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## How to Determine Energy of Wood from Nutrient Analysis?

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In the context of increasing energy demand, forest timber residues and leaves are a potential resource for fuel. How renewable are these resources? What are their qualities as a fuel? These issues can be answered through parallel works in two research fields: forest sciences considering nutrients cycles between plants and soil and growth and yield dynamics of the trees, and energy sciences considering the qualities of fuel such as heating value, and ash content. This interdisciplinary interaction leads to the balanced thinking between nutrient dynamics (harvesting forest residues while maintaining soil fertility and wood production) and energy interests.

In a previous work, a study was presented that intended to bridge the two research fields by predicting the ash content and higher heating value in trees from a model developed by biogeochemists for predicting elemental composition distributed in several tree compartments.

The models developed were applied on predictions of characteristics of forest products. These characteristics were outputted from a growth and yield simulator developed by forest research. This application added energy characterization to the wood biomass described biochemically.

This connexion was the first step for the development of a simulation package which aims at characterizing the production chain of energy wood from forest growth and yield simulations (developed by forest sciences), through energy characterization (use of the interdisciplinary model), to harvesting and transformation chain characterization (energy and engineering sciences).

Here, we quickly describe the models connecting biochemistry to fuel characterization of forest biomass; then we describe the simulation package and how these models are connected to biochemists models in the simulation package and finally we explain why the use of such a package is an important tool toward the improvement of the biomass production chain quality.

### 1. Introduction

In 2008 the Europeans Council and Parliament approved the Energy Climate package. This project fixed objectives for the year 2020: to reduce emissions of carbon dioxide from 20 %, and increase energy efficiency and renewable part of the primary energy consumption both by 20 % (EU, 2009). At European scale, renewable energy accounts for 8.16% of the total final energy consumption in 2010. Biomass accounts for 62 % of the renewable energy resource, of which 19 % are firewood and 23 % are forest residues (AEBIOM, 2012), both directly extracted from forests. Considering this distribution of the resource, these objectives will have a significant impact on the intensity of the forests use.

To face these changes and build a sustainable supply chain from the seed to the conversion plant, foresters, forest scientists and energy experts have to work in a continuum of knowledge.

A methodology was developed to ensure an accurate use of biochemists data for energy characterization. This methodology was an original attempt to bridge the gap between forest nutrition and fuel quality assessment. In the present paper, we present how this methodology is used in the development of a simulation tool of the forest energy wood chain implemented on the open software platform CAPSIS (Dufour-Kowalski et al., 2012).

The simulation tool of the supply chain makes the link between on one side forest growth and yield simulations (G&Y) and on the other side fuel characteristics and life cycle information for energy wood in the form of chips. From the trees in the stand to the dry chips delivered to the heating plant, the resource is characterized in quantities (biomass, mineral content in mass and energy contents in kJ or kWh) and quality (mineral concentrations in g/kg, higher heating value in kJ/kg or kWh/t and ash content in %). Also, the chain is characterized for its performances in terms of energy efficiency and mineral exportation rate. We here describe the general steps of the entire project including (1) models for the prediction of wood HHV and ash content from elemental composition as predicted by biochemists models; (2) a simulation tool for the prediction of forest wood chips supply chain performances and the assessment of the quality of the fuel produced.

## **2. State of the art**

### **2.1 Elemental characterization of wood**

Elemental content of forest biomass is measured in forest sciences by biochemists. The consideration here is the “nutrient content” of tissues in trees, considering the cycles of these nutrients in the forest. This nutrient content as such as the masses distributions in tree are modeled, relying on basic characteristics of trees and forest stand, such as the species, the diameter and the height of trees. These simple parameters are the dendrometric parameters of the tree. Hence, the resulting models are called dendrometric models (e.g. for minerals: Augusto et al., 2008, e.g. for biomasses: (Genet et al., 2011). Elemental composition is measured by ultimate analysis in energy sciences.

### **2.2 HHV prediction models**

Higher heating value and ash content of biomass can be calculated from the elemental information. Many models already exist in energy literature to predict HHV; some of them are particularly designed from elemental composition of wood biomass. In the development of the package, some of these models were compared for their performance on independent data (70 wood samples characterizations gathered from literature and a dataset of 85 samples acquired by the French CEA). Some models with good performances for predictions for wood biomass can be reported here: Tillman (1978) considered only carbon for 10 wood samples, Friedl et al. (2005) developed a model based on 154 biomasses samples, 27 being wood, and considered carbon, hydrogen and nitrogen; more recently, Yin (2011) developed a model considering hydrogen and carbon. The main elements generally retained to determine HHV of biomass are the carbon content [C], hydrogen [H], oxygen [O] and often, ash content (A).

Ash content is an important characteristic of wood fuel quality (AFNOR, 2011): its value is limited, especially to avoid sintering in combustion. It is accepted that ash content is complementary to [C], [H], [O] and [N] to the total mass (Telmo, Lousada and Moreira, 2010), that is why it is often used in energy models to predict HHV.

### **2.3 From physiology to fuel characterization**

It is then theoretically possible to predict ash content and higher heating value from elemental analysis as measured by biochemists and predicted in forestry sciences. Moreover, as this nutrient content and the biomasses are modelled from stand environmental characteristics (such as soil pH, climate influencing nutrient cycles), it becomes possible to predict fuel production in quantity and quality directly from these characteristics. However there are some differences between considerations in energy and in physiology sciences that implied biases in predictions. No characterization of these biases was found before the work performed in the development of the presented package.

## **3. Material and methods**

Then a method was described to predict energy sciences characteristics relying on biochemists data. Finally, two models were calibrated to predict energy characteristics of wood: 1) as ashes were not measured by biochemists in forestry sciences, a model was proposed for ash estimation, relying on sulfur, phosphorus, potassium, calcium and magnesium contents of biomass, as characterized by the biochemists models; 2) HHV was modeled as a function of carbon, nitrogen and ash contents of biomass. As presented in Figure 1, this work resulted in three new methods: 1) conversion of elemental analysis considering mass losses, 2) calculation of the ash content from biochemists' data, 3) calculation of the higher heating value from biochemists' data.

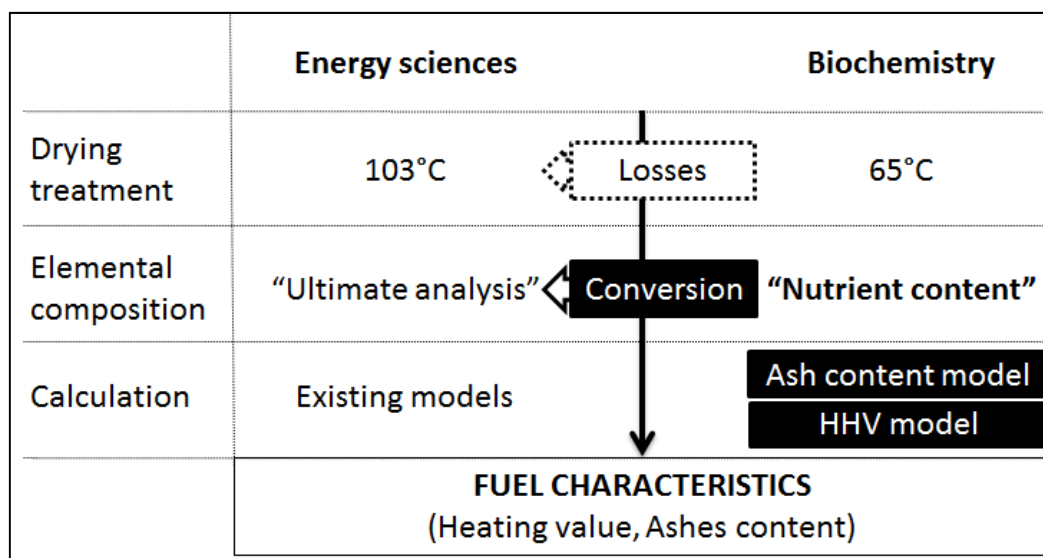


Figure 1: Principle of the work of conversion between biochemistry and energy sciences. Black boxes represent the tools newly developed

### 3.1 Growth and yield simulators

CAPSIS is the name of a platform including several growth and yield simulators (G&Y) for different species of trees and different kinds of forests (even-aged or not, multi-species ...) (Dufour-Kowalski et al. 2012). These simulators are generally based on models for the determination of the variations in diameter and height of trees regarding the growing conditions (stand density, soil fertility) the time and the forest management. Results are given on average for a stand or for a list of trees. Secondary models are applied on this first information to predict some advanced characteristics such as biomass or mineral quantities and repartition.

### 3.2 A simulation tool of the production chain

In addition, CAPSIS contains parallel simulation tools, that can be plugged to these G&Y. ForEnerChips (contraction of Forest Energy Chips) is one of these plugging tools, designed to simulate the production chain of forest wood chips, from the standing tree, to the heating plant.

Growth and yield simulators deliver information about the trees thinned and harvested during interventions of forest management.

The chain simulator integrates the different processes involved in biomass harvesting and processing. It considers ten processes: felling, shaping, combination of these two first blocks to simulate a forest harvester, seasoning, bundling, forwarding, chipping, loading/unloading, drying and transport processes. The simulator calculates for each process in the chain the energy consumed, and the resource eventually lost in processing. The separation of the chain in individual blocks of process allows the construction of any scenario for the chain.

The energy consumption takes into account: the direct fuel consumption of the tool (electricity, gas, eventually considering the primary energy for this fuel); oil consumptions (chains and motors lubrications, hydraulic movements); the life cycle of the tools; the transports of machines and men for the need of the work.

### 3.3 From forest sciences to energy characterization

The protocols in biochemistry used to measure the nutrient content in forestry sciences are found to be slightly different from the protocols used in elemental analysis in energy sciences. The main difference we identified between protocols was the drying treatment: in energy science, wood is considered as a fuel and dried at a temperature of 103°C; in biochemistry, wood is dried at a maximum of 65 °C to avoid volatilization of material. Furthermore, forestry science is able to predict mineral contents in trees for several minerals, but the list of these elements differs from the usual list in energy sciences. For instance, forestry sciences considered the important elements for nutrient cycles, such as carbon (C), nitrogen (N), sulfur (S), phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), manganese (Mn), sodium (Na), and aluminum (Al). Energy sciences consider mostly carbon, hydrogen (H), oxygen (O), nitrogen, sulfur,

calcium and silica (Si). These two differences implied biases in the application of models from energy sciences' literature directly on biochemistry data.

To overcome these biases, a dataset of 37 forest biomass samples was selected in databases from biochemists. The selection was made to cover a large range of elemental composition profiles, regardless to compartment (branch or stem, different diameters and positions in tree) or tissue (wood, bark or leaves). A mass loss can be observed between 65 and 103 °C. This mass loss significantly changes the biomass elemental composition. The mass loss was characterized as such as its potential effect on the consideration of fuel mineral content. A method was described to predict energy sciences characteristics relying on biochemists data.

Then, the 37 samples were characterized according to energy standards in terms of HHV (AFNOR, 2010a) and ash content (AFNOR, 2010b), and a model was developed for the prediction of standard fuel characteristics of wood from the data and models of physiologists from forest sciences.

#### **4. Results: an evaluation package for the production chain of forest biomass for fuel**

G&Y simulations give information about the resource harvested during forest interventions. The production chain simulator ForEnerChips uses this information as input data to characterize the final resource in the form of wood chips after the harvesting, transformation and transports steps. The available processes list is studied to cover any possible scenario for the production chain, from the forest harvesting processes to the delivery of the chips, through the transformation steps. Finally, a model predicts the fuel characteristics in energy standards from the physiologists' information delivered by the two previous steps.

##### **4.1 Parameters**

Before simulation, the forestry and production chain scenarios are set. Growth and yield scenario consists mainly in site index (fertility coefficient), dates of intervention and intensity of the interventions. Production chain scenario for the ForEnerChips tool consists in a list of processes ordered; after the chain is designed for its ordered list of processes, each process is set with technical parameters such as engine power, machine weight and life length, resource processing efficiency, travel distance to the stand ...

##### **4.2 Simulation principle**

During the simulation running, set processes are called one after the other in the scenario list. Each process is input with the resource output from the previous process. Hence, the resource is brought/converted step-by-step into the final product delivered at the heating plant.

##### **4.3 Outputs**

The output consists in the resource characteristics, traced process after process from the standing tree to the chips dried and delivered to the heating plant. The information is given in the form of a table: one row corresponding to a process in the chain, one column corresponding to a characteristic of the resource or the chain. The resource is described for its biomass (in tons) and for its mineral content (carbon, nitrogen, sulfur, phosphorus, potassium in kg). These characteristics are predicted considering the initial resource and the resource chose as raw material from the different aerial compartments of the standing tree (branches superior and inferior to 7cm cut, stem superior and inferior to 7 cm cut and leaves). The chain is also described at each step for the consumptions of the individual step, and the consumptions cumulated along the chain until this step. Consumptions may be summarized in a general consumption or separated in the different modalities previously described: fuel, oil, life cycle and machines and men transportation. Finally, the models for heating value and ash content calculation are applied on the output and the energy production is calculated regarding the higher heating value of the final product, its moisture content, and its mass.

In the end, the chain is traced at all level, including: 1) the quantities of organic material and minerals exported from the stand after a the harvesting of trees; 2) the primary energy finally delivered to the heating plant, 3) the energy spent and the repartition of this along the fuel, oil, life cycle and logistic.

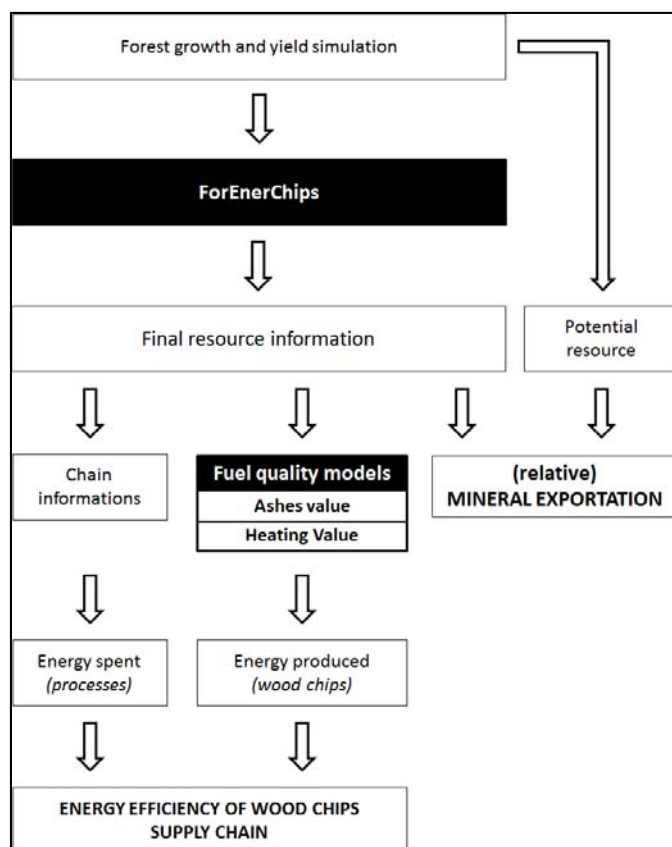


Figure 2: General approach developed for the assessment of the supply chain of wood chips for energy. Focus is made on the link between forest and energy science (box coloured in black)

## 5. Conclusion

The continuum from the forest to the heating plant was made possible by the connection between forest sciences and energy sciences. This connection was made by pointing out the differences between approaches, the characterization of the impacts of these differences, and the development of modeling tools to predict energy standard characteristics from physiologists' characterizations.

The simulation package enables to simulate the whole processes constituting the supply chain of wood chips use for bioenergy, from forest management in the stand to dried chips delivery at the heating plant. This simulation package also enables the simulation of a various set of scenarii of forest management and supply chain. Considering the explicit parameters of the simulations and the explicit outputs detailed before, this package is of a great interest in the evaluation of the sensitivity of the energy balances and nutrient exports to the variations along the production chain of wood chips for energy. This approach is to be developed in further development of the present work to come.

Finally, it is designed to be technically complete but explicit and adjustable, and can be extended as a support for life cycle and other assessments (social and employment ...).

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