Life Cycle Assessment of woody biomass from energy crops

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Summary

To meet the French target of raising to 23% the share of renewable energy by 2020, bioenergy should broadly be used in France. In this context, woody energy crops like short rotation coppices (SRC) and softwood plantations dedicated to produce energy could be developed. The development of such crops will depend on improving their economic efficiency, particularly through mechanization. This is the main purpose of the MECABIOFOR project, focusing on technological enhancement of machines related to planting, weeding, and harvesting for 6 woody energy crops:

- Short rotation coppices of eucalyptus, poplar and black locust,
- Very short rotation coppices of poplar and black locust,
- Maritime pine plantation semi-dedicated to energy.

However, mechanization means also using fuel-consuming equipment, which could reduce the benefit on climate change mitigation, increase energy demand, or create other environmental impacts. It is hence very important to address these sustainability issues in order to confirm the interest of mechanization developments for woody energy crops.
For this, Life Cycle Assessment (LCA) is performed over the entire biomass supply-chain plus the heat production in furnace. The supply-chain includes feedstock production, i.e., all the operations needed for the installation and the growth of the stand, harvesting including chipping, and transport to the combustion plant.
LCA is performed according to the guidance in ISO 14040:2006, ISO 14044:2006, and ILCD handbook.
This paper presents the first LCA results of the MECABIOFOR project.

Keywords: LCA, carbon footprint, woody biomass, energy crops, mechanization

1 Introduction

The promotion of energy from renewable sources and the effort to energy saving constitute two of the main European Union (EU) measures related to climate mitigation and energy security. The European Union has set common targets for the year 2020 by the renewable energy directive (RED) (EC, 2009), which consist of:

- Reducing greenhouse gas (GHG) emissions by 20% relative to those in 1990,
- Raising to 20% the share of renewable energy in the final energy consumption,
- Improving the energy efficiency by 20% (23% for France).

Within this framework, the French national action plan states a significant contribution of the biomass to achieve this target, especially to produce heat (FR, 2010).

Among biomass sources, the woody energy crops have been very limited in France so far, with 3000 ha of short rotation coppices and 3000 ha of maritime pine plantations (Berthelot Alain, personal communication). Nevertheless, in the RED context, the development of these woody energy crops could be potentially more important over the coming years. Among different species adapted to these cropping systems, poplar, eucalyptus and black locust are good candidates for coppice and maritime pine for softwood plantations, because of their fast growth, their relative hardiness and, for coppice, their sprouting capacity after cutting. The mapping of the potential development in France for these crops has been already studied taking into account soil and climatic constraints, and the current land uses. In addition to the mapping, it has been foreseen that the development of short rotation coppice will be mainly limited at abandoned agricultural lands, tens of thousands of hectares maximum, due to land use competition (Berthelot et al., 2011; Nguyen-Thé et al., 2011). Concerning maritime pine plantation semi-dedicated for energy, the scheme consists to combine in the same plot traditional silviculture (felling cycle 35 years) and biomass production (felling cycle 9 years) by doubling the initial stand density. Although still experimental, its development could be thereby more important than short rotation coppice because the area of maritime pine in France covers one million of hectares (http://inventaire-forestier.ign.fr). But no forecast has ever been done so far.

Beyond land use competition, the success of this woody energy crops development will also depend on the improvement of their economic efficiency, particularly from mechanization. This is the main purpose of the MECABIOFOR project (http://www.agence-nationale-recherche.fr/Colloques/BioEnergies2012/posters/mecbiofor.pdf) focusing on technological enhancement of machines related to mechanized planting, mechanized weeding on the row, and harvesting with accumulating felling head. These technological improvements are developed for 6 woody energy crops in France:

- Short rotation coppice (SRC) of eucalyptus, poplar and black locust, with 7-10 years cutting cycle,
- Very short rotation coppice (VSRC) of poplar and black locust, with 2-4 years cutting cycle,
- Maritime pine plantation semi-dedicated to energy (MP).

However, mechanization means also using fuel-consuming equipment, which could reduce the benefit on climate change mitigation, increase energy demand, or create other environmental impacts. It is hence very important to address these sustainability issues in order to confirm the interest of the woody energy crops development. For this, the MECABIOFOR project includes a Life Cycle Assessment (LCA) task, whose main results, in particular energy efficiency assessment and carbon footprint, are presented (section 3) in this paper. LCA was performed according to the guidelines in ISO 14040 (ISO, 2006a), and ISO 14044 (ISO, 2006b), with particular attention to the goal and scope definition (section 2). Indeed, modelling of Life Cycle Inventory (LCI) and the calculation of Life Cycle Impact Assessment (LCIA) are goal dependent. It's hence crucial not to neglect this step (Zamagni et al., 2012) to provide relevant response to the issue addressed and not misleading results, and reciprocally not to interpret the results beyond the limits of the goal and scope of the assessment (EC-JRC, 2010). To carry out this first step as all the other steps of LCA, the guidance given by ILCD handbook (EC-JRC, 2010) was followed.

2 Materials and methods

2.1 Goal definition

The purpose of the MECABIOFOR project is to increase the mechanization of French woody energy crops, focusing on planting, weed control, and harvesting. Even though woody biomass can potentially be used as material or as energy, it's considered in the MECABIOFOR project that biomass from woody crops is fully dedicated to produce solid fuels for the boilers and this scenario is determined at early stage allowing a harvest of full tree. Six base cases scenarios are studied to allow covering the main candidate species (eucalyptus, poplar, black locust and maritime pine) and the main kinds of woody energy crops (coppices with different rotations, and softwood plantation semi-dedicated for energy) in France. The project is commissioned by the French National Research Agency and the Aquitaine Region.

As part of this project, LCA aims to check if the technical developments made in the project will not be counterproductive from the environmental and energy point of view, i.e., to compare woody energy crops with or without these technical developments. The answer of this question will contribute to their validation. The intended application of LCA is hence system improvement (ecodesign). The type of deliverable is a detailed LCI model of the system. The outcomes of this study will be interesting for main stakeholders of the energy and forestry sectors, private or public.

With regard to the context, a global policy to support the development of renewable heat in France has been set up based on the award of financial aid to heat generation facilities and heat networks (FR, 2010). Biomass would be the main resource of renewable heat with several origins as industrial roundwood, forestry residues, industry wood waste, agricultural residues, and energy crops. So far, woody energy crops have been limited to a few thousand hectares on abandoned agricultural lands. Concerning maritime pine plantation semi-dedicated for energy, the crop is managed jointly with regular stand in the same plot. The stand density of plantation is doubled by doubling the number of lines and after the first 9 years of the rotation every added lines are harvested to return to a classic pattern. The biomass from woody energy crops could be hence considered as an additional biomass. But the development of woody energy crops, beyond optimisation of the mechanization, depends on others issues which are not the focus of the study, such as the land use competition, the benchmarking of renewable heat supplies as well. The goal of the MECABIOFOR project is not to address globally the development of woody energy crops. It's to focus on one of potential triggers of the development, which is the mechanization.

Otherwise, progress made by the MECABIOFOR project is estimated with small-scale marginal consequences on the forestry equipment production, as well as all background system.

At last, the renewable energy directive (EC, 2009) requires that the greenhouse gas emission saving thanks to renewable energy use is at least 35%. The French policy forecasts that the development of renewable heat will reduce the use of natural gas to produce heat (FR, 2010). The modelling shall also include a comparison with natural gas heat production.

As the result, the study is mainly assigned to the goal situation A ("micro-level decision support") according to ILCD handbook (EC-JRC, 2010).

2.2 Scope definition

2.2.1 Function, functional unit and reference flows

The woody energy crops are dedicated to produce energy. Even though the study focuses on cropping, the relevant function provided by the to-be-analysed system is the production of energy including the energy conversion, especially to be able to make relevant comparisons. The energy conversion system which has been selected is a simple production of heat in furnace.

In line with the system analysed and the goal of the study, the functional unit is one GJ of heat produced at plant in furnace of wood chips from current woody energy crops. “Current crop” means a crop without land use change, i.e., the previous crop and the subsequent crop are the same crops.
It’s important to highlight that the defined functional unit here is not one additional GJ produced from the development of woody energy crops which shall fit more in a consequential approach. Even though the unit is the same (one GJ), the results are obviously not comparable.

2.2.2 LCI modelling framework

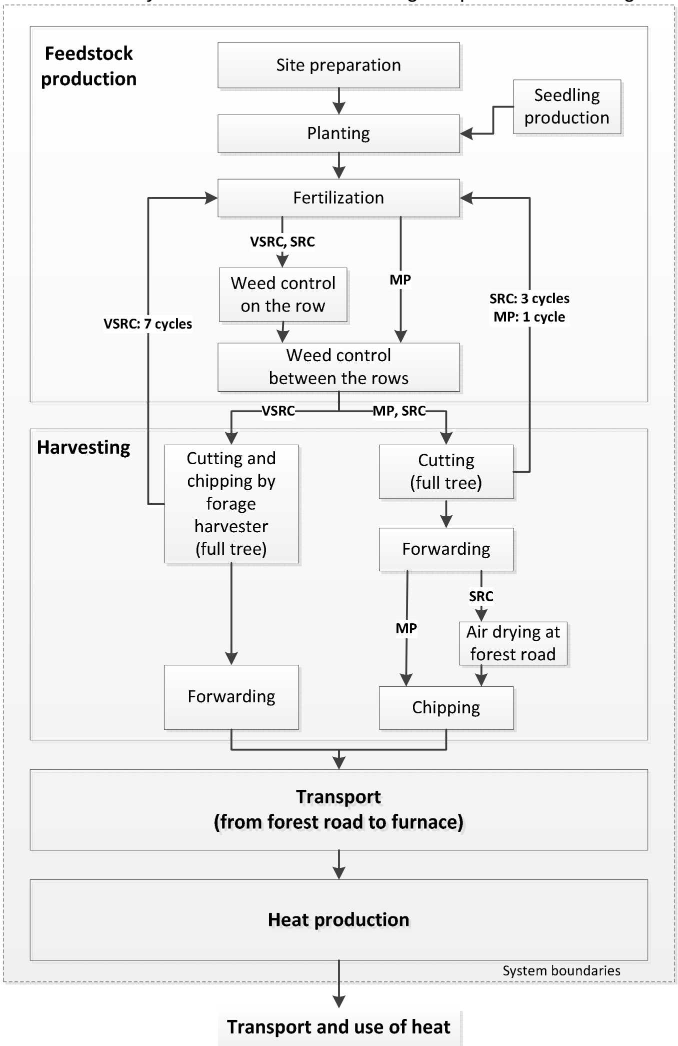
According to the recommendations from the ILCD handbook (EC-JRC, 2010), the modelling needs to be made according to an attributional approach (situation A). Furthermore, use of biomass from the woody energy crops (with or without mechanization developments) produces heat which can replace natural gas heat.

2.2.3 System boundaries

The system boundaries shall define and include the stages in relation with the scope of the study. In line with an attributional modelling, the system is modelled following a general supply-chain and process-chain logic. Both foreground and background data correspond to existing supply chain. Data used for the different alternative scenarios will be based on the technical developments made by the project, which are considered to be short to mid-term changes.
The analysed system includes the entire biomass supply-chain, as well as the subsequent energy conversion. The energy conversion selected is the production of heat in furnace. The biomass supply-chain includes transport to the plant, harvesting, as well as feedstock production. The harvesting stage includes cutting, chipping in the field for VSRC or at forest road for MP and SRC, forwarding to forest road, and air drying for only SRC. The feedstock production stage means the entire process-chain to the installation and the growth of the stand, i.e., seedling production, site preparation (with in first stump destruction for VSRC and SRC), planting, fertilizing, weed control on the row only for VSRC and SRC, and weed control between the rows.
System boundaries are represented in Figure 1, describing globally the processes of the foreground system for all the woody energy crops studied.
Moreover, the modelling of woody biomass systems presents specific issues due to their dynamic character, which is determined by processes in space and time. The temporal and spatial boundaries should be transparently defined and justified with relation to the goal and scope of the study (Agostini et al., 2013).
The spatial level considered is the plot. The time horizon of the modelling is the full rotation, i.e., for the MP 38 years, for the SRC 30 years with 3 cutting cycles of 10 years, and for the VSRC 21-22 years with 7 cutting cycles of 3 years. The time starts at the beginning of rotation and not at the wood combustion, because the main objective of woody crops is the production of harvested wood, i.e., if woody crops had no objective of harvest, woody crops would not be in place. In compliance with the ILCD handbook (EC-JRC, 2010), both uptake of CO2 and release of biogenic CO2 are accounted for. Considering the temporal boundaries described above, it means that CO2 uptakes related to the growth of the woody crops are hence considered occurring before CO2 emissions from the wood combustion.
In line with the goal and scope of the study, no land use change has been considered. It assumes no carbon soil loss between the beginning and the end of the rotation.
The background processes (fuel production, electricity production, fertilizer production, herbicide production, oil production, waste disposals …) have been also covered by the system boundaries. The transport of forest staff and forest equipment, as well as the infrastructures (equipment, road) production and maintenance, have been included and have undergone sensibility analysis.

Only the supply transport of cropping inputs (fuel, fertilizer, herbicide, oil) and the construction of forest road have not been taken into account due to the data lack.

Figure 1: Flow chart of system boundaries describing the processes of foreground system



2.2.4 Allocation rules

Allocation has not been required in the modelling of coppices since the entire biomass is dedicated to produce biofuel, except for the production of the infrastructures, e.g., the production of forestry equipment for which an allocation has been done on the hours of use.

In contrast, the modelling of maritime pine plantation semi-dedicated scenario requires an allocation to partition, the impacts between biomass dedicated to produce energy and all the remaining biomass harvested that is used for other purposes. For this, all the processes before energy biomass cutting, i.e., during the first 9 years, as well as the total land occupation, i.e., the land occupation until to the clear-cutting of the regular stand, are allocated on the total volume of wood harvested during the entire rotation (38 years).

The CO2 uptakes have been allocated on carbon content of harvested wood as an inherent material property and biogenic carbon emissions from the combustion of wood chips have been accounted for.

2.2.6 LCIA methods

The LCIA methods selected have been the methods at midpoint level recommended without caution by ILCD handbook (EC-JRC, 2011), i.e. indicators, Global Warming Potential (GWP), ozone depletion potential (ODP), intake fraction for fine particles (PM), human exposure efficiency relative to U^{235} (HHIR), tropospheric ozone concentration increase (POF), accumulated exceedance for acidification (acidification), accumulated exceedance for terrestrial eutrophication (TE), freshwater eutrophication (FE), and marine eutrophication (ME), scarcity for abiotic resource depletion. For all impacts categories, the characterisation factors used into the assessment have been unchanged, except abiotic resource depletion. Indeed for this indicator, the method of CML selected by the JRC has since been updated in April 2013. The last recommendations of CML (v4.2) have been followed, i.e., abiotic resource depletion of elements (elements ADP) based on ultimate reserves and abiotic resource depletion of fossils fuels (fossil fuels ADP) based on the lower heating value.
In the absence of any relevant indicators to assess impacts from land occupation, the amount of land occupation obtained by adding up land occupation inventory flows has been included in the indicators panel.
In line with the goal of the study, the interpretation (analysis of contributors, sensibility analysis, and comparison with natural gas heat production) was mainly conducted on climate change impact assessment.
For the assessment of GWP, the conventional static approach has been applied. The biomass related GHG uptakes and emissions, as well as fossil GHG emissions, have been accounted for. The chosen time horizon of the GWP assessment is 100 years. The results from fossil origin and results from biogenic origin are presented separately. This conventional static approach of the assessment doesn't allow taking into account the dynamic aspect of the stand growth.

2.2.7. Data quality

Foreground data of biomass supply-chain modelling have been defined by the partners involved in the MECABIOFOR project, in particular French forestry cooperatives and FCBA (French technical centre of forest-based sector) experts of forestry. They have defined for each crop the base scenario, i.e. the scenario as usual without equipment improvement.
Biomass production data come from statistic growth and allometric models (maritime pine plantation semi-dedicated to produce energy (Cavaignac et al., 2010), eucalyptus SRC (Cavaignac et al., 2012; Shaiek et al., 2011), poplar SRC and VSRC (de Morogues et al., 2011), black locust SRC and VSRC (Bastien et al., 2011)).
The descriptions of cropping are based on current practices recommended in France (maritime pine plantation semi-dedicated to produce energy (Bastien et al, 2011), eucalyptus SRC (Melun, 2007), poplar SRC and VSRC (de Morogues et al., 2011), black locust SRC and VSRC (Bastien et al., 2011)). With respect to fertilization aspects, woody energy crops have specific features. Indeed, the fast growth with a lower nutrient efficiency, the harvest of young trees with a higher proportion of leaves and branches, and the harvest of residues with a higher nutrient content than stem especially nitrogen, cause an higher mineral export. To keep soil fertility throughout rotations, an additional fertilization is needed. To assess the potential impact of the additional fertilization, the specie with the most comprehensive nutrient model in short rotation, i.e. poplar, has been selected. The additional fertilization has been estimated according to stem age and biomass productivity (Berthelot et al., 2010). However, for maritime pine and eucalyptus, the phosphorus fertilization has been assumed to be equivalent to standard schemes. An additional fertilization will also be required for these species, but the lack of available data doesn't allow taking it into account. For black locust, the knowledge is too partial to estimate any fertilization, except for nitrogen fertilization which is not necessary due to its ability to fix nitrogen. As the result, these lacks limit the comparison between the crops. Only the comparison between SRC and VSRC of the same specie is relevant.

Concerning data related to equipment like fuel consumption and productivity of the operation, they are mainly collected from forestry cooperatives measurements.
Data of wood furnace modelling correspond to French emissions factors (CITEPA, 2003) which are French averages.
At last, background data, as well as natural gas data, come from V2.2 Ecoinvent database, and correspond to processes representative of French or European data.

3 Results

In this paper, only the results of the base cases for each energy crops and for natural gas are presented. The assessment of the scenarios integrating innovations on planting, weed control, and harvesting is on going. The results of the comparison will be presented in a further paper.

3.1 Inventory analysis

3.1.1 Feedstock production and harvesting

For each crop a base scenario has been defined including all the operations needed to assume no land use change (stump destruction, fertilization). All the successive silvicultural and harvesting operations have been described on a plot scale:

- Type of operation,
- Model of main equipment and tools including weight and lifetime (table 1),
- Productivity,
- Fuel consumption per hour,
- Type and amount of inputs (seedlings, herbicide, fertilizer).

Table 1: equipment data to production impact assessment

	Unit	Tractor	Harvester	Forwarder	Crusher	Tools
Weight	tons	8-14	12-17	15-17	25	0.5-5
Lifetime	hours	10000	10000	15000	7000	5000-10000

An average plot area, an average distance between 2 logging camps for the equipment transport, and a staff average distance to go in forest have been estimated to model the equipment transport in forest, as well as staff transport. In the base scenarios, all the operations are still mechanized, except planting and weed control on the row. The harvesting has been considered for full tree (stem and residues). For VSRC, cutting and chipping have been made together by modified foragers with dedicated SRC headers. A temporary storage and air drying at forest road is possible only for SRC.
The table 2 presents main foreground data used in the modelling of feedstock production according to the different woody energy crops studied.

3.1.2 Biomass transport and heat production

In contrast with the feedstock production, biomass transport and heat combustion have been defined in the same way for all the studied crops.
The transport is carried out by truck over 50 km.
No additional drying is made at plant.
The efficiency of the combustion is assumed 87% with 6% of ash which are landfilled. The emissions of wood furnace have been estimated from French emissions factors (table 3; CITEPA, 2003).

Table 2: description of main foreground data of the feedstock production modelling according to the different woody energy crop studied

		Unit			Maritime pine			Eucalyptus SRC			Poplar SRC			Black locust SRC			Poplar VSRC			Black locust VSRC		
Plot area			ha			5			4			4			4			4			4	
Fresh dryness			%			50%			48%			44%			62%			44%			62%	
Number of felling cycles dedicated to energy			unit			1			3			3			3			7			7	
Full rotation			year			38			30			21			30			21			22	
Harvested wood	Total/ha		dry t.ha^{-1}			217			403			185			186			162			146	
	Only energy/ha		dry t.ha^{-1}			19																
	Total/(ha.an)		dry t.ha^{-1}.yr^{-1}			5.7			13.4			8.8			6.2			7.7			6.6	
Transport distance	Forestry equipment (between 2 camps)		km			15			30			30			30			30			30	
	Staff (one way)		km			30			50			50			50			50			50	
Preparation site	Herbicide on stumps		type	l.ha^{-1}		no			no			no		glyphosate		6		no		glyphosate		6
		l.h^{-1}*	h.ha^{-1}**	l.ha^{-1}***										9	0.5	4.5				9	0.5	4.5
	Stumps destruction	l.h^{-1}*	h.ha^{-1}**	l.ha^{-1}***		non mechanized		30	8	240	30	8	240	30	8	240	30	8	240	30	8	240
	Weeding/land clearing		type	l/ha				glyphosate		6	glyphosate		6	glyphosate		6	glyphosate		6	glyphosate		6
		l.h^{-1}*	h.ha^{-1}**	l.ha^{-1}***	14	2.0	28	9	0.5	5	9	0.5	5	9	0.5	5	9	0.5	5	9	0.5	5
	Ploughing	l.h^{-1}*	h.ha^{-1}**	l.ha^{-1}***	22	1.8	39	22	1.8	39	22	1.8	39	22	1.8	39	22	1.8	39	22	1.8	39
	Chiselling	l.h^{-1}*	h.ha^{-1}**	l.ha^{-1}***	14	1.4	20	14	1.0	14	14	1.0	14	14	1.0	14	14	1.0	14	14	1.0	14
Plantation	Number of seedlings		unit/ha			2500			1000			1667			1667			6700			6700	
	Process	l.h^{-1}*	h.ha^{-1}**	l.ha^{-1}***		manual			manual		12	4.0	48	12	4.0	48	12	8.0	48	12	8.0	48
Weed control			type	l.ha^{-1}		no		gardenet		1.3	gardenet		1.8	gardenet		1.8	gardenet		2.1	gardenet		2.1
		l.h^{-1}*	h.ha^{-1}**	l.ha^{-1}***				12	0.5	6	12	0.5	6	12	0.5	6	12	0.5	6	12	0.5	6
Cleaning			number			2			3			4			3			4			3	
		l.h^{-1}*	h.ha^{-1}**	l.ha^{-1}***	25	1.3	31	14	1.0	14	14	1.0	14	14	1.0	14	14	1.0	14	14	1.0	14
Fertilization			kg N.ha^{-1}			0			0			133			0			99			0	
			kg P2O5.ha^{-1}			90			100			56			0			47			0	
			kg K2O.ha^{-1}			0			0			126			0			102			0	
			number			with ploughing			3			3			0			7			0	
		l.h^{-1}*	h.ha^{-1}**	l.ha^{-1}***				8	0.25	2	8	0.25	2				8	0.25	2			
Cutting+chipping		l.h^{-1}*	fresh t.h^{-1}**	l.fresh t^{-1}													80	28	2.9	80	28	2.9
Cutting		l.h^{-1}*	fresh t.h^{-1}**	l.fresh t^{-1}	9	6	1.5	15	11	1.4	12	9	1.3	12	9	1.3						
Forwarding		l.h^{-1}*	fresh t.h^{-1}**	l.fresh t^{-1}	11	8	1.4	14	19	0.7	14	19	0.7	14	19	0.7	14	14	1.0	14	14	1.0
Air drying at the forest road						no			yes			yes			yes			no			no	
Dryness of chips			%			50%			65%			65%			70%			44%			62%	
Chipping		l.h^{-1}*	fresh t.h^{-1}**	l.fresh t^{-1}	50	27	1.9	50	26	1.9	50	17	3.0	50	27	1.9						

Table 3: description of emissions to air from the combustion of 1 GJ of wood chips

Type of air emission	Unit	Value
Sulfur dioxide	kg	0.02
Nitrogen oxides	kg	0.2
NMVOC, non-methane volatile organic compounds, unspecified origin	kg	0.0048
Methane, biogenic	kg	0.0032
Carbon monoxide, biogenic	kg	0.25
Particulates	kg	0.1
Dioxin, 2,3,7,8 Tetrachlorodibenzo-p-	ng	40
PAH, polycyclic aromatic hydrocarbons	µg	8000
Arsenic	mg	9.5
Cadmium	mg	1.4
Chromium	mg	47
Copper	mg	31
Mercury	mg	0.8
Nickel	mg	11
Lead	mg	90
Selenium	mg	7
Zinc	mg	290
Carbon dioxide, biogenic	kg	depends on dryness

3.2 Energy efficiency

The results of energy balance for the base scenarios (table 4) show an equivalent energy efficiency of heat production, about 80%, between wood chips and natural gas, or slightly better by a few points. The lower combustion efficiency is compensated by a higher energy efficiency of wood fuel supply. The energy consumption to supply wood fuel was compared to results of previous studies (Roedl, 2010; Gasol et al., 2008; Gabrielle et al., 2013). Only the order of magnitude could be checked, because of the scenarios variability.

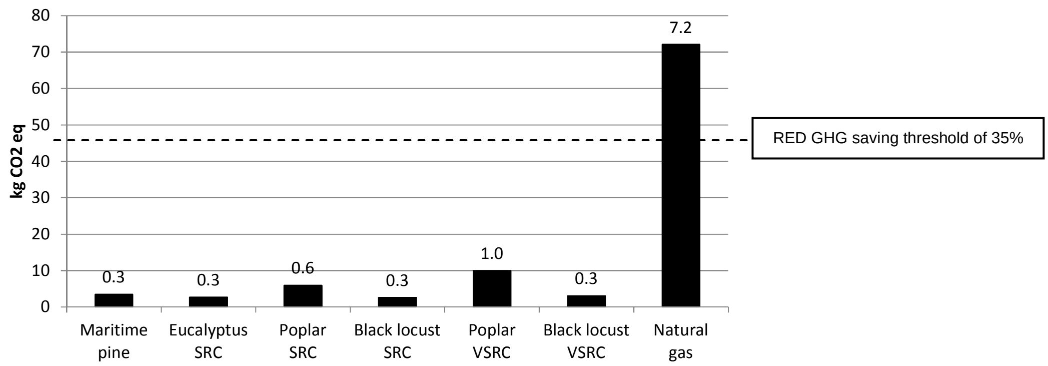
Table 4: energy balance of 1 GJ heat produced at plant for the base scenarios

	Unit	Maritime pine	Eucalyptus SRC	Poplar SRC	Black locust SRC	Poplar VSRC	Black locust VSRC	Natural gas
Energy consumption to supply the fuel	MJ	55	45	69	41	100	46	183
Energy content of fuel	MJ	1150	1150	1150	1150	1150	1150	1050
Energy efficiency of fuel supply	%	95%	96%	94%	97%	92%	96%	85%
Total energy consumption to produce heat	MJ	1205	1195	1219	1191	1250	1196	1233
Energy efficiency of heat production	%	83%	84%	82%	84%	80%	84%	81%

3.3 Impact assessment of Global Warming Potential

The GWP of the heat production at plant for the base scenarios has been assessed in the range from 2.6 to 10 kg CO2 eq/GJ of heat produced from wood chips (figure 2). The GHG saving compared to heat from natural gas is very high, from 86 to 96%, largely greater than 35% of RED threshold.

Figure 2: GWP(100) of 1 GJ of heat produced at plant for the base scenarios
(Nota bene: additional fertilization is taken into account only for poplar)



Concerning biomass-related GHG flows, the uptakes from feedstock production compensate biomass related emissions from combustion and the contribution of biomass-related GHG flows to the total GWP potential is zero.

An analysis of contributor to fossil GWP (figure 3 and figure 4) shows that the nitrogen fertilization, which has been applied only in poplar schemes in the study, have the highest impact on climate change due to nitrogen fertilizer production (ammonium nitrate) and dinitrogen monoxide emissions to air from nitrogen fertilizer use (direct emissions and indirect emissions from nitrate leaching and ammonia). For poplar, the important needs of additional fertilization for VSRC significantly increases the balance sheet compared to SRC. Other than nitrogen fertilization, the harvesting is the main source of GHG emissions. All the operations of harvesting (cutting, forwarding, and chipping) are significant. Site preparation and wood chips transport from forest road to combustion plant are also operations emitting GHG. In the base scenarios, the impacts of planting which is made manually and of weed control which is made by herbicide are not significant in contrast.

Figure 3: fossil GWP(100) of 1 GJ of heat produced at plant for the base scenarios
(Nota bene: additional fertilization is taken into account only for poplar)

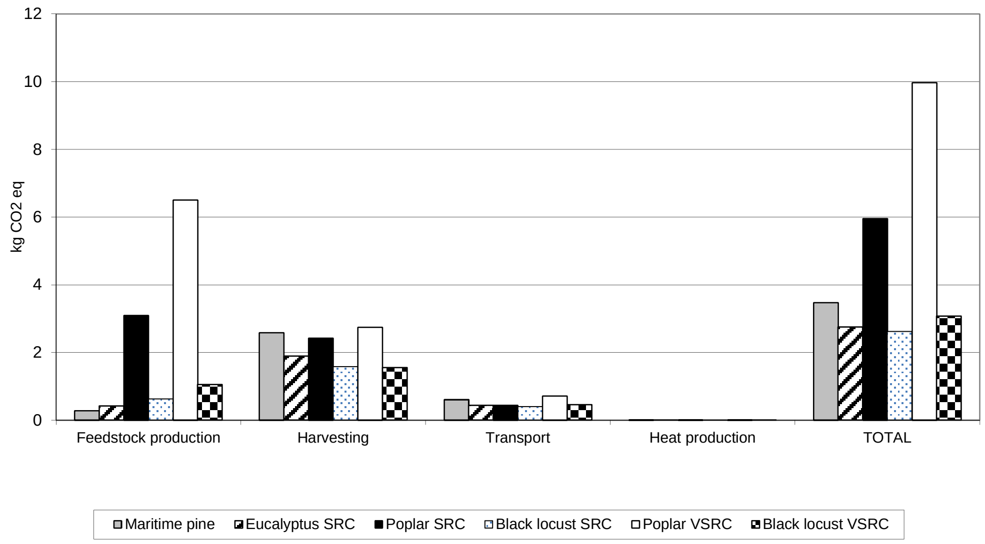
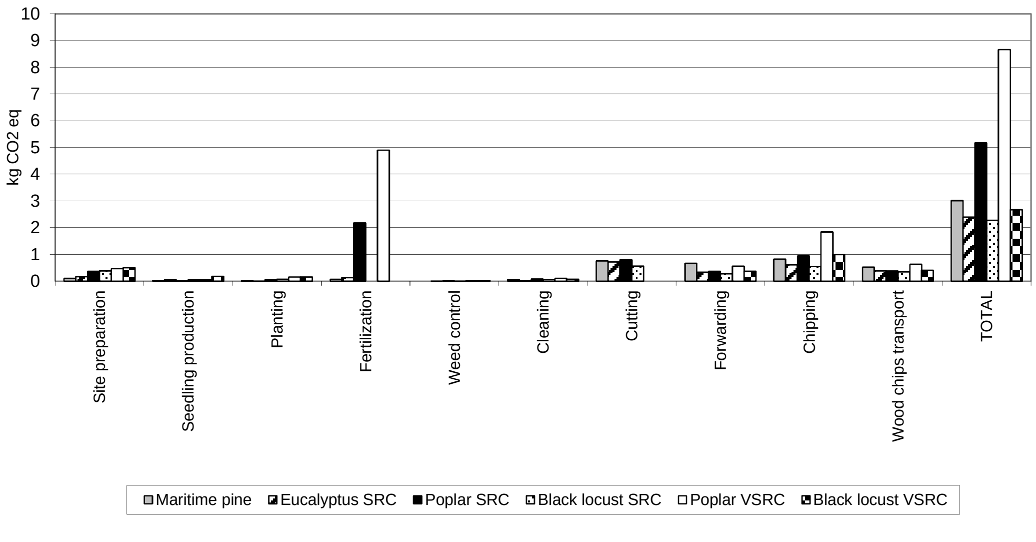


Figure 4: fossil GWP(100) of 1 GJ of wood chips at plant for the base scenarios
(Nota bene: additional fertilization is taken into account only for poplar)



Concerning to the contribution of infrastructures, forest staff transport and equipment transport, the results give respectively a contribution in range of 5.5-8% and 1.5-5%, i.e, in range of 7-13%, against 1% for natural gas heat production (table 5).

Table 5: contribution of infrastructures, forestry staff transport and equipment transport to GHG(100) of heat production at plant for the base scenarios

	Maritime pine	Eucalyptus SRC	Poplar SRC	Black locust SRC	Poplar VSRC	Black locust VSRC	Natural gas
Infrastructures	7.0%	7.5%	6.9%	8.0%	5.5%	6.5%	1.1%
Transport of forestry staff and equipment	3.7%	4.0%	2.8%	5.0%	1.5%	3.2%	/
Total	10.7%	11.4%	9.6%	12.9%	7.0%	9.7%	1.1%

3.4 Impact assessment of others impacts categories

Beyond climate change assessment, LCA is a tool to evaluating all the potential environmental impacts in order to avoid shifting burdens between different environmental issues in an improvement perspective. The table 6 gives all the others results of the assessment.

Table 6: Impact assessment results of 1 GJ of heat produced at plant for the base scenarios
(Nota bene: additional fertilization is taken into account only for poplar)

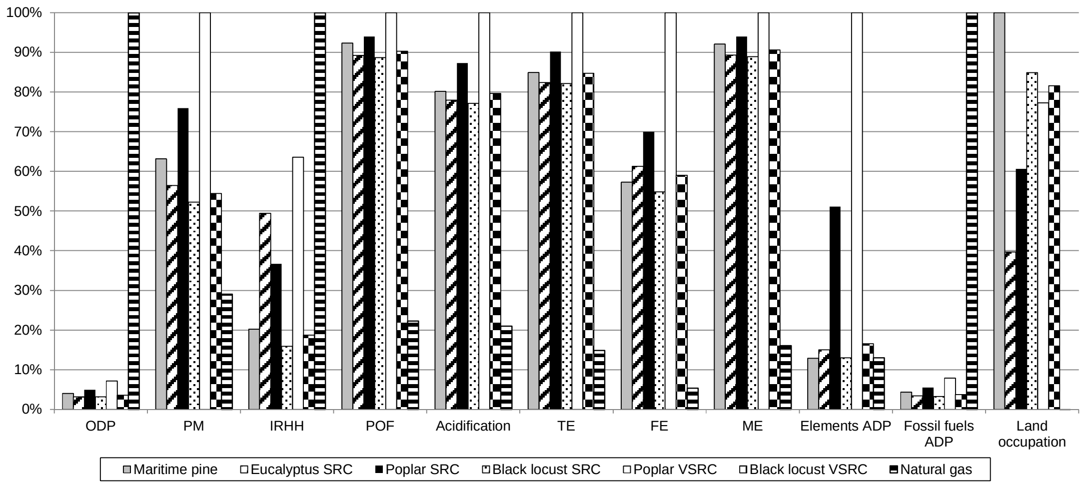
	Unit	Maritime pine	Eucalyptus SRC	Poplar SRC	Black locust SRC	Poplar VSRC	Black locust VSRC	Natural gas
Ozone layer depletion (ODP)	kg CFC-11 eq	4.60E-07	3.62E-07	5.70E-07	3.59E-07	8.21E-07	4.14E-07	1.14E-05
Particulate matter (PM)	kg PM2.5 eq	6.69E-03	5.98E-03	8.05E-03	5.54E-03	1.06E-02	5.77E-03	3.08E-03
Ionizing radiation, human health (IRHH)	kBq U235 eq	5.53E-02	1.35E-01	1.00E-01	4.35E-02	1.73E-01	5.12E-02	2.73E-01
Photochemical ozone formation (POF)	kg NMVOC eq	2.79E-01	2.70E-01	2.84E-01	2.68E-01	3.02E-01	2.73E-01	6.74E-02
Acidification	molc H+ eq	2.34E-01	2.28E-01	2.55E-01	2.26E-01	2.92E-01	2.33E-01	6.14E-02
Terrestrial eutrophication (TE)	molc N eq	1.13E+00	1.10E+00	1.20E+00	1.10E+00	1.33E+00	1.13E+00	1.98E-01
Freshwater eutrophication (FE)	kg P eq	1.50E-03	1.61E-03	1.84E-03	1.44E-03	2.62E-03	1.55E-03	1.40E-04
Marine eutrophication (ME)	kg N eq	1.03E-01	1.00E-01	1.06E-01	9.98E-02	1.12E-01	1.02E-01	1.81E-02
Abiotic depletion (elements ADP)	kg Sb eq	2.54E-06	2.96E-06	1.01E-05	2.56E-06	1.97E-05	3.26E-06	2.56E-06
Abiotic depletion (fossil fuels ADP)	MJ	4.92E+01	3.88E+01	6.18E+01	3.69E+01	8.87E+01	4.17E+01	1.12E+03
Land occupation	m2.an	1.26E+02	5.01E+01	7.65E+01	1.07E+02	9.76E+01	1.03E+02	6.74E-02

The results show significant differences between the woody energy crops and natural gas (figure 5):

- A very high reduction for the ozone depletion potential, ionising radiation on human health, as well as the abiotic depletion potential of fossils fuels, similar to the global warming potential,
- In contrast, a significant increase of intake fraction for fine particles, acidification, eutrophication, tropospheric ozone concentration, and land occupation indicator.

Between the woody energy crops, the results of land occupation indicators vary due to biomass productivity and dryness differences. The nitrogen fertilization has also a significant contribution for elements resource depletion, eutrophication, as well as intake fraction for fine particles.

Figure 5: Comparison of impact assessment results of heat produced at plant
(Nota bene: additional fertilization is taken into account only for poplar)



4 Conclusions

The results presented in this paper constitute a sound basis for the evaluation of heat production from woody energy crops. They show that the energy efficiency of such crops is similar to the energy efficiency of natural gas supply. One must bear in mind that the energy efficiency does not differentiate the renewable and the non renewable energy. The GHG saving compared to heat from natural gas vary from 86 to 96%, largely greater than 35% of RED threshold. Results on other impacts show a more balanced picture: woody biomass is better for the ozone depletion potential, the ionising radiation on human health, as well as the abiotic depletion potential of fossils fuels, but worse for the intake fraction for fine particles, acidification, eutrophication, and tropospheric ozone concentration.

Otherwise, the results also show that the nitrogen fertilization impacts significantly on the environmental balance sheet of the wood fuel production. The difference of data quality related to fertilization severely limits the comparison of results between the woody energy crops.

The assessment of the scenarios integrating innovations on planting, weed control, and harvesting is on going. Even though the results are not yet available, the first results on the base scenarios give information to foresee the conclusions of the study. The mechanization of planting and weed control will increase the energy demand and GHG emissions. However these operations will be made by tractor which low fuel consumption. Moreover the productivity improvement of accumulating felling head should compensate this increase or could be higher than it. The high energy efficiency should not be degraded. Whatever, even though the carbon footprint of heat production from woody crops should increase slightly, the results of the comparison between biomass and natural gas should be unchanged. The technological developments made in the MECABIOFOR project therefore should not be counterproductive from the climate and energy point of view.

Further results will also include a dynamic LCIA on climate change.

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