CHEMICAL ENGINEERING TRANSACTIONS
VOL. 35, 2013
A publication of AIDIC
The Italian Association of Chemical Engineering
www.aidic.it/cet
Guest Editors: Petar Varbanov, Jiří Klemeš, Panos Seferlis, Athanasios I. Papadopoulos, Spyros Voutetakis

ISBN 978-88-95608-26-6; **ISSN** 1974-9791
DOI: 10.3303/CET1335092

Process Integration of Lignocellulosic Biomass Pre-treatment in the Thermo-Chemical Production of F-T Fuels: Centralised Versus Decentralised Scenarios

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The purpose of this study is to evaluate, in terms of process integration, the centralised and decentralised pre-treatment of lignocellulosic biomass for its thermo-chemical conversion into liquid fuels through gasification and Fischer-Tropsch (F-T) synthesis (biomass to liquids, BtL). The aim is to quantify the process integration benefits of a centralised configuration in comparison to the energy savings obtained through the transportation of a higher energy density fuel, in this case torrefied biomass instead of raw biomass. The analysis is carried out through the detailed energy and mass balances, and the pinch analysis of the centralised and decentralised configurations.

1. Introduction

Biomass thermo-chemical conversion into liquid fuels is one of the promising alternatives to fossil derived liquid fuels. The fuels obtained through thermo-chemical conversion belong to the category of second generation biofuels which, in contrast to first generation biofuels, don't enter in direct competition with crops for food and fodder. Biomass, in fact, can be used wholly for the conversion process, as it is broken down to a synthesis gas mainly composed of H_2, CO and CO_2. The synthesis gas may then be used to synthesise fuels and chemicals. Fischer-Tropsch synthesis is an interesting option as it allows producing drop-in fuels that may be used in the current fleet of vehicles. The pre-treatment is a key step in the thermo-chemical conversion process, and it generally consists in drying and torrefaction of biomass. This step of the process may be carried out closer to the harvesting grounds in order to reduce transportation costs to a centralised facility where gasification and synthesis are carried out. Benefits of drying and torrefaction of biomass include higher biomass energy content, improvement of grindability, and reduction of hygroscopicity and biological degradation (Bergman, 2005).

The logistics of biomass supply chains has been studied especially in the context of biorefineries, which require very large amounts of biomass (5,000-1,000 t/d), about 1-2 GW_{th} capacity) to be economically sustainable. In this context the logistic of the supply chain plays an important role for the economic and environmental sustainability of the process. In order to reduce transportation cost Carolan et al. (2007) introduced the concept of delocalized pre-treatment operations using Regional Biomass Pre-processing Centers (RBPC), for cellulosic ethanol production. The study by Ebendewe-Mondzozo (2013) compares environmental and profitability outcomes of a centralized biorefinery and of one where biomass is pre-treated into concentrated briquettes in a decentralised array of local depots. Results show that the dispersed configuration yields less environmental damage than the centralized one.

Kurian et al. (2013) provide an extensive review of pre-treatment options and logistic practices for biorefineries and underline the importance of the supply chain logistics.

Please cite this article as: Peduzzi E., Boissonnet G., Haarlemmer G., Marechal F., 2013, Process integration of lignocellulosic biomass pre-treatment in the thermo-chemical production of f-t fuels. centralised versus decentralised scenarios, Chemical Engineering Transactions, 35, 553-558 DOI:10.3303/CET1335092

In the context of BtL through F-T synthesis a comparison of torrefaction only, torrefaction and pelletisation (TOP process), and pyrolysis as delocalised pre-treatment is carried out by Uslu et al. (2008). This study focuses on long-distance bioenergy transportation by truck and ship from Latin America to Western Europe. Results show that the supply chain energy cost amounts to 8 % of the Higher Heating Value (HHV) of the initial biomass for the TOP process, 10 % for pellets and 8 – 9 % for pyrolysis oil. The present study aims at assessing the energetic cost of biomass transport for BtL plants in the 20 - 200 MW_{th} (Lower Heating Value, LHV) capacity range taking into account the effect of delocalised pre-treatment on the process integration of BtL.

2. Methodology

The methodology used in this study relies on the development of a superstructure of unit operations describing the thermo-chemical conversion process (Gassner and Marechal, 2009). The superstructure allows a flexible approach for the evaluation of several process chains. Each unit operation is modelled in flow-sheeting software (Vali by Belsim S.A.)) and a heat integration model is used to optimally recover heat from the process and co-produce electricity by means of a steam turbine. The process integration optimisation is formulated as a MILP (Mixed Integer Linear Programming) problem, maximizing the combined heat recovery and power and/or fuel production (Maréchal and Kalitventzeff, 1999). The performance and the process integration of a centralised process are compared to one where pre-treatment is carried out in a separate location, at the harvest sites, and dried or torrefied biomass is transported to the conversion plant.

3. Thermo-chemical production of F-T fuels: process description

Biomass thermo-chemical conversion into liquid fuels is carried out in four main steps: pre-treatment, gasification, gas conditioning, and synthesis. For gasification an Entrained Flow (EF) gasifier is considered. For the centralised option the pre-treatment steps and the BtL facility are located on the same site and are therefore integrated. A steam network allows recovering heat and co-producing electricity using a steam-turbine. Raw biomass is transported from the harvesting grounds and it is used to provide both the heat requirements and the feedstock for F-T fuel production. For the decentralised option pre-treatment units are scattered closer to the biomass harvesting locations. For these units natural gas may be used to satisfy the heat requirements. Torrefied biomass is transported to the BtL facility for conversion.
The thermo-chemical models describing the conversion of biomass into liquid fuels are developed based on experimental and literature data. In the following sections the thermo-chemical models are briefly described and the values selected for the main operating variables are summarised. The transportation model used for this evaluation is also presented.

3.1 Thermo-chemical production of F-T fuels: process description

In this study pre-treatment refers to biomass conditioning before gasification, it consist in drying and torrefaction. Natural gas is used to provide the heat requirement if it is carried out in a decentralized location. Drying is achieved in an air drier, where moisture is reduced from 35 % to 10 %. The weight loss of biomass during torrefaction is of 20 % of its initial dry weight (anhydric weight loss, AWL). Gases produced during torrefaction are combusted to provide part of the hot utility. After torrefaction the solid is cooled to ambient temperature for transport/storage.
The reference gasification configuration uses an oxygen/steam blown EF gasifier. For this type of gasifier biomass needs to be ground into fine particles (200 μm) which are entrained with the reacting gasses. Torrefaction is therefore generally required as a pre-treatment step in order to reduce the energy for grinding. The EF gasifier model is based on an equilibrium model (minimisation of the Gibbs free energy) of the product gases, as described by (Gassner and Maréchal, 2009). The oxygen separation unit is not modelled but the energetic cost of oxygen is taken into account by considering an electricity consumption of 1,080 kJ/kgO_2 for cryogenic air separation (Hamelinck et al., 2004).
The gas conditioning step includes a scrubber for gas cleaning, a water gas shift unit and acid gas removal (AGR) through amine absorption. In the water gas shift unit part of the synthesis gas is shifted in order to obtain a final H_2/CO ratio of 2.1/1. The amine scrubber is modelled as a “black box” where electricity and heat requirements are taken into consideration (Tock et al., 2010).
The F-T synthesis converts the synthesis gas into liquid hydrocarbons with chain lengths distributed according to the Anderson–Schulz–Flory distribution. The F-T crude produced is considered directly as the upgrading is not modelled in detail. The main operating variables are summarised in Table 1.

Table 1: Summary of the operating parameters

Description	Variable	Value	Unit
Pre-treatment			
Air dryer inlet T	T_d	200	°C
Wood Φ at outlet	$\Phi_{d,wood}$	10	%
Torrefaction T	$T_{T,out}$	250	°C
Anhydric weight loss	AWL	0.2	-
EF gasifier			
Steam to biomass ratio	$R_{s/b}$	0.6	-
Gasification P	p_g	30	bar
Gasification T	T_g	1350	°C
Water Gas Shift			
WGS react T	T_{WGS}	312	°C
Steam to CO for WGS	$R_{s/co}$	2.5	-
F-T Synthesis			
H_2 /CO	S	2.1/1	-
F-T synthesis P	p_{F-T}	25	bar
F-T synthesis T	T_{F-T}	220	°C
Recycled fraction	R_{F-T}	80	%

The transport distance strongly depends on the location of the plant and the availability of biomass in its surroundings. The study by (Leduc et al., 2009) for example considers 55 and 70 km maximum biomass supply distances for 200 MW_{th}, biomass to methanol plants located in Germany. The study by Steubing et al. (2012) shows the variation of the average biomass supply distances in Switzerland as a function of location, plant size and scenario for biomass availability. For 200 MW_{th} the average distance varies between about 80 to 160 km for the baseline scenario and 40 to 110 km for the “green future scenario”. In this study, in order to take into account the dependence of biomass supply distances with the plant size, the relationship by Stucki et al. (2010) Eq (1) has been considered.

$$Dav = t_1 \cdot pth^{t_2} \tag{1}$$

Where *Dav* is the average driving distance in *km*, and *pth* is the thermal power of the BtL plant in kW_{th}. Two sets of parameters have been used. The first one (*Set 1* $t_1 = 0.0535$ km/kW_{th}, $t_2 = 0.58$) is the original set (which is on average compatible with the “green future scenario” by (Steubing et al., 2012), while the second one (*Set 2* $t_1 = 18.455$ km/kW_{th}, $t_2 = 0.1776$) the parameters have been calibrated on four points of the baseline scenario from the same study resulting in the longest distances (baseline scenario for Bellinzona, CH).

The lorries are assumed to have an average capacity of 10 t (belonging to the 20-28 t lorry category). The average fuel consumption for loaded lorries is of 10.67 MJ/km and for empty lorries is of 8.37 MJ/km (average fleet diesel fuel consumption for Switzerland calculated from data from Ecoinvent.ch (Ecoinvent). The fuel consumption is therefore calculated by considering the tons of raw or torrefied biomass that need to be transported to satisfy the nominal capacity of the plant, and taking into account that for every trip the lorry goes back to the pre-treatment plant empty.

3.2 Efficiency Definitions

In this study only the efficiency of the process is considered as an indicator of performance. The chemical efficiency only takes into account the conversion of biomass into liquid fuels.

$$\eta_{chem} = \frac{LHV_{F-T} \cdot \dot{m}_{F-T}}{LHV_{BM} \cdot \dot{m}_{BM}} \tag{2}$$

The energy efficiency is defined as useful products over inputs. The absolute value of the electricity balance is therefore at the nominator if electricity is produced (E^{-}) or at the denominator if it electricity is consumed (E^{+}).

$$\eta_{en} = \frac{LHV_{F-T} \cdot \dot{m}_{F-T} + \dot{E}^{-} - \dot{E}_{transport}}{LHV_{BM} \cdot \dot{m}_{BM} + \dot{E}^{+} + LHV_{NG} \cdot \dot{m}_{NG}} \quad (3)$$

The power requirement for transportation is subtracted to the F-T fuel produced, considering that the F-T fuel produced is used to fuel the lorries transporting biomass.

These performance indicators are considered here for a preliminary analysis to understand the energy trade-offs involved. The economic and environmental performance analysis is also important when comparing alternative configurations.

4. Results and Discussion

The results of the Process Integration analysis, in terms of Composite Curves, of the centralised and decentralised pre-treatment scenario are presented in Figures 1 and 2 respectively, for the configuration adopting the EF gasifier. These figures present for each configuration the Composite Curve of the pre-treatment (in a), dashed gray line) and the steam network (in b), dashed gray line) along the Composite Curve of the rest of the conversion process (solid black line). These figures graphically show that the integration of pre-treatment in the overall process positively affects the possibility of by-producing electricity.

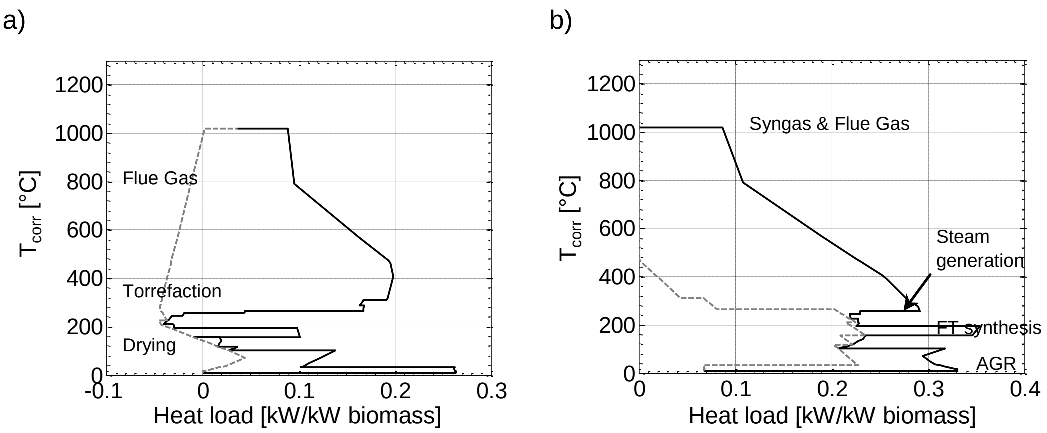

Figure 1: Centralised pre-treatment configuration: Grand Composite Curves of a) the pre-treatment (gray dashed line) and rest of the process (black solid line), and of b) the steam network (gray dashed line) and rest of the process (black solid line)

Figure 3 provides a summary the trade-offs between centralised and decentralised pre-treatment as a function of plant capacity. The relatively small plant scales have been considered for consistency with the study by (Steubing et al., 2012) which also shows that, because biomass is a diffuse resource, optimal plant sizes for biomass conversion plants, in terms of environmental performance are relatively small, from 5 to 40 MW_{th}. Figure 3 shows the energetic gains and losses of the decentralised pre-treatment configuration with respect to the centralised one. The results show that the gain obtained from the reduction of transport of biomass in the decentralised pre-treatment option is balanced by the extra-requirement in natural gas for the heat requirement of the pre-treatment unit, when distances are calculated with *set 2* parameters. The greatest difference between the two configurations is the possibility of producing electricity as a by-product which is significantly greater in the centralised and integrated case.

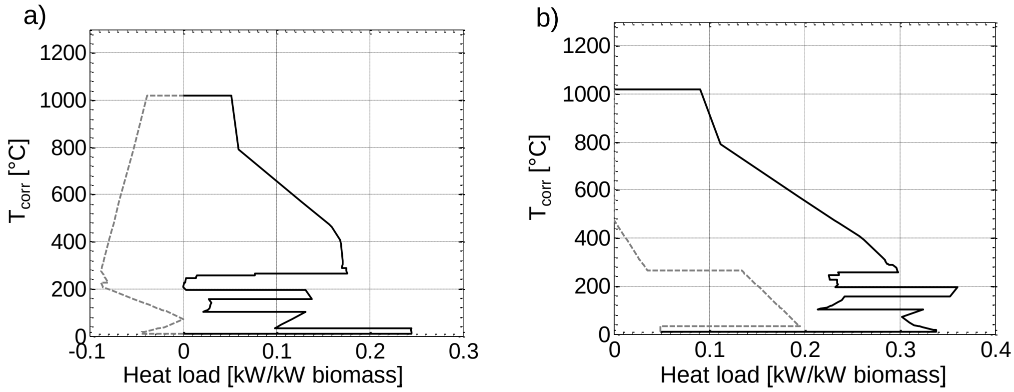

Figure 2: De-centralised pre-treatment configuration: Grand Composite Curves of a) the pre-treatment (gray dashed line) and rest of the process (black solid line), and of b) the steam network (gray dashed line) and rest of the process (black solid line)

For all solutions there is a net electricity requirement which is of 83 kW/MW$_{th}$ for the decentralised configuration and 64 kW/MW$_{th}$ for the centralised one (which includes also oxygen production). This is difference is due to the fact that in the integrated centralised configuration more electricity can be co-produced. The F-T chemical efficiency is of 44 %$_{LHV}$ for all solutions and it is not affected by the delocalisation of pre-treatment. The electricity co-produced is reduced by 27 % from the centralised to the decentralised pre-treatment configuration. The effect on transportation are very small, transportation in fact accounts for only a small fraction of the energy value (LHV) of the biomass used by the process, between 1 and 2.5 %$_{LHV}$. It should be underlined that the analysis is carried out considering a relatively small capacity for the lorries. Larger 40 t lorries could be employed instead, with 20 t capacity and 20 % better fuel economy per t of transported biomass, further reducing the impact of transport. In conclusion the greatest impact of delocalisation is on process integration. Only small differences arise in the overall energy efficiency as defined in Eq(1). The energy efficiencies of the decentralised configurations vary between 39.2 and 38.6 %$_{LHV}$, while for the centralised configuration between 39.7 and 38.9 %$_{LHV}$, with decreasing values for larger plant sizes.

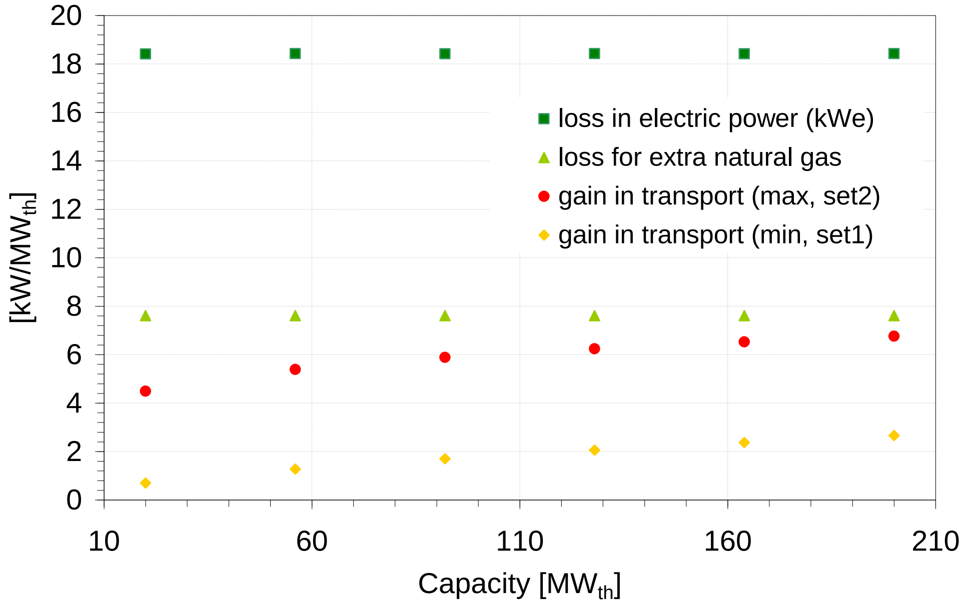

Figure 3: Gains and losses of the decentralised pre-treatment configuration in respect to the centralised one as a function of plant capacity

5. Conclusions

The analysis presented in this study is carried out considering the energy and mass balances and taking into account the effect on process integration. This study addresses the trade-offs of transportation and how they relate to the decentralisation of the pre-treatment step.

The results show that, for the capacity range and the assumptions considered in this study, in terms of fuel consumption, transport accounts for a small fraction (about 1-2.5 $\%_{LHV}$) of the energy of the biomass input. The chemical conversion efficiencies are the same for both the decentralized and centralized pre-treatment configuration (44 $\%_{LHV}$), only a small difference may be accounted for in the energy efficiency, which decreases of about 0.5 $\%_{LHV}$ from the centralized to the decentralized case. The gain obtained through delocalisation of the pre-treatment units appears to approach the extra requirements in natural gas for a separate pre-treatment. Nevertheless, the results show that the greatest effect of the delocalisation of pre-treatment is relative to the process integration as there is a penalty in the integration with the steam network for the delocalised process and therefore the heat that can be recovered and converted into electricity. The values of the energy efficiency are little affected as the definition in Eq.(1) doesn't take into account the different "value" of electricity, fuel and biomass.

The comparison of process options and configurations should take into account energy, environmental and economic performance. This study focuses on the energy trade-offs and provides an analysis of the role of transportation and pre-treatment de-centralisation for the thermo-chemical conversion of biomass into liquid fuels through gasification and F-T synthesis.

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