KTH Industrial Engineering and Management

Comparative study of technological pathways for the energy conversions of cellulosic biomass

Matthieu Frappé

Master of Science Thesis in Energy Technology EGI-2011-021MSC EKV834
KTH School of Industrial Engineering and Management
Department of Energy Technology
STOCKHOLM, SWEDEN

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Approved 15/03/2011	Examiner Torsten Strand	Supervisor Miroslav Petrov
	Commissioner	Contact person

Abstract

A selection of technological pathways of energy conversion from cellulosic biomass was compared. The covered technologies were: combined heat and power (CHP) from combustion, CHP from gasification, production of Bio Synthetic Natural Gas (BioSNG), Di-Methyl Ether (DME), ethanol through hydrolysis and fermentation, and diesel through Fischer-Tropsch synthesis. Each pathway was modelled both technically and economically, sized by either the power or heat output, or biomass input. The comparison was performed with a tool in Microsoft Excel, running performance simulations in the context of specific scenarios. The performance parameters included the thermal and electrical efficiencies, and production costs per unit of energy (heat, biofuel and power where relevant).

A first case study compared two setups of combustion-based CHP. It was shown that for a given heat demand, the option maximizing the electrical efficiency features lower electricity costs despite being more capital intensive. Conversely in the case of given power demand, the option maximizing the total efficiency is more cost effective.

A second case study compared combustion and gasification as regards their ability to meet a heat demand in CHP mode. Results showed that gasification is more cost effective than combustion for small scale heat demand, typically below 20 MW_{th}. This is explained by a comparatively higher electrical efficiency and lower specific investment costs for small gasification units compared to combustion.

A third case study compared the attractiveness of centralized and decentralized biofuels production. This study showed that the scale effect of centralization prevails over the advantages of heat sale and shorter biomass logistic enabled by the decentralized approach, despite higher financial risks with capital intensive pilot plants.

A fourth case study considered the cost of avoided CO_2 for biofuels as a function of the crude oil price. This analysis determined the oil price at which each biofuel becomes cost effective without subsidies on CO_2 avoidance. DME and BioSNG feature the lowest cost of avoided CO_2.

Table of contents

Glossary

BioSNG	Synthetic natural gas from biomass
CER	Certified Emission Reduction of CO_2 equivalent
CHP	Combined heat and Power generation
DH	District heating
DME	Dimethylether
EDF	Electricité de France
EUA	European Union Allowance of CO_2 equivalent emission
FT-Diesel	Diesel from Fischer-Tropsch process
IRR	Internal rate of return
LCA	Life Cycle Analysis
PH	Process heat
Syngas	Synthetic gas produced by gasification

Table of figures

1. Introduction

EDF Group has set as one of its three strategic goals to develop renewable energies. It wants not only to be part of this development but also to take a leading role in this field. EDF R&D is in charge of such research work and devotes one of its R&D teams to the topic of biomass pathways.

EDF R&D efforts focus on lignocellulosic biomass (wood and straw for instance), which presents the advantage of not competing with agriculture. This biomass can be used either for combined heat and power generation (CHP), synthetic natural gas or liquid biofuels production.

In the frame of the current end of studies project, an Excel tool allowing comparing technological pathways of cellulosic biomass utilization into energy was developed. The explored pathways are:

- CHP from combustion.
- CHP from gasification.
- BioSNG (Synthetic Natural Gas) production from gasification + catalytic synthesis.
- Fischer-Tropsch diesel production from gasification + catalytic synthesis.
- DME (DiMethyl Ether) production from gasification + catalytic synthesis.
- Cellulosic ethanol production from cellulose hydrolysis and fermentation.

The tool takes into account the technical, environmental and economic parameters describing each pathway.

2. Frame of work: the company

Electricité De France (EDF) was founded in 1946 and is now renowned as Energy Company. However the diversity of its activities and its development in foreign countries is often underestimated.

EDF owns many subsidiaries abroad, mostly in Europe. Among the most important is EnBW, which is the third biggest energy company in Germany, Edison the second power company and third gas provider, and more recently EDF Energy in the UK.

2.1. Key figures for 2008

Below are the key indicators to take a glance to the size of EDF:

- 38.1 Million Customers worldwide.
- Ca. 161000 employees.

- €64.3 Billion turnover.
- €4.3 Billion net profit.
- 127.1 GWe installed power capacity.
- 4.1% of fossil energy.

[EDF, 2008]

2.2. Strategic line of the EDF group

EDF is providing electricity in France from 80% of nuclear, 15% of hydro, and gradually opening up to other renewable energy sources. This is pledged as efficient response to the issues of global warming and energy independence of France. The former CEO Pierre Gadonneix has stated three strategic goals for 2008-2012:

- Actively participate to the nuclear worldwide come back.
- Develop renewable energies and implement measures for energy efficiency.
- Strengthen its European position.

The goal related to nuclear power has been illustrated through two major recent facts: the takeover of British Energy which the sole nuclear operator in the UK and the purchase agreement on half of the asset on Constellation Energy in the US is currently being discussed. Owning British Energy also represent a stronger presence of EDF in Europe. This external growth also increases the foreign activity of EDF, which accounted for 47% of its turnover in 2008. Investments to develop the power production capacity are increasing and EDF is now the most important corporate investor in France, with over € 2 150 millions in 2008. The objective related to renewable energies are being fulfilled by the installation of several hundreds of MWe of wind power capacity. This was carried out by “EDF Energies nouvelles” which has set its goal of installed power generation capacity to 4000 MW (among which 500 MW of solar power) for 2012. Furthermore, the experimentations on undersea-hydro power in France, as well as the investments of EDF Energy, EnBW (Germany) and Edison (Italy) contribute to this commitment in favour of renewable energies.

To finish with, the offer of EDF as regards eco-efficiency has taken a sharp rise and has particularly diversified in France, with the support of its partners and specialized subsidiaries. The clients are offered comprehensive solutions to keep control of their consumption or manage their renewable energy production. [EDF report of sustainable development 2008]

2.3. Sustainable development at EDF

EDF has committed itself with a list of goals to tackle sustainable development issues:

- Remain the lowest CO_2 emitter among European power producers
- Develop renewable-based energy supply offers

- Improve the access to energy and eco-efficiency
- Contribute to policies developing awareness on energy issues
- Develop the cooperation with regional authorities

Concerning environmental impacts, EDF voluntarily decided to cut by 65% its SO_X, NO_X and dust emissions in the thermal power plants of metropolitan France between 2005 and 2020. 30% of the absolute CO_2 emissions and 50% of the specific emissions (in $kgCO_2/MWh$) will also be cut in the generation plants of continental France between 1990 and 2020. [EDF report of sustainable development 2008]

EDF produces electricity which is significantly less CO_2 intensive than the traditional generation alternatives. Its nuclear development policy guaranties a clear step forward to mitigate greenhouse gases. This strategic choice is of course to be followed by appropriate efforts on the safety and waste management issue. The joint investments of EDF and Areva on these fields are a response to this need.

The IEA forecast announce a shortage in energy production around 2050. [IEA 2008] this means that the current policies of capacity development would not be enough to meet the future demand. Hence research on energy efficiency is part of the response to this energy issue. In line with its strategic goals for 2012, EDF will develop affordable for an energy consumption reduction of its clients.

For the social aspect, the commitment of EDF is to provide one million vulnerable clients with appropriate advice for energy saving. EDF has the ambition to contribute to the roof isolation of 6000 households in financial need by 2012, according to the criteria of the French national housing agency (agence nationale de l'habitat).

3. Objectives

3.1. Strategic context

According to its strategic goals for 2012, EDF wishes to take a leading role in the development of renewable energies. Its R&D department contributes to this purpose through the support of various industrial projects related to these energy pathways. Among these energy fields, biomass enables the production of heat, power and biofuels. The department focuses on the field of ligno-cellulosic biomass (e.g.: wood, straw, etc.)

In the frame of the biomass workgroup, data management is an important issue for the R&D department. Many internal studies have been carried out about various aspects of biomass based energy production. Moreover, results from various European and French collaborative projects to which EDF R&D has taken part, and feedback on projects developed by the various entities of EDF Group are available. It is needed to gather, organize, compare and combine these data into a synthetic tool.

3.2. Thesis objective

The purpose is to develop a calculation tool that capitalizes on available data. Various technological pathways have been modelled from feed to fuel/product, taking technical, environmental and economic aspects into account.

In a first step, available data about selected technological pathways of energy conversion of ligno-cellulosic biomass was collected. It was capitalized within a calculation tool describing each technical pathway through a common set of parameters. The tool was then used to compare the various pathways.

This work has been done mainly from knowledge and previous projects of the biomass research team at EDF R&D. The relevant parameters were first identified; data were collected, made homogeneous and consolidated. Then the technological pathways have been modelled from reference processes key figures of technical, environmental and economic aspects. Finally an overall automated tool was designed to realise scenario based comparisons of performances from each pathway.

4. Methodology

4.1. Key indicators and calculation method

The explored pathways are:

- CHP from combustion.
- CHP from gasification.
- BioSNG (Synthetic Natural Gas) production from gasification + catalytic synthesis.
- Fischer-Tropsch diesel production from gasification + catalytic synthesis.
- DME (DiMethyl Ether) production from gasification + catalytic synthesis.
- Cellulosic ethanol production from cellulose hydrolysis and fermentation.

The model for each pathway is realised in the software environment of Microsoft Excel, chosen for its versatility (calculation, visualisation of results, spreadsheet format, etc.) and its relative universality. Indeed this tool is meant to be used and complemented but many other users among the research workgroup. The use of Visual Basic application has been reduced to minimum so that other users can easily takeover and update the tool.

This tool aims at comparing various biomass conversion pathways through several case studies. Each pathway is characterized by a common set of energy, economic and environmental indicators, as described below. The indicators are often defined as a function of capacity parameters (e.g.: biomass feed power, gross electric capacity, net thermal power, biofuel production capacity, etc.) For example, the electrical efficiency of a steam turbine will increase with the capacity of the turbine. These functions are mostly correlations based on selected reference cases, either real implementations or results from advanced simulation software. (e.g.: Aspen utilities).

When the tool runs a comparison of pathways, each module reads the input values and provides the corresponding results which are gathered back to the main interface. The use of macros can enable to run a scenario on a range of parameter values, and to tabulate each result in a common table. (e.g.: “Cost of electricity for fuel inputs tabulated from 5MW to 40MW”)

The final comparisons are synthesised into graphs representing key indicators of the pathways, while the other graph axis gives a dimension parameter (biomass feed power, gross electric capacity, net thermal power, biofuel production capacity, etc.)

The selected key parameters are divided here-below into three categories:

- Energy indicators :
  - Biofuel conversion rate, in kW_{NCV} [1]/ kW_{NCV} -biomass
  - Gross power efficiency, in kWe/ kW_{NCV} -biomass
  - Thermal efficiency, in kW_{th}/kW_{NCV}-biomass
  - Self consumed electricity ratio, in kWe/kWe-gross

These are three efficiencies linked to the three possible energy products. The energy summary of the pathway is complemented by the consumed electricity ratio.

- Economic indicators :
  - Cost of biofuel production, in €/MWh-ncv
  - Cost of power production, in €/MWh-e
  - Cost of the ton of avoided CO_2, in €/tCO_2eq

The cost of heat production has not been selected because it is always a context parameter rather than an actual criterion of comparison of competitiveness.

- Environmental indicators :
  - CO, in mg/Nm^3@11%O_2
  - NO_X, in mg/Nm^3@11%O_2 (fuel-NO_X only)
  - SO_X, in mg/Nm^3@11%O_2
  - COV, in mg/Nm^3@11%O_2
  - Particles emissions, in mg/Nm^3@11%O_2
  - Water consumption, in ton/year
  - Liquid effluents, in ton/year
  - Solid waste, in ton/year

4.2. Economic calculations

The scenarios are financially assessed in a cash flow analysis. The investment amount is estimated from the type of technology and the plant capacity. The O&M expenses are expressed as a typical percentage of this investment. The biomass feedstock consumption is calculated from the plant capacity with the help of a model of the conversion process. The biomass price is determined by a specific module that will be presented below. Financial hypothesis about the project length and the discount rate are made according to the corporate guidelines. In the end, expenses and incomes are summarized in the form of constant annuities.

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[1] : NCV: « Net calorific value », property of a fuel expressing the quantity of heat released by a complete combustion of mass unit of fuel. The latent heat from flue gas vapour is not taken into account.

At this point, two possible approaches can be taken:

- If the sale price of the product (biofuels or electricity) is already set it is then possible to calculate the Internal Rate of Return (IRR) of the project. This option corresponds to case studies where the project benefits from a feed-in tariff.
- If the sale price is not set, an expected IRR can be chosen and the calculation will yield the required sale price to achieve this IRR. This type of analysis is carried out in the case of public tenders (i.e. call for project proposal), where the sale tariff is one of the decisive factors in the selection of projects.

Various cost statistical data feature a trend known as “scale effect”. According to this trend, the cost variation between a plant of capacity P_1 and P_2 will follow this law:

$$Cost_2 = Cost_1 \cdot \left(\frac{P_2}{P_1}\right)^f$$

Where f is the scale factor between these two variables. Correlations on investments often yield scale factors around 0.7. The case of linearity is found when $f = 1$, and independence between the variables corresponds to the case of $f = 0$.

4.3. Data resources

External resources have mostly consisted in publicly available databases on biomass, such as “Phyllis” and “Biobib”. They contain a wealth of accurate and well documented values on chemical and physical parameters. [Phyllis, Biobib, NREL] Some other public reports have provided more specific information, such as the study “Agrice 2006” from the ADEME (The Environment and Energy Management Agency), providing a comprehensive description of some particular biomass energy crops. [AGRICE 2006]

Among the internal resources should be mentioned the knowledge obtained from the projects that EDF has carried out, known as “experience feedback reports”. These reports also include collaborative projects realized with other partners [AFOCEL, ARVALIS]. They contain practical knowledge and measured performances. Within the biomass research team itself, several experts and simulation tools have also been valuable resources to provide estimations and judgments on particular cases. [BIOCOGEN, ASPEN].

5. Description of the tool to evaluate pathways

5.1. Tool Structure

The tool is an Excel workbook formed of various modules in connexion with an interface page. This interface contains a summary of all the inputs and displays the results in a synthetic manner.

Each pathway module consists of several dedicated worksheets containing key data on energy, economy and environmental aspects. Two more modules are used to describe the biomass resource: the first one compiles technical data about each type of cellulosic feedstock, the second one calculates the biomass cost and its environmental impacts. Besides is also used a module with a simplified combustion mass balance calculator, and a last module contain a database of values for local parameters (energy cost, electric grid emission factor, etc.) The interconnection of these modules can be seen in **Figure 1**.

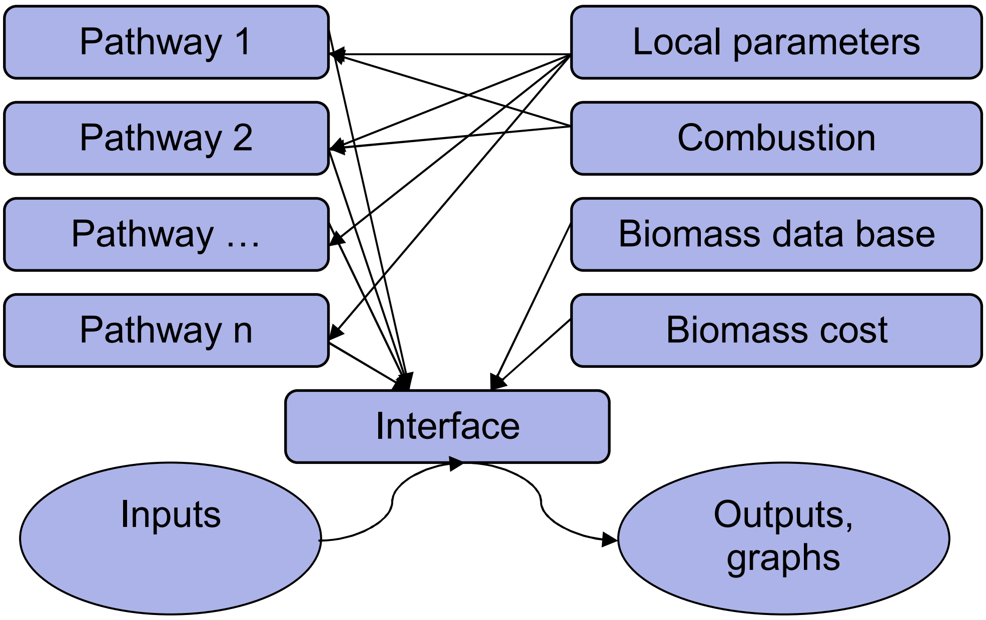

Figure 1 : Structure of the tool

The calculation principle of this tool is based on a set of efficiencies defining each pathway. The central interface contains both key input values and the summary of results from the specific modules.

5.2. Module for the biomass properties

It consists in the compilation of various databases. The public database “Phyllis” and “Biobib” were used, together with three other confidential banks of data from research projects done in partnership with EDF R&D. The described biomass feedstock were organized and split into categories such as woods/straws and hardwood/low-density-wood, perennial/annual.

For some entries, the number of values in the available dataset has required a consolidation. A statistical description is then realized for each parameter, with couples of average and standard deviation. This opens up the possibility of calculations taking into account uncertainty ranges although this hasn't been totally carried out. When the consolidated data were already averages of previous survey, they have been combined following a sample size weighting.

5.3. Module for biomass supply and cost

A model of biomass supply chain was established in order to estimate the feedstock cost as well as the social and environmental impacts. The model was made following the guidance of the Technical Institute of Forest Wood for Construction and Furniture (FCBA).

According to this model, the biomass cost is expressed as the sum of two components:

$$TotalCost = Cost\ at\ the\ production\ site + Transportation\ Cost$$

These two factors are affected by an "accessibility class" with four levels, from "easy access" to "very difficult", which represents the degree of difficulty to collect the resource and transport it.

Two calculation approaches are possible when a given amount of wood is to be extracted. Either the choice of resources is done flowing rising marginal cost in order to achieve a minimized overall cost, or through fixed ratios of class accessibility in the case where the supplier would impose them. The user can choose between these two options. Finally, the calculation of environmental impact is achieved through the effects of the three major consumables used: gasoline, diesel and lubricants. The steps of collect and transport are associated with consumption of these three specific products, from which it is possible to deduce the environmental impact of these steps supply. In the end the module enables to relate the biomass purchased to a cost and associated environmental impacts.

5.4. Module for combustion fluegas

This module aims to estimate the concentrations of NO_X and SO_X in the flue gas [KTH 2007]. It is applied to the pathway of cogeneration from biomass. The module is also used to calculate the volumetric flow of exhaust gases out of gas engines in the case of cogeneration from gasification.

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Figure 2 shows a screenshot of this module.

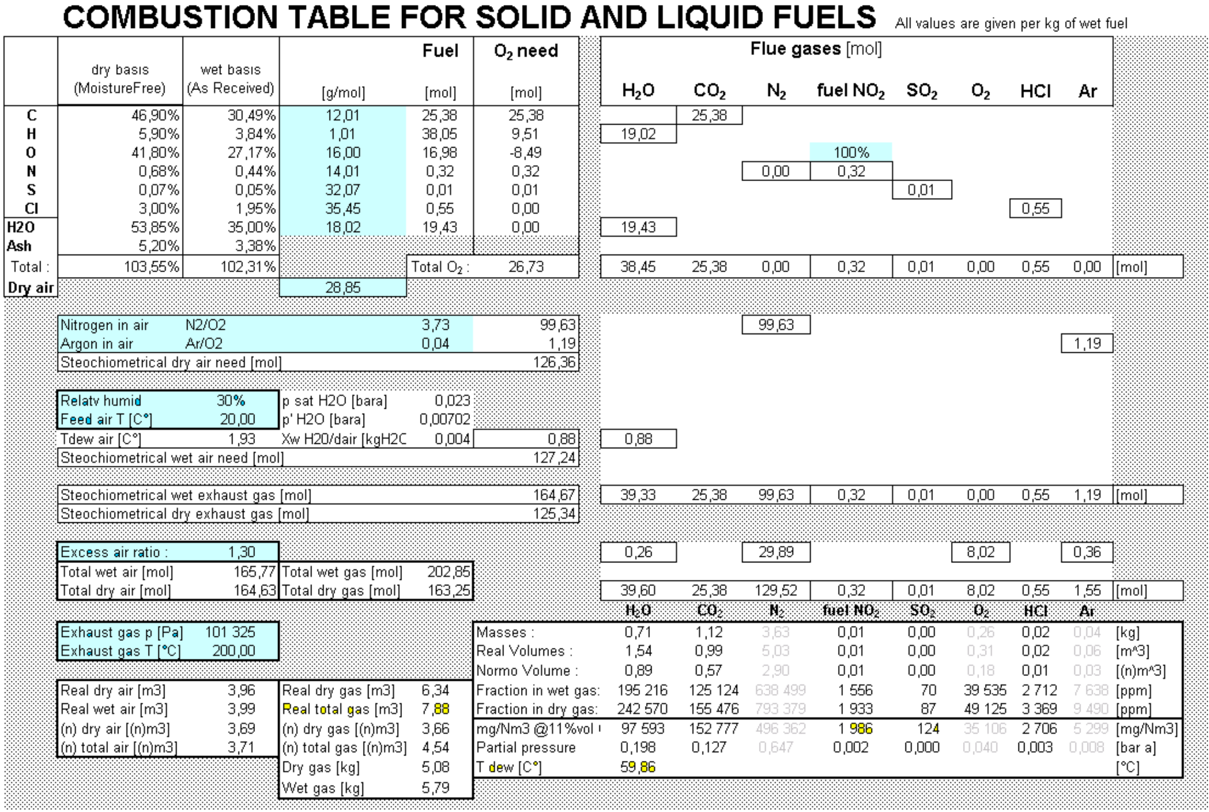

Figure 2 : Combustion flue gas calculator screenshot

In this module it is considered that all of the nitrogen and sulphur in the fuel are oxidized into NO_2 and SO_2 in the flue gas. Without introducing the phenomenon of capture, the model is therefore able to estimate the maximum value of SO_X that may be in the flue gas. Concerning nitrogen oxides, only fuel-NOx are considered and not those of thermal origin. This value is then an indicative estimation but not a particular extremum. This very simplified calculator allows calculating the upper limits for SO_2 and fuel-NOx emissions depending on the initial S and N content in the biomass.

5.5. Module to calculate the cost of avoided ton of CO_2

This module is divided into two parts, with on one hand the determination of the amount of CO_2 avoided per MWh produced from the source of energy replaced, and on the other hand the supplementary costs caused by the replacement of this energy. Ultimately these two values enable to calculate the cost per tonne of CO2 avoided:

$$Cost\ of\ avoided\ CO_2\ [€/t_{CO2}] = \frac{Supplementary\ Cost\ [€/MWh]}{Avoided\ \ CO_2[t_{CO2}/MWh]}$$

To calculate the amount of avoided CO_2, it is necessary to know the factor of CO_2 emissions of the electricity mix of the country. This was done using statistics by country giving the share of each fuel in electricity generation mix. Then the grid emission factor can be deduced using the emission factor of each fuel. The data about power generation are available on the website of the IEA [IEA 2008] and emission factors are those published by the IPCC [IPCC 2006].

5.6. Models of the energy conversion pathways

5.6.1. Combustion based cogeneration

The combustion of biomass in a boiler can power a steam cycle to meet demand for heat while producing electricity. The heat can be obtained in various ways depending on the type of turbine used in the steam cycle:

- **Back-Pressure Turbine**: The steam expands down to the pressure level corresponding to the temperature level for the required heat supply.
- **Cold-Condensing Turbine**: The expansion of the steam is maximized by a cold condensation chamber at its outlet. The turbine output pressure is set by the temperature of the cooling medium available. The steam required to meet the heat demand is extracted at intermediate pressure. This configuration is illustrated in **Figure 3**.

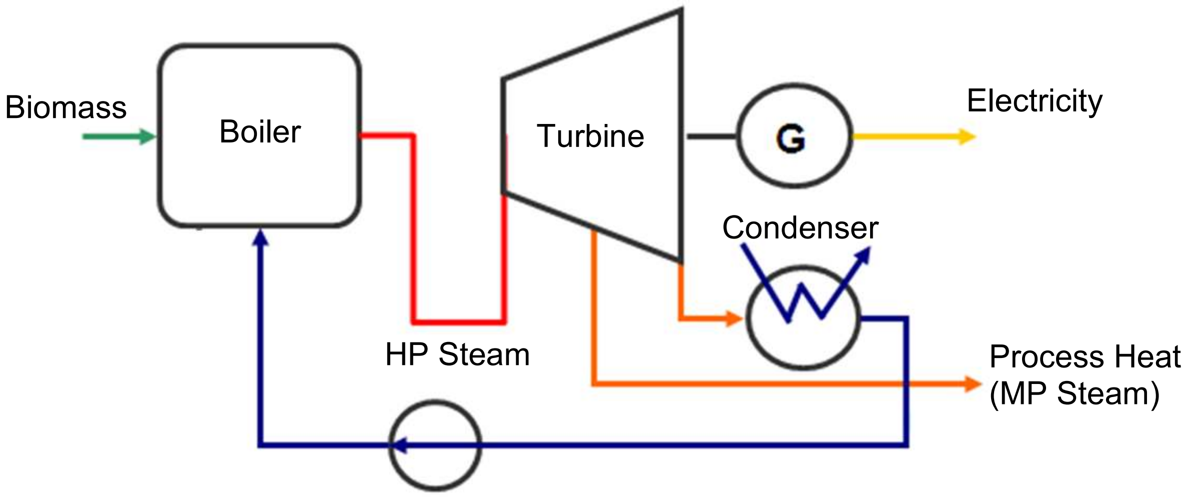

Figure 3 : Block diagram of a cogeneration unit through combustion and condensing turbine

The back-pressure configuration has the drawback of a low flexibility in the cogeneration system and is rarely used for modern facilities. It is also poorly suited to the case of district heating, where an alternative cold source is needed out of the heating season to condense the steam turbine output. For these reasons, only the cold-condensing configuration will be used for the cogeneration pathway through combustion in this report.

This technology is divided into three technical configurations:

- CHP 70 : The first option features a cogeneration efficiency of 70%. This option sacrifices a part of the electrical efficiency for the benefit of thermal efficiency.
- CHP 50 : In this case the electrical efficiency is given priority. The total yield of CHP is maintained at 50%.

- CHP 50 DH : This option is a variant of "CHP 50", suitable for heat demand for district heating (DH). In this case, steam is extracted at 2 bars and used to heat water to 90 ° C.

The energy performances of the three configurations are defined by the electrical and thermal efficiencies. These efficiencies vary with the capacity of the facility, according to correlations obtained from data performance of steam cycles as function of their size.

A correlation taking into account the scale effect gives the specific investment cost according to the power units for biomass combustion. The cost of investment depends primarily on the power input for biomass boiler and is responsible for up to 80% of the total cost. This correlation was based on data from the projects proposed to the CRE 2 tender for project proposal [Agravalor 2008].

Table 1 below gives the magnitudes for key parameters of the pathway in two cases: a 20 MW_{NCV} biomass unit and a biomass unit providing 20 MW_{th}.. These two scale correspond approximately to the typical smallest and largest units respectively.

	20 MW_{NCV} biomass unit	20 MW_{th} heat production
CHP 70		
Biomass capacity	20 MW_{NCV}	40 MW_{NCV}
Gross electrical efficiency	16%	20%
Gross CHP efficiency	70%	
Investment	32 M€	42 M€
O & M	1,8 M€/year	2,0 M€/year
CHP 50 DH		
Biomass capacity	20 MW_{NCV}	82 MW_{NCV}
Gross electrical efficiency	21%	27%
Gross CHP efficiency	50%	
Investment	32 M€	59 M€
O & M	1,7 M€/year	2,2 M€/year
CHP 50		
Biomass capacity	20 MW_{NCV}	74 MW_{NCV}
Gross electrical efficiency	19%	24%
Gross CHP efficiency	50%	
Investment	32 M€	56 M€
O & M	1,7 M€/year	2,2 M€/year

Table 1: Key parameters for the combustion based CHP pathway

5.6.2. Gasification based cogeneration

Cogeneration of heat and electricity can also be achieved by processes based on gasification, in combination with a gas engine. The three technical configurations that will be presented are based on a process of gasification in fluidized bed, well adapted to the considered power range.

The biomass is first dried before feeding the gasifier. It is then gasified and produces a gas consisting mainly of CO, H_2, CO_2, H_2O and CH_4. In the considered case the air is used as gasification agent. The energy required for the gasification is provided by the partial oxidation of pyrolysis vapours released during volatilization of the biomass. The synthesis gas is used to generate electricity in an internal combustion engine. Heat can be recovered during the cooling of the syngas, exhaust gas and while cooling the engine.

This pathway can be broken down into three configurations:

- Cogeneration via gasification (see **Figure 4** below): the heat recovered in the cooling exhaust gas is used to generate steam at 5 bar used as process heat.
- Gasification Cogeneration for DH: the heat recovered in the process is used to supply a network of district heating (DH).
- Cogeneration via gasification and ORC to DH: This is an enhanced version of the previous configuration. The temperature difference between a fraction of the available heat (between 800°C and 150°C) and that of heating network (<100°C)) is used to generate additional power. This can be done by an Organic Rankine Cycle (ORC) which is similar to a conventional steam cycle where an organic fluid replaces the water. This cycle is appropriate for small capacities and low grade heat.

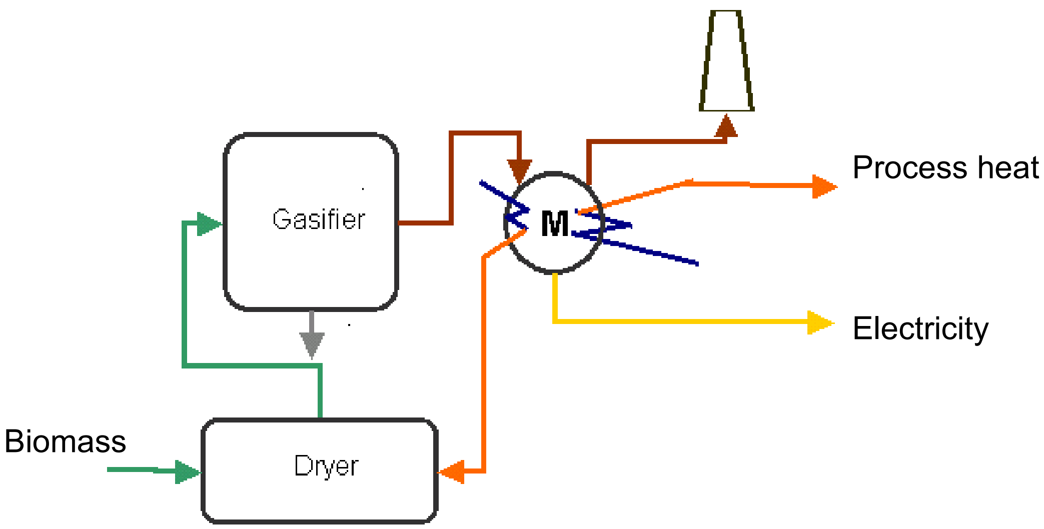

Figure 4 : Block diagram of a gasification-based cogeneration

In this study it is considered that the capacity extension of this type of plant is made by modules of 5 MW_{NCV}. This modular construction reduces the risks associated with the extrapolation of an existing unit to larger capacities, but does not allow cost reductions through scale effect.

Table 2 gives the characteristic parameters of each configuration fuelled by a biomass at 10% humidity. The left column corresponds to a one module setup, and the right column is for a facility meeting a need of 20 MWth heat.

	5 MW_{NCV} biomass unit	20 MW_{th} heat production
CHP gasification		
Biomass capacity	5 MW_{NCV}	105 MW_{NCV}
Gross electrical efficiency	30%	
Thermal efficiency	19%	
Heat type	5 bar steam	
Gross CHP efficiency	49%	
Investment	7,2 M€	99 M€
O & M	1,4 M€/year	14 M€/year
CHP gasification DH		
Biomass capacity	5 MW_{NCV}	47 MW_{NCV}
Gross electrical efficiency	30%	
Thermal efficiency	43%	
Heat type	90°C hot water	
Gross CHP efficiency	73%	
Investment	7,2 M€	58 M€
O & M	1,4 M€/year	8,2 M€/year
CHP gasification DH and ORC		
Biomass capacity	5 MW_{NCV}	51 MW_{NCV}
Gross electrical efficiency	33%	
Thermal efficiency	40%	
Heat type	90°C hot water	
Gross CHP efficiency	73%	
Investment	7,2 M€	64 M€
O & M	1,4 M€/year	9,2 M€/year

Table 2 : Key parameters of the sector cogeneration gasification

5.6.3. Synthetic natural gas through gasification

The synthetic natural gas (BioSNG) is chemically very similar to natural gas fuels, which enable to inject it into the existing distribution networks, thereby avoiding heavy investments in new distribution infrastructures.

The method considered here is based on the production of synthesis gas in a gasifier reactor with two chambers. This synthesis gas is then converted into methane by catalytic reaction. The characteristics of the model are based on the "DFB" process developped by Repotec and CTU, described in the European research project RENEW. [Renew 2008]. It was first demonstrated at the Güssing power plant in Austria, Figure 5 describes the considered system.

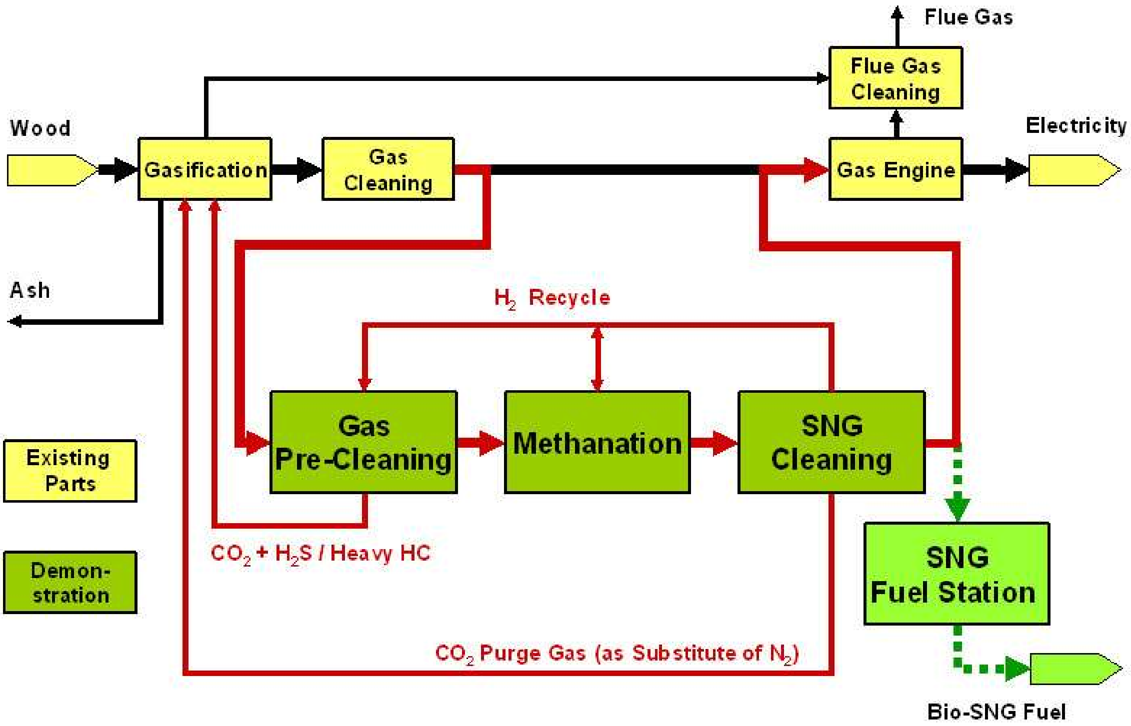

Figure 5 : BioSNG flue gas treatment block diagram

The basic idea of the gasifier concept is to divide the fluidized bed into two zones, a gasification zone and a combustion zone. Between these two zones a circulation loop of bed material is created but the gases should remain separated. The circulating bed material acts as heat carrier from the combustion to the gasification zone. As opposed to the single-chamber gasifier, it offers the advantage of not diluting the product gas with the combustion flue gas, most of which nitrogen. The principle is shown graphically in **Figure 6**.

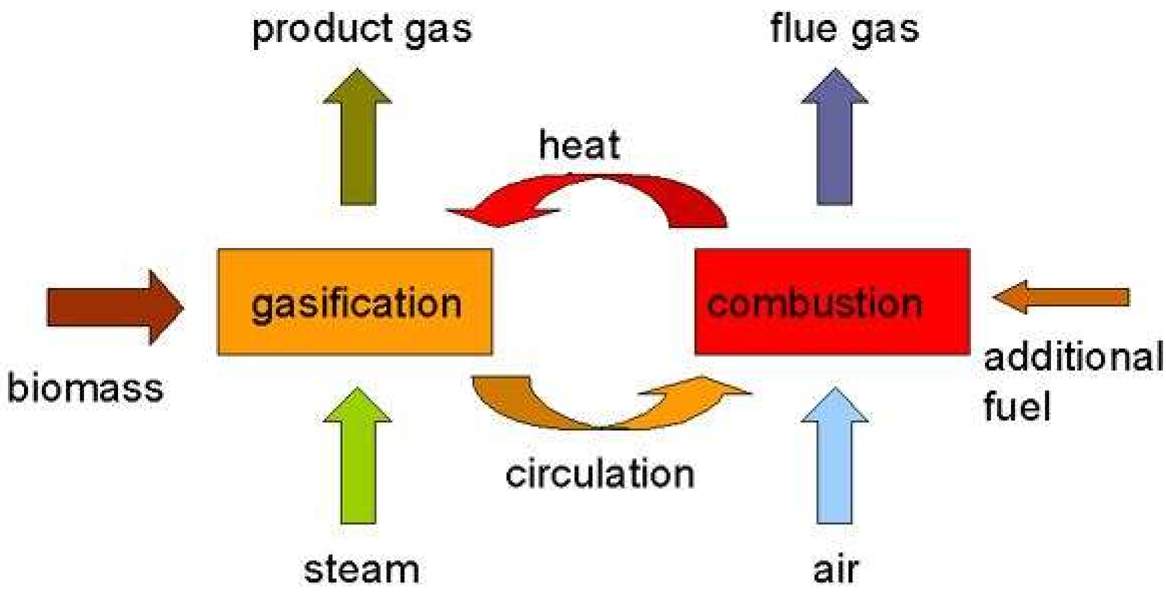

Figure 6: Concept of the dual-chamber gasification

The fuel is fed into the gasification zone and gasified with steam. The gas produced in this zone is therefore nearly free of nitrogen. The bed material, together with some charcoal, circulates to the combustion zone. This zone is fluidized with air and the charcoal is partly burned. The exothermic reaction in the combustion zone provides the energy for the endothermic gasification with steam. Therefore the bed material at the exit of the combustion zone has a higher temperature than at the entrance. The flue gas will be removed without coming in contact with the product gas.

With this concept it is possible to get a high-grade product gas without use of pure oxygen. This process can be realized with two fluidized beds connected with transport lines or with an internally circulating fluidized bed.

The producer gas exits the gasifier at approximately 850°C and is cooled down to 150°C before entering the gas cleaning. Scrubbers are used to reduce the concentrations of tar, ammonia and acid gas components. Further cooling causes the tar and water to condense. This condensate is then sent back to the gasifier chamber to provide water vapour and support the gasification.

Detailed investment data were taken from the European research project “BioSNG”, and these figures were scaled to the needed capacity with appropriate scale factors.

The energy conversion efficiency between the initial biomass and BioSNG is 67% which is fairly high compared with the Fischer-Tropsch process (not higher than 50%).. However, this process is not self sufficient and requires external electricity and heat as input.

Biomass capacity	600 MW_{NCV}
Fuel production efficiency (Biomass to liquid)	67.6%
Heat production efficiency	17.6%
Capital expenditure	253 M€
O & M	3%/year of capital expenditure

Table 3 : Key parameters of the pathway of Bio-SNG

5.6.4. DME and Fischer-Tropsch Diesel

Many biofuels can be produced by catalytic thermo-chemical reactions, depending on the synthesis reactor technology, the conditions of pressure and temperature and the type of catalyst used. Indeed, the synthesis gas obtained from the gasification of biomass can produce methanol, a variety of higher alcohols, hydrocarbon chains or BioSNG (see **Figure 7**). In this study, the conversion pathways evaluated by the tool are the production of di-methyl ether (DME) and Fischer-Tropsch diesel.

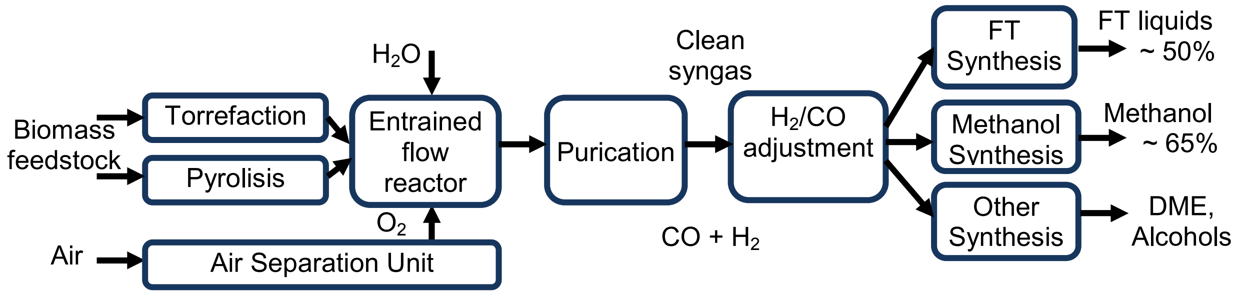

Figure 7 : Production pathways for DME and FT-Diesel

Both considered processes are using an entrained flow gasification technology involving oxygen as gasification agent. This need for oxygen requires the use of an air separation unit (ASU). The synthesis gas produced is purified and the H_2/CO ratio is adjusted in a water-gas shift reactor. The target ratio depends on the type of synthesis which is to be carried out.

For the production of DME, the synthesis gas undergoes a catalytic reactor producing methanol, which is an intermediate product for DME. The process of reference data for this industry is one developed by Chemrec, which was part of the technologies evaluated in the context of the European project RENEW. In this reference process, black liquor is used as fuel.

The production chain of DME is particularly suitable for the gasification of black liquor in synergy with the paper industry. Indeed, the high pressures necessary for this synthesis can be achieved more easily if the fuel is a gasified liquid. In this study it is assumed that a paper mill is available to work in synergy with the fuel synthesis process, and gasify black liquor.

The entire conversion takes place at high efficiency (up to 69%) and the process is self-sufficient in heat and electricity. However self-sufficiency in heat is achieved through the use of an additional amount of solid biomass.

In the case of FT pathway, the considered fuel is ligno-cellulosic biomass. However it is not directly injected into the gasifier. Pre-treatment is necessary to meet the specifications in terms of biomass particle size. This pre-processing may consist of a torrefaction stage or pyrolysis treatment, producing a wood that can be easily crushed or turned into bio-slurry (char + bio-oil). In case the torrefaction and pre-treatment are achieved in small decentralized units, a preliminary fuel densification can reduce transportation costs. The final phase is a Fischer-Tropsch synthesis. This leads to the formation of a range of petrochemical products, mainly in the form of diesel and naphtha. In this study, diesel and naphtha are treated as the same product.

The first modern demonstration unit of FT-diesel production from biomass has been commissioned in Germany in 2008 based on the technology developed by Choren. This plant has also been assessed in the RENEW research project. It has been taken as a reference process for this study.

Biomass capacity	600 MW_{NCV}
Fuel production efficiency (Biomass to liquid)	52%
Capital expenditure	924 M€
O & M	3%/year of capital expenditure

Table 4 : Key parameters of the pathway of FT-Diesel

Biomass capacity	600 MW_{NCV}
Fuel production efficiency (Biomass to liquid)	69%
Capital expenditure	412 M€
O & M	2.5%/year of capital expenditure

Table 5 : Key parameters of the pathway of DME

5.6.5. Cellulosic ethanol

Figure 8 outlines the various processes developed for producing ethanol from cellulosic biomass.

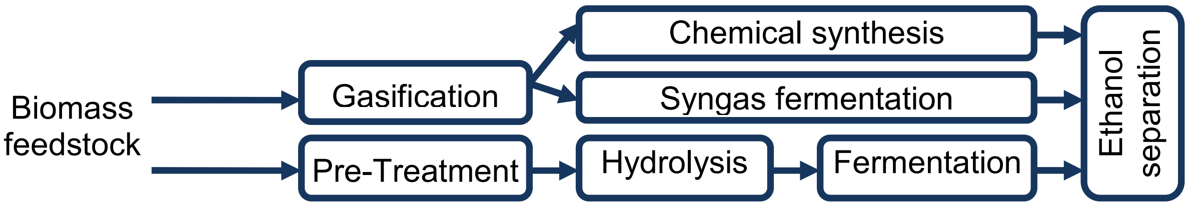

Figure 8 : Compared view of second generation ethanol production

The processes to produce cellulosic ethanol are divided into two distinct pathways.

- The thermo-chemical pathway: it involves a gasification stage followed either by a catalytic synthesis or syngas fermentation by micro-organisms (hybrid path).
- The biochemical pathway: it has a lot of similarities with the process of 1st generation (fermentation of sugar- or starch-rich biomass), but one should note some important differences. The second generation (2G) biochemical process, focusing on complex sugars like cellulose, requires a step prior to hydrolysis, a pretreatment phase to make it accessible to enzymes the chains of cellulose and hemi-cellulose, initially covered by lignin. The hydrolysis step is also more difficult than with starchy biomass. Current research attempts to obtain more efficient enzymes.

The process considered in this study is the one based on the biological pathway, which is today the one closest to commercialisation for large-scale production of ethanol from ligno-cellulosic biomass.

Biomass capacity	600 MW_{NCV}
Pre treatment efficiency (make the cellulose and hemicellullose available)	70%
Hydrolysis efficiency	70% for C5 sugars 85% for C6 sugars
Fermentation efficiency	70%
Capital expenditure	378 M€
O & M	3%/year of capital expenditure

Table 6 : Key parameters of the pathway of cellulosic ethanol

6. Tool applications to case studies

6.1. Reference context of the case studies

The case studies considered in this section were performed using a reference context, described in Table 3.

Project duration:	15 years	Biomass supply type:	Rhône-Alpes 2020
Inflation:	2,5%		
Discount rate:	12%		
Plant operation:	8000 h/year	Biomass:	Poplar
District heating:	4000 h/year	Moisture content (%wet biomass):	35%
Power purchase price:	60 €/MWh	Availability:	Easy : 34%
			Medium : 33%
			Difficult : 33%
Heat sale price:	30 €/MWh	Biomass price:	17 – 19 €/MWh
Heat sale cap:	20 MW_{th}	Availability of the biomass:	20%

Table 7 : Reference context of the case studies

The chart **Figure 9** shows the trend in the average price of biomass as a function of supply need.

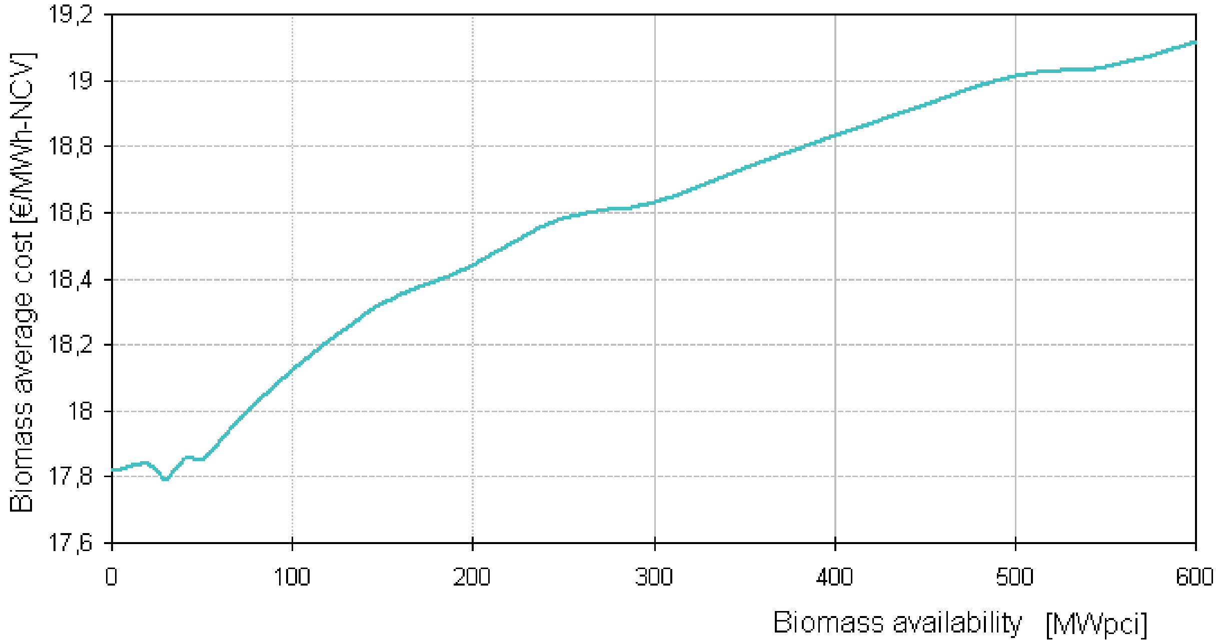

Figure 9: Specific average cost of biomass

The chart above shows the trend of increasing costs of the resource. This is only due to the transportation phase of the biomass, requiring increasingly longer distances to cover a larger circular area of collection, which explains the trend of growth in square root. This increase is relatively small and represents only a 6% difference between a demand of 50 MW_{NCV} and 600 MW_{NCV}. This modest increase is explained by the low proportion that the transport would totally cost. Various irregularities in the curve are due to thresholds phenomena such as truck load threshold. One can however criticize this model for not including a model of increase of the biomass price at its purchase, reflecting the tension between supply and demand.

6.2. Combustion with CHP 70 vs CHP 50

In a situation of industrial cogeneration, the combustion pathway offers two options previously referred to as "CHP 50" and "CHP 70" in sections 5.6.1. These are compared in this section.

In situations where a project is responding to a given heat demand, production costs are shown below in **Figure 10**.

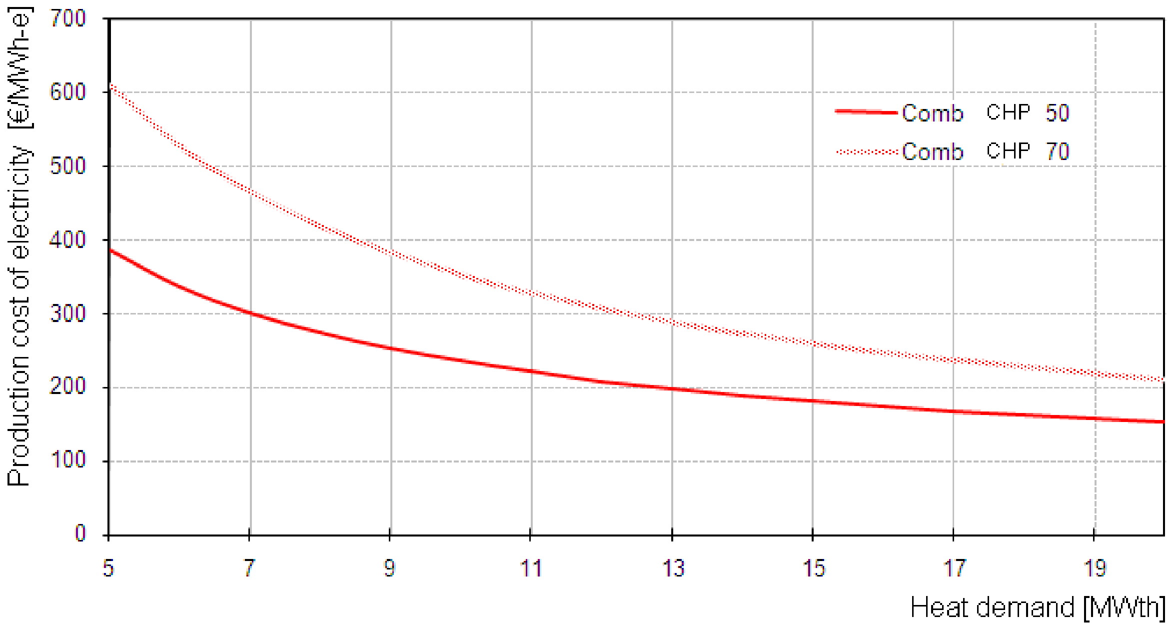

Figure 10 : Production cost of electricity as a function the heat output

For the case analyzed, we observe that it is always more attractive to chose the CHP 50 option. This is because this solution is optimized to produce electricity, and will lead to a significantly greater plant size. As a consequence the plant will benefit from economies of scale and better electrical efficiency. This scale effect tends to disappear as capacity increases.

Plants with higher capacity however feature the drawback of requiring substantially larger investments and need to have sufficient resource supplies of biomass available close to their location.

6.3. Gasification VS Combustion for process heat

In situations where a heat demand is combined with the opportunity to sell electricity, two technologies compete: combustion and gasification. Among the combustion options, "CHP 50" is preferred rather than "CHP 70" in accordance with the conclusions made in the section above.

The combustion and gasification feature different conversion efficiencies, whereas very little change is observed in the case of gasification due to the capacity increase by the addition of standard modules. The electrical efficiency of the gasification option is taken as constant at 30% and thermal efficiency set to 19%. In contrast, the combustion process displays a decreasing thermal efficiency and an increasing electrical efficiency while the capacity is increased.

Regarding the investment, the case of gasification hardly benefits from any economies of scale since we consider a modular system whereas the process by combustion rather outlines a significant specific cost reduction as the size increases.

Figure 11 below illustrates the relative competitiveness of the two options as a function of the process heat demand.

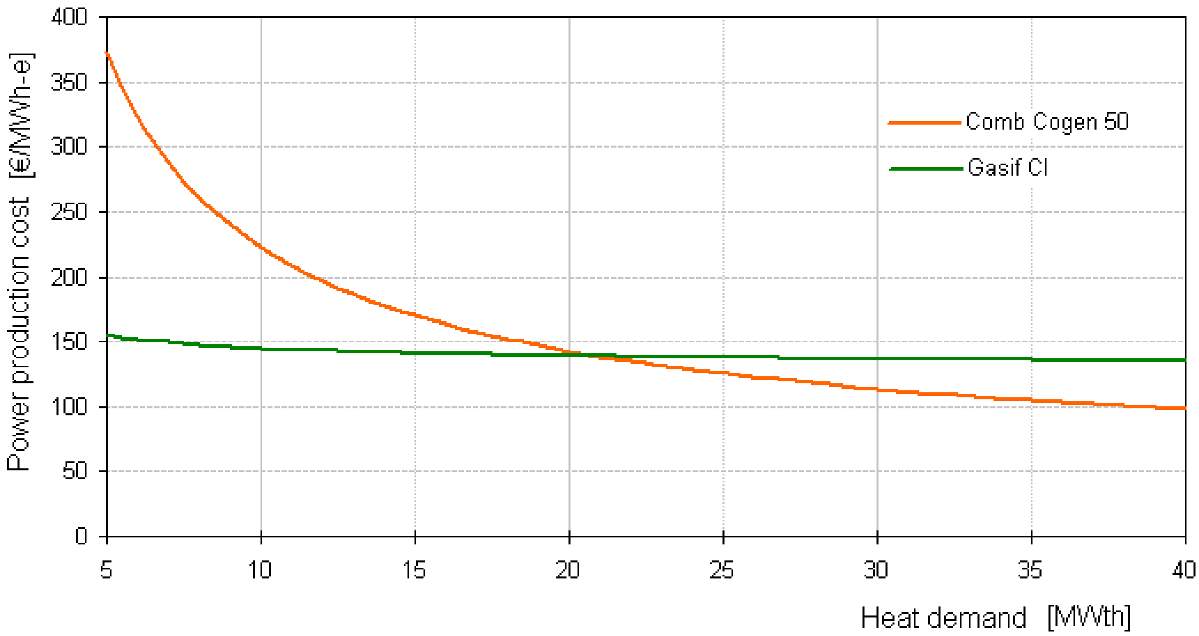

Figure 11 : Competitiveness combustion VS gasification

This diagram shows that with the scale effect, the combustion process takes over the gasification option in terms of competitiveness beyond a certain thermal capacity. In this case study, combustion is of greater interest for large heat demands, beyond 20 MW_{th}.

A sensibility analysis has been carried out in order to assess the impacts of several parameters applied to both pathways, on the relative attractiveness of these two channels. Table 8below summarizes these results by giving the capacity beyond which combustion takes over the gasification in terms of economy.

Variation of certain parameters	**Cross point**
Base scenario (moisture at 35%)	21,0 MW_{th}
Heat sale price = 15 €/MW_{th}	23,0 MW_{th}
Biomass moisture = 50%	23,5 MW_{th}
Biomass moisture = 10%	21,0 MW_{th}
Biomass availability between Difficult and Very Difficult (50% increase in the biomass price)	22,5 MW_{th}
Bretagne region (low resource density)	22,5 MW_{th}

Table 8 : Sensitivity study on the relative competitiveness of gasification VS combustion

It is observed that a decrease in revenues from the heat sale affects more the competitiveness of combustion, as its income from heat sale has more weight than in the case of gasification.

One can also observe that increasing the initial moisture of the biomass to 50% will entail increased biomass consumption in order to maintain the amount of heat input. As in the previous case, this has the effect of penalizing the combustion, which is relies more on this resource because of its lower electrical efficiency.

It can be concluded that any adverse changes prior to the project (more expensive biomass, biomass of poorer quality, reduced heat sales revenue) tend to give advantage to gasification by extending its field of competitiveness against combustion. However these changes are modest.

6.4. Biofuels production pathways

This case study focuses on the biofuel production cost of the considered technological conversion. The influence of the centralized or decentralized aspect of the production is also taken into account.

The size of a biofuel production facility impacts several decisive parameters such as scale economy, the possibility to supply heat to a client, the biomass resource availability locally and hence its price. Various configurations are compared to assess the influence of these factors on the final costs of production. Heat sale is only considered in the case of the decentralised BioSNG production unit.

Figure 12 below shows the production costs for each sector, and draws the distinction between the centralized and decentralized cases for the DME and BioSNG. Centralized plants are given a large capacity of 600MW$_{NCV}$, whereas the decentralized plants feature smaller capacities of 50 and 30 MW$_{NCV}$ respectively.

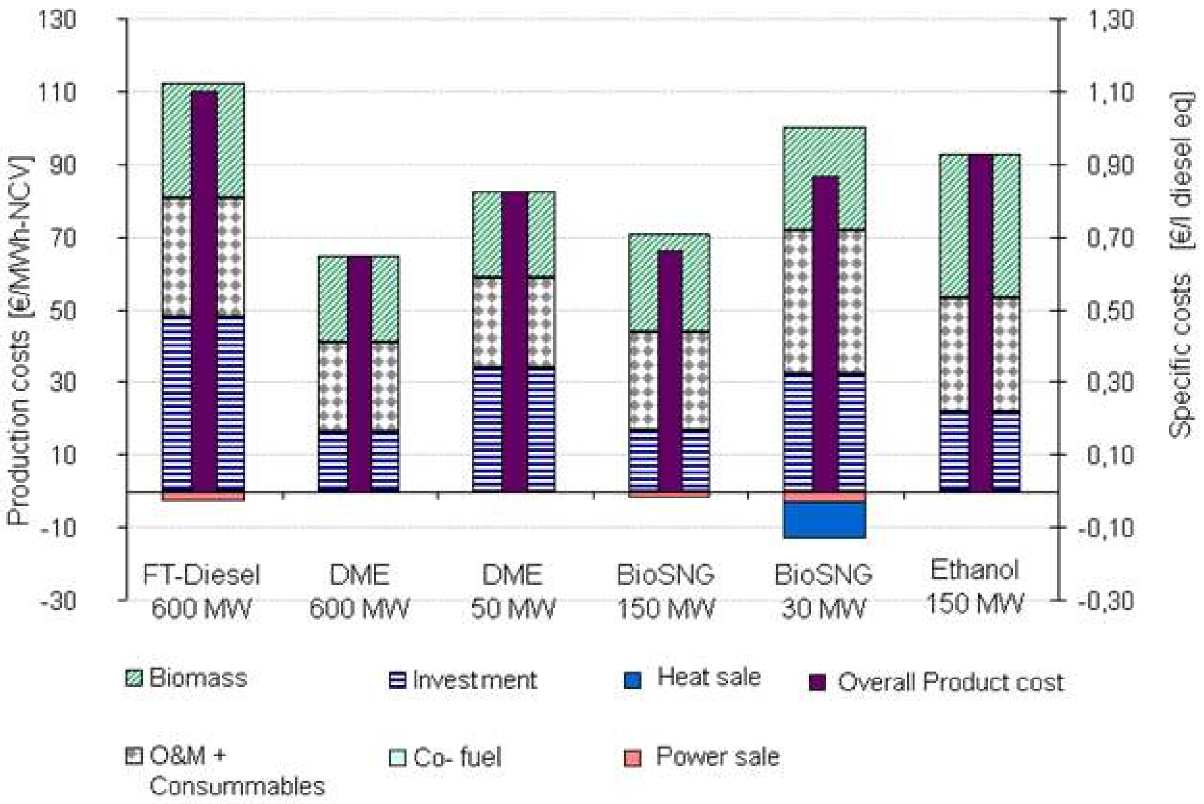

Figure 12 : Breakdown of the production costs

The process efficiencies are considered unchanged regardless of the plants capacities. They remain as described in section 5.

It can be observed that the centralized production of DME biofuel offers the cheapest biofuel, with 55 € / MWh considering a biomass cost of 19 € / MWh, in line with the conclusions of the European project RENEW [RENEW 2008, p136]. Conversely, the FT-Diesel features the highest production cost, with 115 € / MWh.

However one can see from the pair of options for DME and BioSNG that the benefit of centralized facilities compensates the increased cost of biomass, despite the non-utilization of the heat in the case of BioSNG. The pair of DME options illustrates that investment costs do follow a scale effect.

It can also be observed from the results for DME and BioSNG that large centralized units are significantly more profitable than decentralized options. This is due to the behaviour of the model used to calculate the cost of biomass which features little influence of transportation on the final cost, and then probably underestimates the price increase of biomass with the project size.

6.5. Cost of avoided CO_2 by oil price

Since biofuels aim at partially replacingfossil fuels, the competitiveness of these industries depends directly on oil prices. The cost per tonne of avoided CO2 results from the characteristics of the technological pathway and the oil prices. This cost would reach zero for a barrel price sufficiently high, beyond which the biofuel in question would be profitable even without incentive mechanisms. Please see section 5.5 for the related formula.

The relative competitiveness of biofuels will be defined in comparison with crude oil based on energy equivalences. As in the previous case study, co-produced electricity is assumed to be sold at 130 € / MWh [CGC 2008].

The conversion between the oil price per barrel and price per MWh of oil is done in accordance with the definition of a barrel of oil equivalent, set at 5.8*106 BTU by the US Service Tax [IRS], equivalent to 6.12 GJ/barrel. The euro / dollar conversion is taken at the rate of 0.71. (on June 2009)

The current price of Brent crude is around $ 70 / bbl (on June 2009). However the recent past fluctuations incites us to explore a range of values up to $ 200. The chart below outlines the costs per tonne of CO2 avoided for the 4 considered biofuels.

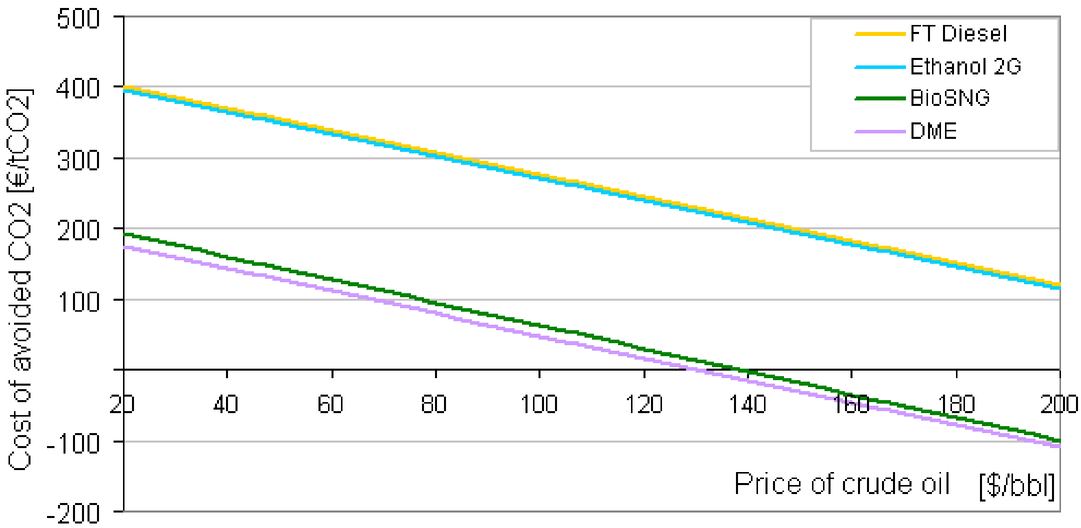

Figure 13 : Cost of avoided CO_2 by crude oil price

The cost per MWh of oil increases proportionally with the price of oil. Given the complexity of the globalized costs system, a strong assumption has been taken by keeping the cost of biofuel production independent from the barrel price. Therefore the extra cost to the preference of a biofuel on oil decreases linearly. Since the amount of CO_2 avoided per MWh of biofuel is independent of oil prices, the cost of CO_2 avoided also decreases linearly with the price of a barrel.

The fact that the cost of biofuel production and hence the cost of biomass, are independent of oil prices is a strong assumption. A more realistic but also more complex approach would be to consider a simultaneous increase in all costs, leading to pushing the threshold of profitability without subsidy to higher prices per barrel. (i.e. "bending" horizontally the cost lines as the oil price increases)

It can be observed that the BioSNG and DME yield the lowest cost per tonne of avoided CO_2, highlighting that these two biofuels are comparatively cheaper to produce. As a general comment, the costs per tonne of avoided CO_2 is substantially higher than the current CO_2 price (Spot EUA about 12.5 €/t, Secondary CER about 11 €/t in February 2010 [Thomson Reuters]). This means that these biofuel productions are not competitive against crude oil without any incentive mechanism.

However the decision to develop biofuels is not only based on short term competitiveness but also on issues such as energy independence and CO_2 mitigation policy. Indeed biofuels together with the electric car technologies are among the few ways to cut CO_2 emission in the transportation sector.

7. Conclusions

The designed tool has demonstrated its ability to provide synthetic results on concretely defined cases, on the basis of technical or economic parameters. The four case studies have shown the flexibility of the tool to respond to various issues. The tool developed was used to assess four different case studies.

The first one analyzed the differences between two combustion-based CHP setups giving priority either to the power efficiency or to the global efficiency. The comparison was based on the electricity production cost. The results show that for a given heat demand, the option maximizing the electrical efficiency features lower costs. Conversely in the case of given power demand, the option maximizing the total efficiency is more cost effective.

In a second case study, combustion and gasification are compared in their ability to meet a heat demand in CHP mode. These two technologies differ on their efficiencies and investment profiles. The combustion based setup features a rising electrical efficiency as the capacity increases, whereas gasification yields are fairly constant. The investment for a combustion setup is characterized by a strong scale effect, but the gasification trend is linear due to its module based nature. Results show that gasification is more cost effective than combustion for small scale heat demand, typically below 20 MW_{th}. This is explained by a comparatively higher electrical efficiency and lower specific investment costs for small gasification units compared to combustion.

A third case study compares the interest of centralized and decentralized biofuels production. Indeed, splitting production into several decentralized units allows to simplify feedstock supply logistics and to reduce the collection distance. Besides, this decentralized approach enables to sell the heat co-produced, which is not possible with a centralized unit. On the other hand, concentrated capacity benefits from the scale effect on investment. This study shows that the scale effect of centralization prevails over the advantages of the decentralized approach. However, the apparent higher economic interest of the centralized approach has to be carefully considered, since it needs important supply logistics as well as a very high initial investment for a first commercial unit, leading to higher financial risks.

A fourth and last case study gives the cost of avoided CO_2 for biofuels as a function of the oil price. This analysis defines the oil price at which each biofuel becomes cost effective without subsidies on CO_2 avoidance.

As a conclusion, the tool conceived and developed throughout this internship has proved its interest for the assessment of a multitude of pathways in various contexts. It gives the basis for a multi-parameter assessment tool that needs now to be further enriched, detailed and validated by the biomass team at EDF R&D.

More scenarios and studies have been identified and will lead to further utilizations of the tool. Its structure in a form of independent standard modules opens up options to complement or easily recycle some components into other tools.

8. Acknowledgment

I am grateful for having had the opportunity of this work which allowed me to develop and implement a project methodology on a vast field of study. Such work requires to continuously drawn the line between essential parts and details. The dilemma is that the consistency and the plausibility of the elements in place can be tested only by a form of result calculation, but it should be done without going overboard to develop the whole interface of result display.

The management of information resources was a priority to ensure the reliability of the whole and the traceability of results.

From a knowledge standpoint, this internship was a unique opportunity to put myself at the forefront of the state of the art on the processes of energy conversion from biomass. My career plan emerges clearly in this direction, and the calculation method proposed by the tool corresponds to the horizontal approach (technical, environmental and economic) that I will adopt for this job. The economic calculations have been particularly valuable additions to my engineering background.

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