Wood assortments suitable for production of chemicals via bioconversion

Birgit Backlund

Innventia Report No. 490
March 2014

Acknowledgements

This study has been made within the project “Technology Impact Assessment” in the research programme Chalmers Energy Initiative (CEI) 2010-2014. The author wishes to thank Niklas Berglin and Anna von Schenck for valuable viewpoints on the investigation.

Table of contents

Page

1 Summary

The goal of this study was to assess the suitability of possible future ("fuel grade") wood assortments for hydrolysis and biochemical conversion to e.g. ethanol, based on the Swedish situation as an example. The market for ethanol is large, due to the increasing demand for biobased motor fuels. Other interesting products are lactic acid, butanol and succinic acid. Wood is an attractive ethanol raw material from a sustainability point of view since forestry generally does not compete with food production. Substantial amounts of the biomass from felled trees are, however, left in the forest today. Only small fractions of the branches, tops, stumps and roots are recovered.

In order to get good biochemical processability, the wood assortment should have low contents of extractives and lignin and a high hexose/pentose ratio. Low ash content is desirable from a processing point of view. For efficient logistics, the material should be available in large amounts per forest area and be easy to harvest and collect, preferably at the same time as thinning or logging. A high bulk density decreases the transport cost. The price pattern today implies that a bioconversion assortment is to be found within the "fuelwood" assortments.

The wood materials that crystallised as most promising future bioconversion assortments were 1) stumps and roots and 2) non-selective early thinnings. Tree stumps, especially from spruce, and preferably without bark and small roots, might be an interesting raw material for biochemical conversion with a potential of up to 5 Mt/year in Sweden. Debranched, and – preferably – debarked, small-diameter (early thinning-size) trees is another possible assortment for biochemical conversion. The Swedish potential is ca 2 Mt/year.

2 Introduction

The goal of this study was to assess the suitability of possible future ("fuel grade") wood assortments for hydrolysis and biochemical conversion. The following questions have been addressed:

- Are there possible wood assortments that are "too good" to be used as fuel but still "not really good enough" to be used as pulpwood?
- Are these assortments suitable raw materials for ethanol or other products from biochemical conversion?
- What would the new value chain look like, and what is needed for its realisation?

At present, ethanol is the product of greatest interest for such bioconversion. The demand for ethanol and other biobased motor fuels is steadily increasing in Sweden, largely as a result of governmental economic incentives. In Sweden´s current climate policy, the government suggests, as one prioritization, a vehicle fleet that is independent of fossil energy by 2030 (Naturvårdsverket 2013). In the budget proposition for 2014, the government suggests a quota obligation system that would double the ethanol admixture in gasoline.

Among chemical products that can be produced through fermentation of sugars from biomass we also find lactic acid, butanol and succinic acid. They are interesting as building blocks for biopolymers and base chemicals for other biobased products.

Wood is an attractive ethanol raw material from a sustainability point of view since forestry generally does not compete with food crops for land or cause any land-use change impact.

3 Bioconversion of wood biomass

3.1 Situation today for biobased ethanol

Large amounts of sugar-based ethanol are produced today. The main biomass raw materials used are sucrose from sugar cane (Brazil) and starch from corn (USA). A considerable part of the ethanol on the market is fossil-based, though, produced from petroleum-based ethene.

Lignocellulosic biomass from wood, annual plants and agriculture residues constitute large potential volumes of feedstock for ethanol production. Much research has been made on these raw materials, including pilot scale trials, but there is still no commercial production of ethanol from wood. In the Swedish development of wood-based ethanol, a pilot plant in Domsjö with capacity 150-200 m^3 ethanol/y has been an important tool.

3.2 Lignocellulose as sugar raw material

Starch is easy to hydrolyze into fermentable glucose via acid or enzymatic hydrolysis. Wood cellulose is more difficult to depolymerise into fermentable sugar than starch, due to the high crystallinity of the cellulose and the presence of hemicelluloses and lignin in wood, hindering the access to the cellulose. A pretreatment step is needed to make the cellulose more accessible for hydrolysis and to remove lignin. Often, hemicelluloses are separated as well in the pretreatment. The pretreated cellulose (with or without hemicelluloses) is thereafter hydrolysed into monomeric sugars with weak acid or enzymes.

The hemicelluloses are usually separated and bioconversed separately. An alternative is to ferment the mixture of hydrolysed cellulose and hemicellulose. Hemicelluloses have an amorphous structure that makes them easily hydrolysable by dilute acid or base. The resulting sugars are both hexoses (mannose, galactose), which are easy to ferment, and pentoses (xylose, arabinose), for which there is no yeast in large-scale commercial use today. Softwood has the advantage of having hemicellulose that mainly consists of hexose sugars (mainly galactoglucomannan). Hardwood hemicellulose is mainly made up of pentose sugars (primarily arabinoxylan). Most research on making ethanol from hemicelluloses has been performed on xylan, since this type of hemicellulose is common in many agro residuals.

The pretreatment and hydrolysis steps may involve hemicellulose degradation products like acetic acid, furfural and hydroxymethylfurfural (HMF) that inhibit fermentation. Phenolics and other lignin degradation products can also interfere.

3.3 Pretreatment methods

A suitable pretreatment method is probably the key to bioconversion of different forest residue assortments, since these materials usually have an even less advantageous chemical composition than stemwood.

The most used pretreatment agents for selective fractionation of hemicelluloses in lignocellulose material are, so far, acids (sulphuric acid or sulphur dioxide) or water (liquid or steam). Supercritical water or CO_2 are efficient but less tested pretreatment agents (Kim and Hong 2001; Gu 2013). Alkaline agents or organic solvents can also be used, but dissolve lignin as well. Ionic liquids enable good dissolution and separation of wood components (Kilpeläinen 2007; Gírio et al 2010; Leu et al 2013), but are expensive today.

4 Desired properties of wood assortments for bioconversion

The following properties would be desirable for a wood assortment to be used as raw material for production of ethanol or other products through biochemical processing:

Biochemical processability

- Low content of extractives
  Extractives may contain substances that inhibit fermentation.
- Low content of lignin
  Decomposed lignin contains substances that inhibit fermentation.
- High hexose/pentose ratio
  Hexose sugars are more easily fermented than pentose sugars. This means that softwood has an advantage over hardwood.

Other processability properties

- Low inorganic (ash) content.
  Metal ions and other inorganic substances need to be taken care of before liquid residual streams can be released to a water recipient, see section 4.1. They also tend to accumulate inside the process and cause problems with precipitation of salts.

Costs for collection, transport and handling

- Large amounts per forest area available.
  The cost for collection, transport and handling of forest biomass is a function of how spread out the material is in the forest land. The distance to the ethanol plant is also important for the transport cost. The biomass needs to be available in enough amounts at a maximum distance from the ethanol plant. The minimum size for a commercial ethanol plant is considered to be 30 000 – 60 000 m^3 ethanol/y. The most probable size for a plant to be built in Sweden is 100 000-150 000 m^3/y (Sekab 2013).
- High bulk density

  A low bulk density of the biomass means poor transport efficiency. The bulk density of e.g. branches and tops can be increased by compaction.
- Possible to harvest/collect efficiently

  Logistics economy might demand that the biomass should be possible to collect at the same time as thinning or logging.

4.1 Inorganic content − ash components

The natural content of ash components in wood consists mainly of Ca, K, Si, Mg, Na, Al and Fe. In addition, the material can be contaminated with ash components during handling. When using wood as raw material for bioconversion, most of the ash content will be separated in the pretreatment step. If the pretreatment involves separation of hemicellulose from cellulose, the ash will mainly follow the hemicellulose stream.

For biochemical conversion systems (like fermentation or anaerobic digestion), the impact of the amount and composition of the ash on such processes is not fully clarified. It has been proved, though, that specific inorganic substances in biomass may lead to fermentation inhibition (depending on the tolerance of the microorganism and the dry matter loading during fermentation). (Biomass Energy 2014)

Ash will anyhow cause a waste stream that needs to be treated or disposed of. From environmental and sustainability points of view, residual water streams containing metal ions should not be discharged to water recipients. Ash material can be returned to the forest, but separating the salts from water streams through e.g. evaporation is expensive.

When used directly as biofuel, biomass should preferably have low ash content, since ash decreases the heat value and causes incineration problems.

5 Available wood assortments

5.1 Situation today

Spruce dominates the logging with 52%, followed by pine (33%) and hardwoods (15%), mainly birch. (Riksskogstaxeringen 2012).

The extraction of wood in Sweden amounts to ca 92 Mm^3s wood, *Table 1*. As much as possible of the stemwood is used for sawn timber, being the product with highest added value.

Table 1. Delivery of wood in Sweden 2012 (Skogsstyrelsen 2013).

Wood assortment	**Mm^3s**	**Mt_{DS}**
Sawlogs	35.8	14.3
Pulp/fibre wood and tree parts (including branches and tops)	40.9	16.3
Pulp chips (from sawmills)	9.7	3.9
Sawdust, bark and biofuel	6.1	2.4
Sum	**92.3**	**37.0**

m^3s = cubic metre solid volume
t_{DS} = ton dry solids

34% of the logged wood was felled in thinning, i.e. as small trees. (Riksskogstaxeringen 2012). The larger the tree has grown, the bigger is its stemwood percentage, *Figure 1*.

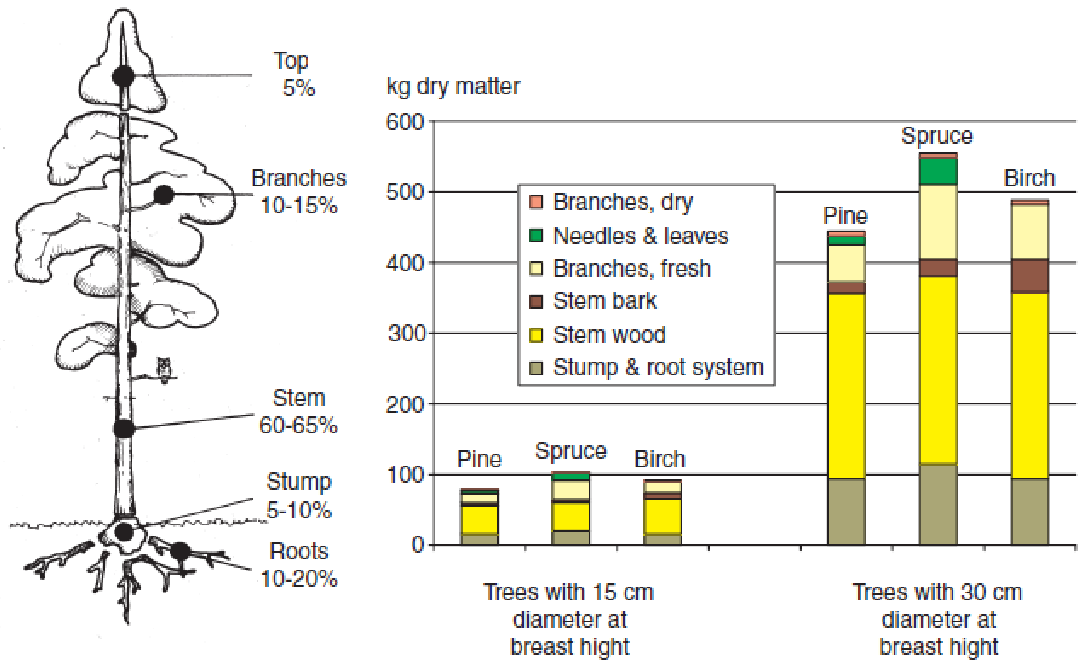


Figure 1 Distribution of "wood assortments" in small and large trees. (Hagström 2006)

Stemwood from final felling has a too high value as sawn timber or pulpwood to be used as raw material for chemicals. That leaves the following assortments, to a large extent used as biofuel today:

Assortments from forestry:

- Thinnings (young trees)
- Branches and tops
- Stumps and roots
- Needles/leaves
- Damaged wood (rot, insects)

Post-treatment possibilities:

- Compaction
- Crushing
- Chipping

Fractionation possibilities:

- Gravimetric separation (cyklone)
- Sieving

Generally, parts of the logging residues from final fellings are recovered in southern and central Sweden. Ca 3 Mt of fuelwood is extracted directly from the forest in Sweden per year, *Table 2*. Branches and tops from final fellings constitute the largest fuelwood assortment today.

Table 2 Extraction of fuelwood directly from the forest in Sweden 2010 (Bergström 2013b).

Assortment	**Mt_{DS}/y**	**TWh/y**
Branches and tops from final fellings	1,67	8,9
Fuelwood (e.g. rejected pulpwood)	0,98	5,2
Thin trees (e.g. clearing before thinning)	0,49	2,6
Stumps from final fellings	0,11	0,6
Sum	**3,24**	**17,3**

Substantial amounts of the biomass from the felled trees are, however, left in the forest, Only small fractions of the branches, tops, stumps and roots are recovered, *Figure 3.*

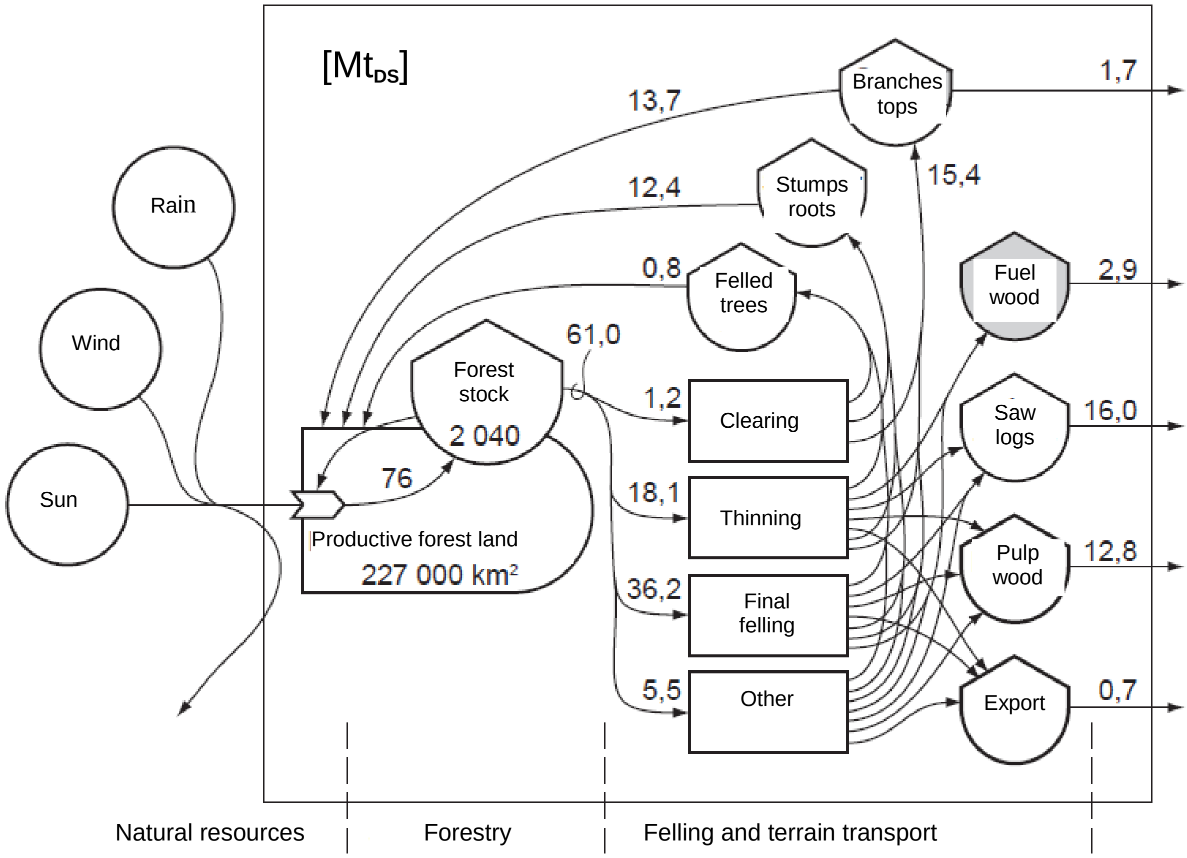


Figure 3 Biomass flows in Swedish forestry 2004 (Nilsson 2006).

5.2 Future forest biomass potential

Stumps from final felling and small roundwood from thinnings might have the potential to be as cost-effective as logging residues. (Eriksson and Gustavsson 2008).

There is a large span in the estimations of the future forest biomass (“biofuel”) potential, *Table 3* and *Figure 4.* One reason for the large span is different opinions regarding what is technically and ecologically possible. The most cautios estimation comes from Skogsindustrierna, the trade and employers’ organisation for the pulp, paper and woodworking industries (Thuresson 2010).

The future extraction potential is discussed more closely for each wood assortment type in the following chapters.

Table 3 Forest biofuel potential in Sweden, according to different sources.

Source	Estimated biofuel potential	
	Mt_{DS}/y	TWh/y
Thuresson 2010	9	49
Hagström 2006	14	75
Skogforsk 2012	16	85
Matisons 2012; Räisenen and Athanassiadis 2012	22	117

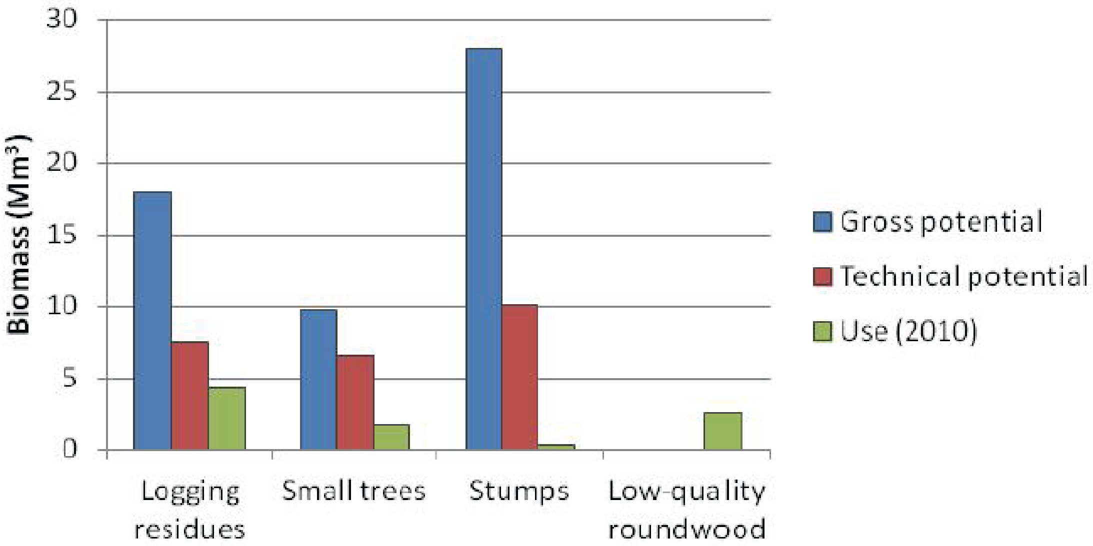


Figure 4 Forest biomass potential (Mm^3/year) in Sweden 2010 (Matisons 2012; Räisenen and Athanassiadis 2012)

5.3 Ash content of wood parts

As discussed in Chapter 4.1, it is desirable to have a low content of inorganics (ash) in biomass to be used for bioconversion. Typical ash content of different tree parts is compiled in *Table 4*. "Fuel grade" wood parts, especially bark, generally have higher ash content than stemwood. The high amounts measured in pine stumps with roots is probably due to the fact that pine roots reach deep down to soil layers with much gravel (Nordström et al 2012).

Table 4 Typical ash content in different softwood tree parts.

	Ash content, % on dry weight					
Reference	**Stem-wood**	**Branches and tops**	**Stumps without roots**	**Stumps with roots**	**Bark**	**Needles**
Natural content						
Lehtikangas (1999)	0,4-0,7	1.0-1.9			2.6-3.2	2.4-5.1
Rehn (2006)	0.36	2.1			3.1	
Including contamination						
Biofuel Impex (2013)	< 1	2-6			3	
Bioenergihandboken (2013)	1	1.5				
Stora Enso (2013)	0,7-1	2-3		3-7		
Lehtikangas (1999)	1	1-2			4	5
Hägg (2008). Before storage	0.6	2.7			4.0	4.2
Hägg (2008). After outdoor storage	0.4-0.9	1.1-4.1			4.5-5.6	3.8-5.3
Strömberg (2008)	0.6	2.7	1.5	8.2		
(Nordström et al 2012). Spruce				5		
(Nordström et al 2012). Pine				16		

5.4 The wood market

A wood assortment for bioconversion probably needs to be available at a cost that is lower than that of saw timber or pulpwood, see *Table 5*. The price pattern today implies that a bioconversion assortment is to be found within the “branches/tops/tree-part” energy wood assortments.

Table 5 Example of prices December 2013. Based on (Skogsaktuellt 2013).
sub=solid under bark

Assortment	Price		
	SEK/MWh	SEK/m^3sub	SEK/t
Energy wood			
Branches and tops	78	166	416
Forest chips	214	457	1 141
Tree parts[1]	98	209	523
Pulpwood			
Hardwood	141	300	750
Softwood	122	260	650
Saw timber			
Spruce	230	490	1 225
Pine	295	630	1 575

1. Small-diameter trees or parts of whole trees (both stem and branches)

6 Branches and tops

6.1 Suitability for biochemical conversion

The main chemical composition of branch wood (with bark) is exemplified in *Table 6* for three important tree species. The composition can vary considerably, especially with the size of the branches; the smaller the branches, the larger the bark share. The amount of hydrolysable carbohydrates is somewhat lower than in stem wood. The extractives content is significantly higher, due to the relatively high bark content in branches. The lower lignin content compared with stem wood is also a result of the high bark share in the material. Branches without bark, on the other hand, have higher lignin contents than stem wood, due to the high share of juvenile wood in branches (Leu et al 2013).

The natural ash content is more than twice that of stem wood, Table 4, and increased further by contamination with sand and gravel in the handling. The main contributor to the increased natural ash level ought to be bark, since most of the needles fall off during storing.

On a whole, branches and tops have a less favourable chemical composition for biochemical conversion than stem wood. If the bark could be separated, the debarked material would probably be a good wood material for biochemical conversion. There is currently no commercially available practical solution for this, though.

Table 6 Typical contents of main components in branches (including bark) for pine, spruce and birch. Comparison with stemwood. (Räisänen and Athanassiadis 2013)

	Cellulose (%)	**Hemicellulose (%)**	**Lignin (%)**	**Extractives (%)**
Pine *(Pinus sylvestris)*				
Branches	32	32	21	17
Stemwood	41	27	27	5
Spruce *(Picea abies)*				
Branches	29	30	23	16
Stemwood	42	28	27	2
Birch *(Betula pendula/pubescens)*				
Branches	33	23	21	13
Stemwood	44	29	20	4

6.2 Collection, transport and handling

The collection of branches and tops is fairly economic due to the large amounts, and the fact that they are harvested at the same time as the main logging. The low bulk density means that it is often advantageous with roadside chipping of the material before transport.

6.3 Potential amounts

The harvestable dry mass of branches and tops corresponds to 20-30 % of the trunk mass for pine and as much as 40-60% for spruce (Eriksson and Gustavsson 2008). In 2004, 15.4 Mt DS branches and tops were harvested altogether in final felling, clearing and thinning (Nilsson 2006). The major part of this was left in or returned to the forest. Only 1.9 Mt was recovered for fuel purpose 2011 (Skogsstyrelsen 2013).

Ca 80 % of the potentially available branches and tops would be harvested in final felling. *Table 7* summarizes the use today and some estimations of the future potential.

Table 7 Branches and tops from final felling. Use today and estimated potential

Branches and tops from final felling	**Mt DS/y**	**TWh/y**
Use today (Bergström 2013b)	1.7	8.9
Use today (Matisons 2012)	1.3	7.1
Technical potential (Matisons 2012)	2.5	13
Technical potential (Hagström 2006)	7.6	44

7 Thinnings

Thinning of a forest is the selective removal of trees, primarily undertaken to improve the growth rate or health of the remaining trees. Trees harvested in thinnings are younger than final-felled wood and of smaller size; a diameter below 10 cm (Skogforsk 2009). Spruce is usually thinned at a height of 12-15 m and pine at 10-13 m, but there is a large variation (Agestam 2009).

The lower diameter limit for using the trees as pulpwood is normally around 5 cm (breast height, with bark). If the thinning is made before that, the wood is used as fuel. Small roundwood from thinnings has the potential to be as cost-effective as logging residues. (Eriksson and Gustavsson 2008)

7.1 Suitability for biochemical conversion

The chemical composition of wood from very early thinning ought to be close to that of branches and tops. The later the thinning, the closer to stem wood will the composition be. The ash content tends to be higher in young trees since they are harvested in a fast growth phase. (Zethræus 2011)

Removal of branches from the thinned wood should decrease the content of lignin and bark (as is the case with full-grown trees). This is supported by the fact that a removal of branches decreases the ash content and the heat value of the material down to the level of ordinary stemwood (Örberg 2004).

7.2 Collection, transport and handling

A comparison has been made of taking out either pulpwood or energy wood – or a combined assortment – at the first thinning (Wide 2011). In all cases, a clearing was first made, leaving the cleared biomass in the forest. With the price structure today, it is generally more economical to thin early, with small dimensions (<0.03 m^3sub per tree), for fuelwood than to thin later, with larger dimensions, for pulpwood. One reason is that, in the fuelwood case, more of the biomass is taken care of. A mean size of >0.05 m^3sub is needed for pulpwood extraction to be worthwhile. The breakpoint in the study was a price relation fuelwood/pulpwood of 0.75.

A combined extraction of two assortments has the drawback today of separate, and therefore more expensive, transports to road. A combined extraction may still be economically interesting though, if the total extracted volume per area is large enough. In the referred study, the limit was ca 30 m^3sub/ha in total. Each assortment should be at least 10m^3sub (15 m^3s)/ha for getting an acceptable transport cost to road.

One way of extracting more biomass per ha, thereby possibly enabling more than one assortment, is discussed by Bergström (2013). Modified felling/compaction/transport technique could make earlier thinning (without preceding pre-commercial thinning, PCT) more attractive. If pulpwood is not the main product aimed at, the first thinning could be made very early. This would enable non-selective "geometric" harvesting without preceding clearing or PCT. More biomass could be harvested with such technique.

The greater biomass extraction per ha might make it economically interesting to transport the biomass unsorted – after compaction – to a terminal or mill. There, suitable operations (debranching, debarking, fractionation) and sorting could be performed efficiently on a large scale.

7.3 A possible supply chain for a "bioconversion assortment"

The possible future thinning logistics outlined in Section 7.2 could enable a "bioconversion assortment" as the main thinning product. This would generate a new supply chain. The supply chains with the thinning methods used today are described schematically in Figures 5-7. In early thinning, selected trees are felled and become fuelwood, *Figure 5*.

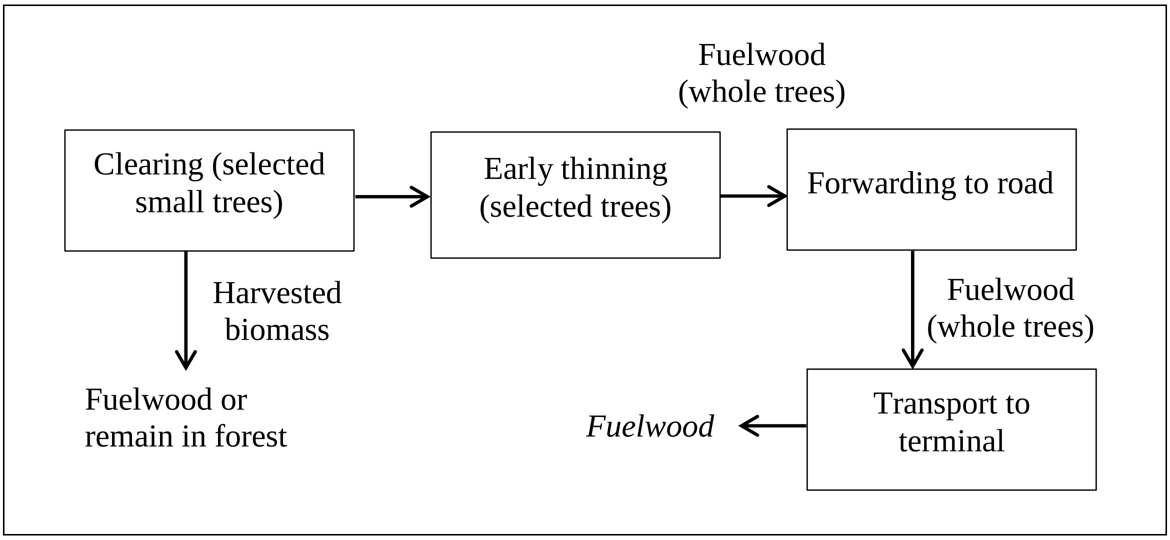


Figure 5 Thinning method 1 used today: Early thinning for fuelwood.

Later thinning means larger trees where the stems can be used as pulpwood. Selected trees are felled and debranched in an integrated operation and the branches are usually left in the forest, *Figure 6*.

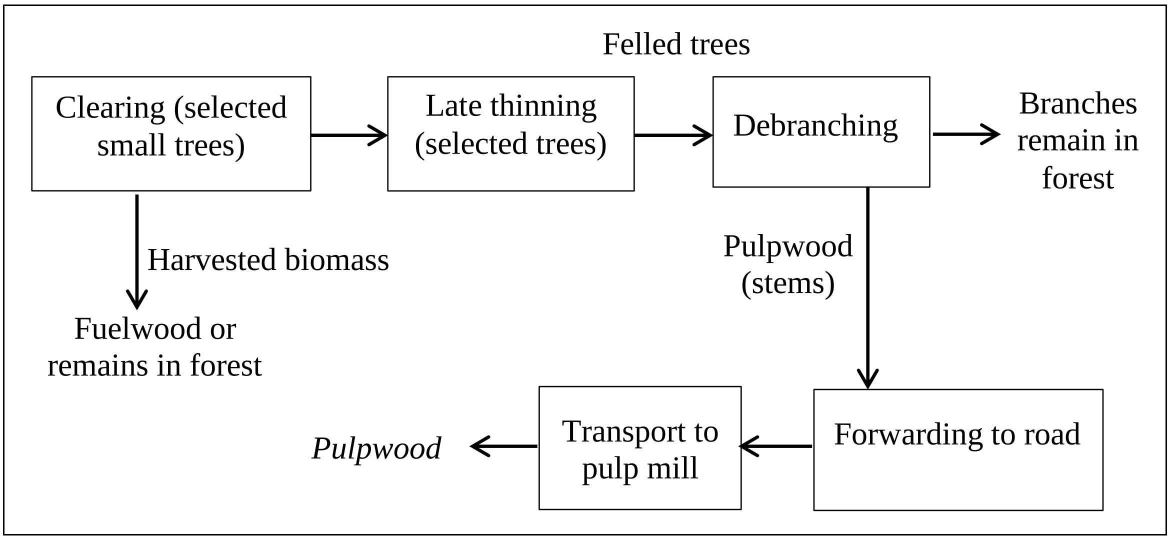


Figure 6. Thinning method 2 used today: Late thinning for pulpwood.

A combined outtake of selected pulpwood and fuelwood, *Figure 7*, is seldom economically attractive with the methods used today (Wide 2011).

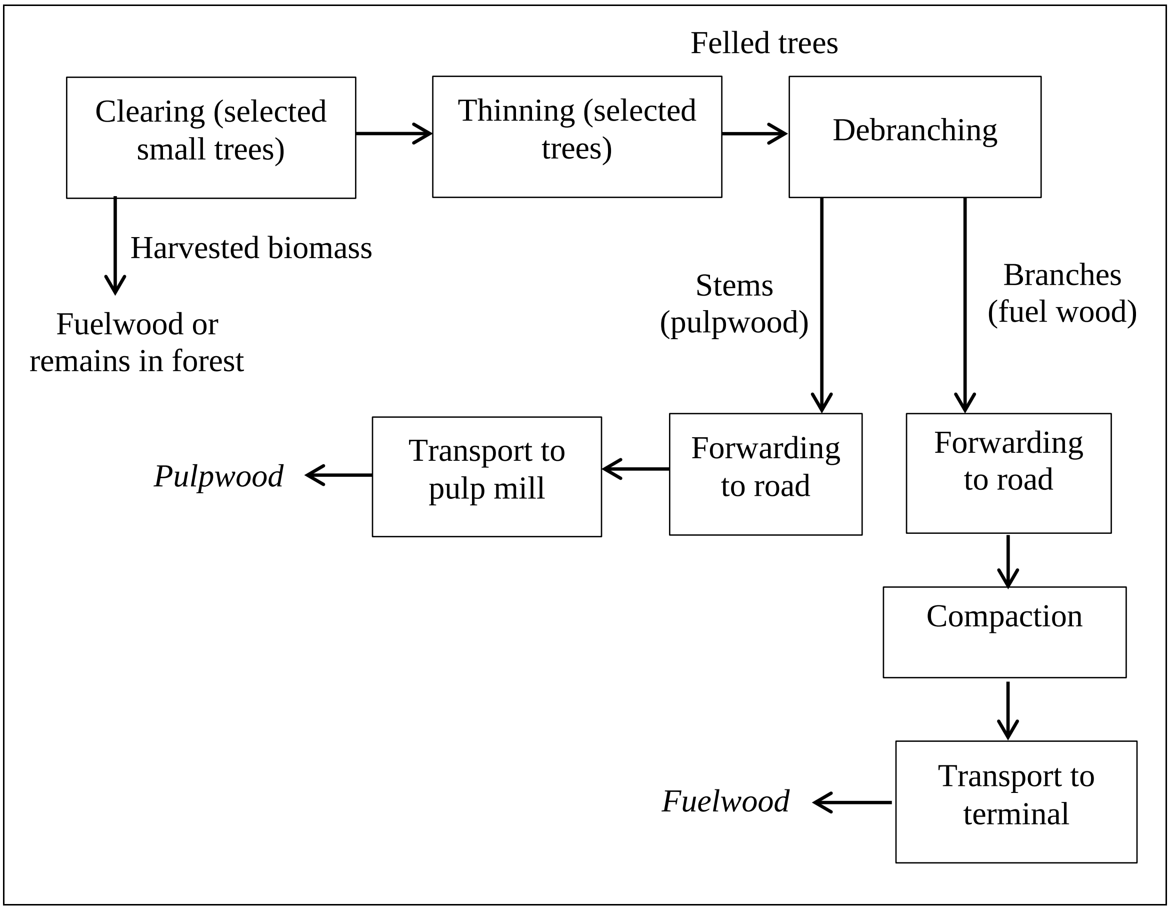


Figure 7 Thinning method 3 used today: Combined thinning for pulpwood and fuelwood.

A possible thinning route for a “bioconversion assortment” is visualised in *Figure 8*. An early non-selective thinning is made without preceding clearing. All material is transported unsorted and compacted to a terminal or pulp mill. There, the stems are debranched and maybe also debarked, giving a “bioconversion assortment” while the residual material becomes biofuel.

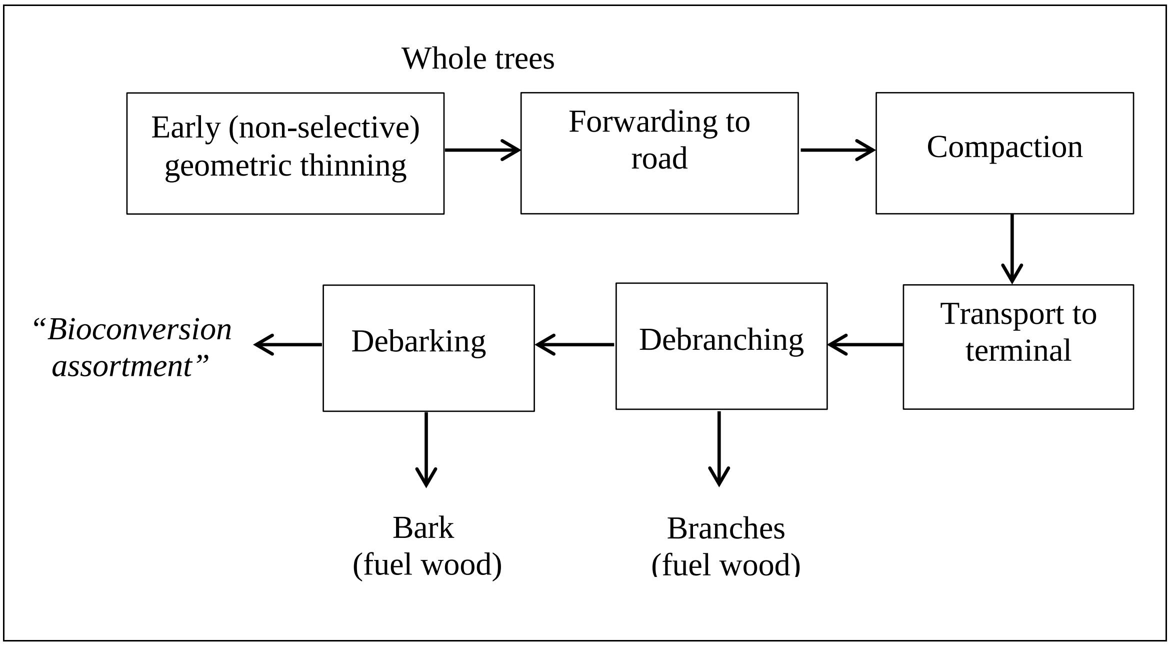


Figure 8 Future possibility: Early thinning for a "bioconversion assortment".

7.4 Potential amounts

Young forests with thin wood make up ca 12% of the forest area. They contain ca 150 Mt_{DS} biomass. 32 Mm^3, corresponding to 34% of the logged wood in Sweden, was felled in thinning, i.e. as small trees, 2011 (Riksskogstaxeringen 2012). Apart from pulpwood, these thinnings resulted in 2.6 TWh forest fuel (Bergström 2013b).

As described in Sections 7.2 and 7.3 and Figure 8, the outtake could be increased if pre-commercial thinning (PCT) is omitted and modified felling/compaction/transport technique is applied. This would enable larger extracted volumes per ha and sorting at terminal or industry, meaning better economy for production of several assortments. The theoretical annual harvesting potential in the first thinning is ca 3.8 Mt (20 TWh)/y in Sweden, *Table 8*. About half of this could be harvested per year profitably with such modified technique (Bergström 2013b).

Table 8 The use today of thinnings and some estimations of the future potential.

Thin trees from thinning	**Mt_{DS}/y**	**TWh/y**
Total use today, pulpwood + fuel (Riksskogstaxeringen 2012)	12.8	68.3
Use today, fuel (Bergström 2013b)	0.5	2.6
Use today, fuel (Matisons 2012)	0.8	4.3
Technical potential, fuel (Bergström 2013b)	1.9	10
Technical potential, fuel (Matisons 2012)	2.8	15
Technical potential, fuel (Hagström 2006)	2.1	12

7.5 Conclusions

Very thin trees – preferably stripped from branches and bark – might be an attractive raw material for bioconversion. If pulpwood is not the main product aimed at, the first thinning could be made very early. Modified felling/compaction/transport technique could make earlier thinning (without preceding pre-commercial thinning, PCT) more interesting (Bergström 2013). This would permit larger volumes per ha, enabling processing and sorting at terminal or industry, meaning better economy for production of several assortments.

8 Stumps and roots

The stump is the lowest part of the tree above the ground. Often, though, the underground part − the roots − are included in the definition. A certain amount of stumps should be left standing in the forest due to their importance as insect habitat, contributing to the biological variety

8.1 Suitability for biochemical conversion

The chemical composition of stumps and roots is exemplified in *Table 9* for three important tree species. The amount of data behind is, however, smaller than in the corresponding figures for other tree parts (in tables 6, 11 and 12).

Table 9 Typical contents of main chemical components in stumps (including bark) and roots for pine, spruce and birch. Comparison with stemwood without bark. (Räisänen and Athanassiadis 2013)

	Cellulose (%)	**Hemicelluloses (%)**	**Lignin (%)**	**Extractives (%)**
Pine *(Pinus sylvestris)*				
Stump	36	28	19	19
Roots	29	19	30	13
Stemwood	41	27	27	5
Spruce *(Picea abies)*				
Stump	43	28	29	4
Roots	29	19	25	16
Stemwood	42	28	27	2
Birch *(Betula pendula/pubescens)*				
Stump	30	19	13	5
Roots	26	17	27	13
Stemwood	44	29	20	4

The difference in composition of *stump wood* (with bark, without roots) compared to stemwood is probably mainly due to the bark content. Unbarked spruce stumps seem to differ rather little in composition compared with spruce stemwood.

Compared with branches with bark, stumps with bark have a more favourable chemical composition. The reason is probably mainly the smaller percentage of bark. The ash content is on the same level as in branches, Table 4.

The chemical composition of *roots* depends on their size, but does not seem to be more favourable than the composition of branches.

Stumps with roots can have very high ash content since the underground parts entrain large amounts of sand and gravel, Table 4. Pine roots entrain more of this material than spruce roots. The reason is probably that pine roots reach deeper down to soil layers with much gravel, while spruce roots are much shallower. (Nordström et al 2012)

A way to decrease the amount of adhered gravel is to let the (chunked) roots be stored while washed by rain for about a year.

If the data in Table 9 are representative, stumps, especially from spruce, without roots might be an interesting assortment for biochemical conversion, even more so after debarking. In addition, softwood hemicellulose mainly consists of hexose sugars which ought to be easily fermented together with the glucose from cellulose (Fengel et al 1989, Stambuk et al 2008).

8.2 Collection, transport and handling

Stumps has the potential to be as cost-effective as logging residues. (Eriksson and Gustavsson 2008)

If at all collected, stumps are today harvested after final felling through clear-cutting. After thinning, there is a too large risk for damage on the remaining trees. Spruce-dominated forests are considered most interesting since the spruce root system make spruce stumps easier to recover compared with other species. Pine stumps could also be harvested, but are more time-consuming to excavate. (Hedman 2008)

8.3 Potential amounts

The harvestable dry mass of stump and root is 23-25% of the trunk mass for spruce and pine (Eriksson and Gustavsson 2008). Ca 28 Mm^3/y of stumps are produced at logging. Out of this, ca 10 Mm^3/y is technically available (Matisons 2012), *Table 10*. Only a very small fraction of this, 0.6 TWh, is taken care of today (Bergström 2013b).

Table 10 The use today of stumps and roots and some estimations of the future potential.

Stumps with roots	**Mt DS/y**	**TWh/y**
Use today (Bergström 2013b)	0.1	0.6
Use today (Matisons 2012)	0.5	2.6
Use today (Thuresson 2011)	0.06	0.3
Technical potential (Matisons 2012)	4.8	26
Technical potential (Svebio 2008)	3.8	20

8.4 Conclusions

Tree stumps constitute a large unused biomass reserve that could be a suitable raw material for biochemical conversion. Removal of small root parts and debarking would improve the material further. Compared with pine stumps, spruce stumps are easier to harvest and have a better chemical composition.

9 Bark

Bark from harvested trees is to a large extent used as biofuel at pulp mills or in other large-scale incinerators.

9.1 Suitability for biochemical conversion

The main chemical composition of bark is exemplified in *Table 11* for three important tree species. Bark contains very high amounts of extractives while the amount of hydrolysable carbohydrates is low. In addition, the natural ash content is high compared to other tree parts, Table 4.

To conclude, the chemical composition of bark makes it less suited for biochemical conversion.

Table 11 Typical contents of main components in bark from pine, spruce and birch. Comparison with stemwood. (Räisänen and Athanassiadis 2013)

	Cellulose (%)	Hemicelluloses (%)	Lignin (%)	Extractives (%)
Pine *(Pinus sylvestris)*				
Bark	22	8	13	25
Stemwood	41	27	27	5
Spruce *(Picea abies)*				
Bark	27	9	12	32
Stemwood	42	28	27	2
Birch *(Betula pendula/pubescens)*				
Bark	11	11	15	26
Stemwood	44	29	20	4

10 Needles and leaves

10.1 Suitability for biochemical conversion

The chemical composition of needles or leaves is exemplified in *Table 12* for three important tree species. Needles and leaves contain very high amounts of extractives and are probably the tree parts that are the least suitable for biochemical conversion.

Table 12 Typical contents of main components in needles/leaves for pine, spruce and birch. Comparison with stemwood without bark. (Räisänen and Athanassiadis 2013)

	Cellulose (%)	**Hemicelluloses (%)**	**Lignin (%)**	**Extractives (%)**
Pine *(Pinus sylvestris)*				
Needles	29	25	7	40
Stemwood	41	27	27	5
Spruce *(Picea abies)*				
Needles	28	25	8	43
Stemwood	42	28	27	2
Birch *(Betula pendula/pubescens)*				
Leaves	N.D	N.D	11	33
Stemwood	44	29	20	4

10.2 Potential amounts

Spruce trees carry relatively more needles than pine trees. A full-grown spruce consists of ca 7 weight-% needles. In hardwood trees, the corresponding mass of leaves is considerably smaller.

11 Sawdust

Sawdust from saw mills is mainly used in particleboard and biofuel pellets. Coarse sawdust may also be used as pulpwood.

11.1 Suitability for biochemical conversion

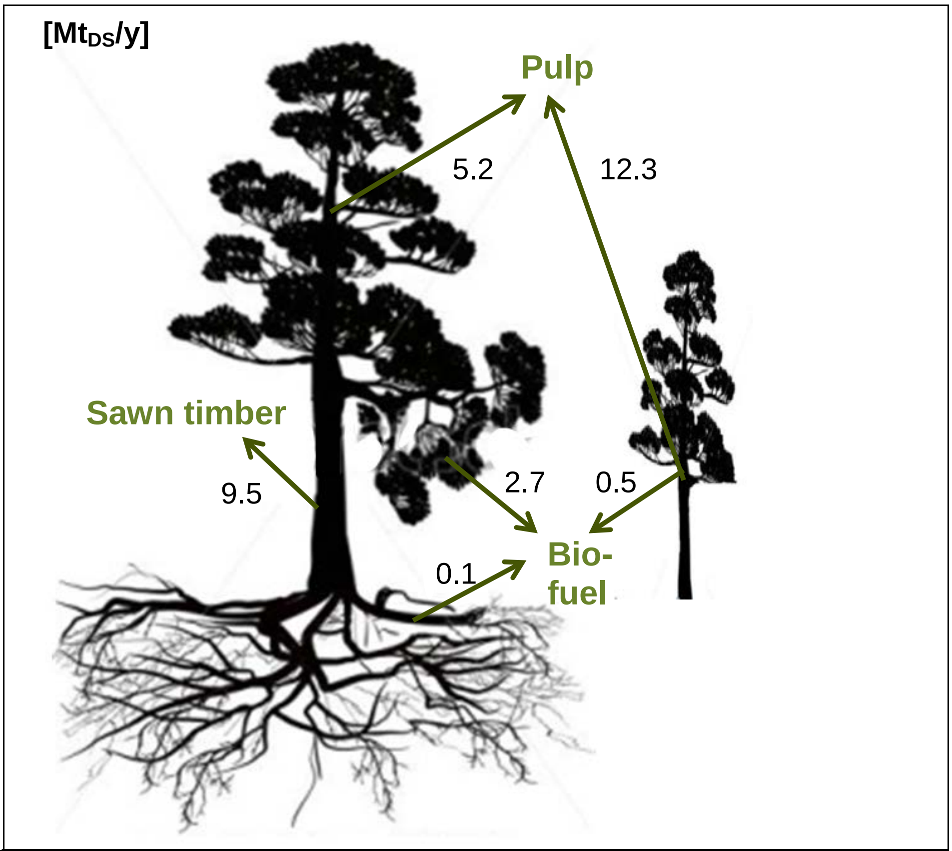
Sawdust basically consists of stem wood and is consequently a good wood byproduct for biochemical conversion.

11.2 Potential amounts

Ca 1.6 Mt_{DS} of sawdust are produced annually at saw mills (Hagström 2006). It would probably not be attractive to use this material for biochemical conversion, though, since its value is rather high as raw material for particle board or pulp.

12 A future scenario

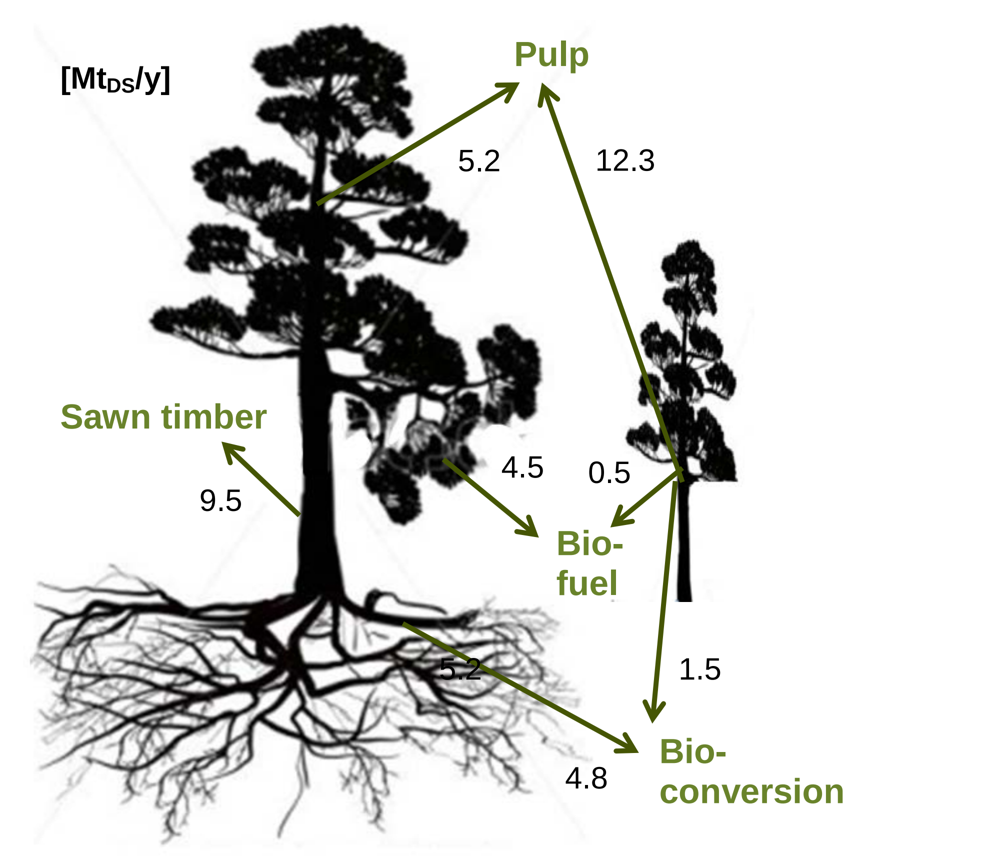
The use of harvested wood (except bark) in Sweden is summarised roughly in *Figure 9*. Young trees from thinning are mainly used as pulpwood. A small percentage is harvested early as fuelwood. Stemwood from final felling is primarily used as sawn timber. Low-quality stemwood parts and sawdust are mainly used as pulpwood. Branches and tops constitute the largest biofuel assortment. Only a few percent of the technically available stumps and roots is utilized, and then as fuel.



[Mt_{DS}/y]	Sawn timber	Pulp	Biofuel	**Sum**
Stemwood	9.5	5.2		**14.7**
Thinnings		12.3	0.5	**12.8**
Branches & tops			2.7	**2.7**
Stumps & roots			0.1	**0.1**
Sum	**9.5**	**17.5**	**3.3**	**30.3**

Figure 9. Use of wood (bark excluded) today in Sweden, roughly divided between wood assortments. Approximate flows based on (Riksskogstaxeringen 2012; Skogsindustrierna 2012; Bergström 2013b)

A possible future scenario is outlined in *Figure 10*. It is assumed that more efficient harvesting/transport/sorting technique will make it possible to increase the outtake of thinnings as well as branches & tops. It is also assumed that a substantial part of the stumps & roots produced in final felling will be utilized.



[Mt$_{DS}$/y]	Sawn timber	Pulp	Bio-conversion	Biofuel	**Sum**
Stemwood	9.5	5.2			**14.7**
Thinnings		12.3	1.5	0.5	**14.3**
Branches & tops				4.5	**4.5**
Stumps & roots			4.8		**4.8**
Sum	**9.5**	**17.5**	**6.3**	**5.0**	**38.3**

Figure 10. Estimated possible future use of wood (bark excluded) in Sweden, roughly divided between wood assortments. Approximate flows based on (Riksskogstaxeringen 2012; Skogsindustrierna 2012; Bergström 2013b)

The 4.8 Mt stumps and roots could, together with the extra outtake of 1.5 Mt thinnings, be suitable raw material for bioconversion. These 6.3 Mt of biomass could theoretically be used for an ethanol production of ca 12 TWh/y. This corresponds to 13 % of all transport fuel used 2012 in Sweden; 90.1 TWh (Energimyndigheten 2013).

13 Conclusions

- Tree stumps, especially without bark and small roots, might be an interesting raw material for biochemical conversion. The potential in Sweden is up to 5 Mt/year (including roots and bark). Spruce stumps are easier to harvest than pine stumps.
- Debranched, and – preferably –debarked, small-diameter (early thinning-size) trees might be another interesting assortment for biochemical conversion. The Swedish potential is ca 2 Mt/year (including branches and bark)
- Development of an efficient bark separation process would be an important contribution to improving the suitability of fuel-grade assortments to a bioconversion assortment
- Modified felling and transport techniques in thinning operations could enable economically feasible production of more specified assortments from thinning.
- For further investigation of the potential of these more specified assortments, pretreatments and bioconversion should be tested and comparison made with stemwood and today´s forest fuel grade. The test could comprise:
    - Spruce stumps
    - Debarked spruce stumps
    - Debarked spruce stumps without small root parts
    - Very thin trees (without needles or leaves)
    - Very thin trees without branches
    - Very thin trees without branches and bark

14 References

Agestam E (2009)
Gallring
Skogsskötselserien nr 7, Skogsstyrelsen

Bergström D (2013a)
Developing biomass supply systems for young thinnings
New Products from Forest Seminar, Kokkola, Finland 2013-05-14

Bergström D (2013b)
Utveckling av system för skörd av biomassa i unga täta gallringsbestånd
BioFuel Regions 10-årsjubileum, Umeå 2013-09-20

Bioenergihandboken (2013)
www.novator.se/bioenergy/facts/fuelinvest.pdf

Biofuel Impex (2013)
www.biofuelimpex.se

Biomass Energy (2014)
Significant biomass properties - Ash content
http://www.biomassenergy.gr/en/articles/technology/biomass/315-significant-biomass-properties-part-2-ash-content

Egnell G et al (2007)
Miljökonsekvenser av stubbskörd – en sammanställning av kunskap och kunskapsbehov
Energimyndigheten Rapport ER 2007:40

Eriksson L N, Gustavsson L (2008)
Biofuels from stumps and small roundwood – Cost and CO2 benefits
Biomass and Bioenergy 32(2008)897-902

Fengel D (Ed.) (1989)
Wood: chemistry, ultrastructure, reactions
De Gruyter, Berlin 1989

Gírio F M, Fonseca C, Carvalheiro LC, Duarte L C, Marques S, Bogel-Łukasik R (2010)
Hemicelluloses for ethanol: A review
Bioresource Techn. 101(2010) 4775-4800

Gu T (2013)
Pretreatment of lignocellulosic biomass using supercritical carbon dioxide as a green solvent
In: Green biomass pretreatment for biofuels production, SpringerBriefs in Green Chemistry for Sustainability, DOI: 10.1007/978-94-007-6052-3_5,

Hagström P (2006)
Biomass potential for heat, electricity and vehicle fuel in Sweden
Doctoral thesis, SLU, Uppsala 2006

Hedman L (2008)
Produktivitet vid stubbskörd
Arbetsrapport 219, SLU, Umeå, 2008

Hägg K (2008)
Mätning av träddelar och flis på Dåvamyran, Umeå Energi
SLU, Umeå, Arbetsrapport 223, ISSN 1401-1204

Kilpeläinen I, Xie H, King A, Granstrom M, Heikkinen S, Dimitris S, Argyropoulos D S (2007)
Dissolution of Wood in Ionic Liquids
J. Agric. Food Chem. 55(2007): 9142–9148

Kim K H, Hong J (2001)
Supercritical CO2 pretreatment of lignocellulose enhances enzymatic cellulose hydrolysis
Bioresource Techn. 77(2001): 2, 139–144

Lehtikangas P (1999)
Lagringshandbok för trädbränslen
SLU, Uppsala, 1999, ISBN 91-576-5564-2

Leu S-Y, Zhu J Y, Gleisner R, Sessions J, Marrs G (2013)
Robust enzymatic saccharification of a Douglas-fir forest harvest residue by SPORL
Biomass and Bioenergy 59(2013), 393–401

Loman (2006)
Trädbränslestatistik i Sverige
Skogsstyrelsen, Förstudierapport 2006-06-05—2006-07-25

Lönner G, Danielsson, B-O, Vikinge B, Parikka M, Hektor B, Nilsson P O (1998).
Kostnader och tillgänglighet för trädbränslen på medellång sikt
Sveriges lantbruksuniversitet, Institutionen för Skog-Industri-Marknad Studier (SIMS), Uppsala, Rapport 51

Matisons M (2012)
Forest Refine – Efficient forest biomass supply chain for biorefineries
4th Nordic Wood Biorefinery Conference, Helsinki, Finland, October 23-25, 2012

Naturvårdsverket (2013)
www.naturvardsverket.se

Nilsson P O (2006)
Biomassaflöden I svensk skogsnäring 2004
Skogsvårdsstyrelsen, Rapport 23

Nordström M, Hannrup B, Anerud E, Johannesson T, von Hofsten H, Eliasson L (2012)
Validering av funktioner för beräkning av kvantitet skogsbränsle vid stubbskörd – En pilotstudie
Arbetsrapport Från Skogforsk nr. 780-2012

Rehn C (2006)
Basic studies on the characterization, pelletising and pellet combustion of spruce woody fuel
SLU, Umeå, Acta Universitatis Agriculturae Suecicae, Doctoral thesis No 2006:83, Faculty of forest science. ISSN: 1652-6880.

Riksskogstaxeringen (2012)
http://www.slu.se/riksskogstaxeringen

Räisänen T, Athanassiadis D (2012)
Available potentials of forest biomass for biorefineries
Forest Refine Seminar, Umeå 2012-10-01

Räisänen T, Athanassiadis D (2013)
Basic chemical composition of the biomass components of pine, spruce and birch,
Forest refine project, Info sheet 1.2, www.biofuelregion.se

Sekab (2013)
www.sekab.se/bioraffinaderi/framtiden/

Skogforsk (2012)
www.skogforsk.se/kunskapdirekt/skogsbransle/energi-fran-skog

Skogforsk (2009)
www.skogforsk.se/kunskapdirekt/skogsbransle/klentrad

Skogsaktuellt (2013)
www.skogsaktuellt.se/marknad

Skogsindustrierna (2012)
Skogsindustrin. En faktasamling. 2012 års branschstatistik
www.skogsindustrierna.org

Skogsstyrelsen (2013)
Skogsstatistisk årsbok 2013
www.skogsstyrelsen.se

Stambuk B U, Eleutherio E C A, Florez-Pardo L M, Souto-Maior A M, Bon E P S (2008)
Brazilian potential for biomass ethanol: Challenge of using hexose and pentose co-fermenting yeast strains
J. Scient. Ind. Res 67(2008)918-926

Stora Enso (2013)
www.storaenso.com/wood-forest/stora-enso-skog/stora-enso-bioenergi/vara-produkter/

Strömberg B (2008)
Stubbar som bränsle
TPS Branschforskningsprogram för Energiverk 2007/08 – Slutrapport inom området Oberoende FoU
TPS Termiska Processer AB, Box 624, 611 10 Nyköping

Svebio (2008)
Potentialen för Bioenergi
Rapport, 2008-08-31

Thuresson T (2010)
Bioenergi från skog. Uppdaterad bedömning av potentialer och förutsättningar för svenskt skogsbruk att producera främst primära skogsbränslen - Vintern 2009/2010
Konsultrapport till Skogsindustrierna

Wide M I (2011)
Var går gränsen? Massaved och/eller energiuttag i klen gallring
Resultat från SkogForsk Nr 9, 2011

Zethræus B (2011)
Vad innebär nya bränslefraktioner?
Seminarium om bioenergi från skogen ur ett kretsloppsperspektiv 2011-09-12

Örberg H (2004)
Värmevärde och askhalt hos gallringsvirke
Info nr 39 från projektet "Bioenergi från skogsprodukter", SLU, Uppsala 2004

Appendix 1: Unit conversions

When specific data was missing, the following unit conversions have been used :

- Density of wood (solid volume excluding bark):
  50 % moisture: 0.80 ton/m³ corresponding to 0.40 t_{DS}/m^3
- Heat value of wood: 5.3 TWh/Mt_{DS}

15 Innventia Database information

Title

Wood assortments suitable for chemical production

Author

Birgit Backlund

Abstract

The goal of this study was to assess the suitability of possible future (“fuel grade”) wood assortments for hydrolysis and biochemical conversion to e.g. ethanol. The market for ethanol is large, due to the increasing demand for biobased motor fuels. Other interesting products are lactic acid, butanol and succinic acid. Wood is an attractive ethanol raw material from a sustainability point of view since forestry generally does not compete with food production. Substantial amounts of the biomass from felled trees are, however, left in the forest today. Only small fractions of the branches, tops, stumps and roots are recovered. In order to get good biochemical processability, the wood assortment should have low contents of extractives and lignin and a high hexose/pentose ratio. Low ash content is desirable from a wastewater handling point of view. For efficient logistics, the material should be available in large amounts per forest area and be easy to harvest and collect, preferably at the same time as thinning or logging. A high bulk density decreases the transport cost. The price pattern today implies that a bioconversion assortment is to be found within the “fuelwood” assortments. The wood materials that crystallised as most promising future bioconversion assortments were 1) stumps and roots and 2) non-selective early thinnings. Tree stumps, especially from spruce, and preferably without bark and small roots, might be an interesting raw material for biochemical conversion with a potential of up to 5 Mt/year. Debranched, and – preferably –debarked, small-diameter (early thinning-size) trees is another possible assortment for biochemical conversion. The potential is ca 2 Mt/year.

Keywords

Bioconversion, biomass, ethanol, forest product, logging residue, root, stump, thinning, wood, wood properties, wood waste

Classification

1131, 1290

Type of publication

Innventia Report

Report number

490

Publication year

March 2014

Language

English

INNVENTIA AB is a world leader in research and development relating to pulp, paper, graphic media, packaging and biorefining. Our unique ability to translate research into innovative products and processes generates enhanced value for our industry partners. We call our approach *boosting business with science.* Innventia is based in Stockholm, Bäckhammar and in Norway and the U.K. through our subsidiaries PFI and Edge respectively.

INNVENTIA AB
Drottning Kristinas väg 61, BOX 5604
SE-114 86 Stockholm Sweden

Tel +46 8 676 7000
Fax +46 8 411 55 18
VATno 556603110901

info@innventia.com
www.innventia.com

INNVENTIA