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LCA OF BIOMASS POWER PLANTS: FROM SOIL TO ELECTRICITY

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Abstract

Biomass is one of the most promising renewable energy. The sustainability of biomass to energy chains needs to be assessed from the soil, including forest management, to the biomass valorization process. A strategy is presented to model the whole life cycle inventory of power production from biomass (beech). The forest growth, management and the wood valorization chain (including pulp, timber, etc., and energy) are modeled by a dedicated platform (called "CAPSIS"). It gives the detailed carbon and minerals (N, S, Cl, P, K) balances for the production and transport of the wood chips for the energy purpose. These results from CAPSIS are included in a "soil to power" model under Aspen Plus®, a process-oriented software. The process model flow sheet handles: CO₂, sun power, and minerals used for biomass growth, wood transport and pretreatment (crushing, drying), gasification and gas engine to produce heat and power. The detailed chemistry of the thermo-chemical reactions is modeled to better assess the emissions (PAH, NO_x, SO_x, etc.) and the fate of minerals in the gasification process. To the best of our knowledge, we provide the first such detailed life cycle inventory for biomass to energy. Minerals, exported from the soil during biomass harvest, could be a major issue for the sustainability of biomass use. The life cycle inventory is then included in a conventional life cycle assessment software (GaBi®).

Keywords: Biomass; forest; nutrient; carbon; gasification

1. Introduction

Biomass is considered as one of the most promising renewable energy alternatives toward sustainable development [1]. Indeed, biomass is a renewable carbon source that could be co-processed with fossil fuels in similar technologies. Hence using biomass in efficient conversion system has the potential to simultaneously mitigate climate change and reduce the dependence on fossil sources. However, the conversion of biomass has input and output flows that can affect the overall environmental performance of the system [2]. As stressed by Reijnders [3], the sustainability of biomass based fuel requires a stability of nutrients and organic matter in soil, and so a high recycling of nutrients present in ashes. The level of volatile carbon compounds and N₂O in the atmosphere has to remain unaffected, and emissions of persistent organics and acidifying compounds have to be low [3].

The environmental assessment of biomass energy routes needs a methodology to join the biomass growth and ecosystem management to the complex conversion of biomass into fuels or power, for instance in thermo-chemical processes such as combustion, gasification or liquefaction. The first task in the life cycle assessment is to model the complete mass and energy from the soil to the final use. To the best of our knowledge, there were not yet models able to depict the forest management, carbon and mineral nutrients issues and the chemical process of biomass conversion. To the best of our knowledge, we present in this workshop the first attempt to combine a forest management model with a process flow sheet model.

The methodology is illustrated on a wood gasification combined heat and power (CHP) plant. We developed a detailed model of a gasification CHP plant at a 10 MW electric scale in order to estimate all the input and output material and energy flows of the process [4]. The model is developed under Aspen Plus and external Fortran codes are used for the description of complex chemical mechanisms [5]. Results from a forest modeling platform ("CAPSIS") [6] are included in the Aspen Plus model to handle, by a simplified method, the mass and energy balances of wood growing and harvesting. Pollutant emissions during biomass gasification (NO_x, PAH, SO_x, Cl compounds, etc.) are accounted for thanks to the detailed Aspen Plus modeling strategy.

2. Materials and Methods

2.1 Methodology for modeling the biomass to energy route: from the ecosystem to the power plant

Figure 1 displays a simplified scheme of our modeling approach.

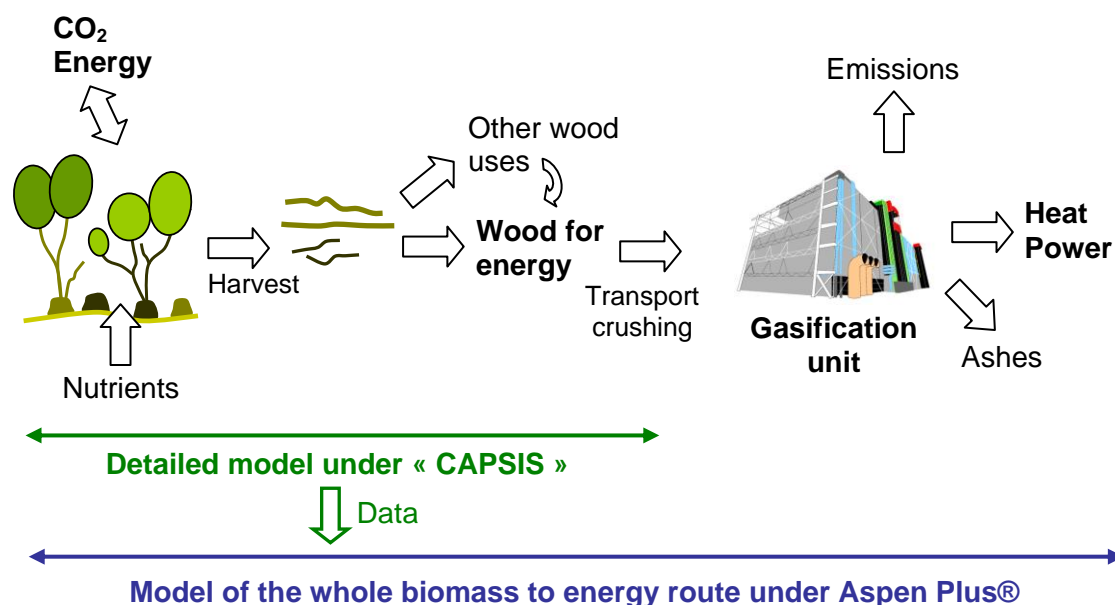


Fig. 1: Scheme of the modeling approach developed in this work: a forest management modeling tool (“CAPSIS”) is combined with a process modeling simulator (Aspen Plus®)

Ligno-cellulosic biomass such as wood wastes represents the highest potential of renewable resource but the biomass to energy route has to be complementary to other wood uses such as timber, pulp (etc.) and should not yield to detrimental nutrient exportation issues. For this reason, our modeling strategy used a forest modeling platform, called CAPSIS [6,7], coupled to a carbon assessment tool (called “CAT” [8]). CAPSIS predicts the biomass growth and CAT handles the use of these tree logs. The logs are distributed as a function of their diameter and quality to different wood valorization chains (pulp, timber, energy, and end-uses, etc.). The results from CAPSIS and CAT are generated in an excel file in the form of “kg of biomass hectare⁻¹ year⁻¹” including minerals flow rates (eg. kg K hectare⁻¹ year⁻¹). These results are included in an advanced Aspen Plus® model. Aspen Plus is a software which is well adapted to model solids, such as biomass, and their chemical conversion to liquids or gases. It predicts mass and energy balances of the process. We included for the first time the forest growth and tree logs chains as “process units” in Aspen Plus. The forest is considered as a “reactor” which produces biomass from CO₂, sun power and other nutrients, based on the results of CAPSIS. This approach allows the simulation of the whole biomass to energy chains under a unique “process” flow sheet.

2.2 Modeling of forest management and wood chips production by the CAPSIS platform and its carbon assessment tool “CAT”

CAPSIS is a Java-programmed platform that is designed to host forest growth models. In addition to the 60 models it already contains, the platform also includes some diagnostic tools. The Carbon Assessment Tool (CAT) is one of the available tools that makes it

possible to estimate the carbon balance of different forest management strategies. For further details about the platform, the readers can refer to Dufour-Kowalski et al. [6] as well as the website capsis.cirad.fr.

In this study, we focused on a specific model within this platform, namely the FAGACEES model, which can predict the growth of pure regular European beech stands. The model is largely detailed in Dhôte [7]. Basically, it predicts the height growth of the dominant trees. The predicted height growth then serves to predict the overall diameter increment at the stand level. The overall increment is split among the individual trees. The model also accounts for between-tree competition through a relative density index. Whenever the index reaches the value of 1, which indicates the maximum size-density, the smallest trees are assumed to die in order to allow survivors to keep growing. As implemented in CAPSIS, simulations with FAGACEES also allow the user to specify a target in terms of relative density. Whenever the target is reached, a harvesting is carried out in order to reduce the density. This way, different management scenarios can be tested by specifying different relative density targets.

CAT is the carbon assessment tool available in CAPSIS. It performs the assessment not only on the carbon in the wood, but also on some other nutrient as well, such as nitrogen, sulfur, phosphorus, and potassium. The tool retrieves the information the model provides at each growth step. It recovers the harvested trees and sends them into a bucking model that provides a set of logs as output. This collection of log is then sent into some production lines according to the log characteristics. The production lines then process the logs into end-use wood products, which are commonly referred to as harvested wood product (HWP) in the carbon assessment terminology. These HWP belongs to some user-defined categories, such as construction wood products, energy wood and so on. Consequently, they have different average lifetime. Once the HWP are generated, CAT handles time, actualizes them all along the useful lifetime, and handles their disposal after it. All the parameters that define the lifetime, the percentage of recycling, as well as the relationship between the different production lines are defined by the user. CAT also evaluates different fluxes, such as the carbon emission due to the log processing into HWP.

Fortin et al. [8] used such a tool to estimate the carbon balance for pure regular oak stands. In this study, we adapted their production lines to make them compatible with beech use in terms of end-use wood products. The flowchart in Figure 2 shows the coupling between the forest growth model and CAT.

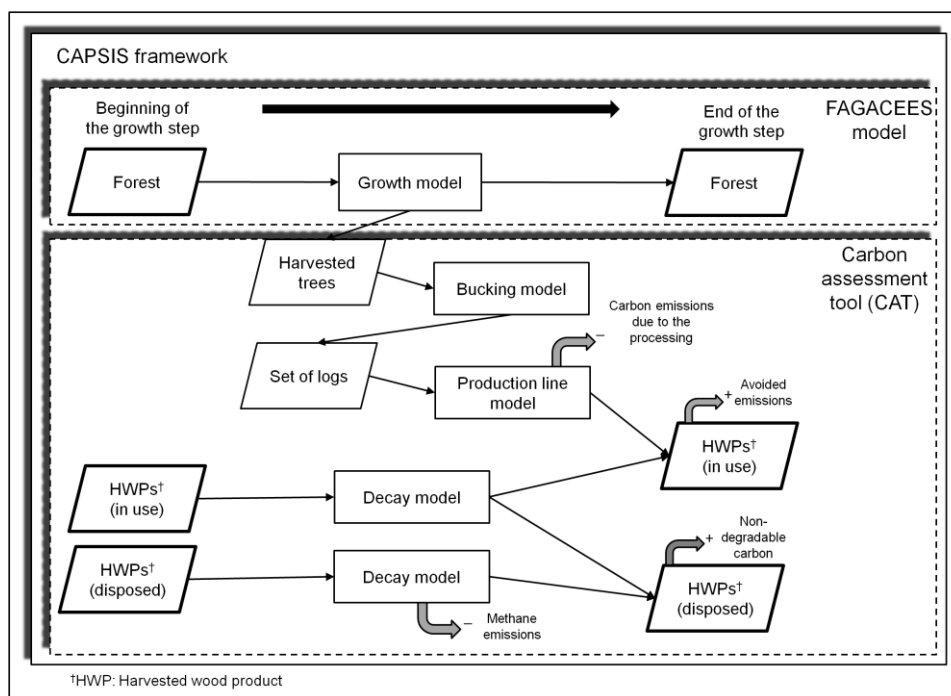


Fig. 2: Flowchart of the carbon balance assessment in CAPSIS

2.3 Modeling under Aspen Plus of the whole biomass to energy chain

The data from CAPSIS are modeled under Aspen Plus with different blocks units (a combination of “reactors” and “separators”) for biomass growth, distribution of logs (including harvesting consumption), wood chips production (including crushing), and transport. Based on this approach, the required surface area of forest and other utilities (eg. fuel for harvesting and transport) are linked with the consumption of the gasification unit. For instance, a need of 1MW of power yields to a flow rate of wood chips (kg/h), calculated by the gasification module of Aspen Plus, and based on the forest growth module (kg/h/hectare) to a land use (hectare).

Furthermore, the Aspen Plus model developed for the gasification process unit describes all the process steps and the complex reactions of gasification, including the fate of minerals. Figure 3 presents the gasification process model. More details can be found in ref. [4, 5].

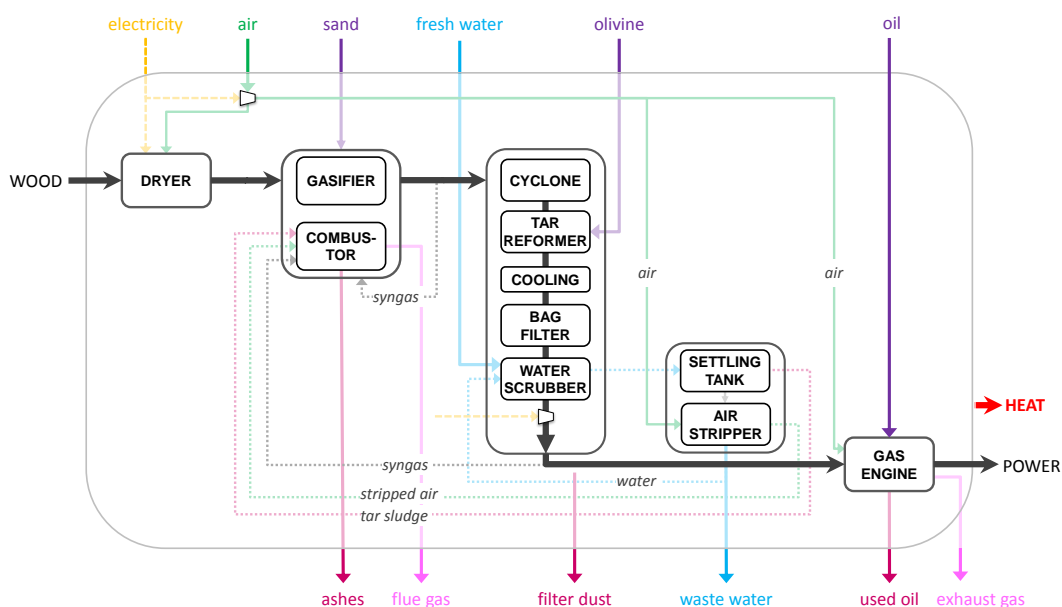


Fig. 3: Simplified scheme of the gasification process modeled under Aspen Plus [5]. Wood chips production (input of the gasification process) from the forest Aspen Plus model is modeled under the same Aspen Plus flow sheet, but is not represented here to focus on the gasification model.

Briefly, the gasification combined heat and power (CHP) system consists of a wood dryer, an atmospheric dual fluidized bed (DFB) gasifier, a syngas cleaning unit coupled with a scrubbing agent regeneration unit and a gas engine. Wood moisture content is reduced in the dryer using hot gases as drying agent. Dry wood is fed to the gasifier compartment of the DFB gasifier. A DFB gasifier consists of two interconnected fluidized bed: one for gasification and one for char combustion. Sand bed is fluidized with a fraction of raw syngas in the gasifier compartment, and circulated in-between the two compartments to transfer heat from the combustor to the gasifier. In the gasification compartment, dry wood is converted into gas, char and tar. Gas and tar undergo secondary reactions (mainly hydrocarbons cracking and water gas shift reactions), while char and soot undergo gasification reactions [5]. Char is then injected with sand to the combustor compartment and oxidized with air. Tar sludge (from the scrubbing agent regeneration step) and a fraction of clean syngas are additionally fueled to the combustor to maintain heat balance in the reactor. Flue gas and ashes exit the combustor zone, while raw syngas exits the gasification zone. Raw syngas contains various contaminants as tars, NH_3 , HCl and entrained particles which are removed in a purification arrangement. The cyclone removes large particles; the tar reformer reduces the amount of tars and NH_3 ; the bag filter removes small particles and the water scrubber separates tars, NH_3 and HCl . Water is regenerated through a settling tank (for tar removal), and an air stripper (for NH_3 and HCl removal). In addition to reused water, fresh water is also continuously fed to the scrubber, and waste water is exiting the regeneration unit. Stripped air is used as combustion air in the combustor. Clean syngas is then fed to the gas engine for power generation. Oil is

consumed and exhaust gas emitted during gas engine operation. Pollutant emissions from the engine and char combustor (NO_x, SO_x, PAH, particles, Cl species, etc.) are predicted by the model.

An important feature of our Aspen Plus model is its suitability to model the evolution of trace/pollutant species [4] thanks to a detailed description of the physical-chemical phenomena. For instance, N species contained in wood are converted to NH₃ and N-moieties in the char during the pyrolysis reactions. NH₃ in the syngas is further washed and oxidized to produce NO_x (in the gas engine). N-moieties in the char are oxidized in the combustor compartment of the gasifier and generate also NO_x. Tar (aromatic species) produced by pyrolysis and washed by the scrubber are also modeled. Such a detailed approach is allowed by dedicated external Fortran files which are coupled through .dll to the Aspen Plus simulator, as described in figure 4. Fortran files allow a more detailed description of the reactors [5].

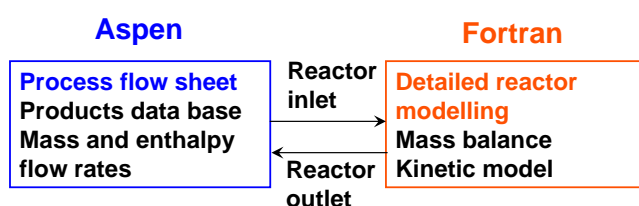


Fig. 4: Fortran models are coupled to the Aspen Plus model for a better description of the chemistry of biomass conversion

3. Results and discussion

3.1 Life cycle inventory from the soil to power

Figures 5 and 6 present the carbon and minerals mass flow rates along the biomass to energy chain, accounted for a 10MWelec gasification unit. N, S, Cl, P and K are predicted separately in the Aspen Plus model, as they are subject to different chemical mechanisms, but only the sum of them is presented for sake of brevity.

Figure 5 shows that 6300kg/h of carbon in CO₂ is absorbed for the production of wood. About 60% of wood is used for energy purpose based on the assumptions of the CAT model. The 3720 kg/h of carbon in wood chips is converted into CO₂ in the gasification unit: about 1360 kg/h in the flue gas from the gasifier combustor compartment and 2360kg/h in the exhaust gas from the syngas engine. More detailed mass balances will be presented at the conference as in ref. [4].



Fig. 5: Carbon mass flow rate (kg/h) along the biomass to energy chain based on a 10MWelec gasification unit

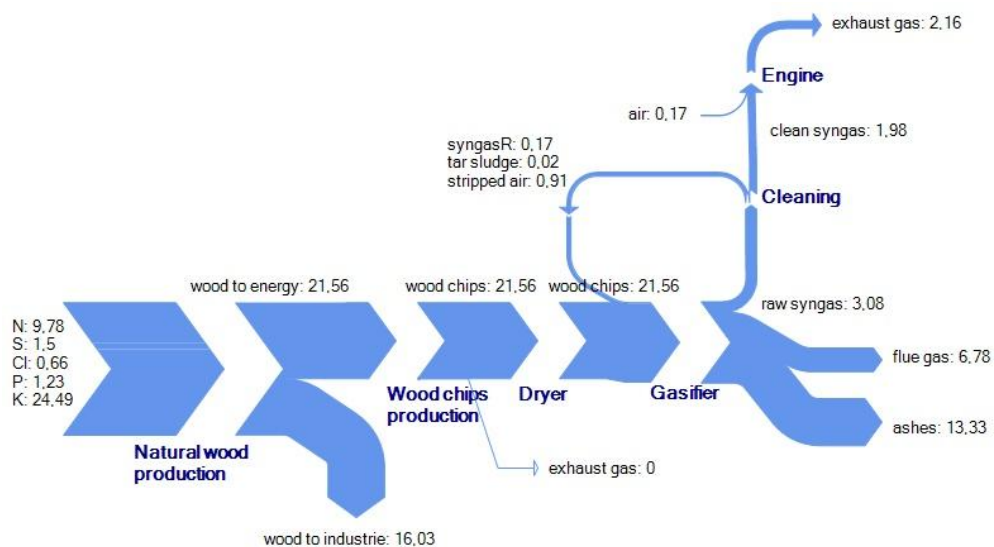


Fig. 6: Minerals mass flow rate (kg/h) along the biomass to energy chain based on a 10MWelec gasification unit

Concerning the evolution of minerals, figure 6 shows that the major exported minerals from the soils, for beech and based on the CAPSIS model, are K and N. These exportations will highly depend on the soil composition, ecophysiological aspects and forest management routes. More detailed works are needed to better model the biogeochemical cycle of nutrients. All these nutrients are globally converted into oxides with different speciations in the gasification process (NO_x, SO_x, K/P/Si/etc. oxides complex). It is important to notice that for the sum of the five nutrients (N, S, Cl, P, K) about 40% are emitted in the gas-phase in the exhaust gas, leading to recovery and environmental issues. The high temperature (~ 950°C) will produce a complex solid matrix

(“ashes” with not converted carbon) with various bioavailabilities if recycled to the soil as a function of biomass composition and gasification temperature [9].

Other elements (H, O, single mineral, etc.), mass, energy and exergy Sankey diagrams are also generated. Mass and energy balances are currently studied as a function of forest management scenario and gasification process.

3.2 Life cycle assessment

The life cycle inventory generated by Aspen Plus is then used for life cycle assessment with the Gabi® software through an excel file in which all the streams and their properties are ranked. The life cycle impact assessment (LCIA) method used is the CML 2001 method [10]. The considered environmental impacts and the respective contribution of the life cycle inventory steps depend on the chosen LCIA method.

The following environmental impacts were assessed by the CML 2001 method: Terrestrial Ecotoxicity Potential (TETP inf.) [kg DCB-Equiv.], RAD = Radioactive Radiation (RAD) [DALY], Photochem. Ozone Creation Potential (POCP) [kg Ethene-Equiv.], Ozone Layer Depletion Potential (ODP, steady state) [kg R11-Equiv.], Marine Aquatic Ecotoxicity Pot. (MAETP inf.) [kg DCB-Equiv.], Human Toxicity Potential (HTP inf.) [kg DCB-Equiv.], Global Warming Potential (GWP 100 years) [kg CO₂-Equiv.], Freshwater Aquatic Ecotoxicity Pot. (FAETP inf.) [kg DCB-Equiv.], Eutrophication Potential (EP) [kg Phosphate-Equiv.], Acidification Potential (AP) [kg SO₂-Equiv.], Abiotic Depletion (ADP) [kg Sb-Equiv.].

The contributions for each impact were assessed for the following life cycle inventory steps: wood growth, wood chips production, wood chips transport, CHP plant operation, waste disposal.

Preliminary results showed that the RAD and PCOP impacts are mainly attributed to CHP plant operation. The main impact, considering the CML 2001 method, would be the MAETP, with about 40% contribution from wood chips production and transport and 60% from CHP plant operation. Wood growth has only a significant contribution on GWP (CO₂ absorption by the photosynthesis). Ashes were assumed to be sent to “sanitary landfill”. Minerals exportation is only considered in the ADP impact and yields globally to a very low impact contribution, based on this method. More details will be provided at the conference and in the associated special-issue paper.

4. Conclusion

In this workshop paper, we present for the first time our methodology to model the whole biomass to energy route: from the forest to the power. Forest management, wood harvesting and uses are modeled in detail under a specific modeling platform called “CAPSIS”. The results from this model are included under Aspen Plus®, a process-

oriented simulator. To the best of our knowledge, the forest growth and tree logs chains are included for the first time as “process units” in Aspen Plus. The forest is considered as a “reactor” which produces biomass from CO₂, sun power and other nutrients, based on the results of CAPSIS. This approach allows the simulation of the whole biomass to energy chains under a unique “process” flow sheet. The Aspen Plus® model generates a unique life cycle inventory based on an advanced description of the chemistry in the gasification unit. Pollutants (tar, PAH, NO_x, SO_x, HCl, etc.) as well as ashes composition are predicted. Mass, elements, energy and exergy diagrams of the biomass to energy route are generated. The life cycle inventory is then used under Gabi® software to assess the environmental impacts.

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