Life Cycle Assessment of wood pellets and bioethanol from wood residues and willow

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Abstract

The uptake of biomass as an energy source can reduce the use of and dependence on fossil fuels in heating and transportation in New Zealand. The environmental impacts and efficiency of three biomass options; wood pellets produced from sawmill residues, and bioethanol produced from forest residues and from purpose grown-willow, are analysed using Life Cycle Assessment.

Wood pellets are a renewable energy fuel used mainly for residential heating. The production of heat from wood pellets is viable from an energy point of view, with varying efficiencies depending on the type of fuel used to dry timber at the sawmill. Heat from wood pellets has a significantly lower global warming potential than the production of heat from a heat pump.

Bioethanol from wood is a renewable fuel that can be used as a partial substitute to petrol in transportation. The production of bioethanol is viable from an energy point of view, as approximately 4.8 MJ and 3.7 MJ of bioethanol are produced from willow and forest residues respectively, for every 1 MJ of input energy.

The use of bioethanol as a partial substitute of petrol reduces the global warming potential and non-renewable energy use of the fuel. The uptake of wood pellets for heating and bioethanol as a fuel for transportation would help reduce fossil fuel use in New Zealand.

Keywords: Biofuels, forest residues, willow, Life Cycle Assessment.

Introduction

Current New Zealand and international trends are leaning away from fossil fuels and towards more renewable forms of energy. Concerns about climate change, as well as the rising costs of fuel, are driving this trend. There is therefore a need to reduce the use of and dependence on fossil fuels in New Zealand.

This work analyses the environmental sustainability and performance of three biomass sources that have the potential to replace fossil fuels:

- Wood pellets from sawmill residues
- Bioethanol from forest residues,
- Bioethanol from purpose grown willow

The environmental impacts of these biofuels have been analysed using Life Cycle Assessment (LCA), and compared with common fossil fuel alternatives.

Methodology

LCA is an analytical methodology for the systematic evaluation of the environmental impacts of a product or service through all stages of its life. It extends from extraction and processing of raw materials through to end-of-life disposal. Upstream processes such as the production of diesel used in transport as well as the emissions during diesel combustion are taken into account, including all related environmental impacts.

LCA is an appropriate methodology for biofuels analysis, and has been used in other New Zealand biofuels studies, in particular *Bioenergy Options for New Zealand. Pathway Analysis* (Hall and Gifford 2008).

An internationally accepted framework for LCA methodology is defined in ISO 14040 and 14044 (International standardisation organisation 2006).

Four different phases can be distinguished:

1. *Goal and Scope Definition*
2. *Inventory Analysis*
3. *Impact Assessment*
4. *Interpretation*

This Life Cycle Assessment was performed following the ISO14040 guidelines.

Impact Assessment Categories

The environmental impacts of the biofuels were assessed using CML2001 baseline methodologies (Guinée 2002), which allow for analysis of environmental impacts in a number of different impact categories. The impact categories assessed in this study are the following:

- Global Warming Potential (kg CO_2 equivalents) (GWP)
- Acidification Potential (kg SO_2 equivalents) (AP)

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- Eutrophication Potential (kg PO_4^3 equivalents) (EP)
- Photochemical ozone creation Potential (kg C_2H_2 equivalents) (POCP)

Renewable and non-renewable energy use were also assessed.

The life cycles of the biofuels were analysed using the GaBi 4.3 software (IKP, PE international).

Allocation

The outputs of forestry and sawmill operations were allocated a share of the total process impacts proportional to their contribution by mass. Mass allocation is consistent with the ISO 14044 standard.

The choice to allocate by mass was made because the future economic value of many of the by-products of forestry and sawmilling is uncertain. Allocation by mass allows a proportion of the impacts of multi-output processes to be attributed to the by-products, without changes due to price variation.

Literature also suggests that where timber production is the main function of the forest system (as is the case for wood pellets and bioethanol from forest residues), mass allocation is the most practical allocation method to use (Jungmeier *et al*. 2002).

Carbon flows

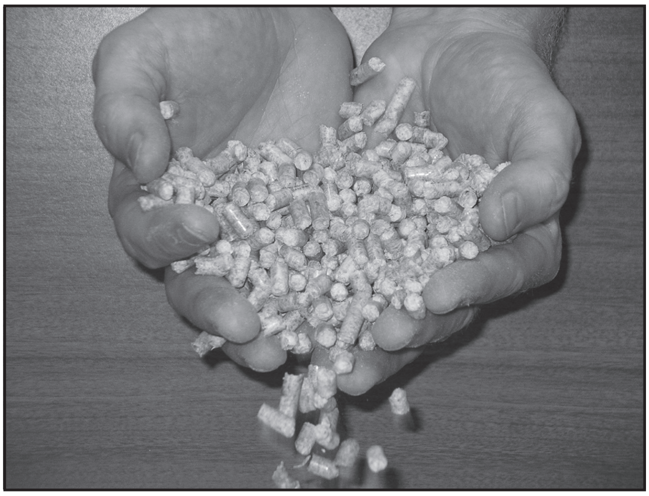
The wood life cycle is assumed to be carbon neutral, in that all carbon sequestrated during growth of the wood is assumed to be released during combustion of the wood pellets/bioethanol. The PAS (Publicly Available Specification) specification on carbon footprinting (PAS 2050: 2008) says that emissions arising from the use of biomass shall include the carbon emissions arising from the production of the fuel, but exclude the carbon emissions arising from the biogenic carbon component of the fuel.

Goal

The goals of this study were;

- determine the viability of wood pellets and ethanol production from an energy point of view (i.e. to determine if the ratio of embodied energy to energy output is favourable)
- compare the environmental impacts wood pellets and ethanol to current fossil fuel alternatives, to see which is the most environmentally friendly
- identify the hotspots of the wood pellet and ethanol life cycles to target future research

The results are presented separately for wood pellets and bioethanol.



Wood pellets

Wood pellets are typically made from dried shavings and/or sawdust. Shavings are produced from the planing of kiln dried timber and so have a low moisture content. Sawdust must be dried in a furnace before it can be processed to produce wood pellets. Once made, the pellets are transported to consumers, and are combusted to produce heat. In this analysis, the environmental performance of wood pellets are compared with heating from heat pumps

Four scenarios were analysed in this study, using different feedstocks for pellet production and different boiler fuels for kiln drying:

Scenario 1. Feedstock: shavings
Boiler: national average boiler fuel mix (82% biomass, 12% coal, 6% gas)

Scenario 2. Feedstock: shavings
Boiler: 100% biomass (sawmill residues)

Scenario 3. feedstock: shavings
Boiler: 100% coal.

Scenario 4. Feedstock: Combination of shavings and dried sawdust
Boiler: 100% forest residues.

System Boundary

The analysis took into account the life cycle stages: forestry, forest residue production (scenario 4 only), sawmilling, wood drying from the boiler and furnace, timber planing, pellet production and transportation, and pellet combustion (presented visually in Figure 1 and Figure 2).

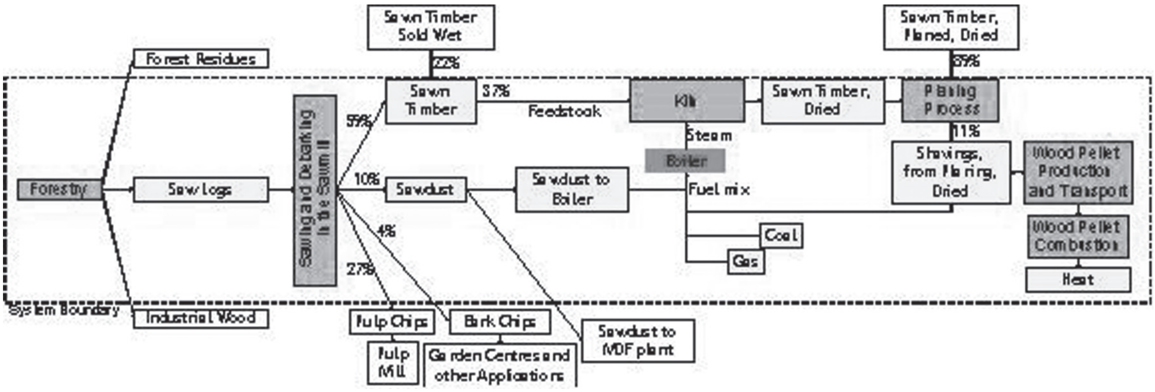


Figure 1: System Boundary of heat from wood pellets - Existing boiler fuel scenarios

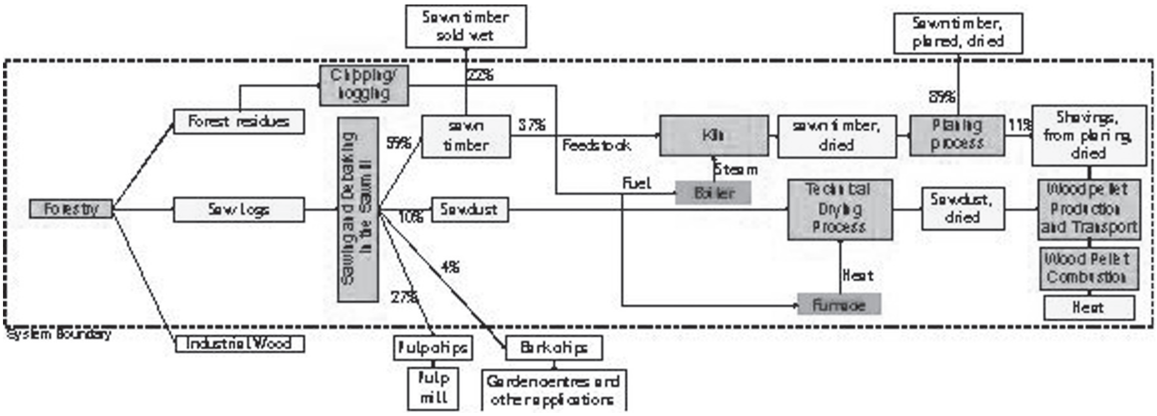


Figure 2: System Boundary of heat from wood pellets - Forest residues as boiler fuel scenario

The results are presented in terms of the production of 1MJ of heat (the 'functional unit'). Using the functional unit, the environmental impacts of the four wood pellet scenarios are able to be compared with the production of 1MJ of heat from a heat pump.

Inventory

The inventory data is structured according to the stages of the wood pellet life cycle.

Forestry

Forestry includes the processes nursery, site preparation, forest establishment, forest tending, and harvesting.

The forestry stage of the wood pellet life cycle was taken from Greenhouse Gas emissions of the forestry sector in New Zealand (Sandilands and Drysdale 2008).

Forest Residue Production

Forest residue production involves the collection of forest residues from the forest, transportation to a diesel or electric hogger, and the hogging of the residues. Data for forest residue production was taken from *Life Cycle Analysis of energy production from forest residues and purpose grown forest* (Sandilands *et al.* 2008).

Sawmill

The New Zealand average sawmill converts sawlogs to sawn timber (kiln-dried and green), bark, pulp chips and sawdust. Sawmill input data was obtained from EF+ project surveys (Hodgson, 2008).

Data for the planing of kiln-dried timber was taken from the ecoinvent v2.0 database (Ecoinvent 2008).

Boiler and Furnace

The boiler dries sawn timber from a moisture content

of 100% dry basis (d.b.) to 11% d.b. The New Zealand average boiler fuel mix is 82% wood, 12% coal and 6% gas on an energy basis (Jack, 2008). The boiler requires 2.9 GJ of energy from fuels to produce one dried cubic metre of timber (Hodgson *et al*. 2002).

The furnace is used to dry sawdust in the forest residues scenario only (scenario 4). The furnace requires 2.4 GJ of energy from forest residues to produce one dried cubic metre of sawdust (Hodgson *et al*. 2002).

Pellet Production and Transport

The wood is converted into wood pellets using electricity-driven processes. The pellets are then transported to individual homes for combustion. Data for wood pellet production was taken from the ecoinvent v2.0 database (Ecoinvent 2008). The wood pellet transportation distance is based on a weighted average estimate of the current pellet distribution.

Pellet Combustion

Pellet combustion requires a small amount of electricity to operate a fan to disperse the heat, provide air for combustion, to supply pellets and for ignition. Data for wood pellet combustion was taken from the ecoinvent v2.0 database (Ecoinvent 2008).

Heat Pump

A heat pump is a current home heating option that uses electricity to extract heat from the outside environment. The impacts to produce 1MJ of heat from a heat pump are due to electricity use. The New Zealand electricity mix has a fossil fuel (non-renewable energy) component (approximately 45%) (Ministry of Economic Development 2004).

Two heat pumps were evaluated in this study;

- The 'New Zealand average' heat pump (consumer.org.nz 2006): efficiency of 1:2.2.
- A 'high efficiency' heat pump: efficiency of 1:4. This heat pump is readily available on the New Zealand market, and therefore represents a currently obtainable 'best practice' heat pump.

The amount of electricity required to produce 1 MJ of heat is dependent on the efficiency of the heat pump.

Results

The global warming potential of wood pellets using the national boiler fuel mix is 40% lower than a high efficiency heat pump. The heat pumps have a high global warming potential due to the fossil fuel component of the New Zealand electricity mix.

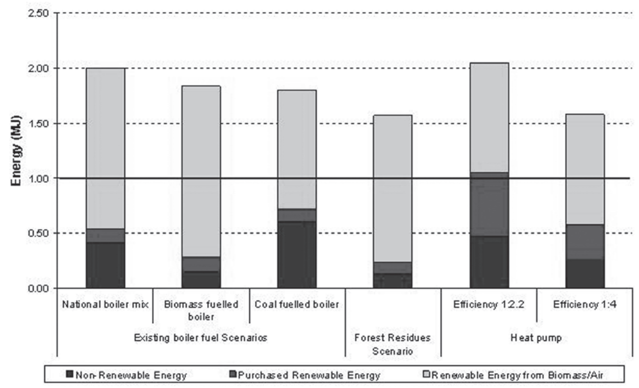


Figure 3: Renewable and non-renewable energy input to produce 1 MJ of heat from wood pellet combustion and from a heat pump

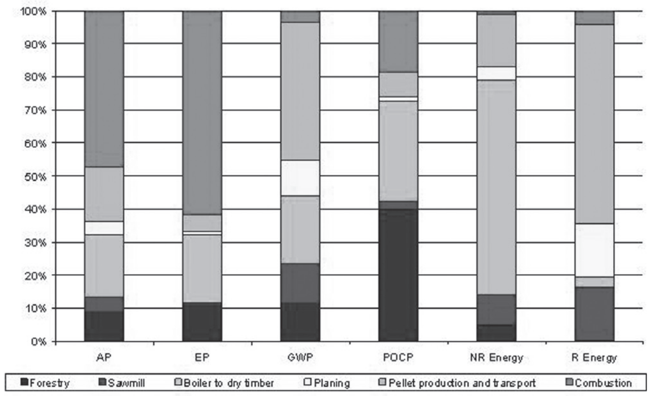


Figure 4: Life cycle impacts of 1 MJ of heat from wood pellet combustion -scenario 1: national boiler fuel mix

The energy required to produce 1MJ of heat can be divided into non renewable (fossil fuel), 'purchased' renewable, and 'free' renewable energy (see Figure 3).

The purchased renewable energy is predominantly the renewable energy contained in the New Zealand electricity mix (i.e. hydroelectricity, electricity from wind, geothermal energy). The combined non-renewable and purchased renewable energy represent the total purchased energy.

The remaining renewable energy is the 'free' energy. For wood pellets this is the energy contained within the wood in the forest (the 'biomass energy'). For the heat pumps, this energy is the heat contained in the outside air, which is extracted by the heat pump to heat the house.

The national boiler mix and the coal-fuelled boiler scenario have a higher non-renewable energy use than the wood-fuelled boiler scenarios due to the fossil fuels (coal and natural gas) used to fuel the boiler.

The large contribution of the boiler to the non-renewable (NR) energy use is due to the coal and natural gas used to fuel the boiler.

Acidification and eutrophication are dominated by the combustion of wood pellets, due to ammonia, nitrogen oxide, and other emissions during pellet combustion (see Figure 4).

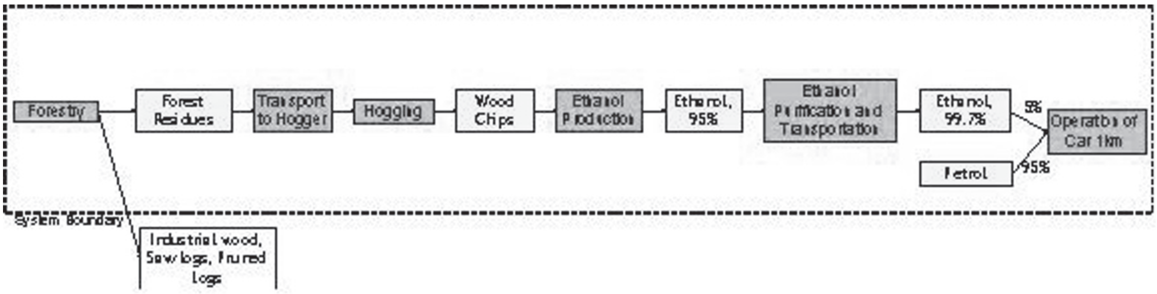


Figure 5: System Boundary of bioethanol from forest residues

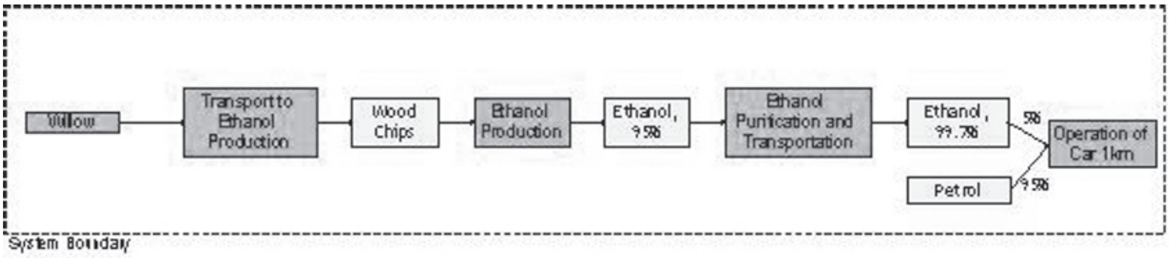


Figure 6: System Boundary of bioethanol from willow

Forestry is the largest contributor to the photochemical ozone creation potential, partially due to diesel and other fossil fuel use in forestry operations.

The small global warming and non-renewable energy consumption of wood pellet combustion is due to electricity use for the fan, etc.

Bioethanol

Bioethanol is a renewable fuel that can be mixed with petrol to fuel a car.

The use of forest residues as a source of bioethanol is attractive because, as a by-product of forestry operations, forest residues do not use additional land. This is important where land competition is present between (for example) agriculture, forestry, food crops or energy crops.

Forest residues form only a small percentage of the outputs of forestry. Large scale bioethanol production would require a forest purpose-grown for bioethanol production. Willow was chosen as a purpose-grown forest option because of its fast growth and ability to coppice (re-grow from the cut stump) (Snowdon et al. 2008).

Bioethanol is produced from the hogged wood residues/ willow and is then purified. This purified bioethanol is mixed with petrol and used to drive a car a distance of 1 km.

System Boundary

The analysis of bioethanol from wood took into account the life cycle stages: forestry, forest residue processing (bioethanol from forest residues), wood production from willow (bioethanol from willow), bioethanol production, bioethanol purification, and burning of the bioethanol/ petrol mix in a passenger car (presented visually in Figure 5 and Figure 6).

Functional Unit

The results are presented in terms of 1km distance driven by a passenger car (the 'functional unit'). Using the functional unit, the environmental impacts of the bioethanol life cycle are able to be compared with petrol.

Inventory

The inputs into the bioethanol from forest residues and willow life cycles are detailed by life cycle stage:

Forestry and Forest Residue Production

See Wood pellets inventory

Wood from Willow

The production of wood from willow is based on the paper 'Life cycle assessment of a willow bioenergy cropping system' (Heller *et al*. 2002) and on 'Energy Farming with Willow' (Snowdon *et al*. 2008).

The harvested willow chips are transported 50 km to the bioethanol production plant.

Bioethanol Production

Bioethanol is produced from the cellulosic content of the wood. The efficiency of bioethanol production on an energy basis is 42% (Ecoinvent 2008). Bioethanol production from wood chips occurs using enzymatic hydrolysis of cellulose and the co-fermentation of glucose and xylose to bioethanol (Ecoinvent, Jungbluth 2007).

Bioethanol Purification

The bioethanol is then purified so that it can be mixed with petrol. The purification process requires electricity and natural gas. Data for the production and the purification of bioethanol was taken from the ecoinvent v2.0 database (Ecoinvent 2008).

Passenger Car and Petrol

The purified bioethanol is then mixed with petrol at a ratio of 5% bioethanol, 95% petrol by mass. This is used to drive a passenger car a distance of 1 km.

The burning of bioethanol is assumed to produce only biogenic CO_2 and water.

Results

The use of bioethanol as a partial substitute for petrol reduces all environmental impacts analysed, using both willow and forest residues as a feedstock (see Figure 7). The renewable energy consumption is higher for bioethanol than petrol, which increases the overall energy use. The majority of the renewable energy is due to the solar energy in the wood (biomass energy).

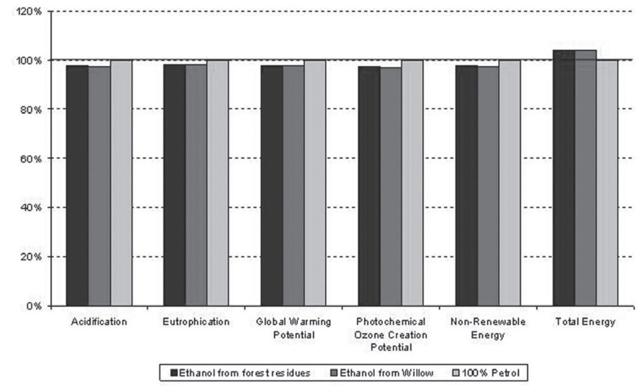


Figure 7: Life cycle impacts relative to petrol of the combustion of 5% bioethanol mixed with 95% petrol by mass to transport a passenger car a distance of 1km

The reduction in the environmental impacts of fuel combustion with the addition of bioethanol is necessarily small, as bioethanol contributes only 5% to the fuel on a mass basis.

Excluding the impacts of petrol, bioethanol production is the largest contributor to the environmental impacts of the bioethanol life cycle for the majority of impact categories analysed, including non-renewable energy consumption.

Bioethanol production is the largest contributor to the acidification, eutrophication, and photochemical ozone creation potentials, although processes with high diesel use also contribute.

Discussion

The production of heat from wood pellets is viable from an energy point of view, as between 0.24 MJ (forest residues scenario) and 0.72 MJ (coal-fed boiler scenario) of energy input is required to produce 1 MJ of heat from wood pellets (excluding the inherent biomass energy in the wood).

Equally, the production of bioethanol from forest residues and from willow is viable from an energy point of view, as 7.3 MJ and 5.6 MJ of energy are required to produce 26.8 MJ (1 kg) of bioethanol from forest residues and from willow, respectively. This excludes the inherent 64.4 MJ in the wood which is regarded as 'free' energy from the sun.

The choice of allocation has a large impact on the environmental impact results of the bioethanol from forest residues and wood pellet from sawmill residues life cycles. Mass allocation was used in this study, however, if economic allocation had been used, the by-products would have received little or no share of the environmental impacts, as they have low economic value. The use of economic allocation would greatly improve the environmental impact results of the wood pellet and bioethanol from forest residues life cycles.

The low global warming potential of wood pellets and bioethanol is due to the carbon neutrality of wood. The net carbon dioxide (and carbon dioxide equivalent) emissions over the life cycle of the wood are zero.

The energy ratio (energy in versus energy out) for producing wood pellets using the national boiler fuel mix at the sawmill is similar to international studies (Craven 2008 and Chan *et al*. 2008, for example). However, differences in

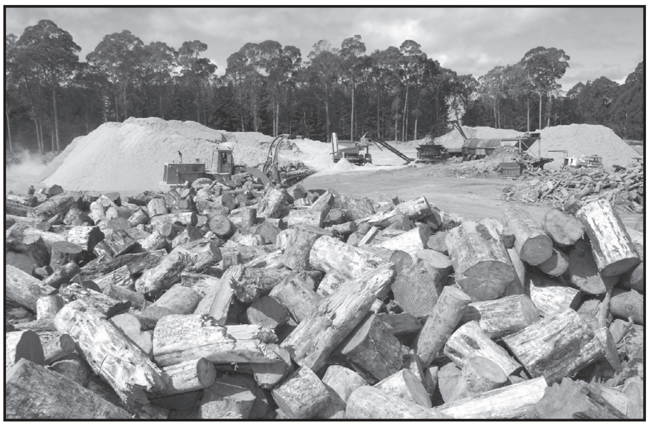
the system boundaries of the studies mean that results are not strictly comparable.

The global warming impact of wood pellets is significantly lower than a heat pump.

For the national boiler fuel mix and coal fuelled boiler scenario, the use of coal and natural gas in the boiler has a significant impact on the global warming potential and non-renewable energy use. The elimination of coal and natural gas as boiler fuels will significantly improve the global warming potential and non-renewable energy use of the wood pellet life cycle. The use of biomass as the boiler fuel would also improve environmental performance of dried timber.

Research into more efficient means of wood pellet production would help improve the environmental impacts of wood pellets, as the high electricity use in the wood pellet production process has a high global warming potential and non-renewable energy use.

The affect on human health of small particle emissions during wood pellet combustion was not accounted for in this study. These small particle emissions can have a significant impact on human health, although in many parts of New Zealand this is not a problem, as small particles do not stay in the air for long periods. In places such as Christchurch however, small particle emissions from combustion are a significant problem, particularly in winter months.



The affect of these small particle emissions needs further research.

The main environmental hotspots in the bioethanol life cycle are in bioethanol production, which particularly contributes to the acidification and global warming potential of the bioethanol from forest residues life cycle.

Targeted research on the bioethanol production process to improve the efficiency and reduce the environmental impact of the production process would have the greatest effect on the environmental impacts of bioethanol from forest residues.

An increase in the percentage of bioethanol in the bioethanol-petrol mix would reduce the amount of petrol required to be produced. This would not only reduce the environmental impacts of petrol production, but would also reduce the emissions from the car, as the emissions from burning bioethanol have fewer environmental impacts than the burning of petrol.

As commercial bioethanol production from wood currently does not occur in New Zealand, this study is necessarily a streamlined Life Cycle Assessment, with data taken from literature rather than from measured values of bioethanol production in New Zealand. If bioethanol production from wood becomes an established practice in New Zealand, a Life Cycle Assessment using measured values and with a specific bioethanol production method would more accurately reflect the environmental impacts of New Zealand bioethanol production.

Conclusions

This study examined the environmental sustainability and performance of three biomass sources that have the potential to replace fossil fuels:

- Wood pellets from sawmill residues as an alternative to a heat pump
- Bioethanol from forest residues as an alternative to petrol,

- Bioethanol from purpose grown willow as an alternative to petrol

Wood pellets are a renewable source of energy, currently produced in New Zealand from sawdust and wood shaving residues in sawmills. A Life Cycle Assessment of wood pellets shows that the production of heat from wood pellets is viable from an energy point of view, and has a lower global warming potential than the production of heat from a heat pump.

The current use of coal and natural gas as fuel to dry timber considerably increases the non-renewable energy use of the wood pellet life cycle in New Zealand, despite coal and gas being used to dry approximately only 18% of New Zealand's dried sawn timber. The elimination of coal and natural gas as a fuel to dry timber would improve the non-renewable energy use and global warming potential of wood pellets and of sawn timber.

Although wood pellets have been shown in this study to have a lower global warming potential than a heat pump, a comparison of wood pellets with other heating options is necessary to determine the best heating alternative.

A key benefit of producing bioethanol from forest residues is that forest residues do not require additional land, and therefore do not compete for land resources. Willow plantations are an option for large-scale bioethanol production.

A life cycle assessment shows that the use of bioethanol from wood as a partial substitute for petrol reduces the global warming impact of the fuel, and reduces the non-renewable energy consumption.

The production of bioethanol requires a small quantity of fossil fuels in electricity and the transportation of wood and other inputs. However, bioethanol is predominantly a renewable fuel, and the uptake of bioethanol use as a fuel would reduce the use of fossil fuels in transportation in New Zealand. If bioethanol production from wood is to become an established practice in New Zealand, processing must be validated and a market infrastructure developed. Snowdon *et al*. (2008) report that possible returns of $242/ha/yr have been calculated for bioethanol production from willow.

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