IEA Bioenergy

Task 38

Greenhouse Gas Balances of Biomass and Bioenergy Systems

BIOMITRE

Greenhouse Gas Benefits of Wood Substitution: Comparing Concrete- and Wood-Framed Buildings in Finland and Sweden

Summary

Increasing the use of wood material in construction is a potential option for reducing net carbon dioxide (CO_2) emission because of the relatively low energy needed to manufacture wood products compared with alternative materials, the increased availability of potential biofuels from wood byproducts, and the storage of carbon in wood building materials. In this study we compare the net CO_2 emission over the lifecycle of materials in functionally equivalent buildings constructed with concrete and wood frames. Carbon accounting includes emissions from fossil fuel use during building material production, the replacement of fossil fuels by biomass residues from logging, wood processing, construction and demolition, carbon stock changes in forests and buildings, and cement process reactions. CO_2 emission from on-site construction and on-going maintenance and operation are not considered, and are not expected to differ between buildings of different frame materials. The results show that wood-framed construction requires less energy, and emits less CO_2 to the atmosphere, than concrete-framed construction. Replacement of fossil fuels by recovered biofuels contributes significantly to the lower net CO_2 emission of wood-frame buildings. We conclude that the use of wood building material instead of concrete, coupled with the greater integration of wood by-products into energy systems, would be an effective means of reducing fossil fuel use and net CO_2 emission to the atmosphere.

Figure 1. Building in the Wälludden project in Växjö, Sweden

Figure 2a. Group of wood-frame multi-storey apartment buildings in the Viikki area of Helsinki, Finland

Figure 2b. Building in the Viikki area of Helsinki, Finland

Leif Gustavsson, Roger Sathre

Ecotechnology, Mid-Sweden University, Östersund, Sweden

Kim Pingoud

Finnish Forest Research Institute, Helsinki, Finland and VTT Processes, Espoo, Finland

Methodology

Case study buildings

The functional unit in this study is the physical enclosure provided by a multi-storey apartment building during its 100-year lifespan. We compare two wood-framed buildings to two hypothetical buildings of identical size and functionality constructed with concrete frames. We define the baseline as the net CO_2 emission from the concrete-framed versions. The energy use and carbon emission resulting from on-site construction, maintenance and operation of the buildings are assumed not to differ between the concrete- and wood-framed buildings (Cole and Kernan 1996).

One of the buildings is in the Wälludden project constructed in Växjö, Sweden, and is a 4-storey building containing 16 apartments with a total usable floor area of 1190 m^2 (Figure 1). The other building is one of a group of seven buildings with 2 to 4 storeys built in the Viikki ecological area in Helsinki, Finland, and contains 21 apartments with a total usable floor area of 1175 m^2 (Figure 2). The materials required to construct wood-framed and concrete-framed versions of the two buildings were calculated (Adalberth 2000, Perälä 2004), and amounts of selected materials are shown in Table 1.

Table 1. Comparison of amounts of selected materials (tonnes) contained in the case study buildings.

Material \ Frame	Wälludden Wood	Wälludden Concrete	Viikki Wood	Viikki Concrete
Lumber	59	33	103	23
Particleboard	18	17	27	9
Plywood	21	20	15	0
Concrete	223	1352	190	2014
Plasterboard	89	25	139	22

Energy and CO_2 accounting

Final-use energy needed to produce the building materials is based on Fossdal (1995). We assume the end-use fossil fuel used in material production is petroleum. Primary energy use for electricity supply is based on a coal-fired condensing plant with a conversion efficiency of 40 % and distribution loss of 2 %. Natural gas-fired generation is also considered in the full report (Gustavsson et al. 2005). Variation of material processing energy, and its impact on carbon balance of wood substitution, is addressed by Gustavsson and Sathre (2005). Specific full-fuel-cycle carbon emission from fossil fuel use is 22 g C/MJ petroleum and 30 g C/MJ coal (Gustavsson et al. 1995).

The amount of biofuel available per unit of wood construction material is calculated from tree characteristics and material conversion efficiencies, and assumed 70 % recovery of logging residues (branches and treetops), 100 % recovery of wood processing residues (bark, sawdust and slabs) not used for particleboard manufacture and fuel for internal processing operations, 100 % recovery of wood construction waste, and 90 % recovery of wood demolition material (Figure 3). Biomass expansion factors for the dominant tree species in Sweden and Finland (Lehtonen et al. 2004) are used to determine quantities of stemwood, bark, branches, etc. Non-recovered logging residue and demolition wood are assumed to decompose aerobically.

We assume that the recovered biofuels replace coal. The CO_2 that would have been emitted during the entire fuel cycle of the replaced coal is calculated, using appropriate emission and combustion efficiency conversion factors to relate the heat value of the biofuel to the avoided fossil CO_2 emission. Replacement of natural gas by recovered biofuels is included in the full report (Gustavsson et al. 2005).

The recovery and transportation of biomass fuels is assumed to use diesel fuel, quantified as a percentage of the heat energy content of the biomass:
1 % of the heat content of the sawmill residue,
5 % of the logging residue (Börjesson 1996), and
1 % of the construction and demolition waste.

Changes in carbon stock in wood building materials and in forest biomass are calculated. It is assumed that the forest harvested when the building is constructed has completely re-grown by the end of the building lifecycle, consistent with Nordic forestry practice using an average 100-year rotation period. The carbon locked up in the wood building materials is assumed to be released at demolition through burning and decomposition. Thus, the net carbon stock is unchanged between the beginning and end of the lifecycle: the forest that is cut when the building is constructed re-grows by the end of the building lifecycle, and carbon sequestered in wooden building materials at construction is released at demolition. However, carbon stock in wood products is permanent as long as the wood frame building, at the end of its life, is replaced by another building with equal carbon

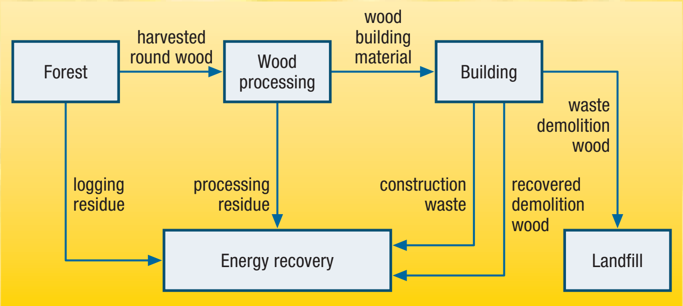

Figure 3. Schematic flow chart of wood materials during the building lifecycle.

content. Hence, the carbon stock change occurs only once, at the time when wood first replaces concrete.

The same amount of forestland is assumed available regardless of the frame material. This amount is the forest area required to produce the lumber, plywood and particleboard used in the wood-frame building. Less wood is used in the concrete-framed building, so some of the available forest is not used for building materials. We assume the carbon stock in this surplus forest does not change during the life span of the building, as the forest stand will have reached equilibrium where natural death and decay equals new growth. An increase in biomass of the surplus forest, and harvesting the surplus forest for bioenergy, are considered in the full report (Gustavsson et al. 2005).

CO_2 released by calcination reactions during Portland cement manufacture was taken into account, and we assumed that part of this CO_2 was re-fixed by carbonation reactions during the building lifecycle.

Results

Primary energy use

Based on total material mass inputs for the buildings, specific end-use energy use data for the manufacture and transportation of building materials, and data on fuel cycle, conversion and distribution losses, we calculated the total primary energy used for material production of the buildings (Figure 4). Biofuels shown are those used internally in the lumber production process for kiln drying.

Biofuel production

Quantities of biofuels derived from forest harvesting, wood-product manufacture, building construction and building demolition are shown in Figure 5. For comparison, the heat value of the sawmill residue used to make particleboard is also shown. The biofuels shown are available for external use and do not include the biomass used internally, shown in Figure 4.

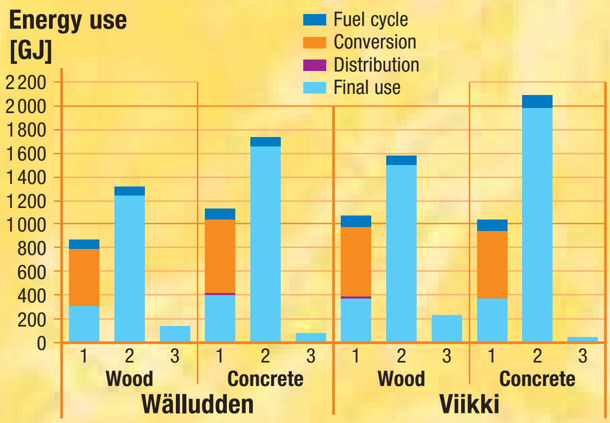

Figure 4. Primary energy use for production and transportation of building materials for the Wälludden and Viikki buildings with wood and concrete frames, divided into end-use electricity (1), end-use fossil fuels (2), and end-use biofuels (3).

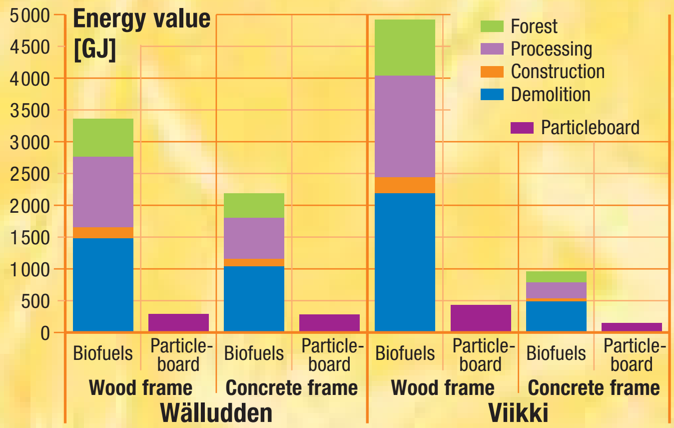

Figure 5. Production of biofuels derived from wood byproducts of the Wälludden and Viikki buildings with wood and concrete frames. For comparison, the heat value of sawmill residue used to make particleboard is also shown.

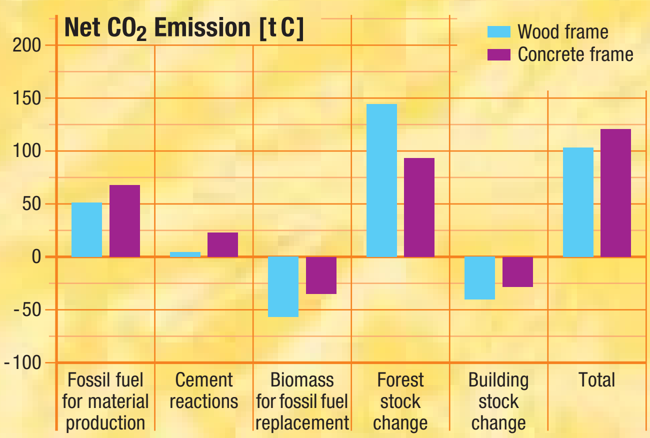

Figure 6a. Net CO_2 emission during year of construction of the Wälludden building.

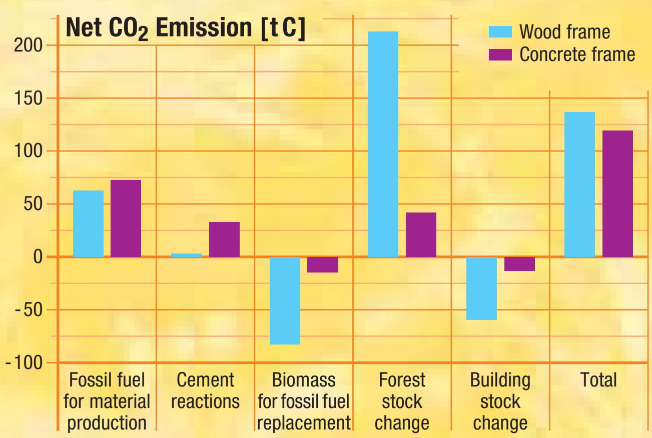

Figure 6b. Net CO_2 emission during year of construction of the Viikki building.

Net CO_2 emission at year of construction

The net CO_2 emission at the year of construction includes emissions from fossil fuel used for production of the materials, process reactions from cement manufacture, substitution of fossil fuel by forest and sawmill residues and construction waste, and carbon stock changes due to the cutting of the forest and construction of the buildings. Net CO_2 emission is positive in all cases. The total net CO_2 emission is slightly lower when the Wälludden building is built with a wood frame, and when the Viikki building is built with a concrete frame, due to the different proportional use of concrete and wood in the two buildings.

Net CO_2 emission for 100-year lifecycle

Net CO_2 emission for the 100-year lifecycle of the buildings includes all the emissions from the year of construction, plus re-growth of the forest, uptake of CO_2 by cement carbonation, demolition of the buildings, and replacement of fossil fuel by wood-based demolition waste.

Figure 7 shows the lifecycle net CO_2 emission for the Wälludden and Viikki buildings. The wood-framed buildings have the lowest lifecycle carbon emissions, with negative emissions of 46–83 tonnes. The concrete-framed buildings have positive net carbon emissions because of higher emission during material manufacture and less replacement of fossil fuel by recovered biofuels.

Building with wood instead of concrete results in a lifecycle emission reduction of 69 tC and 157 tC for the Wälludden and Viikki buildings, respectively. Per service unit of usable floor area, this is 0.058 tC/m^2 and 0.13 tC/m^2, respectively. Per unit of dry biomass used (including construction material and recovered logging and processing residues), this is 0.86 tC/t biomass and 0.63 tC/t biomass, respectively.

Carbon sequestration in wood products

In Table 2 the carbon sequestration in wood products (i. e. the difference in carbon stock of the wood- and concrete-framed buildings) is compared to the fossil fuel and cement process emission changes. The carbon stock of wood products in the building is of minor importance to the lifecycle net CO_2 emission. During a building's life span the stock could be significant, but over the complete lifecycle the change in carbon stock will be about zero.

Table 2. Net CO_2 emissions from fossil fuels, cement reactions and carbon stock changes (in tonnes of C) of the wood-framed and concrete-framed versions of the Wälludden and Viikki buildings. Surplus forest in concrete-framed case is not included.

Type of net CO_2 emission	Wälludden			Viikki		
	Wood (W)	Concrete (C)	Difference (W–C)	Wood (W)	Concrete (C)	Difference (W–C)
Net fossil fuel emission	-49.9	1.7	**-51.6**	-85.7	43.3	**-129.0**
Fossil fuel use in material production	51.3	67.7	-16.4	62.6	72.4	-9.9
Fossil fuel replacement by biofuel	-101.2	-66.0	-35.2	-148.3	-29.1	-119.2
Emission from cement reactions	4.0	21.0	**-17.0**	2.9	30.4	**-27.6**
Carbon stock in building materials	-40.3	-28.2	**-12.0**	-59.5	-13.1	**-46.3**

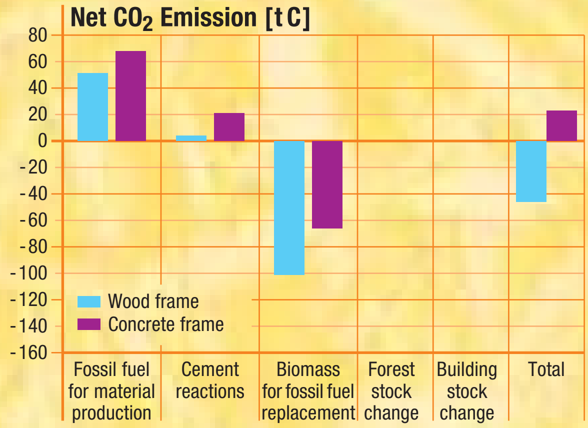

Figure 7a. Lifecycle net CO_2 emission for the Wälludden building.

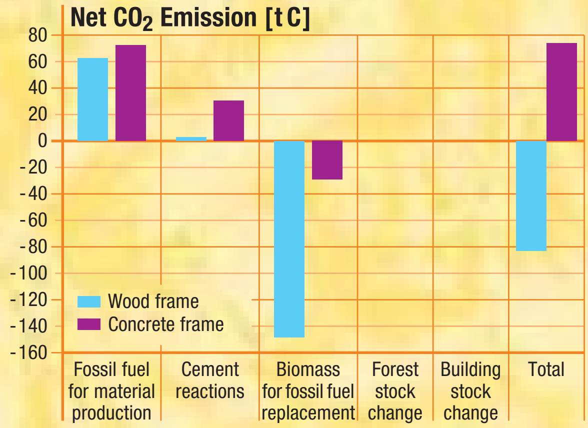

Figure 7b. Lifecycle net CO_2 emission for the Viikki building.

Uncertainties

The results of this study are subject to a number of uncertainties:

- The quantities and types of materials used will vary with each building type and design.
- Primary energy use in material production varies with time, place, and process technology.
- The carbon intensity of energy supply will affect the net CO_2 emission.
- The percentage of total biomass residue that is recovered, and the carbon intensity of the fossil fuel replaced by the recovered biofuel, will affect the net CO_2 emission.
- The decomposition dynamics of unburned biomass, such as roots, stumps and unrecovered demolition wood in landfills is variable and not well known.

Nevertheless, Gustavsson et al. (2005) and Gustavsson and Sathre (2004) varied several of these uncertain parameters and found wood-frame building construction to generally have lower lifecycle primary energy use and CO_2 emission compared to concrete-frame buildings. These results also corroborate other studies reaching similar conclusions (e.g. Buchanan and Levine 1999, Pingoud and Perälä 2000, Scharai-Rad and Welling 2002, Lippke et al. 2004).

Conclusions

The results show that the production of materials for wood-framed construction requires less energy, and emits less CO_2 to the atmosphere, than the production of materials for concrete construction. Furthermore, this study shows the importance that fossil fuel replacement has on total net CO_2 emission. Over the lifecycle of wood-framed buildings, the recoverable amounts of logging, wood processing, construction and demolition residues is greater than the fossil energy inputs to material production, leading to negative net CO_2 emission. The CO_2 advantage of wood over concrete construction thus depends strongly on the percentage of biomass residues recovered for fossil fuel substitution. The CO_2 advantage of wood-framed buildings becomes more favourable when fossil fuels of higher carbon intensity are replaced. The carbon stock of wood products in the building is of minor importance to the lifecycle net CO_2 emission.

This study suggests that a net reduction of CO_2 emission can be obtained by increasing the proportion of wood-based materials used in building construction relative to concrete materials, coupled with the greater integration of wood by-products into energy systems.

References

Adalberth, K.: 2000. Energy Use and Environmental Impact of New Residential Buildings. Ph. D. Dissertation, Department of Building Physics, Lund University, Sweden.

Buchanan, A. H., Levine, S. B.: 1999. Wood-based building materials and atmospheric carbon emissions. Environmental Science and Policy. 2, 427–437.

Börjesson, P.: 1996. Energy analysis of biomass production and transportation. Biomass and Bioenergy. 11(4), 305–318

Cole, R. J., Kernan, P. C.: 1996. Life-cycle energy use in office buildings. Building and Environment. 31(4), 307–317.

Fossdal, S.: 1995. Energi- og Miljøregnskap for bygg (Energy and Environmental Accounts of Building Construction). Report 173, The Norwegian Institute of Building Research, Oslo. (in Norwegian)

Gustavsson, L., Börjesson, P., Johansson, B., Svenningsson, P.: 1995. Reducing CO_2 emissions by substituting biomass for fossil fuels. Energy. 20(11), 1097–1113.

Gustavsson, L., Pingoud, K., Sathre, R.: 2005. Carbon dioxide balance of wood substitution: comparing concrete- and wood-frame buildings. Mitigation and Adaptation Strategies for Global Change (in press). Web accessible at www.joanneum.at/iea-bioenergy-task38/projects/task38casestudies/finswe_fullreport.pdf

Gustavsson, L., Sathre, R.: 2005. Variability in energy and carbon dioxide balances of wood and concrete building materials. Building and Environment (in press).

Lehtonen, A., Mäkipää, R., Heikkinen, J., Sievänen, R., Liski, J.: 2004. Biomass expansion factors (BEFs) for Scots pine, Norway spruce and birch according to stand age for boreal forests. Forest Ecology and Management. 188(1–3), 211–224.

Lippke, B., Wilson, J., Perez-Garcia, J., Bowyer, J., Meil, J.: 2004. CORRIM: Life-cycle environmental performance of renewable building materials. Forest Products. 54(6), 8–19.

Perälä, A-L.: 2004. VTT Building and Transport, Finland. Personal communication.

Pingoud, K., Perälä, A-L.: 2000. Studies on greenhouse impacts of wood construction. 1. Scenario analysis of potential wood utilisation in Finnish new construction in 1990 and 1994. 2. Inventory of carbon stock of wood products in the Finnish building stock in 1980, 1990 and 1995. Publication 840, Technical Research Centre of Finland, VTT Julkaisuja, Espoo. (in Finnish, abstract in English) www.inf.vtt.fi/pdf/julkaisut/2000/J840.pdf

Scharai-Rad, M., Welling, J.: 2002. Environmental and energy balances of wood products and substitutes. Food and Agricultural Organization of the United Nations. Rome.

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IEA Bioenergy

Task 38

IEA Bioenergy (www.ieabioenergy.com) is an international collaborative agreement, set up in 1978 by the International Energy Agency (IEA) to improve international cooperation and information exchange between national bioenergy research, development and demonstration (RD & D) programs. IEA Bioenergy aims to realize the use of environmentally sound and cost-competitive bioenergy on a sustainable basis, thereby providing a substantial contribution to meeting future energy demands.

IEA Bioenergy Task 38 brings together the work of national programs in 13 participating countries on GHG Balances for a wide range of biomass systems, bioenergy technologies and terrestrial carbon sequestration. As one example of work, case studies have been conducted by applying the standard methodology developed by the Task 38. The case studies have assessed and compared GHG balances of different bioenergy and carbon sequestration projects in the participating countries, and the Finnish and Swedish case study is one example.

Task Coordination

Bernhard Schlamadinger
Joanneum Research
Elisabethstrasse 5, A-8010 Graz, AUSTRIA
Phone: +43 316 876-1340 • Fax: +43 316 8769-1340
e-mail: bernhard.schlamadinger@joanneum.at

Kimberly Robertson
New Zealand Force Consulting
444 Pukehangi Rd., Rotorua, NEW ZEALAND
Phone: +64 7 343-9559 • Fax: +64 7 343-9557
e-mail: kimberlyrobertson@xtra.co.nz

National Team Leaders

AUSTRALIA
Annette Cowie
State Forests New South Wales
P. O. Box 100 Beecroft, New South Wales 2119
Australia
Phone: +61 2 9872-0138 • Fax: +61 2 9871-6941
e-mail: annettec@sf.nsw.gov.au

AUSTRIA
Susanne Woess-Gallasch
Joanneum Research
Elisabethstrasse 5, A-8010 Graz, Austria
Phone: +43 316 876-1330 • Fax: +43 316 8769-1330
e-mail: susanne.woess@joanneum.at

CANADA
Terry Hatton
Canadian Forest Service, Natural Resources Canada
580 Booth St., Ottawa, Ontario
K1A OE4 Canada
Phone: +1 613 947-9077 • Fax: +1 613 947-9020
e-mail: thatton@ncran.gc.ca

CROATIA
Snjezana Fijan-Parlov
EKONERG
Koranska 5, PP 144, HR-10000 Zagreb, Croatia
Phone: +385 1 6000-122 • Fax: +385 1 6171-560
e-mail: sfijan@ekonerg.hr

DENMARK
Niels Heding
Danish Forest and Landscape Research Institute
Hoersholm Kongevej 11
DK 2970 Hoersholm, Denmark
Phone: +45 45 763-200 • Fax: +45 45 763-233
e-mail: NIHE@kvl.dk

FINLAND
Sampo Soimakallio
VTT-Processes
P.O. Box 1606,FIN-02044 VTT (Espoo)
Phone: +358 9 456-6767 • Fax: +358 9 456-7026
e-mail: sampo.soimakallio@vtt.fi
Kim Pingoud
Finnish Forest Research Institute
Unioninkatu 40 A, FIN-00170 HELSINKI
Phone: +358 10 211 2063, Fax: +358 10 211 2104
e-mail: kim.pingoud@metla.fi

IRELAND
Kenneth Byrne
Centre for Hydrology, Micrometeorology & Climate Change, Department of Civil and Environmental Engineering, University College Cork
Phone: +353 21 490-3025 Fax: +353 21 427-6648
e-mail: k.byrne@ucc.ie
Carly Green
Forest Ecosystem Research Group
University College Dublin
Phone: +353 1 716-7673, Fax: +353 1 716-1102
e-mail: carly.green@ucd.ie

THE NETHERLANDS
Kees Kwant
NOVEM
Catharijnesingel 59, Postbus 8242, 3503 RE Utrecht
The Netherlands
Phone: +31 30 2393-587 • Fax: +31 30 2316-491
e-mail: a.de.zeeuw@novem.nl

Andre Faaij
Utrecht University, Copernicus Institute
Heidelberglaan 2, 3584 CS Utrecht, The Netherlands
Phone: +31 30 2537-643 • Fax: +31 30 2537-601
e-mail a.p.c.faaij@chem.uu.nl

NEW ZEALAND
Kimberly Robertson
Force Consulting
444 Pukehangi Rd., Rotorua
New Zealand
Phone: +64 7 343-9559 • Fax: +64 7 343-9557
e-mail: kimberlyrobertson@xtra.co.nz

NORWAY
Birger Solberg
Agricultural Univ. of Norway, Dep. of Forest Sciences
P. O. Box 5044, N-1432 Ås, Norway
Phone: +47 64 94 88 80 • Fax: +47 64 94 88 90
e-mail: birger.solberg@umb.no

SWEDEN
Leif Gustavsson
Mid Sweden University
SE-831 25 Östersund, Sweden
Phone: +46 63 165-979 • Fax: +46 63 165-450
e-mail: leif.gustavsson@miun.se

UNITED KINGDOM
Robert Matthews
Forest Research, Alice Holt Lodge, Farnham, Surrey, GU10 4LH, United Kingdom
Phone: +44 1420 526-235 • Fax: +44 1420 234-50
e-mail: robert.matthews@forestry.gsi.gov.uk

UNITED STATES
Matthew Ringer
National Renewable Energy Laboratory
1617 Cole Blvd. MS-1613, Golden, Colorado, U.S.A.
Phone: +1 303 384-7747 • Fax: +1 303 384-6363
e-mail: matthew_ringer@nrel.gov

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