SUSTAINABILITY_IMPACTS_OF_SCENARIOS_FOR_DIFFERENT_FUEL_SOURCES_AND_P.

Tuomasjukka, D., Athanassiadis, D. & Vis, M. 2017. Threefold sustainability impact assessment method comparison for renewable energy value chains. International Journal of Forest Engineering, 28(2), pp.116–122.

Tuomasjukka, D., Martire, S., Lindner, M., Athanassiadis, D., Kühmaier, M., Tumajer, J., Vis, M., Spinelli, R., Dees, M., Prinz, R., Routa, J. & Asikainen, A. 2018. Sustainability impacts of increased forest biomass feedstock supply – a comparative assessment of technological solutions. International Journal of Forest Engineering, 1, 18.

UNAC. 2018a. Floresta 4.0. In Seminário da Floresta 4.0 - digitalização na criação de valor e de vantagens competitivas para a gestão e produção florestal. Retrieved from http://www.unac.pt/images/01_FLORESTA_4.0_UNAC.pdf.

UNAC. 2018b. Floresta 4.0 Digitalização na Cadeia de Valor Florestal – Factos e Tendências. In Seminário da Floresta 4.0 - digitalização na criação de valor e de vantagens competitivas para a gestão e produção florestal. Retrieved from http://www.unac.pt/images/02_AM_Digitalizacao_nas_Cadeias_de_Valor_Florestal-ilovepdf-compressed.pdf.

Vaahtera, E., Aarne, M., Ihalainen, A., Mäki-Simola, E., Peltola, A., Torvelainen, J., Uotila, E. & Ylitalo, E. 2018. Finnish forest statistics.

Vasaitis, R., Stenlid, J., Thomsen, I., Barklund, P. & Dahlberg, A. 2008. Stump removal to control root rot in forest stands. A literature study. Silva Fennica 42.

Verkerk, P., Fitzgerald, J., Datta, P., Dees, M., Hengeveld, G. M., Lindner, M. & Zudin, S. 2019. Spatial distribution of the potential forest biomass availability in Europe. For. Ecosyst. 6, 5.

VTT. 2016. Database Lipasto [Energy use and GHG emissions of working machines in Finland in 2016]. Retrieved July 25, 2019, from http://lipasto.vtt.fi/yksikkopaastot/muut/tyokoneet/tyokoneet_teho.htm.

Walmsley, J.D. & Godbold, D.L. 2010. Stump Harvesting for Bioenergy - A Review of the Environmental Impacts. Forestry 83: 17–38.

Westerberg, S. 2014. Semi-automating forestry machines – Motion planning, system integration and humanmachine interaction. Doctoral thesis. Department of applied physics and electronics/Industrial doctoral schoool. Umeå university, Sweden.

Winther, T. 2016. Bioeconomy strategies and policies in the Baltic Sea Region countries. Working Paper no. 1 – The Baltic Sea Regional Bioeconomy Council. Retrieved from http://www.bsrbioeconomy.net/resources/2016_docs/Working_Paper_1_%20BSR_Council.pdf.

Woźniaka, E. & Twardowski, T. 2018. The bioeconomy in Poland within the context of the European Union. New Biotechnology, 40A, 96–102. Retrieved from https://www.sciencedirect.com/science/article/pii/S1871678417300389.

Annex

Annex I - Constraints on potential forest biomass availability

Table I.1. Maximum extraction rates for extracting logging residues from final fellings due to environmental and technical constraints

Type of constraint	Base & Enhanced production scenarios	Improved supply & Combined R&I scenarios
Site productivity	35% extraction rate on poor soils (Acrisol, Podzoluvisol, Histosol, Podzol, Arenosol, Planosol, Xerosol); not a constraining factor on other soils.	Not a constraining factor.
Soil and water protection: ruggedness	Not a constraining factor on slopes up to TRI moderately rugged; 0% over moderately rugged.	Not a constraining factor.
Soil and water protection: Soil depth	0% on Rendzina, Lithosol and Ranker (very low soil depth).	Not a constraining factor.
Soil and water protection: Soil surface texture	0% on peatlands (Histosols).	Not a constraining factor.
Soil and water protection: Soil compaction risk	0% on soils with very high compaction risk; 25% on soils with high compaction risk; not a constraining factor on other soils.	Not a constraining factor.
Biodiversity: protected forest areas	0%; not a constraining factor in areas with high or very high fire risk.	0%; not a constraining factor in areas with high or very high fire risk.
Recovery rate	70% on slopes up to TRI moderately rugged; 0% over moderately rugged.	70%
Soil bearing capacity	0% on Histosols, Fluvisols, Gleysols and Andosols.	0% on Histosols, Fluvisols, Gleysols and Andosols, not a constraint in Finland and Sweden.

Table I.2. Maximum extraction rates for logging residues from thinnings due to environmental and technical constraints

Type of constraint	Base & Enhanced production scenarios	Improved supply & Combined R&I scenarios
Site productivity	0% on poor soils (Acrisol, Podzoluvisol, Histosol, Podzol, Arenosol, Planosol, Xerosol); 33% on other soils.	Not a constraining factor.
Soil and water protection: Slope	Not a constraining factor on slopes up to TRI moderately; 0% over TRI moderately rugged.	Not a constraining factor.
Soil and water protection: Soil depth	0% on Rendzina, Lithosol and Ranker (very low soil depth).	0% on Rendzina, Lithosol and Ranker (very low soil depth).
Soil and water protection: Soil surface texture	0% on peatlands (Histosols).	33% on peatlands (Histosols).
Soil and water protection: Soil compaction risk	0% on soils with very high compaction risk; 25% on soils with high compaction risk; not a constraining factor on other soils.	0% on soils with very high compaction risk; 50% on soils with high compaction risk; not a constraining factor on other soils.
Biodiversity: protected forest areas	0%; not a constraining factor in areas with high or very high fire risk.	0%; not a constraining factor in areas with high or very high fire risk.
Recovery rate	70% up to TRI moderately rugged; 0% over TRI moderately rugged.	70%
Soil bearing capacity	0% on Histosols, Fluvisols, Gleysols and Andosols.	0% on Histosols, Fluvisols, Gleysols and Andosols, not a constraint in Finland and Sweden.

Table I.3. Maximum extraction rates for extracting stumps from final fellings due to environmental and technical constraints

Type of constraint	Base & Enhanced production scenarios	Improved supply & Combined R&I scenarios
Countries	Finland, Sweden, UK.	All.
Species	Conifers.	All.
Site productivity	33% on poor soils (Acrisol, Podzoluvisol, Histosol, Podzol, Arenosol, Planosol, Xerosol); 67% on other soils.	67%
Soil and water protection: Slope	0% on TRI highly rugged/extremely rugged; not a constraining factor on less steep soils.	0% on TRI highly rugged/extremely rugged; not a constraining factor on less steep soils.
Soil and water protection: Soil surface texture	0% on peatlands (Histosols).	33% on peatlands (Histosols).
Soil and water protection: Soil depth	0% on soils < 40 cm (including Rendzina, Lithosol and Ranker); 33% on soils >40 cm.	0% on soils < 40 cm (including Rendzina, Lithosol and Ranker); not a constraining factor on other soils.
Soil and water protection: Soil compaction risk	0% on soils with very high compaction risk; 15% on soils with high compaction risk; not a constraining factor on other soils.	0% on soils with very high compaction risk; 33% on soils with high compaction risk; not a constraining factor on other soils.
Biodiversity: protected forest areas	0%	0%
Recovery rate	Not a constraining factor.	Not a constraining factor.
Soil bearing capacity	0% on Histosols, Fluvisols, Gleysols and Andosols.	0% on Histosols, Fluvisols, Gleysols and Andosols; not a constraint in Finland and Sweden.

Table I.4. Maximum extraction rates for extracting stumps from thinnings due to environmental and technical constraints

Type of constraint	Base & Enhanced production scenarios	Improved supply & Combined R&I scenarios
Countries	None	All.
Species	None	All.
Site productivity	0%	67%
Soil and water protection: Slope	0%	0% on TRI highly rugged/extremely rugged; not a constraining factor on less steep soils.
Soil and water protection: Soil surface texture	0%	33% on peatlands (Histosols).
Soil and water protection: Soil depth	0%	0% on soils < 40 cm (including Rendzina, Lithosol and Ranker); not a constraining factor on other soils.
Soil and water protection: Soil compaction risk	0%	0% on soils with very high compaction risk; 33% on soils with high compaction risk; not a constraining factor on other soils.
Biodiversity: protected forest areas	0%	0%
Recovery rate	0%	Not a constraining factor.
Soil bearing capacity	0%	0% on Histosols, Fluvisols, Gleysols and Andosols; not a constraint in Finland and Sweden.

Annex II - List of country abbreviations

Table II.1 List of country abbreviations.

Abbreviation	Country
AT	Austria
BE	Belgium
BG	Bulgaria
CH	Switzerland
CY	Cyprus
CZ	Czech Republic
DE	Germany
DK	Denmark
EE	Estonia
ES	Spain
FI	Finland
FR	France
EL	Greece
HU	Hungary
HR	Croatia
IE	Ireland
IT	Italy
LT	Lithuania
LU	Luxembourg
LV	Latvia
MT	Malta
NL	Netherlands
NO	Norway
PL	Poland
PT	Portugal
RO	Romania
SE	Sweden
SI	Slovenia
SK	Slovakia
UK	United Kingdom

Annex III - List of rejected scenarios

These are the scenarios which were brought forward by the T4E experts in WP2-4, and which were investigated in WP7 but ultimately rejected as they did not contribute to the T4E targets and goals or due to no appropriate data being available.

Table III.1. List of rejected scenarios.

Country	Scenario
Norway	Winch-assested harvesting (steep terrain)
Norway	Cable yarding (flat terrain)
Finland	Intensified forest management (incomparable to conditions in the ToSIA baseline) (Routa et al. 2019)
Finland	Mechanized early tending (too low productivity to contribute T4E goals) (Routa et al. 2020)
Denmark	Forced Quality Broadleaves (planting high-value timber trees such e.g. ash, walnut, cherry) in forests
Italy	-
Poland	Planting versus natural regeneration

Routa, J., Nuutinen, Y., & Asikainen, A. 2020. Productivity in mechanizing early tending in spruce seedling stands. CROJFE 41: 1–11.

Routa, J., Kilpeläinen, A., Ikonen, V.-P., Asikainen, A., Venäläinen, A., & Peltola, H. 2019. Effects of intensified silviculture on timber production and its economic profitability in boreal Norway spruce and Scots pine stands under changing climatic conditions. Forestry: An International Journal of Forest Research, 1–11.

Annex IV - Productivities and fuel consumptions of operations

Values are based on figures presented in INFRES D5.3. Small adjustments have been made according to Wojtala & Szewczyk (2010).

Table IV.1. Productivities and fuel consumptions of forest operation in different EU regions.

	CEU		SEU		EEU		NEU	
	productivity (m^3/h)	fuel consumption (l/m^3)	productivity (m^3/h)	fuel consumption (l/m^3)	productivity (m^3/h)	fuel consumption (l/m^3)	productivity (m^3/h)	fuel consumption (l/m^3)
Motorsaw CTL	2	0.5	1.5	0.5	1.1	0.536364	1.5	0.5
Motorsaw WTS	3	0.54	1.5	0.5	1.1	0.536364	1.5	0.5
Harvester CTL	9	16.2	5.5	11	10.1	15.7	5.5	11
Forwarder CTL	11	11	13	9	3.9	11.1	13	9
Skidding WTS	9	7.2	4.1	1.3	6.5	7.3	n/a	n/a
Cable yarding	6	16	4.7	4	6	16	n/a	n/a

Annex IV - Upscaling results for France

Table V.1. Total values of indicators per scenario and relative difference in comparison to the baseline.

	Unit	Baseline	Stump extraction	Stump extr. (cost 0)	Tree breeding
Rotation	yr	47	45	45	47
Scenario Total Outflow	m^3 / ha	573.5	663.4	663.4	745.4
Total Productivity	m^3/h	1.7	1.7		2.14
Difference with baseline			-0.30%		25.40%
Total Productivity	h/m^3	0.587	0.589		0.468
Difference with baseline			0.30%		-20.30%
Fuel use	l/m^3	8.51	8.61		7.38
Difference with baseline			1.20%		-13.30%
Costs	€/m^3	46.58	46.63	45.78	40.47
Difference with baseline			0.10%	-1.70%	-13.10%
Total Work hours along rotation	h/rotation	337	391		349
Employment	FTE/m^3	0.000347	0.000348		0.000277
Difference with baseline			0.30%		-20.30%
GHG machinery	kg CO2 eq./m^3	22.181	22.444		19.239
Difference with baseline			1.20%		-13.30%
Energy use	kWh/m^3	84.391	85.393		73.197
Difference with baseline			1.20%		-13.30%
18.2.2 Energy use - Direct fuel	MJ/m^3	303.807	307.414		263.508
Difference with baseline			1.20%		-13.30%
Production costs	€/m^3	46.58	46.63	45.782	40.474
Difference with baseline			0.10%	-1.70%	-13.10%

Table V.2. Annual average indicators extrapolation to the maritime pine area in France and relative difference in comparison to baseline.

	Unit	Baseline	Stump extraction	Stump extr. (cost 0)	Tree breeding
Rotation	yr	47	45	45	47
Scenario Total Outflow	m^3 / ha	573.5	663.4	663.4	745.4
Total Area	1000x ha	943	943	943	943
Employment	FTE	3996	4842	4842	4842
Difference with baseline			21.00%	21.00%	21.00%
GHG machinery	1000x Tons of CO2 eq.	255	312	312	312
Difference with baseline			22.00%	22.00%	22.00%
Energy use	1000x MWh	971	1187	1187	1187
Difference with baseline			22.00%	22.00%	22.00%
18.2.2 Energy use - Direct fuel	MJ	3,495,789,922	4,273,677,053	4,273,677,053	4,273,677,053
Difference with baseline			22.00%	22.00%	22.00%
Production costs	mill €	536	654	648	636
Difference with baseline			22.00%	21.00%	19.00%

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