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Life cycle assessment applied to electricity generation from renewable biomass

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Abstract

This work concerns the production of electricity from renewable sources produced from biomass (wood waste) in cogeneration plants. Two facilities are compared: a 2 MW electricity power plant and a 10 MW one. They are also compared to electricity production in a diesel engine cogeneration.

The objective is to compare the environmental impact of various power plants, using two different fuels and/or of different power. A detailed LCA methodology is therefore presented. The results - in favor of the 2 MW wood plant but sensitive to assumptions - are then discussed.

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Keywords: Life Cycle Assessment (LCA), biomass, energy balance, pollutants, environmental impacts, diesel engine, cogeneration power plant, Hirn Cycle, Organic Rankine Cycle (ORC).

1. Introduction

Life Cycle Assessment (LCA) is a tool for the environmental assessment of a product or process "from cradle to grave" and comprises four main steps: definition of objectives, inventory of consumption and emissions, assessment of potential impacts, interpretation / synthesis. The life cycle assessment of a system takes into account the impact of the extraction, processing and transportation of fuels and raw materials and the construction of the system, its operation and decommissioning [1].

This analysis is applied to the electrical energy obtained from renewable biomass (wood waste) in cogeneration plants. Two facilities are compared: a 2 MW electricity power plant and a 10 MW one. They will also be compared to electricity production in a diesel engine cogeneration.

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The objective is to compare the environmental impact of various power plants, using two different fuels and / or of different powers. This paper also aims to detail the terms of the life cycle assessment by applying it to a production energy process. Through this example, the detailed LCA methodology is therefore presented. The results obtained are then discussed with a particular focus on indicators related to energy.

For this study [2] the software SimaPro[®] was used. The four stages of life cycle assessment are successively applied to the plants studied (2 and 10 MW).

2. Defining objectives and systems - Step 1

The aim of this step is to identify the problem, and to define the objectives and scope of the study. This phase determines a set of critical elements: the function of the system, and the functional unit which provides a quantified reference unit to which all the emissions and extractions of the system can then be related. It also defines the limits of the system under consideration. The basic scenarios and alternatives to be studied are defined in detail during this phase.

The LCA was applied to two cases of biomass cogeneration plants operating with different powers (2 and 10 MW). An attempt to define the environmental impact of electricity produced by such plants will be presented. This impact was also compared with that of a conventional system. The technical characteristics of the facilities selected for the life cycle assessment are presented here.

2.1. Systems definition

The function of the system is to produce electricity and heat (called CHP: combined heat and power, or cogeneration). In our study, we focus primarily on the production of electricity, the heat being considered as a co-production. We will see the implications of this assumption on efficiencies in the section on allocations.

2.2. Functional Unit

All the indicators of the study such as consumption or emissions are sorted on the basis of the functional unit which is defined as 1 MJ of electricity generated. Heat is considered as a co-product in this environmental report which is dedicated to electric power generation only.

2.3. Systems boundaries

To consider the same reality in different scenarios, the life cycle assessment covers the entire chain of the following steps (Figure 1). Knowledge of these limits is strategically very important when comparing systems with each other in order to avoid misinterpretation.

In order to assess the environmental load of the process, an account of the inputs and outputs of materials and energy is first necessary (for the full life cycle process from cradle to grave). These input and output flows are shown in the diagram (fig.1). These points will be detailed in the inventory.

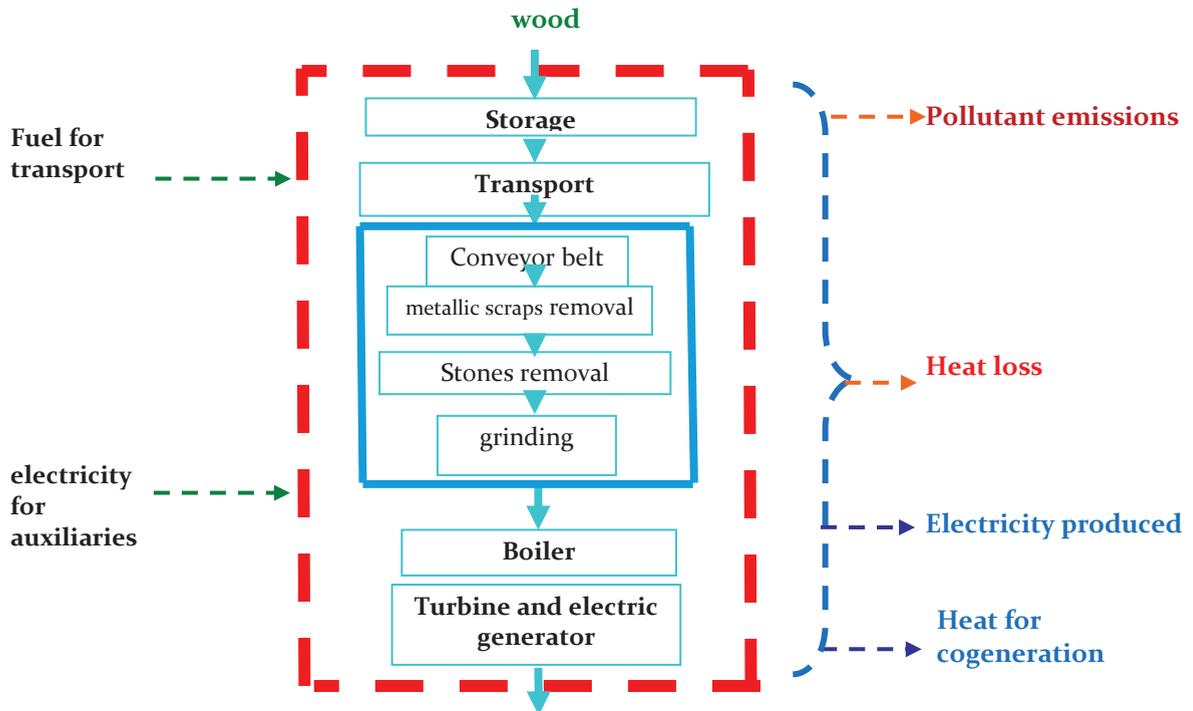


Fig. 1 – System boundaries (dotted line)

2.4. Baseline scenario and alternatives

The scenarios are:

- 10 MW biomass power plant (steam Hirn cycle):
 - Electricity generation efficiency $\eta_{elec} = 19\%$
 - Cogeneration efficiency $\eta_{coge} = 51\%$
- 2 MW biomass power plant (ORC cycle):
 - Electricity generation efficiency $\eta_{elec} = 16.2\%$
 - Cogeneration efficiency $\eta_{coge} = 80\%$
- scenarios to which a diesel reciprocating engine scenario is added:
 - Electricity generation efficiency $\eta_{elec} = 35\%$
 - Cogeneration efficiency $\eta_{coge} = 80\%$

An efficiency of 35% was chosen for the 2 MW diesel engine, which is a lower limit for these big power plants that can easily reach 40%. The cogeneration efficiency was chosen equal to that of the 2 MW wood plant, i.e. 80%.

Note: In the above scenarios the cogeneration performance is 80% for the 2 MW ORC plant, and 51% for the 10 MW steam plant. The reason why a different assumption was made for the two cases is more regulatory than technological. French cogeneration regulations require the heat resale to be contractualised in order to be awarded the cogeneration label. In fact, it is more difficult to find a buyer for the quantity of heat produced by the 10 MW plant than for the 2 MW one. In addition, the minimum critical performance demanded by the Energy Regulation Commission to benefit from cogeneration regulation is 50%, which justifies the choice made. The impact on results will be seen later.

3. Inventory and quantification of raw materials extraction and pollutant emissions - Step 2

The inventory of emissions and extractions quantifies emissions to air, water and soil as well as extraction of renewable and non renewable raw materials. It also determines the land use necessary to achieve the system function. This is called LCI (Life cycle inventory).

3.1. Data Source

As stated in [1], calculation of the inventory is simple, but data collection requires considerable work. Fortunately databases include information for a large number of processes, the application-specific processes remaining to be modeled in detail with the industries concerned. In this study, the databases "Ecoinvent" included with the software SimaPro were used for general processes (such as trucking, for example). For more specific processes, two basic documents are used:

- Data provided by an industrial company (Enertime)
- French pollutant emission regulations.

These data are supplemented when necessary by certain assumptions and calculations specified below. The data should be considered critically in order to guarantee the validity of the life cycle assessment.

As this study is not applied to an existing installation, but aims to determine the potential of such installations, the emission values chosen for the calculations are those given by the regulations. The facilities are equipped with flue gas treatment in order to comply with these regulations. The impacts of non-regulated pollutants will therefore not be observed in this study.

Plant emissions are regulated in France by two decrees, that of July 25, 1997 consolidated by a new version of December 15, 2008 [3], and that of June 20, 2002 [4]. Both 2 MW facilities (ORC and diesel) are affected by the 1997 decree and the 10 MW plant by the 2002 decree.

3.2. Inventory and energy and CO₂ balances

For the inventory, data must be expressed in coherent units, which requires some formatting before use. Moreover, the energy and CO₂ emissions balances can be calculated by hand. Primary energy is an excellent way to test the orders of magnitude and validity of the inventory. These balances will be completed by calculation of pollutant emissions for the combustion phase. They will then be compared with the results obtained by the software. This will also help in clarifying and understanding the procedure.

Table 1 - regulated pollutants

	CO mg/m ³	NO _x mg/m ³ equiv. NO ₂	Particles mg/m ³	NMVOC mg/m ³ equiv CH ₄	SO _x mg/m ³ equiv. SO ₂
2 MW wood plant Decree of July.25, 1997	250	500	150	50	200
10 MW wood plant Decree of June 20, 2002	200	400	50	110	200
2 MW diesel plant Decree of July.25, 1997	650	1500	100	150	160

3.2.1. Energy produced

The energy (electricity and heat) generated during one year (8,000 h) is calculated for each plant. These are the values that are then used in SimaPro. For the software, the energy produced per year is an input. The results are then related to the functional unit of 1 MJ of electricity generated.

3.2.2. Fuel consumption and associated CO₂ emissions

Biomass is the fuel for the two plants studied. This biomass consists of wood chips, bark and edgings... It may contain shredded pallets. Overall it is wood waste. The main asset is the local use of the by-products of wood processing for their energy, thus avoiding landfilling or destruction in the open air. The wood humidity is around 45% on arrival at the boiler after natural drying in the place of cutting.

The composition by weight of the dry wood in question is as follows:

C = 49.0%; H = 5.5%; O = 45.0%; N = 0.5%;

Wet wood (45% moisture) average LHV is 9 000 kJ/kg.

Dry wood LHV is $9\,000 / (1 - 0.45) = 16\,364$ kJ/kg.

Thus the wet biomass annual consumption is 39,250 t for the 2 MW power plant for an 8,000 h per year operation. From this wood consumption, associated CO₂ emissions can be calculated by the equation of combustion. Burning 100 g of dry wood produces 179.52 g of CO₂. In summary, for the three plants, we obtain the following results (table 2).

Note on CO₂ emissions from renewable sources [5]

Because of its plant origin, wood is a renewable energy. Like fossil fuels, its combustion produces CO₂, which is a greenhouse gas, but unlike these other fuels, it does not contribute to the increase in CO₂ since it traps an equivalent amount during its growth.

Table 2: annual fuel consumption and CO₂ emissions associated to combustion

	Fuel consumption		associated CO ₂ emissions	
	MJ /year	kg /MJelec	t /year	kg /MJelec
2 MW ORC plant 39,250 t/year of biomass	353.10 ⁶	0.681	38,754	0.674
			(CO ₂ from renewable sources)	
10 MW steam plant 168,400 t/year of biomass	1,515.10 ⁶	0.585	166,271	0.577
			(CO ₂ from renewable sources)	
2 MW diesel plant 3,863 t/year of diesel fuel	164.10 ⁶	0.067	12,034	0.209

3.2.3. Combustion: other pollutants

As this work is based on the regulation that gives pollutant concentrations expressed relative to a volume of dry gas with a given content of oxygen in the flue gas (11% oxygen for the 2 MW unit), this volume needs to be determined. This will allow pollutants expressed in g/m³ to be converted to pollutants emitted by the facility for one year (for example), and then to g/MJ of electricity generated. The intermediate conversion (g/year) serves as input for the software, and the final conversion (g/MJ) serves to control the value obtained by the software.

Burning 1 kg of wet wood which has an LHV of 9 000 kJ / kg produces 4.95 m³ of dry smoke under normal conditions (p = 1.013 bar and T = 273 K). This result was obtained for 11 % oxygen content in the smoke (2 MW ORC power plant) and must be adapted to other situations.

The values of pollutants in g/m³ can also be converted to g / MJ, the plant performance being taken into account. They are reported in Table 3.

Table 3 – Pollutant emissions for 1 MJ of electricity produced

	CO g/MJ	NO ₂ g/MJ	Particles g/MJ	VOC (equiv CH ₄) g/MJ	SO ₂ g/MJ
2 MW wood plant $\eta = 16.2\%$	0.848	1.697	0.509	0.170	0.679
10 MW wood plant $\eta = 19.0\%$	0.389	0.779	0.097	0.214	0.389
2 MW diesel plant $\eta = 35.0\%$	0.613	1.414	0.094	0.141	0.151

These emissions are related to biomass combustion in the boiler (or fuel oil in the engine). In LCA, it is also necessary to take into account the consumption of materials and energy by other processes :

- Primary energy consumption for auxiliaries' electricity,
- Transporting biomass by truck,

3.2.4. Summary of energy consumption and CO₂ emissions.

Following the hand-calculation, the results for the 2 MW plant can be summarized (Figure 2). This figure shows the different extractions of raw materials and emissions of pollutants in a quantified manner.

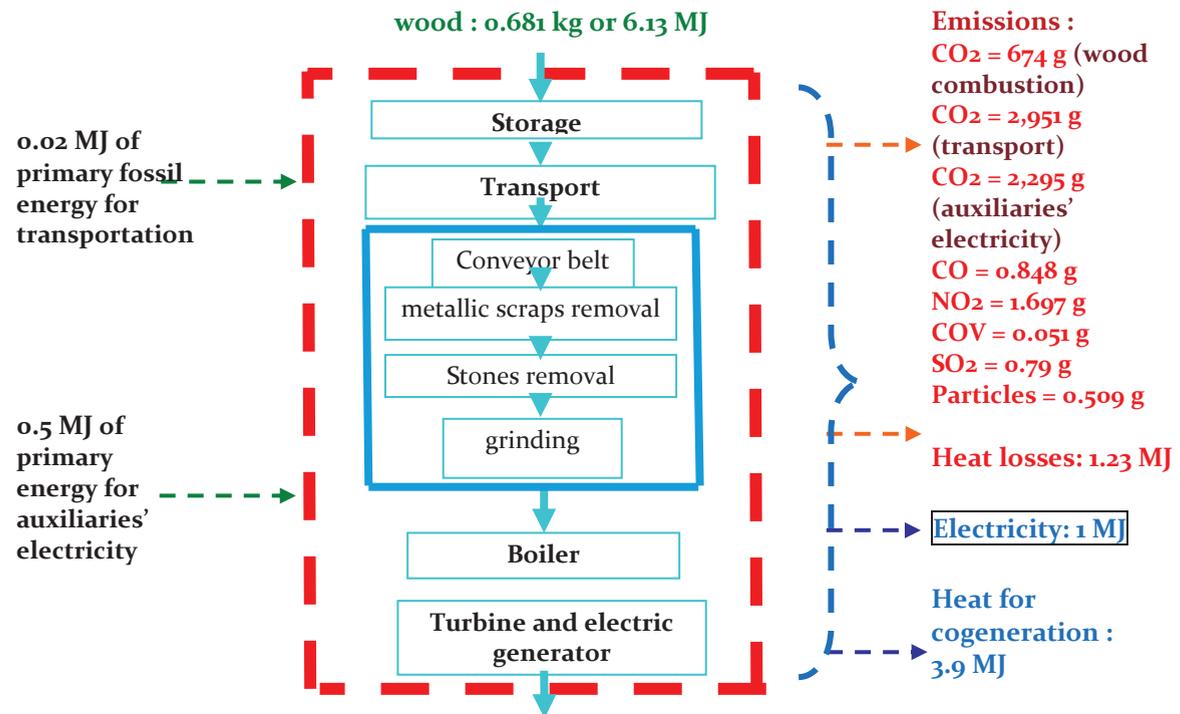


Fig. 2 - Material flows balances, 2 MW wood plant (functional unit: 1 MJ of electricity)

3.3. Co-products and allocations

In previous calculations we considered only electricity generation and allocated the entire fuel consumption and emissions to this electricity. However, the plants studied operate in cogeneration; in other words, they also produce useful heat for industry or district heating. It therefore seems logical to allocate a portion of the fuel consumption and emissions to heat production.

Many processes are multi-product systems. In a life cycle assessment, one is generally only interested in one of these products (in this case electricity). It is then necessary to attribute (or “allocate” or “assign”) some environmental costs and use of certain raw materials to the product studied (in this case electricity) and other co-products (here useful heat energy). There are various methods to deal with this problem.

- **Avoided impacts method**

One way is to avoid the allocation, that is to say, to extend the system: this is the avoided impacts method. For example, in addition to electricity, the heat co-produced substitutes a similar heat energy obtained from another sector. In this case the extractions and emissions related to the substituted heat are avoided. A bonus equal to the emission reduction can therefore be attributed to electricity. For example [6] used this method on a cogeneration plant replaced by a natural gas engine for electricity and a coal-fired boiler for heat.

- **Method of imputation to the energy content**

This method (used in particular for biofuels) allocates energy consumption and emissions to co-productions in proportion to their energy content. This method seems well suited to cogeneration, since the valorized heat is no less useful than electricity. This method was therefore chosen for the rest of the study.

For the 2 MW plant, 1 MJ of electricity is produced with 3.9 MJ of valorized heat (Figure 2). So while the aim is still the electricity generated, using the previous method, primary consumption and emissions will be assigned the coefficient $1 / (1 + 3.9) = 20.41\%$. For the 10 MW plant, this coefficient is 37.04%, while for the 2 MW diesel engine, it is 43.75%.

This method of distribution is to the advantage of the 2 MW plant, due to the smaller allocation coefficient (which corresponds to an inefficient electric power generation but a good cogeneration efficiency, the coefficient of allocation being roughly equal to the ratio of these two efficiencies).

3.4. Inventory overall balance

The different input data entered into the software and the output data are summarized here. Emissions are normalized to 1 MJ of generated electricity by using the pro rata method.

Table 4– Emission results (SimaPro) normalized to the MJ of electricity (pro rata method) - Electricity allocation = 20.41% for the 2 MW plant, 37.04% for the 10 MW one and 43.75% for the Diesel plant.

	CO mg/MJ	NO ₂ mg/MJ	Particles mg/MJ	NMVOC (CH ₄ equiv) mg/MJ	SO ₂ mg/MJ	CO ₂ g/MJ	CH ₄ mg/MJ
2 MW wood plant	179	367	104	42	138 +7 SO	137 bio +2 fossile	3.61
10 MW wood plant	165	359	37.6	103	144 + 13.4 SO	214 bio +5 fossile	7,2
2 MW Diesel plant	268	619 + 78 NO	41	62	66 + 81 SO	91.4 Fossile CO ₂	130

4. Environmental impact analysis - Step 3

The environmental impact analysis assesses the environmental impact of emissions and extractions inventoried in the previous phase. To achieve this, the classification determines which emissions contribute to which environmental impacts (global warming, human toxicity, ecotoxicity, resource depletion etc.).

First, the emissions are allocated to categories of intermediate impact. This midpoint characterization weights emissions within each category of impact. Then the characterization of damage groups the impact categories into damage categories (damage to human health, to ecosystems, to climate change ...).

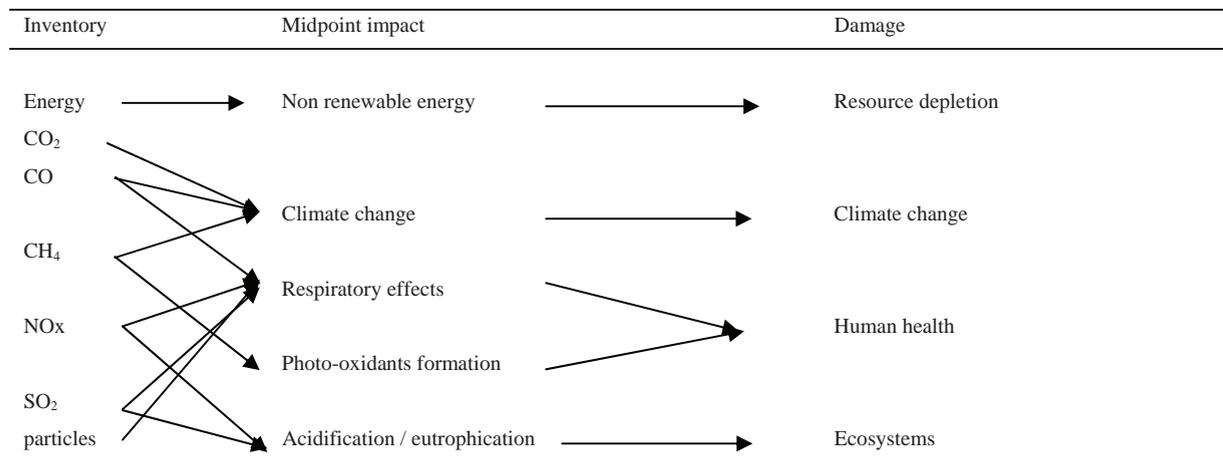


Figure 3- Characterization of damage grouping the impact categories [Jolliet 2005]

4.1. Environmental impact of a CHP plant

In most cases, a given scenario is better for a number of substances but negative for others; hence the need to assess the magnitude of the impacts generated by each substance. It is therefore necessary to have methods for aggregating emissions based on their potential to cause one or more environmental impacts.

Several methods of impact analysis are available in the SimaPro software. IMPACT 2002 + was used. It is a method for analyzing impact which provides both an assessment at the midpoint level and at the damage level.

4.1.1. Midpoint characterization

Within each category, the characterization factor converts each amount of emitted substance into an equivalent amount of a reference substance specific to the category.

For example for the "climate change" category, the greenhouse potential of CH₄ is 25 (for a time horizon of 100 years), which means that the emission of 1 kg of methane is equivalent to 25 kg of CO₂. Thus the score for climate change is obtained by multiplying each of the substances in the inventory (CO₂, CH₄, N₂O ...) by their greenhouse potential, then summing these values.

The figure 4 shows the midpoint characterization for the three plants studied.

For each of the three plants, the value of 100% of the index is assigned to the plant with the highest impact on the environment. When the values are negative, this is an environmental benefit.

This shows that the cogeneration diesel engine has the greatest negative impacts on the environment, except for the following two indices:

- Ionizing radiation. This is due to the fact that for the auxiliaries operation, steam and ORC plants use French electricity, over 80% of which comes from nuclear power, which is not the case of the diesel engine.
- Land use.

The two biomass plants are more environment-friendly. It can also be seen that both have a positive impact against global warming and fossil resources depletion (the "non-renewable primary energy" index is negative).

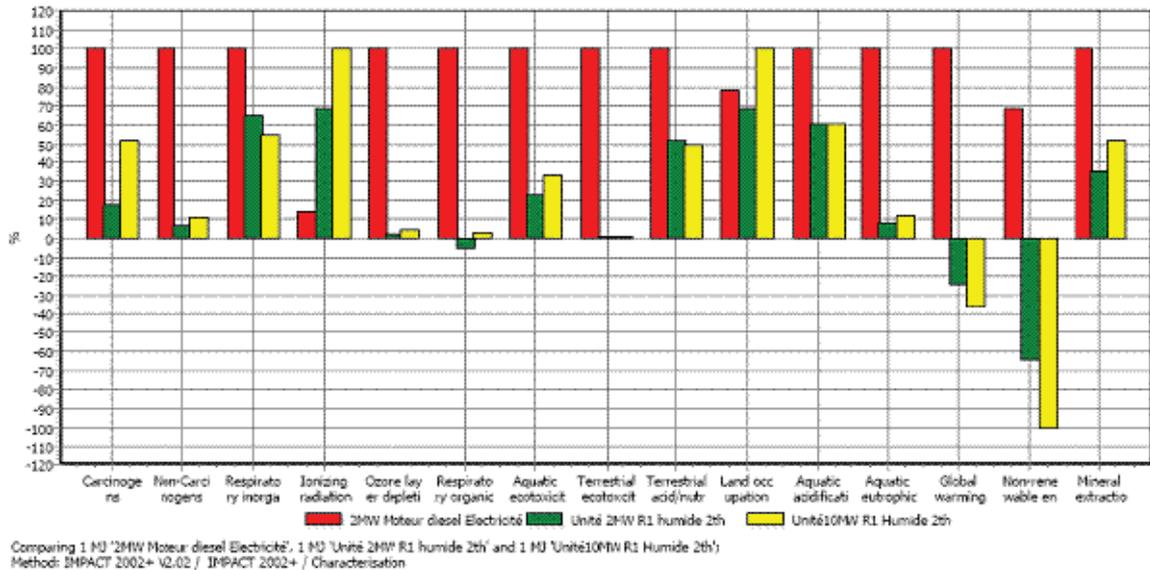


Figure 4- comparative midpoint characterization of the 3 plants with the IMPACT 2002+ method. Impacts for each midpoint category. Carcinogens, Non-Carcinogens, respiratory inorganic, Ionizing radiation, Ozone layer depletion, Aquatic ecotoxicity, Terrestrial ecotoxicity, Terrestrial acidification/eutrophication, Land occupation, Aquatic acidification, Aquatic eutrophication, Global warming, Non-renewable energy, Mineral extraction.

4.1.2. Damage characterization

The IMPACT 2002 + method aggregates the intermediate impacts in four categories of impacts, as follows:

- **Impact on human health**, in life-years of incapacity (or life lost years), DALY (disability adjusted life years). Human health impacts include cancer and non cancer effects, respiratory effects, ionizing radiation and destruction of the stratospheric ozone layer.
- **Impact on the ecosystem quality** expressed in $\text{PDF} \cdot \text{m}^2 \cdot \text{year} = \text{fraction of extinct species on one m}^2 \text{ and for one year}$. Ecosystem quality impacts include the effects on terrestrial ecosystems (ecotoxicity, acidification and aquatic eutrophication) and land use.
- **Impact on climate change** (in CO_2 equivalent) related to the greenhouse effect. Climate change is considered a damage category in itself with the kg of CO_2 equivalent unit. The various emissions in the atmosphere (CO_2 , CH_4 , N_2O) are expressed in kilograms of CO_2 equivalent.
- **Impact on resource depletion** (MJ / unit extracted, which represents the additional energy to be used in the future due to lower ore grades in mining. The energy is expressed in terms of primary non-renewable energy dissipated). The use of resources includes the extraction of minerals and non-renewable energy.

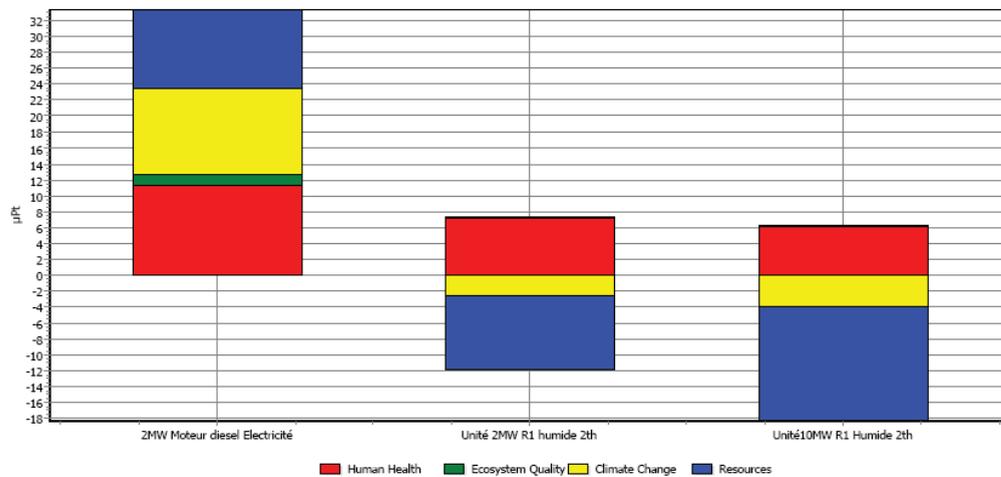
Midpoint damage can be converted into endpoint damages using the damage factors. Jolliet [1] explains that to assess the overall impact of different scenarios, it is sometimes desirable to aggregate the individual damage scores in a single score. By assigning a default weight of 1 in each category, the user considers that

the total impacts of Europe in health, quality of ecosystems, climate change and resources are equivalent. For the three plants studied the results, with a weight of 1 for each category, are shown on Figure 5.

5. Interpretation - step 4

In the previous three steps, we began to interpret the results. The point of step 4 is to pursue and complete this interpretation in order to interpret the results obtained in each of the previous phases and to evaluate the uncertainties. Critical points and possible improvements of the process are identified. Sensitivity studies are performed to identify the most influential parameters. The impact of the assumptions made is critically discussed.

Recall that in the first step - defining goals and systems - we specified that the purpose of our study concerned the production of 1 MJ of electricity from different biomass cogeneration plants in particular.



Comparing 1 MJ '2MW Moteur diesel Electricité', 1 MJ 'Unité 2MW R1 humide 2th' and 1 MJ 'Unité10MW R1 Humide 2th';
Method: IMPACT 2002+ V2.02 / IMPACT 2002+ / Single score

Figure 5- Damage characterization for the 3 plants with the IMPACT 2002 +method.

In the second part - Inventory – the balance of the different fuel consumptions and emissions of the different plants was performed, using data from industry and regulations along with some calculations and assumptions.

We saw that the emissions associated with fuel transportation were low, which allowed us to reduce the number of scenarios by keeping only one wood collection radius for each plant.

To account for the co-production of heat from power plants, consumption and emissions were then allocated in proportion to the energy content of the two forms of energy produced.

The results, presented in the third stage - impact analysis - and complemented by a comparison with a conventional diesel engine power plant, were the following. The two biomass fuel power plants are much more environmentally friendly than the diesel engine with regard to:

- less impact on health,
- no impact on the ecosystem quality,
- a positive impact in reducing the greenhouse effect (CO₂ from renewable sources),
- a positive impact in reducing fossil fuel depletion.

With the allocation in proportion to energy, as the efficiency for the 2 MW cogeneration plant (80%) is much higher than that of the 10 MW plant (51%), the primary energy (wood) used is less for the small power plant for the same service.

The influence of the allocation method chosen for co-production is also highlighted. Other methods could have been studied, such as avoided impacts, or an allocation based on the different economic value for electricity and heat (not a recommended method) or based on exergy content.

The results would be different again if instead of a functional unit of 1 MJ of electricity, the focus had been on 1 MJ of heat or on undifferentiated energy (heat and electricity). The main difficulty lies in this co-production of heat and electricity. So there is no ideal and unique solution.

As emission regulations are overall more severe for the 10 MW plant, this induces a slight advantage for this plant in terms of impact on health, compared to the 2 MW power plant (Figure 5 - Step 3).

Bibliographic data were mainly used in this study. In particular, regulation values were used in the various calculations.

This study could therefore be completed by taking into account the values emitted by existing plants, particularly to clarify the health impact (through emissions of sulfur and nitrogen oxides that may be overestimated by the regulation values). Since wood contains little sulfur, the regulatory values may overestimate reality slightly.

The same is true for nitrogen oxides as wood burns at low temperatures, whereas nitrogen oxide production is exponential with temperature beyond 1200°C and almost non-existent below.

Moreover the production of PAHs (polycyclic aromatic hydrocarbons) during combustion should also be considered in a further more detailed analysis.

This is confirmed by a study [7] that shows the emissions from the wood energy sector on the national level (France), compared with other sectors: SO₂ and Nox emissions are very low (2%), whereas this is not the case for PAHs (77%) for example.

Finally, the authors have highlighted the difficulties associated with using the software, which cannot be used as a black box. The data from the database concerning French electricity were false, as were some coefficients for the calculation of emissions associated with transport. This had no impact given the low weight of these two items in this study, but shows the importance of carefully controlling the default values. Similarly, it would have been preferable to hand-define the biomass fuel. Using the one supplied by the database introduces the emissions and extractions associated with the production of this biomass, whereas we wished to exclude this stage of the study, since the wood used is waste wood.

6. Conclusion

This simple case study has highlighted the different stages and the difficulties of a life cycle assessment applied to energy production. Data quality has emerged as an absolute necessity to ensure the value of the analysis. The use of software and a database means that a large amount of data can be taken into account and the calculations simplified, but we can see the dangers that using them as a black box would entail. It is recommended to use several methods in comparison.

For the effective conduct of an LCA, it is important to make reliable calculations and conclusions. For this it is recommended to:

- Specify the objectives (and thus the needs) as precisely as possible in order to limit the scope of the study,
- Establish negligibility criteria to limit data collection,
- Validate the data collected through all available information,
- Re-use existing work to limit the amount of work involved,

- Make a full report, including all assumptions, choices and data, so that it can also be reused later.

LCA is first and foremost a tool for decision support that allows one to define action priorities, highlighting the points that require improvement. Environmental accounting involves a number of assumptions and one should remain critical towards the results. The main limitation of LCA is that the assumptions and choices (the allocation method for example) made throughout the study can affect the results. For this reason, all the options must be recorded in writing and justified.

In the comparative study conducted here, with the assumptions used (especially the pollutants selected and allocation in proportion to energy), the environmental benefit of biomass CHP compared to a conventional power plant (diesel engine) can be summarized as follows:

- Lesser impact on health,
- Non-use of depletable fossil energy resources,
- Limiting the greenhouse contribution, since the CO₂ is reabsorbed during the growth of the plant.

In addition, for the same service provided (1 MJ of electricity), the 2 MW plant uses less biomass than the 10 MW plant.

Note however that with respect to impacts on health, a study including PAHs would be needed before coming to any firm conclusions.

In conclusion, wood - when a renewable energy source (sustainable management of the forest) - is particularly useful in reducing the use of fossil fuels and in reducing greenhouse gas emissions. Moreover wood is an economically viable energy in most cases.

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