Citation for the published paper:

Valente, C., Spinelli, R. & Hillring, B.G. (2011). LCA of environmental and socio-economic impacts related to wood energy production in alpine conditions: Valle di Fiemme (Italy). *Journal of Cleaner Production 19*(17-18),1931-1938.

DOI: 0.1016/j.jclepro.2011.06.026

LCA of environmental and socio-economic impacts related to wood energy production in alpine conditions: Valle di Fiemme (Italy)

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abstract

An extended Life Cycle Assessment (LCA) is performed for evaluating the impacts of a woody biomass supply chain for heating plants in the alpine region. Three main aspects of sustainability are assessed: greenhouse gas emissions, represented by global warming potential (GWP) impact category, costs and direct employment potential. We investigate a whole tree system (innovative logging system) where the harvest of logging residues is integrated into the harvest of conventional wood products. The case study is performed in Valle di Fiemme in Trentino region (North Italy) and includes theoretical and practical elements. The system boundary is the alpine forest fuel system, from logging operations at the forest stand to combustion of woody biofuels at the heating plant. The functional unit is 1 m3 solid over bark of woody biomass, delivered to the district heating plant in Cavalese (Trento). The relative sustainability of traditional and innovative systems is compared and energy use is estimated. Results show that the overall GWP and costs are about 13 kg CO2equivalent and 42 euro per functional unit respectively for the innovative system. Along the product supply chain, chipping contributes the greatest share of GWP and energy use, while extraction by yarder has the highest financial costs. The GWP is reduced by 2.3 ton CO2equivalent when bioenergy substitutes fuel oil and 1.7 ton CO2equivalent when it substitutes natural gas. The sensitivity analysis illustrates that variations in fuel consumption and hourly rates of cost have a great influence on chipping operation and extraction by cable yarder concerning GWP and financial analysis, respectively. This is confirmed by sensitivity analysis. Better technologies, the use of biofuels along the product supply chain and more efficient systems might reduce these impacts. Replacing the traditional system with the innovative one reduces emissions and costs. A low energy input ratio is required for harvesting logging residues. The direct employment potential is a conflicting aspect and needs further investigations.

1. Introduction

International and national policies support the utilization of renewable energy and bioenergy for several purposes i.e. climate change mitigation, energy supply security and energy source diversification. The Kyoto protocol agreement (United Nations, 1998), the European Union target of a 20% reduction in greenhouse gas emissions (GHG) emissions, energy consumption and energy based on fossil fuels (European Union, 2009), and the assumption of carbon neutrality for biomass (International Energy Agency, 2007) are the main drivers behind the implementation of bioenergy production. Along the Alps, local communities show high levels of awareness regarding renewable energy sources, while provincial policy-makers have a keen concern for environmental protection, and are open to the use of bioenergy for mitigating the effects of global warming.

In this perspective, mountain forests can play an important role as source of raw material for energy purpose. In the Alps, the use of woody biomass for energy can stimulate an active forest management. The preservation of wood production for commercial purposes is very valuable for the management of the alpine areas (Giovannini, 2004). It is important to maintain an economic interest in timber production, in order to limit abandonment and the consequent decay of forest stands, as has happened in alpine regions. However, the use of woody biomass for energy should occur on a sustainable basis, i.e. its utilization should not cause negative impacts, or damage the availability of natural resources in the long run.

The aim of this paper is to present an example of an alpine forest fuel system performing a life cycle assessment, based on integrating the harvest of logging residues with the harvesting of conventional wood products (saw logs). The main objectives of the study are to:

- assess the GHG emissions, the financial cost and the direct employment potential;
- compare two logging systems e traditional (short wood system or SWS) and innovative (whole tree system orWTS) e in terms of GHG emissions, costs and effects on employment;
- evaluate the energy use of each unit process involved in the studied chain;
- highlight the most sensitive elements.

1.1. Overview of forestry studies in a life cycle assessment prospective

Several studies concerning the evaluation of the impacts of forest operations through the life cycle assessment methodology are performed in Nordic countries. Examples come from Berg (1997), Berg and Lindholm (2005) and Athanassiadis (2000) in Sweden. Forest technologies systems, in the first study, and forest operations in different parts of Sweden in the second one, are compared for finding out the system with less emissions and energy use. Athanassiadis calculates fuel consumption and GHG emissions for logging operations. Primary energy and long transportation distance are studied in Finland (Karjalainen and Asikainen, 1996). Berg and Karjalainen (2003) compare the GHG emissions of forest operations between Sweden and Finland. In an European context Schwaiger and Zimmer (2001) compare fuel consumption and GHG emissions. González-García et al. (2009) compare two case studies from Sweden and Spain regarding the environmental impacts of forest production and supply of pulpwood. In USA Sonne (2006) studies GHG emissions of forestry operations in the Pacific Northwest coast. However, all these studies are performed in lowland conditions, excluding both the integration of bioenergy in the forest operations and socioeconomic aspects.

1.2. Background

A case study was performed in Valle di Fiemme, in the province of Trento (Italy) (Fig. 1) in the year 2010. In Italy, this province (region Trentino-Alto Adige) is at the forefront both in the forestry sector and in conservation of the environment. Around 17% of the land of the Trento province is covered by national parks and regional reserves. This province has invested heavily in the Natura 2000 European network, where sites with a specific value to nature are placed under a special protection regime for the conservation of biodiversity. Hence, around 28% of the territory in the Trento province is managed both for nature conservation and habitat improvement.

The economy of Trentino is mainly based on tourism. The development of tourist activities goes hand in hand with the increased role of forests for recreation (Wolynski et al., 2008). Hence, there is growing economic interest in the conservation of the landscape and in the enhancement of its hedonic value (Provincia autonoma di Trento, 2009). Forest management follows the rule of nature based silviculture, where the biological stability and the fertility of the forest stand are safeguarded (Piussi, 1994). Consequently there has been a steady effort to limit clear cutting, to introduce continuous cover forestry and to foster natural regeneration. Local silviculture generally aims to restore the composition of the vegetation, by tuning the balance between structure and volume, in relation to the geographic location (Diaci, 2006).

2. Goal and scope of the LCA

The methodological approach is Life Cycle Assessment (LCA) as recommended by International Standards Organization (ISO, 2006a,b). Several methods (Environmental Impact Assessment, Energy Analysis, Strategic Environmental Assessment etc.) exist for evaluating environmental impacts as suggested by Finnveden and Moberg (2005). However, LCA is the tool more adapted to the current study, as analytical method for targeting the significant points in the life cycle of the woody biomass product. The key elements pointed out by the LCA definition of Glavic and Lukman (2007) are followed: identification and quantification of the environmental loads, assessment of the potentiality of these loads and proposal of environmental impacts reduction.

GHG emissions, i.e. CO2, CH4 and N2O, are calculated for each step of the production supply chain, including combustion at the heating plant. Our focus is limited to standing woody biomass of the trees while carbon stored in the soil is not taken into account. Furthermore, a socio-economic assessment is performed, through the evaluation of financial costs and direct employment potential, so as to cover the three main aspects of sustainability: environmental, economic and social aspects.

Four critical elements are determined: functional unit, system boundary, type of data used and impact assessment methodology.

The functional unit used as a reference for all studied system is 1m^3 solid over bark (s.o.b.) of woody biomass, delivered to the district heating plant (DHP) of Cavalese (Trento). m^3 solid is a common unit of measure in the forestry sector (Kofman, 2010) and the bark is included (over bark), because valuable for bioenergy.

The system boundary is the alpine forest fuel system shown in Fig. 2. TheWTS starts with the logging operation at the forest stand, and ends with energy conversion at the heating plant. Trees are felled with chainsaws at the stump site and extracted with a mobile cable yarder. Once at the yarder landing, trees are delimbed, bucked and stacked by an excavator-mounted processor. Here the logging residues are separated from the round wood and chipped. The wood chips produced from logging residues are transported from the yarder landing to the district heating plant in Cavalese by trucks, and handled by front-end loader.

All forest machines use fossil fuel (diesel).

Instead, in the SWS trees are felled, delimbed and bucked with chainsaws and extracted by cable yarder. Once at the landing, logs are stacked with a loader, often fitted to a tractor.

Emissions, costs and direct employment potential generated from felling and extraction are charged to the total volume of woody biomass (round wood and logging residues) and later prorated, whereas all emissions and costs generated from chipping and chip transport are entirely charged on the energy biomass component. At the heating plant emissions and costs are charged to the total volume of chips consumed by the bioenergy plant of Cavalese in 2008, constituted by both logging residues (tops and branches) and from sawmill residues (slabs, offcuts, slovens).

3. Inventory

3.1. Data collection and assumptions

Reliable data are necessary for quantifying inputs and outputs related to each unit process. Inputs are represented by woody biomass (m^3 s.o.b.), time consumption (h), productivity (m^3 s.o.b./ h) and fuel consumption (l/h) (Table 5). Outputs are GHG emissions, costs (euro/m^3s.o.b.) and direct employment potential (h/m^3 s.o.b.). GHG emissions are symbolized by the global warming potential impact category (kg CO2e/m^3 s.o.b.), where e means equivalent. According to IPPC (IPCC, 2006), the time horizon for the GWP is 100 years, where the corresponding emissions factors for the calculation of GWP come from IPCC, for the mobile source in the forestry sector (IPCC, 2006). Data concern the years 2008 and 2009. Data regarding cutting volume, stand position etc. are obtained from the Planning Department of the State Forest Administration of Paneveggio (Valle di Fiemme, Trento). Data related to the introduction of innovative forest harvesting techniques (mechanized whole tree system) come from previous studies (Spinelli et al., 2008). Data on time consumption for forest machinery come from specific work studies conducted by the authors and published separately (Spinelli et al., 2007, 2008), During these studies, time consumption was measured with the built-in clock of hand-held field computers running the dedicated Siwork 3 software installation (Spinelli and Kofman,1995). Delays were included in the calculation, since data collection lasted several days and allowed obtaining a reliable representation of delay incidence. Data on fuel consumption and mass output were also measured during the same studies (Piegai, 2000; Spinelli et al., 2007, 2008) or come from the internal records of the State Forest Administration. Data associated with the front-end loader are not included.

Data linked to the silviculture and management of alpine forests are collected at Provincia di Trento, Forest and Fauna Department (Provincia autonoma di Trento, 2010). The biomass plant of Cavalese has provided data about biomass consumption and other management costs (Bioenergia Fiemme, 2010). Data concerning employment potential are derived from the State Forest Administration and from previous studies (Spinelli et al., 2008).

Several assumptions related to woody biomass characteristics, conversion factors for the calculation of biomass volume, energy equivalence (Hellrigl, 2006) and energy content (AIEL, 2009; Hellrigl, 2006) were made, and they are summarized in Table 1. The amount of logging residues was measured as dry tons in previous studies (Spinelli et al., 2006, 2008) and was transformed in m3 s.o.b. using the recorded data for wood basal density.

Our alpine forest fuel system is assumed to be CO2 neutral, i.e. it does not increase the CO2 level into the air (the CO2 emitted during the combustion of the wood fuels is taken up during the growth of the forest) see e.g. (European Commission, 2007; PAS, 2008). This concept is the base for calculating the GHG benefits of our wood fuel system assumed to replace fossil fuels as fuel oil and natural gas at the DHP. However, the alpine fuel supply chain cannot be assumed completely CO2 neutral, due to the use of fossil fuels along the supply chain (Schlamadinger et al., 1997).

According to the mentioned assumption of CO2 neutrality, only CH4 and N2O emissions are considered during the combustion process. The value assumed for calculating the emissions from a wood-fired heating plant comes from Wihersaari (2005). Table 2 shows data related to the DHP of Cavalese.

10% of the wood chips delivered to the DHP is assumed to be constituted by logging residues, while the remaining amount comes from sawmill residues sourced in the area.

Machine rates for harvesting equipment are estimated with conventional costing methods (Miyata, 1980), using 2010 input values, as shown in Table 3. Subsidies are not taken into account. Machine rates were divided by productivity figures, in order to estimate unit harvesting cost (euro/m^3 s.o.b.).

3.2. Calculation

The GHG emissions have been calculated using the following formulas:

fuel consumption (TJ) > * emission factor (kg/TJ),

where fuel is calculated as

fuel (1) * density fuel (kg/1) * Net factor value (TJ/Gg /10^6

The fuel used in the forest operations is diesel. Data related to these formulas are presented in Table 4. The fuel consumption per functional unit is calculated beginning from productivity data. Productivity figures come from field studies and are representative of actual commercial operations. They are calculated as volume output (m^3 s.o.b.) divided time input (hours, including delays). At the DHP of Cavalese, it is calculated the GHG benefit of replacing fossil fuels (natural gas and fuel oil plant) by our wood fuel system. The CO2 emissions from the alpine fuel supply chain are taken into account together with CH4 and N2O generated both from supply chain and combustion. The GHG benefits are calculated as difference between the emissions from our alpine forest fuel system and the above mentioned reference systems based on fossil fuels. The costs are calculated as the sum between operating costs and profit and overheads. The operating costs are equal to the sum of hourly fixed costs and hourly variable costs. The above mentioned costs derive by calculation from base data presented in Table 3.

The direct employment potential is equal to the ratio between hour (h) and total woody biomass (m^3 s.o.b.).

3.3. Further analyses

3.3.1. Energy balance

Energy use is estimated as kWh/m^3 s.o.b. The following equation (Ayres, 1978; Hohle, 2010) was used for calculating the energy balance (inputeoutput ratio) of the assortments used for energy production (logging residues):

IE = Fc x Ec / OE

IE is the energy input ratio and it is calculated in percentage. Fc is the fuel consumption of forest machineries in l/m^3 s.o.b., while Ec is the energy content of fuel in kWh divided by OE or the energy output, i.e. the amount of energy released burning wood chips at the combustion plant. The unit of measure for energy input and energy output is kWh, because related to the power of the DHP.

The energy content of 1 l of chainsaw fuel and diesel are respectively 9.1 kWh and 10.1 kWh. The energy output of chips is calculated as the yearly ratio between heat production and wood chip consumption at the DHP of Cavalese.

3.3.2. System comparisons

A comparison between WTS and SWS concerning GWP, costs and direct employment potential was performed for stump site, extraction and landing operations (op.). In the traditional system the harvest of logging residues is excluded. Inputs, as mentioned above, related to both systems are illustrated in Table 5.

3.4. Sensitivity analysis

A sensitivity analysis was conducted in order to gauge the variation of emission levels and production costs as a function of increments or reductions in fuel consumption (l/h) and logging costs (euro/h). Two different levels were considered both for reductions and increments, respectively 10% and 20% below and above the average reference values.

4. Results and discussion

4.1. Environmental and financial analysis

The total GWP of the product supply chain was 13.2 kg CO2e/m^3 s.o.b. (Table 6), including all work steps from the stump site to the arrival at the heating plant. Chipping was the process step with the largest GWP, i.e. 40% of overall emissions (5.29 kg CO2e/m^3 s.o.b.). Transportation came second, contributing 27% of the total GWP (3.54 kg CO2e/m^3 s.o.b.). The remaining kg CO2e was divided between felling, extraction and landing operation, respectively with 1%, (0.10 kg CO2e/m^3 s.o.b.), 9% (1.25 kg CO2e/m^3 s.o.b.) and 23% (3.02 kg CO2e/m^3 s.o.b.) of the total GWP. The product supply chain had an overall costs of 42 euro/m^3 s.o.b., where extraction by yarder was the most expensive operation, accounting for 31% of the total costs (13 euro/m^3 s.o.b.). Chipping came second with 25% (10 euro/m^3 s.o.b.), and transport third, with 21% (8 euro/m^3 s.o.b.). The remaining costs were shared between felling (17% or 7 euro/m^3 s.o.b.) and processing at the landing (6% or 2 euro/m^3 s.o.b.). According to Van Belle (2006) during chipping each single variable can strongly influence the level of CO2 emissions. Therefore, it is important to consider the technical measures capable of reducing fuel consumption, and consequent emissions. Yarder extraction is the most expensive process, even if it is still economically viable when the slope gradient exceeds 35% and no other techniques are applicable (Heinimann, 2004). Furthermore, cable yarder offers the benefit of environmentally friendly extraction, with limited impacts on the environment, forest soil and the residual stand (Stampfer et al., 2006; Visser and Stampfer, 1998). Cable yarder has already been used in bioenergy supply in Italian mountain areas (Zimbalatti and Proto, 2009). Recent studies showed that between 85% and 95% of the theoretical potential of forest residues can be harvested by yarder in Trentino (Zambelli et al., 2010). At present, local energy plants mostly use sawmill residues, while the amount of forest fuel is still small due to difficulties encountered when harvesting forest residues in steep terrain, and the resulting high supply costs (Secknus, 2007). Other authors have already pointed out the high cost of harvesting mountain forests and the consequent trend to disregard active forest management (Brang et al., 2002). However, since 2006, the State Forest Administration in Paneveggio has recorded a steady increase in the productivity of forest stands by introducing the recovery and chipping of forest residues. This innovation has not resulted in any increase in the harvesting cost of conventional products. Hence, direct experience by the State Forest Administration seems to corroborate our hypothesis, regarding the financial benefit of wood chip utilization for energy purposes. Hence, there is a strong interest in expanding the utilization of forest residues, which would help stabilizing the market of wood chips. In turn, that would require improving the quality of forest chips and developing the forest road network. Short transportation distances between the forest area and the DHP of Cavalese also allowed reduced transportation costs, ultimately achieving positive net income (Hamelinck et al., 2005).

However, WTS allows integration of the recovery of logging residue with the extraction of conventional timber assortments, helping to reduce the costs of both operations, as already stated long ago within the International Energy Agency circle (Hohle, 2010; Hudson, 1995) and confirmed in our study. In the last decade the price trend of wood chips sold as by-products from sawmills to the DHP of Cavalese has increased exponentially, which highlights the urgent economic interest in finding and utilizing wood chips from alternative sources, such as forest residues.

For a GHG point of view, the benefit of using wood fuel is clear at the DHP. Fig. 3 shows the GHG emitted by our wood fuel system compared to two reference systems based on fossil fuel (fuel oil and natural gas plant). In a heating plant, the use of woody biomass allows to avoid 2.3 ton CO2e (169 kg CO2e/m^3 s.o.b.) or 1.7 ton CO2e (122 kg CO2e/m^3 s.o.b.) if replacing fuel oil and natural gas respectively.

4.2. Energy balance

The results for energy use of theWST system are shown in Fig. 4. Each slice in the pie chart represents the amount of kWh/m^3 s.o.b. used by each process step in the years 2008 and 2009. Chipping is the process with the highest energy use in the observed alpine supply chain, explaining the high GWP presented above. The high fuel and energy use of this operation is compensated by its high productivity.

The energy input - output ratio for the supply of logging residue for energy use is 4.9%, meaning that 20 units of wood energy fuel are produced per unit of energy based on fossil fuel consumed. This low energy ratio for fuel chip production is confirmed by previous Nordic studies, see e.g. Wihersaari (2005). The low amount of energy required for tapping the forest fuel resource and the replacement of fossil fuel at a systemic level are crucial advantages of the alpine forest fuel system.

4.3. System comparisons and direct employment potential

The comparative analysis between the traditional (SWS) and innovative (WTS) logging system demonstrates the advantage of using theWTS when trying to curtail emissions and costs (Table 7). In general, WTS incurs higher hourly fuel consumption than SWS, but also offers higher productivity. As a result, the specific fuel consumption per product unit is lower for the WTS, compared tothe SWS. Opting for WTS allows a saving of 1.79 kg CO2e/m^3 s.o.b. and 12.17 euro/m^3 s.o.b. In contrast, SWS harvesting has a larger direct employment potential.

The transportation of logging residues after WTS harvesting generates the highest potential for direct employment, followed by extraction. Regarding the comparison betweenWTS and SWS,WTS seems to offer greater environmental and financial benefits, although its direct employment potential is a key point to discuss. SWS creates more jobs compared to the WTS as far as the harvesting of conventional round wood is concerned. However, since SWS offers little opportunities for biomass production, it misses all the job potential related to the biomass supply chain. Furthermore, one may wonder if the employment potential is really an issue in logging operations, which seem to attract fewer and fewer people, regardless of availability. Logging is experiencing a severe shortage of qualified labor, and for this reason it seems better to allocate the few available resources to the more productiveWTS (Spinelli et al., 2001).

4.4. Sensitivity analysis

A sensitivity analysis was performed for estimating the impact of the key parameters fuel consumption (l/h) and labor cost (euro/h) on total GWP and cost levels. The relative variations in the GWP and labor costs with respect to the base case are presented in Table 8: these correspond to the effect of 10% and 20% increase and decrease in the value of the reference key parameters.

The sensitivity analysis shows that the most sensitive parameter to variations in fuel consumption is chipping. A reduction of 20% in the fuel consumption causes a reduction of 1.05 kg CO2e/m^3 s.o.b., while an increment of 20% results in an increase of 1.07 kg CO2e/m^3

s.o.b. 10% increase or decrease in fuel consumption causes additional 0.55 kg CO2e/m^3 s.o.b. or a reduction of 0.52 kg CO2e/m^3 s.o.b., respectively. Transport is also a sensitive process step: a reduction of 20% in fuel consumption reduces GWP by 0.75 kg CO2e/m^3 s.o.b., while an increment of 20% generates additional 0.35 kg CO2e/m^3 s.o.b. At the landing, a decrease of 0.61 kg CO2e/m^3 s.o.b. and an increment of 0.6 kg CO2e/m^3 s.o.b. of the GWP are respectively associated to a 20% decrease and a 20% increase in the fuel consumption. The same 10% variation in fuel consumption causes a GWP increase or decrease in the order of 0.30 kg CO2e/m^3 s.o.b. from landing operations.

Extraction was the most sensitive parameter to variations in labor cost. A reduction or increment of 20% in labor cost induces a 2.61 euro/m^3 s.o.b. reduction or increment of the total supply costs. Similarly, a 10% reduction or increase in labor cost causes respectively a reduction of 1.36 euro/m^3 s.o.b., or an increase of 1.26 euro/m^3 s.o.b. of the extraction costs in the base scenario. Chipping is also a sensitive parameter. A decrease of 20% in labor cost generates savings for 2 euro/m^3 s.o.b. in chipping costs. In contrast, an increment of 20% in labor cost results in a cost increase of 2.02 euro/m^3 s.o.b. The same 20% increase or decrease in labor cost cause a parallel increase or decrease of transportation cost equal to 1.71 and 1.70 euro/m^3 s.o.b., respectively.

In conclusions, the sensitivity analyses show that chipping is most sensitive to changes in fuel consumption and extraction to changes in labor cost, as these operations are respectively the most intense users of fuel and labor. In contrast, stump site operations and landing operations are relatively insensitive to variations in fuel consumption and labor cost.

4.5. Sustainability

Different assumptions can strongly influence the results. Furthermore, the harvesting of forest residues may have long-term effects on soil fertility, raising important questions about its sustainability. Since impacts on fertility will vary depending on site conditions, these questions must be addressed on a case by case basis. When implementing the new forest energy supply system, it is important to simultaneously consider all the ecological, economic and social aspects. In addition, in the study area it is important to preserve the esthetic value of the mountain forests, while exploiting the forest for timber production in a sustainable way. A combined analysis of environmental and socio-economic impacts is a good option for carrying out a LCA (Kniel et al., 1996) and for decision makers, that need to find a sustainable solution to environmental problems (Ness et al., 2007). A complete assessment of sustainability requires gauging the effects on soil carbon storage, land use change and biodiversity impacts, consequences on the local economy and on the society. Several studies deal with the introduction of land use change and biodiversity in the LCA (Cherubini et al., 2009; Lindeijer, 2000), although there are still no international standard and common agreements within the LCA field. However, recent studies may provide some comfort, as they have shown the principle feasibility of creating a sustainable forest fuel system in the Italian mountains (Freppaz et al., 2004).

5. Conclusions

The study analyzes the possible exploitation of woody biomass resources for energy in an alpine context. The purpose of the study was to utilize life cycle assessment as a tool for examining the environmental, economic and social impacts in terms of GHG emissions, financial costs and direct employment potential respectively, in an alpine forest fuel supply chain from the forest stand to the DHP. Our case study demonstrates that mountain forests are a viable source of wood fuel, which can be exploited without generating excessive impacts. From the environmental viewpoint, cable yarder is most compatible with the sustainable management of alpine mountain forests. However, the sensitivity analysis indicates that traditional cable extraction is a costly process. Suggested innovations allowreducing both GHG emissions and costs, while offering an affordable bioenergy feedstock. At the same time, the use of local biomass by a local DHP generates a “green” profile of the local community. However, the GWP contribution of each unit process in the supply chain is significant, especially for chipping operation: all along the supply chain one might resort to better technologies, more efficient machines and innovative of biofuels to achieve a radical reduction of GHG emissions (Neupane et al., 2010). The direct employment potential of the suggested innovation needs further analysis: if the innovative system may reduce employment needs in the conventional logging component of the supply chain, it also generates new business and employment through the collateral biomass opportunity. Furthermore, one also needs to consider the current difficulty in recruiting new loggers: in its light, increasing logging labor needs may represent a problem more than a real advantage. An integrated harvesting system based on mechanical equipment and designed to produce both conventional wood products and energy biomass will reduce labor needs, but at the same time may stimulate the forest sector and generate further income for both forest owners and logging companies.

Acknowledgments

The authors gratefully acknowledge the support of the Planning Department of the State Forest Administration of Paneveggio (Valle di Fiemme, Trento), The Forest and Fauna Department of the Provincia di Trento, and the Management of the district heating plant in Cavalese (Trento). We thank you Jos Milner for English revision.

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Figures

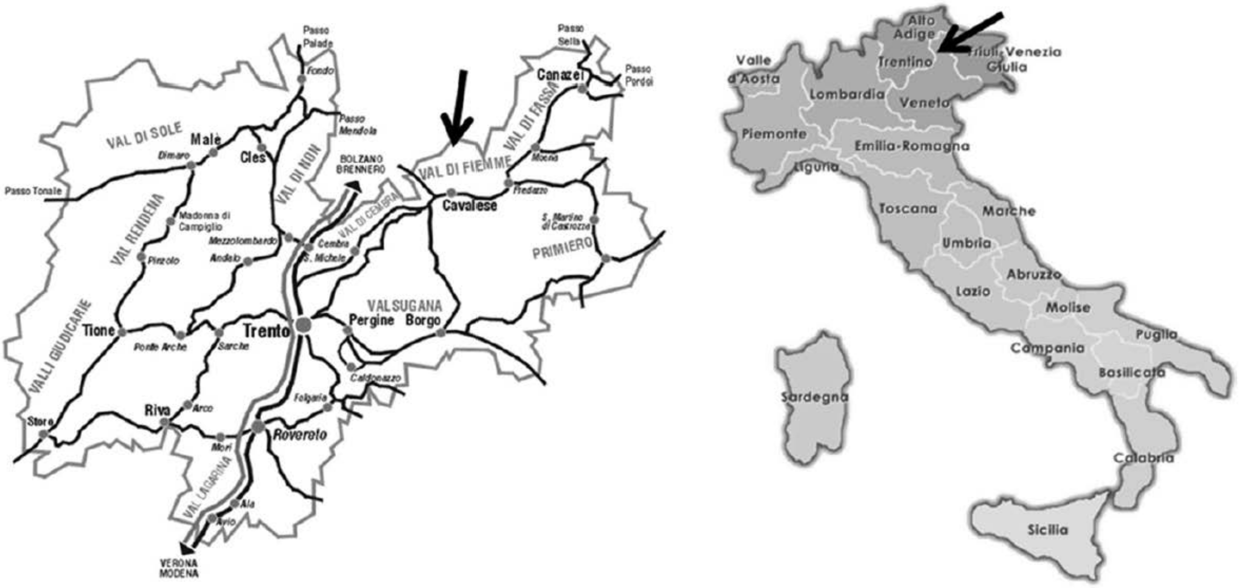


Fig. 1. Map of Valle di Fiemme, located in Trentino-Alto Adige region (North Italy), indicated by arrows.

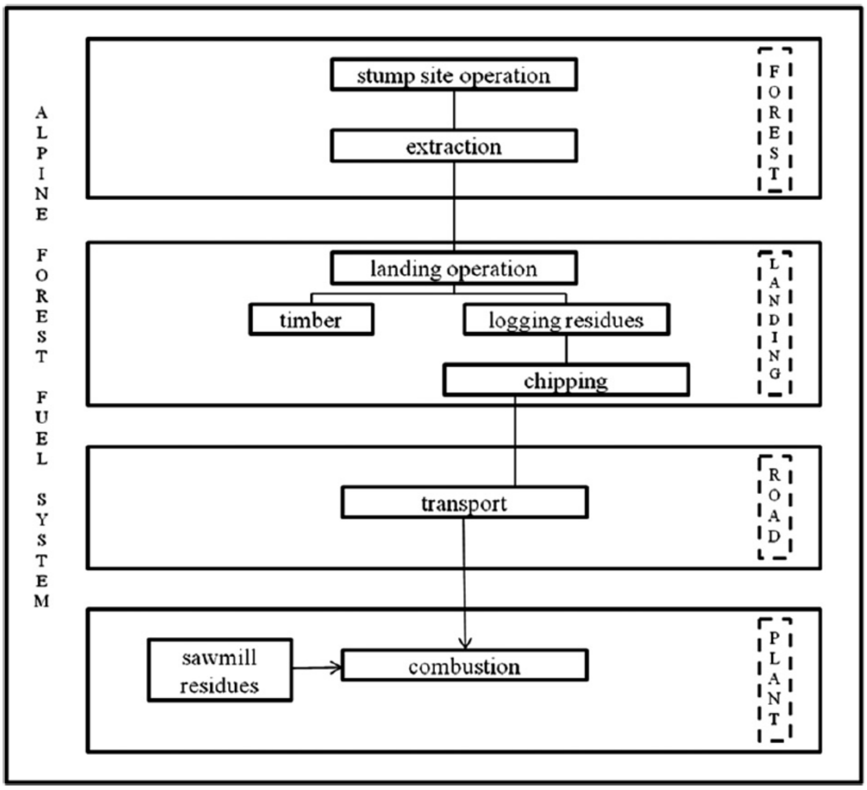


Fig. 2. System boundary of the alpine forest fuel system. Vertical boxes bordered by dotted line represent the operational sites from the forest stand to the end user.

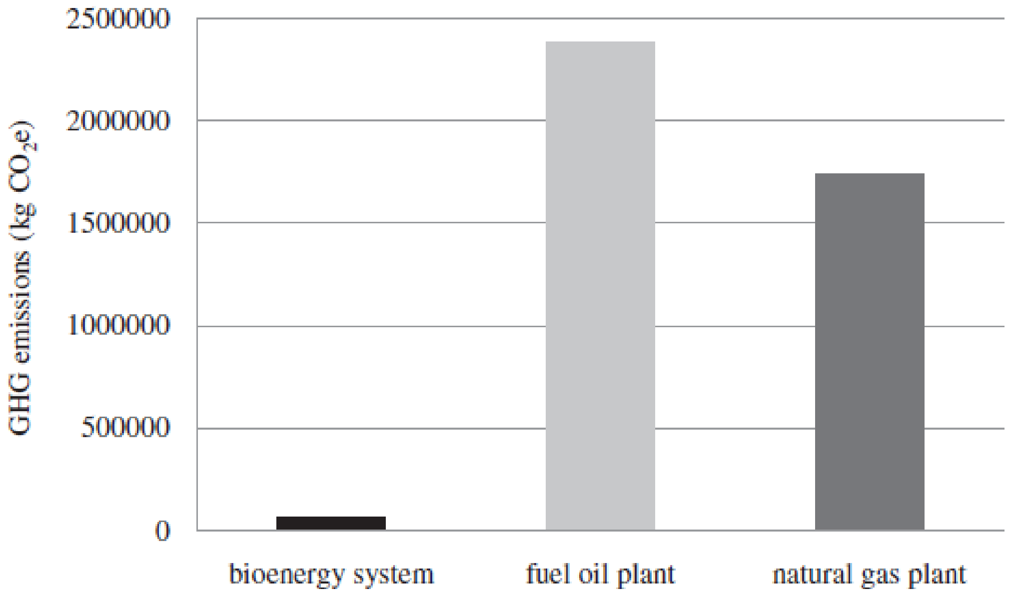


Fig. 3. GHG emitted by our alpine forest fuel supply chain, including emissions from combustion, in comparison to two reference systems based on fossil fuel (fuel oil and natural gas plant).

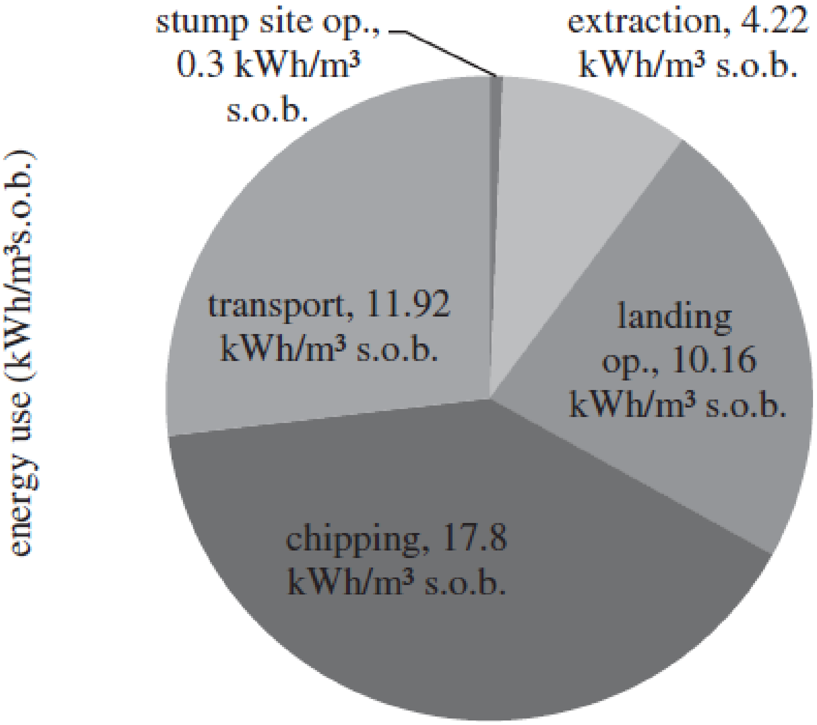
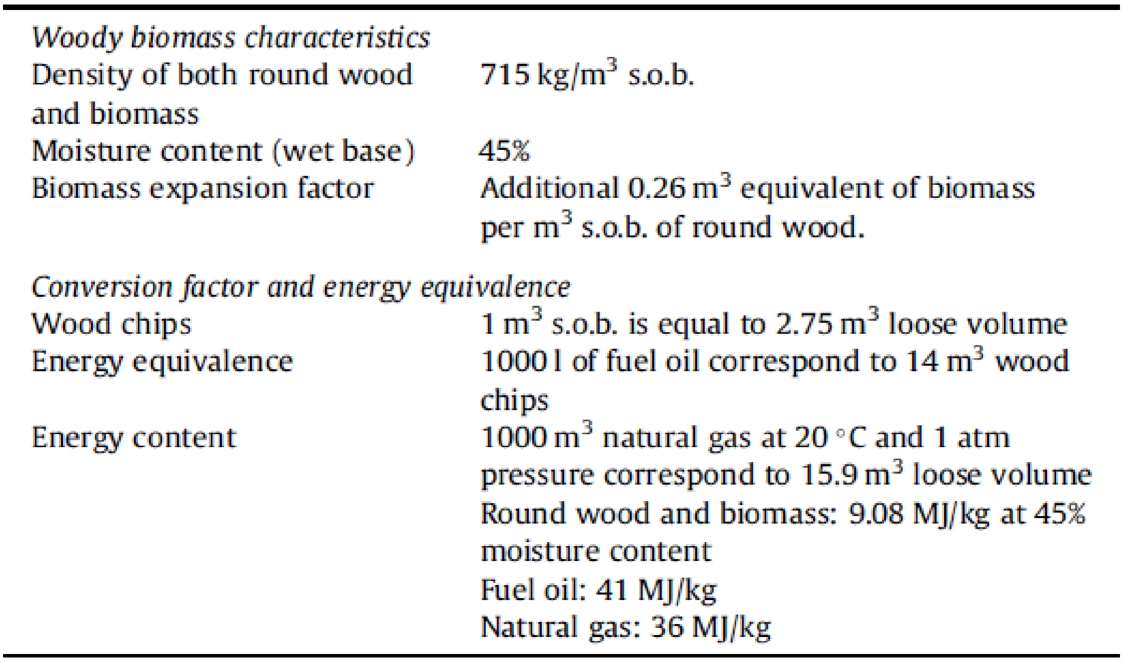


Fig. 4. Energy use (kWh/m^3 s.o.b.) of each unit process in the years 2008 and 2009.

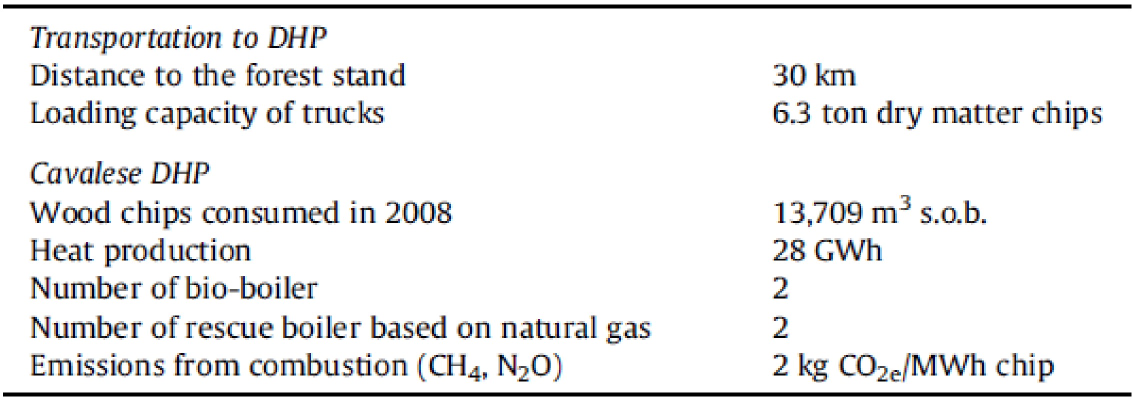
Tables

Table 1
Assumptions for woody biomass characteristics, conversion factors, energy equivalence and energy content of different fuel.



Woody biomass characteristics	
Density of both round wood and biomass	715 kg/m^3 s.o.b.
Moisture content (wet base)	45%
Biomass expansion factor	Additional 0.26 m^3 equivalent of biomass per m^3 s.o.b. of round wood.
Conversion factor and energy equivalence	
Wood chips	1 m^3 s.o.b. is equal to 2.75 m^3 loose volume
Energy equivalence	1000 l of fuel oil correspond to 14 m^3 wood chips
Energy content	1000 m^3 natural gas at 20 °C and 1 atm pressure correspond to 15.9 m^3 loose volume Round wood and biomass: 9.08 MJ/kg at 45% moisture content Fuel oil: 41 MJ/kg Natural gas: 36 MJ/kg

Table 2
Data related to transportation and management of the DHP in Cavalese.



Transportation to DHP	
Distance to the forest stand	30 km
Loading capacity of trucks	6.3 ton dry matter chips
Cavalese DHP	
Wood chips consumed in 2008	13,709 m^3 s.o.b.
Heat production	28 GWh
Number of bio-boiler	2
Number of rescue boiler based on natural gas	2
Emissions from combustion (CH_4, N_2O)	2 kg CO_{2e}/MWh chip

Table 3
Base components for cost estimation.

Machine	Type	Chainsaw	Yarder	Processor	Chipper	Truck
Purchase price	euro	700	150,000	200,000	320,000	110,000
Economic life	years	2	8	8	7	5
Recovery value	%	0	20	20	20	20
Interest rate	%	4	4	4	6	6
Fuel cost	euro/l	1.4	1.2	1.2	1.2	1.2
Crew	number	1	3	1	1	1
Depreciation	euro/year	350	15,000	20,000	36,571	17,600
Annual use	h/year	1000	1000	1000	1200	1200
Repair and maintenance	%	120	80	60	60	35
Personnel cost[a]	euro/h	21	21	21	21	21
Total fixed cost	euro/h	0.4	23	30	48	14
Total variable cost	euro/h	23	82	55	89	38
Overhead	%	20	20	20	25	25
Total cost	euro/h	28	125	102	171	65

[a] Current national contract for this worker category.

Table 4
Elements for calculating GWP.

	Emissions factor (kg/TJ)	GWP (100 years)
CO_2	74,100	1
CH_4	4.15	25
N_2O	28.6	298
	Density (kg/l)	Net calorific value (TJ/Gg)
Diesel	0.8439	43

Table 5
Comparisons of woody biomass, time consumption, productivity and fuel consumption of whole tree system (WTS) and short wood system (SWS).

	Woody biomass (m^3 s.o.b.)		Time consumption (h)		Productivity (m^3 s.o.b./h)		Fuel consumption (l/h)	
	WTS	SWS	WTS	SWS	WTS	SWS	WTS	SWS
Stump site op.	6966	6966	592	1321	11.76	5.27	0.4	0.4
Extraction	6966	6966	728	938	9.57	7.42	4	5
Landing op.	6966	6966	500	711	13.92	9.79	14	8
Chipping	1442	–	85	–	17.03	–	30	–
Transport	1442	–	189	–	7.63	–	9	–

Table 6
GWP (kg CO_{2e}/m^3 s.o.b.) and costs (euro/m^3 s.o.b.) for the alpine forest fuel supply chain.

	GWP (kg CO_{2e}/m^3 s.o.b.)	Costs (euro/m^3 s.o.b.)
Stump site op.	0.10	2.38
Extraction	1.25	13.06
Landing op.	3.02	7.32
Chipping	5.29	10.07
Transport	3.54	8.51

Table 7
Comparison of GWP, costs and direct employment potential[a] between WTS and SWS.

	GWP (kg CO_{2e}/m^3 s.o.b.)		Costs (euro/m^3 s.o.b.)		D.e.p. (h/m^3 s.o.b.)	
	WTS	SWS	WTS	SWS	WTS	SWS
Stump site op.	0.10	0.23	2.38	10.00	0.08	0.19
Extraction	1.25	2.02	13.06	20.43	0.10	0.13
Landing op.	3.02	4.29	7.32	5.39	0.07	0.10
Total	4.37	6.54	22.76	35.83	0.25	0.42

[a] d.e.p.: direct employment potential.

Table 8
Sensitivity analyses: variation of GWP and production costs achieved in the base case (base), increasing and decreasing fuel consumption and labor cost of 10% and 20% of each operation one at a time.

	GWP (kg CO_{2e}/m^3 s.o.b.)					Costs (euro/m^3 s.o.b.)				
	Base	−20%	−10%	10%	20%	Base	−20%	−10%	10%	20%
Stump site op.	0.1	0.08	0.09	0.1	0.12	2.38	1.87	2.12	2.63	2.89
Extraction	1.25	1	1.13	1.38	1.5	13.06	10.45	11.7	14.32	15.67
Landing op.	3.02	2.41	2.71	3.32	3.62	7.32	5.88	6.6	8.04	8.75
Chipping	5.29	4.24	4.77	5.84	6.36	10.07	8.07	9.07	11.07	12.09
Transport	3.54	2.79	3.18	3.89	3.89	8.51	6.81	7.66	9.37	10.22