

From trees to electricity, the physics beyond the LCA

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Abstract – A critical issue in life cycle assessment (LCA) often lies in the accuracy of the data collected during the inventory process. Moreover when processes involved are linked to breakthrough or uncommon technologies, or when the data are deeply connected to local parameters, collection for the inventory relies on many assumptions that cannot be handled properly with standard commercial databases. To avoid this common and well-known drawback of LCA, Institut Jean Lamour has been developing for some years a hybrid LCA methodology based on process modeling. To generate the inventory, all the main processes of the chain are modeled using a process flowsheeting software, which ensures rigorous mass and energy balances. This methodology offers the possibility to assess different configurations of the processes involved. In this paper we illustrate this methodology through a recent study focused on the use of biomass for combined heat and power (CHP) production. We conducted a comparative LCA in which two options were modeled and assessed to produce CHP: a standard combustion process and an alternative innovative gasification process. All the main steps, from forest growth to heat and electricity distribution were considered and modeled. An application to the local context of the city of Nancy in France, in which heat was assumed used for local district heating and electricity delivered to the grid, is presented. Modeling the whole chain of processes made it possible to assess and compare several scenarios including different options of forest harvesting. Globally the study showed that both combustion and gasification of biomass exhibit lower impacts than conventional fossil systems. Influence of harvesting options was found to be weak regarding global results. However, improvement in the characterization of soil depletion due to forest exploitation could be made to refine the results. Eventually, a strong influence of the electricity grid mix was found.

Key words: Life cycle assessment (LCA) / process modeling / biomass / combined heat and power production (CHP) / forest harvesting

1 Combined heat and power production from biomass

Combined heat and power production (CHP) from fuel combustion is an efficient technology that is bound to strongly expand worldwide in the next decades. In Europe for example a 16% to 29% increase in each country's total cogenerated electricity is expected by 2030 [1].

In the common CHP installations fuels used for combustion are fossil ones, which results in questionable results from an environmental point of view. On the one hand, CHP installations offer very high global efficiencies that can reach 90%, which results in very low environmental impacts in comparison to standard power

plants. On the other hand, as the current CHP plants still make use of fossil fuels, their environmental impacts remain strong, especially concerning the greenhouse gases emissions.

A promising alternative [2] would be to run CHP plants using renewable biomass fuel, which would offer a high efficiency from an energetic point of view [3] and very low environmental load due to the weak impact of renewable biomass combustion on global warming. Indeed it is commonly recognized that the CO₂ generated during biomass combustion, the so called biogenic CO₂, is to be captured and sequestered by photosynthesis in the following generation of trees (in the case of trees) to be replanted, resulting in a neutral balance of CO₂ over the time (Fig. 1).

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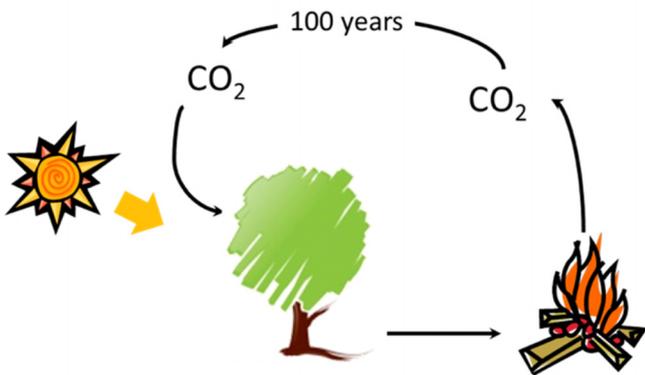


Fig. 1. Schematic representation of CO₂ balance of renewable biomass combustion.

Of course, this neutral balance is theoretical and the full chain of biomass production and transformation has to be studied in details to establish a rigorous balance. In addition if CO₂ and global warming are clearly very important matters, it has to be kept in mind that only a full and holistic environmental assessment conducted through a rigorous LCA can provide elements of conclusions regarding the benefit of a technology compared to another one. It also has to be noted that using biomass to produce energy cannot be considered as a universal answer to the global warming issue. Indeed such an alternative may be only considered in regions where biomass is abundant and where its quality (physical properties) meets the technical requirements of the CHP plant considered.

Two different processes may be considered to run a CHP plant with biomass. First, the biomass can be simply dried and prepared for a classic combustion in a standard boiler. A part of the heat generated is used to produce electricity through a steam turbine. Such an installation is quite classical and easy to run but the resulting power efficiency is however rather low. Second, another route to produce CHP with biomass is to convert the prepared biomass into a syngas in a first step, which is to be burnt in a turbine or an engine to produce electricity and recover heat in a second step. Such a route offers higher electric efficiency but is much more complicated and difficult to run. In addition this technology, the so called gasification, is relatively recent and very few data on the process at industrial scale are available. As a conclusion these two routes offer different efficiencies, need different biomass processing and are not well documented. Thus comparing these two routes on the simple basis of a standard data collection seems to be impossible at this step.

Being able to compare these processes from an energetic and environmental point of view is however a matter of prime importance in the framework of the expected growth of CHP production in the coming years. In this framework we decided to conduct a full LCA of these processes to be able to establish a rigorous comparison of between them. In order to do so, we applied a hybrid methodology [4, 5], which consist in modeling the full life cycle through a process engineering systemic approach with the commercial software ASPEN PLUSTM.

The model results were used to calculate rigorous balances based on the real physico-chemical processes and to generate the life cycle inventory. With this method the uncertainties linked to the standard data collection process can be avoided. In addition we decided to include in the full process flowsheet a model of the forest, which can predict the forest evolution growth and the minerals exportation associated to the forest exploitation.

With such an approach a full model was built (Fig. 2), from the trees to the heat and electricity delivery. This model was applied to the study case of the district of Nancy, in the North East of France.

2 Principle of forest modeling

In the framework of our study we focus on the Lorraine region, around Nancy, where beech (*Fagus sylvatica* L.) forests are under exploited and constitute a real potential for biomass energy. It is of course considered that the forest is sustainably managed. Only a fraction of the natural increase of the forest is taken for energy needs.

Only selected parts of a tree are usually used for biomass energy, as shown in Figure 3. Traditionally fine woody debris (FWDs), which represent the highest nutrient concentration of the tree, are left on the ground and participate to a natural fertilization of the soil. To increase the part of energy wood, FWDs could be collected as well and exploited. However such a harvesting practice automatically results in an increase in mineral exportation and, correspondingly, in a decrease in the natural process of soil fertilization, which could result in the long term in a decrease in the forest productivity [6].

To be able to predict the local forest productivity and the nutrient uptake, taking into account the way the forest is exploited, a model of the forest was developed using different dedicated tools (CAPSIS [7, 8], FAGACEES, Carbon Assessment Tool (CAT)) and integrated in the ASPEN PLUSTM Software. Similar approach was used in reference [9] for example. Our model was previously presented in details in a previous paper [10]; we just recall here the main features of this model.

On the basis of physico-chemical considerations, the model calculate the evolution of a plot of forest with time in a four-step method: prediction of height growth of the dominant trees; prediction of the overall diameter increment at stand level; calculation of the relative surface density of wood of the plot (calculated at 1.40 m above ground); prediction of the amount harvested when the relative density exceeds a user-defined target.

Once the amount of harvested trees is calculated, a production line model converts the wood amount into end-use wood products as follows: calculation of the distribution of logs in each category of size; transformation of the logs into end-use wood products according to log characteristics; calculation of the residues used as energy wood at each step the chain; calculation of the final flows of minerals exported (C, N, S, P, K).

Four different forest management practices were assessed. Two options were considered: a standard final cut

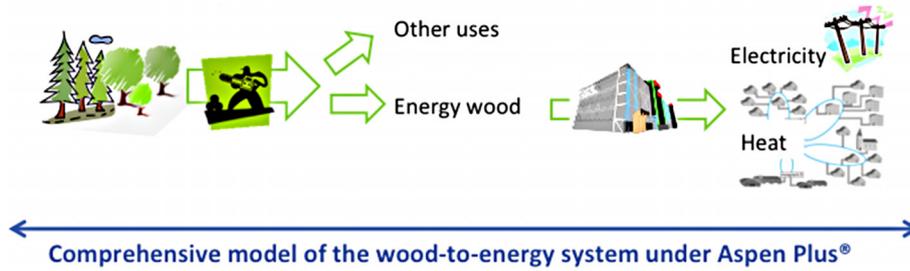


Fig. 2. Overview of the whole chain modeled under ASPEN PLUS™.

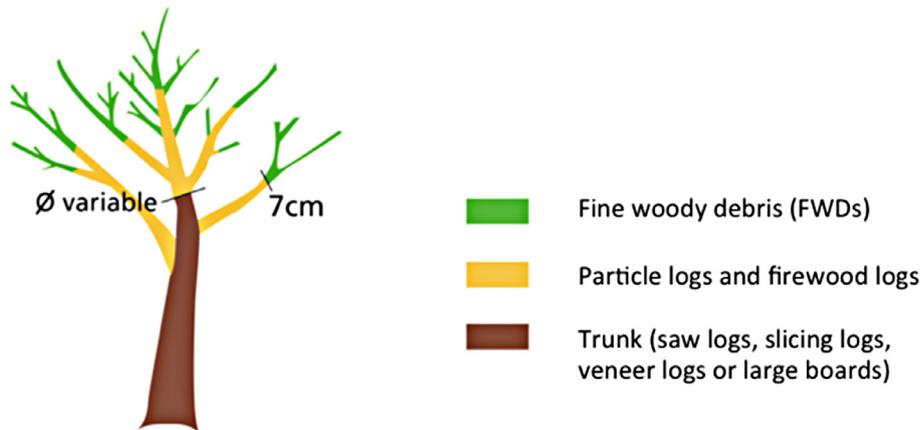


Fig. 3. Tree compartments according to French National Forest Inventory (IFN).

of the trees at 140 years of age and a shorter rotation with a final cut at 100 years of age. Those options were crossed with two possible wood utilizations: with and without FWDs collection.

All those results are then integrated into ASPEN PLUS™ (Fig. 4), where they were used by the other sub-models included in the global life cycle model.

Figure 5 shows example of the kind of results the model produces, a Sankey representation of the nutrients mass balance for the production of 10 MWh of electricity (corresponding to a consumption of 2.5 ha/hr in the case studied).

3 CHP modeling

Detailed physico-chemical models of the CHP production via direct wood combustion and via wood gasification were developed under ASPEN PLUS™. The main features of those models are presented in the following section. Both installations were dimensioned to generate a net power of 10 MW of electricity. Details of the models can be found in [11, 12].

3.1 Direct combustion

In the case of the direct combustion CHP plant, a standard combustor with a fixed grid was considered. The prepared wood chips enter the combustor with a moisture

content of 30% on wet basis (40% on dry basis), corresponding to a naturally dried wood.

Heat from the combustion and from the fumes is recovered through a network of heat exchangers. From this heat, overheated steam is produced through an overheated Hirt thermodynamic cycle [13]. The steam then goes through a counter-pressure turbine to produce electricity. In a last step this steam is condensed resulting in extra production of heat that is used for the district heating. Cold fumes exit the system at a temperature of 110 °C after a cleaning step in a bag filter.

Based on these assumptions, a global energy efficiency of 81% was calculated on the basis of the lower heating value of dry wood, with an electric efficiency of 18% and a thermal efficiency of 63%. The exergy efficiency, calculated on the basis of the chemical exergy of wood, reaches 29% with 16% for the electricity efficiency and 13% for the thermal efficiency. These results are illustrated in Figure 6.

3.2 Gasification

The dual fluidized bed gasifier technology from tunzini nesi entreprises d'équipement (TNEE) was chosen for our modeling [14]. This gasification technology is associated with a IC Jenbacher gas engine producing 10 MW of electricity. The syngas produced by the gasifier is cleaned and cooled to meet the engine requirements. The cleaning step is composed of a cyclone followed by a tar cracker, a bag filter and a water scrubber. Part of the cleaned syngas

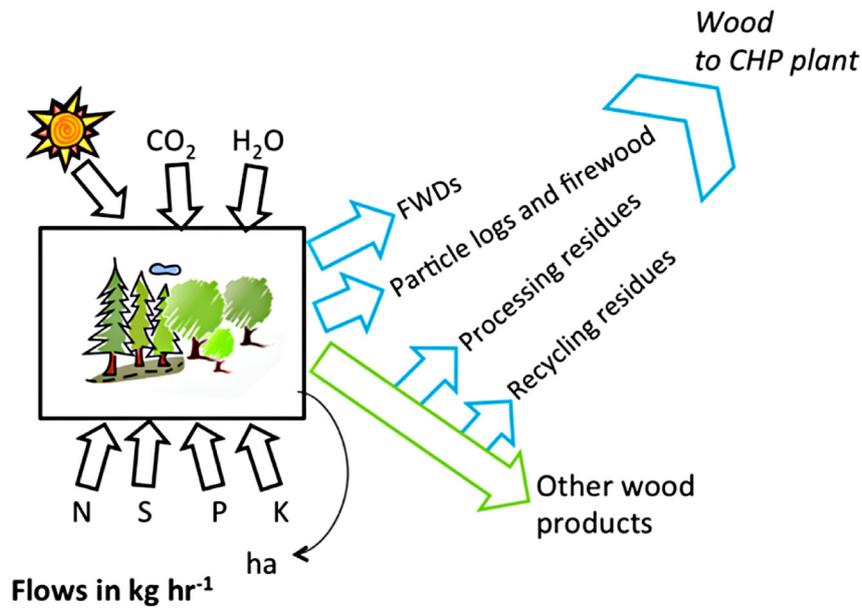


Fig. 4. Schematic representation of the forest modeling part of the model.

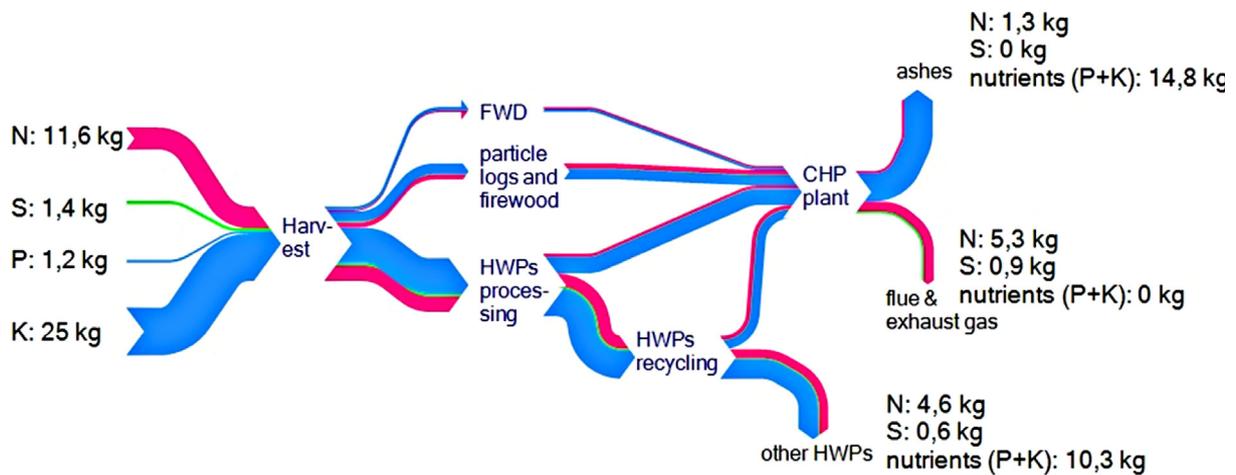


Fig. 5. Nutrients mass balance for producing 10 MWh of electricity.

is used for combustion, together with tars recovered from the water scrubber, to run the gasifier. The heat produced by the IC engine and the heat recovered from the syngas and the fumes through heat exchangers are partly used onsite to run the plant, the rest being exported for local district heating. A global optimization of the process was performed through a pinch analysis.

Details of the model can be found in [11] and a study of the influence of various parameters (sand flow rate in the circulating bed, nature of the catalyst and the scrubbing agent) was reported in reference [12].

The influence of wood moisture at gasifier inlet, which is responsible for an important exergy loss, and that of the wood drying process, which requires a large amount of heat, were investigated as well. Results showed that the highest global energy efficiency, equal to 74%, is obtained with a natural wood drying (no forced drying) and inlet

moisture content equal to 30%. With such a configuration, the electric efficiency is equal to 23% and the thermal efficiency is equal to 51%. From an exergy point of view, it was shown that an optimum of 40% (corresponding to a lower 63% energy efficiency) could be reached if the wood was dried to 15% of moisture content with forced drying and if a fraction of the recovered heat were converted into electricity through a steam turbine. This last case corresponds to maximizing the electricity efficiency (32%) and is probably the best option from an economic point of view.

Results for natural wood drying with 30% of moisture on wet basis, a nickel catalyst in the tar reformer and a full valorization of the recovered heat for district heating are presented in Figure 7. This configuration was selected to make a reliable comparison with the combustion CHP plant.

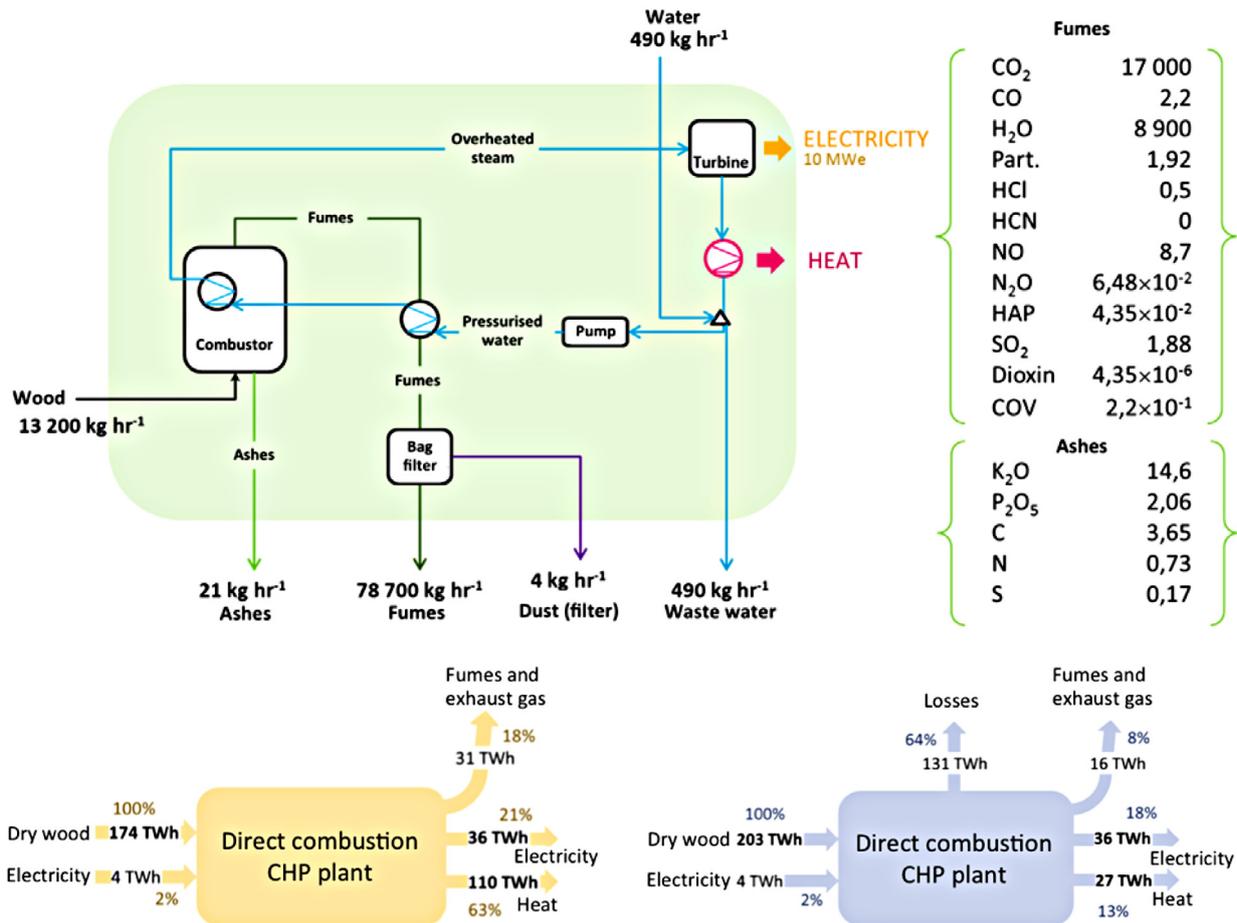


Fig. 6. Mass balance (top), energy balance (left), exergy balance (right) for direct wood combustion CHP plant.

4 Application to a local case study

Though this study is speculative, we wanted to apply it to a real case study. We chose to draw our comparison of CHP gasification and combustion plants on the basis of the local energy demand conditions of the district of Nancy, France.

Both CHP plants were designed to produce 15 MW of heat at peak load. On the basis of the annual heat demand of the district of Nancy, and following the assumptions that the wood combustion CHP plant can be operated without any loss of efficiency from 30 to 100% of the maximum load and that the wood gasification, which is less flexible, can be operated in the range 70 to 100% of the maximum load, we were able to draw a precise diagram of the potential load of the CHP plants throughout the year, as presented in Figure 8. When the heat demand exceeds 15 MW or when it is below 4.5 and 10.5 MW for combustion and gasification respectively, an extra boiler is used to produce the difference.

To draw a coherent comparison of the considered systems, we went through a complete attributional life cycle assessment, from cradle (forest growth) to gate (energy production). The functional unit was defined as “producing 1 kWh of heat for district heating and 0.4 kWh of

electricity” (Fig. 9). This production of electricity corresponds to the electricity produced by the gasification CHP plant, which exhibits the highest electricity production. Accordingly we used a system expansion to account for the lower electricity production of the combustion CHP plant, which is 0.2 kWh. The missing 0.2 kWh are taken from conventional power plants (national grid mix). Most data were calculated from our models to establish the life cycle inventory. These data were supplemented with data from Ecoinvent database for standard processes.

The ReCiPe egalitarian approach (v.1.08) was selected to calculate selected midpoint indicators: terrestrial ecotoxicity (TEEX), terrestrial acidification (TEAC), photochemical oxidant formation (PHOX), particulate matter formation (PMF), ozone depletion (OZOD), marine eutrophication (MAEU), human toxicity (HUMX), freshwater eutrophication (FWEU), freshwater ecotoxicity (FWEX), fossil depletion (FOSS), climate change excluding biogenic CO₂ (CLIM) and agricultural land occupation (AGLO). The ReCiPe single score (SCOR) was also used as an endpoint indicator.

A comparison between wood gasification and combustion CHP plants in the framework of Nancy district is reported in Figure 10. The extra electricity needed in the

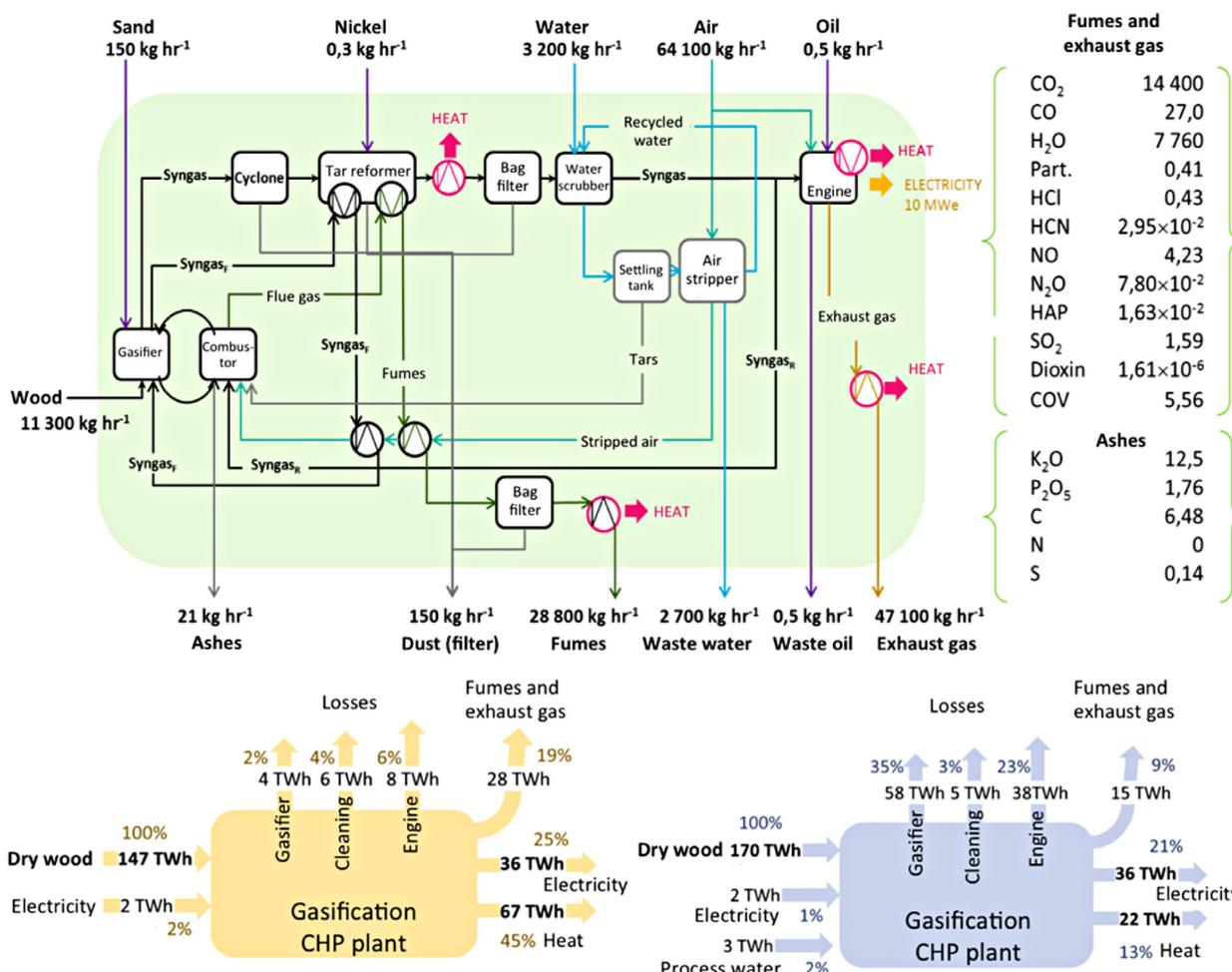


Fig. 7. Mass balance (top), energy balance (left), exergy balance (right) for gasification CHP plant.

case of combustion CHP system comes from the grid and the extra heat production comes from boilers running on light fuel oil and natural gas. A standard management of the forest is considered.

In this context it appears that both systems are in the same range of impacts for most indicators. Combustion is slightly better than gasification for most indicators except for FWEX, FWEU and HUMX. For these 3 indicators, the high impacts of the combustion CHP plant are mainly attributed to the 0.2 kWh electricity brought by the French grid to complete the functional unit in the framework of the system expansion considered. Combustion and gasification CHP process phases have the greatest share in TEAC, PHOX, PMF, MAEU and HUMX with 40 to 60% of total impact.

The wood supply chain is entirely responsible for the AGLO indicator and for about 20% of the other indicators. Around 20% less biomass is necessary to feed the combustion CHP plant, which directly influences the area of forest required (1.50 m² for gasification against 1.21 m² for combustion with standard management practices) and this contributes to the better results of combustion CHP plant for most impacts. As previously said, 4 scenarios of forest management were assessed, but very limited effects

on selected indicators were observed, except for AGLO. For this indicator a reduction of 10%, in comparison to the baseline scenario, is observed for intensive forestry practices.

Other configurations were considered and compared to the studied systems. Results of these comparisons are summarized in Table 1, in terms of single score indicators, expressed in ecopoints. Although single scores (not compliant with ISO standard) must be considered with care and are not sufficient to draw proper conclusions, they give in the present study a reliable overview for the comparison of the different scenarios considered. For more details the reader should refer to [15] where all the LCIA results are commented in detail and discussed.

This comparison clearly shows that whatever the scenario, wood CHP systems are far better than conventional fossil systems. In the French context, it appears that combustion is slightly better than gasification whatever the extra heating system is. This is mainly due to the lack of flexibility of the gasification system, which results in higher needs of extra heating –10% more compared to the combustion system. Not surprisingly, the best results are obtained for both systems when extra heating is produced from biomass. In that case both system are equivalent

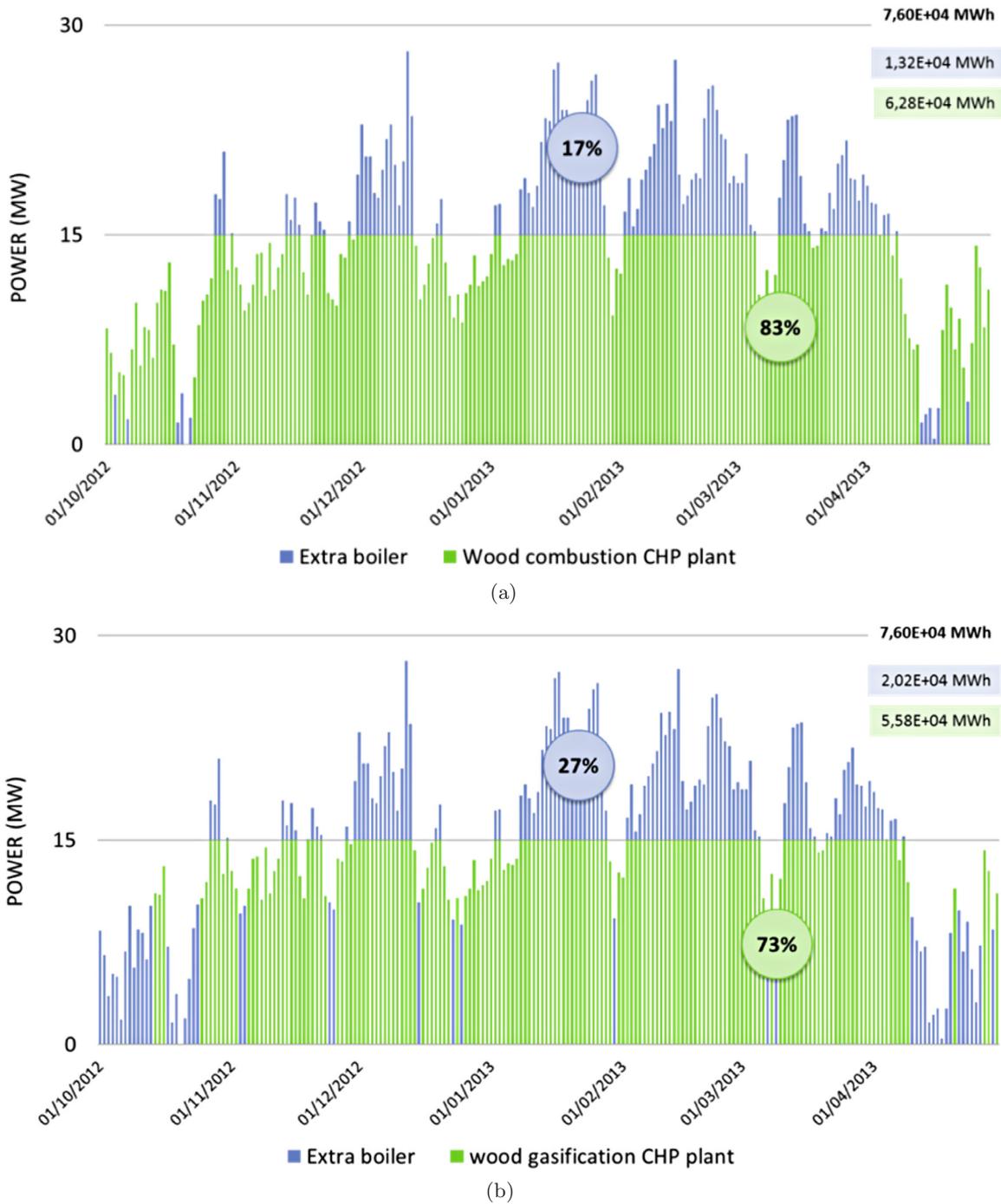


Fig. 8. Heat demand of Nancy district during the period from 1/10/12 to 30/04/13. (a) Heat supply repartition between wood combustion CHP plant and extra boiler. (b) Heat supply repartition between wood gasification CHP plant and extra boiler.

in terms of SCOR indicator. As previously said, forestry practices are not discriminant in terms of environmental impacts and have insignificant influence regarding the SCOR indicator.

As Nancy district is close to the German border, it was interesting to add an extra scenario in which we consider a similar case in Germany. For the gasification system it appears that the SCOR results are similar on both sides of

the border. Indeed no extra electricity is required for gasification and extra heating systems considered are equivalent. For combustion, the SCOR impacts are doubled on the German side of the border. This can easily be explained considering the German grid mix, which provides the extra electricity required by the system to respect the functional unit. If combustion system would be preferable in the French context of Nancy district, gasification would

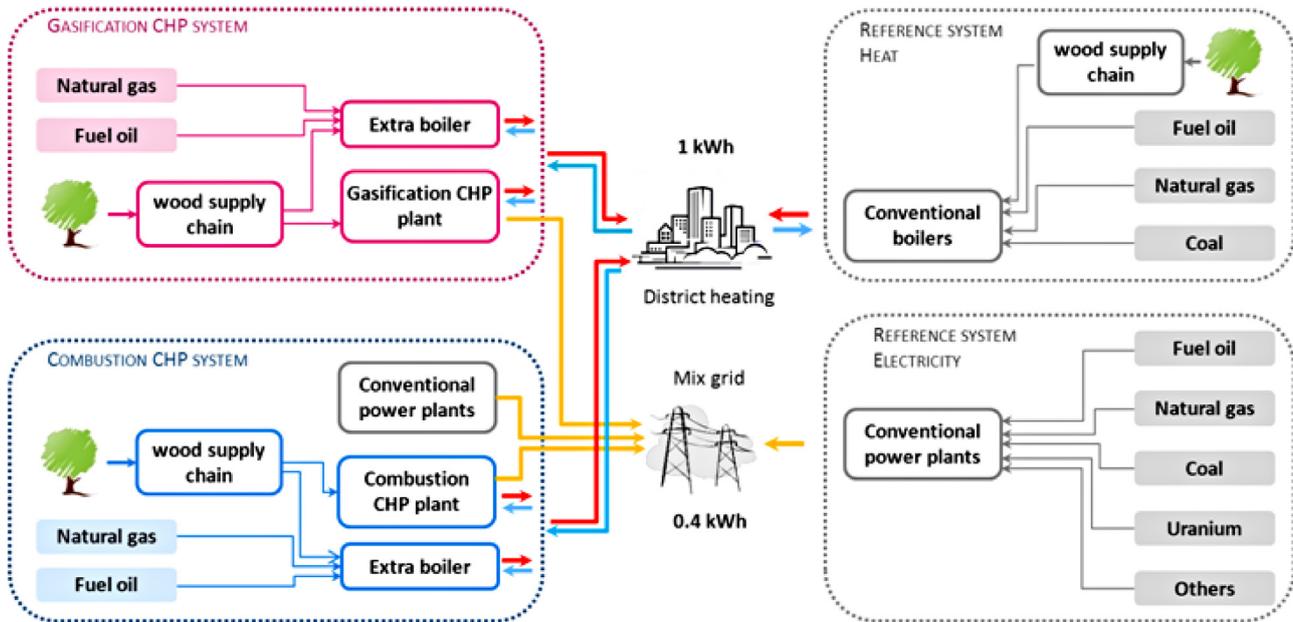


Fig. 9. Considered systems for the LCA.

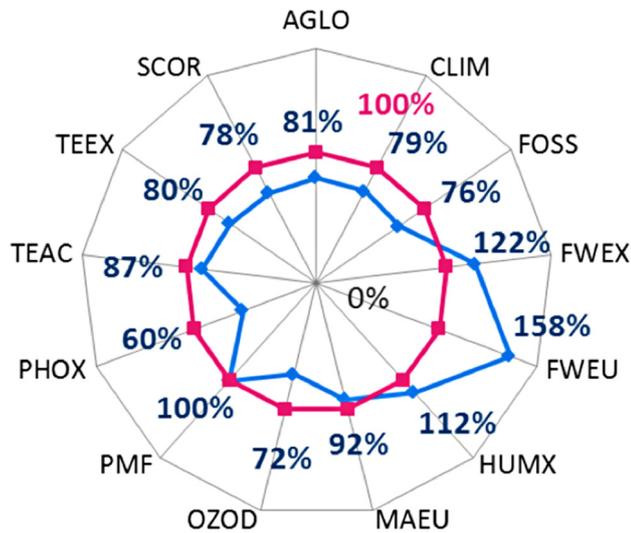


Fig. 10. Comparison of gasification (pink) and combustion (blue) in the framework of Nancy District (France). The results are normalized by the gasification LCIA values.

be more environmentally friendly in Germany. It should be stated, however, that though consistent with LCA practice, those calculations did not account for the electricity grid interconnection between France and Germany.

5 Prospects

This study clearly shows the ability of our ASPEN PLUS™ model to provide precise and reliable data to perform a prospective LCA. With this methodology a lot

of uncertainty are avoided and many cases can be simulated and studied. Some results of our modeling go beyond standard LCA. As the matter of fact one of the main feature of this model lies in its ability to calculate precisely the nutrient uptakes generated by the forestry practices, as shown in Figure 11.

These nutrient uptakes are unfortunately not taken into account in current LCA, as no indicator exists to characterize these uptakes that are closely linked to local conditions in terms of environmental impacts. Our modeling of the forest opens the door to the development of such an indicator for “soil nutrient depletion”.

6 Conclusions

Detailed models of wood gasification and combustion CHP plant were designed using the commercial flowsheeting software ASPEN PLUS™. These models were built on the basis of rigorous physico-chemical considerations and respect mass and energy balances. Energy integration was performed on each model to optimize the systems from the energy and exergy points of view. These models were complemented with a dedicated model of the forest, which calculates the energy wood production, as well the nutrient uptakes as a function of the forest management practices. Applied to the case study of the Nancy district, located in France close to the German border, our models showed their ability to provide detailed and rigorous data for the life cycle inventory. Several configurations were tested and compared through the LCA approach. Results showed that in the local context of Nancy district, a combustion CHP plant would be the best option from an environmental point of view, a gasification CHP plant being penalized by its lower flexibility. On the German

Table 1. Comparison of the different scenarios considered (less ecopoints means more environmentally friendly).

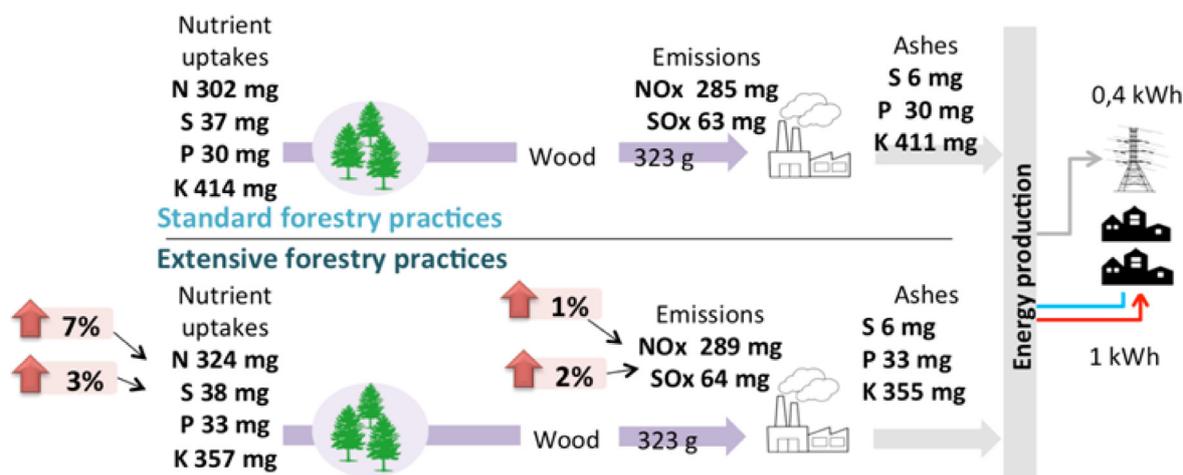
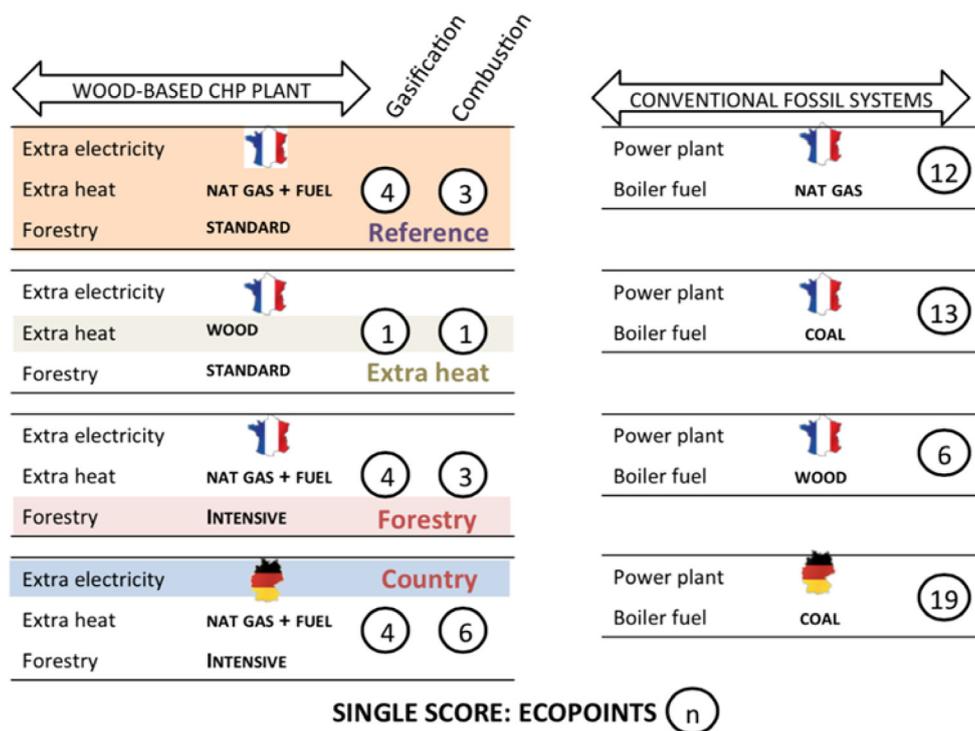


Fig. 11. Influence of forestry practices on nutrient uptakes in the case of wood gasification system.

side of the border, similar calculations led to better results for the gasification, due to its better electrical efficiency. Such a study clearly shows the interest to associate LCA to rigorous process modeling to be able to simulate and compare many cases with very limited assumptions.

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