Assessment of biomass-to-energy chains from the forest to the combustion in individual or district heating boilers

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Abstract

The European Union has set targets for the reduction of greenhouse gas emissions and the increase in the share of renewables in the energy mix. These targets will not be met without a dramatic increase in the use of biomass for energy, particularly ligno-cellulosic biomass. Wood can be converted into various forms of energy such as heat, electricity, synthetic gas, liquid fuels, etc. This study focuses on the direct combustion of forest wood for heat production. The objective of this work was to compare the efficiencies and greenhouse gas emissions of the combustion of wood in different scenarios: the burning of wood chips in a district heating boiler, and the use of logs or wood pellets in individual houses. The bioenergy chain was modelled from forest growth to energy production under the Aspen Plus® software. This allows for a complete Life Cycle Inventory of the whole chain, including emissions of minor species (NOx, aromatics, etc.) and detailed mass and energy balances. The global warming potential (GWP) of different scenarios was determined and put in relation with the cost of the heat produced. The varying parameters included energy efficiency, the wood supply distance, the distance to the nearest landfill for ashes disposal, etc. Wood scenarios are also compared with other energy resources (electricity from the French mix and natural gas combustion). The importance of some minors pollutants (e.g. CH_4 and PAH), emitted during wood combustion, on the GWP of the whole chain is highlighted. The results from three different impact factor datasets (ReCiPe, EDIP 2003, CML 2001) are finally discussed.

Keywords

Biomass, Combustion, Efficiency, Energy, Forest, Modelling, Sustainability.

1. Introduction

Climate change and the increasing scarcity of fossil resources have generated high interest in the development of renewable energies. Compared to other sources of energy, biomass is a particularly interesting resource because of its reliability (as opposed to intermittent energies like wind or photovoltaic electricity) and the various ways it can be converted into energy, from heat to electricity and storable fluids such as gas or liquid fuels. However, the conversion to bioenergy raises a number of sustainability issues: soil quality, water consumption, land-use change, overall greenhouse gas emissions of the conversion chain, etc. Life Cycle Analysis has been widely used in the assessment of environmental impacts of bioenergy, especially for forestry-to-energy chains in northern Europe [1–13]. In this study, we compare the environmental and economic performance of three heating systems: individual stoves burning wood logs, individual stoves burning wood pellets, and collective boilers burning wood chips. Gas and electricity-based scenarios complete the analysis. Biomass is assumed to come from the forests of the Lorraine region, in north-eastern

France, where the forest industry is strongly implanted and wood is a widespread source of energy. Figure 1 shows the production and use of wood in Lorraine in 2012. The data comes from a survey conducted by the Interprofessional Group for the Promotion of the Wood Economy in Lorraine (Groupe Interprofessionnel de Promotion de l'Economie du Bois en Lorraine, GIPEBLor) [14]. The numbers are given in tons of wet wood, i.e. ignoring all later drying.

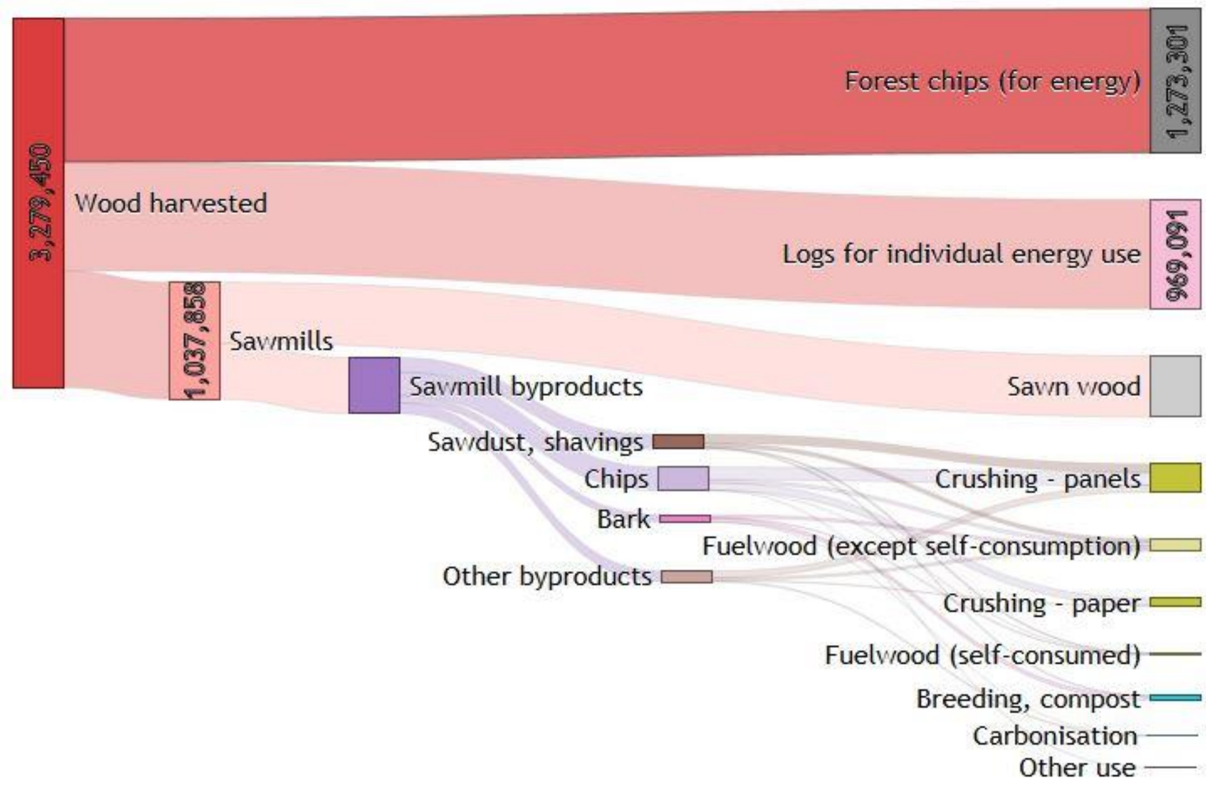

Figure 1: Wood production and use in Lorraine, 2012 (tons of wet wood), adapted from [14].

The production of heat from wood creates greenhouse gas emissions at several stages (Figure 2). While the main contributor is the combustion of wood, the impact of harvesting, transforming and transporting the biomass from the forest to the final user is not negligible. Depending on the facilities and logistics, the impact of these steps can greatly reduce the benefits associated to the energy production from biomass.

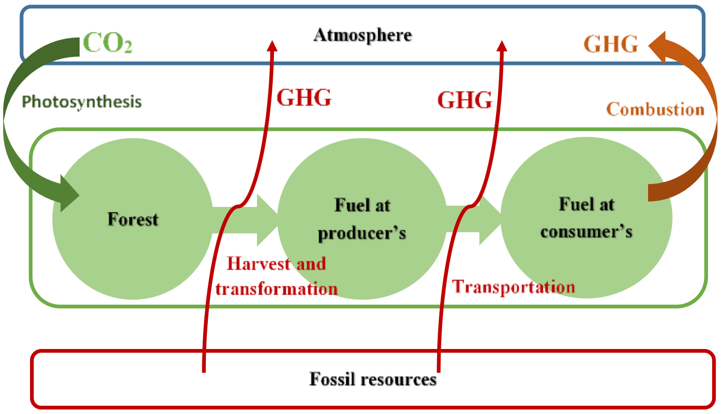

Figure 2: The forest-to-heat chain highlighting the emission of Green-house Gas (GHG)

Basic comparisons, such as emissions simulators aimed at the general public, as well as the current European legislation [15], often rely on the assumption that the emissions of the combustion phase are entirely compensated by the CO_2 absorbed during the growth phase through photosynthesis. However, this assumption is not strictly correct for two reasons. Wood contains a large array of elements other than carbon and some of these elements are not captured through photosynthesis. Moreover, wood combustion is not perfect and it produces small quantities (but far from negligible) of species with higher Global Warming Potential (GWP) than CO_2. (CO, NOx, and Volatiles Organic Compounds-VOC, among others). For a more comprehensive assessment of the production chain, the modelling of forest growth and wood combustion is necessary. It makes it possible to better assess the mass and energy balances of the whole chain, and to predict more accurately the yields of pollutants emitted to the atmosphere.

2. Methodology

2.1. Studied scenarios

The three main studied scenarios are (1) a wood boiler connected to a medium-sized district heating network, (2) an individual stove using logs, and (3) an individual stove using wood pellets. The district heating scenario was declined for three different supply distances, and two assumptions on the distance to the landfill site where the ashes are disposed of. The log and pellets scenarios both have a variant where the stove is fitted with a back boiler, providing hot water to one or two individual heaters as well. This is represented in the model by a better heat exchange efficiency. The use of logs of different sizes was considered in the economic analysis, but has no effect on the environmental balance. Finally, for comparison purposes, the following scenarios were added: district heating with a natural gas boiler, natural gas boiler for the individual house (two different efficiencies), and electric heating system for the house. The description of the different scenarios is given in Table 1.

Table 1: Definition of the scenarios

Technology	Scenario ID	Heating needs	Varying factors	Other assumptions
Wood District Heating (WDH)	WDH-L100 WDH-R100 WDH-N100 WDH-L200 WDH-R200 WDH-N200	9500 MWh/year: 8500 MWh from wood, 1000 MWh from complementary gas boiler [16]	Wood supply distance: Local (L) (<20km) Regional (R) (50-75km) National (~300km) Distance to ash landfill: 100km / 200km	
Gas District Heating (GDH)	GDH	9500 MWh/year	None	Thermal efficiency 85%

Log Stove (LS)	LS-50 LS-33 LS-50lab LS-33lab	100 m^2 house, 20000 kWh/year [17,18]	Log size and labelling: 50cm logs 33cm logs 50cm labelled logs (following the French Label "France Bois Bûches") 33cm labelled logs Labelled logs follow a number of specifications on dimensions, tree species and moisture content. The effect of these on wood combustion was not studied in this particular work, but the differences in price were taken into account for the economic comparison of scenarios.	
Back boiler – equipped Log Stove (BLS)	BLS-50 BLS-33 BLS-50lab BLS-33lab	100 m^2 house, 20000 kWh/year [17,18]		
Pellet Stove (PS)	PS	100 m^2 house, 20000 kWh/year [17,18]	None	
Back boiler – equipped Pellet Stove (BPS)	BPS	100 m^2 house, 20000 kWh/year [17,18]	None	
Gas Boiler (GB)	GB GB-N	100 m^2 house, 20000 kWh/year [17,18]	Average thermal efficiency : 80% (old stove) 90% (new stove)	
Electric Heating (EH)	EH	100 m^2 house, 20000 kWh/year [17,18]	None	Thermal efficiency 100%

2.2. Modelling

2.2.1. Modelling the forest growth

The methodology we used was first developed by François et al. [19]. It consists of a coupling between the Aspen Plus® platform, widely used to model chemical processes and thermochemical conversion of biomass [20–22], and the CAPSIS platform, which contains a large array of growth models for forest stands under management [23]. The forest growth model selected for this study was FAGACEES, which is designed for pure even-aged high-forest stands of European beech [24]. The predictions obtained from these growth simulations (wood production per hectare per year, CO_2, N, Cl, and S absorbed per hectare per year) served as inputs for the Aspen Plus model and are modelled under Aspen Plus® by a FORTRAN subroutine that calculates the different flows. The input flow contains CO_2, H_2O, Nitrogen, Chloride, and Sulfur. The output comprises wood and its calculated composition, water contained in the wood, and the O_2 produced by the photosynthesis.

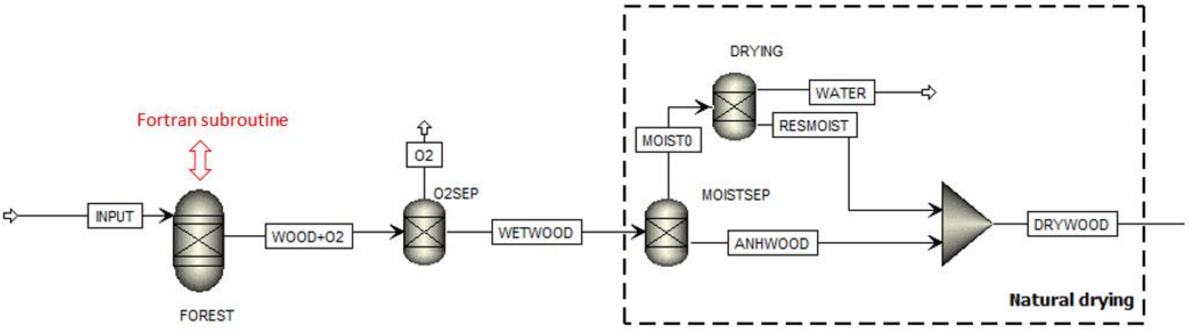

Figure 3: Modelling of wood growth in forest and natural drying under Aspen Plus®

Green wood is assumed to be at 70% moisture (dry mass basis). It is then dried naturally, down to 41% moisture.

2.2.2. Harvesting, transformation and transport of wood

The harvest, transformation and transportation steps were not modelled under Aspen Plus®, but greenhouse gas emissions and costs were compiled from the literature [25–28], as well as unpublished work from the European Institute for Energy Research [29].

2.2.3. Modelling the wood combustion process

A FORTRAN subroutine, based on the 2013 work of François et al. [30], was tied into the Aspen Plus model in order to determine the combustion reaction and products. For each form of wood fuel (logs, pellets, wood chips), the factors of the subroutine were slightly adjusted in order to have the final emissions matching with the real-life (experimental) values (for example, pellets generate less CO than logs).

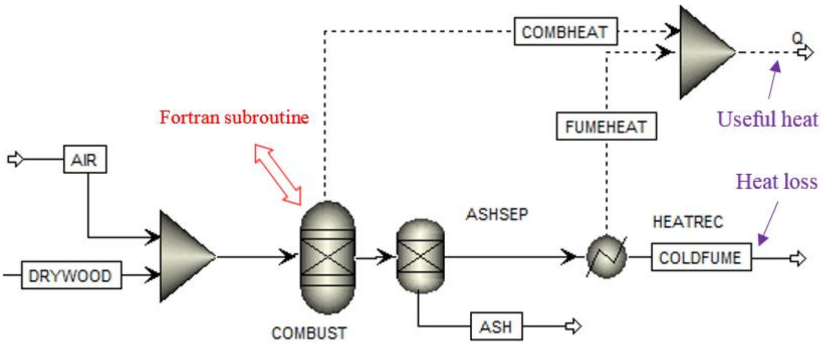

Figure 4: Modelling the combustion of wood in a stove under Aspen Plus

A more advanced model for the district heating scenario, not represented here, included post-treatment of fumes and forced drying of wood chips through the recycling of residual heat. The stoichiometry of the combustion reaction follows an equation of the following form:

$$\begin{aligned} C_aH_bO_cN_dS_eCl_f + \nu_{O2i}O_2 + \nu_{N2i}N_2 \rightarrow\ & \nu_{CO2}CO_2 + \nu_{H2O}H_2O + \nu_{CO}CO + \nu_C C + \nu_{C10H8}C_{10}H_8 \\ & + \nu_{C12H8}C_{12}H_8 + \nu_{C14H10a}C_{14}H_{10a} + \nu_{C14H10p}C_{14}H_{10p} \\ & + \nu_{C16H10}C_{16}H_{10} + \nu_{C10H16}C_{10}H_{16} + \nu_{CH4}CH_4 + \nu_{SO2}SO_2 \\ & + \nu_{HCl}HCl + \nu_{NO}NO + \nu_{N2O}N_2O + \nu_{ASHN}ASH_N + \nu_{ASHS}ASH_S + \nu_{N2}N_2 \end{aligned} \tag{R1}$$

All the species presented in equation (R1) are modelled by the Aspen Plus® model and their yields are adjusted based on experimental data on real-scale wood combustion systems.

2.3. LCIA method

In a Life Cycle Analysis framework, each input and output to the system is multiplied by an impact factor to obtain the total potential impact of the studied scenario. Although there is a general consensus about the impact of major pollutants such as CO_2, the impact factor for minor pollutants may vary according to the dataset. Here we focus only on one impact, the Global Warming Potential. It was calculated for each scenario using three different datasets: ReCiPe Midpoint (Hierarchist) [31], EDIP2003 [32], and CML2001 [33]. For electricity, the average French mix was used; due to the high proportion of nuclear power in the French grid, the GWP impact of French electricity is quite lower than that of nearby Germany for example. The used impact factors are shown in Table 2. In order to compare the different scenarios, the functional unit is the kWh of heat delivered to the user, i.e. either 1kWh of hot water for the heating district case, or 1kWh of heat transferred from the stove to the room.

Table 2: Impact factors for LCIA methods

Flow	ReCiPe Midpoint (H)	EDIP2003	CML2001
CO_2	1 kg CO_2 eq. /kg	1 kg CO_2 eq. /kg	1 kg CO_2 eq. /kg
CH_4	25 kg CO_2 eq. /kg	23 kg CO_2 eq. /kg	25 kg CO_2 eq. /kg
CO		2 kg CO_2 eq. /kg	
N_2O	298 kg CO_2 eq. /kg	296 kg CO_2 eq. /kg	298 kg CO_2 eq. /kg
$C_{16}H_{10}$			16.1 kg CO_2 eq. /kg
Production and combustion of natural gas	0.198 kg CO_2 eq. /kWh	0.198 kg CO_2 eq. /kWh	0.198 kg CO_2 eq. /kWh
Electricity (French mix)	0.180 kg CO_2 eq. /kWh	0.180 kg CO_2 eq. /kWh	0.180 kg CO_2 eq. /kWh

3. 3. Results and discussion

3.3.1. Calculated thermal efficiencies and emissions for biomass scenarios

Table 3 presents the thermal efficiencies and emissions values calculated by the Aspen Plus models for the Wood District Heating, Log Stove and Pellet Stove scenarios. These emissions correspond to one year of operation in each case. The model underestimates thermal efficiencies for stoves by an average of 5% compared to values found in the literature [34]. This is due to the fumes temperature, set a little too high for present-day technology.

Table 3: Thermal efficiencies and combustion emissions from Aspen Plus models for one year of operation

Scenario	WDH - all	LS - all	BLS - all	PS	BPS
Thermal efficiency on LHV (anhydrous biomass)	81%	69%	78%	75%	83%
CO_2 absorbed during photosynthesis (kg)	$3.83 \cdot 10^6$	$1.06 \cdot 10^4$	$9.35 \cdot 10^3$	$9.55 \cdot 10^3$	$8.67 \cdot 10^3$
Emissions from the combustion of wood (kg)					
CO	$2.58 \cdot 10^4$	$1.49 \cdot 10^2$	$1.32 \cdot 10^2$	$4.49 \cdot 10$	$4.07 \cdot 10$
N_2	$1.13 \cdot 10^7$	$3.65 \cdot 10^4$	$3.22 \cdot 10^4$	$2.82 \cdot 10^4$	$2.56 \cdot 10^4$
O_2	$5.37 \cdot 10^5$	$3.05 \cdot 10^3$	$2.69 \cdot 10^3$	$1.38 \cdot 10^3$	$1.26 \cdot 10^3$
CO_2	$3.58 \cdot 10^6$	$1.02 \cdot 10^4$	$8.96 \cdot 10^3$	$9.30 \cdot 10^3$	$8.44 \cdot 10^3$
H_2O	$2.04 \cdot 10^6$	$5.58 \cdot 10^3$	$4.92 \cdot 10^3$	$3.65 \cdot 10^3$	$3.32 \cdot 10^3$
$C_{10}H_8$	$1.03 \cdot 10^3$	$5.98 \cdot 10^{-4}$	$5.27 \cdot 10^{-4}$	$5.39 \cdot 10^{-4}$	$4.89 \cdot 10^{-4}$
$C_{12}H_8$	$1.03 \cdot 10^3$	$5.98 \cdot 10^{-4}$	$5.27 \cdot 10^{-4}$	$5.39 \cdot 10^{-4}$	$4.89 \cdot 10^{-4}$
$C_{14}H_{10a}$	$1.03 \cdot 10^3$	$5.98 \cdot 10^{-4}$	$5.27 \cdot 10^{-4}$	$5.39 \cdot 10^{-4}$	$4.89 \cdot 10^{-4}$
$C_{14}H_{10p}$	$1.03 \cdot 10^3$	$5.98 \cdot 10^{-4}$	$5.27 \cdot 10^{-4}$	$5.39 \cdot 10^{-4}$	$4.89 \cdot 10^{-4}$

$C_{16}H_{10}$	$1.03 \cdot 10^3$	$5.98 \cdot 10^{-4}$	$5.27 \cdot 10^{-4}$	$5.39 \cdot 10^{-4}$	$4.89 \cdot 10^{-4}$
HCl	$1.11 \cdot 10^2$	$3.07 \cdot 10^{-1}$	$2.71 \cdot 10^{-1}$	$2.77 \cdot 10^{-1}$	$2.52 \cdot 10^{-1}$
NO	$2.95 \cdot 10^3$	$1.18 \cdot 10^1$	$1.04 \cdot 10$	$1.07 \cdot 10$	9.67
N_2O	$2.21 \cdot 10$	$8.76 \cdot 10^{-2}$	$7.73 \cdot 10^{-2}$	$7.89 \cdot 10^{-2}$	$7.17 \cdot 10^{-2}$
SO_2	$7.33 \cdot 10^2$	9.50	8.38	8.56	7.78
FURAN	$5.10 \cdot 10^{-2}$	0.00	0.00	0.00	0.00
$C_{10}H_{16}$	$1.96 \cdot 10^3$	$4.54 \cdot 10$	$4.01 \cdot 10$	$4.09 \cdot 10$	$3.72 \cdot 10$
CH_4	$6.19 \cdot 10^2$	$1.43 \cdot 10$	$1.27 \cdot 10$	$1.29 \cdot 10$	$1.17 \cdot 10$
Soot	$5.16 \cdot 10^4$	2.39	2.11	1.62	1.47
Ashes	$2.06 \cdot 10^4$	$5.91 \cdot 10$	$5.22 \cdot 10$	$5.33 \cdot 10$	$4.84 \cdot 10$

3.3.2. Comparison of the Global Warming Potential of the different scenarios

Figure 5 presents the CO_2 content of energy in the different scenarios for the CML2001 method, and the contribution of each step of the production chain to the overall emissions. Overall, the best environmental performance is obtained by the Wood District Heating scenario. However, it should be noted that the analysis does not take into account neither the emissions associated with the construction of the facility nor those of its eventual dismantling. The scope of this work is not to conduct a complete life cycle assessment of the chains.

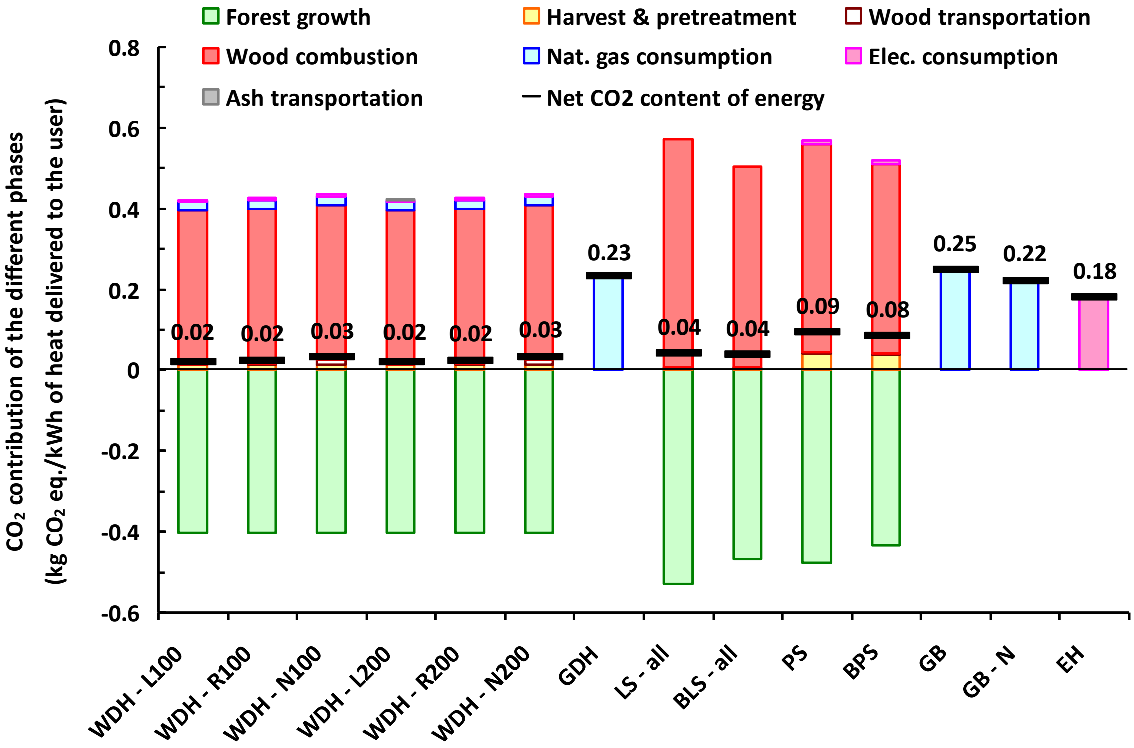

Figure 5: CO_2 contribution of the different chain steps in the different scenarios and impact of the different stages (CML2001 method)

The case of wood pellets is interesting, because the wood harvesting and pre-treatment steps account for more than 6% of the total positive emissions (excluding the CO_2 absorbed during the growth stage), while they represent less than 1% in the log stove scenarios. Indeed, pellets are produced by drying and compressing sawdust and shavings which require a higher consumption of fossil fuels than wood logs production. Lower emissions for the production of pellets could be achieved by drying the wood with residual wood heat (available in the sawmill) instead of fossil fuels as assumed here. The net impact of the wood pellets scenarios is nonetheless very good compared to gas or electricity scenarios.

3.3.3. Economic aspects and carbon content

In order to compare the environmental and economic performance of the different scenarios, a rough economic analysis was performed. The costs taken into account are the initial investment (data taken from a study by the French Environment and Energy Management Agency (ADEME) [35] and internet browsing), amortised over 20 years, annual maintenance costs, and of course fuel costs [36]. Figure 6 shows the cost and carbon content for 1kWh of energy for each scenario. Electric heating is by far the most expensive scenario. The cheapest alternative is Wood District Heating, which costs in average 4.9 c€ per kWh, in line with the results in [35]. In cases where district heating is not available, wood stoves are economically interesting, all the more because of the financial support currently offered by the government e.g. in the form of tax credit (this was not taken into account in this study, as the conditions for benefiting from this support are not met by all house owners). Generally pellet stoves are more expensive than log stoves to buy and maintain, but are nonetheless increasingly popular, because they require less handling than traditional wood log stoves, and can be programmed electronically to maintain a certain temperature, heat the house at certain times, etc.

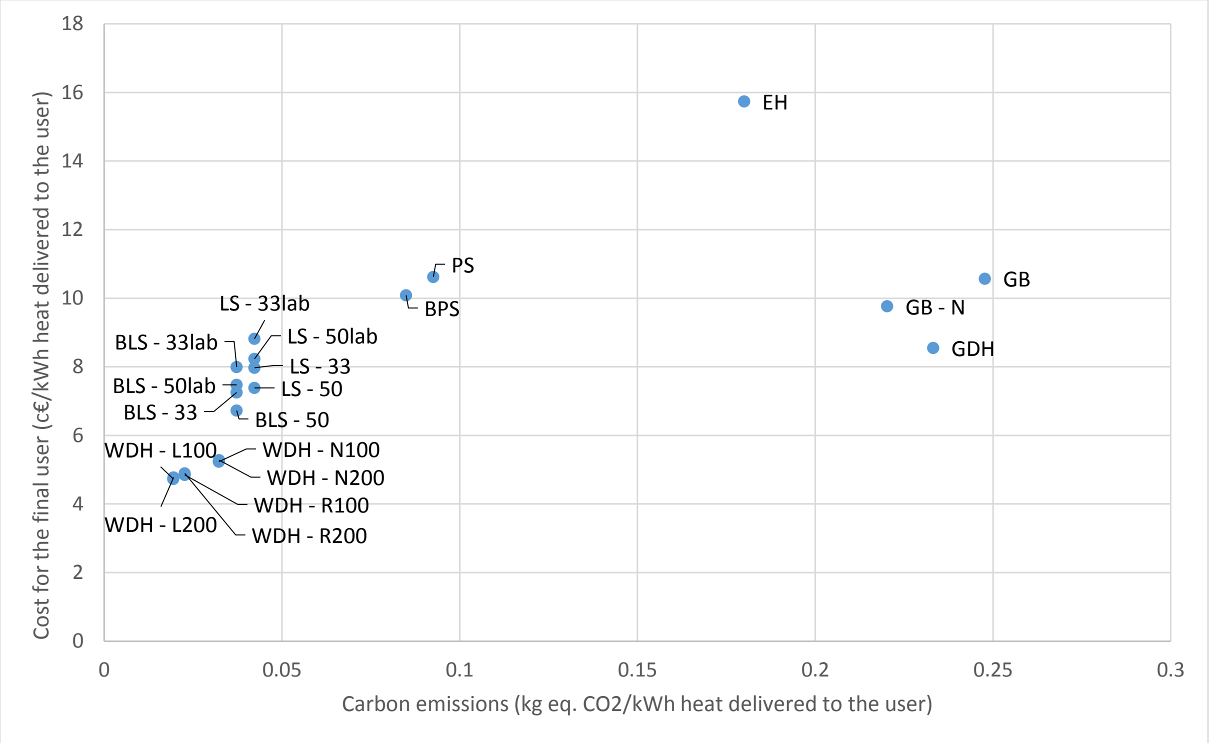

Figure 6: Cost and carbon content for 1 kWh of energy in the different scenarios

3.3.4 The importance of minor pollutants and of the LCIA method

Figure 7 shows the GWP of all scenarios according to the LCIA method used. Differences in results appear mainly for the log stove and pellet stove cases.

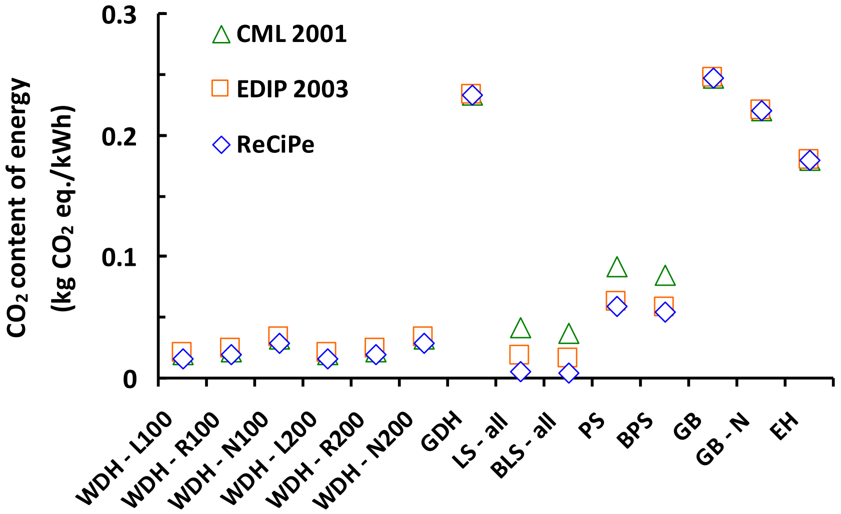

Figure 7: GWP of the scenarios according to the three LCIA methods

These scenarios (Figure 8) clearly show that the components responsible for these variations are CO and the VOC, lumped under the $C_{10}H_{16}$ compound (as a surrogate of other VOC emitted). The three methods do not account for the same impact (in terms of kg CO_2 equivalent, see table 2) for these compounds and this discrepancy can increase or decrease the calculated impact by a factor 7. This effect is less prominent in the case of district heating because the quality of the combustion is higher, resulting in lower emissions of pollutants. The accuracy of the process models and the choice of the impact factor methods are crucial for a reliable assessment of the environmental impact of biomass-to-energy chains.

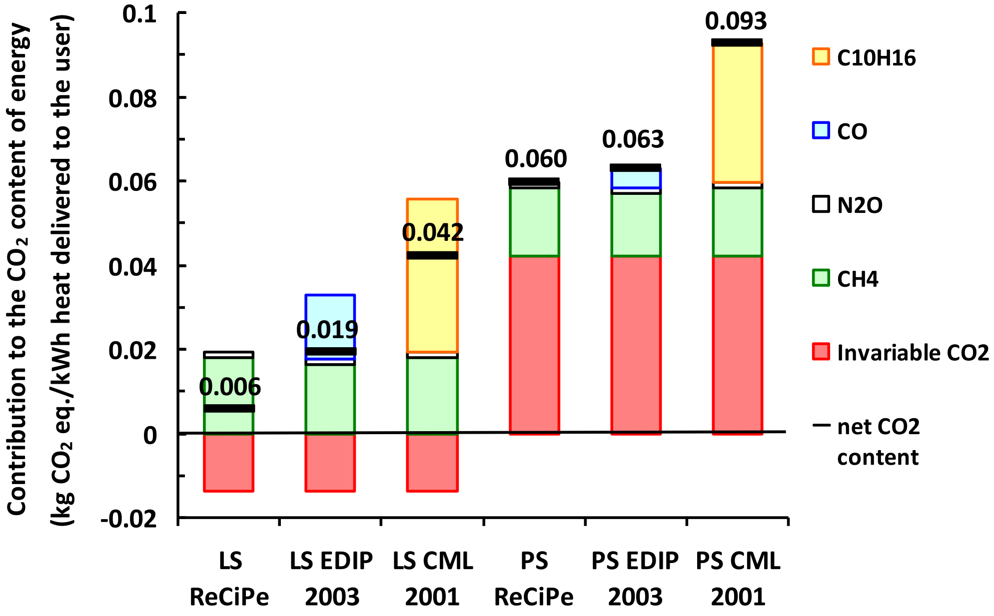

Figure 8: Impact of minor pollutants on the GWP result, according to the three LCIA methods, for log (LS) and pellet stoves (PS)

4. Conclusion

In this study, we modelled three different wood heating scenarios, and highlighted the importance of taking into account the pollutants produced by the combustion of wood. Due to inconsistencies in impact factor datasets, minor pollutants such as CH_4 or PAH can radically change the outcome of the calculations and lead to an important contribution to Global Warming Potential impact. Not taking this into account would signify taking the risk of underestimating the environmental impact of wood-based energy projects. Further research should compare the environmental performance of different stove technologies, in order to determine if it would be more carbon-efficient to improve on the quality of combustion, i.e. to reduce the amount of pollutants emitted per kg of wood burnt, or on heat transfer efficiencies, to reduce the quantity of wood burnt for the targeted energy output.

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