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Bioenergy Chain and Process Scales

The outline of this book follows the different scales of investigation of biomass conversion which are presented in Figure 1.1. First the bioenergy routes are presented then followed by the reactor, particle and molecular scales.

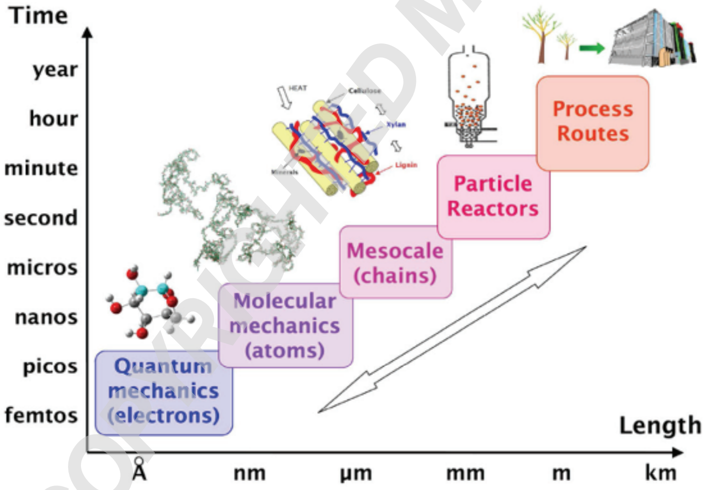


Figure 1.1. *The different scales of investigation in chemical engineering illustrated for biomass conversion: from electrons to routes*

1.1. Biomass production and ecological issues

There are two different contexts on biomass production:

– in some developing countries, biomass production may result in deforestation, a potential loss of biodiversity (especially in the rainforest), land-use competition and soil erosion (see Figure 1.2). Wood is often the main energy resource and is burnt in wood stoves with a very bad efficiency;

– in developed countries, forest is aging and in expansion due to the lack of wood valorization. Wood energy should be promoted in some regions to better valorize the small stems in forests.

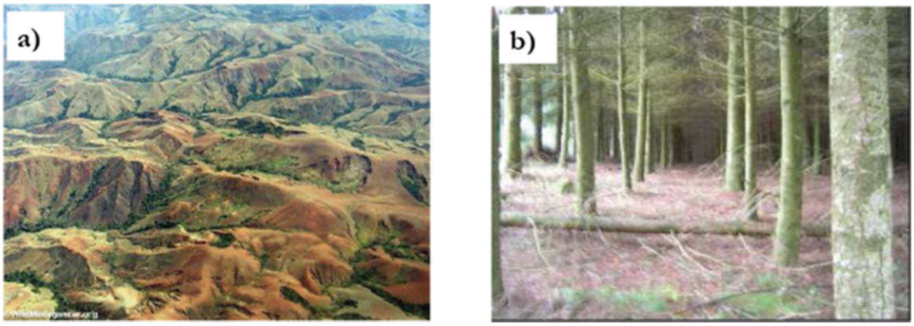


Figure 1.2. *Two different contexts for wood valorization: (a) in developing countries (here in Madagascar), wood valorization results in deforestation and soil erosion; (b) in developed countries (as in France), wood is not well valorized and wood energy should be promoted to reduce the aging of trees and stems density in forests*

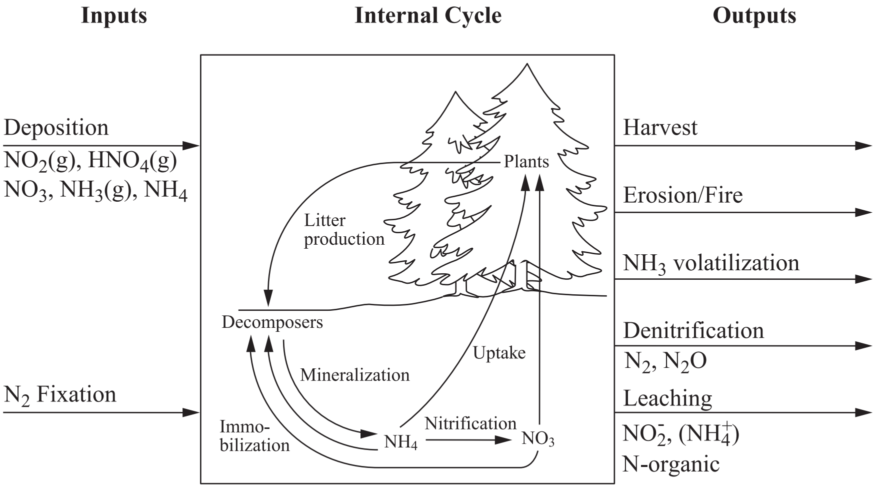


Figure 1.3. *Biogeochemical cycle of nitrogen in forests*

A very important feature for ecosystems is the biogeochemical cycle that is represented in Figure 1.3 for forests. The main inputs (especially in nutrients such as N, P and K) are atmospheric deposition and rock mineralization. The outputs are soil leaching or erosion and biomass harvesting. Wood harvesting can considerably impact the cycle if it results in too high a flow of nutrient exportation (nutrients are present in the harvested wood) and thus in soil impoverishment.

For these reasons, a global assessment of the whole bioenergy chain (from forest to final use) is required to assess the sustainability of bioenergy. It is especially of high importance to assess the fate of carbon and nutrients in the whole bioenergy chain.

1.2. Modeling of bioenergy chains

1.2.1. *Global model of the whole bioenergy chain*

Lignocellulosic biomass such as wood waste represents the highest potential of renewable resources but the biomass-to-energy route has to be complementary to other wood uses such as timber and pulp and should not yield to detrimental nutrient exportation issues. For this reason, our group has developed a modeling strategy (presented in Figure 1.4) that combines a forest modeling platform, called CAPSIS [DUF 12c, FOR 12], and a process modeling simulator (Aspen Plus®) [FRA 14].

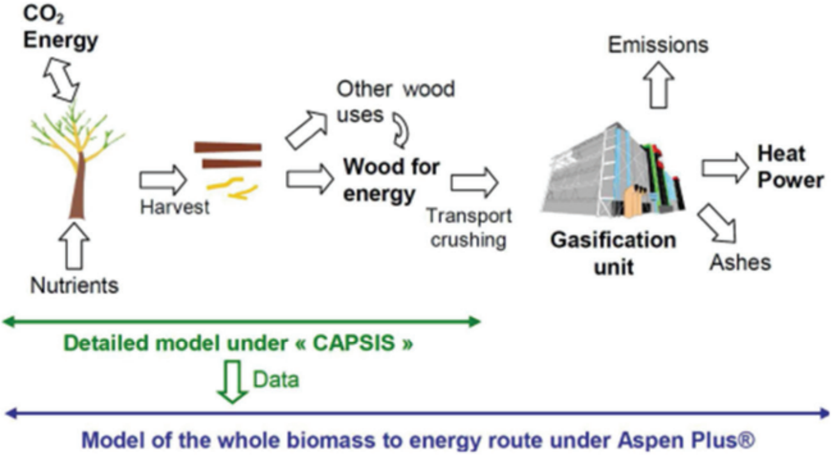


Figure 1.4. *Diagram of the approach developed at CNRS, Nancy, for bioenergy chain modeling: a forest management modeling tool (“CAPSIS”) is combined with a process modeling simulator (“Aspen Plus”) [FRA 14]*

CAPSIS predicts the biomass growth and CAT handles the different uses of the 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). The results from CAPSIS and CAT are generated in an excel file in the form of “kg of biomass hectare^{-1}year^{-1}” including mineral flow rates (e.g. kg K hectare^{-1}year^{-1}). These results are included in an advanced Aspen Plus model. Aspen Plus is a piece of software that is well adapted to modeling solids, such as biomass, and their chemical conversion to liquids or gases. It yields mass and energy balances of the process. The forest growth and tree log chains have been included as “process units” in Aspen Plus. The forest is considered as a “reactor” that produces biomass from CO_2, sun power and other nutrients, based on the results of CAPSIS. This approach helps the simulation of the whole biomass to energy chains under a unique “process” flow sheet.

In Aspen Plus, the photosynthesis process is modeled in a reactor with the following simplified equation [FRA 14]:

$$aCO_2 + b/2\,H_2O + dN + eS + fCl + pP + kK \rightarrow C_aH_bO_cN_dS_eCl_fP_pK_k + (2a + b/2 - c)/2\ O_2$$

The flows in C, N, S, P and K (in kg ha^{-1}yr^{-1}) as estimated by CAPSIS were used as input parameters for the Aspen Plus photosynthesis reactors. The scope of this work was not yet to model in details the forest biogeochemical process but to propose a simplified method to handle forest management under a process flow sheet such as Aspen Plus.1

The forest growth process provides the amounts of energy wood by hectare and year. Given a particular amount of electricity and heat power, this integrated forest-to-energy model made it possible to predict the annual flows in wood, carbon and nutrients, including N, S, P and K, from the forest to the air emissions (NOx, SOx, polycyclic aromatic hydrocarbons (PAHs), etc.) and ash flows. The model of the gasification plant is described in the following section. On the basis of this approach, the required surface area of forest and other utilities (e.g. fuel for harvesting and transport) are linked with the consumption of the gasification unit. For instance, a need of 1 MW power yields 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). Results from this integrated bioenergy chain model are presented in Figures 1.5 and 1.6.

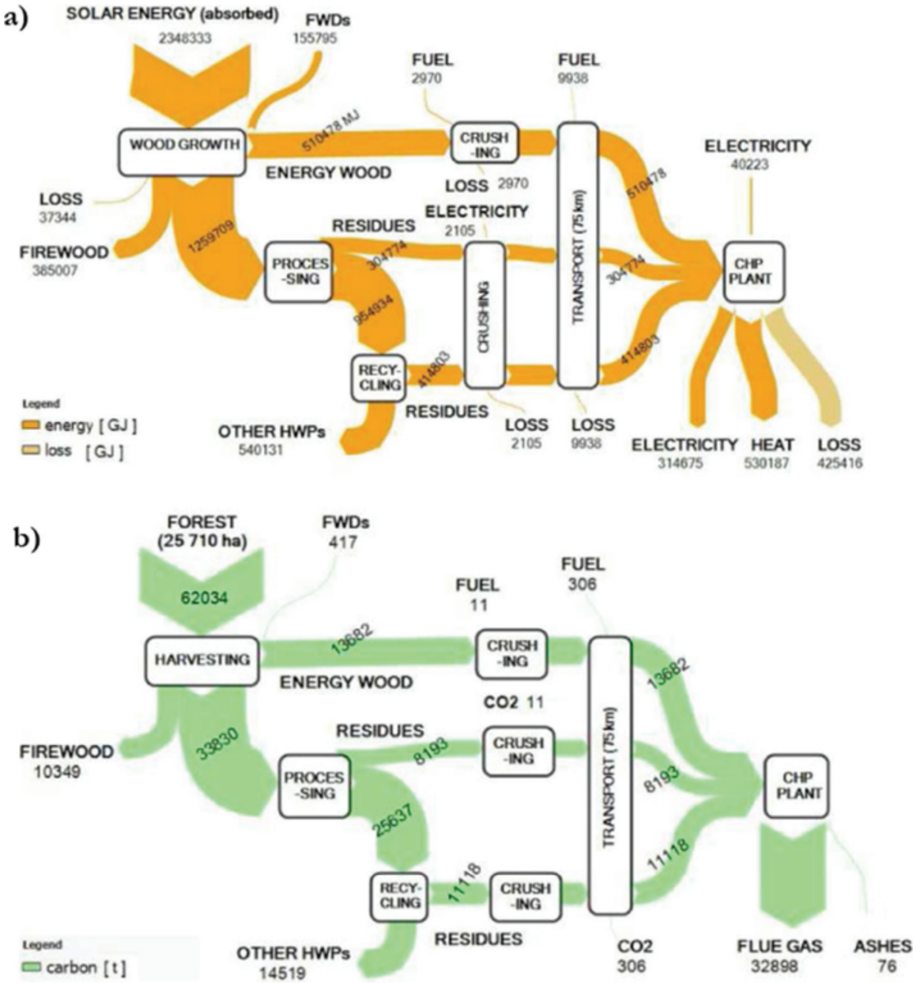
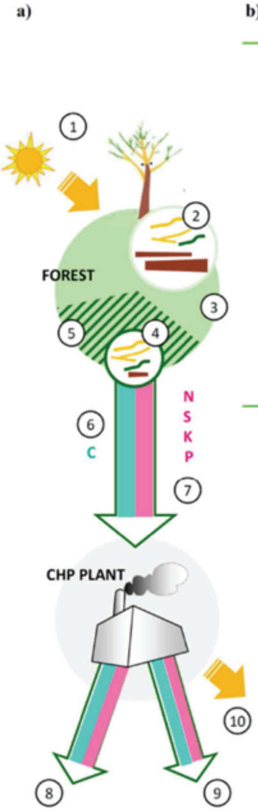
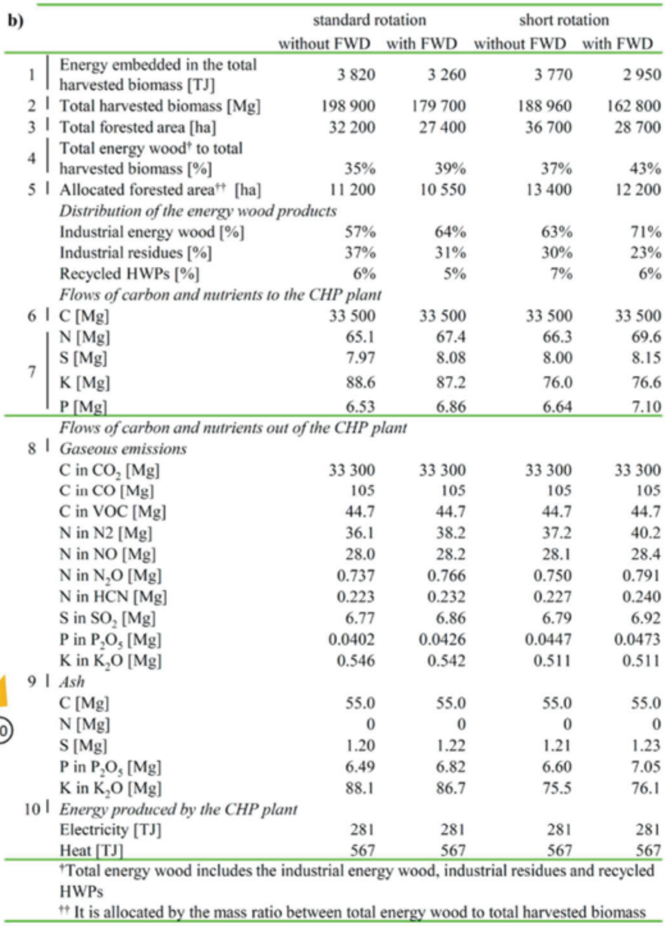


Figure 1.5. *(a) Energy and (b) carbon balance for the whole bioenergy chain from forest to power for the production of 10 MW of electricity during one year. “HWP” means “harvesting wood products”*

The bioenergy potential of pure even-aged high-forest stands of European beech, an abundant forest type in northeastern France, has been studied. Two forestry management practices were studied, a standard-rotation and a shorter-rotation scenario, along with two wood utilizations: with or without fine woody debris (FWD) harvesting (results not shown). FWD harvesting tended to reduce the forested area required to feed the combined heat and power (CHP) plant as larger amounts of energy wood were available for the CHP process, especially in the short-rotation scenario. The short-rotation scenario with FWD decreased the nutrient exports per hectare, compared to the standard practices, but increased the amount of nutrients in the CHP process. This increase in the input nutrient flows had direct consequences on the inorganic air emissions.




b)

		standard rotation		short rotation	
		without FWD	with FWD	without FWD	with FWD
1	Energy embedded in the total harvested biomass [TJ]	3 820	3 260	3 770	2 950
2	Total harvested biomass [Mg]	198 900	179 700	188 960	162 800
3	Total forested area [ha]	32 200	27 400	36 700	28 700
4	Total energy wood† to total harvested biomass [%]	35%	39%	37%	43%
5	Allocated forested area†† [ha]	11 200	10 550	13 400	12 200
	Distribution of the energy wood products				
	Industrial energy wood [%]	57%	64%	63%	71%
	Industrial residues [%]	37%	31%	30%	23%
	Recycled HWPs [%]	6%	5%	7%	6%
	Flows of carbon and nutrients to the CHP plant				
6	C [Mg]	33 500	33 500	33 500	33 500
7	N [Mg]	65.1	67.4	66.3	69.6
	S [Mg]	7.97	8.08	8.00	8.15
	K [Mg]	88.6	87.2	76.0	76.6
	P [Mg]	6.53	6.86	6.64	7.10
	Flows of carbon and nutrients out of the CHP plant				
8	*Gaseous emissions*				
	C in CO_2 [Mg]	33 300	33 300	33 300	33 300
	C in CO [Mg]	105	105	105	105
	C in VOC [Mg]	44.7	44.7	44.7	44.7
	N in N2 [Mg]	36.1	38.2	37.2	40.2
	N in NO [Mg]	28.0	28.2	28.1	28.4
	N in N_2O [Mg]	0.737	0.766	0.750	0.791
	N in HCN [Mg]	0.223	0.232	0.227	0.240
	S in SO_2 [Mg]	6.77	6.86	6.79	6.92
	P in P_2O_5 [Mg]	0.0402	0.0426	0.0447	0.0473
	K in K_2O [Mg]	0.546	0.542	0.511	0.511
9	*Ash*				
	C [Mg]	55.0	55.0	55.0	55.0
	N [Mg]	0	0	0	0
	S [Mg]	1.20	1.22	1.21	1.23
	P in P_2O_5 [Mg]	6.49	6.82	6.60	7.05
	K in K_2O [Mg]	88.1	86.7	75.5	76.1
10	*Energy produced by the CHP plant*				
	Electricity [TJ]	281	281	281	281
	Heat [TJ]	567	567	567	567

†Total energy wood includes the industrial energy wood, industrial residues and recycled HWPs

†† It is allocated by the mass ratio between total energy wood to total harvested biomass

Figure 1.6. *(a) Schematic diagram of the annual flows from the forest to the biomass CHP plant; (b) annual flows and area required to supply a CHP plant as a function of two forest management practices and two wood utilizations for the production of 10 MW electricity and 18 MW heat for one year [FRA 14]*

These mass and energy balances have since been used for a life-cycle assessment (LCA) of biomass gasification and combustion to produce heat and power.

1.2.2. *Model of a gasification plant*

Gasification of biomass could be a process of choice for producing heat and power with a higher efficiency of power production compared with combustion. Figure 1.7 presents the gasification CHP plant modeled under Aspen Plus and used in the model of the whole bioenergy chain [FRA 13a].

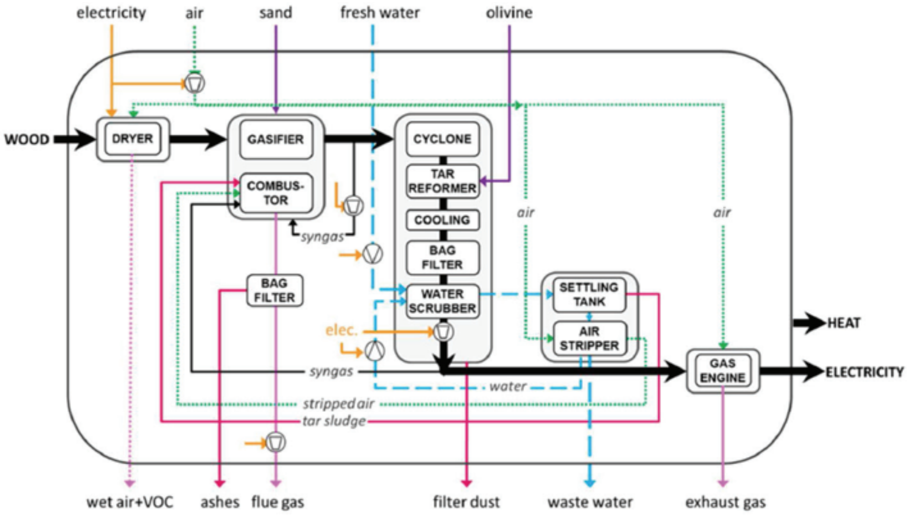


Figure 1.7. *Simplified diagram of the gasification process modeled under Aspen Plus. For a color version of the figure, see www.iste.co.uk/dufour/biomass.zip*

Schematically, the gasification 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 air as a drying agent. Dry wood is fed to the gasifier compartment of the DFB gasifier. A DFB gasifier consists of two interconnected fluidized bed reactors: one for gasification and one for char combustion. A sand bed is fluidized with a fraction of the 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. Char is injected with sand to the combustor compartment and oxidized with air. More details on the DFB model are given in section 2.3. Tar sludge (from the scrubbing agent regeneration step) and a fraction of clean syngas are additionally fueled into the combustor to maintain heat balance in the reactor. Flue gas and ashes exit the combustor zone whereas raw syngas exits the gasification zone.

Figure 1.8 shows the main compounds predicted by the model throughout the process.

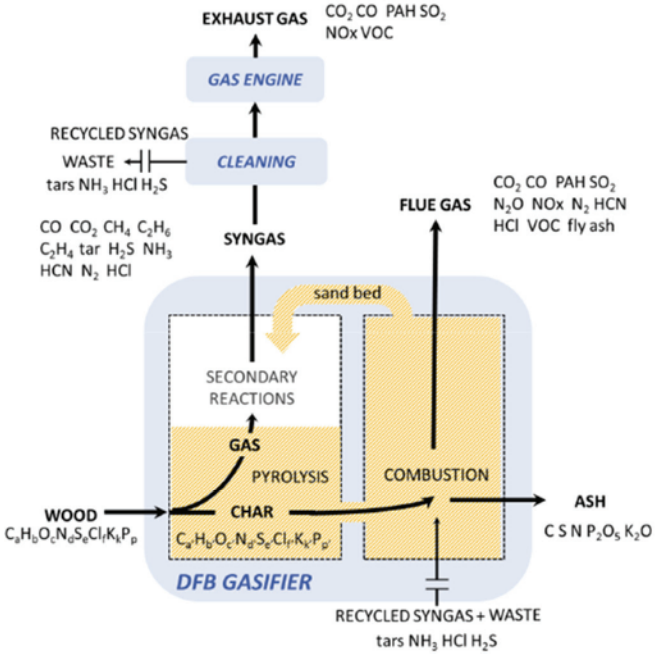


Figure 1.8. *Thermochemical conversion of the biomass and minerals throughout the gasification CHP process [FRA 14]*

Raw syngas contains various contaminants such as tar, NH_3, HCl and entrained particles, which are removed in a purification arrangement (Figure 1.8). The cyclone removes large particles; the tar catalytic reformer reduces the amount of tar and NH_3; the bag filter removes small particles and the water scrubber separates tar, 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, freshwater is also continuously fed to the scrubber, and wastewater exits 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.

An important feature of this Aspen Plus model is its suitability to model the evolution of trace/pollutant species due to a detailed description of the physical–chemical phenomena. For instance, N species contained in wood are converted to NH_3 and N moieties in the char in the gasifier. NH_3 in the syngas is further washed and oxidized to produce NOx (in the gas engine). N moieties in the char are oxidized in the combustor compartment of the gasifier and also generate NOx. Pollutant emissions from the engine and char combustor (NOx, SOx, PAHs, particles, Cl species, etc.) are predicted by the model based on the literature review. Tars (aromatic species) are also modeled. Such a detailed approach is realized by dedicated external Fortran files that are coupled to the Aspen Plus simulator.

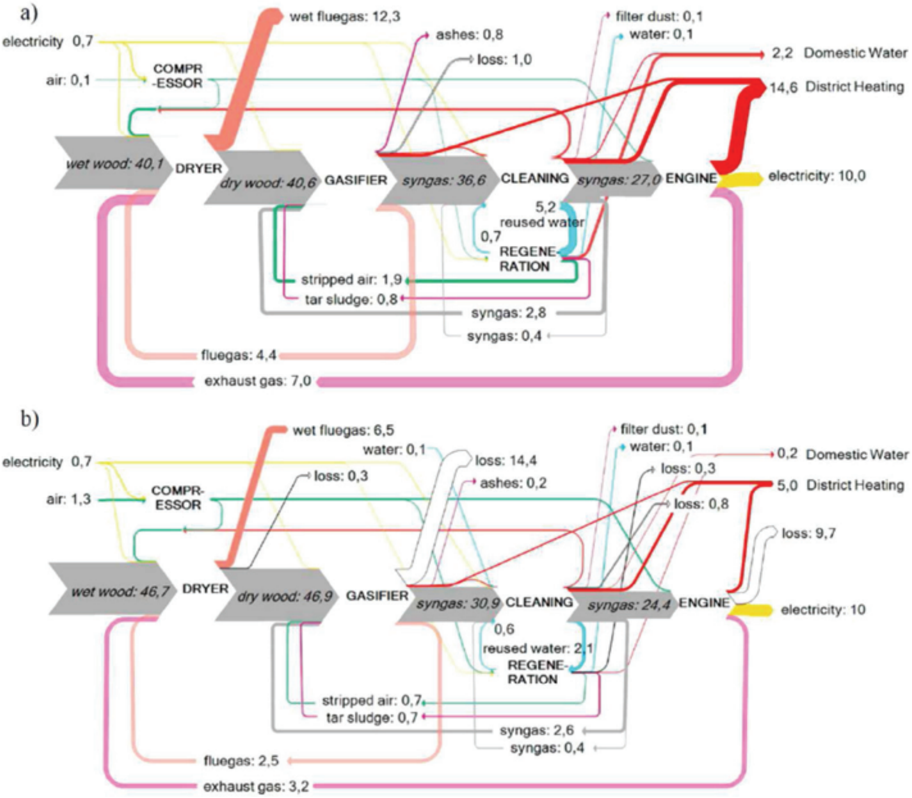


***Figure 1.9.** (a) Energy and (b) exergy balances of the CHP gasification plant (streams in megawatts) [FRA 13b]. For a color version of the figure, see www.iste.co.uk/dufour/biomass.zip*

This detailed modeling approach has enabled us to calculate the mass, energy and exergy balances of different process configurations. A pinch analysis has been used to optimize heat recovery throughout the process. The influence of wood moisture content, drying process, flow rate of the sand circulating in the DFB reactor, catalyst type (olivine or Ni-based) for tar reforming and scrubbing agent efficiencies, as well as additional electricity production through steam turbine, on the overall process performances was reported [FRA 13b]. Figure 1.9 presents an example of Sankey diagrams derived from the model for a nominal process configuration.

The main exergy degradations occur in the gasification reactor and the engine (Figure 1.9(b)) where high-temperature reactions lead to important irreversibilities. The highest energetic efficiencies are obtained when no forced drying is implemented in the CHP system. Lowering the inlet wood moisture content with natural drying (energetically free) prior to the CHP plant improves the electrical efficiency. An overall energetic efficiency of 74% (23% electric and 51% thermal) is then reached with wood fed at 30% moisture content. The best exergetic efficiency is reached when wood (naturally dried to 30%) is additionally dried to 15% by forced drying in the CHP plant and when a part of the high-temperature heat is recovered for electricity production through steam turbine instead of being used for district heating. In this case, the overall energetic efficiency is 63% (32% electric and 31% thermal).

1.2.3. *Models of biorefinery sections*

To the best of our knowledge, there is still a lack of the literature on detailed modeling of the whole thermochemical biorefinery as it is presented for the biomass gasification chain. In the following sections, we present some examples of detailed modeling of biorefinery sections.

1.2.3.1. *Model of a partly integrated biorefinery: from biomass fractionation to lignin depolymerization*

The scope of this work is the production of aromatics from lignin liquefaction. The fractionation of biomass into carbohydrates and lignin has been experimentally studied by various methods [ERD 14] and then modeled into Aspen Plus. The quality and yield in lignins were compared. Then these lignins were converted into phenols by base-catalyzed depolymerization (NaOH in water under pressure). The work of CNRS-Nancy consists of the modeling and integration of all the streams (solids, liquids, solvents) and of closing the elemental balances (C, H, O) throughout the process (Figure 1.10). The main issue of all this work on modeling complex reactive systems is the closing of mass balance under Aspen Plus with "lumped pseudo-species" because an important part of compounds, notably heavy species, are not experimentally quantified.

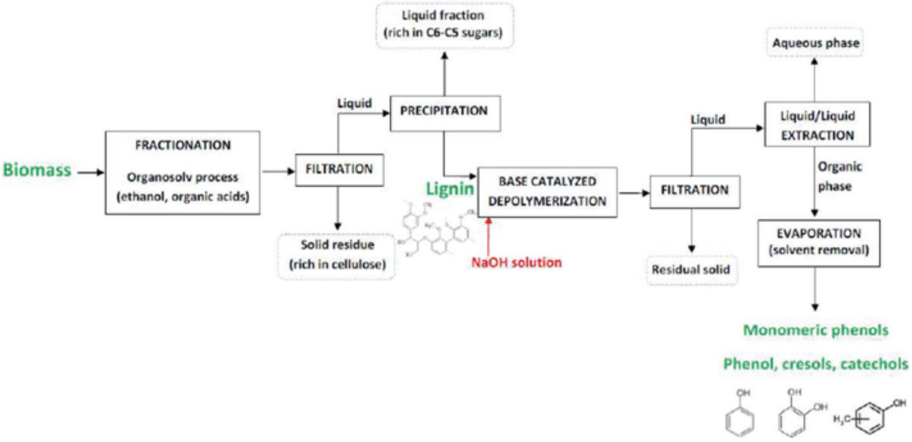


Figure 1.10. *Simplified scheme (without exchangers, pumps and solvents recycling) of the partly integrated process from biomass fractionation to lignin depolymerization*

1.2.3.2. *Model of aromatics production from lignin*

In one scenario of a future lignocellulosic biorefinery, cellulose and hemicelluloses would be depolymerized to be converted into ethanol and chemicals, thus generating considerable amount of lignin (~25 wt.% lignocellulosic biomass) [HOL 07, HAV 08].

Lignin is a very heterogeneous resource. Its composition and properties vary with biomass type, growing conditions and polymer fractionation process [HOL 07, ZAK 10]. However, lignin is always composed of aromatic monomers with different fractions in guaiacyl, syringyl or coumaryl groups [ZAK 10]. It is used to produce heat and power in the pulp and paper industry, but new valorization routes are needed to improve the revenue of lignocellulosic biorefinery [HUB 06, HOL 07]. It could be used to coproduce heat and power, a syngas, activated carbon [ROD 93], carbon fibers [KAD 02], aromatic hydrocarbons (benzene, toluene and xylenes (BTX)) [SHA 03, MA 12], fine chemicals (such as vanillin) [DEW 11, RØD 12], phenol [GOH 66], phenolic resins [EFF 08], etc.

Among these potential lignin uses, our research work has focused on the development of processes for the conversion of lignin into aromatic hydrocarbons

(Figure 1.11). The importance of this route for increasing revenues of biorefineries has been outlined in literature [SHA 03, HOL 07, HAV 08, ZAK 10].

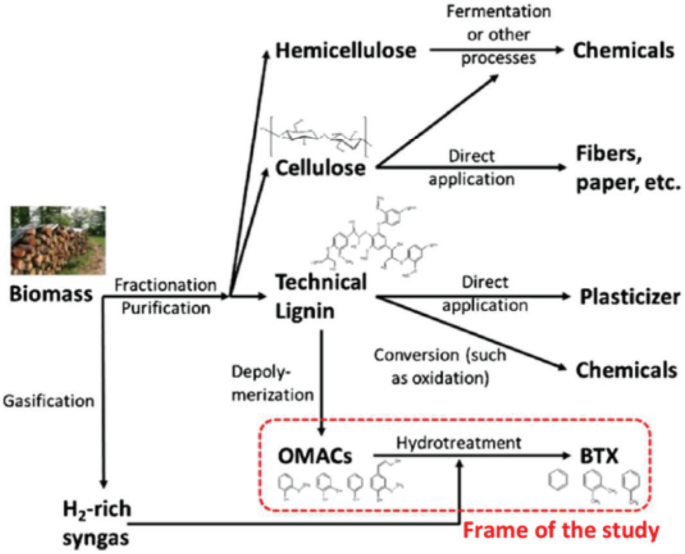


Figure 1.11. *A concept of biorefinery showing the frame of this study [OLC 12]: the production of aromatic compounds from lignin thermochemical conversion. "OMACs" means oxygenated monoaromatic compounds; "BTX" means benzene, toluene and xylenes*

Biosourced aromatics (BTX or phenols) could be produced by lignin pyrolysis coupled with catalytic hydrodeoxygenation (HDO) of uncondensed pyrolysis vapors. The vapor-phase hydrotreatment of pyrolysis vapors over cheap catalysts (iron-based catalysts) was the chosen strategy in this work instead of the liquid-phase hydrotreatment of bio-oils. Indeed, this process could reduce the problem of handling the reactive lignin oils and promote heat recovery. Moreover, the hydrogen partial pressure could be low (0.2 bar, typical of a syngas) and separating pyrolysis and catalytic reactors offer a more versatile process (different temperatures, regeneration cycles, etc.) than the direct catalytic pyrolysis. A second hydrotreatment refining step could be used on condensed bio-oils after the first HDO of vapors.

Guaiacol was used as a model compound to study the catalytic HDO over an Fe/SiO_2 catalyst. Experimental results were used to predict major and minor products by a semidetailed kinetic mechanism. The kinetic model is then included in an Aspen Plus model of lignin to BTX process (Figure 1.12).

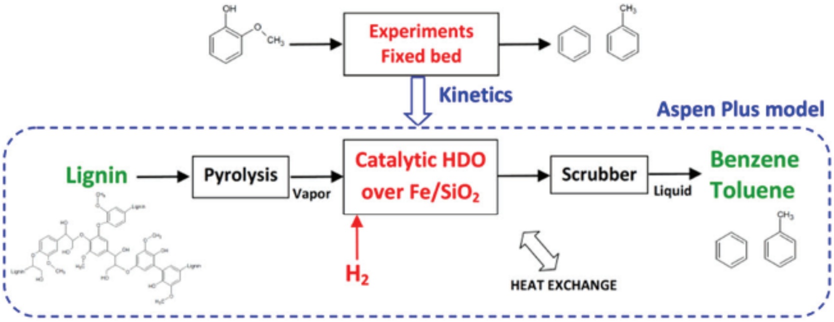


Figure 1.12. *Scope and methodology: experiments on a model compound (guaiacol) are used to model the whole lignin to BTX process under Aspen Plus [OLC 13]*

The Aspen Plus model handles (Figure 1.13): (1) pyrolysis of lignin, including char, oligomers, gases and aromatic yields; (2) catalytic conversion of aromatics by the kinetic model; (3) heat exchangers and (4) BTX vapor recovery by scrubbing with 1-methylnaphthalene. The elemental balances (C, H and O) of lignin pyrolysis were determined based on literature [DEW 09].

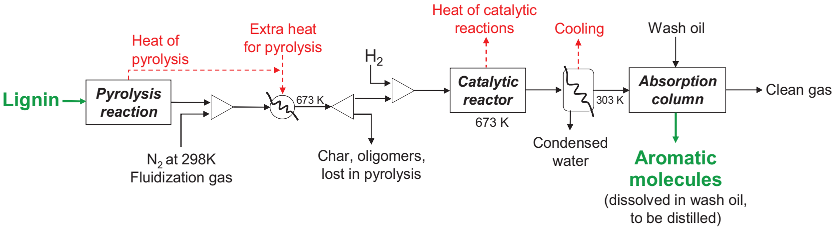


Figure 1.13. *Diagram of the lignin to BTX process by HDO of pyrolysis vapors and its simplification for modeling under Aspen Plus [OLC 13c]*

Figure 1.14 displays the mass flows obtained from Aspen Plus model (besides N_2 and 1-methylnaphthalene). It can be pointed out that the amount of catalytic coke is relatively low compared with that of char, oligomers and pyrolysis loss. Char, oligomers and pyrolysis loss lead to the major loss in mass and carbon.

The “gases” output in Figure 1.14 represents both non-condensable gases (CO_2, CH_4, H_2 and CO) and low amounts of condensable molecules (H_2O, benzene, etc.) that are entrained in the N_2 flow. Condensable products are mainly water (43.9 kg/h), benzene (17.8 kg/h), toluene (4.3 kg/h) and other compounds not converted by the catalytic reactor (650 kg), because the mass of catalyst was set only to match with a 0.1-kg/h phenol flow rate. If phenol becomes the desired product from lignin-derived pyrolytic vapors HDO over Fe/SiO_2, the mass of catalyst would be reduced from 650 kg (for 500 kg/h dry lignin and to reach 0.1 kg/h phenol if BTX are the desired products) to 52 kg to reach the maximum phenol yield.

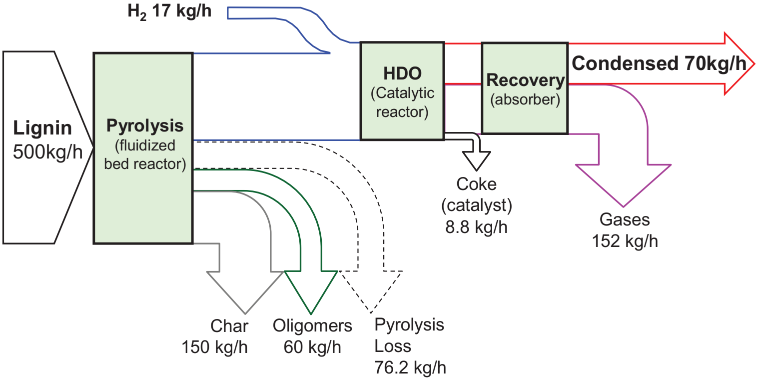


Figure 1.14. *Mass flows from Aspen Plus simulation of the lignin to BTX process. N2 (7,200 kg/h) and 1-methylnaphthalene (14.4 m3/h) (wash oil for recovery) are not represented. Condensed species (70 kg/h) are composed of 43.9 kg/h water, 17.8 kg/h benzene and 4.3 kg/h toluene (rest: methanol, cresols, etc.)*

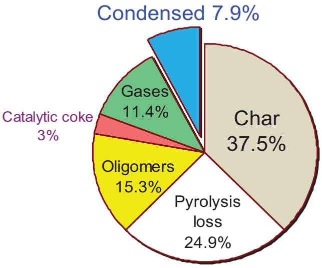


Figure 1.15. *Lignin-based carbon yield of lignin to BTX process by pyrolysis and gas-phase hydrotreatment at standard conditions (650 kg catalyst for 500 kg/h lignin, 7,200 kg/h N_2 carrier gas for a pyrolysis reactor). Condensed benzene and toluene account for 7.5% carbon*

Figure 1.15 shows the distribution of carbon yields in the different streams based on carbon in lignin. The char, oligomers and pyrolysis loss (carbon balance not closed during experiments) account for 77.7% carbon atoms from lignin, whereas the yield of benzene and toluene (BT) is only 7.5% carbon (4.4%wt. dry lignin). The species condensed by the scrubber, which are not aromatics (acetone, acetic acid), represent only 0.4% carbon. This yield in BT is still low and should be increased by process developments. The activity of the catalyst for the HDO of light aromatic compounds (lumped by guaiacol in the model) should even be lower in a real pyrolysis gas than that in the predicted gas (based on a model gas conversion) due to higher carbonaceous deposit. Consequently, the yield of desired products obtained from lignin experiments would most probably be lower than the predicted yield.

The carbon loss by the catalytic conversion or scrubber is very low compared with that from the pyrolysis reaction. A more efficient pyrolysis technology is needed to obtain higher yields in volatile oxygenated aromatic compounds that can be further converted into chemicals. The pyrolysis loss represents a substantial amount of missing carbon, three times (24.9% on lignin carbon yield) as much as the desired product (7.5%). An important loss in carbon, not converted into desired products, can also be attributed to oligomers (15.3%). However, solid carbons from pyrolysis can be valorized for heat production in the biorefinery or for higher added-value products.

The effect of gas dilution from a pyrolysis reactor on BTX losses, heat demand and scrubbing solvent flow rate has also been highlighted in this study. We have shown in this study [OLC 13c] that high carrier gas flow rates (as required for biomass pyrolysis in fluidized bed) lead to the entrainment of fines and oligomers, dilute the products and impact considerably the process.

1.3. Technical–economical analysis of bioenergy chains

The development of detailed model of bioenergy chains (e.g. from Aspen Plus simulations) is required to calculate the mass and energy balances of the processes and then to further assess the technical–economical feasibility. The technical–economical analysis of biofuel production from thermochemical conversion of biomass has been comprehensively reviewed [BRO 15] and is not presented in this book.

1.3.1. *Technical–economical analysis of power production*

The cost of electricity production from biomass decreases considerably with the scale of the unit (Table 1.1).

A very detailed study has been performed by Bridgwater *et al.* [BRI 12] on the comparison of the cost of electricity production from four technologies: pyrolysis followed by combustion of bio-oils in engine, gasification followed by gas engine or combined cycle (IGCC) and combustion associated with a steam cycle.

Capacity	< 10 MW	10–50 MW	>50 MW	Co-firing*
Typical power generation efficiency (%)	14–18	18–33	28–40	35–39
Capital costs (USD/kW)	6,000–9,800	3,900–5,800	2,400–4,200	300–700
Operating costs (% of capital costs)	5.5–6.5	5–6	3–5	2.5–3.5

* Co-firing costs related only to the investment in additional systems needed for handling the biomass fuels, with no contribution to the costs of the coal-fired plant itself. Effeciences refer to a plant without CCS.

Source: IEA analysis baed on DECC (2011), IPCC (2011), Mott MacDonald (2011), Uslu *et al.* (2012).

Table 1.1. *Overview of bioenergy power plant conversion efficiencies and cost components [IEA 12]*

The cost of electricity is between 0.2 and 0.25 €/kWhe at 1 MWe (electricity) and decreases to 0.1 €/kWhe at 20 MWe (Figure 1.16). The fast pyrolysis and diesel engine system is handicapped by the typical characteristics of all novel technologies: high capital costs, high labor and low reliability. The more established technology (combustion and steam cycle) produces lower cost electricity under current conditions. The fast pyrolysis and diesel engine system have relatively low system efficiency at high capacities because of a low conversion efficiency of biomass into pyrolysis liquids and char by-product.

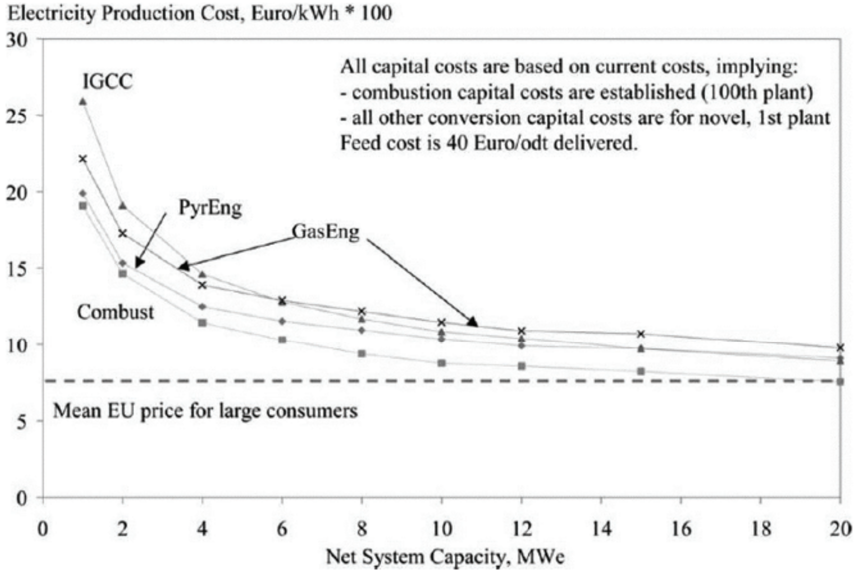


Figure 1.16. *Comparison of electricity production costs for four biomass-to-electricity systems [BRI 02]*

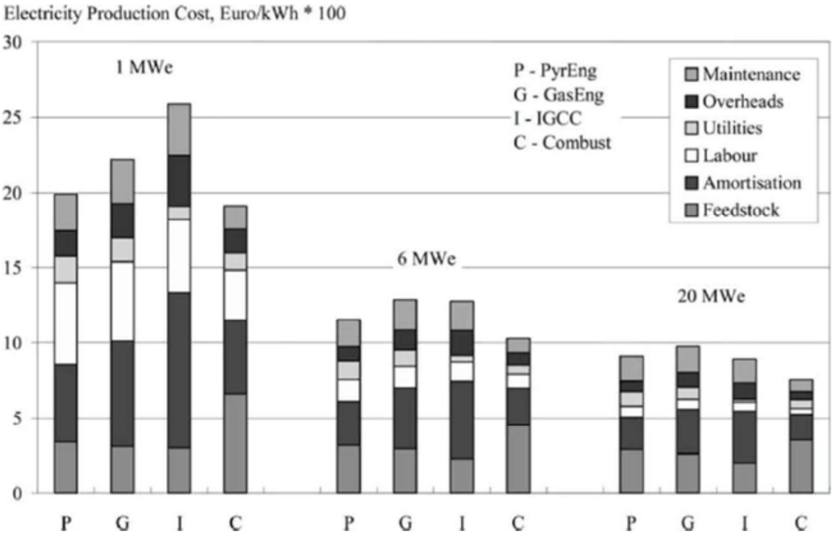


Figure 1.17. *Breakdowns of electricity production costs by cost sector for four biomass-to-electricity systems [BRI 02]*

The distribution of electricity cost by sectors is presented in Figure 1.17. The main costs are related to feedstock and amortization for all technologies. The capital costs decrease very significantly for all technologies with the scale of the units (Figure 1.18).

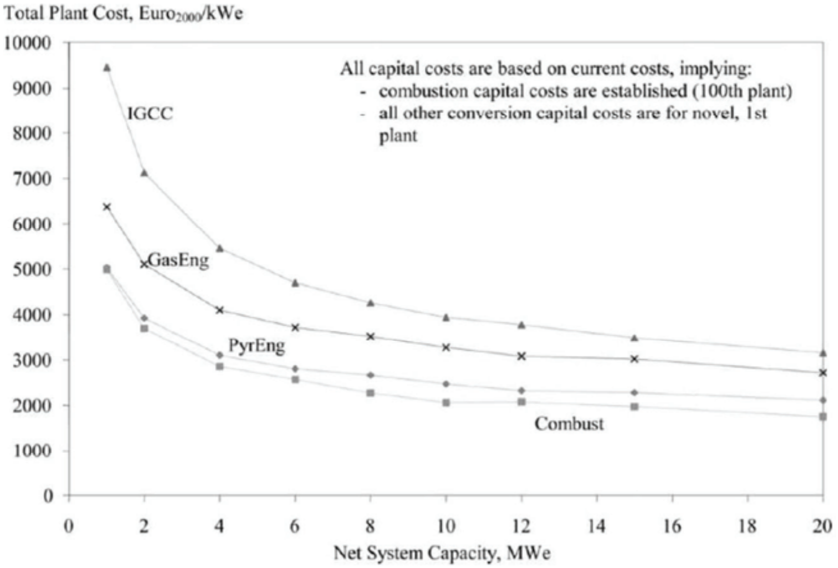


Figure 1.18. *Effect of system capacity on the total plant cost [BRI 02]*

1.3.2. *Technical–economical analysis of heat production*

Our group has undertaken a study [PEL 15] on the technical–economical analysis of heat production from biomass combustion (Figure 1.19) in collaboration with EIFER (Karlsruhe, Germany) and CIRED (Nogent, France) laboratories.

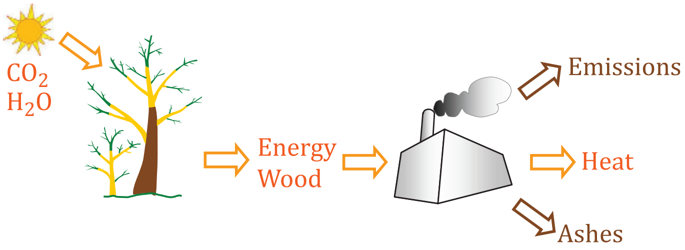


Figure 1.19. *System boundary of the study (from forest to wood pretreatment, combustion and emissions, and final heat). This whole bioenergy route is modeled under Aspen Plus software for a detailed calculation of mass and energy balances. For a color version of the figure, see www.iste.co.uk/dufour/biomass.zip*

Figure 1.20. *Different options for wood combustion and heat production studied in a technical–economical analysis*

The scope of this study is to assess the technical–economical feasibility for the heating of a 100 m^2 house in Lorraine (France), with heating needs of 6,500 kWh/year and a hot water production for a family of four people of 2,500 kWh/year. Various technologies and process options are studied (Figure 1.20). These bioenergy routes are compared with conventional electric heating (with the French electricity mix) or gas boiler.

Our approach consists of a detailed modeling of the whole bioenergy chain from forest to combustion devices under Aspen Plus (as presented previously for gasification). The Aspen Plus model gives the complete mass and energy balances of the bioenergy routes (from forest growth to final heat). These balances are then used for the technical–economical and environmental assessments.

Table 1.2 gives the main data used for the technical–economical analysis and for the various technologies. Table 1.3 displays the costs and emissions of fuels.

	Heating/ hot water coverage (%)	**Thermal yield**	**Electrical needs of equipment (kWh/year)**	**Total investment cost (equipment + labor) (€)**	**Available tax cuts (€)**	**Maintenance cost (€/year)**
Log stove	50/0	Calculated by model	-	1,500 + 300	450	200
Log boiler	100/100	Calculated by model	400	6,500 + 1,500	1,950	250
Pellet stove	70/100	Calculated by model	200	2,800 + 500	750	200
Pellet boiler	100/100	Calculated by model	600	13,500 + 1,500	4,050	250
Condensing gas boiler	100/100	105%	30	5,000	-	250
Electric heating	100/100	100%	-	1,000 + 200	-	-
Wood district heating	100/100	Calculated by model, with heat losses in network	16	4,000	-	80
Gas district heating	100/100	85% including heat losses	200	2,000	-	50

Table 1.2. *Technical–economical parameters for combustion equipment [PEL 15]*

Fuel	**Price for an individual user**	**Price for a large facility (district heating scenarios)**	**Impact of production and transport of solid fuels**[a] **(kg CO_2eq/ton)**	**Global impact of use**
Wood logs (50 cm)	170 €/ton	N/A	20	Dependent on technology and combustion conditions, from the modeling under Aspen Plus
Wood pellets	280 €/ton	N/A	155	
Wood chips	N/A	80 €/ ton[b]	61[b]	
Natural gas	6.6 c€/kWh_{LHV}	5.1 c€/kWh_{LHV}	-	0.234 kg CO_2eq/kWh_{LHV}
Electricity (French mix)	15.1 c€/kWh	13.8 c€/kWh	-	0.18 kg CO_2eq/kWh_{LHV}

[a] For fossil fuels and electricity, the impact of production and transport is included in the global value.
[b] For a transport range of 150 km.

Table 1.3. *Prices and impact of production of wood fuels*

1.4. Life-cycle and multicriteria assessment of bioenergy chains

1.4.1. *Methodology of life-cycle assessment applied to bioenergy routes*

The LCA methodology is used to assess the processes or products from an environmental point of view.

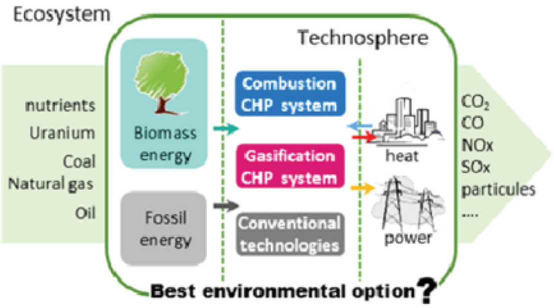


Figure 1.21. *From the ecosystem to the technosphere. The technosphere (processes, products, etc.) impacts the ecosystem*

Figure 1.21 describes the general methodology of LCA applied to the production of heat and power. The goal of LCA is to define what the “best process” is from an environmental point of view.

The first step in the LCA methodology is the definition of the function and functional units.

For instance, a function of the process can be to produce electricity and heat for a district heating or to produce a biofuel or to produce only heat in a house.

Then the functional units should be defined. It could be, for instance, the production of 1 kWh heat in a house or the production of 1 kWh heat for district heating and 0.4 kWh electricity. It could also be the valorization of 1 kg wood to compare different processes giving different products. The functional unit could also be 1 hectare of land to compare various uses of the land or even one defined territory.

Then the system boundaries should be defined. For instance, the life cycles of the biomass plants can be from cradle to grave: from forest growth to energy production. It could be only from dry wood input of the plant (without the transport) to the final product (heat or biofuels or chemicals).

Then all the input and output of the system has to be quantified. The detailed modeling under Aspen Plus, as previously presented in this chapter, is an interesting tool to give the complete and detailed life-cycle inventory (or mass and energy balances) on the whole bioenergy chain.

1.4.2. *Life-cycle assessment of heat production from biomass*

As in the previous study, the life cycle assessment of wood combustion for heat production for a house has been made [PEL 15]. The system boundaries were defined as: the forest growth, harvest, the transformation of wood into chips, logs and pellets, the transportation from the forest to the final user, and finally the combustion of wood in the different equipment. The manufacturing and transportation of the equipment itself were not included in the environmental analysis due to a lack of available data.

The main data for wood combustion technologies emissions are presented in Table 1.4. They are based on industrial experiments on wood combustion units [ROG 15].

Equipment	**Log stove**	**Pellet stove**	**Log boiler**	**Pellet boiler**	**Wood district heating**
Fumes exit temperature (°C)	330	125	150	160	110
Pollutant concentrations corrected for O_2 %vol. in smoke	13% O_2		10% O_2		11% O_2
Carbon monoxide (CO), mmol/Nm	361.61	22.32	133.93	3.18	8.625
Nitrogen oxides (NO_x), mmol/Nm	1.64	3.11	4.19	4.39	3.3
Particles, mg/Nm	42.04	48.16	7.66	99.44	10.0
Total volatile organic compounds (VOC), mmol/Nm	48.13	1.72	6.06	2.25×10^{-2}	9.07×10^{-2}
Methane (CH_4), Mmol/Nm	5.81	2.12×10^{-1}	1.81	8.13×10^{-3}	2.94×10^{-2}
Polycyclic aromatic hydrocarbons (PAHs), mmol/Nm	7.32×10^{-2}	3.65×10^{-3}	7.35×10^{-3}	3.47×10^{-5}	3.75×10^{-2}

Table 1.4. *Main emissions for wood combustion technologies used as input data for LCA [PEL 15]*

In an LCA framework, each input and output to the system is multiplied by an impact factor to obtain the total potential impact of the studied scenario. Although there is a general consensus about the impact of major pollutants such as CO_2, the impact factor for minor pollutants may vary according to the dataset. Here we only present one impact, the global warming potential (GWP). It was calculated for each scenario using three different methods of LCA (Table 1.5): ReCiPe Midpoint (Hierarchist) [PRÉ 15], EDIP2003 [POT 06] and CML2001 [DEB 02]. For electricity, the average French mix was used due to the high proportion of nuclear power in the French grid; the GWP impact of French electricity is somewhat lower than that of nearby Germany for example. The used impact factors are shown in Table 1.5. In order to compare the different scenarios, the functional unit is kWh of heat delivered to the user, that is either 1 kWh hot water for the heating district case or 1 kWh heat transferred from the stove to the room.

Flow	ReCiPe Midpoint (H)	EDIP2003	CML2001
CO_2	1 kg CO_2eq./kg	1 kg CO_2eq./kg	1 kg CO_2eq./kg
CH_4	25 kg CO_2eq./kg	23 kg CO_2eq./kg	25 kg CO_2eq./kg
CO		2 kg CO_2eq./kg	
N_2O	298 kg CO_2eq./kg	296 kg CO_2eq./kg	298 kg CO_2eq./kg
$C_{16}H_{10}$ (PAH surrogate)			16.1 kg CO_2eq./kg
Production and combustion of natural gas	0.198 kg CO_2eq./kWh	0.198 kg CO_2eq./kWh	0.198 kg CO_2eq./kWh
Electricity (French mix)	0.180 kg CO_2eq./kWh	0.180 kg CO_2eq./kWh	0.180 kg CO_2eq./kWh

Table 1.5. *Impact factors for different LCIA methods*

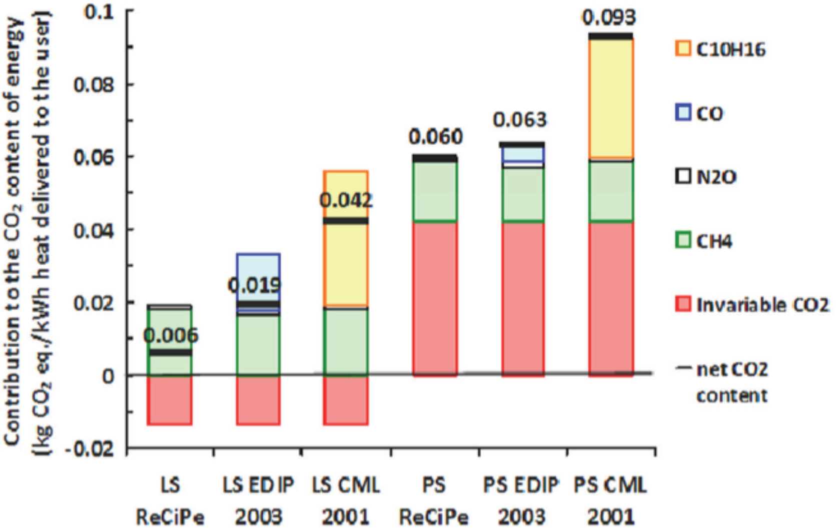


Figure 1.22. *Impact of minor pollutants on the GWP result, according to the three LCA methods (Table 1.5), for log (LS) and pellet stoves (PS) [PEL 15]. Each of the columns presents the different contributions to global warming expressed. The figure on top of the column is the total global warming estimated. For a color version of the figure, see www.iste.co.uk/dufour/biomass.zip*

The three methods do not account for the same impact (in terms of kg CO_2eq., see Table 1.5) for the various compounds emitted during wood combustion and this discrepancy can increase or decrease the calculated GWP impact by a factor 7 as highlighted in Figure 1.22.

Figure 1.22 highlights the huge uncertainty of the quantification of environmental impacts. The main issue to reduce this uncertainty is to specify the emissions of pollutants (by analysis of industrial units and Aspen Plus modeling) and to better quantify the impact factors for each pollutant species.

Figure 1.23 presents the cost of heat for the final user as a function of GWP impact of the different heating systems. It shows that all wood combustion systems result in a lower GWP impact than gas or electricity. Wood combustion associated with a district heating would be the cheapest option and pellet boiler the most expensive option.

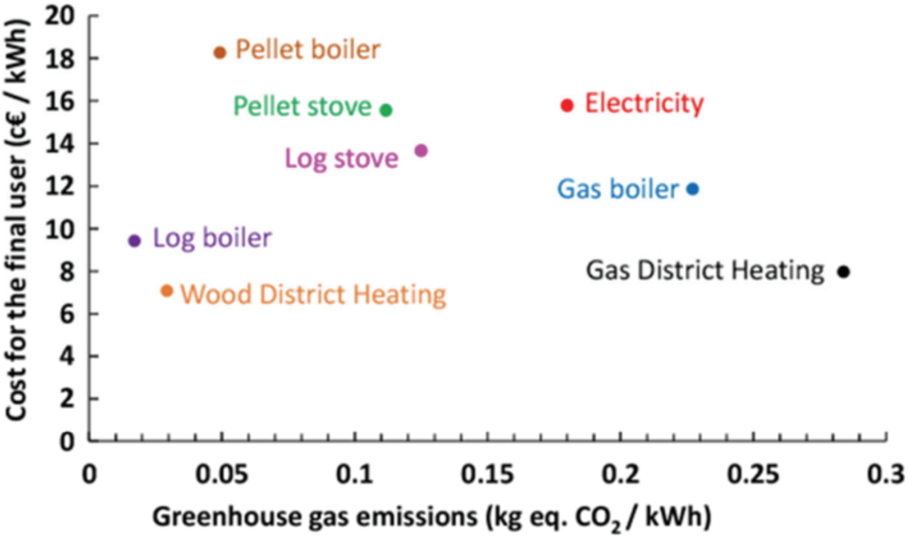


Figure 1.23. *Cost of heating technologies as a function of their greenhouse gas emissions [PEL 15]*

1.4.3. *Various aspects of the bioenergy chain*

Beyond the aspects of “physical” flows (mass and energy balances and LCA), various other aspects have to be considered in the bioenergy chain such as its impact on the society (employment, quality of life, health, etc.) (Figure 1.24).

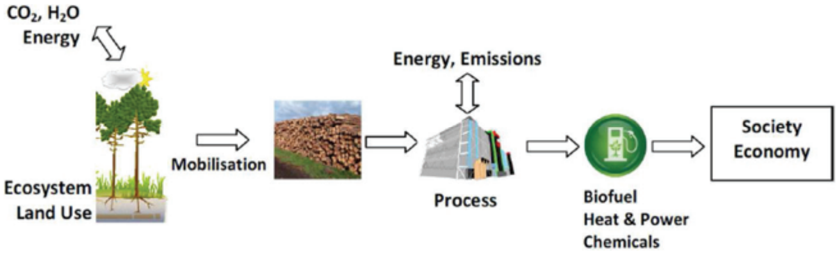


Figure 1.24. *Various aspects of the bioenergy chains: from the ecosystem to the society and global world economy*

Bioenergy can promote rural employment compared to fossil resources (Table 1.6).

Chain	Job created for 1,000 toe supplied
Forest biomass energy	4.2–6.3
Wood waste	2.3–3.7
Oil	1.4
Gas	1.2

Table 1.6. *Forest biomass energy creates more local employments than fossil resource*

For instance, the production of cleaner wood cookstoves for developing countries may promote the employment of women (in the cookstove and fuel value chain), saves time for the consumers (lower needs in energy wood), favor education, etc. It will also impact child development and survival due to a better indoor air quality [ANE 13].

1.4.4. *An example of a multicriteria discussion on a bioenergy route: the sequestration of biochar to mitigate climate change*

It has been shown that limiting anthropogenic climate change requires developing new routes for energy supply with net negative emissions, such as bioenergy with carbon capture and storage (BECCS) [VAN 13]. To achieve this goal, a large amount of work has dealt with the land application of biochar [LEH 06] or the sequestration of CO_2 from biomass combustion [Van 13]. In our opinion, the concept of wood geostorage [KRE 09, ZHE 08] has not yet received enough attention. We have proposed to extend this concept to the geological sequestration of biochar (GSB), displayed in Figure 1.25 [DUF 13a].

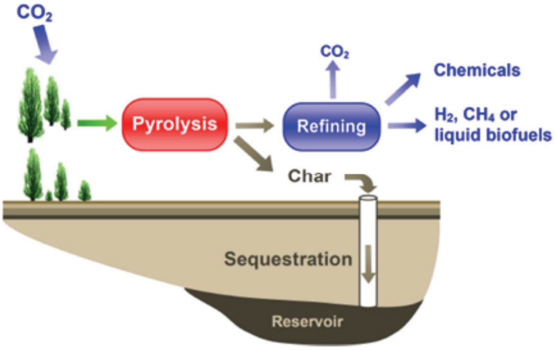


Figure 1.25. *Diagram of the concept of GSB. Biochar, a partly decarbonized energy vector (H_2, CH_4 or liquid biofuels), and added-value chemicals (e.g. aromatics) could be produced by a pyrolysis process. Biochar would be stored in geological cavities such as former coal mines*

1.4.4.1. *About biosphere management and the potential of carbon sequestration by biomass*

The potential of biomass for energy and carbon sequestration depends on critical uncertainties with respect to land and biomass availability, technology development and economical or societal aspects. Long-term primary forests have to be absolutely preserved for biodiversity, cultural heritage and landscape preservation. Other land could be used to manage the carbon pool of the biosphere, with fast-growing crops (such as *Miscanthus* and *Eucalyptus*) or small stems harvested to reduce stem density and to promote a sustainable management of forests (e.g. Douglas fir, pines). An advanced integrated model has shown that the total potential for negative emissions would be in the order of 10 GtCO$_2$/year for BECCS (with biogenic CO_2 sequestration) [VAN 13]. Kreysa [KRE 09] showed by assuming a reforestation scenario that the atmospheric CO_2 concentration could be lower than 400 ppm in the year 2100 (with a temporary maximum of 444 ppm around 2060) due to wood geostorage instead of 550ppm in 2100. Lehmann *et al.* [LEH 06] estimated a potential of 5.5–9.5 GtC/year for biochar sequestration by land application. These results differ depending on the model used and on the assumptions made, but they all highlight the big potential of carbon sequestration by biomass.

1.4.4.2. *GSB compared to wood geostorage and to land application of biochar*

GSB is a true carbon sink, the forest being the "pump and concentrator" of atmospheric CO_2 and the pyrolysis process the second "concentrator" of carbon into char. This concept is close to the geostorage of wood [ZHE 08, KRE 09] but different by two important features: (1) char is more stable and concentrated in carbon (mass of carbon per volume unit) than biomass and (2) a fraction of biomass is valorized as a (partly) decarbonized energy vector (such as CH_4, H_2 and methanol) and chemicals, leading to fossil fuel substitutions. These two features enhance the benefits argued for wood geostorage [ZHE 08, KRE 09]. Extensive work has dealt with the land application of biochar showing that it reduces greenhouse emissions to a greater extent than when biochar is used to offset fossil fuel emissions [LEH 06]. Biochar in soils also reduces fertilizer consumption and N_2O emission [LEH 06]. Nevertheless, the carbon in char is not stored in perpetuity when applied to land and it can affect the soil microbial activity. The land application is an interesting strategy though probably with a lower potential for long-term carbon sequestration than GSB. Furthermore, the char stored in geological reservoir such as former coal mines could be recovered whereas it seems hardly feasible after land application. In my opinion, these two sequestration methods could be combined and complementary.

1.4.4.3. *Potential societal and economic benefits of GSB*

The harvested biomass would be converted to wood chips and then transported to a medium-scale (<50 MW) pyrolysis unit. This medium scale should promote the local use of biomass, reduce transport costs and generate employment in rural areas or remote sites. The coproduction of syngas and added-value chemicals (e.g. BT) would offset a part of the lost revenue from the char not valorized. A small fraction of char could also be used for producing activated carbons to increase revenue. Syngas could be further converted to energy vectors or chemicals, for example H_2, CH_4 or a liquid biofuel. The capital cost and revenue will highly depend on site-specific parameters: the cost of biomass, electricity and fossil fuel, market need and price of chemical commodities, etc. The production of biobased chemicals, with a negative carbon footprint, would be a strong asset of the proposed process. The sequestered char would not be lost, but stored in "bio-mines." This carbon source remains available for future generations in case of energetic crisis or when new technologies will be available to mitigate the climate change. The societal acceptance is an important constraint for carbon sequestration. There may be a better perception by local communities for biochar sequestration, which is a recoverable stable solid, than for CO_2 sequestration from fossil fuel valorization.

1.4.4.4. *Technical and scientific perspectives*

The proposed concept would address some technical and scientific issues that have to be balanced with the relative complexity of the recovery, separation and sequestration of CO_2 from fossil fuel combustion! Batch or continuous processes are under operation for char production, for instance for the steel manufacturing industry. The selectivity in terms of gas, char and aromatic chemicals can be adjusted as a function of pressure, temperature and residence times in the reactors. Considering a pyrolysis at 700°C final temperature, the carbon in wood will be transferred for about 35% into char, 55% into permanent gas and 10% into aromatic compounds [DUF 09a]. Wood chips could be pyrolyzed under high-pressure conditions to reduce the conversion time, to promote exothermic reactions and thus to increase the energy balance and the char mass yield. The cracking of hydrocarbons over char could be used to fill the pores of biochar with a pyrolytic carbon and to promote H_2 production. Experiments with low-cost catalysts are needed to optimize the selectivity in added-value aromatics. Char could then be stored (as pellets, powder, etc.) in former coal mines or in other geological cavities. Long-term stability and geostorage studies have to be conducted, but a biochar would exhibit long-term stability in geological reservoirs.