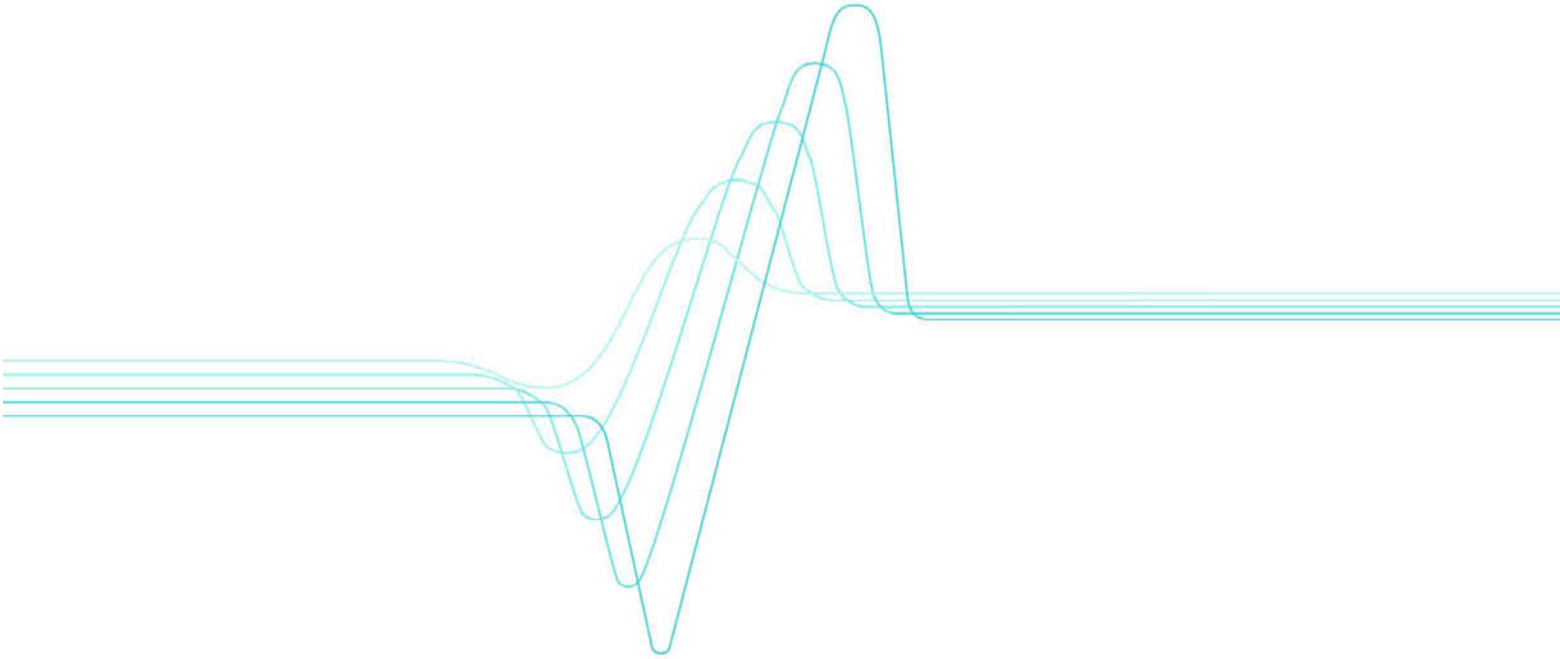
ESPOO 2005 VTT RESEARCH NOTES 2312

Paterson McKeough, Yrjö Solantausta,
Hilkka Kyllönen, Andre Faaij,
Carlo Hamelinck, Martijn Wagener,
David Beckman & Björn Kjellström

Techno-economic analysis of biotrade chains

Upgraded biofuels from Russia and Canada to the Netherlands



VTT TIEDOTTEITA – RESEARCH NOTES 2312

Techno-economic analysis of biotrade chains

Upgraded biofuels from Russia and Canada to the Netherlands

Paterson McKeough, Yrjö Solantausta & Hilkka Kyllönen
VTT Processes, Finland

Andre Faaij & Carlo Hamelinck
Utrecht University, the Netherlands

Martijn Wagener
Essent Energie, the Netherlands

David Beckman
Zeton Inc., Canada

Björn Kjellström
Luleå University of Technology, Sweden

ISBN 951–38–6745–5 (soft back ed.)
ISSN 1235–0605 (soft back ed.)

ISBN 951–38–6746–3 (URL: http://www.vtt.fi/inf/pdf/)
ISSN 1455–0865 (URL: http://www.vtt.fi/inf/pdf/)

JULKAISIJA – UTGIVARE – PUBLISHER

VTT, Vuorimiehentie 5, PL 2000, 02044 VTT
puh. vaihde 020 722 111, faksi 020 722 4374

VTT, Bergsmansvägen 5, PB 2000, 02044 VTT
tel. växel 020 722 111, fax 020 722 4374

VTT Technical Research Centre of Finland, Vuorimiehentie 5, P.O.Box 2000, FI–02044 VTT, Finland
phone internat. +358 20 722 111, fax +358 20 722 4374

VTT Prosessit, Biologinkuja 3–5, PL 1601, 02044 VTT
puh. vaihde 020 722 111, faksi 020 722 7048

VTT Processer, Biologgränden 3–5, PB 1601, 02044 VTT
tel. växel 020 722 111, fax 020 722 7048

VTT Processes, Biologinkuja 3–5, P.O.Box 1601, FI–02044 VTT, Finland
phone internat. +358 20 722 111, fax +358 20 722 7048

Technical editing Anni Kääriäinen

Otamedia Oy, Espoo 2005

McKeough, Paterson, Solantausta, Yrjö, Kyllönen, Hilkka, Faaij, Andre, Hamelinck, Carlo, Wagener, Martijn, Beckman, David & Kjellström, Björn. Techno-economic analysis of biotrade chains. Upgraded biofuels from Russia and Canada to the Netherlands. Espoo 2005. VTT Tiedotteita – Research Notes 2312. 40 p. + app. 25 p.

Keywords biofuels, upgrading, fuel trade, pyrolysis oils, pellets, techno-economy assessment, trade chains, Russia, Netherlands, Canada

Abstract

This study consisted of in-depth techno-economic analyses of biofuel upgrading processes and of whole biotrade chains. The chains encompassed the production of pyrolysis oil or pellets from biomass residues in the source regions, the transportation of the upgraded fuels internationally over long distances and the final utilisation of the fuels. The techno-economic analysis of the biofuel upgrading processes was undertaken primarily to generate techno-economic data that were needed as input data for the assessment of the biotrade chains. The evaluation of pyrolysis-oil production was deemed to be one of the most reliable assessments made to date. The estimated pyrolysis-oil production costs, e.g. below 25 EUR/MWh for stand-alone production from forestry residues, compare favourably with the current consumer-prices of heavy fuel oil in many European countries. Integration of the pyrolysis process with an industrial combined heat and power (CHP) plant would lower the production costs by more than 20%. The production of pellets was assessed to be somewhat more energy-efficient and more cost-efficient than the production of pyrolysis oil. However, the higher production costs of pyrolysis oil would be counteracted by lower costs in connection with product handling and utilisation.

Four international biotrade chains were analysed in detail. The chains cover two source regions, North-Western Russia and Eastern Canada, and two traded commodities, pyrolysis oil and pellets. The chains terminate in the Netherlands where the imported biofuels are co-fired with coal in condensing power stations. The costs of the delivered biofuels were estimated to be in the range 18–30 EUR/MWh, with the costs of pellets about 25% lower than those of pyrolysis oil. The estimated electricity-generation costs displayed little dependence on the type of biofuel – pyrolysis oil or pellets – because the costs associated with the utilisation of the biofuels for co-firing are higher for the pellets. For the Canada-Netherlands chains based on zero-cost sawmilling residues, the costs of the delivered biofuels were estimated to be about 20% lower, and the electricity-generation costs about 10% lower, than those of the Russia-Netherlands chains. With the electricity consumption calculated as the equivalent amount of fuel that would be needed for its generation, the energy consumptions of the biotrade chains,

prior to the end-use of the biofuels, were estimated to be in the range 13–23% of the energy content of the original biomass residues.

Local-utilisation alternatives were also evaluated. It was concluded that, particularly when the local reference energy system is carbon intensive, local utilisation can be a more cost-efficient and a more resource-efficient option than international trade and use of biomass resources elsewhere. This type of comparison is, however, very dependent on both the greenhouse-gas emission intensities and the costs of the reference energy systems in the exporting and importing regions. In practice, there are many factors which may limit local utilisation or make utilisation of biomass resources elsewhere more attractive. Obviously, when increased local utilisation is not feasible, exporting surplus biofuel is a highly beneficial and fully justified option. Other drivers for international bio-energy trade, such as improving access to markets, developing biomass production potentials over time and securing stable supply and demand, fuel supply security and other issues were not part of the present work programme. Overall, it was concluded that biotrade will have a definite and important role to play in reducing humankind’s dependency on fossil fuels.

Preface

This report covers a large part of the work carried out in the International Energy Agency (IEA) Bioenergy Task 35, Techno-Economic Assessments for Bioenergy Applications. The specific objectives of Task 35 were

- to carry out techno-economic case studies related to production of heat, power, combined heat and power, cooling and refrigeration, fuels and/or chemicals from biomass in each participating country using standardised procedures

- to identify opportunities for biomass conversion processes, if bioenergy is used as a commodity in international trade in reducing the CO_2 emissions.

Countries participating in the task were Austria, Canada, Finland, the Netherlands, Sweden and the USA. The authors wish to acknowledge the financial support of the respective governmental funding agencies in the participating countries. Finland was the country coordinating the Task and Task Leader was Yrjö Solantausta from VTT Processes, VTT Technical Research Centre of Finland. Paterson McKeough from the same institute was the leading researcher in the biotrade chain analyses presented in this report. The other working group members were Erich Podesser and Henrike Bayer (Joanneum Research, Austria), David Beckman (Zeton Inc., Canada), Hilkka Kyllönen (VTT Processes, Finland), Andre Faaij and Carlo Hamelinck (Utrecht University, The Netherlands), Martijn Wagener and Rob Remmers (Essent Energie, The Netherlands), Björn Kjellström (Luleå University of Technology, Sweden) and Ralph Overend (National Renewable Energy Laboratory, USA).

Contents

1. Introduction

This report covers the main part of the work carried out in the IEA Bioenergy Task 35, Techno-Economic Assessments for Bioenergy Applications. This work was carried out during 2002 and 2003. The objectives of the Task were to carry out techno-economic studies of selected bioenergy utilisation routes. Certain regional and intercontinental biotrade schemes were evaluated in detail. The performances and costs of the biotrade chains were compared to those of local utilisation options in the source regions. The biotrade chains that were evaluated in detail are summarised in Table 1.

Table 1. Summary of evaluated biotrade chains.

Export region	**Feedstock**	**Traded commodity**	**Importing country**	**End-use**
North-Western Russia	Forestry residues	Pyrolysis oil	The Netherlands	Co-firing in coal-fired power station
North-Western Russia	Forestry residues	Pellets	The Netherlands	Co-firing in coal-fired power station
Eastern Canada	Sawmilling residues	Pyrolysis oil	The Netherlands	Co-firing in coal-fired power station
Eastern Canada	Sawmilling residues	Pellets	The Netherlands	Co-firing in coal-fired power station

The chains evaluated in detail were considered to be very relevant to the countries participating in the task. The Netherlands has implemented programs to promote increased utilisation of biofuels for electricity production and imported biofuels are making, and will make, a major contribution. Essent Energie, the largest producer of sustainable energy in the Netherlands, actively participated in this Task. The other countries that took part in the Task – Austria, Canada, Finland, Sweden, and the USA – are all potential exporters of biofuels, in spite of significant extents of domestic utilisation in all cases.

2. Techno-economic assessment of production of pyrolysis oil and pellets

2.1 Background

During the course of the Task, there emerged a need for additional techno-economic analyses of the conversion of forestry residues to either pyrolysis oil or pellets. In the first place, information about the effects of integration of the conversion technology with a combined heat and power plant (CHP) was required. It was expected that integration would reduce costs significantly. Integration was also considered a way to render the production of export biofuel more socio-economically acceptable.

Further analysis was also required in respect of the drying operation. Both pyrolysis-oil and pellets production incorporate drying of the feedstock material down to around 10% moisture. In general, a significant part of the production costs can be attributed to the drying step. In the previous IEA study /1/, steam drying was indicated to be a very promising option in cases where the heat recoverable from the output vapour stream of the dryer can be utilised for district-heating purposes. However, the previous analysis considered an ideal case, where heat is cascaded down to the lower district-heat level without loss, so that the district-heat output matches the heat consumption in the drying operation. In practice, a part of the drying heat is not recoverable. The main alternative to steam drying is drying with hot gases. Although primary energy is often used in this case, utilisation of low-level or waste heat is possible when it is available. For example, if the conversion plant is integrated with a CHP boiler, the final flue gases of the boiler may contain sufficient residual heat for the drying operation. Utilisation of low-level heat was not considered in the earlier IEA analysis /1/. Thus there emerged a need for a thorough comparison of steam drying with hot-gas drying in both stand-alone and integrated conversion plants.

The effect of feedstock quality on the production costs of pyrolysis oil was the third topic of the techno-economic analysis. Virtually all of the earlier assessments had focused on production of pyrolysis oil from feedstocks derived from stemwood. In recent years, forestry residues have emerged as the most likely future feedstocks for widespread production of pyrolysis oil or pellets. VTT has undertaken pioneering experimental research on the pyrolysis of forestry residues /2/. Both the yield and quality of the oil product differ measurably from those obtained in earlier experiments with stemwood. For certain of the biotrade chains, analysed later in Chapter 3, the feedstock for pyrolysis-oil and pellets production is comprised of forestry residues. Thus, new techno-economic data for pyrolysis-oil production from forestry residues needed to be generated. Note that, for other chains of Chapter 3, the feedstock consists of bark-dominated sawmilling residues, for which specific experimental data are not available. The basis of the mass and energy balances for pyrolysis of this feed material is discussed in Chapter 3. This feedstock has not been included in the techno-economic analysis of this chapter.

2.2 Description of evaluated processes and cases

Descriptions and flow sheets of stand-alone pyrolysis-oil plants are available, for example, in earlier IEA reports /1, 3/ while those of pelletisation plants are provided in Appendix 4. The main operations of the plants are listed in Table 2. The feedstock received to the plant is in the form of chips. In the full chain analysis, presented later in Chapter 3, all the operations from forest to plant are included. In the pyrolysis plant, the heat for drying and pyrolysis is obtained from combustion of pyrolysis co-products, char and gas. In the pelletisation plant, the heat for drying is obtained from combustion of additional feedstock.

Table 2. The main operations of the conversion plants.

Pyrolysis plant	**Pelletisation plant**
Drying	Drying
Grinding	Grinding
Fuel feeding	Fuel feeding
Pyrolysis	Pellets pressing
Oil condensation	Pellets cooling
Combustion (heat for drying, pyrolysis)	Combustion (heat for drying)
Gas handling	Gas handling
Feedstock and product storage	Feedstock and product storage

In addition to the two conversion alternatives (pyrolysis oil vs. pellets), the main variables explored in the present techno-economic analysis were

- integration with a CHP plant: integrated vs. non-integrated
- dryer type: flue-gas dryer vs. steam dryer
- feedstock type: forestry residues vs. wood wastes derived predominantly from stemwood.

Two types of CHP plant were considered when evaluating integrated conversion plants: (1) an industrial CHP plant and (2) a district-heating CHP plant. From the point of view of this analysis, the major difference between these two cases is the number of operating hours per annum. The industrial plant is assumed to operate for 7800 h/a, whereas the district-heating plant for only 5000 h/a (effective operating time at full capacity). In the case of the district-heating plant, two plant sizes were considered: (1) large plant with at least 100 MW of heat output and (2) medium-sized plant with 30 MW of heat output. In the case of the pyrolysis conversion plant, the pyrolysis reactor is very closely coupled to the CHP boiler according to the ITP method developed by VTT /4/. One consequence of this coupling is that the boiler furnace serves as the combustor for the pyrolysis process. The other operation which, for both conversion processes, benefits greatly from the integration is the drying operation.

According to the earlier IEA study /1/, steam drying is a very promising drying option in cases where the heat recoverable from the output vapour stream of the dryer can be utilised for district-heating purposes. As already discussed above, the need had emerged for a more detailed comparison of steam drying with hot-gas drying, particularly when low-level or waste heat is available in the latter case. In the present analysis, hot-gas drying is based on the utilisation of hot or warm flue-gases. In the case of integrated plants, a significant part, even all, of the drying heat can be provided by the residual waste heat of the final flue gases of the CHP boiler.

The feedstock comparison was made to determine the impact of resulting differences in pyrolysis-oil yields and qualities on process performance and economics. In addition to these differences, the cost of wastes derived from stemwood is likely to differ from that of forestry residues. This possible cost difference was not taken into account in the comparison.

2.3 Bases of the techno-economic analysis

For the assessment of pyrolysis-oil production, a confidential detailed plant design and cost estimate, compiled by an equipment supplier for a Finnish company, was used as the basis for equipment sizing and costing. The original data were adjusted for the present cases without revealing the details of the original study. It should be noted that few, if any, of the previously published techno-economic assessments of pyrolysis-oil production have been based on estimates compiled by equipment manufacturers. For this reason, the present results can be considered to be among the most reliable estimates to date. The pyrolysis mass and energy balances were obtained from experiments on VTT’s PDU facility (20 kg/h feed) /2/. Various feedstocks have been successfully tested on this facility and a total of about 30 tons of pyrolysis oil has been produced.

For the assessment of pellets production, the same approach as in the previous IEA study /1/ was used. As evident from Table 2, many operations in the pelletisation plant are technically the same as, or very similar to, those in the pyrolysis plant. For the pelletisation plant, the cost of such a common operation was estimated from the cost of the corresponding operation of the pyrolysis plant, taking into account possible differences in capacity. For the few operations specific to the pelletisation plant, e.g. the pellets presses, cost data were obtained from the previous study /1/ and from generic data available in the biotrade chain data base of Utrecht University /5, 6/.

The assumed moisture contents and heating values of the feedstocks are given in Table 3. The same values were applied for both forestry residues and wastes derived from stemwood.

Table 3. Moisture contents and heating values of the feedstocks.

HHV of dry feedstock	20.2 MJ/kg
Moisture content of as-received feedstock	50%
LHV of as-received feedstock	8.23 MJ/kg
Moisture content of feed to pyrolysis reactor	8%
Moisture content of feed to pellets press	10%

Table 4. The pyrolysis mass and energy balances on a dry-matter basis.

	Green forestry residues		**Stemwood-derived wastes**	
Product fraction	Mass, % of dry feed	Energy, % of feed HHV	Mass, % of dry feed	Energy, % of feed HHV
Oil (dry)				
– top phase	6	9		
– bottom phase	46	53	64	76
Gas and Char	14 + 22	39	12 + 12	25
Pyrolysis water	12		12	
Total	100	101 Pyrolysis heat: 1	100	101 Pyrolysis heat: 1

The pyrolysis mass and energy balances, applied in this analysis, are summarised in Table 4. These are primarily based on results of VTT's PDU experiments /2/. Note that the quality of the forestry residues depends on the collection and handling methods, as well as on the forest type. The assumed collection and handling method comprises bundling of green residues, transportation of the bundles to the plant and short-term storage of the bundles at the plant. The material is chipped just prior to processing, yielding what are called green forestry-residue chips. The forestry residues are assumed to be predominantly derived from spruce trees.

Note that a two-phase oil product is formed from the forestry-residue feedstock. This was first observed in the experiments at VTT /2/. In earlier studies of the flash pyrolysis of woody feedstocks, single-phase products had been observed – presumably due to predominance of feed material derived from stemwood. The pyrolysis oils, as produced, contain a significant amount of water derived from both the pyrolysis water (formed in the reaction) and the water introduced into the reactor with the moist feedstock. The moisture contents and heating values of the oil products, as applied in this study, are provided in Table 5. These values are consistent with the data in Tables 3 and 4.

Table 5. The moisture contents and heating values of the product oil phases.

	Green forestry residues		**Stemwood-derived wastes**	
Product fraction	Moisture	LHV	Moisture	LHV
Oil (including H_2O)				
– top phase	12.2%	24.8 MJ/kg		
– bottom phase	30.2%	14.5 MJ/kg	24.4%	16.4 MJ/kg

Key input data and bases used for calculating production costs are presented in Table 6. For all bases except plant capacity, the bases presented in Tables 3–6 are the same as those used in the full chain analysis, presented later in Chapter 3. For example, the feedstock cost is that obtained in the full chain analysis by adding together the costs of the individual operations involved in the collecting and the delivering of forestry residue chips to the plant. This estimated cost is consistent with the current market price in Finland.

Table 6. Key bases of the estimates of production costs.

Conversion plant capacity	
– feedstock dry matter to conversion reactor	2.67 kg/s
Feedstock and energy costs	
– feedstock	8.2 EUR/MWh (LHV basis)
– electricity	35 EUR/MWh
– district heat (sales)	15 EUR/MWh
Labour	
– requirements	
– stand-alone plant	8 persons
– integrated plant	2 persons
– costs, including payroll overheads	50 EUR/manhour
Cost factors	
– annual capital charges factor	0.1175 (10% interest, 20 a)
– costs for startup, interest during construction	21% of plant investment
– scale-up exponent	0.7
– maintenance, insurance, taxes	4% of total investment
Operational time (equivalent at full capacity)	
– stand-alone plant	7800 h/a
– plant integrated with industrial CHP plant	7800 h/a
– plant integrated with district-heating CHP plant	5000 h/a

2.4 Results and discussion

The estimated performances and costs of various alternatives for producing pyrolysis oil from forestry residues are summarised in Table 7. Selected results are also presented graphically in Figures 1 and 2. In the case of stand-alone production, it was found that the energy provided through combustion of the pyrolysis co-products, gas and char, exceeded that required for drying and pyrolysis. Two separate cases were considered: (1) excess energy not utilised and (2) excess energy used for district heating for 5000 h/a. Note that the steam dryer is an economically viable alternative only when there is a demand for district heat.

The beneficial effect of integration on the efficiency of oil production is evident from the results of Table 7 and Figure 1. A commendable efficiency of about 68% for the stand-alone plant increases to high values of 81–91% through integration with a CHP plant. The highest efficiency of 91% is attained when the heat output of the CHP plant exceeds about 100 MW. In this case, and when about 30 MW of pyrolysis oil is produced, there is sufficient residual waste heat in the final flue gases of the CHP boiler to dry all the feedstock for the pyrolysis conversion plant. For the medium-sized CHP plant (heat output 30 MW), the efficiency is measurably higher when a steam dryer, rather than a flue-gas dryer, is applied. The steam dryer can not compete economically with the flue-gas dryer for the case of integration with a large CHP plant (heat output > 100 MW) because, in that case, the flue-gas drying is based entirely on exploitation of waste heat.

Table 7. Estimated performances and costs of producing pyrolysis oil from forestry residues.

Case:	**1**	**2**	**3**	**4**	**5**	**6**	**7**
Configuration	Stand-alone, surplus energy unused	Stand-alone, district heat from surplus	Stand-alone, district heat from surplus	Integrate dwith industrial CHP, >100 MW heat	Integrate dwith district heat CHP, >100 MW heat	Integrate dwith district heat CHP, 30 MW heat	Integrate dwith district heat CHP, 30 MW heat
Dryer type	Flue-gas	Flue-gas	Steam	Flue-gas	Flue-gas	Flue-gas	Steam
Operating time, h/a	7800	7800	7800	7800	5000	5000	5000
Plant performance:							
Feedstock input, MW (LHV)	43.9	43.9	43.9	32.9	32.9	37.1	34.6
Electricity requirement, MW	1.5	1.5	2.0	1.5	1.5	1.5	2.0
District heat produced *, MW		4.1	7.7				
Oil produced							
– top phase, MW (LHV)	4.5	4.5	4.5	4.5	4.5	4.5	4.5
– bottom phase, MW (LHV)	25.5	25.5	25.5	25.5	25.5	25.5	25.5
LHV-efficiency **, %	68.3	68.3	68.3	91.2	91.2	80.9	86.8
Total investment, MEUR	11.6	11.7	14.5	10.2	10.2	10.2	10.9
Production costs, MEUR/a:							
Feedstock	2.81	2.81	2.81	2.10	1.35	1.52	1.42
Electricity	0.42	0.42	0.54	0.42	0.27	0.27	0.35
District heat (income)		-0.31	-0.58				
Labour & overhead	0.83	0.83	0.83	0.21	0.21	0.21	0.21
Maintenance, taxes, etc.	0.46	0.47	0.58	0.41	0.41	0.41	0.44
Capital costs	1.36	1.37	1.70	1.19	1.19	1.19	1.28
Total, M EUR/a	5.89	5.60	5.88	4.33	3.43	3.61	3.69
Production costs, EUR/MWh oil products	25.2	23.9	25.1	18.5	22.8	24.1	24.6

* For integrated plants, the overall heat output corresponds to that of the CHP plant prior to integration.

** Defined as: 100*(LHV-energy output of oil products)/(LHV-energy input of feedstock).

From the results of Table 7 and Figure 2, it can be concluded that integration with an industrial CHP plant leads to a significant lowering in production costs but, because of the significantly shorter annual operating time, the advantage is lost when the CHP plant is a district-heating plant. From the results in Table 7, it is also evident that there is no cost advantage for steam drying over flue-gas drying and that the size of the CHP plant does not have a major impact on costs for sizes greater than 30 MW heat output (Table 7). The estimated production costs in Table 7 and Figure 2 assume that the two oil products – top phase and bottom phase – have the same value. The main product is the bottom phase, which can be considered as a typical low-viscosity biomass-derived pyrolysis oil. Although much more viscous, the top phase has a significantly higher heating value (refer Table 5). In the worst case, the value of the top phase would be similar to that of heavy fuel oil, the price of which is currently about 20 EUR/MWh (without value-added tax) in Finland. With this value for the top phase, the production costs of the main bottom-phase product increase, at most, by about 1 EUR/MWh compared to the corresponding values in Table 7.

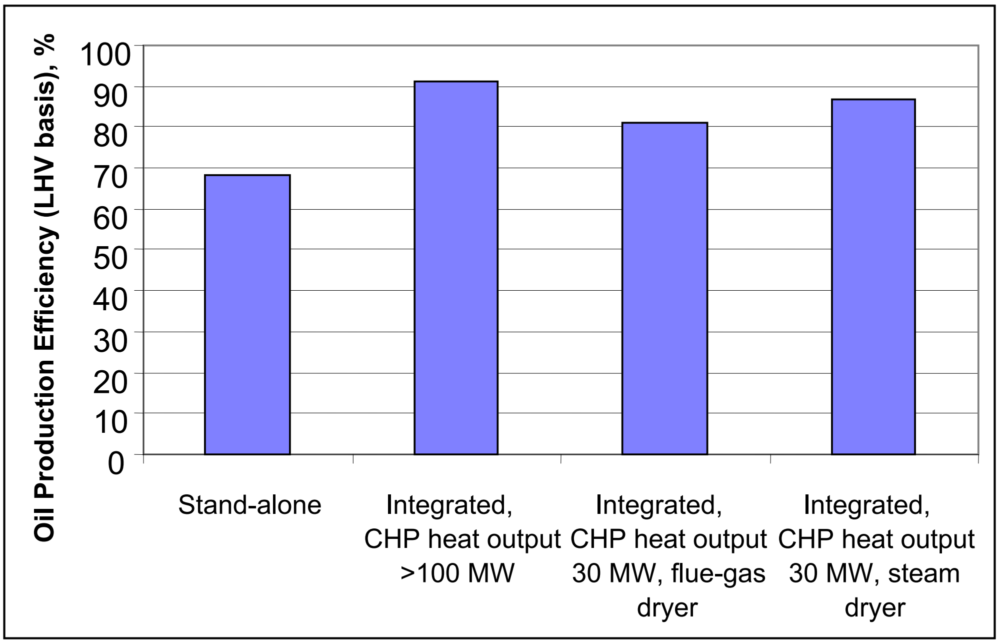


Figure 1. Estimated LHV-efficiencies of pyrolysis-oil production from forestry residues for various configurations; 30 MW (LHV) output of oil products.

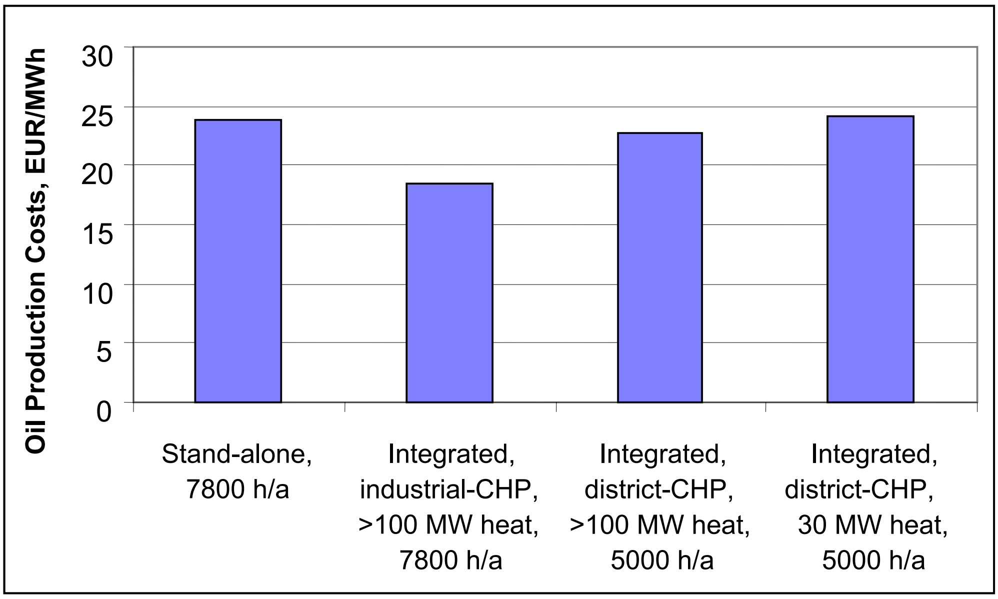


Figure 2. Estimated costs of pyrolysis-oil production from forestry residues for various configurations; flue-gas drying; 30 MW (LHV) output of oil products.

The estimated performances and costs of various alternatives for producing pyrolysis oil from wastes derived from stemwood are summarised in Table 8. In Figures 3 and 4, selected results are compared to the corresponding results for pyrolysis-oil production from forestry residues. Note that, in contrast to the forestry-residues case, the heat released through the combustion of the co-products (gas and char) of the pyrolysis of stemwood wastes does not exceed the heat requirements for drying and pyrolysis.

Table 8. Estimated performances and costs of producing pyrolysis oil from stemwood-derived wastes.

Case:	**8**	**9**	**10**	**11**	**12**
Configuration	Stand-alone	Integrated with industrial CHP, >100 MW heat	Integrated with district heat CHP, >100 MW heat	Integrated with district heat CHP, 30 MW heat	Integrated with district heat CHP, 30 MW heat
Dryer type	Flue-gas	Flue-gas	Flue-gas	Flue-gas	Steam
Operating time, h/a	7800	7800	5000	5000	5000
Plant performance:					
Feedstock input, MW (LHV)	46.8	40.1	40.1	45.0	41.8
Electricity requirement, MW	1.5	1.5	1.5	1.5	2.0
Oil produced					
– top phase, MW (LHV)					
– bottom phase, MW (LHV)	37.1	37.1	37.1	37.1	37.1
LHV-efficiency **, %	79.3	92.5	92.5	82.5	88.8
Total investment, MEUR	11.6	10.2	10.2	10.2	10.9
Production costs, MEUR/a:					
Feedstock	2.99	2.57	1.64	1.84	1.71
Electricity	0.42	0.42	0.27	0.27	0.35
Labour & overhead	0.83	0.21	0.21	0.21	0.21
Maintenance, taxes, etc.	0.46	0.41	0.41	0.41	0.44
Capital costs	1.36	1.19	1.19	1.19	1.28
Total, MEUR/a	6.07	4.79	3.72	3.92	3.99
Production costs, EUR/MWh oil product	21.0	16.6	20.1	21.1	21.5

** Defined as: 100*(LHV-energy output of oil products)/(LHV-energy input of feedstock).

As expected, the various process configurations affect the performances and costs of pyrolysis-oil production from stemwood derived wastes in ways similar to those predicted for the case of forestry residues. The higher oil yield from stemwood material leads to improvements in efficiency and reductions in costs (Figures 3 and 4). The improvement in oil production efficiency, attainable through integration, is greater for the case of forestry residues. Note that the same feedstock cost has been applied in each case.

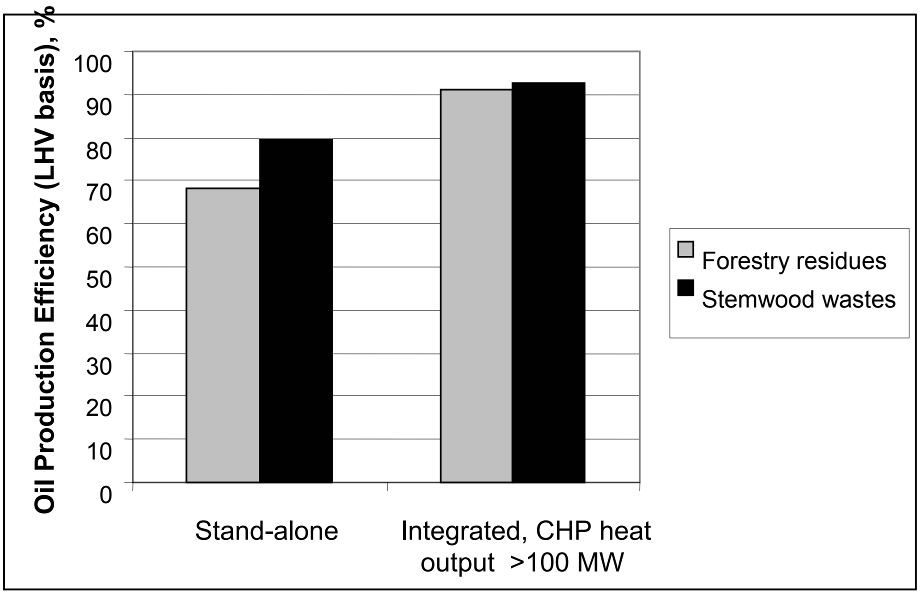


Figure 3. Comparison of estimated LHV-efficiencies of pyrolysis-oil production from forestry residues to those of pyrolysis-oil production from wastes derived from stemwood; feed-rate to pyrolyser same in both cases; oil production rates: 30 MW from forestry residues, 37.1 MW from stemwood-derived wastes; flue-gas drying.

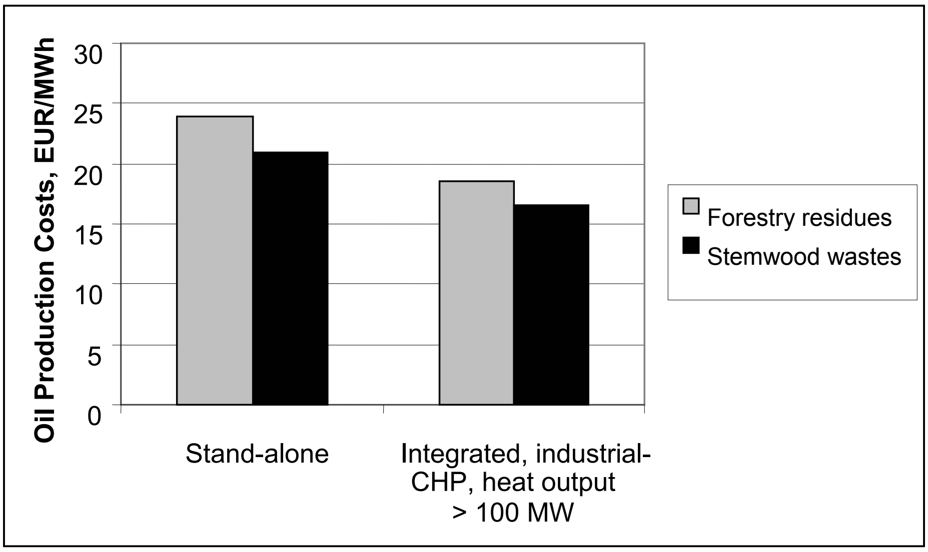


Figure 4. Comparison of estimated costs of pyrolysis-oil production from forestry residues to those of pyrolysis-oil production from wastes derived from stemwood; feed-rate to pyrolyser and cost of feedstock same in both cases; oil production rates: 30 MW from forestry residues, 37.1 MW from stemwood-derived wastes; flue-gas drying; in the case of stand-alone production from forestry residues, surplus energy utilised for district heating.

The estimated performances and costs of various alternatives for producing pellets from either forestry residues or stemwood derived wastes (at the same feedstock cost) are summarised in Table 9. Selected results are compared to the corresponding results for pyrolysis-oil production from forestry residues in Figures 5 and 6.

Table 9. Estimated performances and costs of producing pellets.

Case:	**13**	**14**	**15**	**16**	**17**	**18**
Configuration	Stand-alone	Stand-alone, drying heat to district heating	Integrated with industrial CHP, >100 MW heat	Integrated with district heat CHP, >100 MW heat	Integrated with district heat CHP, 30 MW heat	Integrated with district heat CHP, 30 MW heat
Dryer type	Flue-gas	Steam	Flue-gas	Flue-gas	Flue-gas	Steam
Operating time, h/a	7800	7800	7800	5000	5000	5000
Plant performance: Feedstock input, MW (LHV)	51.1	52.6	43.9	43.9	49.7	45.6
Electricity requirement, MW	2.4	2.8	2.4	2.4	2.4	2.8
District heat produced *, MW		5.9				
Pellets produced, MW (LHV)	49.7	49.7	49.7	49.7	49.7	49.7
LHV-efficiency **, %	97.3	94.5	113.1	113.1	100.0	108.9
Total investment, MEUR	12.1	14.0	11.2	11.2	11.2	11.9
Production costs, MEUR/a: Feedstock	3.27	3.37	2.81	1.80	2.04	1.87
Electricity	0.66	0.78	0.66	0.42	0.42	0.50
District heat (income)		–0.44				
Labour & overhead	0.83	0.83	0.21	0.21	0.21	0.21
Maintenance, taxes, etc.	0.43	0.51	0.40	0.40	0.40	0.43
Capital costs Total, MEUR/a	1.42 6.66	1.64 6.73	1.31 5.43	1.31 4.19	1.31 4.43	1.40 4.46
Production costs, EUR/MWh pellets	17.2	17.4	14.0	16.9	17.8	17.9

* For integrated plants, the overall heat output corresponds to that of the CHP plant prior to integration.

** Defined as: 100*(LHV-energy output of pellets products)/(LHV-energy input of feedstock).

The various process configurations affect the performances and costs of pellets production in ways similar to those predicted for pyrolysis-oil production. One difference is that application of steam drying lowers the pellets production efficiency of the stand-alone plant. The reason is that credit for district-heat is not included in the applied efficiency definition. The situation is actually reversed if the district-heat product is given the same weight as the pellets product. Note that energy-conversion processes incorporating efficient drying methods can exhibit LHV-efficiencies over 100% – as in the present cases of integrated pellets production.

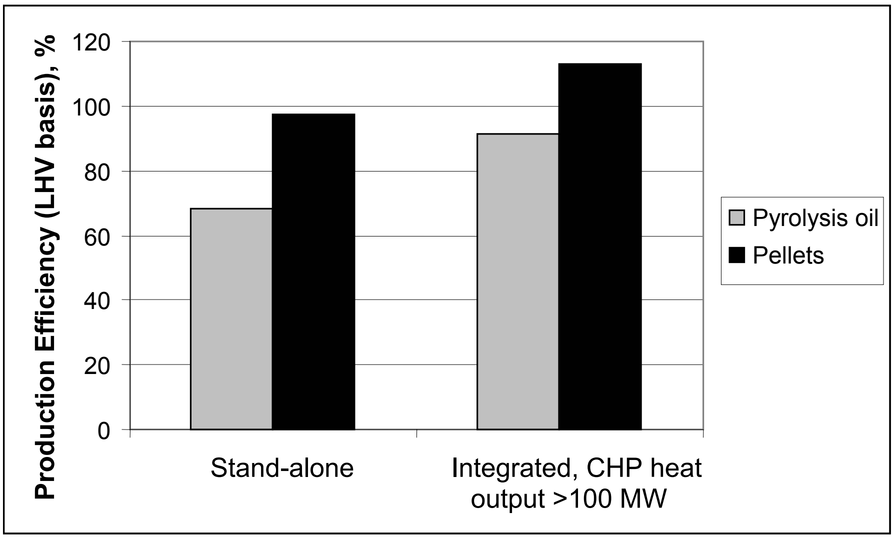


Figure 5. Comparison of estimated LHV-efficiencies of pellets production to those of pyrolysis-oil production; forestry residues; feed-rate to conversion step same in both cases; pyrolysis-oil production rate: 30 MW; pellets production rate: 49.7 MW; flue-gas drying.

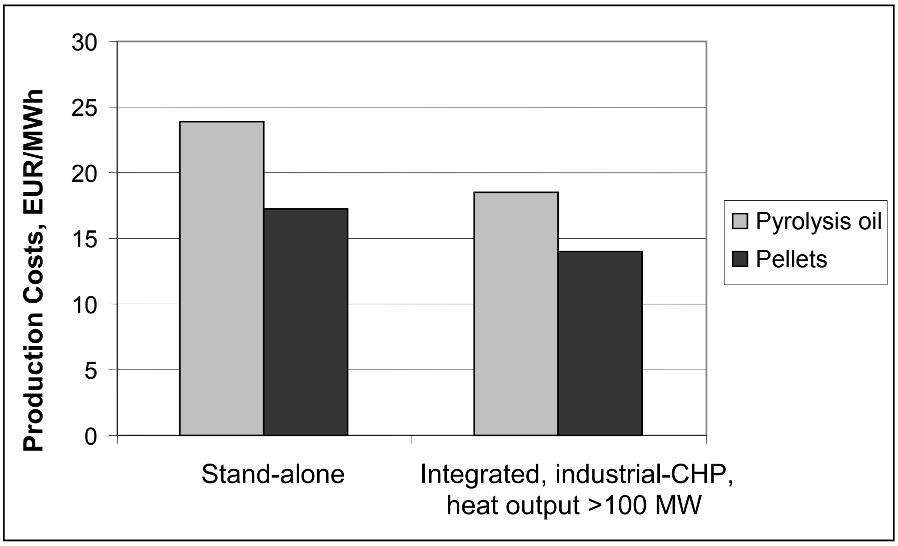


Figure 6. Comparison of estimated costs of pellets production to those of pyrolysis-oil production; forestry residues; feed-rate to conversion step same in both cases; pyrolysis-oil production rate: 30 MW; pellets production rate: 49.7 MW; flue-gas drying; in the case of stand-alone pyrolysis-oil production, surplus energy utilised for district heating.

According to the estimates in Figures 5 and 6, pellets can be produced at higher efficiencies and with lower costs than pyrolysis oil. The estimated production costs of pellets are 25%–30% lower than those of pyrolysis oil from forestry residues and 15%–20% lower than those of pyrolysis oil from stemwood derived wastes (Figures 4 and 6). However, pyrolysis oil, with its lower handling costs, is a more valuable fuel product than pellets. According to the previous IEA study /1/, the costs of transportation and handling for utilisation in small boilers in Sweden would typically be about 6 EUR/MWh higher for pellets than for pyrolysis oil. This difference corresponds to about 30% of the production costs of pyrolysis oil and so levels out the difference between the pyrolysis-oil production costs and pellets production costs. Similar conclusions are reached in the present biotrade chain analysis presented in Chapter 3, although, in that case, the transportation is over much greater distances and the fuels are co-fired with coal in large boilers. It should also be borne in mind that this analysis has assumed that pellets can be formed as readily from (dried and ground) forest residues as they can be, and are, formed from stemwood derived residues, such as sawdust. This assumption has yet to be proven. Note that, for both pyrolysis oil and pellets, substitution of light fuel oil – technically possible for both fuels in certain applications – will, in general, be more a profitable option than substitution of heavy fuel oil.

2.5 Concluding remarks

Because the present cost estimates of pyrolysis-oil production are based on a detailed plant design and cost estimate compiled by an equipment supplier, the present analysis of pyrolysis-oil production can be considered as one of the most reliable hitherto undertaken. The analysis yielded promising results. The estimated pyrolysis-oil production costs, e.g. below 25 EUR/MWh for stand-alone production from forestry residues, compare favourably with the current consumer-prices of heavy fuel oil in many European countries. Integration of the pyrolysis plant with an industrial CHP plant would lower the production costs by more than 20%. The production of pellets is assessed to be somewhat more energy-efficient and more cost-efficient than the production of pyrolysis oil. However, the higher production costs of pyrolysis oil will be counteracted by lower costs in connection with product handling and utilisation.

3. Techno-economic assessment of the biotrade chains

3.1 Conceptual approach

The methodology adopted for the techno-economic analysis of biotrade chains was that previously developed at the Department of Science, Technology and Society of Utrecht University in the Netherlands /5, 6/.

3.1.1 System outline

For structuring international supply systems four general system components are distinguished: biomass production, pretreatment, transport and energy conversion. For each system component various parameters determine its performance (Table 10) and individual cost and energy analysis can be made. A more elaborate description of the separate system components is available elsewhere /5/.

Table 10. System components, with possible options and key model variables.

System component	**Options**	**Key variables**	
Biomass production	Forestry residues Energy crops Felling Industrial rest stream Chipping Baling	Harvesting window[1)] Production costs (location dependent)	
Pretreatment	Storage Chipping Drying Pelletising	Equipment capacity Capital and O&M Energy consumption (power, fuel, heat)	Load factor[2)] Dry matter loss Moisture loss
Transport	Truck Train Ship	Transport distance Speed Capacity Product weight Product volume	Capital and O&M Fuel consumption Load factor Transfer time & costs
Energy conversion	Power Methanol Pyrolysis oil	Conversion efficiency Capital and O&M Load factor	

[1)] Section of the year in which the biomass comes available, e.g. October – March. A window can also apply on apparatus only available during part of the year.

[2)] Or: operation time, part of the time that a facility or transport means is available within its operation window.

Chain components can be selected and organised in many ways, but many aspects are interdependent, so there is a limited degree of freedom in choosing alternatives (e.g. pelletising is only possible with size-reduced biomass). In addition, some arrangements are unrealistic because of obvious disadvantages (e.g. pelletising of already transported biofuels is not advisable because the advantages of a higher energy density are only to be gained during transport).

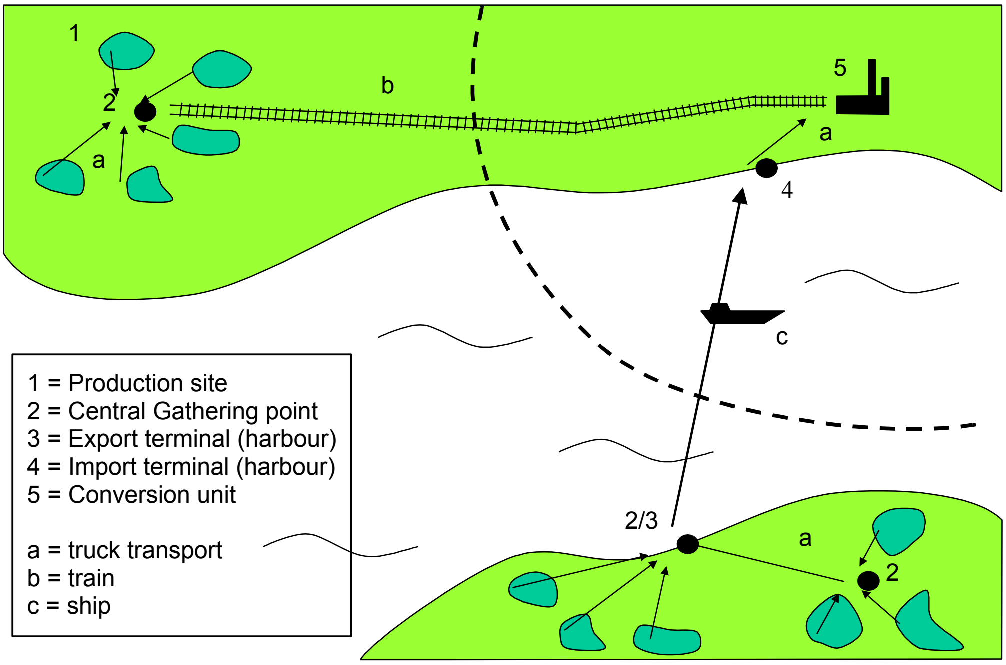


Figure 7. Geographical system outline.

Several generic logistic situations are shown in Figure 7. A situation with five possible transfer points is assumed: the production site, a central gathering point (CGP), two transport terminals (export and import) and the energy plant. In general, biomass is collected locally at smaller scale production sites and transported to a CGP. This allows for larger capacity treatment facilities, which makes the use of costs-intensive pretreatment and conversion technologies economically more attractive. Local transport to CGP, harbour or conversion facility takes place by truck (a). Long distance transport is done by train or ship (b & c).

The efficiency of the bio-energy transport can be improved when drying and/or densification are applied early in the chain. At the production site, baling or chipping can be integrated in the harvest method. At the CGP and the energy plant, the biofuels can undergo pretreatment and conversion operations, e.g. sizing, drying, densification but also the conversion of woody biomass to liquid fuels like methanol or ethanol. The biomass could also be converted to intermediate products such as pyrolysis oil, pellets or charcoal. Various techniques for energy densification like drying, methanol synthesis or pelletising, are only efficient at larger scales (at the CGP).

Capacities and throughputs of operations decrease along the chains, due to dry matter losses, drying, or conversion. As most processes have a volume-limited throughput, the influence of moisture content on their size is of minor importance.

For capital-intensive steps in the chains, an important aspect is the actual effective operation time, which is determined by Operation Window (OW) and the load factor. The OW is defined by the number of months in a year that the equipment is used for processing, e.g. feedstock supply may limit the use of a harvester to several months. If equipment or transport means are dedicated to (i.e. only suitable for) biomass processing, then the system's OW should be as wide as possible, e.g. by combining multiple biomass chains to minimise the share of capital costs. The load factor is a percentage of the time that the equipment can be used within the OW, it may depend on the working shift (8 hours/day, 5 days/week), the delivery of truck loads, equipment reliability, or equipment transfer from one harvesting site to another.

3.1.2 Model set-up

A flexible modular spreadsheet has been developed to enable the technical-economic analysis of a large variety of chains /5/. First a chain is defined by the user, then the chain is processed by the spreadsheet, to yield results on costs, energy use and emissions of all separate links in the chain and cumulative for the end product.

In each step along the transport chain, a biomass processing action can be chosen. This can be cultivation of biomass, harvesting, storing, different pretreatment technologies, transport by truck, train or ship, and intermediate or final energy conversion of the biomass. Each step results in costs and energy use depending on parameters, as described in the previous paragraph. In each step, characteristics of the biomass, such as amount, moisture content and form could change. This is incorporated in the model.

The model (Figure 8) processes all the steps in consecutive order. After each step the results for costs, energy use and emissions are retained for the overview and the new biomass characteristics are written to the next step.

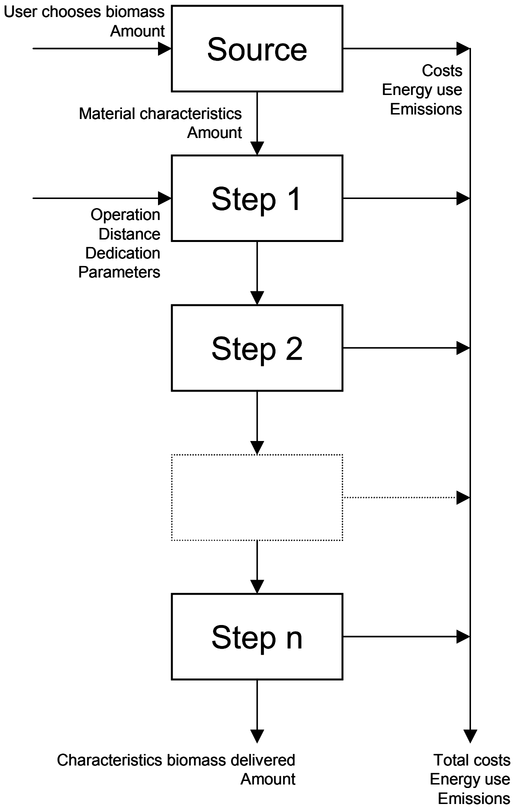


Figure 8. Information flow through the modelled chain.

Annual costs for a step consist of the annual capital costs, operating and maintenance, and auxiliary energy use (electricity, heat or fuel) and labour. Possible benefits from co-produced electricity, heat or products may decrease the costs. Costs for biomass are only relevant in the beginning of a chain. When biomass is lost or used for heat generation along the chain, this is implemented in terms of efficiency. The annual capital costs are the pay-down and interest of the Total Capital Requirement (TCR), and depend on lifetime and interest rate. The TCR is calculated from a base capital at a base scale, using an exponent factor. Annual O&M costs are generally inputted as a percentage of the TCI.

The costs for consumed energy and required labour can vary per location. For example, the local mix of electricity sources influences the specific CO_2 emissions. Those parameters can be varied for specific local or national conditions.

3.2 Bases of the assessment

The Utrecht University research group has built up an impressive generic data base pertaining to the individual operations of biotrade chains and has applied these data to several studies of such chains /5, 6/. However, for the present evaluations, it was decided to base the performance and cost estimates, as much as possible, on first-hand input data specific to the biotrade chains in question. In particular, acquisition of reliable data pertaining to feedstock procurement and feedstock conversion in the source regions was given high priority. However, in respect of shipping operations, the generic data of the Utrecht University data base were deemed to be among the most reliable available and certainly better than other shipping data acquired during the project. Thus, the Utrecht University shipping data were applied in this evaluation. The Utrecht University shipping data cross-checked well with other available data.

All the input data and most of the bases of the assessment are presented in Appendices 1 and 2. Key economic bases are summarised in Table 11. Unless otherwise specified, energy contents of fuels are for as-received fuels and are based on lower heating values.

Upgrading of the biomass residues was considered to be an essential step in the long-distance trade chains. The residues, as such or in chipped form, have low bulk densities and high moisture contents. Transportation costs for these residues would be significantly higher than those for the corresponding upgraded fuels. For residues as such or in chipped form, decomposition reactions would occur within the material en route leading to material losses and even to hazardous situations. An earlier study carried out by Utrecht University /5/ recommended that long-distance transportation of residue-derived biofuels be based on upgraded residues rather than chipped residues.

Table 11. Key economic bases of the assessments.

Feedstock costs:	
- for Russia, value of the bundled forestry residues at the roadside (= cost of forest operations)	5 EUR/MWh
- for Canada, range of value of the sawmilling residues at the sawmills	–1.67 to +5 EUR/MWh
Cost of heavy fuel oil	16.3 EUR/MWh
Cost of coal in the Netherlands	5.5 EUR/MWh
Interest rate	10%
For conversion plant:	
- plant life	20 a
- load factor	0.89 or 7800 h/a
- operations and maintenance	4% of investment
- start-up, interest during construction	21% of investment
- electricity cost	35 EUR/MWh
- labour cost (incl. payroll overheads	50 EUR/man-hour

3.3 Descriptions of the evaluated chains

Brief descriptions of the chains are presented below. Further details are provided in Appendices 1 and 2. More information about the resources of sawmilling and forestry residues in Eastern Canada is given in Appendix 3.

3.3.1 Russia-Netherlands chains

The feedstock for these chains is residual material from forestry operations in the Russian province of Carelia, adjacent to the Finnish border. The residues are collected, compacted and bundled by tractor-driven portable machinery into what have been termed composite residue logs (CRL). The CRL bundles are transported to the conversion plant by truck – the same type of truck as used for transporting the logs harvested in the forestry operations. This procurement chain, as it has been applied to the Alholmens power-plant project in Finland, is illustrated in Figure 9.

The capacity of each conversion plant is 250 000 t/a of residues, resulting in an average distance of 70 km from the logging sites to the plant. Six plants are located in various parts of the province of Carelia. Each plant is a stand-alone plant with a single production line and each is located adjacent to a waterway of the Baltic-Ladoga-Onega system. Two alternative biofuel commodities are considered: pyrolysis oil and pellets. Two alternative chains are examined, a separate chain for each of the commodities. The conversion technologies have been discussed in detail in the Chapter 2. In the case of pyrolysis oil production, some excess heat is produced and this is sold to the local community as district-heat (for 5000 h/a; Chapter 2). As mentioned earlier, an original intention had been to apply a configuration featuring integration of the conversion plant with a combined district-heat and power plant (CHP). This was considered to be a way to render the production of export biofuel more socio-economically acceptable. However, the techno-economic analysis of the Chapter 2 indicated no economic advantage of integration with district-heating plants, mainly because of the limited annual operating times of such plants. Furthermore, in Carelia, this alternative would require large investments in infrastructure. The fact that the stand-alone configuration was selected for this particular assessment does not mean that integration with a district-heating plant would necessarily be a less favourable option. For such an integrated plant, production costs would be similar and conversion efficiency would be higher (Figures 1 and 2, Chapter 2).

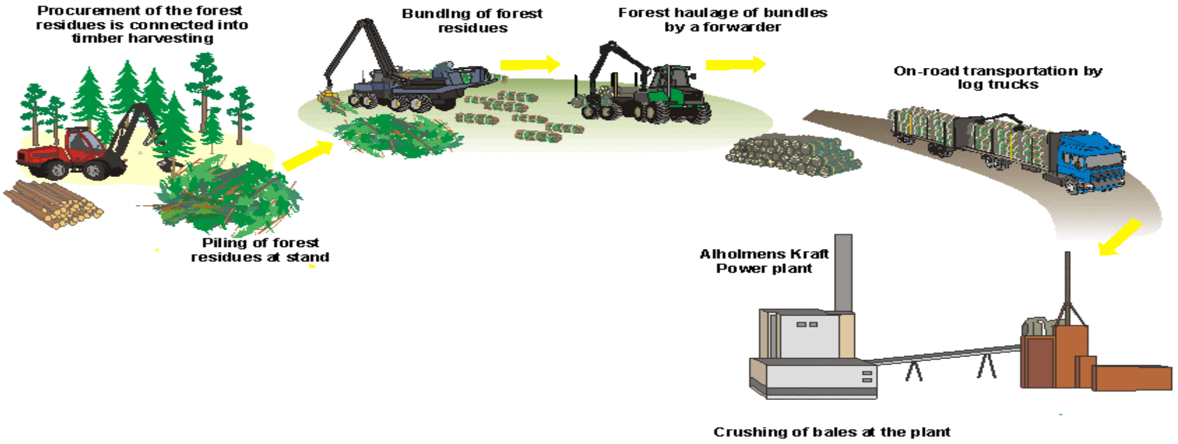


Figure 9. Scheme for procurement of forestry residues based on CRL bundling.

The converted products are transported by relatively small ships (draught 4 m) directly from the plants to Rotterdam harbour. The limitation on draught corresponds to that of shipping lanes of the Baltic-Ladoga-Onega system. At Rotterdam harbour the biofuels are transferred to barges and barged directly to several coal-fired power plants for co-firing. Overall rounded-off production figures for the chains are summarised in Table 12.

Table 12. Overall production figures for the Russia-Netherlands chains.

Commodity	**Feedstock requirement, Mt/a**	**Amount of commodity delivered, Mt/a**	**Amount of bioelectricity**	
			TWh/a	MW
Pyrolysis oil	1.5	0.5	0.8	100
Pellets	1.5	0.7	1.35	170

3.3.2 Canada-Netherlands chains

The feedstock for these chains are sawmilling residues generated at many sawmills throughout Eastern Canada, but particularly in the province of Quebec. The residues are transported, as such, to the conversion plant by large bulk-transport trucks. The maximum transportation distance to the plant is about 100 km, corresponding to an average transportation distance of about 70 km.

The average capacity of each conversion plant is 330 000 t/a of residues. Eight plants are located in various parts of Eastern Canada – seven in Quebec and one in New Brunswick. Each plant is a stand-alone plant with a single production line. As for the Russian case, above, two alternative chains are examined: one for pyrolysis oil and one for pellets. The conversion technologies have been discussed in detail in the Chapter 2.

Pyrolysis data pertaining specifically to the sawmilling residues of the type in question are not available. Based on earlier laboratory studies of various separate components of these residues, it is concluded that both the yield and the quality of the pyrolysis oil would be about midway between those of pyrolysis oil derived from stemwood and those of pyrolysis oil derived from forestry residues. This conclusion is the basis of the pyrolysis mass and energy balances for the Canada-Netherlands chain.

The converted products are first transported by relatively large trucks from the conversion plants to harbours at either Montreal or Quebec City. The average transport distance is 220 km. From these harbours, the biofuels are transported by ship to Rotterdam harbour. For pellets, the type of ship considered is a relatively large vessel (25 000 dwt), similar to ones actually used for this purpose. For pyrolysis oil, both a relatively small chemical tanker (4500 dwt) and a hypothetical large tanker, especially adapted for pyrolysis oil (25 000 dwt), are considered. From Rotterdam harbour onwards, the chains are identical to the corresponding Russia-Netherlands chains. Overall rounded-off production figures for the chains are summarised in Table 13.

Table 13. Overall production figures for the Canada-Netherlands chains.

Commodity	**Feedstock requirement, Mt/a**	**Amount of commodity delivered, Mt/a**	**Amount of bioelectricity**	
			TWh/a	MW
Pyrolysis oil	2.65	1.1	1.9	230
Pellets	2.65	1.3	2.4	300

3.4 Results of the techno-economic analysis of the chains and discussion of the results

Figure 10 presents the estimated costs and cost breakdowns for the Russia-Netherlands chains. The estimated delivered costs of the biofuels at the power plant are 30 EUR/MWh and 23 EUR/MWh for pyrolysis oil and pellets, respectively. The costs of shipping and barging from the conversion plant in Carelia to the power plant in the Netherlands account for 25–30% of the delivered costs of the fuels. Because of the higher costs of co-firing the pellets, there is little difference between the estimated electricity-generation costs for the two biofuels (Figure 10). The co-firing extras are comprised of the actual extra costs associated with the handling of the biofuels and risk premiums that need to be paid to cover possible power-plant outages resulting from biofuel co-firing. The data are based on the experiences of an international energy company and are applicable in the Netherlands. The risk premium for pellets pertains to a co-firing system where the pellets are premixed with coal. Presumably, the risk premium would be smaller, but the other co-firing costs larger, if a completely separate feeding and handling system were procured for the pellets. As expected, the costs of the bioelectricity produced at the end of these chains are significantly higher than the corresponding costs of electricity produced from coal (Figure 11).

Estimates of the energy consumed by the chains, prior to the end-use of the biofuels, are presented in Figure 12. Over 90% of the total electricity consumption is attributable to the conversion operation, while 70–85% of the total oil consumption occurs during shipping and barging. The total energy consumptions, expressed as % of the energy content of the original feedstock, are about 10% for pyrolysis oil and 15% for pellets (Figure 12). If the electricity were to be weighted by a factor of 2.5, in effect converting the electricity into the amount of fuel needed for its generation at 40% efficiency, the total energy consumption figures, prior to the end-use of the biofuels, would increase to 16% and 23% for pyrolysis oil and pellets, respectively.

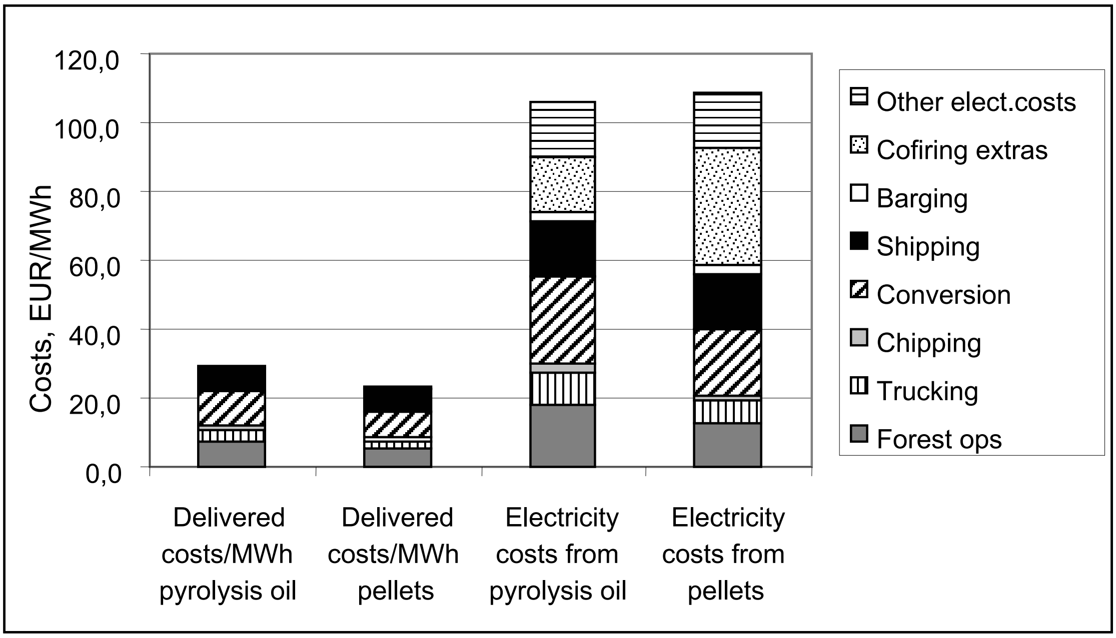


Figure 10. Estimated delivered costs of biofuel and bioelectricity-generation costs for the Russia-Netherlands chains.

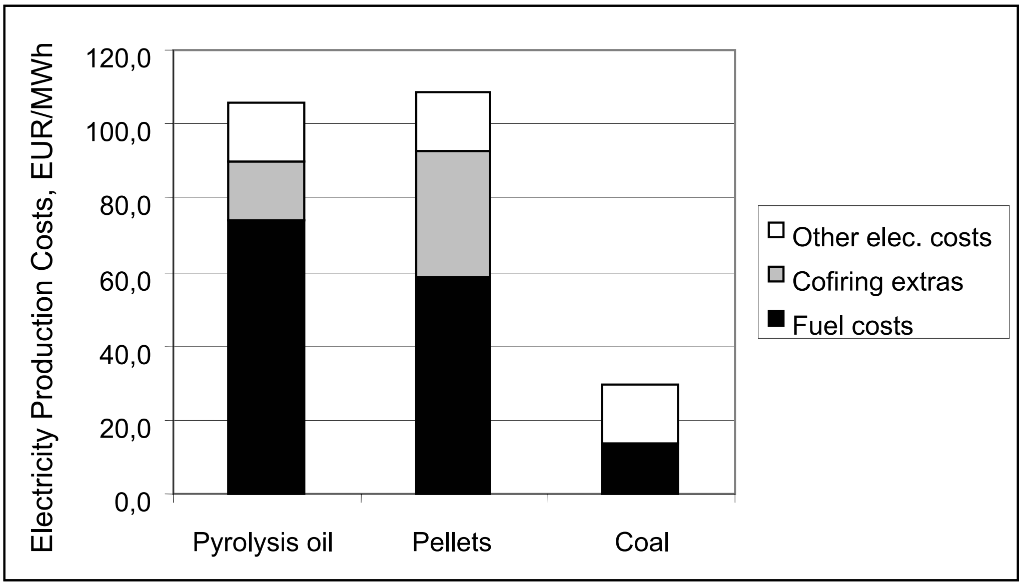


Figure 11. Comparison of estimated costs of the bioelectricity produced at the end of the Russia-Netherlands chains to the cost of producing electricity from coal.

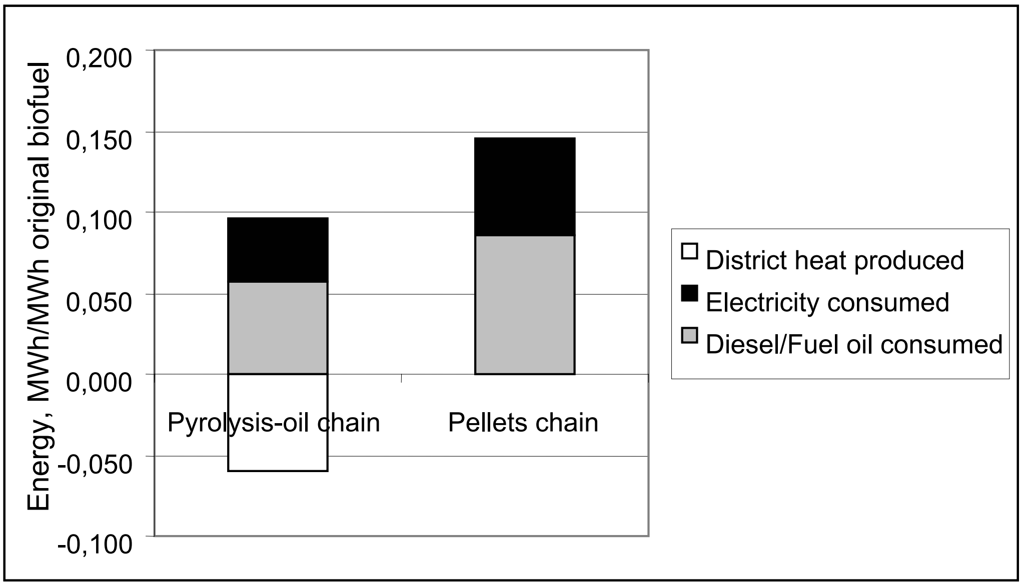


Figure 12. Estimates of energy consumed and energy produced as by-product in the Russia-Netherlands chains.

Figure 13 and 14 present the estimated costs and cost breakdowns for the Canada-Netherlands chains for two different cases, corresponding to the two types of ship for transporting pyrolysis oil. These cases assume that the value of the residues at the sawmills in Canada is zero. The effect of ship size (pyrolysis oil) is quite considerable. In all cases, dedicated shipping fleets have been assumed and full shipping costs, i.e. including depreciation of capital, have been assigned. Bearing this in mind, the larger custom-built pyrolysis-oil tanker would seem to be the more relevant case and this case is given priority in the following discussion. For this case, the estimated delivered costs of the biofuels at the power plant are 24 EUR/MWh and 18 EUR/MWh for pyrolysis oil and pellets, respectively, lower than the corresponding costs for the Russia-Netherlands chains, reflecting the lower feedstock costs. On the other hand, the costs of trucking, shipping and barging from the conversion plant in Eastern Canada to the power plant in the Netherlands account for 40–45% of the delivered costs of the fuels, clearly higher proportions than in the case of the Russia-Netherlands chains. Again, because of the higher costs of co-firing the pellets, there is little difference between the estimated electricity-generation costs for the two biofuels (Figure 14). For the Canada-Netherlands chains based on zero-cost sawmilling residues, the costs of the delivered biofuels are about 20% lower, and the costs of bioelectricity are about 10% lower (Figure 14), than the corresponding costs for the Russia-Netherlands chains (Figure 10).

For the Canada-Netherlands pyrolysis-oil chain, the effects of the cost of the feedstock on the cost of the delivered biofuel and on the electricity-generation cost are shown in Figures 15 and 16, respectively. Estimates of the energy consumed by the Canada-Netherlands chains, when large custom-built tankers are used for shipping pyrolysis oil, are presented in Figure 17. Virtually all the electricity consumption is attributable to the conversion operation, while 85% of the total oil consumption occurs during transportation of the biofuel from the conversion plant to the power plant. The total energy consumptions prior to the end-use of the biofuels, expressed as % of the energy content of the original feedstock, are about 9% for pyrolysis oil and 13% for pellets (Figure 17). For pyrolysis oil, the total consumption would increase to the same level as that for the pellets if the oil were shipped by relatively small chemical tankers. If the electricity were to be weighted by a factor of 2.5, in effect converting the electricity into the amount of fuel needed for its generation at 40% efficiency, the total energy consumptions prior to the end-use would, for the case of Figure 17, increase to 13% and 21% for pyrolysis oil and pellets, respectively.

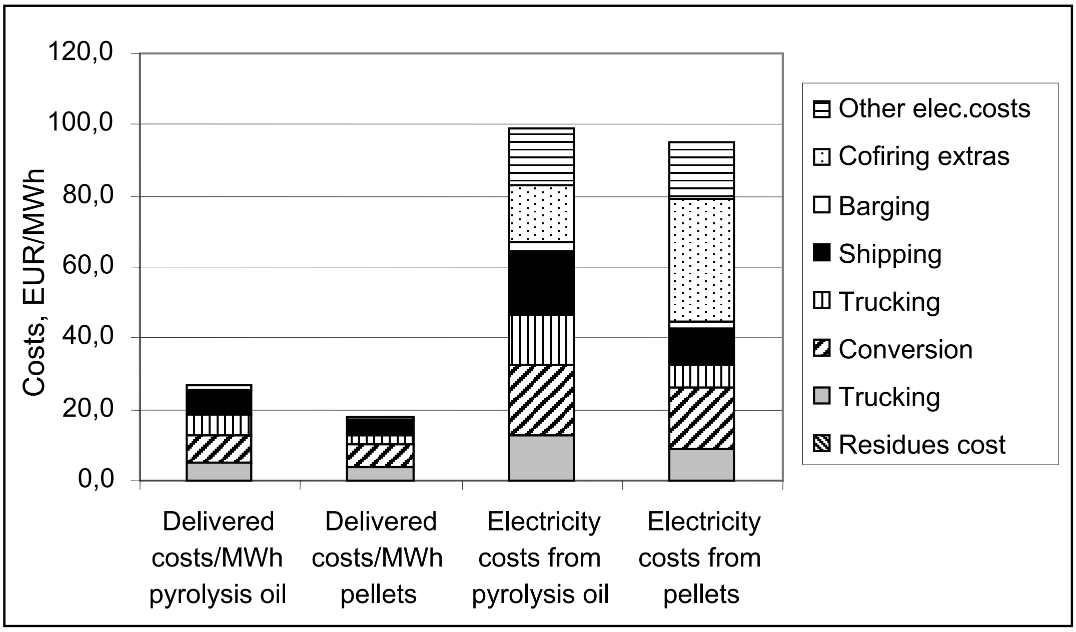


Figure 13. Estimated delivered costs of biofuel and bioelectricity-generation costs for the Canada-Netherlands chains; zero cost for sawmill residues; existing type of small chemical tanker used for shipping pyrolysis oil.

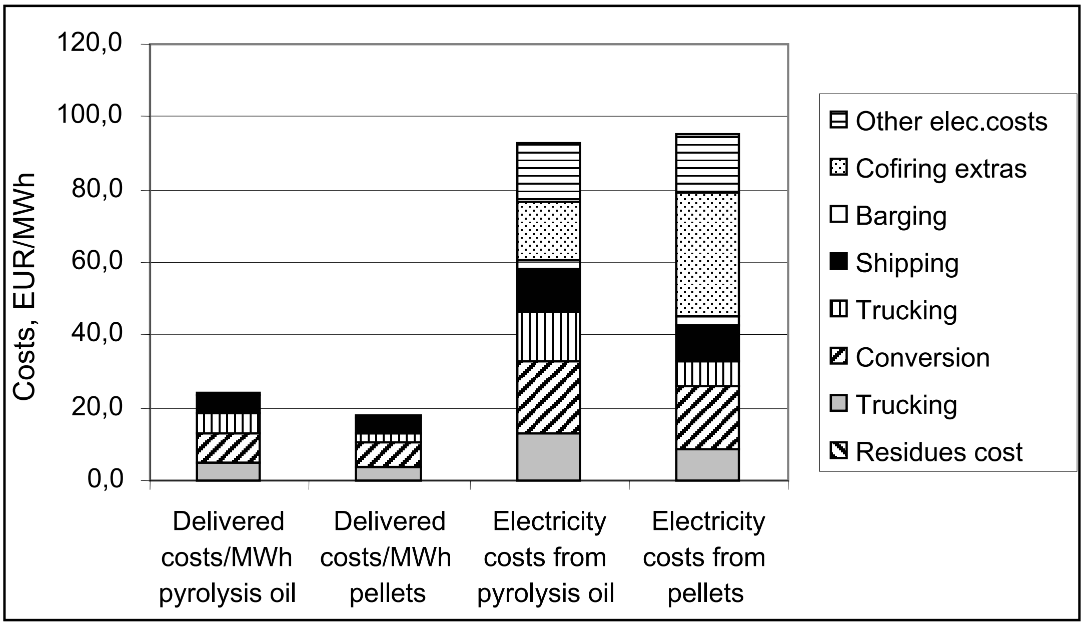


Figure 14. Estimated delivered costs of biofuel and bioelectricity-generation costs for the Canada-Netherlands chains; zero cost for sawmill residues; large custom-built tanker used for shipping pyrolysis oil.

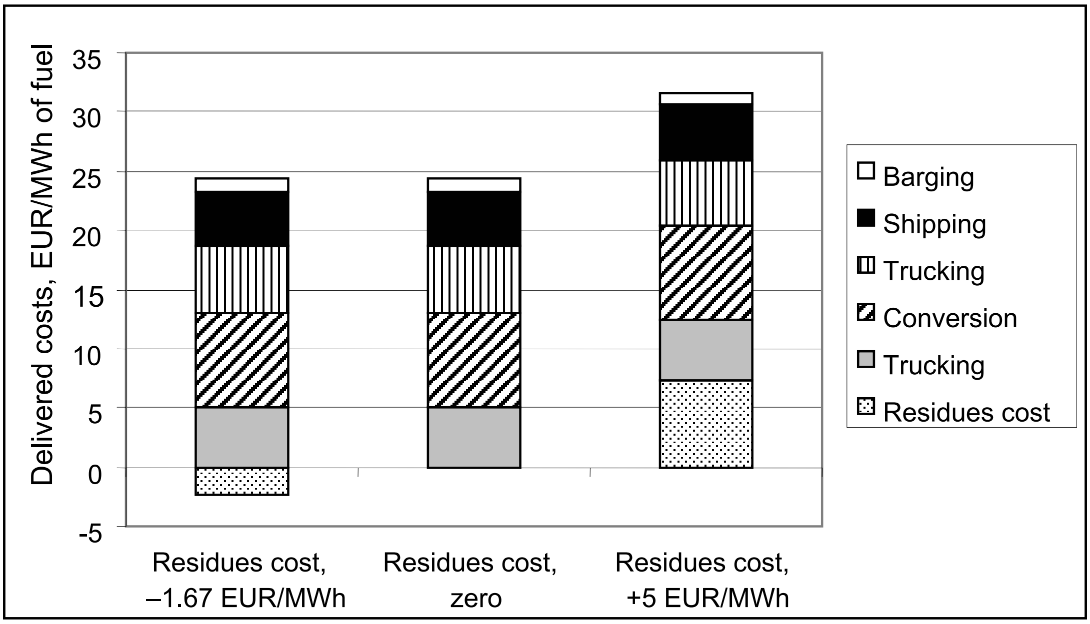


Figure 15. Estimated delivered costs of pyrolysis oil for the Canada-Netherlands chains; large custom-built tanker used for shipping pyrolysis oil.

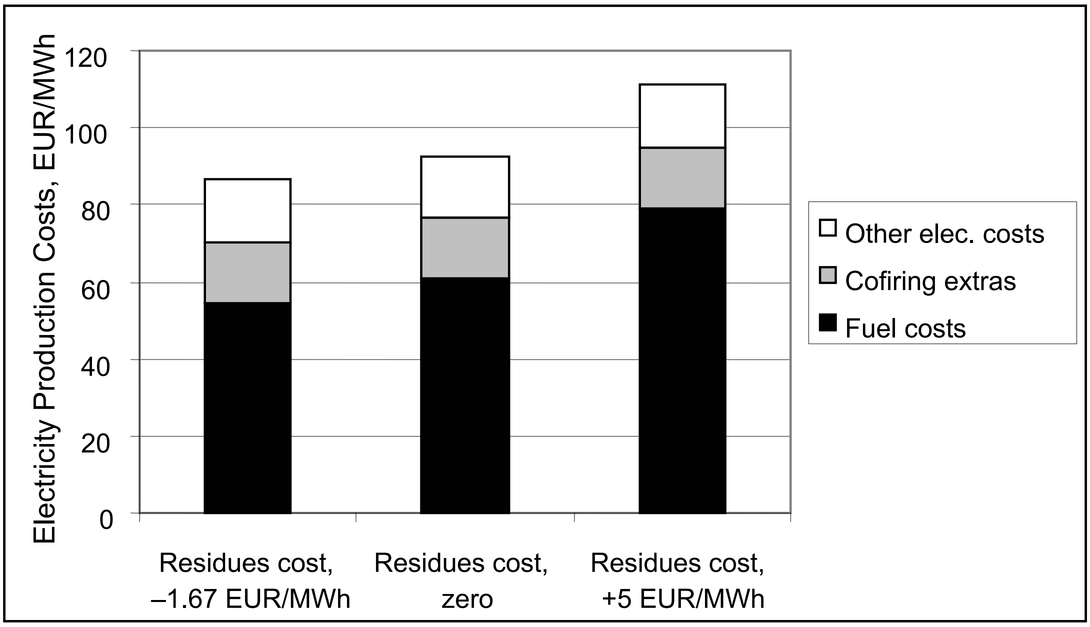


Figure 16. Estimated bioelectricity-generation costs from pyrolysis oil for the Canada-Netherlands chains; large custom-built tanker used for shipping pyrolysis oil.

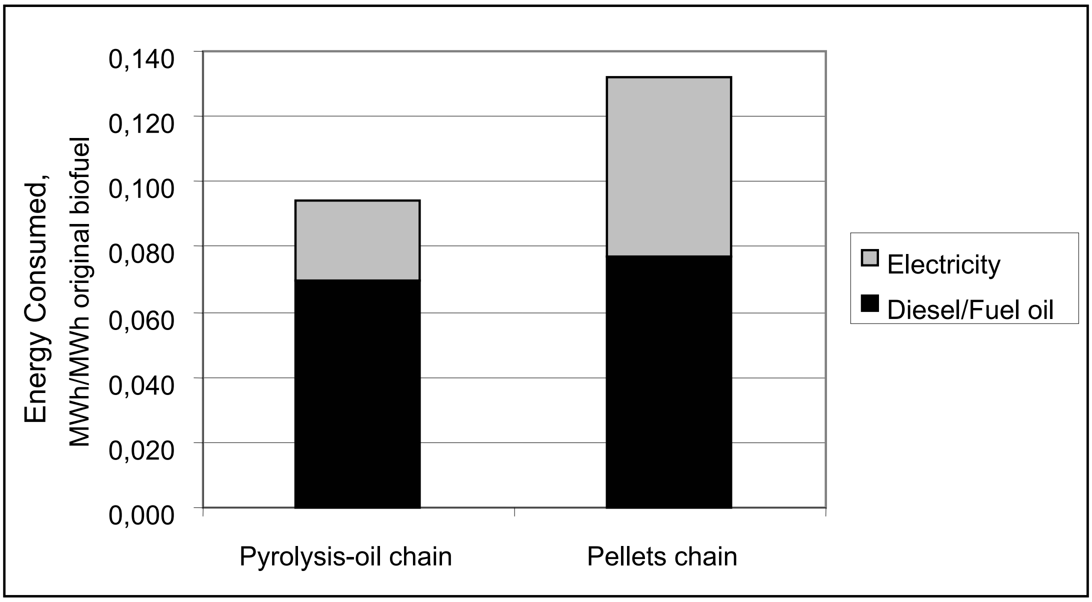


Figure 17. Estimates of energy consumed in the Canada-Netherlands chains; large custom-built tanker used for shipping pyrolysis oil.

3.5 Evaluation of local-utilisation alternatives

The costs and performances of the chains are compared to those of the following local alternatives:

- increased combined heat and power (CHP) production from the residues
- co-firing the residues locally in large existing condensing-power stations
- separate generation of electricity in biomass-fired condensing power stations.

The first option above includes two different situations. The more favourable situation is one where small plants producing district heat, only, are replaced by a large CHP plant. The total heat load of the system remains the same and the biofuel input is increased to cover the new back-pressure power produced by the CHP plant. This is an extremely efficient option, 1 MWh of biofuel being converted, in effect, into about 0.85 MWh of electricity. This option will be available in certain cases, only. In Sweden, for example, there is still some potential for increasing CHP production in this way. The more common situation is one where the increased utilisation of biofuels increases both power and heat production in accordance with the power-to-heat ratio of the power-plant process. This is the situation if new biofuel-fired CHP capacity is brought on line or if fossil fuel is replaced by biofuel in existing CHP plants. Only this second, more common situation is examined in more detail in the following.

Based on cost data presented in references /7/ and /8/, the following typical costs of generating electricity from forestry residues for the three local-utilisation cases were estimated:

- combined heat and power (CHP): 25 EUR/MWh_e
- co-fired condensing-power: 60 EUR/MWh_e
- biomass-fired condensing power (output 50 MW_e): 70 EUR/MWh_e.

These estimates are based on chipped forestry residues being received at the power plant at a cost of 8–9 EUR/MWh, i.e. in keeping with the cost estimated for the forestry residues in the Russia-Netherlands chains. For the case of co-fired condensing power, the extra costs of co-firing have been assumed to be the same as those for co-firing of pellets in coal-fired condensing-power stations in the Netherlands. Note that the capacity of the third option above has been set at 50 MW_e. The capacity of this alternative has significant impact on the electricity-generation costs: increasing the capacity increases fuel costs (longer transportation distances) but significantly decreases other costs. The chosen capacity is consistent with fuel costs of 8–9 EUR/MWh. From the above electricity-generating costs, the corresponding costs of avoided CO_2 emissions were calculated, assuming that coal would be the fossil fuel replaced. Table 14 presents the results of these calculations and compares them to the corresponding results for the Russia-Netherlands chains. In addition, Table 14 presents estimates of how much coal would be replaced, in each case, by 1 MWh of the original feedstock.

Table 14. Comparison of the costs and performances of local-utilisation alternatives with those of the Russia-Netherlands chains.

	Local CHP	**Local co-firing**	**Local condensing power**	**Russia-Netherlands pyrolysis oil**	**Russia-Netherlands pellets**
Electricity-generating costs, EUR/MWh_e	25	60	70	106	109
Costs of avoided CO_2, EUR/t of CO_2	0	35	47	90	93
Coal replaced by 1 MWh of original biofuel, MWh	1	1	0.9	0.6*	0.8

* Note: In conjunction with pyrolysis-oil production, 0.06 MWh of district heat is co-produced.

From the estimates in Table 14, it is seen that, as expected, local utilisation can be a more cost-efficient and a more resource-efficient option than trading upgraded biofuels over long distances. The difference would be particularly significant if the biofuel resources could be used for local CHP production. For the generally-applicable local alternative – utilisation in biofuel-fired condensing-power plants – the difference is smaller but still significant.

This type of comparison is, however, very dependent on both the greenhouse-gas emission intensities and the costs of the reference energy systems in the exporting and importing regions. For the above comparison, a carbon-intensive reference system (coal-fired condensing power) was assumed for both the exporting and importing regions. In general, the lower the carbon intensity of the energy system of the exporting region, the more favourable will be international trading in comparison to local utilisation. In practice, there are many factors which may limit local utilisation or make utilisation of biomass resources elsewhere more attractive. Obviously, when increased local utilisation is not feasible, exporting surplus biofuel is a highly beneficial and fully justified option.

4. Conclusions

This study consisted of in-depth techno-economic analyses of biofuel upgrading processes and of whole biotrade chains. The chains encompassed the production of pyrolysis oil or pellets from biomass residues in the source regions, the transportation of the upgraded fuels internationally over long distances and the final utilisation of the fuels. The techno-economic analysis of the biofuel upgrading processes was undertaken primarily to generate techno-economic data that were needed as input data for the assessment of the biotrade chains. In addition, valuable information about the effects of process configuration on costs and performance was generated. The analysis of pyrolysis-oil production was considered to be one of the most reliable hitherto undertaken, being based on a detailed plant design and cost estimate compiled by an equipment supplier. The analysis yielded promising results. The estimated pyrolysis-oil production costs, e.g. below 25 EUR/MWh for stand-alone production from forestry residues, compare favourably with the current consumer-prices of heavy fuel oil in many European countries. Integration of the pyrolysis process with an industrial CHP plant would lower the production costs by more than 20%. The production of pellets was assessed to be somewhat more energy-efficient and more cost-efficient than the production of pyrolysis oil. However, the higher production costs of pyrolysis oil would be counteracted by lower costs in connection with product handling and utilisation.

Four international biotrade chains were analysed in detail. The chains cover two source regions, North-Western Russia and Eastern Canada, and two traded commodities, pyrolysis oil and pellets. The chains terminate in the Netherlands where the imported biofuels are co-fired with coal in condensing power stations. The costs of the delivered biofuels were estimated to be in the range 18–30 EUR/MWh, with the costs of pellets about 25% lower than those of pyrolysis oil. The estimated electricity-generation costs displayed little dependence on the type of biofuel – pyrolysis oil or pellets – because the costs associated with the utilisation of the biofuels for co-firing are higher for the pellets. For the Canada-Netherlands chains based on zero-cost sawmilling residues, the costs of the delivered biofuels were estimated to be about 20% lower, and the electricity-generation costs about 10% lower, than those of the Russia-Netherlands chains. With the electricity consumption calculated as the equivalent amount of fuel that would be needed for its generation, the energy consumptions of the biotrade chains prior to end-use were estimated to be in the range 13–23% of the energy content of the original biomass residues.

Local-utilisation alternatives were also evaluated. For the selected cases and chains, it is concluded that local utilisation can be a more cost-efficient and a more resource-efficient option than international trade and use of biomass resources elsewhere. This type of comparison is, however, very dependent on both the greenhouse-gas emission intensities and the costs of the reference energy systems in the exporting and importing regions. For the comparison performed in this study, a carbon-intensive reference system (coal-fired condensing power) was assumed for both the exporting and importing regions. In general, the lower the carbon intensity of the energy system of the exporting region, the more favourable will be international trading in comparison to local utilisation. In practice, there are many factors which may limit local utilisation or make utilisation of biomass resources elsewhere more attractive. Obviously, when increased local utilisation is not feasible, exporting surplus biofuel is a highly beneficial and fully justified option.

The present study concentrated on evaluating the costs and carbon impacts of certain biotrade chains. The results confirmed that, when the traded commodity is pellets or pyrolysis oil, long-distance transport, itself, does not have an overwhelming impact on the costs and energy balances of biomass utilisation. Other drivers for international bio-energy trade, such as improving access to markets, developing biomass production potentials over time and securing stable supply and demand, fuel supply security and other issues were not part of the work programme of Task 35. Overall, it is concluded that biotrade will have a definite and important role to play in reducing humankind's dependency on fossil fuels. The techno-economic performances of biotrade schemes should be evaluated on a case by case basis as illustrated in this report. The methodological approach for doing so can be considered as an important generic outcome of the work.

References

/1/ Solantausta, Y., Podesser, E., Beckman, D., Östman, A. & Overend, R. 2000. IEA Bioenergy Task 22: Techno-economic assessment for bioenergy applications 1998–1999. Final Report. VTT Research Notes 2024. Espoo: VTT. 241 p. http://www.vtt.fi/inf/pdf/tiedotteet/2000/T2024.pdf.

/2/ Solantausta, Y., Oasmaa, A. & Sipilä, K. 2003. Fast pyrolysis of forestry residues. In: Bridgwater, A.V. (Ed.). Proc. Conf. on Future for Pyrolysis and Gasification of Biomass and Waste: Status, Opportunities and Policies for Europe. Strasbourg, 30 Sept. –1 Oct. 2002. CPL Press.

/3/ Solantausta, Y., Diebold, J., Elliott, D., Bridgwater, T. & Beckman, D. 1994. Assessment of liquefaction and pyrolysis systems. VTT Research Notes 1573. Espoo: VTT. 123 p. + app. 79 p. 951-38-4667-9

/4/ Sipilä, K. 2003. Patent application SE 9903702-0, application approved 9.7.2003.

/5/ Hamelinck, C.N., Suurs, R. & Faaij, A.P.C. 2003. International bioenergy transport costs and energy balance. Copernicus Institute, Utrecht University, the Netherlands. Report NWS-E-2003-26. August 2003.

/6/ Faaij, A.P.C., Schlamadinger, B., Solantausta, Y. & Wagener, M. 2002. Large-scale international bio-energy trade. In: Proc. 12th European Conf. on Biomass for Energy, Industry and Climate Protection, 17–21 June 2002, Amsterdam, the Netherlands. Pp. 1193–1196.

/7/ Sipilä, K., McKeough, P. & Mäkinen, T. 2004. The pulp and paper industry can offer new innovative bioenergy platforms. In: Proc. Pulpaper 2004 Conf., Helsinki, 1–3 June 2004.

/8/ Cameron, J., Kumar, A. & Flynn, P. 2002. Optimizing technology for biomass usage for power generation. In: Proc. 12th European Conf. on Biomass for Energy, Industry and Climate Protection, 17-21 June 2002, Amsterdam, the Netherlands. Pp. 123–126.

Appendix 1: Input data for Russia-Netherlands chains

Compiled by P. McKeough, VTT, 15.4.2004

Overview of Russia-Netherlands chains

Two alternative chains for each of two commodities: pyrolysis oil and pellets

Plants and locations: 6 plants in different parts of Carelia, Russia but all adjacent to a waterway of the Baltic-Ladoga-Onega-system.

Plant size: Basis: 250 000 t/a of forestry residues (50% H_2O)

Plant configuration: plants are stand-alone, except that, for the pyrolysis plant, the small amount of surplus energy is sold as district heat (5000 h/a) to the local community.

Feedstock: green forestry residues
Feedstock chain: stacking, compacting & bundling (= CRL bales), transfer to roadside, truck transport to plant, storage as bundles, chipping for process

Shipping chain: products (oil or pellets) transported by relatively small vessels – e.g. 4000 dwt – having a maximum draught of 4 m, from the conversion plant to Rotterdam harbour, the Netherlands; followed by transfer to barges (about 2000 dwt) and barge transport direct to the power plant.

Chain data

Start of chain: compacted bundles of forestry residues at the roadside near the logging site.

Fuel properties of the residues:

50% H_2O
HHV dry: 20.2 GJ/t
LHV wet: 8.23 GJ/t; 2.29 MWh/t

Value of the residues at the roadside: 5 EUR/MWh
Prior consumption of diesel fuel: 1.1 litre/MWh

Truck transport to plant:

Truck type: same as used for log transport
Load: max load 37 t (total max weight 60 t)
Average transport distance: 70 km
Total cost of transport: 6 EUR/t, 2.5 EUR/MWh
Diesel fuel consumption (includes return trip): 0.7 litres/MWh

Storage as bundles at plant: 0 cost / 0 losses

Chipping for process:

Total costs: 0.7 EUR/MWh
Electricity consumption: 4 kWh/MWh

Conversion processes:

Operations included in this step:

- Chip storage (small; short-time)
- Feeding systems
- Drying
- Grinding
- Conversion
- Product recovery
- Heat generation for drying (pelletisation)
- District-heat generation (pyrolysis)
- Product storage
- Buildings, site, etc

Complications arising from pyrolysis-oil quality: two-phase pyrolysis oil is formed from forestry residues. Bottom phase (about 90%) can be considered a normal fast-pyrolysis oil. The top phase (about 10%) is a more viscous product. The two phases need to be separated from each other and then handled separately. It is envisaged that the top phase would be shipped to Sweden to be used as a substitute for heavy fuel oil (favourable market). The bottom phase would be shipped to the Netherlands. When utilised in this way, the values of the two products at the conversion plant should be similar to each other. With this assumption, the production costs can be calculated for the combined product oil. (On the other hand, if desired, a more detailed calculation can be made with the top phase considered as a byproduct.)

Pyrolysis conversion data:

Base scale (single-line): 43.9 MW (LHV input)
Base capital: 11.7 MEUR
Scale-up exponent: 0.7
Maximum scale (single-line): 100 MW
Load Factor: 89% or 7800 h/a
Operation & Maintenance: 4% of investment
Electricity: 80 kWh/t feed (of which 46 kWh/t for grinding)
District-heat credit: –137 kWh/t feed (yearly average)
Labour: 8 persons
Lifetime: 20a
Efficiency LHV wet: 68.2%
Product HHV dry: 23.9 GJ/t
Product moisture: 28.5%
Product H: 6.15% of dry matter
Product density: 1200 kg/m3

Notes:

1. Above figures correspond to the case of a mixed product (top phase + bottom phase).

2. Only bottom-phase oil is shipped to the Netherlands. LHV of bottom phase: 14.4 GJ/t. Amount of bottom-phase oil: 1.76 kg/s = 25.5 MW (LHV) for plant with input of 43.9 MW.

Pelletisation conversion data:

Base scale (single-line): 51.1 MW (LHV input)
Base capital: 12.1 MEur
Scale-up exponent: 0.7
Maximum scale (single-line): 100 MW
Load Factor: 89% or 7800 h/a
Operation & Maintenance: 4% of investment
Electricity: 126 kWh/t feed (of which 46 kWh/t for grinding)
Labour: 8 persons
Lifetime: 20a
Efficiency LHV wet: 98.3%
Product HHV dry: 20.2 GJ/t
Product moisture: 10%
Product H: 6% of dry matter
Product bulk density: 550 kg/m3

Shipping to Rotterdam harbour:

Dedicated ships are employed. Ships are relatively small vessels, e.g. 4000 dwt, having a maximum draught of 4 m. Vessel for pyrolysis oil is a bulk chemical tanker with lining (add 10% to capital cost of tanker) of capacity 4000 t of oil. Vessel for pellets is conventional bulk carrier of capacity 5000 m^3 = 2750 t of pellets.

Performance and cost data are derived from the generic data base of the Utrecht University:

1. Pyrolysis oil:

Ship type: dedicated bulk chemical tanker
Load: 4000 t
Average transport distance: 2500 km
Total cost of transport: 26 EUR/t, 6.5 EUR/MWh
Diesel fuel consumption (includes return trip): 5 litres/MWh

2. Pellets:

Ship type: dedicated bulk vessel
Load: 2750 t
Average transport distance: 2500 km
Total cost of transport: 30 EUR/t, 6.5 EUR/MWh
Diesel fuel consumption (includes return trip): 6 litres/MWh

Cost figures for comparison: (1) cost of shipping chemicals from Porvoo, Finland, to Rotterdam (1900 km), when vessel size is 2000–3000 dwt, is in range 20–30 EUR/t; (2) Dutch data for pellets transport: 16 EUR/t for 1500–2000 km in 2000–3500 dwt vessels.

Transfer to barges and barging to the power plants. Data for these operations (solid fuels from Rotterdam to Geertruidenberg) were obtained from Dutch sources: combined costs 4.2 EUR/t.

Fuel utilisation in the Netherlands. Base case is co-firing in large coal-fired power plants. Data were obtained for (1) co-firing of pellets in a pulverised coal boiler and (2) co-firing of palm oil in an oil-fired boiler. The data are based on the experiences of an international energy company and are applicable in the Netherlands.

Extra Costs Associated With Co-firing of Biofuels, EUR/MWh of electricity	
Pellets in coal-fired boiler	Palm oil in oil-fired boiler
34.1	15.8

In the present assessment, it was assumed that the extra costs associated with the co-firing of pyrolysis oil in a coal-fired boiler would be the same as the data for co-firing of palm oil.

Production figures for 1 Russian plant

1. Pyrolysis alternative:

Biomass input:
– 572 500 MWh/a
– 250 000 t/a (50% H_2O)

Bottom-phase pyrolysis oil:
– 331 500 MWh/a
– 82 900 t/a (30.2% H_2O, LHV: 14.4 GJ/t)

Top-phase pyrolysis oil:
– 60 000 MWh/a
– 8 300 t/a (12.2% H_2O, LHV: 25.5 GJ/t)

2. Pellets alternative:

Biomass input:
– 572 500 MWh/a
– 250 000 t/a (50% H_2O)

Pellets:
– 562 800 MWh/a
– 121 000 t/a (10% H_2O, LHV: 16.75 GJ/t)

Total production for 6 Russian plants

1. Pyrolysis alternative:

Biomass input:
– 3 430 000 MWh/a
– 1 500 000 t/a (50% H_2O)

Bottom-phase pyrolysis oil:
– 1 990 000 MWh/a
– 497 400 t/a (30.2% H_2O, LHV: 14.4 GJ/t)

Top-phase pyrolysis oil:
– 360 000 MWh/a
– 49 800 t/a (12.2% H_2O, LHV: 25.5 GJ/t)

2. Pellets alternative:

Biomass input:
– 3 430 000 MWh/a
– 1 500 000t/a (50% H_2O)

Pellets:
– 3 375 000 MWh/a
– 726 000 t/a (10% H_2O, LHV: 16.75 GJ/t)

Appendix 2: Input data for Canada-Netherlands chains

Compiled by P. McKeough, VTT, 15.4.2004

Overview of Canada-Netherlands chains

Two alternative chains for each of two commodities: pyrolysis oil and pellets

Plants and locations: 8 plants in different parts of Quebec and New Brunswick, Canada. Locations and sizes of plants based on data gathered by D. Beckman (Zeton, Canada) and presented in Appendix 3 of the main report. The plant locations and sizes are summarised in the following table.

Region	**Plant capacity, t/a of sawmilling residues**	**Maximum distance to plant, km**	**Distance from plant to port, km**	**Port**
Quebec	340 000	100	20	Quebec City
Quebec	340 000	100	100	Quebec City
Mauricie	340 000	100	200	Quebec City
Mauricie	320 000	80	50	Montreal
Bas-Saint-Laurent	280 000	100	250	Quebec City
Gaspe, New Brunswick	340 000	100	500	Quebec City
Abitibi	340 000	100	550	Montreal
Saguenay-LacSaint-Jean	340 000	100	100	Quebec City
Total	**2 640 000**			

Plant configuration: plants are stand-alone

Feedstock: sawmill residues, bark-dominated

Road transport: residues are transported as such by dedicated bulk-transport trucks to the conversion plant; conversion products are transported by dedicated bulk-transport trucks (pellets) or dedicated bulk chemical tankers (pyrolysis oil) from the conversion plant to the relevant port.

Shipping chain: products (oil or pellets) are transported by dedicated ships from the relevant port to Rotterdam harbour, the Netherlands; followed by transfer to barges (about 2000 dwt) and barge transport direct to the power plant. For pellets, the ship considered is a relatively large vessel (25 000 dwt), similar to ones actually used for this purpose. For pyrolysis oil, both a relatively small chemical tanker (4500 dwt) and a hypothetical large tanker, especially adapted for pyrolysis oil (25 000 dwt) are considered.

Chain data

Start of chain: piles of sawmilling residues at the mills.

Fuel properties of the residues:

50% H_2O
HHV dry: 20.2 GJ/t
LHV wet: 8.23 GJ/t; 2.29 MWh/t

Value of the residues at the mills: 3 cases considered: –1.67 EUR/MWh (dumping fee), 0 EUR/MWh, 5 EUR/MWh

Truck transport to plant:

Truck type: dedicated bulk-transport truck
Load: maximum load 37 t
Average transport distance: 70 km
Total cost of transport: 8 EUR/t, 3.5 EUR/MWh
Diesel fuel consumption (includes return trip): 1.0 litres/MWh

Conversion processes:

Operations included in this step:

Feeding systems
Drying
Grinding
Conversion
Product recovery
Heat generation for drying (pelletisation)
Product storage
Buildings, site, etc.

Yield and quality of pyrolysis oil: pyrolysis data pertaining specifically to the type of residues in question are not available. Based on earlier laboratory studies of various separate components of these residues, it is concluded that both the yield and the quality of the pyrolysis oil would be about midway between those of pyrolysis oil derived from stemwood and those of pyrolysis oil derived from forestry residues. This conclusion is the basis of the pyrolysis mass and energy balances for the Canada-Netherlands chain.

Pyrolysis conversion data:

Base scale (single-line): 43.9 MW (LHV input)
Base capital: 11.6 MEUR
Scale-up exponent: 0.7
Maximum scale (single-line): 100 MW
Load Factor: 89% or 7800 h/a
Operation & Maintenance: 4% of investment
Electricity: 57 kWh/t feed (of which 23 kWh/t for grinding)
Labour: 8 persons
Lifetime: 20a
Efficiency LHV wet: 77.6%
Product HHV dry: 24.0 GJ/t
Product moisture: 26.0%
Product H: 6.15% of dry matter
Product density: 1200 kg/m3

Pelletisation conversion data:

Base scale (single-line): 51.1 MW (LHV input)
Base capital: 12.1 MEUR
Scale-up exponent: 0.7
Maximum scale (single-line): 100 MW
Load Factor: 89% or 7800 h/a
Operation & Maintenance: 4% of investment
Electricity: 103 kWh/t feed (of which 23 kWh/t for grinding)
Labour: 8 persons
Lifetime: 20a
Efficiency LHV wet: 98.3%
Product HHV dry: 20.2 GJ/t
Product moisture: 10%
Product H: 6% of dry matter
Product bulk density: 550 kg/m3

Truck transport to port:

1. Pyrolysis oil:

Truck type: dedicated bulk chemical tanker
Load: Maximum load 25 t
Average transport distance: 220 km
Total cost of transport: 25 EUR/t, 5.6 EUR/MWh
Diesel fuel consumption (includes return trip): 1.8 litres/MWh

2. Pellets:

Truck type: dedicated bulk-transport truck
Load: maximum load 37 t
Average transport distance: 220 km
Total cost of transport: 12 EUR/t, 2.6 EUR/MWh
Diesel fuel consumption (includes return trip): 1.0 litres/MWh

<u>Shipping to Rotterdam harbour</u>:

Dedicated ships employed. Average transport distance (one way) = 6400 km. For pellets, the ship considered is a relatively large vessel (25 000 dwt), similar to ones actually used for this purpose. For pyrolysis oil, both a relatively small chemical tanker with added lining (4500 dwt) and a hypothetical large tanker, especially adapted for pyrolysis oil (25 000 dwt) are considered.

Performance and cost data are derived from the generic data base of Utrecht University:

1. Pyrolysis oil / Case I:

Ship type: dedicated bulk chemical tanker (available at this time)
Load: 4500 t
Average transport distance: 6400 km
Total cost of transport: 32 EUR/t, 7.2 EUR/MWh
Diesel fuel consumption (includes return trip): 11 litres/MWh

2. Pyrolysis oil / Case II:

Ship type: large dedicated special bulk tanker (not available at this time)
Load: 25 000 t
Average transport distance: 6400 km
Total cost of transport: 21 EUR/t, 4.7 EUR/MWh
Diesel fuel consumption (includes return trip): 6 litres/MWh

3. Pellets:

Ship type: dedicated bulk vessel
Load: 25 000 t
Average transport distance: 6400 km
Total cost of transport: 19 EUR/t, 4.0 EUR/MWh
Diesel fuel consumption (includes return trip): 5 litres/MWh

Cost figure for comparison: Dutch data for pellets transport: 20 EUR/t from Halifax, Canada to Rotterdam (6000 km) in 15000 dwt vessels.

Transfer to barges and barging to the power plants. Data for these operations (solid fuels from Rotterdam to Geertruidenberg) were obtained from Dutch sources: combined costs 4.2 EUR/t.

Fuel utilisation in the Netherlands. Base case is co-firing in large coal-fired power plants. Data were obtained for (1) co-firing of pellets in a pulverised coal boiler and (2) co-firing of palm oil in an oil-fired boiler. The data are based on the experiences of an international energy company and are applicable in the Netherlands.

Extra Costs Associated With Co-firing of Biofuels, EUR/MWh of electricity	
Pellets in coal-fired boiler	Palm oil in oil-fired boiler
34.1	15.8

In the present assessment, it was assumed that the extra costs associated with the co-firing of pyrolysis oil in a coal-fired boiler would be the same as the data for co-firing of palm oil.

Production figures for 1 (average-sized) Canadian plant

1. Pyrolysis alternative:

Biomass input:
– 755 700 MWh/a
– 330 000 t/a (50% H_2O)

Pyrolysis oil:
– 586 400 MWh/a
– 131 800 t/a (26.0% H_2O, LHV: 16.0 GJ/t)

2. Pellets alternative:

Biomass input:
– 755 700 MWh/a
– 330 000 t/a (50% H_2O)

Pellets:
– 742 800 MWh/a
– 159 700 t/a (10% H_2O, LHV: 16.75 GJ/t)

Total production for 8 Canadian plants

1. Pyrolysis alternative:

Biomass input:
– 6 045 000 MWh/a
– 2 640 000 t/a (50% H_2O)

Pyrolysis oil:
– 4 690 000 MWh/a
– 1 055 000 t/a (26.0% H_2O, LHV: 16.0 GJ/t)

2. Pellets alternative:

Biomass input:
– 6 045 000 MWh/a
– 2 640 000 t/a (50% H_2O)

Pellets:
– 5 940 000 MWh/a
– 1 280 000 t/a (10% H_2O, LHV: 16.75 GJ/t)

Appendix 3: Wood residues in Eastern Canada for international bioenergy trade

Bioenergy Trade Chains
Report for IEA Bioenergy Task 35

David Beckman
Zeton Inc.

May 3, 2004

Introduction

IEA Bioenergy Task 35 is studying the possibilities for international trade of bioenergy. One case being investigated is the conversion of wood residues in Eastern Canada to a liquid biofuel (bio-oil). The biofuel would then be exported to the Netherlands for co-firing in large scale power production plants.

This report is divided into two parts. The Part 1 considers the amount of surplus wood residues available in Eastern Canada – Quebec, New Brunswick and Newfoundland that could potentially be converted to bio-oil for international trade. Part 2 presents data on a specific case study of wood residues in north-western Quebec.

Part 1: Wood residues available in Eastern Canada

1. Surplus wood residues in Eastern Canada

The source of wastewood available in Eastern Canada is residues from sawmills. The majority of surplus, unused wastewood from sawmills consists of bark residues. Whitewood residues from sawmills are used in value-added applications and existing cogeneration applications. The total amounts of surplus sawmill residues potentially available in Eastern Canada are shown in Table 1.

Forest residues such as roadside waste and forest floor waste are not considered to be economically available for processing to bio-oil in this region.

Table 1. Surplus wood residues in Eastern Canada.

Province	Surplus (millions of BDt per year)
Quebec	1.64
New Brunswick	0.18
Nova Scotia	0.06
Newfoundland	0.02

(*Source: Canadian Forest Service, 1999, (1).*)

2. Basis of availability for use in a bio-oil plants

The surplus wood residue from sawmills would be transported by truck to a bio-oil production plant. To determine how much of the above surplus wood residue could potentially be converted to bio-oil and how many bio-oil plants could be operated economically the following criteria were used:

1. The capacity range for a single bio-oil plant is 0.09–0.17 MBDt/a (million bone dry tonnes per year).
2. The maximum transport distance of the wood residue from the sawmill to the bio-oil production plant is 100 km.

Using the above criteria the number of possible bio-oil production plants and plant capacity was estimated by region in eastern Canada. Table 2 summarizes the estimate. The total surplus wood residue available in eastern Canada is approximately 1.32 million bone dry tonnes per year. A total of eight bio-oil production plants would process this wood residue.

Table 2. Potential waste wood to bio-oil plants in Eastern Canada.

Plant	Region (1)	Capacity (Mbdt/a)	Maximum Distance of Wastewood to Plant (km)	Distance from Plant to Port (km)	Port
1	Quebec	0.17	100	20	Quebec City
2	Quebec	0.17	100	100	Quebec City
3	Mauricie	0.17	100	200	Quebec City
4	Montreal	0.16	80	50	Montreal
5	Bas-Saint-Laurent	0.14	100	250	Quebec City
6	Gaspe, New Brunswick	0.17	100	500	Quebec City
7	Abitibi	0.17	100	550	Montreal
8	Saguenay-LacSaint-Jean	0.17	100	100	Quebec City
Total Wastewood Capacity		1.32			

Notes: 1. Regions are by Quebec Administrative Regions.
2. Waste wood is surplus waste from sawmills, consisting of mainly bark.
3. Mbdt/a = millions of bone dry tonnes per year

Part 2: Wood residues in North-Western Quebec

This section presents the estimated amounts of waste wood available for conversion to bio-oil and the cost for collection, processing and transportation in the specific region of northwestern Quebec.

The data presented is based on the forest management and processing operations of Domtar Inc. in northwestern Quebec. Domtar is currently investigating the feasibility of bioenergy uses for the sawmill wastes and forestry residues in the area. The wastes would be transported to a central bio-oil production facility in the region, operating at a capacity of 400 bdt/d (0.13 Mdbt/a) waste wood. The data is from a report on greenhouse gas emissions from the bioenergy systems under investigation, prepared for IEA Task 38 (2).

This data represents only the waste wood available from Domtar operations in northwestern Quebec, for which waste wood collection and disposal costs was available.

1. Sawmill wastes

1.1 Description

The sawmill waste data presented is from three sawmills (Malartic, Matagami and Val D'Or) operated by Domtar. The mills are located approximately 550 to 850 km northwest of Montreal. See Figure 1. The waste wood from these mills is currently dumped in local landfills where a tipping fee of CA$ 11.93/bone dry tonne (bdt), (US$ 7.52/bdt, Euro 7.64/bdt) is charged. The mills are operated throughout the year, usually at two shifts per day, depending on demand.

The sawmill wastes would be transported by truck to a fast pyrolysis bio-oil production plant located in Val D'Or.

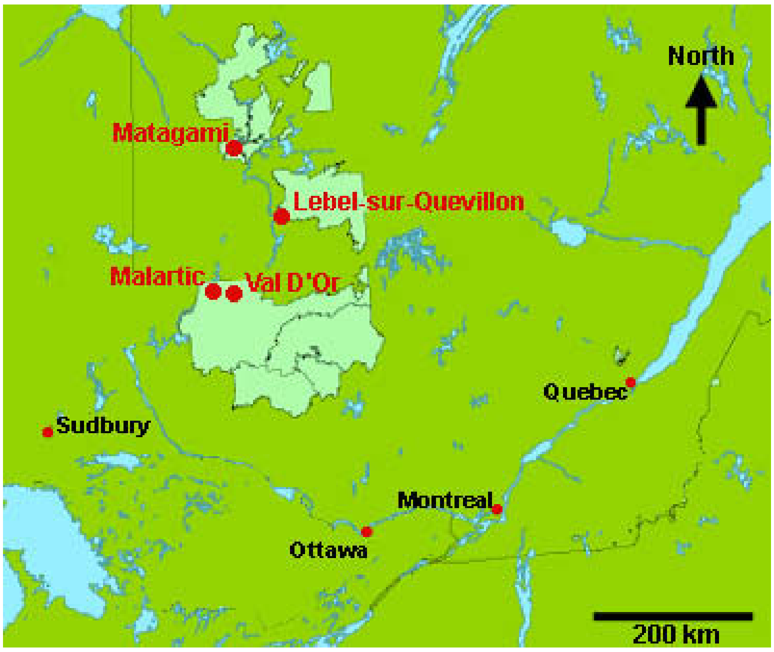


Figure 1. Domtar's operations in Northwest Quebec.

1.2 Production amounts, properties

Table 3 shows the annual sawmill surplus waste production from the three mills considered.

Table 3. Surplus mill waste production.

Mill	**Mill waste (bdt/yr)**
Malartic	19.856
Matagami	20.840
Val D'Or	15.298
Total	**55.994**

Table 4. Typical sawmill waste wood properties.

HHV (dry)	20.2 MJ/kg
LHV (dry)	18.9 MJ/kg
LHV (wet)	8.2 MJ/kg
Moisture content	50%
Density	750 kg/m3
Ash content	1.0%

1.3 Costs

Table 5 shows the distances from the sawmills to the bio-oil production plant.

Table 5. Distances from Val D'Or facility.

Distances from Val D'Or Facility	
Malartic	30 km
Matagami	270 km
Montreal port	550 km

The average cost to transport the sawmill waste to the bio-oil production plant is CA$ 6.91/bdt (Euro 4.42/bdt, US$ 4.35). This cost is the average transportation cost for the sawmill waste from the Malartic and Val D'Or mills only. The Matagami mill at 270 km from Val D'Or is too far away for economical transportation, so waste from that mill was not considered. The typical truck load is 35 m3. The diesel fuel consumption rate is 40 L/100 km.

2. Roadside waste

2.1 Description

Roadside waste or slash results from full-tree to roadside harvesting methods. Currently, roughly 90% of Domtar's operations around Val D'Or are full-tree logging. Domtar's operations are shifting away from full-tree methods since cut-to-length harvesting produces higher quality roundwood, while improving nutrient and environmental management. Over the next five years Domtar's full tree logging is expected to drop to 50%.

Domtar estimates that 750,000 cubic metres of roadside slash will be produced in 2002 in its licenses around Val D'Or. This represents 90% of the total slash produced from harvesting operations in these licenses. The roadside slash is currently piled into large slash piles and approximately 70% is burnt and 30% is left to decompose.

The roadside waste is recovered by chipping the slash at the roadside landings and transporting the chips to the bio-oil production plant.

2.2 Production amounts, costs

In 2002 an estimated 750,000 cubic meters, approximately 281,000 bdt, of roadside waste were produced.

The total cost to collect, process (chipping) and transport to the bio-oil plant is CA$ 63/bdt, (Euro 40.3/bdt, US$ 39.7/bdt). The chipping machine processes 33 m3/hr of waste and consumes 35 l/hr of diesel fuel.

3. Forest floor waste

3.1 Description

Forest floor waste or slash results from cut-to-length harvesting methods. Currently, roughly 10% of Domtar's operations around Val D'Or are cut-to-length logging, producing approximately 85,000 cubic meters of forest floor waste. This amount is expected to increase over the next five years as the full-tree harvesting operations shift to cut-to-length harvesting.

Currently the forest floor waste is left to decompose in the forest. To process in a bio-oil facility the waste is gathered using a forwarder, chipped and transported by truck to the bio-oil plant.

3.2 Production amounts, costs

In 2002 Domtar estimates that 85,000 cubic meters, approximately 32,000 bdt of forest floor waste were produced.

The total cost to gather, process (chipping) and transport the waste to the bio-oil plant is CA$ 78/bdt, (Euro 50/bdt, US$ 49.1/bdt). The forwarder processes 12m3/hr of waste, and consumes 8 L/hr of diesel fuel. The chipping machine processes 33 m3/hr of waste, and consumes 35 l/hr of diesel fuel.

References

1. Hatton, T. 1999. Canada's Wood Residues. A Profile of Current Surplus and Regional Concentrations. Canadian Forest Service, March 1999.
2. Bird, D.N. 2002. Greenhouse Gas Emissions from Bioenergy Systems. A Case Study – Liquid Fuels from Forest Waste. Prepared for IEA Bioenergy Task 38, May 25 2002.

Appendix 4: Energy inputs for biofuel pellet production and long distance transport

IEA Bioenergy task 35
Techno-Economic Assessments for Bioenergy Applications
3rd Working Group Meeting 2002-06-14

Björn Kjellström
Luleå University of Technology

Summary

Data for energy inputs for pellet production from biomass in Swedish pellet factories and long distance transport by ship have been collected. The study covers the production plants in Luleå, Skellefteå and Härnösand. All the plants use raw sawdust as feedstock and produce pellets with a diameter 6 or 8 mm with a moisture content of about 8%.

The production processes are however quite different. The most important difference is to what extent latent heat is recovered from the exhaust gas from the biofuel dryer. The specic inputs of drying energy and electric energy are also quite different as shown by the ranges given in the table below.

Type of input	Input kWh/ton product
Drying energy	310–1050
Electric energy	100–200
Steam for conditioning	0–25

The data show no correlation between the consumptions of drying energy and electric energy.

Ship transport in ships with capacities between 2500 ton and 5500 ton requires an input of gasoil equivalent to 1.9–4.1 kg/1000 tonkm. The consequence of this is that for instance transport of pellets between Luleå and Rotterdam leads to a fossil fuel consumption equivalent to less than 2.8% of the energy content of the biofuel pellets brought by the ship.

Introduction

One of the issues studied within IEA Bioenergy task 35 for the period 2001–2003 is international bioenergy trade. Some of this trade is expected to include biofuel pellets made in Sweden. Data regarding the energy input for production of such pellets and the energy input for long distance transport of the pellets by ship are necessary as input data for Life Cycle Analysis of biofuel pellet import.

The data presented in the following have been collected by interviews with plant managers of three large plants for pellet fuel production in Northern Sweden. The Swedish National energy Administration has financed the work.

Energy input for pellet production in Sweden

Production processes and product properties

This study covers the three large plants for biofuel pellet production in Sweden, namely

- Bioenergi I Luleå AB, located in Luleå
- Skellefteå Kraft AB, located in Skellefteå
- Bionorr, Bioenergi I Norrland AB, located in Härnösand.

All three plants use raw sawdust from softwood as feedstock but the processes used and the energy source used for drying of the feedstock are quite different, see Table 1.

Table 1. Production processes and product properties.

	Production plant		
	Bioenergi i Luleå	**Skellefteå Kraft**	**Bionorr, Härnösand**
Annual production capacity	90 000 ton	130 000 ton	80 000 ton
Feedstock:			
Source	Raw softwood sawdust	Raw softwood sawdust	Raw softwood sawdust
Moisture content	60–46%	About 55%	Average 52%
Product properties:			
Diameter	8 mm	8 mm	6 mm
Length	5–32 mm	5–15 mm	5–15 mm
Bulk density kg/m^3	635 kg/m^3	650 kg/m^3	650 kg/m^3
Moisture content	less than 10%	about 8%	6–8%
Lower heating value	at least 4.8 kWh/kg	at least 4.8 kWh/kg	4.9 kWh/kg
Short process description	The feedstock is dried in a rotary drier by means of flue gases (450 °C) from a back-pressure steam co-generation plant fuelled with combustible gases from a steel mill. The feedstock is then reduced to smaller particles in hammer mills, is heated by steam and pelletised. An electrostatic precipitator is used to mini-mise particulate emission.	The feedstock is dried by indirect heating by condensing steam. It is then ground in a hammer mill and pelletised. The steam is extracted at 26 bar from a back-pressure turbine in a co-generation plant, using biomass residue as fuel. The residual heat from the steam heated dryer is used for generation of low pressure steam that is expanded in a turbine.	The feedstock and hot flue gases from combustion of reject feedstock are brought into hammer mills where the feedstock is simultaneously dried and turned into smaller particles. The material is then pelletised. A scrubber is used to minimise particulate emissions. Residual heat is collected from the scrubber water and delivered to the district heating system of the town.
Energy source for drying	Flue gas from combustion of a mixture of gases from a steel mill	Steam generated by combustion of biomass residue	Flue gas from combustion of reject feedstock

Data on energy inputs

Material and energy balances for production of briquettes or pellets from sawdust have been presented by Arvidsson /1/ in 1997. The results are given in Table 2. The data apply for four plants in Sweden operated by Svensk BrikettEnergi AB. The data have been presented for production of 1 MWh of fuel energy in pellets or briquettes. In order to facilitate comparisons with data from the pellet production plants included in the present study a recalculation has been made to show inputs required for 1 ton of product.[1]

Table 2. Energy input for production of briquettes and pellets according to Arvidsson /1/.

Type of input	**Required input**	
	for 1 MWh product	**For 1 ton of product**
Feedstock	1010 kWh	4848 kWh
Fuel for drying	110 kWh	528 kWh
Electricity	21 kWh	101 kWh
Diesel fuel for internal transport and loaders	2.3 kWh	11 kwh
Lubrication oil	0.46 kWh	2.2 kWh
Binder material	5.0 kwh	24 kWh

It should be noticed that the energy required for drying varies dramatically with the moisture content of the feedstock. This is illustrated by Table 3, showing the theoretical heat requirement for evaporation of water so that a final moisture content of 8% is reached. The actual fuel energy input for drying will be somewhat higher, but the net energy use for drying might be less if latent heat in the wet off-gas stream is recovered. The processes used in Skellefteå and Härnösand include such heat recovery.

Table 3. Theoretical drying energy required.

Initial moisture content	**Drying energy per ton of product at 8% moisture, kWh**
60%	903
55%	725
50%	583
45%	467

Drying energy can also reduced by use of the open absorbtion process that was employed for a biofuel dryer at Martinsons sawmill in Bygdsiljum, Sweden, see Johansson and Westerlund /2/. The conventional dryer consumed 5970 kJ of fuel energy

---

[1] Assumed heating value of product 4,8 MWh/ton.

per evaporated kg of water whereas the dryer using recovery of latent heat consumed 1400 kJ of fuel energy and 360 kJ of electricity per kg of evaporated water.[2]

The plant managers at the three plants included in this study are not prepared to release energy input data that can be utilised by a third party for evaluation of the production costs. The data received have therefore been used to present the ranges of the specific energy inputs used in these plants. The results are shown in Table 4.

Table 4. Ranges in specific energy inputs for three pellet production plants in Sweden.

Type of input	**Input kwh/ton product**
Drying energy	310–1050
Electric energy	100–200
Steam for conditioning	0–25

It should be noticed that the three pellet production plants included in the present study are not using any binder material.

The large range in drying energy requirements reflects the measures taken to recover latent heat in the exhaust gas from the dryer. The difference in the moisture content of the feedsctock is less important. Examination of the data indicates no relationship between the drying energy used and the electric energy used. The plant with the lowest drying heat input is a different one that that with the lowest electric energy input and that with the highest drying heat input is not the same as that with the highest electric energy input. This is illustrated in Table 5 where the energy inputs are ranked (with rank 1 showing the lowest energy input).

Table 5. Ranking of energy inputs to the three pellet production plants.

Type of input	**Plant A**	**Plant B**	**Plant C**
Drying energy	1	3	2
Electric energy	3	2	1

---

[2] The theoretical consumption is about 2500 kJ per kg of evaporated water.

Energy sources for electricity generation in Sweden

The electricity supply system in Sweden is based primarily on hydro power and nuclear power, each roughly generating 50% of the supply. A small fraction of the electricity, usually less than 5%, is generated in co-generation plants. About 70% of that generation uses a fossil fuel, mainly coal.

As a consequence of the large dependence on hydro power, there are variations between years. For Life Cycle Analysis of the pellets production it is suggested that the electric energy consumed is generated as follows:

- hydro power 47%
- nuclear power 48%
- co-generation from biomass 1%
- co-generation from coal 4% (with marginal efficiency 70%).

Energy input for long distance transport by ship

Ships that are being used for transport of pellets to the Stockholm area can load between 2500 and 5500 ton of pellets.

The fuel used is gasoil with a sulphur content below 0.1%.

The fuel consumption is about 6 m3 or 5 ton for 24 hours of operation at the typical cruising speed, 11 knots.

The specific gasoil consumption will then be 1.9–4.1 kg/1000 tonkm depending on the size of the ship used.

Table 6 shows distances between the three pellets production plants in northern Sweden and two ports for supply to possible market areas, namely Stockholm and Rotterdam.

Table 6. Distances for sea transport of biofuel pellets.

Receiving port	**Location of pellet production plant**		
	Hörnösand	**Skellefteå**	**Luleå**
Stockholm	350 km	665 km	795 km
Rotterdam	2145 km	2460 km	2590 km

The conclusion is that even a fairly long sea transport to the Netherlands does not contribute significantly to the fossil fuel use caused by pellet transport. One ton of pellets representing about 5 Mwh of biofuel will require at most 11.8 kg of gasoil or 0,14 MWh of fossil fuel for the transport.

References

1. Arvidsson, A.M. 1997. Bioenergins material- och energibalans. Bioenergi nr 1, (1997), p. 14.

2. Johansson, L. & Westerlung, L. 2000. An open absorption system installed at a sawmill – description of a pilot plant used for timber and bio-fuel drying. Energy 25 (2000), pp. 1067–1079.

Published by

Series title, number and report code of publication

VTT Research Notes 2312
VTT–TIED–2312

Author(s)
McKeough, Paterson, Solantausta, Yrjö, Kyllönen, Hilkka, Faaij, Andre, Hamelinck, Carlo, Wagener, Martijn, Beckman, David & Kjellström, Björn

Title

Techno-economic analysis of biotrade chains

Upgraded biofuels from Russia and from Canada to the Netherlands

Abstract

This study consisted of in-depth techno-economic analyses of biofuel upgrading processes and of whole biotrade chains. The chains encompassed the production of pyrolysis oil or pellets from biomass residues in the source regions, the transportation of the upgraded fuels internationally over long distances and the final utilisation of the fuels. Four international biotrade chains were analysed in detail. The chains cover two source regions, North-Western Russia and Eastern Canada, and two traded commodities, pyrolysis oil and pellets. The chains terminate in the Netherlands where the imported biofuels are co-fired with coal in condensing power stations. The costs of the delivered biofuels were estimated to be in the range 18–30 EUR/MWh, with the costs of pellets about 25% lower than those of pyrolysis oil. The estimated electricity-generation costs displayed little dependence on the type of biofuel. Local-utilisation alternatives were also evaluated. It was concluded that, particularly when the local reference energy system is carbon intensive, local utilisation can be a more cost-efficient and a more resource-efficient option than international trade and use of biomass resources elsewhere. In practice, there are many factors which may limit local utilisation or make utilisation of biomass resources elsewhere more attractive. Overall, it was concluded that biotrade will have a definite and important role to play in reducing humankind's dependency on fossil fuels.

Keywords
biofuels, upgrading, fuel trade, pyrolysis oils, pellets, techno-economy assessment, trade chains, Russia, Netherlands, Canada

Activity unit
VTT Processes, Biologinkuja 3–5, P.O.Box 1601, FI–02044 VTT, Finland

ISBN			Project number
951–38–6745–5 (soft back ed.) 951–38–6746–3 (URL: http://www.vtt.fi/inf/pdf/)			C1SU00234
Date	**Language**	**Pages**	**Price**
November 2005	English	40 p. + app. 25 p.	B

Name of project	Commissioned by
22IEATEA3	International Energy Agency (IEA)
Series title and ISSN	**Sold by**
VTT Tiedotteita – Research Notes 1235–0605 (soft back edition) 1455–0865 (URL: http://www.vtt.fi/inf/pdf/)	VTT Information Service P.O.Box 2000, FI–02044 VTT, Finland Phone internat. +358 20 722 4404 Fax +358 20 722 4374

This study consisted of in-depth techno-economic analyses of biofuel upgrading processes and of whole biotrade chains. The chains encompassed the production of pyrolysis oil or pellets from biomass residues in the source regions, the transportation of the upgraded fuels internationally over long distances and the final utilisation of the fuels. Four international biotrade chains were analysed in detail. Local-utilisation alternatives were also evaluated. It was concluded that, particularly when the local reference energy system is carbon intensive, local utilisation can be a more cost-efficient and a more resource-efficient option than international trade and use of biomass resources elsewhere. In practice, there are many factors which may limit local utilisation or make utilisation of biomass resources elsewhere more attractive. Biotrade will have a definite and important role to play in reducing humankind's dependency on fossil fuels.

Tätä julkaisua myy	Denna publikation säljs av	This publication is available from
VTT TIETOPALVELU PL 2000 02044 VTT Puh. 020 722 4404 Faksi 020 722 4374	VTT INFORMATIONSTJÄNST PB 2000 02044 VTT Tel. 020 722 4404 Fax 020 722 4374	VTT INFORMATION SERVICE P.O.Box 2000 FI–02044 VTT, Finland Phone internat. + 358 20 722 4404 Fax + 358 20 7226 4374

ISBN 951-38-6745-5 (soft back ed.)
ISSN 1235-0605 (soft back ed.)

ISBN 951-38-6746-3 (URL: http://www.vtt.fi/inf/pdf/)
ISSN 1455-0865 (URL: http://www.vtt.fi/inf/pdf/)