Forest biomass for energy in the EU: current trends, carbon balance and sustainable potential

for BirdLife Europe, EEB, and Transport & Environment

- ANNEX to the FINAL REPORT -

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Darmstadt, Madrid, Joensuu, Graz May 2014

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1 Biomass Sources

1.1 Biomass from Forests

Forests undisturbed by man are rare in Europe (less than 5%), while semi-natural forests – i.e. influenced by human interventions but to a certain extent maintaining the natural characteristics - make up almost 90%.

Plantation forests - a group in particular comprising forests made up by exotic tree species – is thus on the whole relatively rare but nevertheless significant in a few European countries. Forest biomass for bioenergy can come from three different compartments. This includes:

- Stemwood, i.e. wood from the stem of a tree as distinct from branches, roots or stumps.
- Harvest residues i.e. stem tops, branches, and foliage. During thinnings and final fellings, logging residues are formed. These residues consist of stemwood harvest losses (e.g. stem tops) as well as branches and foliage that are separated from harvested stemwood.
- Stumps and coarse roots which are - in addition to logging residues - also potentially available as biomass.

In EFISCEN, to assess biomass in branches, coarse roots, fine roots and foliage, stemwood volumes are converted to stem biomass by using basic wood density (dry weight per green volume) and expanded to whole-tree biomass using age- and species specific biomass allocation functions.

The biomass can come from the following harvest activities:

- Early thinning, i.e. thinning in very young forest stands which formerly was considered to be pre-commercial; also referred to as energy wood thinning. Stem dimensions are usually smaller than the typical pulp wood assortments. All the biomass extracted during an early thinning is commonly used for bioenergy.
- Thinning, usually producing assortments of different quality. This can include stemwood for both material and energy use as well as harvest residues.
- Final Harvest, i.e. removal of the remaining tree canopy. This usually produces stemwood predominantly for material use, but lower quality assortments can be used for bioenergy. Harvest residues and stumps and coarse roots may be extracted as well.

1.2 Other Woody Biomass

Wood from trees outside the forest is another important source of primary woody biomass. It becomes available during maintenance operations that are performed in order to keep the trees in the desired state. Hence, this biomass source differs from forests. In forestry, wood is regarded as a product whereas the wood from trees outside the forest is most often considered and/or treated as waste. The material is in many European countries referred to as landscape care wood. For this reason primary woody biomass from trees outside forests was in the EUwood study called "landscape care wood" (LCW). All fresh wood (e.g. roundwood, chips and branches) that is harvested from other sources than forests was included under this category. It does not refer to post-consumer wood or industrial wood residues. Landscape care wood comprises woody plants or plant components, which accumulate within landscape care activities. It refers to woody residues from landscape care such as:

• Maintenance operations, tree cutting and pruning activities in agriculture and horticulture industry

• Other landscape care or arboricultural activity in parks, cemeteries, etc.

• Maintenance along roadsides, hedgerows and boundary ridges, rail- and waterways

• Gardens

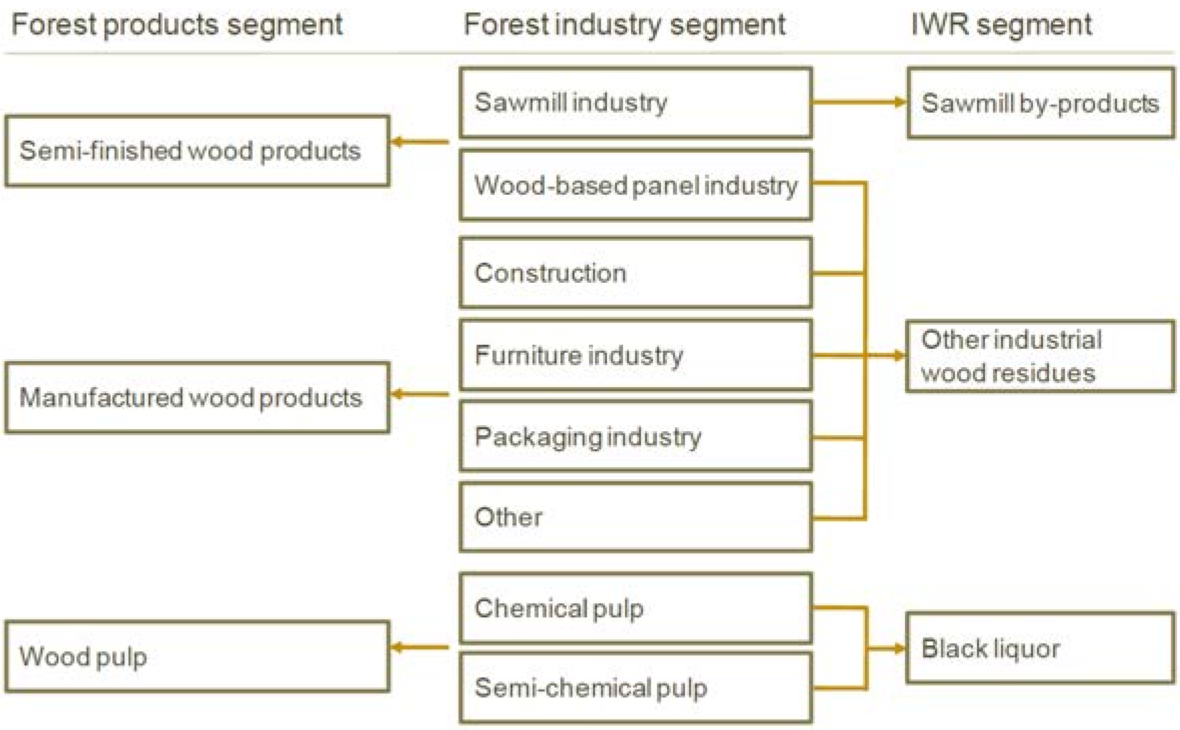
1.3 Short Rotation Coppice on Agricultural Land

Short-rotation coppices (SRC) are defined as plantations established and managed under short-rotation intensive culture practices. For energy purposes, SRC have rotations of 2 to 4 year with coppice management. Only plantations on agricultural land are considered as planted forests (plantations) are already accounted for under biomass from forests.

1.4 Secondary Forest Residues

The potential of secondary residues is interdependent on other forest production categories. Note that post-consumer wood was not considered in the potential analysis of this study, but data for the scenarios were taken from the BiomassFutures project results.

Figure 1 Secondary forest residues



Source: Mantau et al. (2010b)

1.4.1 Sawmill By-products

The segment of sawmill by-products comprises wood residues originating from sawnwood production. It includes wood chips, sawdust and particles, as well as sawmill rejects, slabs, edgings and trimmings. The assortments are suitable for material uses such as pulping, particleboard and fibreboard production as well as for energy use.

Sawmill by-products exclude wood chips made either directly in the forest from roundwood or made from forest residues (i.e. already counted as pulpwood, round and split or wood chips and particles).

1.4.2 Other Industrial Wood Residues

This comprises wood residues accumulated during production of semi-finished wood products as well as during their processing (resawing, planing) and the production of manufactured wood products (construction, furniture). These residues include dust and shavings from planing, milling and drilling. Other assortments are trimmings, rejections, peeler cores, square cuttings. These residues can be modelled using input-output calculations and respective material recovery.

1.4.3 Liquid Forest Industry By-products (Black Liquor)

The pulp industry creates a huge amount of secondary residues in the form of black liquor. This by-product of pulp mills is almost completely used for energy production in the pulp and paper industry. Efficiency of pulp-making is low and thus a huge source of biomass for bioenergy is created.

The amount as well as the composition of the liquid residues called "black liquor" depends highly on the specific pulping process as well as the tree species in each country (see chapter 5.4.4 in Mantau et al. 2010b).

In many countries, chemical and semi-chemical pulp production represents the major energy producer and pulp mills are often the most important producer of electricity from biomass, today.

Heat and power generated from these residues are mostly directly used to keep the pulping process running, notably for the recovery of the pulping chemicals.

2 Quantification of Biodiversity Constraints

The following Tables provide an overview of the assumptions made to quantify the constraints included in this study for the mobilisation scenarios for different types of biomass and different felling activities.

Table 1 Maximum extraction rates for stemwood during early thinning due to environmental and technical constraints in mobilisation scenarios

Type of constraint	**Current (2010)**	**Reference mobilisation**	**Low mobilisation – strictest site constraints**
Site productivity	Not a constraining factor	Not a constraining factor	Not a constraining factor
Soil and water protection: Slope	0% on slopes over 35%; not a constraining factor on slopes up to 35%	0% on slopes over 35%; not a constraining factor on slopes up to 35%	0% on slopes over 35%; not a constraining factor on slopes up to 35%
Soil and water protection: Soil depth	Not a constraining factor	Not a constraining factor	Not a constraining factor
Soil and water protection: Soil surface texture	Not a constraining factor	Not a constraining factor	Not a constraining factor
Soil and water protection: Soil compaction risk	Not a constraining factor	Not a constraining factor	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	0%; not a constraining factor in areas with high or very high fire risk
Recovery rate	95%	95%	95%
Soil bearing capacity	Not a constraining factor	Not a constraining factor	Not a constraining factor

Source: EFI compilation

Table 2 Maximum extraction rates for crown biomass during early thinnings due to environmental and technical constraints in mobilisation scenarios

Type of constraint	Current (2010)	Reference mobilisationmobilization	Low mobilisation – strictest site constraints
Site productivity	0% on poor soils (Acrisol, Podzoluvisol, Histosol, Podzol, Arenosol, Planosol, Xerosol); 70% on other soils	Not a constraining factor	0% on poor soils (Acrisol, Podzoluvisol, Histosol, Podzol, Arenosol, Planosol, Xerosol); 20% on other soils
Soil and water protection: Slope	0% on slopes over 35%; not a constraining factor on slopes up to 35%	0% on slopes over 35%; not a constraining factor on slopes up to 35%	0% on slopes over 35%; not a constraining factor on slopes up to 35%
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)	0% on Rendzina, Lithosol and Ranker (very low soil depth)
Soil and water protection: Soil surface texture	35% on peatlands (Histosols)	40% on peatlands (Histosols)	0% 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	0% on soils with very high and 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	0%; not a constraining factor in areas with high or very high fire risk
Recovery rate	80%	80%	80%
Soil bearing capacity	0% on Histosols, Fluvisols, Gleysols and Andosols	0% on Histosols, Fluvisols, Gleysols and Andosols; not a constraining factor in Finland and Sweden	0% on Histosols, Fluvisols, Gleysols and Andosols

Source: EFI compilation

Table 3 Maximum extraction rates for residues from final fellings due to environmental and technical constraints in mobilisation scenarios

Type of constraint	**Current (2010)**	**Reference mobilisation**	**Low mobilisation – strictest site constraints**
Site productivity	Not a constraining factor	Not a constraining factor	35% extraction rate on poor soils (Acrisol, Podzoluvisol, Histosol, Podzol, Arenosol, Planosol, Xerosol); not a constraining factor on other soils
Soil and water protection: Slope	67%on slopes up to 35%; 0% on slopes over 35%, unless cable-crane systems are used	67% factor on slopes up to 35%; 0% on slopes over 35%, unless cable-crane systems are used	67% factor on slopes up to 35%; 0% on slopes over 35%, unless cable-crane systems are used
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)	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)	0% 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	0% on soils with high or very high compaction risk; 50% on soils with medium 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	0%; not a constraining factor in areas with high or very high fire risk
Recovery rate	67% on slopes up to 35%; 0% on slopes over 35%, but 67% if cable-crane systems are used	70% on slopes up to 35%; 0% on slopes over 35%, but 67% if cable-crane systems are used	65% on slopes up to 35%; 0% on slopes over 35%, but 67% if cable-crane systems are used
	Cable cranes are applied in Austria, Italy, France, Germany, Czech Republic, Slovakia, Slovenia, Romania	Cable cranes are applied in Austria, Italy, France, Germany, Czech Republic, Slovakia, Slovenia, Romania, Bulgaria	Cable cranes are applied in Austria, Italy, France, Germany, Czech Republic, Slovakia, Slovenia, Romania

Type of constraint	Current (2010)	Reference mobilisation	Low mobilisation – strictest site constraints
Soil bearing capacity	0% on Histosols, Fluvisols, Gleysols and Andosols	0% on Histosols, Fluvisols, Gleysols and Andosols; not a constraining factor in Finland and Sweden	0% on Histosols, Fluvisols, Gleysols and Andosols

Source: EFI compilation

Table 4 Maximum extraction rates for residues from thinnings due to environmental and technical constraints in mobilisation scenarios

Type of constraint	Current (2010)	Reference mobilisation	Low mobilisation – strictest site constraints
Site productivity	0% on poor soils (Acrisol, Podzoluvisol, Histosol, Podzol, Arenosol, Planosol, Xerosol); 33% on other soils	67%	0%
Soil and water protection: Slope	33% on slopes up to 35%; 0% on slopes over 35%, unless cable-crane systems are used	67% factor on slopes up to 35%; 0% on slopes over 35%, unless cable-crane systems are used	0%
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)	0%
Soil and water protection: Soil surface texture	0% on peatlands (Histosols)	33% on peatlands (Histosols)	0%
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	0%
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	0%

Type of constraint	Current (2010)	Reference mobilisation	Low mobilisation – strictest site constraints
Recovery rate	67% on slopes up to 35%; 0% on slopes over 35%, but 47% if cable-crane systems are used	70% on slopes up to 35%; 0% on slopes over 35%, but 47% if cable-crane systems are used	0%
	Cable cranes are applied in Austria, Italy, France, Germany, Czech Republic, Slovakia, Slovenia, Romania	Cable cranes are applied in Austria, Italy, France, Germany, Czech Republic, Slovakia, Slovenia, Romania, Bulgaria	
Soil bearing capacity	0% on Histosols, Fluvisols, Gleysols and Andosols	0% on Histosols, Fluvisols, Gleysols and Andosols ,not a constraint in Finland and Sweden	0%

Source: EFI compilation

Table 5 Maximum extraction rates for stumps from final fellings due to environmental and technical constraints in mobilisation scenarios

Type of constraint	**Current (2010)**	**Reference mobilisationmobilization**	**Low mobilisation – strictest site constraints**
Countries	Finland, Sweden, UK	All	0%
Species	Conifers	All	0%
Site productivity	33% on poor soils (Acrisol, Podzoluvisol, Histosol, Podzol, Arenosol, Planosol, Xerosol); not a constraining factor on other soils	67% on poor soils (Acrisol, Podzoluvisol, Histosol, Podzol, Arenosol, Planosol, Xerosol); not a constraining factor on other soils	0%
Soil and water protection: Slope	0% on slopes over 20%; 33% - slope[%] * 0.33 on slopes up to 20%	0% on slopes over 35%; 67% - slope[%] * 0.67 on slopes up to 35%	0%
Soil and water protection: Soil surface texture	0% on peatlands (Histosols)	33% on peatlands (Histosols)	0%
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); 67% on soils >40 cm	0%
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	0%
Biodiversity: protected forest areas	0%	0%	0%
Recovery rate	Not a constraining factor	Not a constraining factor	0%
Soil bearing capacity	0% on Histosols, Fluvisols, Gleysols and Andosols	0% on Histosols, Fluvisols, Gleysols and Andosols; not a constraint in Finland and Sweden	0%

Source: EFI compilation

Table 6 Maximum extraction rates for stumps from thinnings due to environmental and technical constraints in mobilisation scenarios

Type of constraint	**Current (2010)**	**Reference mobilisation**	**Low mobilisation –strictest site constraints**
Countries	0%	All	0%
Species	0%	All	0%
Site productivity	0%	67% on poor soils (Acrisol, Podzoluvisol, Histosol, Podzol, Arenosol, Planosol, Xerosol); not a constraining factor on other soils	0%
Soil and water protection: Slope	0%	0% on slopes over 35%; 67% - slope[%] * 0.67 on slopes up to 35%	0%
Soil and water protection: Soil surface texture	0%	33% on peatlands (Histosols)	0%
Soil and water protection: Soil depth	0%	0% on soils < 40 cm (including Rendzina, Lithosol and Ranker); 67% on soils >40 cm	0%
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	0%
Biodiversity: protected forest areas	0%	0%	0%
Recovery rate	0%	Not a constraining factor	0%
Soil bearing capacity	0%	0% on Histosols, Fluvisols, Gleysols and Andosols; not a constraint in Finland and Sweden	0%

Source: EFI compilation

3 Detailed Calculations of Biodiversity Risks

Table 7 The theoretical (TP) and reference (RP) potentials of forest biomass in 2010 and for 2020 and 2030 from final harvest, thinnings and pre-commercial (PC) thinnings

	PC Thin Stemwood	PC Thin Biomass	Thin Stemwood	Thin Res	Thin Stump	Harvest Stemwood	Harvest Res	Harvest Stump	Total
TP 2010	10	8	237	134	94	411	184	165	1243
TP 2020	12	9	224	123	89	413	186	167	1224
TP 2030	11	8	229	127	91	415	189	170	1241
RP 2010	9	2	224	16	0	388	77	9	726
RP 2020	11	5	219	56	35	403	84	64	876
RP 2030	10	4	224	58	36	405	85	66	889

Source: EFISCEN calculations - EFI compilation; data given in volumes Mm^3 overbark

Table 8 The effect of removing the constraint on residue extraction from protected forest

	PC Thin Stem-wood	PC Thin Bio-mass	Thin Stem-wood	Thin Resid	Thin Stump	Harvest stem-wood	Harvest resid	Harvest stump	Total
2010	9.4	2.1	223.8	16.5	0.0	388.1	76.5	9.4	725.8
2020	11.0	4.7	218.7	55.7	35.3	402.7	84.0	64.1	876.2
RP 2020 without dedicated constraints on stump and residue removal in protected areas	11.0	5.7	218.7	65.7	41.5	402.7	98.1	75.2	918.7
RP 2030	10.4	4.4	223.6	57.9	36.3	404.9	85.4	65.6	888.6
RP 2030 without dedicated constraints on stump and residue removal in protected areas	10.4	5.3	223.6	68.2	42.5	404.9	99.5	76.8	931.2

Source: EFISCEN calculations - EFI compilation; data given in volumes Mm^3 overbark

Table 9 The effect on biomass potentials of increasing the area of strictly protected forest by 5% in 2020

	PC Thin Stemwood	PC Thin Biomass	Thin Stemwood	Thin Res	Thin Stump	Harvest Stemwood	Harvest Res	Harvest Stump	Total
Ref 2010	9.4	2.1	223.8	16.5	0.0	388.1	76.5	9.4	725.8
Ref 2020	11.0	4.7	218.7	55.7	35.3	402.7	84.0	64.1	876.2
Ref 2020 with additional 5% strict forest protection	10.4	4.5	207.8	52.9	35.3	382.6	79.8	60.9	834.1
Ref 2030	10.4	4.4	223.6	57.9	36.3	404.9	85.4	65.6	888.6
Ref 2030 with additional 5% strict forest protection	9.9	4.1	212.5	55.1	36.3	384.6	81.2	62.4	846.0

Source: EFISCEN calculations - EFI compilation; data given in volumes Mm^3 overbark

Table 10 The effect of additional 5% strict forest protection plus 5% retained trees on biomass potential by 2020

	PC Thin Stem-wood	PC Thin Bio-mass	Thin Stem-wood	Thin resid	Thin Stump	Harvest stem-wood	Harvest resid	Harvest Stump	Total
2010	9.4	2.1	223.8	16.5	0.0	388.1	76.5	9.4	725.8
Ref 2020	11.0	4.7	218.7	55.7	35.3	402.7	84.0	64.1	876.2
Ref 2020 with additional 5% strict forest protection and 5% retention trees	9.9	4.2	196.9	50.1	35.3	362.4	75.6	57.7	792.1
Ref 2030	10.4	4.4	223.6	57.9	36.3	404.9	85.4	65.6	888.6
Ref 2030 with additional 5% strict forest protection and 5% retention trees	9.4	3.9	201.3	52.2	36.3	364.4	76.9	59.1	803.3

Source: EFISCEN calculations - EFI compilation; data given in volumes Mm^3 overbark

Table 11 Realizable forest biomass potentials under reference, medium and low mobilizations for EU28 in 2020 and 2030

	PC Thin Stemwood	PC Thin Biomass	Thin Stemwood	Thin Res	Thin Stump	Harvest Stemwood	Harvest Res	Harvest Stump	Total
REF 2020	11.0	4.7	218.7	55.7	35.3	402.7	84.0	64.1	876.2
REF 2030	10.4	4.4	223.6	57.9	36.3	404.9	85.4	65.6	888.6
LOW 2020	9.9	0.6	195.1	0.0	0.0	358.9	50.9	0.0	615.3
LOW 2030	9.3	0.6	199.2	0.0	0.0	360.8	51.3	0.0	621.2

Source: EFISCEN calculations; data given in volumes Mm^3 overbark

Table 12 Energy potentials from in 2020 and 2030 from other biomass sources (PJ)

Year	Prunings (fruit trees, vine-yards, olives, citrus, nuts)	Landscape care wood 2020	Perennials: woody crops	Sawmill by-products (excl. saw dust)	Saw-dust	Other industrial wood residues	Black liquor
2020	423	461	1648	423	209	229	701
2030	370	461	196	474	234	272	366

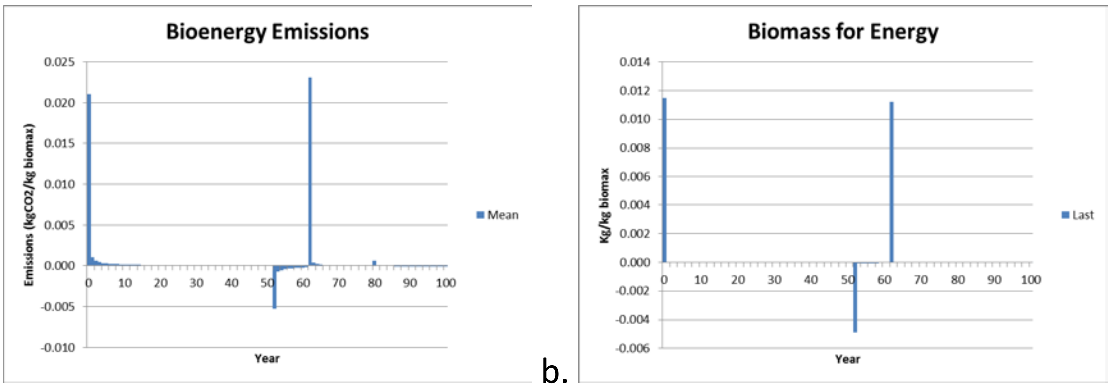
Source: IC et al. 2012- Sustainability Scenario of the Biomass Futures project

4 GHG Emission Calculations for Forest Bioenergy

When a single decision is made in a given year, defined as y=0, to consume biomass for energy, it results in two time series. There is a continuous series of greenhouse gas emissions, the bioenergy emission series, due to both use of energy in the supply-chain and carbon stock changes. The decision also results in a biomass-for-energy time series; a sporadic series of events when energy is produced For example, in a forest, a decision is made to manage stands by thinning at 10 years of age. If the stand has a rotation of 62 years, then there is a bioenergy emission series that starts with the stand at age 10 and is repeated every 62 years (Figure 2). There is also an biomass-for-energy time series with energy created in year 0 when the stand is 10 years old and in year 52 when the stand is harvested at age 62 (if energy is part of the harvest use strategy).

Figure 2 An example net biomass emission (a) and net biomass-for-energy time series (b)

a. b.



Source: *Joanneum (2014) own elaboration*

If the biomass is not used for energy, there is also a time series of emissions, which is defined here as the **reference** emission series. Of course there is also a reference biomass for energy series. Using the same example as above, let us assume that the stand is normally not thinned then the same stand would be harvested in year 52, when it is 62 years old. The amount of biomass for energy resulting from the final harvest (if energy is part of the harvest use strategy) will likely be different than in the bioenergy case as the amount of total biomass may be different. To have comparable systems, energy, probably of fossil origin, would need to be consumed as part of the reference energy series. The difference between the two emission time series is the net emission time series of the decision in year 0 to consume biomass for energy. There is also a net biomass for energy time series. It is important to realise that the reference system and its associated reference emission series is counterfactual. It should represent the most likely situation **in absence** of the bioenergy system. The selection of reference system effects the net emissions and energy dramatically. In some cases where the choice of reference system is not clear, it is advisable to produce two net emission and energy series which represent the systems that produce the lowest and highest net emissions and energy.

To estimate the net emissions from continuous consumption of biomass for energy, a convolutional model was adopted since this consumption is also a time series. The net emission and biomass-for-energy time series for the decision to consume biomass for energy in year ψ have the same shape as the series for y=0. However, they are scaled by the amount consumed and shifted in time so that they start in year ψ. The convolution model comes from filter theory. The consumption series is the signal, and the net emission and energy time series are filters.

A correction needs to be made for the amount of biomass for energy in the future because the decision to switch now may already the amount of biomass for energy in the future, as explained above. Hence the amount of biomass for energy in the future must be reduced if the decision today creates more biomass in the future than the reference case or increased if the decision today produces less biomass in the future that the reference case. This is mathematically performed not by correcting the consumption series, but by calculating a correction filter that when applied to the net biomass-for-energy series makes it have the value 1 at time y=0, and 0 for all other times. The same filter is then applied to the net emission time series (convolution is associative and commutative – i.e. the order of the filters does not matter).

As an alternative assessment approach, the 20-year and 100-year total net emissions and total energy from biomass are calculated using the uncorrected series. The total net emissions are divided by the total energy from biomass to calculate a 20-year and 100-year emission factor. This is typically the method used in the LCA community. This method does not represent actual emissions in a specific year but is indicates the impacts of a decision over the length of time selected (i.e. 20 or 100-years) and places this value at the time of the decision. For example, the 20-year value for an action in 2010 sums all emissions from 2010 to 2030 and places that value in 2010. For example, the 20-year value for an action in 2050 sums all emissions from 2050 to 2070 and places that value in 2050. As the emissions for bioenergy systems tend to decrease with time, the 20 and 100-year impacts will be less than the actual emissions and the cumulative sum of emissions in a specific year.

4.1 Description of bioenergy and reference systems

4.1.1 Emissions from the use of forest residues

Bioenergy system

In the bioenergy system it is assumed that biomass used for bioenergy production is composed of branches, tops, and standing dead wood. The biomass is not "de-barked". For this reason, the net calorific value used for the conversion of mass to energy must be specifically for forest residues and not for clean wood.

Reference system

In the reference system, it is assumed that the biomass is left on site where it decays following simple exponential decay.

4.1.2 Emissions from the use of stumps

For the description, please see the description for forest residues. The model is the same as is used for forest residues except that a correction is made to the decay rate to account for the stumps.

4.1.3 Emissions from pre-commercial thinnings

Bioenergy system

In the bioenergy system it is assumed that the biomass that is used for bioenergy production comes from thinned forests.

1. The biomass is extracted at 10 years and 1/3 of the biomass is removed. It is assumed that the annual increment remains the same with and without thinning. Hence the thinned forest always has less biomass than the unthinned forest by the amount removed.
2. Dead wood on site is also remove at this time
3. All biomass from these operations (including branches and tops) is used for energy
4. The biomass is not "de-barked". For this reason, the net calorific value used for the conversion of mass to energy will be a weighted mixture of forest residues and clean wood.

Reference system

There are two options for the reference system for pre-commercial thinning. Either:

a) in the reference system, the forest is not thinned. The model for this option is described below. This option causes almost constant net emissions from the decision to apply pre-commercial thinning. This option is referred to further as “the pessimistic pre-commercial thinning option” since it creates more emissions than the alternative (below); or

b) in the reference system, the forest is thinned and the material is left as residues. The residue model already discussed is applicable for this option This option is referred to further as “the optimistic pre-commercial thinning option” since it creates fewer emissions than the previous option (above).

Results from both models will be presented.

4.1.4 Emissions from commercial thinning - thinnings used for energy instead of products and energy

Bioenergy system

In the bioenergy system, it is assumed that the forest is thinned exactly the same as in the reference system. However, all biomass is used for bioenergy.

Reference system

If the reference system, it is assumed that the forest is thinned exactly the same as in the bioenergy system. However, the biomass is used in a manner typical for thinnings.

% Sawnwood	0%
% Panels	25%
% Paper	22%
% Energy	53%

A discussion point is the fate of residues from commercial thinning in the reference system. Just like pre-commercial thinnings, there are two options. Either

a) in the reference system, the residues are used as above. The model for this option is described below. This option causes increasing net emissions from the decision to use the residues; or
b) in the reference system, the thinning residues are left on site. The residue model already discussed is applicable for this option.

Model

Since the forest is managed the same in both systems only the wood product chains must be modelled. They are modelled using the same system as the previous example.

4.1.5 Emissions from the harvesting of forests - advanced harvests

Bioenergy system

In the bioenergy system it is assumed that the biomass that is used for bioenergy production comes from a shortening of the rotation time.

1. The biomass is extracted at the "optimal" time when the mean annual increment is a maximum.
2. The biomass including dead wood is used proportioned to the various production chains in the normal manner.

Shortening the rotation length causes an increase in biomass for harvest since one may be switching from a system where for example 1.5 units are harvest every 120 years to one where 1.2 units are harvested every 90 years.

Reference system

In the reference system, it is assumed that forest is harvested, but later than the "optimal" time. In Austria for example, beech forests are often harvested at about 120 year of age. The optimal time is about 90 years, however. The delayed harvest and age class structure resulting from increased consumption during the World War II causes the Austrian forests to have increasing biomass.

Model

The details of the model are the same as for pre-commercial and commercial thinning with the exception of the differences in harvesting.

Table 13 Summary of reference systems for various biomass types

Biomass Source	**Reference System**
Forest residues	Residues remain in the forest and decay naturally without catastrophic disturbance
Stumps	Stumps remain in the forest and decay naturally without catastrophic disturbance
Pre-commercial thinning	Optimistic option: Thinnings remain in the forest and decay naturally without catastrophic disturbance. The forest grows in a similar manner with and without biomass use for energy. Pessimistic option: Pre-commercial thinning does not occur. The unthinned forest has consistently more biomass than does the thinned forest (i.e. parallel growth curves)
Commercial Thinning	Thinning occurs in the same manner as in the bioenergy system, but the biomass from thinning is used for a mixture of purposes: % Sawnwood 0% % Panels 25% % Paper 22% % Energy 53%
Advanced Harvests	The forest is harvested, but later than the "optimal" time. In the bioenergy systems, the forest is harvested at the "optimal time". The delay, as compared to the bioenergy system, allows for an increase in forest biomass, and biomass at final harvest. The same proportion extracted biomass is used directly for sawnwood, panels, paper and energy in both the bioenergy and reference systems

Source: Consortium assumptions

4.2 Details of models and parameters

4.2.1 Emissions from the use of forest residues

The emissions from the use of residues are given by

$$Bio\_Emission(t) = \delta(t)B_o\left[\frac{44}{12} * 0.5 + Supp\right]$$

Where the first term is the emission from burning the biomass, B_o[1] including the emissions from the supply chain, *Supp*. The 0.5 is the carbon fraction of dry biomass and the 44/12 is used to convert mass C into mass CO_2.

If the residues are not used, then the emissions in the first year are given by

$$Ref\_Emission_1 = [B_o e^{-k}] * \frac{44}{12} * 0.5$$

Emissions in year 2 are given by:

$$Ref\_Emission_2 = Ref\_Emissions_1(e^{-k} - 1)$$

Emissions in all other years are

$$Ref\_Emission_j = Ref\_Emissions_{j-1} e^{-k}$$

The decay constant has been shown to be a function of temperature and rainfall. Brovkin et al (2012) use the following relationship

$$k_{wood} = k_{wood10} Q_{10}^{(\frac{T-10}{10})}$$

And have studied a global compilation of reports to attain values for k_{wood10} and Q_{10}. (see Table 12).

Table 14 Parameters for the estimation of decay-rate

Biome	k_{wood10}	Q_{10}
Temp. needleleaved evergreen	0.041	1.97
Temp. broadleaved	0.104	1.37
Boreal needleleaved	0.041	1.97
Boreal broadleaved	0.104	1.37

Source: *Joanneum (2014) own elaboration*

For the purpose of this study, I will assume that temperate forests are predominantly broadleaved and boreal forests are predominantly needleleaved.

Auxiliary data are provided in Table 15.

[1] δ(t) is the dirac function. It equals 1 when t = 0, and = 0 when t ≠ 0

Table 15 Auxiliary data for the emissions from forest residues

	Boreal	**Temperate**
Average temperature (deg C)	Country dependent	Country dependent
Annual rainfall (mm)	Not required	Not required
Net calorific value (MJ/kg)	18.5 – 20.7	19.0 – 20.0 SRC: 17.3 – 19.7

Source: for boreal EUBIONET (2003), ORNL (2011); for temperate Gravalos et al. 2010, McKendry (2002), OMAFRA (2001)

4.2.2 Emissions from the use of stumps

The model is the same as is used for forest residues except that a correction is made to the decay rate to account for the stumps. Generally, it is thought that stumps decay more slowly that do branches and residues. However, there is very little published data to support this claim. Repo et al modelled stumps to decay more slowly than branches ($k_{stumps} \approx 0.5\ k_{branches}$). However, Shorohova et al measured stumps to decay more slowly and more quickly than branches ($0.8\ k_{branches} \leq k_{stumps} \leq 1.5\ k_{branches}$). Both studies were for boreal forests.

Since the biomass has more wood and less bark. net calorific values more typical of wood than residues will be used.

Finally, stumps require more energy to extract that does collection of residues. Lindholm et al (2011) found that stumps required approximately 1.5 g CO_2 / MJ more emissions than loose residues. Auxiliary data are shown in Table 16**.**

Table 16 Auxiliary data for stumps

	Boreal	**Temperate**
k_{stumps} / $k_{branches}$	0.5 – 1.0	0.5 – 1.0
Net calorific value (MJ/kg)	18.6 – 21.1	18.6 – 20.7

Source: *Joanneum (2014) own compilation*

4.2.3 Emissions from pre-commercial thinning of forests

Above-ground live biomass (AGB)

To model the biomass growth of the forest I will use a "logistic" curve (Zweitering et al 1990).

$$B(t) = \frac{B_o B_{mx}}{B_o + (B_{mx} - B_o)e^{-ct}}$$

Where B_o = biomass at t=0, B_{mx} = maximum biomass and c is a constant that scales the time axis. If we assume that B_o = 0.01 B_{mx}, we can simplify the equation to

$$B(t) = \frac{0.01B_{mx}}{0.01 + 0.99e^{-ct}}$$

In this situation the maximum of the mean annual increment occurs when ct = 6.26. Therefore

$$c = \frac{6.26}{T_{rotation}}$$

This is the time at which the biomass would be harvested. At this time $B_{harvest}$ = 0.84 B_{mx}

So the biomass equation can be rewritten in terms of the harvest biomass as:

$$B(t) = \frac{0.01B_{harvest}}{0.84 * (0.01 + 0.99e^{-ct})}$$

Below-ground live biomass (BGB)

I will assume a constant root-to-shot ratio, *R*.

Li et al (2003) suggest that fine-root biomass is a proportion of total root biomass using the equation

$$\frac{FR}{R} = 0.072 + 0.354e^{-0.060R}$$

However, this equation is not very conducive to the model formulation that I am using (normalized to harvest biomass), so I will use a simpler formula:

$$FR = kR$$

And calculate an average value from the Li equation for the range of root biomass expected.

Above-ground dead biomass

Litter

Every year the forest produces litter which decays following simple exponential decay. Litter is typically about 4% of above ground biomass. The decay rate of litter is temperature and biome following an equation derived by Brovkin et al. (2012). In this paper they suggest

$$k_{litter} = k_{litter10} Q_{10}^{\left(\frac{T-10}{10}\right)}$$

and have studied a global compilation of reports to attain values for $k_{litter10}$ and Q_{10}. They suggest:

Table 17 Parameters for the estimation of litter decay-rates

Biome	$K_{litter10}$	Q_{10}
Temp. needleleaved evergreen	0.70	1.97
Temp. broadleaved	0.95	1.37
Boreal needleleaved	0.76	1.97
Boreal broadleaved	0.94	1.37

Source: Brovkin et al. (2012)

Dead wood

In addition the forest produces dead wood due to mortality. Typical mortality rates are shown in Table 18. It is assumed that 50% of the dead wood is harvested for bioenergy when the stems are harvested.

Table 18 Average mortality rates

Biome	**Average mortality rate (fraction of standing biomass per year)**
Evergreen forests	0.0116
Deciduous forests	0.0117

Source: IPCC. (2003)

Below-ground dead biomass

Below-ground dead biomass comes from two sources: decaying roots post-harvest and fine root litter. The latter is a bit of a problem to model. The IPCC default method has soil organic carbon on a per hectare basis depending on soil type, forest type and management.

Coarse roots post-harvest

It is assumed that all dead roots decay following Brovkin's relationship for wood.

Fine roots

Brunner et al (2013) have recently published root turnover rates for European forests. They found that fine root turnover = 1.11 mean fine root biomass. This value is used for an estimate of fine root turnover for both temperate and boreal forests.

For tropical forest a relationship based on that derived by Finér et al. (2011) is used. They found that

$$Ln(FRP) = 0.515 * ln(FR) + 2.51$$

Where FRP= fine-root production and FRB = fine-root biomass. I will simplify this equation to

$$FRP \approx FRBe^{0.515}$$

And the fine root turnover

$$FRT = FRP - FRB = FRB * (e^{0.515} - 1) = 0.673$$

Fine-roots are assumed to decay following Brovkin's relationship for wood.

Initial biomass in dead biomass pools

One must estimate the initial biomass in the dead biomass pools. To do so, it is assumed that the forest is in dynamic equilibrium. This means that the initial biomass in each of the dead biomass pools is the same as in the year of harvest.

Harvested wood products

At final felling a typical mix of biomass to various wood products is assumed. The table below shows the end distribution. A higher amount goes directly to the sawmill, however a large portion of the amount entering the mill is used for energy

% Sawnwood	21%
% Panels	14%
% Paper	28%
% Energy	37%

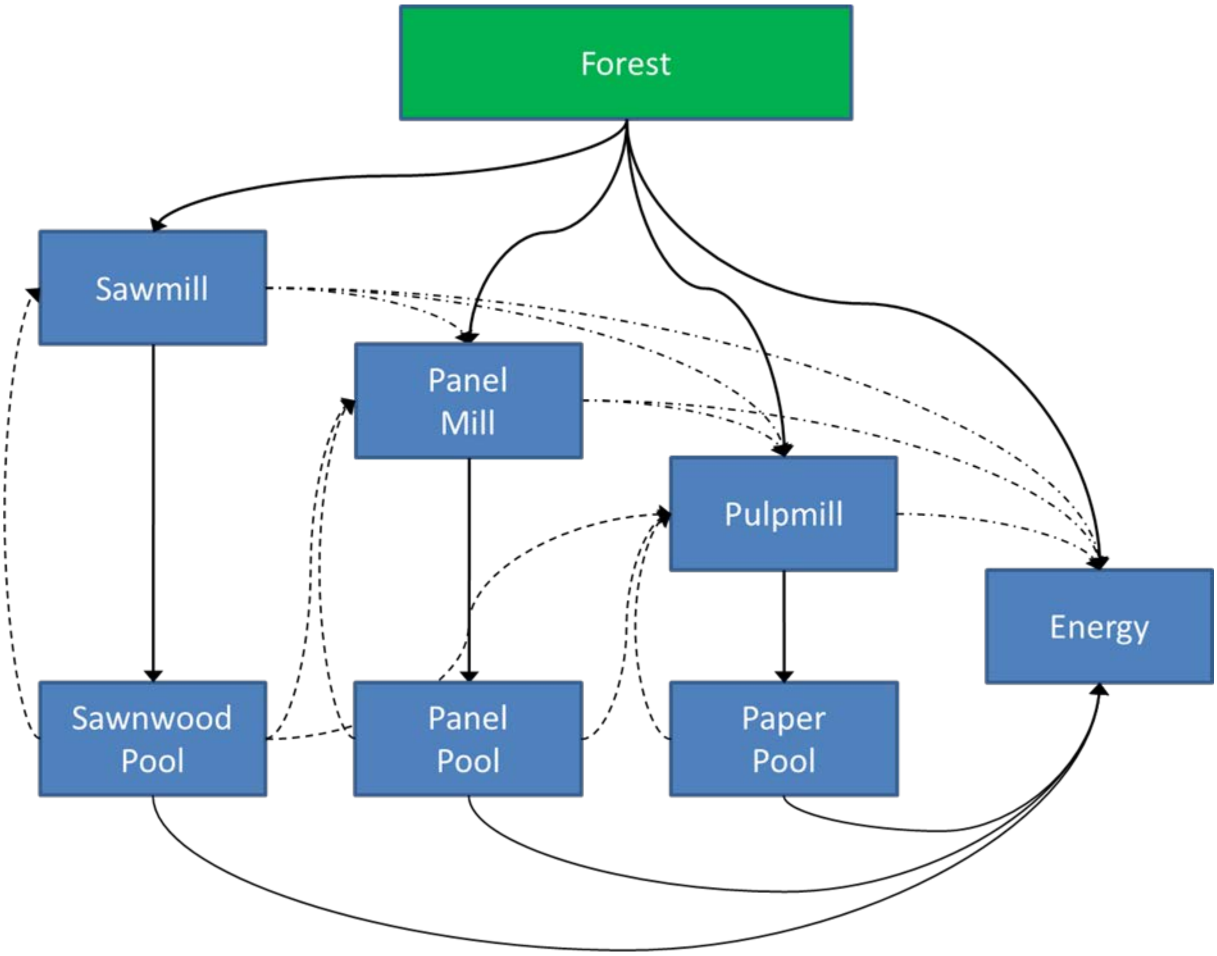
The biomass is cascaded through the various processing streams. The values above represent the final end product proportions. The biomass follows typical processing paths. Fresh biomass goes to the saw mill, panel mill, pulp mill and directly for energy.

The biomass in each of the mills is used to create a product and the residues are cascaded to subsequent mills and energy.

In addition, the product pools decay, each with a specific decay rate and the discarded material is recycled (sent back to the various mills) or used for energy.

Biomass can only be recycled or down-cycled (i.e. paper discards cannot be used in the sawmill).

Figure 3 Biomass flows in the wood processing chain



Source: Joanneum (2014) own elaboration.

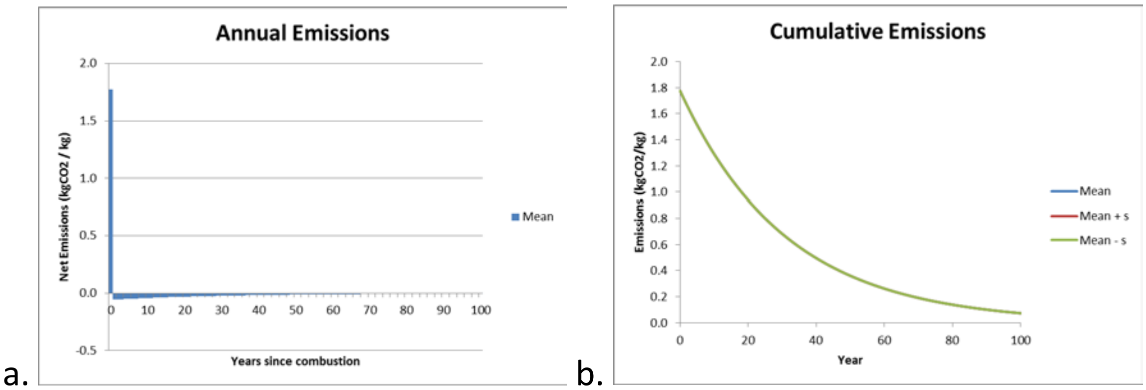
Emissions from the processing of the wood products are included in the analysis as are emissions from the substitution of wood-based material products by non-wood based material products (cement for sawnwood and panels, plastics for paper).

4.3 Results

4.3.1 Emissions from forest residues

Figure 4 a & b show the annual and cumulative emissions from the use of forest residues in Austria. There is a large emission upon combustion and this is followed by a string of negative emissions as the residues decay, had they been left in the forest in the reference case. After 16 years the cumulative emissions without supply-chain emissions are 1.06 kg CO_2 / kg – approximately equivalent emissions to natural gas.

Figure 4 Forest residues – annual net emissions (a.) and cumulative net emissions (b.) from the use of forest residues in Austria



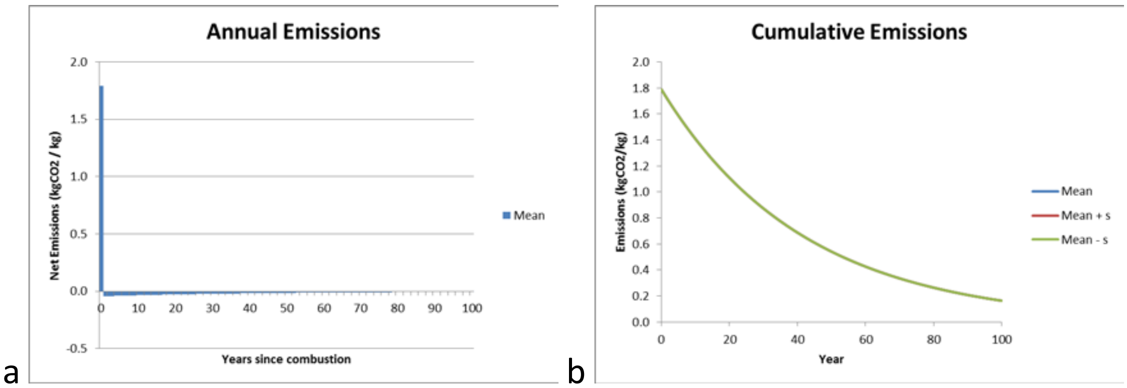
Note: Values shown are typical for Austria. The 20-year and 100-year impacts are 0.94 and 0.07 kg CO_2/kg biomass respectively

Source: Joanneum (2014) own elaboration

4.3.2 Emissions from stumps

The annual and cumulative emissions from the use of stumps in Austria are shown in Figure 5 a & b respectively. The form is similar to that of residues but with slower decay. After 22 years the cumulative emissions without supply-chain emissions are 1.06 kg CO_2/ kg – approximately equivalent emissions to natural gas.

Figure 5 Net GHG Emissions from Stumps – annual (a) and cumulative (b)



Note: Values shown are typical for Austria assuming a 0.75 decrease in k. The 20-year and 100-year impacts are 1.1 and 0.16 kg CO2/kg biomass respectively

Source: Joanneum (2014) own elaboration

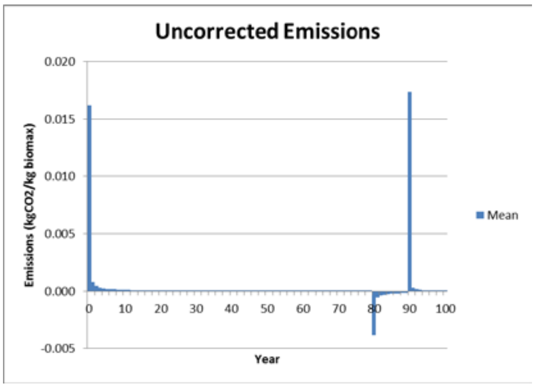
4.3.3 Emissions from pre-commercial thinnings (optimistic option)

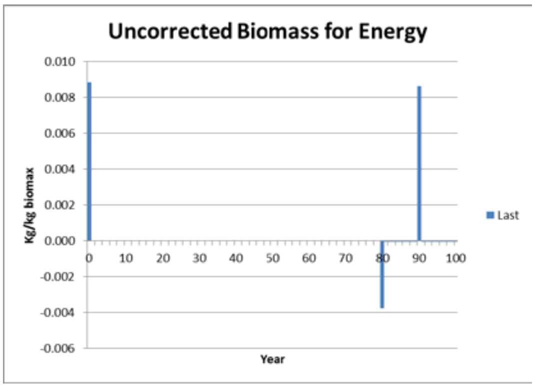
The results from the use of pre-commercial thinnings under the optimistic option are the same as Figure 3 (above) since the assumed reference system is that the thinned material would be left as residues.

4.3.4 Emissions from pre-commercial thinnings (pessimistic option)

Figure 6 shows the uncorrected emissions and biomass for energy from the pessimistic pre-commercial thinning model. There is a large emission with the initial use of energy and a negative emission and biomass use when the final harvest occurs, due to less biomass available for use in the bioenergy system as in the reference system.

Figure 6 Pre-commercial thinnings – uncorrected annual net emissions (a.) and uncorrected annual net biomass for energy

a.


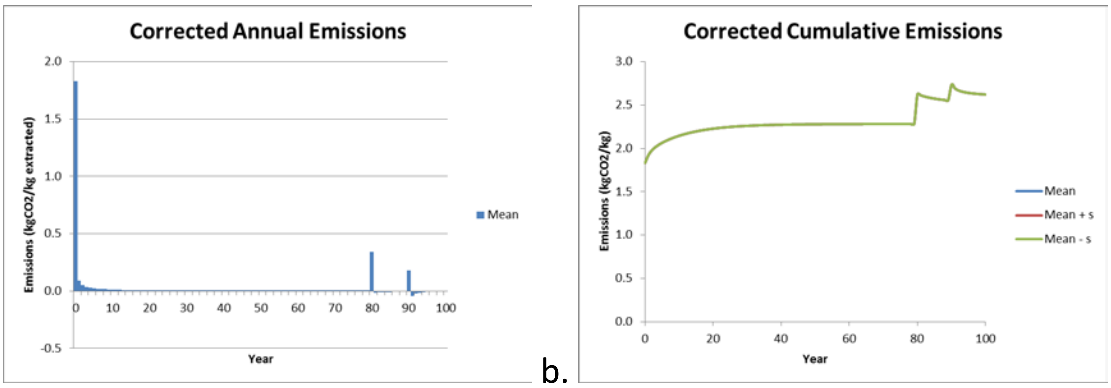
b.


Note: Values shown are typical for Austria. The pre-commercial thinning produces biomass for energy at year 0 and year 90 (the rotation length). There is a negative net biomass in year 80 because there is less biomass at the final felling in the bioenergy system than in the reference system.

Source: Joanneum (2014) own elaboration

Figure 7 a & b show the annual and cumulative emissions from the pre-commercial thinning model after correction. The loss of biomass for energy at final harvest in the bioenergy system must be compensated by a small amount of pre-commercial thinning. As a result there is a second emission at final felling. Since the forest does not grow faster after thinning there is no sequestration or negative emissions after thinning as the cumulative emissions do not decrease over time. In fact they increase because with less above ground biomass, there is less dead wood, litter and soil organic matter as compared to the reference case.

Figure 7 Pre-commercial thinning – corrected annual net emissions (a.) and corrected cumulative net biomass for energy

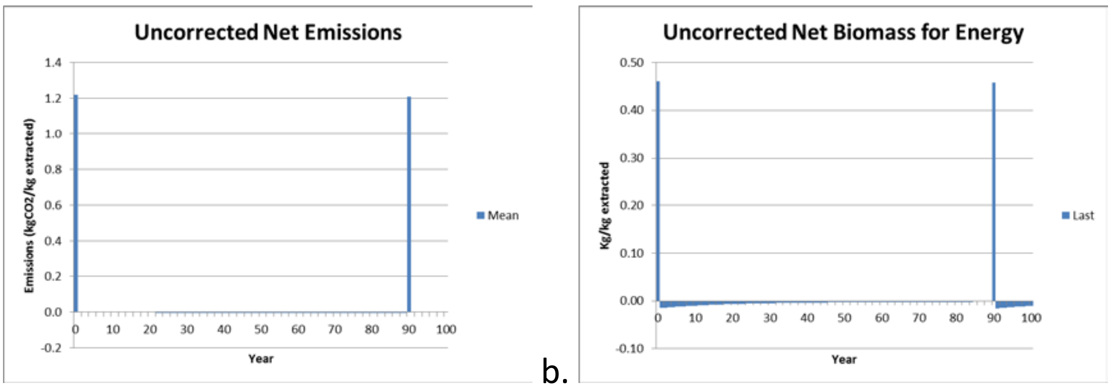


Source: Joanneum (2014) own elaboration; note: values shown are typical for Austria

4.3.5 Emissions from commercial thinning - thinnings used for energy instead of products and energy

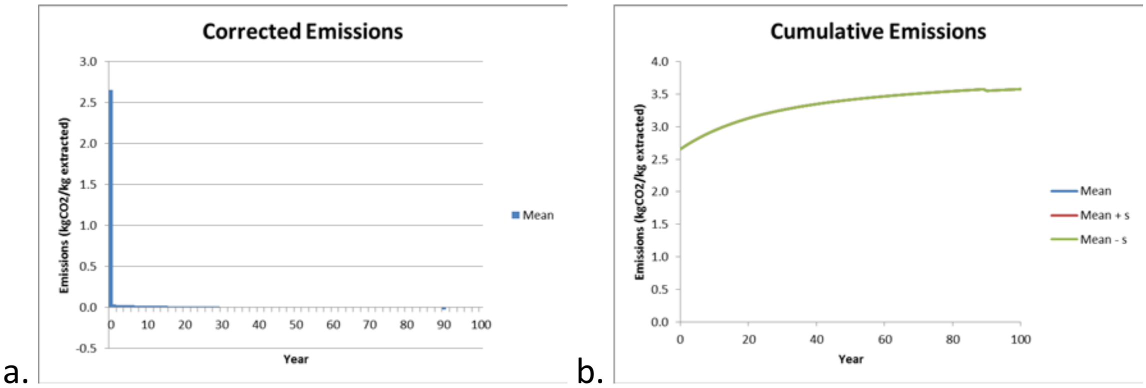
The uncorrected biomass for energy and net emissions are shown in Figure 8 a & b. The thinning produces biomass for energy at year 0 and year 90 (the rotation length). However, the net biomass is not 1 kg biomass / kg extracted because some of the biomass would have been used for energy in the reference system. There is negative net biomass for many years after the thinning takes place because the cascaded biomass in the reference system also provides biomass for energy.

Figure 8 Thinnings – uncorrected annual net emissions (a.) and uncorrected annual net biomass for energy (b.)



Note: Values shown are typical for Austria. The thinning produces biomass for energy at year 0 and year 90 (the rotation length). However, the net biomass is not 1 kg biomass / kg extracted because some of the biomass would have been used for energy in the reference system. There is negative net biomass for many years after the thinning takes place because the cascaded biomass in the reference system also provides biomass for energy.
Source: Joanneum (2014) own elaboration

Figure 9 Thinnings - corrected annual net emissions (a.) and corrected cumulative net emissions for forest bioenergy



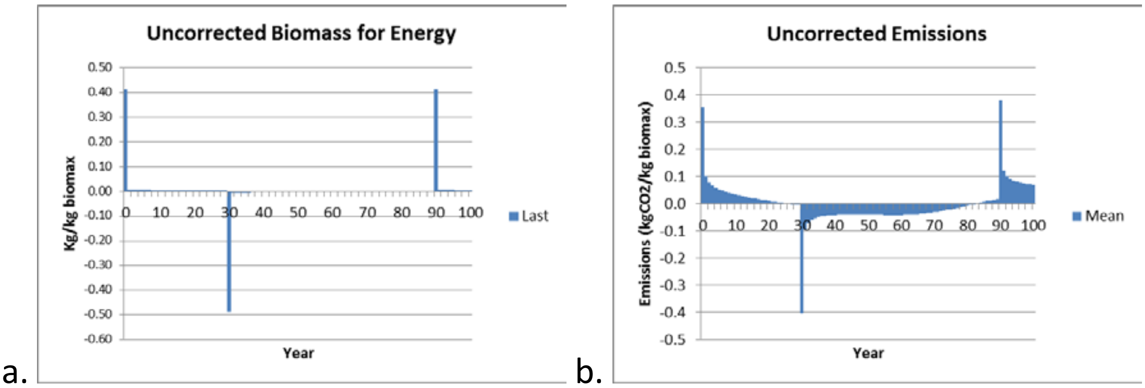
Source: Joanneum (2014) own elaboration; note: values shown are typical for Austria

There is a large negative emission at the thinning event. The emissions are significantly larger than the default emissions (1.83 kg CO_2/kg biomass) because there is a large emission that results from the required substitution of paper products in the bioenergy system. The negative net biomass for energy means that a small amount of biomass through thinning must be applied consistently to compensate for the energy that would be produced through the wood product chain in the reference system. This means that cumulative emissions begin at 2.6 kg CO_2/kg and increases to about 3.4 kg CO_2/kg. As the rotation period approaches, the bioenergy system enters dynamic equilibrium.

4.3.6 Emissions from the harvesting of forests - advanced harvests

The shortening the rotation causes biomass to be harvested at year 0 and year 90 (the optimal rotation length). However, there is the loss of a harvest at year 120 (the delayed rotation length). There is a large emission (or negative emission) associated with all harvesting events. There is also a continuous, smaller, stream of emissions after each harvest event as the wood products resulting from the harvest are used, recycled and discarded (Figure 10 a & b).

Figure 10 Advanced harvest – uncorrected annual net emissions (a.) and uncorrected annual net biomass for energy



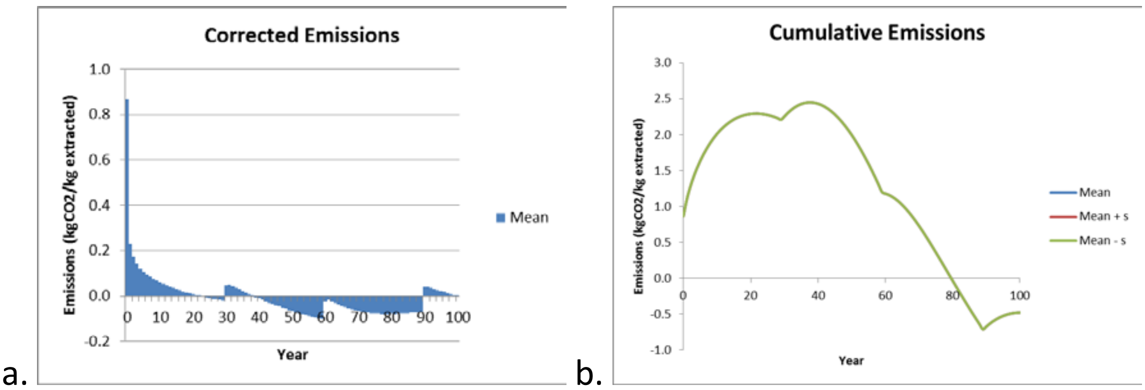
Note: Values shown are typical for Austria. The shortening the rotation causes biomass to be harvested at year 0 and year 90 (the optimal rotation length). However, there is the loss of a harvest at year 120 (the delayed rotation length). There is a large emission (or negative emission) associated with all harvesting events. There is also a continuous, smaller, stream of emissions after each harvest event as the wood products resulting from the harvest are used, recycled and discarded.

Source: Joanneum (2014) own elaboration

Figure 11 a & b show the corrected net annual and net cumulative emissions from advancing the harvest. The corrected net annual emissions start at 0.86 kg CO_2 / kg biomass for energy. This value is less that the default value for combustion of biomass for energy (1.83 kg CO_2 / kg) because there are emissions saved due to the substitution of products made from non-woody materials by the wood products. However, over time, these products are discarded, downcycled and inevitably used for energy causing an emission.

The cumulative emissions increase as the forest moves to a new dynamic equilibrium. However, once reached the cumulative emissions decrease because of the increase in wood products being generated from the advanced harvest.

Figure 11 Advanced harvest – corrected annual net emissions (a.) and corrected cumulative net biomass for energy



Source: Joanneum (2014) own elaboration Note: Values shown are typical for Austria.

There are actually two types of emission factors to consider; the emission factor from the consumption of an amount of biomass in a single year, and the effective emission factor of the continuous consumption of biomass. The latter is calculated by summing the emissions from a specific year to the year of interest and dividing it by the total biomass consumed over the same period, hence it is the time average emission factor.

Figure 6a shows the emission factors excluding supply-chain emissions of the presented models for Austrian forests and conditions. For example, the emission factor for the use of residues decreases quickly with time. The effective emission factor, however, is dependent on the amount of biomass consumed in specific year. For example, if the amount of bioenergy from residues is increasing the effective emission factor will decrease less quickly than for the case of consumption in a single year. This occurs because the effective emission factor includes both biomass extracted for many years and extracted recently. Since more biomass is extracted recently, it has a greater impact on the effective emission factor. Figure 6b shows the effective emission factors of the various biomass sources for a specified biomass scenario.

Of the five models, only biomass from the two residues the advanced harvest biomass have intensities that over time are below the intensities of fossil fuels (coal = 88 g CO_2/MJ, oil = 73 g CO_2/MJ, and natural gas = 51 g CO_2/MJ).

Typically the intensity should start somewhere near that of wood without regrowth (94 g CO_2/MJ). The advanced harvest model starts with a lower intensity because there are wood products created. The commercial thinning model starts with a higher intensity because material products are forsaken to create energy. The amounts above and below the typical value are approximately the same.

When the models are applied to a biomass supply scenario, the emission factors are different than for the individual models because intensity of the scenario is calculated as the sum of emissions to a specific year divided by the sum of energy to the same year.

When considering effective emission factors by country for different types of biomass, the general trend is that warmer countries have faster decay rates and hence lower emission factors from the use of residues. This was also suggested by Repo et al (2011). There are slight variations in the effective emission factors of other biomass sources too.

For example, countries with longer rotation lengths have a lower emission factors from the use of harvest stemwood than do countries with shorter rotation period. This is because the typical current harvest delay is assumed to be 1/3 of the rotation period.

4.4 Life-Cycle GHG Emissions of European Bioenergy Supply Chains

In addition to the CO_2 emissions from forest C stock changes which were described above, the bioenergy supply chains for electricity, heat and transport fuels imply also GHG emissions from the production of the feedstocks, the various transport steps, and the conversion to the end-uses.

The respective GHG emission factors for all bioenergy life-cycles (see Table 17) were taken from the GEMIS database (IINAS 2013), making use of the data compiled in the BiomassFutures project (IC et al. 2012).

These emission factors exclude the CO_2 emissions from forest C stock changes, as those depend on the time horizon, and assumptions on the forest reference cases (see Section 3.3 of the final report).

Furthermore, the emission factors do not account for possible GHG emissions from indirect land use changes (iLUC), as only those potentials for e.g. SRC or biogas from grasslands were included in this study which do not imply displacement of previous use for food or feed.

Table 19 Life-Cycle GHG Emission Factors for European Bioenergy Supply Chains in 2020 and 2030

CO_2eq in g/MJ$_{output}$	2020	2030
pellets-EU forest-products	6.4	5.8
pellets-EU wood-industry	3.9	3.5
pellets-EU SRC	11.5	10.9
pellets-US-import	16.2	15.6
wood-logs EU	0.0	0.0
biogas-maize	23.2	22.4
biogas-grass cuttings	9.5	9.1
biogas-manure	3.5	3.2
biogas-org.wastes	3.7	3.2
biomethane-maize	26.9	25.8
biomethane-grass cuttings	13.2	12.6
biomethane-manure	7.3	6.6
biomethane-org.wastes	7.4	7.3
AME-EU	7.1	6.9
rapeseed-oil-EU	33.4	30.6
RME-EU	38.8	35.6
PME-EU	26.5	24.3
SME-EU	18.2	18.0
BtL-black-iquor-EU	0.3	0.3
BtL-forest-residue-EU	37.2	32.9
BtL-SRC-EU	49.4	44.9
EtOH-wheat-EU	47.5	42.1
EtOH-sugarbeet-EU	44.8	42.4
EtOH-sugarcane-EU	27.1	24.7
EtOH2G-straw-EU	9.0	8.4
EtOH2G-forest-residues-EU	7.6	7.5
EtOH2G-SRC-EU	18.4	18.0

*Source: GEMIS version 4.8 (IINAS 2013); note that the emission data **exclude** CO_2 emissions from forest C stock changes, and also assume **no** indirect land use changes (iLUC)*

4.5 Total GHG Emission Balances

To calculate the overall GHG balances of bioenergy and the other energy carriers in the scenarios (see Section 5.6 of the final report), the following contributions were considered:

- Life-cycle GHG emissions for all bioenergy systems (see Table 21)
- For bioenergy from forests also CO_2 emissions from forest C stock changes, depending on time horizon (20 or 100 years), and optimistic or pessimistic forest reference case (these data are given in Table 3 of the final report)
- Life-cycle GHG emissions for all other energy systems (see Table 21 and Table 22)
- GHG emission savings from substituting construction materials with wood (see Table 23).

Table 20 Life-Cycle GHG Emission Factors for European Non-Renewable Energy Sources in 2020 and 2030

CO_2eq in g/MJ$_{input}$	**2020**	**2030**
coal	109	108
oil	87	87
gas	66	66
nuclear	6	6

Source: GEMIS version 4.8 (IINAS 2013)

Table 21 Life-Cycle GHG Emission Factors for European Non-Bio-Renewable Electricity Sources in 2020 and 2030

CO_2eq in g/kWh$_{el}$	**2020**	**2030**
hydro	11	10
wind	3	3
solar-PV	26	23

Source: GEMIS version 4.8 (IINAS 2013)

Table 22 Life-Cycle GHG Emission Factors for European Construction Materials in 2020 and 2030

CO_2eq in t/t$_{material}$	**2020**	**2030**
concrete	0.16	0.16
steel (mix)	1.49	1.50

Source: GEMIS version 4.8 (IINAS 2013)

5 Scenario Description

5.1 Background Data for the Wood Demand in the REF Scenario

5.1.1 EUwood Project and related work

The EUwood project aimed to examine the **potential supply and demand of forest resources** in Europe by 2020 and 2030 both for materials and energy.

The **theoretical** biomass potential from European forests in 2010 was 1,277 Mm^3. About 52% of the total potential is in stems, while logging residues represent 26%, and stumps 21%, respectively. Other biomass, i.e. stem and crown biomass from early thinnings, represent only 1% of the total potential.

The "realistic" potential from European forests estimated within the EUwood project is **747 M m^3 per year** (overbark) in 2010 and could **range from 625 to 898 million m^3 per year** by 2030. This potential represents the total potential that could be supplied by forests in the EU, regardless whether it is used for material or for energy use.

It was not assessed whether the potential could become economically available.

In the year 2010 the wood **consumption** in solid wood equivalents (swe) for all **material uses** was about 458 Mm^3. It is assumed to increase by 15.4% to 529 Mm^3 by 2020 and by 17.2 % to 620 Mm^3 solid wood equivalents by 2030, as depicted in the following table.

Table 23 Breakdown of the wood resource balance in 2010

Potential in Mm^3_{swe}		**Demand in Mm^3_{swe}**	
Stemwood C, ME	362	196	Sawmill industry
Stemwood NC, ME	182	11	Veneer/plywood industry
Forest residues, ME	118	143	Pulp industry
Bark, ME	55	92	Panel industry
Landscape cw (USE) ME	59	15	Other material uses
Short rotation coppices*		21	Producer of solid wood fuels
Sawmill by products	87	86	Forest sector internal use
Other industrial residues	30	83	Biomass power plants
Black liquor	60	23	Households (pellets)
Solid wood fuels	21	155	Households (other)
Post consumer wood	52	0	Liquid biofuels
Total	**1026**	**825**	**Total**

*Source: Mantau (2013); C: Coniferous; NC: Non-Coniferous; ME: Medium mobilization scenario; * The potential of SRC was not quantified within the project*

About 100 to 200 Mm^3 of additional wood could be needed, depending on the scenarios and the qualitative assumptions on new product developments.

The **share** of material uses in total wood consumption is expected to decrease from 55.5% in 2010 to 46.5% in 2020 and 43.5% in 2030.

It is worth noting that a relevant part of the material uses is used directly to energy. According to Mantau (2012) the wood resources from trees represent 577 Mm^3 in 2010 (544 Mm^3 from forestry and 33 Mm^3 from wood outside of forests). From this total, 260 Mm^3 were used for wood production and 108 Mm^3 for pulp and paper. The remaining 209 Mm^3 were used for energy. Wood consumption for **energy** generation is expected to grow from 346 Mm^3 in 2010 (3.1 EJ) to 573 Mm^3 (5 EJ) by 2020 and might reach 752 Mm^3 by 2030 (6.6 EJ).

The results of the EUwood analysis show that for the **medium mobilisation scenario** and for **high bioenergy demand growth** the expected demand is **likely to exceed** the sustainable wood potential by 2020. Even if all measures for increased wood mobilization were implemented, wood demand from industry and meeting the renewable energy targets can hardly be satisfied from domestic sources by 2020.

EUwood has shown that with a high mobilization scenario it is difficult but not impossible to supply, on a sustainable basis, enough wood to satisfy the needs of the industry and to meet the targets for renewable energy in 2020.

There is definitely not enough wood to satisfy the **combined** needs from forest-based industries and wood energy producers from **domestic** EU-27 sources by 2030.

5.1.2 EFSOS II (UNECE, FAO 2011)

The EFSOS II study focused on a reference scenario and four policy storylines between 2010 and 2030. The reference scenario assumes no major change in policies so consumption of forest products and wood energy will grow steadily, and trends outside the forest sector are considered according to the IPCC B2 scenario.

The EFSOS-II policy scenarios provide insights of “what if”:

- **Maximizing biomass carbon**: maintaining the level of harvest it explores the amount of carbon that could be stored in forests. In the short term, the best strategy is to combine forest management with the aim of accumulating carbon in the forests (longer rotations and a greater share of thinning) with a steady flow of wood for products and energy while in the long term regular harvesting should be promoted because the sequestration capacity limit of forest would have been reached.

- **Priority to biodiversity**: considers biological diversity a priority and assumes, for example, that forest residues and stumps are not harvested for bioenergy. The supply in this scenario is 12 % lower than in the reference scenario so reduced consumption of products and energy and/or increased imports and/or intensified use of other sources would be needed.

Promoting wood energy: investigates the amount of wood needed to meet the RED targets. This scenario implies that supply should increase by nearly 50 %in 20 years. SRC should be established on the agricultural land. The EFSOS-II study resumes:
"Europe is, and will remain in all scenarios, a net exporter of wood and forest products: significant net exports of products outweigh relatively minor net imports of wood, even in the Promoting wood energy scenario". On the other hand, "Projections show a steady rise in prices of forest products and wood over the whole period, driven by expanding global demand and increasing scarcity in several regions" (UNECE, FAO 2011).

In these scenarios[2], wood for material use would increase from 534 Mm^3 in 2010 to 585 Mm^3 by 2030 (see Table 25).

Table 24 Overview of EFSOS scenarios

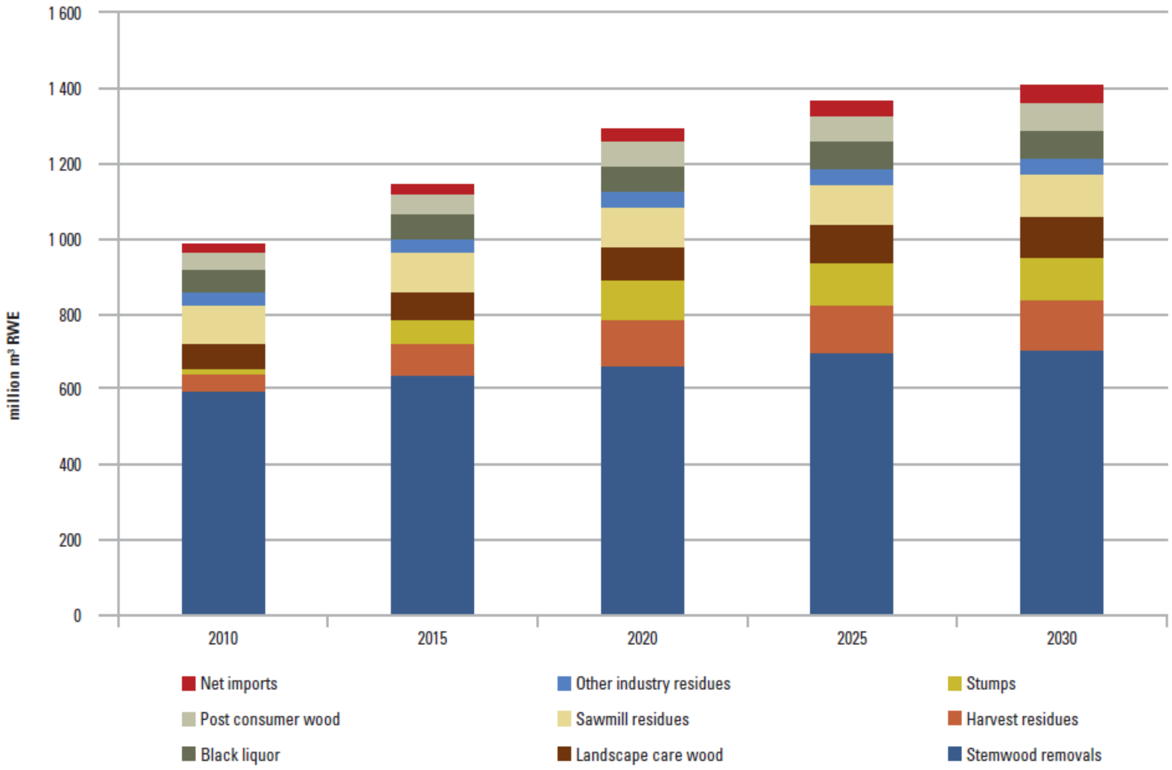
				Reference scenario		Maximising carbon		Priority to biodiversity		Promoting wood energy	
				2010	2030	2030		2030		2030	
		Unit	source			absolute	difference	absolute	difference	absolute	difference
Wood balance											
Wood supply	Stemwood removals	Mm^3 o.b.	EFISCEN	595.1	684.7	685.0	0.3	600.4	-84.3	700.8	16.1
	Harvest residues	Mm^3	EFISCEN	32.8	91.4	77.8	-13.6	0	-91.4	158.2	66.9
	Stump extraction	Mm^3	EFISCEN	3.6	12.1	10.7	-1.4	0	-12.1	113.7	101.5
	Landscape care wood	Mm^3	EUwood	63.4	81.0	81.0	0.0	81.0	0.0	108.0	27.0
	Post-consumer wood	Mm^3	EUwood	45.6	71.4	71.4	0.0	71.4	0.0	71.4	0.0
	Industrial residues	Mm^3	EFI-GTM	210.4	237.4	237.4	0.0	237.4	0.0	236.3	-1.0
	Trade	Mm^3	EFI-GTM	12.5	1.3	1.3	0.0	1.3	0.0	32.9	31.6
	Total	**Mm^3**		**963.5**	**1 179.2**	**1 164.5**	**-14.7**	**991.5**	**-187.8**	**1 421.3**	**242.1**
Wood demand	Products	Mm^3	EFI-GTM	531.4	582.3	582.3	0.0	582.3	0.0	560.4	-21.9
	Energy	Mm^3	EFI-GTM	434.6	585.3	585.3	0.0	585.3	0.0	858.7	273.4
	Total	**Mm^3**		**965.9**	**1 167.6**	**1 167.6**	**0.0**	**1 167.6**	**0.0**	**1 419.1**	**251.4**
Gap	Supply-Demand	Mm^3		-2.5	11.6	-3.1	-14.7	-176.2	-187.8	2.2	-9.4

Source: UNECE, FAO (2011)

2 The additional "Fostering innovation and competitiveness" scenarios provide only a qualitative view, i.e. no data given.

The EFSOS-II study resumes:
"Europe is, and will remain in all scenarios, a net exporter of wood and forest products: significant net exports of products outweigh relatively minor net imports of wood, even in the Promoting wood energy scenario". On the other hand, "Projections show a steady rise in prices of forest products and wood over the whole period, driven by expanding global demand and increasing scarcity in several regions" (UNECE, FAO 2011).

Table 25 Components of wood supply in "Promoting wood energy" scenario, 2010-2030



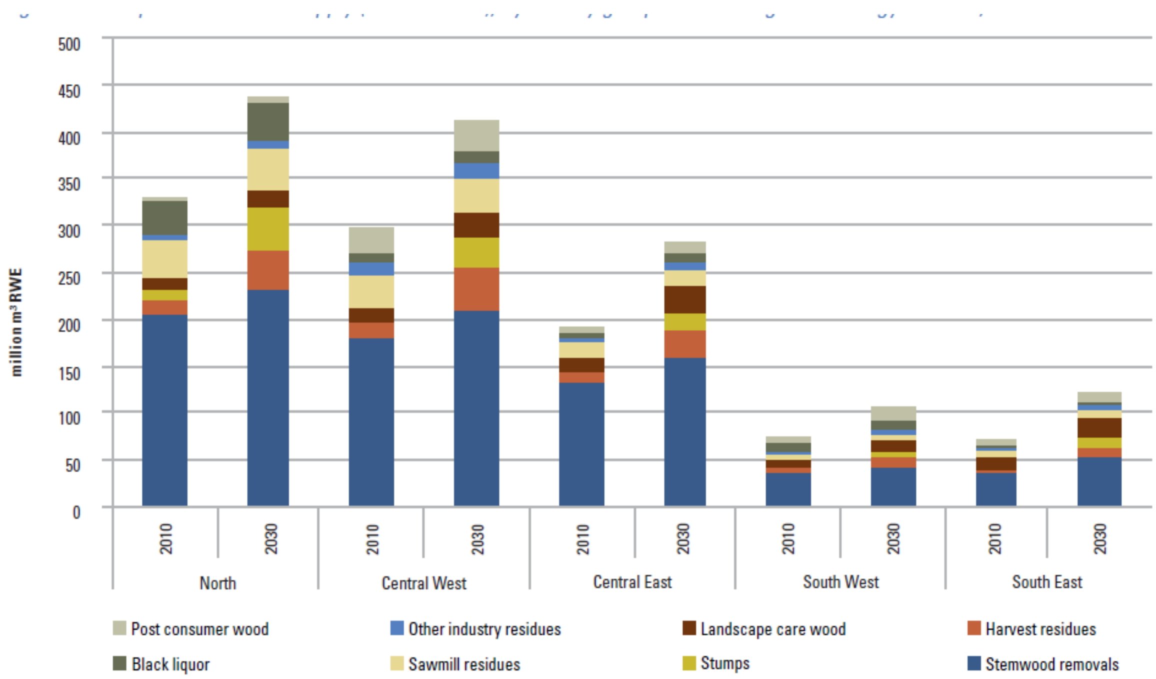
Source: UNECE-FAO (2011)

Table 26 Use of wood for energy in Promoting wood energy scenario, 2010-2030

	2010	2020	2030	Change 2010 to 2030	
	million m³			million m³	%/year
Forest industry process energy	92	107	126	34	1.59
Wood burning CHP	105	271	406	301	6.99
Households (pellets)	24	70	83	60	6.50
Households (other)	214	223	204	-10	-0.24
Liquid biofuels	0	1	40	40	NA
Total wood for energy	435	673	859	424	3.46

Source: UNECE-FAO (2011)

Table 27 Components of wood supply (without trade), by country group in "Promoting wood energy" scenario, 2010-2030



Source: UNECE-FAO (2011)

5.2 The Reference (REF) Scenario

5.2.1 Wood Material Demand

Given the variety of study results presented above, the following basic assumptions for the REF scenario are recommended with regard to materials from woody biomass:

- Wood demand **for materials** will increase from 531 Mm^3 in 2010 to 550 Mm^3 by 2020 and to 585 Mm^3 by 2030, based on the EFSOS-II study. This represents energy equivalents of about 4,800 PJ (2020) and 5,100 PJ (2030), respectively. The demand growth from 2010 to 2020 will be approx. 4%, rising to 10% until 2030.
- It is assumed most of the increment will be for **short-life products** (< 10 years) so that the energy content could be recovered from post-consumer wood, packaging materials etc. if adequate waste collection is implemented.
- Demand growth will be for rather low-quality wood (for pulp & paper/packaging, MDF etc.).

5.2.2 Background Data on Solid Bioenergy Consumption

Table 22 depicts the consumption of solid biomass in the EU in 2011 by use.

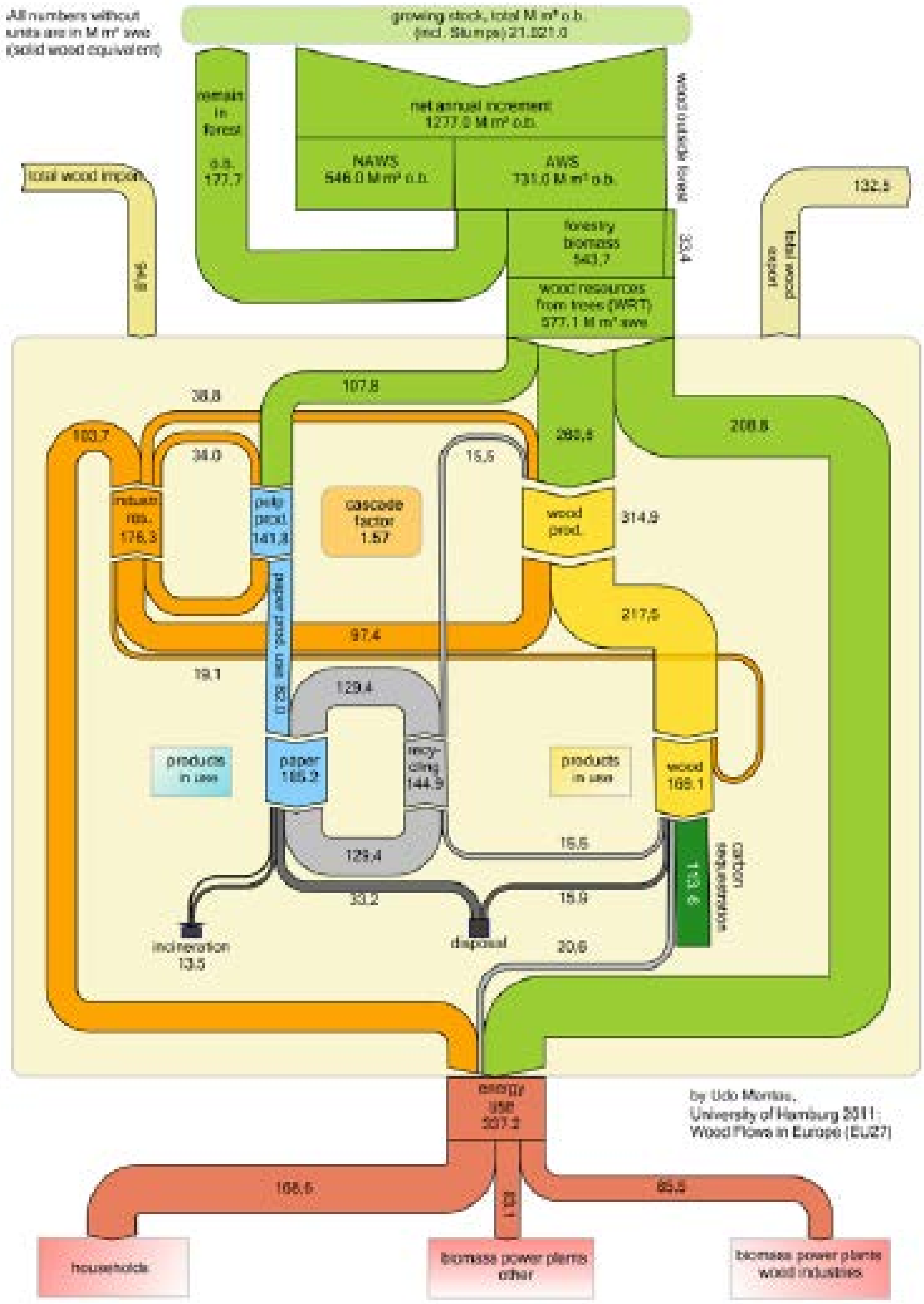
Table 28 Consumption of solid biomass in the EU in 2011 by use

Solid Bioenergy Use	Consumption	Unit
for heat consumption in	64.9	MtOE
- residential and industrial sector	58.0	MtOE
- processing sector	6.9	MtOE
- heat plants	2.7	MtOE
- CHP plants	4.2	MtOE
for electricity produced from	72.8	TWh
- electricity-only plants	30.6	TWh
- CHP plants	42.2	TWh
Primary energy production	**78.8**	**MtOE**

Source: EurObserv'ER (2012)

The overall flows of wood from sources to end uses in the EU-27 in the year 2010 are shown in the following figure.

Figure 12 Condensed wood flow chart from resources to end-use in the EU-27 in 2010



Source: Mantau (2012)

5.3 Bioenergy Demand and Supply Projections

According to the NREAPs, bioenergy will contribute approximately 12 % of the final energy demand by 2020, representing an increase about 60 % in comparison with 2010 (Uslu, van Stralen 2012). Several research studies with different specific targets have been conducted aiming at assessing the bioenergy potential supply and demand within the EU taking particular consideration of forest biomass i.e. Biomass Futures (IC et al. 2012), EUwood (Mantau et al. 2010) or EEA (2006, 2013) assessments.

Biomass Futures Project

The purpose of this IIE project was to examine the **role that biomass could play into meeting the RED targets.**

It concluded that meeting NREAPs will be very challenging (IC et al. 2012; van Stralen et al. 2013) despite the surplus of biomass available at European level.

The demands according to the Biomass Futures scenarios assumptions are shown in Table 23. An additional "reference" scenario resulted in a demand of 618 TWh bioenergy with a demand of 357 TWh from wood directly from forestry and 261 TWh of wood byproduct from industry. The relevant differences in demand between the RED and RED+ scenario come from different assumptions on issues related to sustainability such as GHG balances and land requirements (Uslu et al. 2012).

Table 29 Demands in the Biomass Futures project for 2020

Feedstock	Unit	High biomass scenario	Sustainability scenario
Primary forestry residues	TWh	334	110
Sawmill by-products	TWh	90	90
Landscape care wood	TWh	100	96
SRC	TWh	498	180
Final energy from wood	**TWh**	**1022**	**476**
Feedstock LHV	TWh	1795	858
	MtOE	154	74
Feedstock volume	**Mm^3_{swe}**	**646**	**309**

Source: own calculation based on data from Biomass Futures project (IC et al. 2012)

In the reference scenario, despite the significant roundwood and additional harvestable roundwood potential in 2020 and 2030, these resources are not utilized due to their higher prices (> 400 €/tOE; 83.5 €/m^3_{swe}) in comparison to alternatives, i.e. wood pellets imports.

In the sustainability scenario, due to more stringent environmental constraint there are potentials neither from roundwood production nor from additional harvest roundwood. Primary forestry potentials are reduced dramatically due to the sustainability criteria but this is compensated by larger utilization of perennial energy crops and more use of expensive biomass coming from wood processing such as sawmill by-products and higher imports.

The high biomass scenario doesn´t foresee neither roundwood nor additional harvests of solid biomass but expects high utilization of residues.

In any case, for all scenarios and timeframes, EU27 bioenergy potentials are higher than current supply and far less than the demand, as illustrated in Table 24. However, the biomass Futures project concluded that around 15 % of the total primary biomass would be imported and this share would be higher in the "high biomass scenario" (Uslu et al. 2012).

Table 30 Overview of the final bioenergy demand per sector in the EU27 in different scenarios for 2020

Final demand (all) biomass (PJ)	**2010**	**NREAP**	**Reference**	**Sustainability**	**High Biomass**
Electricity	440	835	796	677	867
Heat	3081	3768	3182	3186	3517
Biofuels	544	1244	1163	547	1163
total	**4065**	**5847**	**5141**	**4410**	**5547**

Source: van Stralen et al. (2013)

6 Detailed Scenario Results

Table 31 Electricity Generation in the EU27 from 2010 to 2030

		2020			2030		
Electricity generation, TWh$_{el}$	**2010**	**REF**	**GHG**	**SUS**	**REF**	**GHG**	**SUS**
total generation	**3.410**	**3.414**	**3.290**	**3.290**	**3.650**	**3.320**	**3.320**
- fossil & nuclear	2.722	2.185	1.848	1.848	2.030	958	958
- RES	688	1.229	1.442	1.442	1.620	2.362	2.362
of that: non-bio renewables	528	1.008	1.192	1.192	1.377	2.112	2.062
of that: bioenergy	160	221	250	250	243	300	300
of that: non-woody bioenergy	-11	50	75	115	60	139	275
of that: woody bioenergy	171	171	175	135	183	161	25
share of fossil & nuclear	79,8%	64,0%	56,2%	56,2%	55,6%	28,9%	28,9%
share of RES	20,2%	36,0%	43,8%	43,8%	44,4%	71,1%	71,1%
share of bioenergy	4,7%	6,5%	7,6%	7,6%	6,6%	9,0%	9,0%
share of woody bioenergy	5,0%	5,0%	5,3%	4,1%	5,0%	4,9%	0,8%

Source: IINAS calculations

Table 32 Heat Production in the EU27 from 2010 to 2030

		2020			2030		
Heat Production, PJ	**2010**	**REF**	**GHG**	**SUS**	**REF**	**GHG**	**SUS**
fossil, direct	16.657	16.657	15.389	15.389	15.800	11.046	11.046
district heat incl. cogen	2.336	2.336	2.219	2.219	2.330	1.981	1.981
electricity incl. heatpumps	1.330	1.330	1.197	1.197	1.721	1.291	1.291
RES (excluding cogen heat)	2.892	6.034	4.550	4.550	5.530	6.885	6.885
- non-bio renewables	127	1.550	1.550	1.550	3.500	5.000	5.000
- bioenergy	2.765	4.484	3.000	3.000	2.030	1.885	1.885
of that: forest products EU	2.383	2.847	968	975	1.269	353	71
of that: woody residues EU	368	1.603	1.965	1.965	736	1.461	1.673
of that: SRC EU	14	34	68	60	25	71	141
of that: forest products imported	0	0	0	0	0	0	0
heat final energy demand	**23.215**	**26.357**	**23.355**	**23.355**	**25.381**	**21.202**	**21.202**
share of RES	12,5%	22,9%	19,5%	19,5%	21,8%	32,5%	32,5%
share of RES incl. cogen heat + el.	17,9%	28,6%	26,7%	26,5%	28,8%	42,8%	41,8%
share of bioenergy	11,9%	17,0%	12,8%	12,8%	8,0%	8,9%	8,9%
share of woody bioenergy	11,9%	17,0%	12,8%	12,8%	8,0%	8,9%	8,9%

Source: IINAS calculations

Table 33 Transport Fuel Production in the EU27 from 2010 to 2030

		2020			2030		
Transport Fuels, PJ	**2010**	**REF**	**GHG**	**SUS**	**REF**	**GHG**	**SUS**
fossil, direct	14.564	13.178	10.322	10.322	12.467	6.722	6.722
electricity	520	666	699	699	1.121	1.271	1.271
biofuels	546	1.096	888	888	1.140	730	730
- annual crops EU	524	939	648	613	690	0	0
- non-woody residues/wastes EU	4	16	13	16	21	27	27
- straw EU	0	16	24	37	110	164	182
- crops imported	19	102	73	49	72	18	0
- forest products EU	0	8	64	77	0	192	137
- woody residues EU	0	16	64	97	83	328	383
- SRC EU	0	0	0	0	0	0	0
- forest products imported	0	0	0	0	165	0	0
transport final energy demand	**15.630**	**14.940**	**11.909**	**11.909**	**14.729**	**8.723**	**8.723**
RE share including electricity	4,2%	8,9%	10,0%	10,0%	11,1%	18,7%	18,7%
Bioenergy share	3,5%	7,3%	7,5%	7,5%	7,7%	8,4%	8,4%
Woody bioenergy share incl. el.	0,2%	0,4%	1,4%	1,7%	2,1%	6,7%	6,1%

Source: IINAS calculations; note than no double-counting for biofuels nor multipliers for electricity were applied

Table 34 Final Energy Demand in the EU27 from 2010 to 2030

		2020			2030		
Final Energy Supply	**2010**	**REF**	**GHG**	**SUS**	**REF**	**GHG**	**SUS**
fossil, direct	31.220	29.835	25.711	25.711	28.267	17.768	17.768
non-renewable electricity	9.799	7.865	6.653	6.653	7.307	3.449	3.449
renewable electricity	2.478	4.425	5.191	5.191	5.832	8.503	8.503
of that: bioenergy	576	795	900	900	873	1.080	1.080
of that: woody bioenergy	615	615	630	486	657	581	90
fossil cogen heat	1.343	1.302	1.061	1.106	1.311	712	912
renewable cogen heat	992	1.034	1.158	1.113	1.019	1.269	1.068
of that: woody bioenergy	615	593	635	508	432	627	200
non-bio renewables	127	1.550	1.550	1.550	3.500	5.000	5.000
non-woody bioenergy	546	1.073	759	715	892	210	210
woody bioenergy	2.765	4.507	3.129	3.173	2.278	2.405	2.405
total	**49.271**	**51.591**	**45.212**	**45.212**	**50.407**	**39.316**	**39.316**
RE share (incl. el + cogen heat):	14%	24%	26%	26%	27%	44%	44%
bio share (incl. el + cogen heat):	9%	14%	12%	12%	9%	11%	10%
woody share (incl. el + cogen heat):	8%	11%	10%	9%	7%	9%	7%

Source: IINAS calculations

Table 35 Primary Energy Supply in the EU27 from 2010 to 2030

		2020			2030		
	2010	**REF**	**GHG**	**SUS**	**REF**	**GHG**	**SUS**
Primary energy, in PJ	**70.676**	**69.337**	**64.600**	**64.625**	**67.110**	**45.130**	**45.204**
- fossil & nuclear	63.004	57.827	51.350	51.244	53.854	26.438	26.323
of that: coal	11.722	9.878	8.295	8.248	7.268	3.590	3.537
of that: oil	25.834	22.952	20.061	20.014	21.643	11.702	11.656
of that: natural gas	18.497	16.896	15.057	15.046	16.518	7.992	7.982
of that: nuclear	9.905	8.101	7.936	7.936	8.424	3.155	3.148
- RES	7.672	11.597	13.251	13.381	13.341	18.692	18.882
of that: non-bio renewables	2.029	4.469	5.841	5.841	8.719	12.603	12.423
of that: bioenergy & waste	6.644	7.128	7.410	7.540	4.622	6.089	6.458
of that: non-bio waste	500	383	383	383	364	364	364
of that: non-woody bio	1.434	1.961	2.055	2.501	1.686	1.457	3.069
of that: woody bioenergy	4.711	4.784	4.971	4.656	2.572	4.268	3.025
share of RE	11%	17%	21%	21%	20%	41%	42%
share of bioenergy	9%	10%	11%	11%	6%	13%	13%
share of woody bioenergy	7%	7%	8%	7%	4%	9%	7%

Source: IINAS calculations

Table 36 Primary Bioenergy Supply and Use of Sustainable Potentials in the EU27 from 2010 to 2030

		2020			2030		
in PJ	**2010**	**REF**	**GHG**	**SUS**	**REF**	**GHG**	**SUS**
total woody bioenergy	**4.711**	**6.253**	**4.971**	**4.656**	**3.718**	**4.268**	**3.025**
- forest products, EU	3.204	3.387	1.554	1.291	1.682	1.058	345
- woody residues/wastes, EU	1.384	2.185	3.119	3.049	1.276	2.960	2.539
- SRC, EU	14	34	68	60	25	87	141
- forest products, imported	108	647	231	256	734	163	0
share of potential (REF/SUS)	**2010**	**REF**	**GHG**	**SUS**	**REF**	**GHG**	**SUS**
- forest products, EU	52%	100%	77%	64%	49%	51%	17%
- woody residues/wastes, EU	56%	78%	68%	67%	64%	74%	64%
- SRC, EU	2%	4%	4%	4%	10%	44%	72%

		2020			2030		
in PJ	**2010**	**REF**	**GHG**	**SUS**	**REF**	**GHG**	**SUS**
total non-woody bioenergy	**116**	**273**	**352**	**861**	**590**	**1.179**	**3.069**
straw for biofuels	8	57	68	96	217	319	350
straw for biogas	0	0	25	315	0	314	1153
residues for biogas el-cogen	108	216	260	450	373	546	1567
share of potential (REF/SUS)	**2010**	**REF**	**GHG**	**SUS**	**REF**	**GHG**	**SUS**
straw for biofuels	0%	3%	3%	5%	11%	16%	18%
straw for biogas el-cogen	0%	0%	1%	15%	0%	16%	58%
residues for biogas el-cogen	6%	11%	13%	23%	18%	26%	75%

Source: IINAS calculations

Table 37 GHG Emissions from Bioenergy Supply and Use from 2010 to 2030

GHG emissions woody bioenergy, Mt CO_2eq/a		**2020**			**2030**		
20 year horizon, pessimistic REF	**2010**	**REF**	**GHG**	**SUS**	**REF**	**GHG**	**SUS**
from electricity (incl. CHP)	78.7	104.3	61.7	47.5	78.5	47.1	11.8
from heat	2.8	4.5	3.0	3.0	2.0	1.9	1.9
from biofuels	22.1	42.1	35.7	34.8	35.4	22.2	16.2
from materials substitution			**-6.3**	**-6.3**		**-63.0**	**-63.0**
total from bioenergy	**103.5**	**150.9**	**94.1**	**79.0**	**116.0**	**8.2**	**-33.2**

GHG emissions woody bioenergy, Mt CO_2eq/a		**2020**			**2030**		
20 year horizon, optimistic REF	**2010**	**REF**	**GHG**	**SUS**	**REF**	**GHG**	**SUS**
from electricity (incl. CHP)	70.9	85.4	53.2	40.4	65.5	40.9	11.6
from heat	2.8	4.5	3.0	3.0	2.0	1.9	1.9
from biofuels	22.1	42.1	35.3	34.3	35.4	20.9	15.3
from materials substitution			**-6.3**	**-6.3**		**-63.0**	**-63.0**
total from bioenergy	**95.7**	**132.0**	**85.2**	**71.3**	**102.9**	**0.7**	**-34.3**

GHG emissions woody bioenergy, Mt CO_2eq/a		**2020**			**2030**		
100 year horizon (independent from REF)	**2010**	**REF**	**GHG**	**SUS**	**REF**	**GHG**	**SUS**
from electricity (incl. CHP)	16.9	25.9	15.8	19.7	21.8	12.6	10.1
from heat	2.8	4.5	3.0	3.0	2.0	1.9	1.9
from biofuels	22.1	41.6	31.1	29.3	35.4	8.4	6.3
from materials substitution			**-6.3**	**-6.3**		**-63.0**	**-63.0**
total from bioenergy	**41.7**	**72.0**	**43.6**	**45.7**	**59.2**	**-40.2**	**-44.7**

total GHG Emission Balances for Bioenergy		**2020**			**2030**		
	2010	**REF**	**GHG**	**SUS**	**REF**	**GHG**	**SUS**
20 year horizon, pessimistic REF	103.5	150.9	94.1	79.0	116.0	8.2	-33.2
20 year horizon, optimistic REF	95.7	132.0	85.2	71.3	102.9	0.7	-34.3
100 year horizon (independent from REF)	41.7	72.0	43.6	45.7	59.2	-40.2	-44.7

Source: IINAS calculations

Table 38 GHG Emissions from Energy Supply and Use in the EU27, 2010 to 2030

		2020			2030		
Overall GHG emissions, in Mt CO_2eq/a	**2010**	**REF**	**GHG**	**SUS**	**REF**	**GHG**	**SUS**
coal	1.213	1.075	863	861	783	387	381
oil	2.226	2.007	1.841	1.837	1.878	1.015	1.011
natural gas	1.200	1.107	916	914	1.093	529	528
nuclear	62	50	52	52	52	20	20
renewables excluding bioenergy	1	12	12	12	18	18	18
bioenergy excluding woody	28	49	33	37	38	6	11
woody bioenergy (20 a, pessimistic REF)	104	151	94	79	116	8	-33
woody bioenergy (20 a, optimistic REF)	96	132	85	71	103	1	-34
woody bioenergy (100 a, indep. from REF)	42	72	44	46	59	-40	-45
total (20 year horizon, pessimistic REF)	**4.834**	**4.451**	**3.811**	**3.792**	**3.978**	**1.983**	**1.936**
total (20 year horizon, optimistic REF)	**4.826**	**4.432**	**3.802**	**3.784**	**3.965**	**1.975**	**1.935**
total (100 year horizon, indep. from REF)	**4.772**	**4.372**	**3.760**	**3.759**	**3.921**	**1.934**	**1.924**
GHG reduction vs. 2010 (20 a, pess. REF)		-8%	-21%	-22%	-18%	-59%	-60%
GHG reduction vs. 2010 (20 a, opt. REF)		-8%	-21%	-22%	-18%	-59%	-60%
GHG reduction vs. 2010 (100 a)		-10%	-22%	-22%	-19%	-60%	-60%

Source: IINAS calculations; data include upstream life-cycle GHG emissions for all energy, and GHG emissions from forest bioenergy using different time horizons and reference systems