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**Interim Report IR-04-047**

# Biomass gasification for the co-production of Fischer-Tropsch liquids and electricity

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## Contents

# Abstract

This report examines the co-production of Fischer-Tropsch (F-T) liquids and electricity using biomass gasification. F-T liquids and electricity derived from biomass gasification appear as attractive alternatives for meeting energy needs in the medium-term. Biomass-based electricity generation constitutes an attractive option for the introduction of renewable energy resources and the gasification technology could offer an efficient, flexible and clean option for electricity production, as compared to conventional combustion-based plants. On the other hand, F-T liquids could have applications in the transportation sector, enabling the use of advanced internal combustion engines while being compatible with today's fuel delivery infrastructure. However, they still have to undergo substantial cost reductions in order to become competitive in the energy markets. Our analysis illustrates that a sales strategy for the co-product electricity could substantially contribute to improve the economics of F-T liquids.

The biomass gasification could act as a facilitating technology for the development of integrated and flexible bioenergy strategies, since it allows the production or co-production of, among others, electricity, hydrogen and clean liquid fuels. Biomass-based "energyplexes" would have an inherent flexibility that could be an important asset in liberalized energy markets.

We also illustrate the costs and energy consumption associated with long-distance bioenergy transport to Japan using two scenarios where forest residues produced in North America and energy crops produced in Latin America are transported to Japan via ship. A variety of supply chains were compared, including transport in the forms of logs, bales, chips, pellets and F-T liquids. Early conversion of biomass to F-T liquids in advance of long-distance transport via ship appears as a favorable option on economic and energy-consumption grounds.

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# Biomass gasification for the co-production of Fischer-Tropsch liquids and electricity

## 1 Introduction

Energy carriers derived from biomass could be an alternative to meet future energy needs in a number of sectors. Conversion of biomass into high-quality and more flexible final-energy carriers is a convenient vehicle to “add value” to biomass as an energy resource, and discourage its direct use as a final-energy fuel, which is associated with several environmental and social problems (WEC/FAO, 1999). Being clean and low-carbon-intensive, biomass-based energy carriers could contribute to meet environmental goals in the areas of air pollution and climate change, among others. Specifically, in what concerns climate change, if biomass is produced in a sustainable way, it can be carbon-neutral. In addition, if biomass-based energy systems could incorporate $CO_2$ capture and storage (CCS), these systems can offer possibilities for net removal of $CO_2$ from the atmosphere (Obersteiner *et al.,* 2001).

Biomass-based energy carriers may as well bring benefits in terms of security of energy supply, which has become a pressing concern for policy makers in view of structural weaknesses in this area in many countries. Specifically, the overall dependence of OECD countries on oil supply from politically-volatile regions and the definition of appropriate responses to potential oil-supply disruptions remain difficult issues that require both short and long term measures (EC, 2001; IEA, 2001; DOC, 1999).

Moreover, the transportation sector has become a growing concern for policy makers, in terms of energy consumption, oil dependence and polluting emissions. Biomass-based fuels are being considered as one of the possibilities that could displace currently dominating petroleum products in this sector and, thus, enable a transformation of transport systems into a more sustainable configuration in the long term (IEA, 2003). For instance, a European biofuels Directive has been introduced with the purpose of promoting the use of biofuels or other renewable fuels in the transportation sector (European Parliament, 2003). As a result, EU member states are requested to ensure that a minimum proportion of biofuels be placed on their markets taking into account competitiveness, security of supply and cost-effective environmental benefits.

However, the viability of an energy-supply strategy based on biomass-based energy carriers depends on a number of factors related to technological progress, economic incentives and institutional developments, among others. In particular, the availability of biomass for energy purposes and the feasibility of solving the logistic problems associated with large-scale production and/or transport of biomass (or biomass-derived energy carriers) are important aspects.

Biomass gasification is one of the promising technologies that could be strategic in enabling biomass to meet future energy needs in an efficient manner. Specifically, the gasification technology allows production or co-production of hydrogen, electricity and clean liquid fuels. Thus, it could provide a much needed product flexibility and would offer a route for an integrated bioenergy concept. In addition, gasification could enable convenient ways for capturing carbon dioxide from biomass-based energy systems. Moreover, biomass can be co-gasified with coal and the combined system could offer operative and environmental advantages for both feedstocks.

Co-production, or poly-generation, systems could be an attractive alternative for the production of electricity and fuels. These systems could improve the economics of fuels production and exploit synergies between the constituent processes (Williams *et al.*, 2000; NETL, 2001; Yamashita and Barreto, 2003). Moreover, in multiplying the market segments that can be supplied and, thus, the potential sources of profit, they could increase the adaptability and robustness of energy-services companies in the marketplace.

Among other biofuels, biomass-derived Fischer-Tropsch (F-T) liquids are seen as an attractive medium-term option. F-T liquids are premium products, with no sulfur or nitrogen and very low contents of aromatics, having attractive applications. Initially, they could be used as blending stock for petroleum-derived gasoline and diesel in order to comply with more stringent environmental regulations being enforced today or in preparation. Specifically, they could be used to assist refiners in meeting ultra-low-sulfur diesel specifications. Later on, they can be introduced more broadly as high-quality fuels that, while compatible with the available fuel-delivery infrastructure, could enable the introduction of advanced internal combustion engines and/or be used in hybrid-electric cars or in fuel cell vehicles (using on-board reforming).

Some automobile manufacturers are pursuing activities to support the introduction of F-T liquids (e.g., Snyder *et al.*, 2000; Steiger, 2000; Heinrich, 2003). Although short-term efforts appear to be concentrated on F-T liquids from natural gas (using the so-called gas-to-liquids or GTL technologies), subsequent steps in their strategy head towards biomass-based fuels.

On the other hand, biomass-based electricity generation constitutes an attractive option for the introduction of renewable energy resources. It is already used in several countries, although mainly in co-generation schemes where low-cost surplus biomass is available, such as pulp and paper industrial facilities. The gasification technology could offer an advanced and more convenient option for electricity production from biomass, as compared to conventional combustion-based plants. Higher conversion efficiencies can be achieved, in particular in small-size facilities, a wide range of feedstock qualities could be used and pollutant control can be facilitated.

In this report, we examine the co-production of Fischer-Tropsch (F-T) liquids and electricity using biomass gasification, and present costs and energy consumption for selected international transport chains of bioenergy to Japan. The remainder of this report is organized as follows. Section 2 presents a brief description of biomass gasification technologies. Section 3 presents our illustrative calculations of the co-production of Fischer-Tropsch (F-T) liquids and electricity using biomass gasification. Section 4 examines costs and energy consumption of international trade of bioenergy for the case of Japan using two illustrative cases, namely the production of forest residues in North America and the production of energy crops in Latin America. Finally, Section 5 outlines some conclusions from this analysis.

## 2 Biomass Gasification Technologies

Biomass gasification is the conversion of an organically derived carbonaceous feedstock (e.g., wood, energy crops, agricultural residues and municipal solid wastes) by partial oxidation into synthesis gas, also known as "syngas". This synthesis gas is a mixture of hydrogen and carbon oxide that can be converted into a number of chemicals and/or energy carriers. The gasification process consists of two main steps, pyrolysis, where the biomass feedstock is decomposed into gases, liquids and solids (referred to as char) and the gasification (combustion) itself where the "syngas" is generated. The chemical reactions in the gasification process take place at high temperatures (approx. 500-1400$^{o}$C). Pressures can be atmospheric or higher (up to approx. 480 psia). The oxidizing agent can be air, oxygen, steam or a mixture of them (Ciferno and Marano, 2002).

Depending on the type of gasifier, the applications and the characteristics of the fuel, there may be a need for cleaning and cooling the syngas product (BTG, 2003). Hydrocarbon-based contaminants (tar), particulates, ammonia, sulfur, chlorine, alkali metals, etc., may appear in the syngas and have to be removed (Ciferno and Marano, 2002). Hydrocarbon-based tar is one of the most critical contaminants in the gasification process. The presence of tar in the syngas represents a problem for its use in engines, turbines or fuel-synthesis systems because it can lead to malfunctioning, wearing, and/or increased maintenance costs of the equipment (BTG, 2003). Tar can be removed by chemical or physical methods. Chemical methods basically convert tar into other substances. Physical methods produce a tar waste stream that can be collected and removed. Although progress has been made in both areas, additional work is required in order to ensure an effective way to deal with tar. Other contaminants can be removed by using filters, scrubbers or additives.

An important aspect concerns the supply and handling of the biomass feedstock. Although several methods are available, there are still difficulties in ensuring a reliable and continuous feeding of biomass to the gasifier. This is due, among others, to the heterogeneous nature of biomass. Specifically, inconsistent moisture content, density, size and energy content of the feedstock could interfere with an adequate supply of biomass to the gasifier and, therefore, impact the quality of the gas product and the operation of the gasifier (Ciferno and Marano, 2002). Pre-treatment operations such as drying, re-sizing and pelletizing (see section 4) may contribute to improve the quality and homogeneity of the biomass feedstock.

Different types of gasifiers have been developed. They are typically classified according to the means to support the biomass in the reactor vessel, the direction of flow of both the biomass feedstock and oxidant and the way heat is supplied to the reactor (Ciferno and Marano, 2002). Four main categories are typically considered as follows: Updraft fixed bed (UFB), downward fixed bed (DFB), bubbling fluidized bed (BFB) and circulating fluidized bed (CFB). These four gasifier tyes are briefly described below. The discussion here relies mainly on Ciferno and Marano (2002).

The UFB gasifier is a simple, proven, low-cost technology, able to handle biomass with high moisture content. However, during the gasification hydrocarbon-based tar is formed. Due to the large content of tar in the resulting syngas in the UFB gasifier, extensive clean-up systems are required. The configuration of the downdraft gasifier (DFB) is similar to that of the UFB gasifier, except that the oxidant and product gases flow down the reactor, in the same direction as the biomass feedstock. This process allows the combustion of most of the tar formed and, therefore, minimum clean-up of the syngas is required. However, it requires the biomass feedstock to be dried, in order to achieve low moisture content prior to enter the gasifier. Also, the syngas product is at high temperature, thus requiring a secondary heat recovery system. In addition, part of the carbon (char) remains unconverted.

Because of their disadvantages regarding the production of tar and the fraction of carbon (char) that remains unconverted, fixed bed (i.e., UFB, DFB) gasifiers have in many cases not been favored for further development. Most biomass gasification systems under development today employ fluidized bed (BFB or CFB) gasifiers. We concentrate on these two types here.

The BFB gasifier uses a bed of fine, inert particles (sand or alumina) with good thermal characteristics. The oxidant is forced through the bed of inert particles. The gas velocity is such that a "fluidization" process occurs, where the gas bubbles and channels through the "fluidized" particle bed, such that the particles remain in the reactor. This fluidized bed of particles breaks up the biomass feedstock effectively and ensures good heat transfer in the reactor. A high conversion rate of the feedstock is possible with low tar production and a low fraction of unconverted carbon. Also, the BFB system supports a wide range of fuel particle sizes. This gasifier has already undergone extensive demonstration programs, under a wide range of conditions and biomass feedstocks. It could have advantages for production of hydrogen, liquid fuels or chemicals.

The circulating fluidized bed (CFB) gasifier operates under the same principle of the BFB gasifier, except that the gas velocities are such that the particles become part of the gas stream. The particles, then, must be separated at the gas exit and returned to the reactor. This configuration is useful for fast reactions, has also a high conversion rate of the feedstock with low tar production and a low fraction of unconverted carbon. However, the heat transfer is less efficient than in the BFB system and the range of fuel particle sizes is limited. The CFB gasifier is at an earlier stage of development than that of the BFB gasifier, and demonstration has been much more limited.

Biomass gasifiers are also categorized by the ways of supplying the heat needed for the chemical reactions in the pyrolysis step, namely directly- or indirectly-heated. In the directly-heated gasifiers the oxidant combusts a portion of the biomass feedstock to produce the required heat and the pyrolysis and gasification reactions are conducted in the same vessel. This, however, means that the products from the combustion step appear in the gas product.

When gasifiers use air as the oxidant (i.e., the so-called air-blown gasifiers) and are directly heated, a large fraction of the nitrogen present in the air is diluted in the gas product. As a consequence, the gas product typically has a low heating value. If oxygen is used as an oxidant (i.e., the so-called oxygen-blown gasifier), the syngas product is typically rich in hydrogen ($H_2$) and carbon monoxide (CO) and has a high heating value. However, an air-separation unit must be added in the case of oxygen-blown gasifiers, increasing their investment costs. Therefore, they may be less attractive for small-scale facilities.

In the indirectly-heated gasifiers the pyrolysis and gasification are physically separated and heat from the gasification (combustion) step is re-circulated from the combustion reactor to the pyrolysis reactor in order to provide the heat required for the pyrolysis reactions to take place (Ciferno and Marano, 2002). This approach prevents the products of the combustion process from appearing in the fuel gas.

## 3 Co-production of Fischer-Tropsch (F-T) Liquids and Electricity

Clean and flexible biomass-based energy carriers have been identified as an important element of technology strategies heading towards a sustainable global energy system in the future. They could contribute to reduce dependence on fossil fuels, specifically oil use in the transport sector, and improve air quality. Also, if biomass is grown in a sustainable manner, biomass-based energy carriers can be carbon neutral. That is, biomass can absorb as much carbon dioxide during its growing cycle as it is produced when it is transformed to final energy. Bioenergy could also have an important contribution to rural development (Turkenburg *et al.*, 2001).

The biomass gasification technology offers an attractive and flexible alternative for the production of a wide variety of high-quality energy carriers and could improve the future competitiveness of bioenergy. Moreover, co-production strategies, specifically those involving electricity in combination with hydrogen, liquid fuels or chemicals could improve the performance of biomass gasification technologies by yielding a higher overall efficiency.

The Fischer Tropsch (F-T) synthesis process, which allows production of liquid fuels (e.g., diesel and gasoline) from gaseous or solid fuels, has been known for several decades and is currently applied at a commercial scale in some countries (i.e., South Africa, Malaysia) mainly in combination with coal or natural gas feedstocks. Recently, it has received increased attention as an alternative to fulfill environmental constraints in the production of transportation fuels and as a possible route to exploit “stranded” (low-cost, remote) natural gas resources (Tijmensen, 2000).

Electricity generation also constitutes a sound alternative for biomass conversion and is already being used to a significant extent in several countries (e.g., Sweden, Finland). However, mainly combustion-based systems are in place, which have inherent limitations on efficiency and facility size. The gasification option could relax some of the key constraints for the utilization of biomass in electricity generation (Craig and Mann, 2002). The technology has potential to substantially increase the efficiency of biomass-fired electricity generation systems, since it can be used together with advanced gas turbine and combined cycle technology and, in the long term, possibly with fuel cells as well.

The co-production of biomass-based F-T liquids and electricity could be an important step in a strategy to increase the contribution of bioenergy in the global energy supply. F-T liquids could gain importance in the short term as environmental regulations imposed on fuels and transportation technologies become more stringent. Unlike other energy carriers such as hydrogen or methanol that require major infrastructure and/or technology changes, F-T liquids could be introduced in the medium term, profiting from their compatibility with current fuel delivery infrastructure and vehicle technologies. Renewable-based electricity, on the other hand, is being promoted in a number of countries (e.g., European Parliament, 2001). Among others, the biomass option constitutes a good candidate for support. Moreover, the sales of the co-product electricity could improve the economics of F-T liquids derived from biomass.

A co-production facility based on biomass gasification would also facilitate the separation and capture of a concentrated $CO_2$ stream. As mentioned above, under the assumption that biomass is carbon-neutral, the capture and geological storage of $CO_2$ from biomass gasification facilities could lead to a net removal of $CO_2$ from the atmosphere (Kraxner *et al.*, 2003; Obersteiner *et al.*, 2001). In such a way, the bioenergy system could contribute to the mitigation of greenhouse gases (GHG) by both providing carbon-neutral, high-quality energy carriers and as a long-term carbon sink. This, of course, presupposes that CCS systems would be able to overcome a number of existing technical, economic, environmental and public-acceptance problems in the future. These aspects have to be addressed before CCS becomes a viable option in a global GHG mitigation strategy.

In this section, we examine the co-production of F-T liquids and electricity for an illustrative system configuration. The technical and economic characteristics of the process analyzed here have been adopted from several sources in the literature (Hamelinck *et al.*, 2003a; Ciferno and Marano, 2002; Williams *et al.*, 1995).

## 3.1 F-T synthesis technology

The Fischer Tropsch (F-T) synthesis is a process that converts syngas into a mixture of mainly paraffinic and olefinic hydrocarbons of variable chain lengths, using an iron- or cobalt-based catalyst. With the help of the catalyst, a gas mixture of carbon monoxide (CO) and hydrogen ($H_2$) is converted into a variety of hydrocarbons from light gases (C2-C4) to heavy waxes (C50+)[1] and water, as described in the following reaction.

$$n\,CO + (2n+1)\,H_2 \rightarrow C_nH_{2n+2} + n\,H_2O \qquad (1)$$

An important parameter of the F-T synthesis is the chain growth probability, i.e., the probability that a hydrocarbon chain formed during the reaction continues growing after a given length. With a higher probability of chain growth, a higher amount of longer hydrocarbon chains are obtained in the process. The F-T product distribution depends on the chain growth probability and typically follows the so-called Anderson-Schulz-Flory (ASF) distribution[2] (Schulz, 1999). As the chain growth probability rises, the liquid (C5+) selectivity, i.e., the proportion of the F-T production in liquid state, increases. The selectivity depends, among others, on the type of catalyst, the ratio between $H_2$ and CO in the gas fed to the F-T synthesis reactor, temperature, pressure and reactor type. The presence of inert gas ($CO_2$, $CH_4$, $N_2$, light hydrocarbons) does not directly influence the selectivity, other than by decreasing the partial pressure of $H_2$ and CO and consequently decreasing the selectivity (Hamelinck *et al.*, 2003a).

A higher C5+ selectivity leads to a lower amount of gaseous products (C1-C4) and a higher amount of the heavier products. If light liquid products, such as diesel (C13-C17), are the

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[1] The notation CX, with X being an integer number, refers to the length of the hydrocarbon chain, which is related to the number of carbon elements present in it.

[2] The ASF distribution describes the molar yield in carbon number as: fraction $C_n=\alpha^{n-1}(1-\alpha)$, where $\alpha$ is chain growth probability and n the length of the hydrocarbon, which makes $(1-\alpha)$ the chance that the chain growth terminates.

desired product, hydro-cracking, i.e., the break-up of longer (heavier) hydrocarbon chains such as waxes into smaller (lighter) ones, is necessary (NETL, 2001; Tijmensen, 2000). A certain amount of hydrogen is needed to cut long chains into smaller parts in this process. Typically, maximum C5+ selectivity is favorable because it yields a maximum amount of liquids. However, in a co-production mode, the C1-C4 products contained in the off-gas of the F-T synthesis can be used to generate electricity. Depending on the liquid selectivity it will be (thermally) more efficient to produce additional F-T liquids or to generate electricity (Tijmensen, 2000).

## 3.2 System configurations

Figure 1 presents the block flow diagram of the F-T liquids/electricity co-production system examined here. In the system under analysis, biomass is initially fed to a pre-treatment unit where drying and size selection/reduction of the feedstock takes place. The pre-treated biomass, together with air or oxygen obtained in an air separation unit, enters the gasifier. The syngas exiting the gasifier undergoes a clean-up process. After being cleaned, the syngas is sent to an auto-thermal reformer (ATR) where the fraction of methane ($CH_4$) and heavier hydrocarbons contained in the syngas is converted to carbon monoxide (CO) and hydrogen ($H_2$).

The syngas stream is split in two flows. The first flow goes to a water gas shift (WGS) reactor, followed by a pressure swing adsorption (PSA) unit from where hydrogen for hydro-cracking is obtained. The rest of the syngas coming out of the clean-up unit goes, together with the purge gas from the WGS unit, through a $CO_2$ capture system (in the situations where maximizing the productivity of F-T liquids occurs or when considering CCS, otherwise the stream goes directly to the F-T synthesis reactor). The output is sent to the F-T synthesis reactor. Two main products result here: F-T liquids and off gas, the latter being used for electricity production in a gas turbine/steam turbine system.

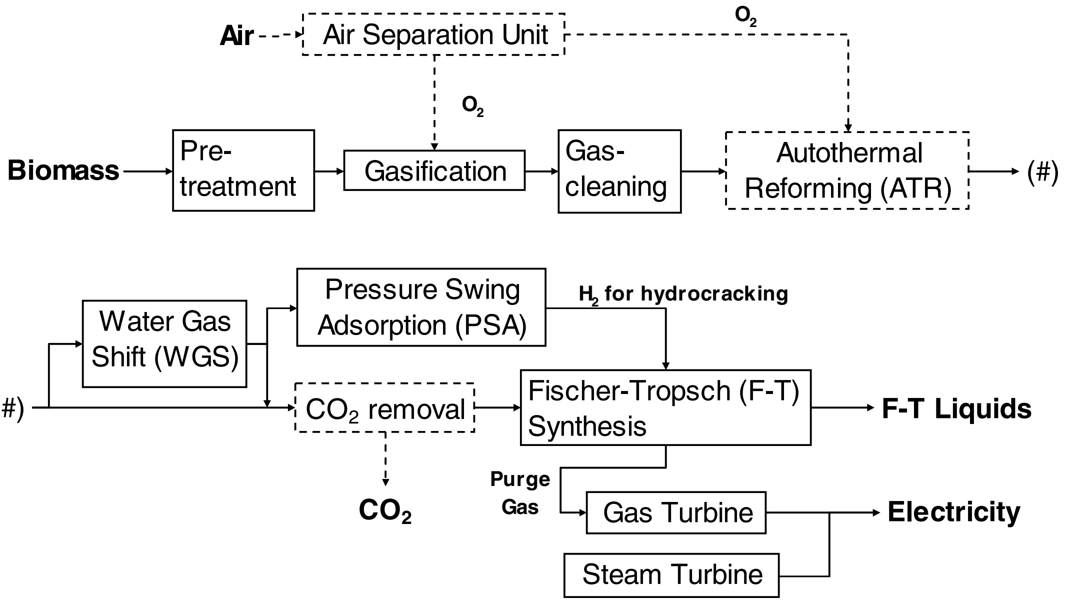

Figure 1: Schematic diagram of F-T liquids/electricity co-production system. Dotted lines indicate optional processes.

We consider three different gasifiers, namely the BCL (Battelle Columbus Laboratory), IGT (Institute of Gas Technologies) and TPS (Termiska Processor AB) gasifiers. Although a wide range of biomass resources, i.e., wood agricultural residues, energy crops, and municipal wastes, can be utilized as feedstock, in this study, wood is assumed to be used because the chemical composition of wood is relatively constant and data for wood gasification are widely available. Table 1 summarizes the characteristics of these gasifiers used for this analysis. It should be noted that the syngas from the TPS gasifier is diluted by nitrogen and has lower heating value than the BCL and IGT gasifiers. This could negatively affect the productivity of F-T liquids and electricity as explained above. Key features of the IGT gasifier are that it is operated under pressure and that pure oxygen is needed. The former will imply a higher cost of the gasifier, but down-stream equipments could be smaller and more economical especially at larger scales (Tijmensen *et al.,* 2002). The latter requires an air separation plant, which increases the investment cost, but it could benefit from scale effects if the auto-thermal reforming (ATR), which also needs pure oxygen, is used.

Table 1: Summary of selected gasifiers for this analysis.

| Name | BCL | IGT | TPS |
|---|---|---|---|
| Gasifier type | Circulating fluidized bed | Bubbling fluidized bed | Bubbling fluidized bed |
| Heat supply for gasification | Indirectly | Directly | Directly |
| Oxidizing agent | Air | Oxygen | Air |
| Biomass input ($GJ_{HHV}/h$) | 1540 (430 $MW_{th}$) | 1540 (430 $MW_{th}$) | 1540 (430 $MW_{th}$) |
| Pressure (bar) | 1.2 | 35 | 1.3 |
| Oxygen input (kg/kg dry feed) | 0 | 0.3 | 0 |
| $H_2$/CO ratio | 0.45 | 1.39 | 0.77 |
| Syngas composition mole fraction (%) on a wet basis | | | |
| $H_2O$ | 19.9 | 31.8 | 13.6 |
| $H_2$ | 16.7 | 20.8 | 13.3 |
| CO | 37.1 | 15.0 | 17.2 |
| $CO_2$ | 8.9 | 23.9 | 12.2 |
| $CH_4$ | 12.6 | 8.2 | 2.8 |
| $C_2$+ | 4.8 | 0.3 | 1.0 |
| $N_2$ | 0.0 | 0.0 | 39.2 |
| Syngas heating value($MJ_{HHV}/Nm^3_{dry}$) | 19.0 | 10.8 | 6.5 |
| Gasifier efficiency (a) (%) | 78 | 76 | 72 |

(a) Gasifier efficiency defined as [energy content syngas/energy content biomass input], based on HHV basis. Energy content of steam and air/oxygen added is not taken into account.

A variant of this process includes an auto-thermal reformer (ATR) where the fraction of methane ($CH_4$) and heavier hydrocarbons contained in the syngas is converted to carbon monoxide (CO) and hydrogen ($H_2$). Since methane and heavier hydrocarbons are thought to be inert in the F-T reactor, reforming of these hydrocarbons in the syngas can maximize the amount of product. Conversely, the amount of purge gas made available for electricity production is reduced, therefore resulting in a smaller amount of generated electricity. We examine cases with and without auto-thermal reforming (ATR).

The following notation is used to identify the different cases considered here. The cases will be primarily identified by the gasifier that is assumed (i.e., BCL, IGT or TPS). In addition, for the cases with auto-thermal reforming (ATR), an ‘a’ is added to the label (e.g., BCLa). Regarding separation and capture of $CO_2$, two possibilities have been considered here. In the first case, referred to as ‘-r’ (added to the previous label, e.g., BCL-r or BCLa-r), it is assumed that $CO_2$ is removed from the system but not captured, i.e., it is finally emitted to the atmosphere. The rationale behind this case is the hypothesis that by separating the $CO_2$, the amount of F-T products could be increased as mentioned above. In the second case, $CO_2$ is both removed and captured for storage in geological reservoirs. This is referred to as '-rr' (the corresponding label for this case becomes e.g., BCL-rr or BCLa-rr). Table 2 presents a summary of the different combinations of components examined in this study together with their labels.

Table 2: Summary of the combinations of components in the system configurations examined in this study.

| Gasifier | Reforming | $CO_2$ Removal | Acronym |
|---|---|---|---|
| BCL | No ATR | • No $CO_2$ removal | BCL |
| | | • $CO_2$ removed but emitted $^{(a)}$ | BCL-r |
| | | • $CO_2$ removed for storage | BCL-rr |
| | ATR | • No $CO_2$ removal | BCLa |
| | | • $CO_2$ removed but emitted $^{(a)}$ | BCLa-r |
| | | • $CO_2$ removed for storage | BCLa-rr |
| IGT | No ATR | • No $CO_2$ removal | IGT |
| | | • $CO_2$ removed but emitted $^{(a)}$ | IGT-r |
| | | • $CO_2$ removed for storage | IGT-rr |
| | ATR | • No $CO_2$ removal | IGTa |
| | | • $CO_2$ removed but emitted $^{(a)}$ | IGTa-r |
| | | • $CO_2$ removed for storage | IGTa-rr |
| TPS | No ATR | • No $CO_2$ removal | TPS |
| | | • $CO_2$ removed but emitted $^{(a)}$ | TPS-r |
| | | • $CO_2$ removed for storage | TPS-rr |
| | ATR | • No $CO_2$ removal | TPSa |
| | | • $CO_2$ removed but emitted $^{(a)}$ | TPSa-r |
| | | • $CO_2$ removed for storage | TPSa-rr |

(a) only for the improvement in F-T liquids productivity
(b) In all configurations a once-through F-T synthesis reactor is considered
(c) ATR stands for auto-thermal reforming

## 3.3 Technical and economic assumptions

Based on the chemical equations of the F-T synthesis, auto-thermal reforming and water gas shift reaction, the mass flows were calculated for each configuration. The key assumptions for the calculation are as follows (details are explained in Appendix B).

- The variety of chain lengths of the hydrocarbons in the F-T synthesis is determined according to the Anderson-Schulz-Flory (ASF) distribution.
- In this study, only once-through concepts were examined. For such schemes, 80% of CO is converted to F-T product (liquids and gases).
- Light products here refer to C5-C9 chains. Heavy products refer to C10-C19 chains.
- All C20+ chains are hydrocracked to lighter liquids (C10-C19).
- Only the liquid part of the F-T product (i.e., C5+) is recovered as F-T liquids. The gaseous part of it is burned to produce electricity.
- The fraction of liquids (C5+) in the F-T product is negatively affected by the fraction of inert gases in the input gas to the F-T reactor. $H_2O$ in the input gas is removed before the F-T reaction.
- The degree of shift reaction is determined in such way that the $H_2/CO$ ratio in volume of the input gas to the F-T reactor is 2:1, where production of liquid F-T products (C5+) is maximized.

- Off gas from the F-T reactor is burned in a gas turbine if its heat value is above 5 $MJ_{LHV}/Nm^3$ on a wet basis. Otherwise it is burned in a steam turbine.
- For the cases with $CO_2$ removal for sequestration, the $CO_2$ that is separated from the F-T liquids production plants is compressed to supercritical pressures for pipeline transportation.

The F-T liquids production costs are calculated by dividing the total annual costs by the total amount of F-T product. The total annual costs consist of annual capital investments, operation and maintenance costs, biomass feedstock and electricity sales/purchase. The main assumptions for this economic evaluation are shown in Table 3.

Table 3: Parameters for the economic evaluation in this study.

| | |
|---|---|
| Total capital requirement | 130% of total investment costs |
| Total investment costs | 140% of sum of hardware costs |
| Hardware costs | see Table 4 |
| O&M costs | 4% of annual investment costs |
| Interest rate | 10% |
| Economic lifetime | 15 years |
| Capacity factor | 90% |

The total investment costs are based on cost data at the component level, which were obtained from a literature survey. Table 4 shows basic cost and size for each component together with the scaling factor used in this study. These parameters are derived from several studies. It is assumed that the cost of each component is affected by its capacity as follows:

$$\text{CostA/CostB} = (\text{SizeB/SizeA})^{R}, \text{ with R = scaling factor} \qquad (2)$$

Table 4: Basic costs and scales for the components used. These costs are hardware costs, which do not include installation labor, engineering and contingencies, based on several sources; Hamelinck *et al* (2003a), Ciferno and Marano (2002), Tijmensen *et al* (2002), Hamelinck and Faaij (2001), Williams *et al* (1995). For details, see Appendix C.

| | | Base cost million US$2000 | Base Scale | | Scaling factor |
|---|---|---|---|---|---|
| Pre-treatment | | 12.1 | 1000 | GJ/h | 0.68 |
| Gasification | BCL gasifier | 11.1 | 1000 | GJ/h | 0.78 |
| | IGT gasifier | 30.6 | 1440 | GJ/h | 0.70 |
| | TPS gasifier | 26.9 | 1199 | GJ/h | 0.70 |
| | $O_2$ plant | 23.7 | 600 | t/day | 0.75 |
| | $O_2$ compressor | 16.8 | 13.2 | MWe | 0.85 |
| Gas Cleaning | | 18.1 | 1548 | GJ/h | 0.70 |
| Syngas Processing | Compressors | 12.0 | 13.2 | MWe | 0.85 |
| | Auto-thermal reformer | 24.9 | 10000 | Kmol-feed/h | 0.72 |
| | Shift reactor | 32.9 | 14600 | Kmol-$H_2$,CO | 0.70 |
| | PSA | 25.8 | 9600 | Kmol-feed/h | 0.70 |
| | Selexol $CO_2$ removal | 16.0 | 810 | Kmol-$CO_2$/h | 0.70 |
| | $CO_2$ drying and compressing | 10.3 | 1.945 | Mmol-$CO_2$/h | 0.51 |
| Fuel Production | F-T reactor | 26.9 | 472 | GJ-FT/h | 0.70 |
| | Fuel upgrading including hydrocracking | 171.4 | 10973 | GJ-C5+/h | 0.70 |
| Power Generation | Gas turbine + HRSG [(a)] | 16.2 | 26.3 | $MW_e$ | 0.70 |
| | Steam turbine + steam system | 5.2 | 10.3 | $MW_e$ | 0.70 |

(a) Heat Recovery Steam Generator (HRSG)

It should be noted that, for the cases with $CO_2$ removal for sequestration (i.e., '-rr' in Table 2), we include the costs of $CO_2$ compression as well as $CO_2$ capture into the plant investment costs. Also, following Kreutz *et al.* (2002), we include the costs of $CO_2$ transport and storage of 5 US$/t$CO_2$, which corresponds to a 100-km pipeline and a 2-km deep injection well. This aggregate estimate is in line with the ranges reported by Freund *et al.* (2003), who give 1-3 US$/t$CO_2$ as a plausible range for costs of storing $CO_2$ in deep saline aquifers or depleted oil/gas fields and a likely range of 1-3 US$/t$CO_2$/100 km for transportation of captured $CO_2$ from sources to reservoirs.

## 3.4 Results

### 3.4.1 *Production costs*

This section discusses the production costs of F-T liquids for the different configurations of the biomass co-production system examined here. The underlying assumption of this calculation is that, if there is a net surplus of the co-product electricity, it can be sold at a given price. If there is a deficit, i.e., if the process requires a net input of electricity, it will be bought at the same price. Besides other factors, the relative amounts of the co-products, i.e., F-T liquids and electricity, and the investment costs have a key influence on the resulting production costs. Therefore, the explanation here will highlight the differences in these two elements between the different cases.

Figure 2 shows the amounts of electricity, heavy F-T liquids and light F-T liquids produced in each case (in GJ/hour). The left-most part of the graph shows the figures for the BCL gasifier. The central part of the graph corresponds to the IGT gasifier and the right-most part to the TPS gasifier. Also, the total production costs of F-T liquids resulting in each case are shown as a continuous line for reference purposes.

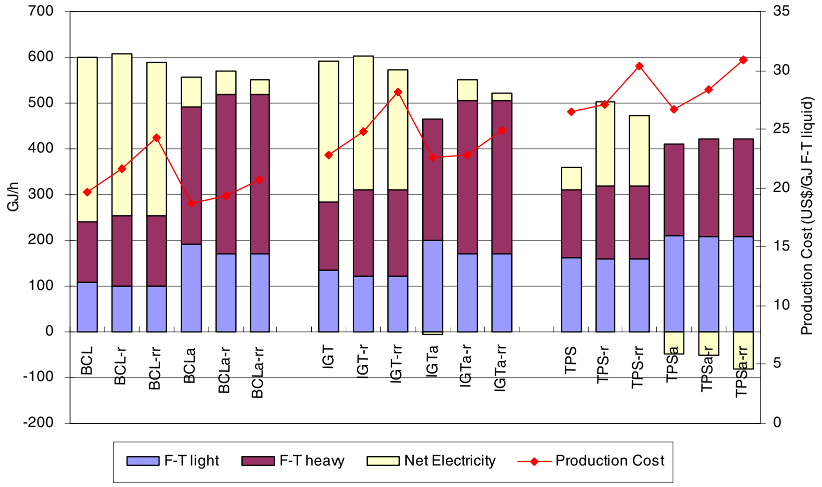

Figure 2: The amount of electricity, heavy F-T liquids and light F-T liquids produced in each case (in GJ/hour). The label "a" after the names of gasifier types (i.e., BCL, IGT and TPS) indicates the cases with auto-thermal reformer. The label 'r' means $CO_2$ removal without sequestration and the label 'rr' $CO_2$ removal with sequestration. Production costs of F-T liquids, assuming a biomass price of 2 US$/GJ and electricity price of 0.04 US$/kWh, are also shown as a reference.

As can be seen, for all gasifier types, a larger amount of F-T liquids (mainly heavy products) is produced in the cases with auto-thermal reformer (ATR) than in those without ATR. This is mainly because ATR converts $CH_4$ and heavier hydrocarbons, which would be inert in the F-T reactor, into CO and $H_2$ to be utilized for F-T synthesis. However, in the TPS gasifier, the contents of $CH_4$ and heavier hydrocarbons in the syngas are smaller than in the other gasifiers (Table 1), resulting in less gains in the amount of F-T liquids when ATR is included. On the other hand, the syngas from the TPS gasifier contains a significant amount of nitrogen. Therefore, the heating value of the off-gas from the F-T reactor is too low to be burned in the gas turbine, resulting in the net import of electricity.

As shown in Figure 2, the separation of $CO_2$ leads to a slight increase in the amount of F-T liquids and to a small decrease in the amount of electricity generated (e.g., 'IGT-r' versus 'IGT'). These are due to the higher selectivity brought by the higher partial pressures of $H_2$ and CO through $CO_2$ removal as mentioned above. The cases with $CO_2$ removal and sequestration (i.e., '-rr') show a slight decrease in the amount of electricity as compared to the $CO_2$-removal-only case (i.e., '-r'). This is due to the consumption of electricity necessary for the compression and drying of the $CO_2$ stream. Still, differences are not significant.

Figure 3 presents the disaggregated investment costs for the different cases considered here. Figure 4 shows the production costs which are disaggregated into capital investment, O&M, feedstock, $CO_2$ transport and storage and electricity sales. As before, the left-most part of the graph shows the figures for the BCL gasifier. The central part of the graph corresponds to the IGT gasifier and the right-most part to the TPS gasifier. Also, the production costs of F-T liquids resulting in each case are shown as a continuous line. This calculation assumes a biomass price of 2 US$/GJ and an electricity price of 0.04 US$/kWh. An analysis of the sensitivity of the production costs of F-T liquids to these two factors is conducted in section 3.4.2 below.

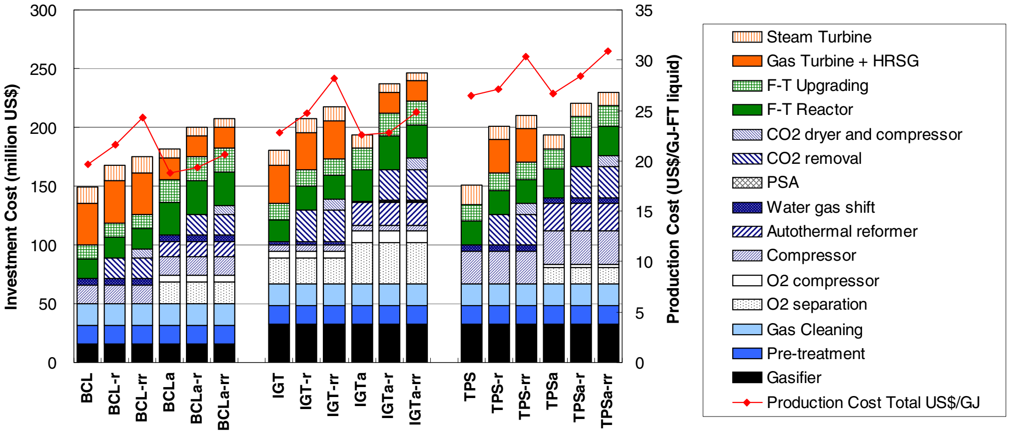

Figure 3: The disaggregated investment costs for the cases examined. The label "a" after the names of gasifier types (i.e., BCL, IGT and TPS) indicates the cases with auto-thermal reformer. The label 'r' means $CO_2$ removal without sequestration and the label 'rr' $CO_2$ removal with sequestration. Production costs of F-T liquids, assuming a biomass price of 2 US$/GJ and an electricity price of 0.04 US$/kWh, are also shown as a reference.

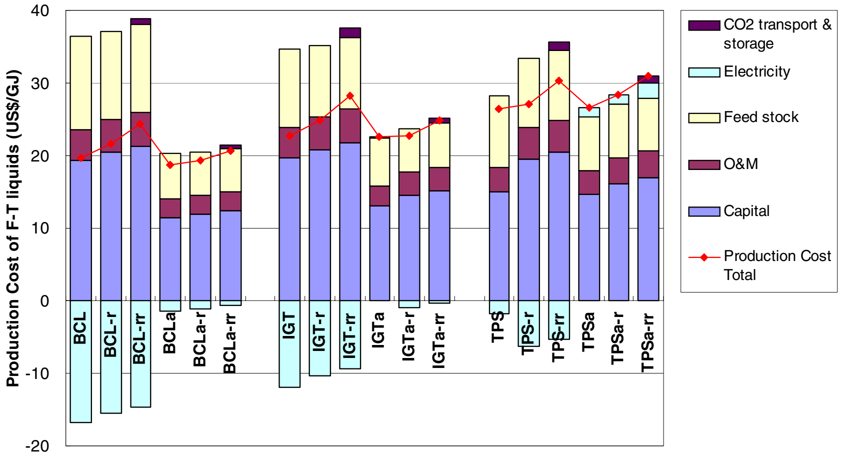

Figure 4: The disaggregated production costs of F-T liquids for the cases examined, assuming a biomass price of 2 US$/GJ and electricity price of 0.04 US$/kWh. Total production costs are shown as a continuous line. The label "a" after the names of gasifier types (i.e., BCL, IGT and TPS) indicates the cases with auto-thermal reformer. The label 'r' means $CO_2$ removal without sequestration and the label 'rr' $CO_2$ removal with sequestration. Electricity sales are negative (i.e., they are subtracted from the cost), while purchases are positive (i.e., they are added to the cost).

It can be noticed that, in general, production costs of F-T liquids in the cases using the BCL gasifier are lower than in the cases using the IGT and the TPS gasifiers. This is due to the higher efficiency of gasification (see Table 1 and Figure 2) and the lower total investment cost (Figure 3) in the former. For the cases using the IGT gasifier, although the gasification efficiency is as high as that of the BCL gasifier, total capital costs are higher because a costly $O_2$ production plant and a pressurized gasifier, which is more expensive than an atmospheric one, are required. For the cases with the TPS gasifier, although total capital costs are not higher than those of the cases using the BCL gasifier, its lower gasification efficiency worsens the economic performance.

Although including ATR increases the total investment costs, for the BCL and IGT gasifiers, gains in the F-T products are large enough as to make the production costs in the cases with ATR lower than those in the cases without ATR. For the TPS gasifier, on the other hand, the inclusion of ATR results in higher production costs due to the lower gains in the amount of F-T products and the fact that the system becomes a net consumer of electricity, as illustrated in Figure 2 above.

As discussed in the context of Figure 2 above, the separation of $CO_2$ leads to a slight increase in the amount of F-T liquids and to a small decrease in the amount of electricity generated. However, the increase in the amount of F-T liquids is too small to compensate for the large increase in the investment cost (Figure 3), and accordingly, $CO_2$ removal leads to the higher production costs (Figure 4). Thus, under the assumptions here, $CO_2$ removal just for the sake of increasing the amount of F-T liquids does not seem to be a good option for lowering the F-T liquid production cost. But, if $CO_2$ sequestration is considered, it could become a reasonable measure to improve the economy due to its double function, i.e., increasing the amount of F-T liquids production and reducing $CO_2$ emission. This issue is discussed in section 3.4.3 below.

### 3.4.2 *Sensitivity to the prices of biomass and electricity*

Figure 5 presents the production costs of F-T liquids as a function of the price at which the co-product electricity can be sold. Production costs of F-T liquids were calculated based on the assumptions described in Table 3 above. For reference purposes, the production costs of petroleum-derived diesel with and without taxes are also shown.[3]

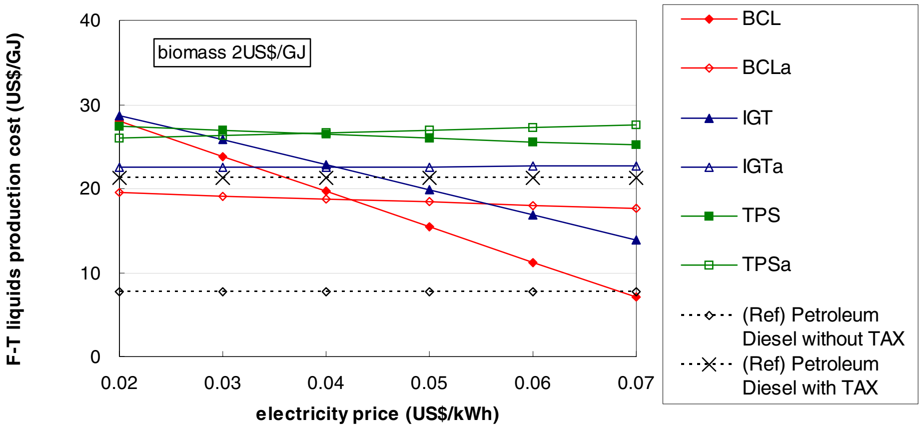

Figure 5: Estimated F-T liquids production costs as a function of the co-produced electricity price. Price of biomass is assumed 2 US$/GJ. Suffix 'a' after a name of gasifier type (i.e., BCL, IGT and TPS) is for the case with auto-thermal reforming. For reference purposes, the production costs of petroleum-derived diesel without and with taxes are also shown (see footnote 3 for assumptions).

As can be seen, for systems without ATR, increasing the selling price of electricity has a positive impact on the economics of F-T products. The effect is more significant for the BCL and IGT gasifiers where a larger amount of net electricity becomes available. As for the TPS gasifier, with a much smaller amount of net electricity for sale, the reduction in the production costs of F-T liquids is much lower.

When the ATR process is incorporated, the amount of net electricity is substantially reduced in the BCL and IGT cases and the effects of selling the co-product electricity become barely noticeable. In the TPS case, the inclusion of the ATR process makes the system change from a net producer to a net consumer of electricity. Thus, increasing the selling price of electricity has now a negative impact on the production costs of F-T liquids.

To summarize, the effectiveness of the co-production strategy depends not only on the price at which electricity can be sold but also on whether the system configuration of the co-production system allows the production of enough electricity as to make an impact on the production costs of F-T liquids.

Also, whether the co-production strategy makes F-T liquids competitive with petroleum-derived diesel, depends on the reference for the comparison, i.e., with or without taxes.

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[3] The cost of petroleum-derived diesel without tax is calculated based on the average retail price of diesel excluding taxes in November 2003 of five European countries (i.e., France, Germany, Spain, Italy and UK), which is 8.8 US$/GJ, assuming the distributor margin of 15%. The cost with tax is obtained by adding the average tax, which is 13.6 US$/GJ, of the same European countries on the cost without tax.

Clearly, if compared with non-taxed petroleum-derived diesel, even a co-production strategy bringing strong cost reductions can not make biomass-derived F-T liquids competitive. However, when compared against taxed petroleum-derived diesel, the co-production strategy proves very beneficial for the competitiveness of biomass-based F-T liquids.

The price of biomass has a significant influence on the F-T liquids production costs. Figure 6 shows the F-T liquid production costs as a function of the biomass feedstock price. It is assumed that the electricity sales/purchase price remains constant at 0.04 US$/kWh. For reference purposes, the production costs of petroleum-derived diesel with and without taxes are also shown. It should be noted that, as mentioned above, we assume wood as the biomass feedstock here. Although biomass in the form of municipal solid waste can have negative prices, additional pretreatment or syngas cleaning process might be needed, thus resulting in a higher investment cost.

As expected, higher biomass prices result in higher production costs. The effects appear larger in the cases without ATR than with ATR. This is because the cases without ATR need more biomass feedstock input per unit of F-T liquids since a larger part of the biomass feedstock is used to produce electricity. The effect appears more substantial for the BCL gasifier without ATR, because it is the technology where the least F-T liquids and most electricity are produced. This trend is visible in Figure 5. The BCL gasifier case without ATR is the most sensitive to the prices of both electricity and biomass.

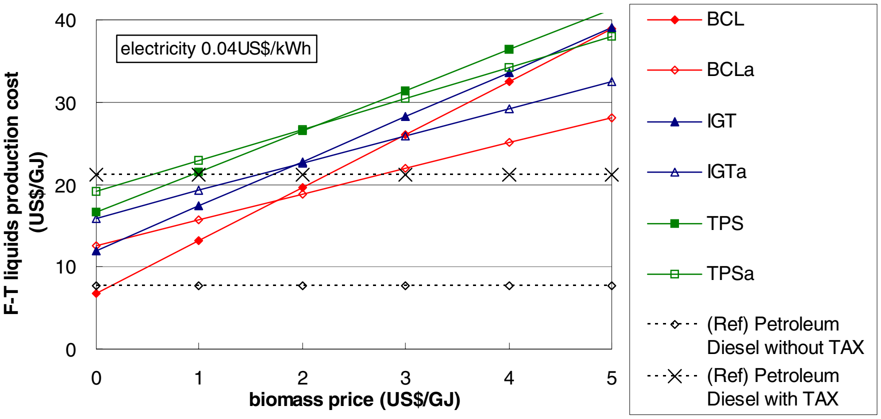

Figure 6: Estimated F-T liquids production costs as a function of the biomass feedstock price. Price of electricity co-produced is assumed 0.04 US$/kWh. Suffix ‘a’ after a name of gasifier type (i.e., BCL, IGT and TPS) is for the case with auto-thermal reforming. For reference purposes, the production costs of petroleum-derived diesel without and with taxes are also shown (see footnote 3 for assumptions).

As indicated in Figure 5 and Figure 6, F-T liquids from biomass are not competitive with the untaxed petroleum-derived diesel even if the co-produced electricity is sold at higher prices or if a cheaper biomass feedstock is available. However, taking into account the tax imposed on the petroleum-derived diesel in many countries makes F-T liquids from biomass competitive with the conventional diesel in a wide range of prices of electricity and biomass (except for the TPS gasifier). Figure 6 shows that the maximum biomass price that leads to competitiveness at about 3 US$/GJ.

As discussed above, incorporating ATR leads to more F-T liquids production and less electricity and the economy of F-T liquids production depends on the prices of the biomass feedstock and the electricity sold. It is illustrative to learn which configuration (i.e., ATR, no ATR) would be more economical in a variety of prices of both the feedstock and sold electricity. Figure 7 shows economic break-even lines between the configurations with and without ATR for three gasifier types examined here. These lines give prices of biomass and electricity where the production costs of F-T liquids from the configurations with and without ATR become equal. When the prices of electricity and biomass are in the areas above these lines, the cases without ATR, where more electricity is produced, are more economical, and vice versa.

That is, if the price at which the co-product electricity can be sold is high enough, a configuration that maximizes electricity production and, therefore, the effects of the co-production strategy on the production costs of F-T liquids is more attractive, especially if biomass prices are low enough. If, on the other hand, the price of the biomass feedstock is high, a configuration that favors a larger amount of F-T liquids becomes more attractive, in particular when the selling prices of electricity are small and, thus, the co-production strategy does not have a sizeable impact on the production costs of F-T liquids.

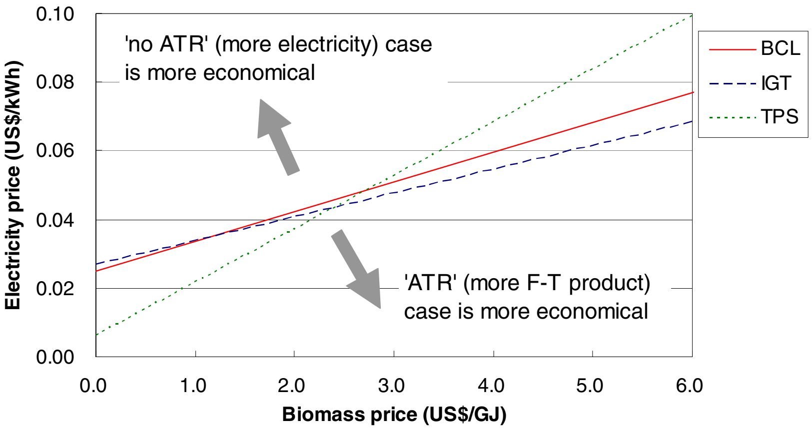

Figure 7: Economic break-even lines between the configurations with and without ATR for the different gasifier types examined here. When the prices of electricity and biomass are in the areas above these lines, cases without ATR, where more electricity is produced, are more economical than cases with ATR, and vice versa.

### 3.4.3 *$CO_2$ emissions and carbon tax*

Figure 8 depicts the $CO_2$ balance for each of the cases analyzed here. $CO_2$ emitted during the process, $CO_2$ contained in the product and $CO_2$ removed for sequestration are distinguished here. The carbon content of the biomass feedstock is assumed to be 24.5 kgC/GJ-HHV. In the cases without $CO_2$ capture, a large part of the carbon input is emitted to the atmosphere as carbon dioxide during the process (nearly 90% for the cases without ATR and nearly 80% for the cases with ATR) and the rest remains in F-T liquids product. This remaining fraction is emitted into the atmosphere at the end-use stage.

With the inclusion of the CCS system (i.e., '-rr'), a certain amount of carbon can be captured for sequestration (approximately 30% for the BCL gasifier and 55% for the IGT and TPS gasifiers). The amount of captured carbon for the BCL gasifier is lower than for the other gasifiers because in the BCL case a lower fraction of carbon in the biomass feedstock leaves the gasifier as synthesis gas.[4] This fraction represents the maximum practical ratio (i.e., upper bound) of carbon capture for the co-production systems of F-T liquids and electricity examined here. Although, in principle, it is possible to capture more carbon by increasing the degree of the water gas shift reaction, where CO and $H_2O$ are converted into $CO_2$ and $H_2$, this would produce a higher $H_2/CO$ ratio, resulting in less productivity of F-T liquids and, consequently, higher production costs.[5]

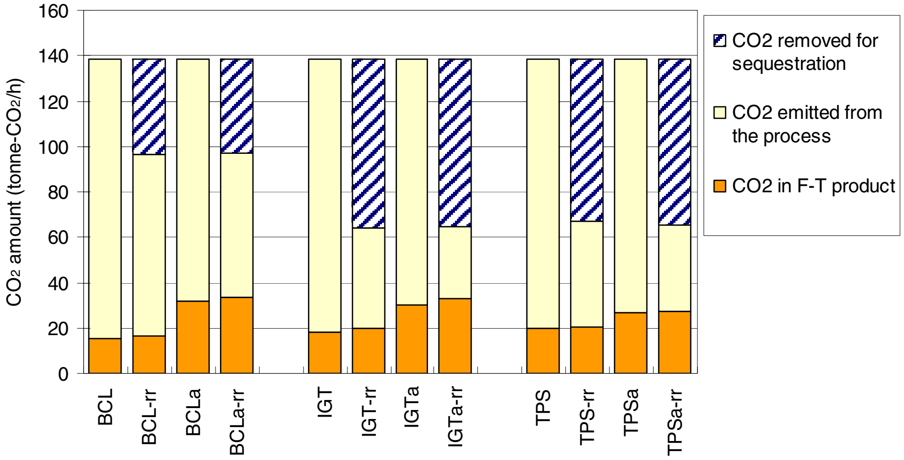

Figure 8: $CO_2$ balance for each of the cases under analysis here. The label 'a' after a name of a gasifier type, i.e., BCL, IGT and TPS, indicates the cases with auto-thermal reformer. The label 'rr' means $CO_2$ removal and sequestration.

We now examine the effects of a carbon tax on the production costs of F-T liquids for our biomass-based co-production systems. Carbon taxes are one of a number of policy instruments available for achieving emission reduction targets and promoting the diffusion of cleaner, low-emissions energy technologies. The taxes provide a disincentive for emitting $CO_2$ without specifying the amounts of emissions that should be reduced. They may encourage the development and deployment of technologies that make emissions reductions less costly in the long term (e.g., Jaffe *et al.*, 2000). Carbon taxes or similar instruments have been implemented in some countries (e.g., Norway, Christiansen, 2001) and have been proposed at the international level by the European Commission, among others.

Figure 9 presents the influence of a carbon tax on the production costs of F-T liquids for our biomass-based co-production system. It is assumed that the biomass feedstock is carbon-neutral and has a price of 2 US$/GJ. The price at which the co-product electricity is sold is 0.05 US$/kWh. In this estimation, $CO_2$ emissions from F-T liquids production and end use

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[4] The fraction of carbon in the biomass feedstock that leaves the gasifier as part of the syngas, calculated using the compositions of syngas and gasifier efficiencies in Table 1, is as follows; 79% for the BCL gasifier, 98% for the IGT gasifier and 96 % for the TPS gasifier. Williams *et al* (1995) indicate 75.2% for the BCL gasifier and 96.2% for the IGT gasifier.

[5] We examined only pre-combustion capture of carbon in this study. Post-combustion capture could enable capture of more carbon, but it could possibly raise the production cost.

stages are taken into account. $CO_2$ emissions from production and transport of the biomass feedstock are not included. For reference purposes, the production cost of petroleum-derived diesel without taxes is also shown (see footnote 3 for assumptions). Notice that we have chosen only the case of petroleum-derived diesel without taxes as reference for the comparison on the assumption that if a carbon tax would be imposed on the system, other taxes may be phased out.

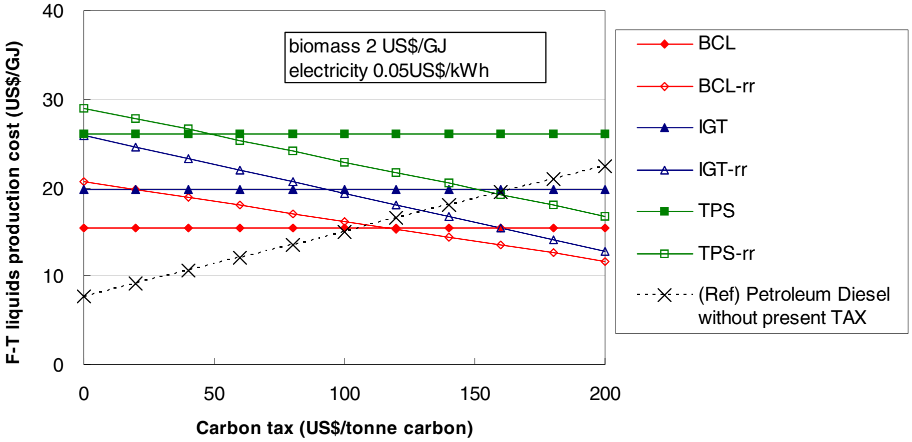

Figure 9: The influence of a carbon tax on the production costs of F-T liquids, assuming that the biomass feedstock is carbon-neutral. Label 'rr' means $CO_2$ removal with sequestration. Production cost of petroleum-diesel is also shown (see footnote 3 for assumptions). $CO_2$ emissions examined here include those in the production and end use stage of the F-T liquids but not those in the production and transport of the biomass feedstock.

Assuming a carbon-neutral biomass feedstock, the imposition of a carbon tax will not affect the production costs of F-T liquids, when no carbon capture is incorporated. If carbon capture for sequestration is incorporated into the co-production system, the imposition of the carbon tax leads to a decrease of the production costs of F-T liquids making them more competitive. The effect appears lower in the BCL case with $CO_2$ capture (i.e., 'BCL-rr') than in the other gasifiers (i.e., 'IGT-rr' and 'TPS-rr'). This is because the BCL system has a lower amount of $CO_2$ captured as mentioned above.

The carbon taxes needed to make these systems with $CO_2$ capture competitively with the systems without $CO_2$ capture are approximately 110, 95 and 45 US$/tC for the BCL, IGT and TPS gasifiers respectively. On the other hand, the production costs of petroleum-derived diesel increase as the level of the carbon tax is increased.

Under the assumptions here, and without the current tax on petroleum-derived diesel, the carbon tax needed to make biomass-derived F-T liquids competitive with petroleum-derived diesel is higher than 100 US$/tC even if $CO_2$ capture is incorporated. This is because, due to the upper limit for the amount of $CO_2$ captured as mentioned above and the fact that F-T liquids are carbon-containing products, the downward slopes for the cases with $CO_2$ capture are not sufficiently steep. That is, the F-T production costs are not reduced fast enough as the carbon tax is increased as to intercept the price of non-taxed petroleum-derived diesel below a carbon tax of 100 US$/tC. A combination of a carbon tax and some other taxation measures might be needed for making the biomass-derived F-T liquids with $CO_2$ capture competitive with petroleum-derived diesel.

# 4 International Transport of Biomass

An adequate, continuous and reliable supply of biomass is a fundamental aspect for the successful introduction of biomass-based energy carriers at a large scale. In this section, we examine the costs and energy consumption associated with long-distance bioenergy transport to Japan. For this purpose, we use illustrative cases involving the production of forest residues in North America and the production of energy crops in Latin America and their subsequent transport in the form of logs, bales, chips, pellets or biomass-derived F-T liquids via ship to Japan.

## 4.1 International trade of bioenergy

Several analyses have examined the potential availability of bioenergy. Hoogwijk *et al.* (2003) have conducted a comparative analysis of the bioenergy potentials reported in the literature and examined the main factors that influence biomass availability. The range of global bioenergy potentials for the year 2050 estimated by Hoogwijk *et al.* (2003) is very wide, between 32 EJ/year and approximately 1130 EJ/year. These two figures represent two extreme scenarios. In the first scenario, very favorable conditions are assumed. If conditions for bioenergy development are, however, highly unfavorable, then only the lower bound could be exploited. Although both scenarios are highly unlikely, they provide a valuable insight on the possible range of potentials. Actual values may lie in between. The conclusions of Hoogwijk *et al.* (2003) also point out to the fact that in the studies under scrutiny there has been insufficient analysis of the influence of competing uses of land and competing uses of biomass in the estimates for bioenergy potentials.

But, even with a sizeable technical bioenergy potential at hand, a number of obstacles have to be surmounted if it is to be tapped, at least partially, and there is uncertainty in the feasibility of the transitions required for doing so (Faaij *et al.*, 2000a). Thus, it cannot be taken for granted that the technical potential can be exploited. The ability to exploit the global bioenergy potential will depend on a number of actions related to technological progress, economic incentives and institutional developments, among others. Besides technical and economic aspects, the successful application of biomass technologies, particularly at a large scale, presupposes finding solutions to a number of issues that currently prevent biomass from having a more relevant role in meeting energy needs. These include, among others, minimizing associated environmental impacts, development of dedicated fuel supply systems, avoiding conflicts with food production, bio-materials production and other land uses, solving logistics-of-supply problems, particularly those related to transport of the feedstock, and overcoming organizational difficulties related to the co-ordination of a large number of actors (Turkenburg *et al.*, 2001).

If the bioenergy potential could be tapped in a sustainable and effective manner, an international system for trade of energy from biomass could come into place. Several world regions appear to have a much larger bioenergy potential than others and could become net exporters. According to Vesterinen and Alakangas (2001), bioenergy trade has increased rapidly during the past ten years thanks mainly to the dynamic growth in the use of biomass for district heating, especially in Northern Europe. Vesterinen and Alakangas (2001) present known and estimated international biomass flows from/to European countries. While the bulk of biofuels is traded between European countries, some inter-continental trade also takes place, mainly in the form of imports from Canada and Northern Africa and exports to the Middle and Far East. Bioenergy is most often traded in the form of refined wood fuels (pellets and briquettes) and industrial by-products (sawdust, chips), although in Central Europe also wood waste is included. The total volume of the international bioenergy trade in Europe has been estimated to be at least 50 PJ/year (Vesterinen and Alakangas, 2001).

International trade of bioenergy could have both positive and negative impacts at the global level. On the positive side, it may foment the utilization of bioenergy at the international level, particularly on those countries without indigenous biomass resources, and could have stabilizing effects on biomass prices. It could help importing countries to meet environmental constraints such as caps on $CO_2$ emissions. It could also serve as a driving force of economic development and sustainable use of natural resources in countries producing bioenergy (Faaij *et al.*, 2000a).

On the negative side, it could be difficult to ensure that the biomass is grown in a sustainable manner in the producing countries. If demand is large enough, bioenergy production for exports could impose a substantial burden on their resources and enter in conflict with competing uses of land such as food production or with the use of water resources, eventually affecting poor segments of the population (Faaij *et al*. 2000a). In addition, large-scale biomass production and export could not necessarily be the most effective way of reducing greenhouse gases emissions in the importing countries.

If, however, an international biomass-trade system develops, different alternatives for the long-distance transport of bioenergy are possible: unprepared biomass (i.e., logs, chips or bales), upgraded biomass (as pellets), shipment of intermediate energy carriers such as charcoal or pyrolysis oil, shipment of high-quality biofuels (methanol, F-T liquids, hydrogen, etc), or even transmission of electricity produced from biomass-fired power plants.

A typical biomass chain is composed of biomass production, pre-treatment operations, transportation and energy conversion steps. The composition of this chain affects the costs and energy input of alternative routes for the delivery of biomass and/or biomass-based energy carriers. Specifically, the biomass production and harvesting methods, the order and choice of pre-treatment operations (storage, chipping, drying, pelleting), the transport mode used (truck, train, ship or other) and the energy conversion technologies used (if any) have an influence in the relative competitiveness of alternative bioenergy transport chains. Other influential factors are distances, fuel prices and the operation characteristics of the equipment involved (Suurs, 2002).

Besides storage, the main pre-treatment operations are sizing, drying and densification of biomass. Sizing operations basically allow obtaining smaller chips. Drying reduces the moisture content and, thus, the risk of decomposition of the feedstock. It also reduces weight (but not volume) of the material. Densification refers to the production of dry pellets (compressed wood chips), which constitute a high-quality fuel and are cheaper and safer to transport than chips or logs. Pelletization is, however, an energy-intensive process. Another possible operation is baling, that is, the compression of forest residues into log-shaped compressed bales, which can be handled like logs by conventional forestry equipment.

Suurs (2002) has analyzed some of these issues in the European context for the case of the Netherlands, considering transport of bioenergy within Europe and from Latin America using a number of alternative transport chains. Based on his figures, we examined the delivery of bioenergy to Japan as an illustration of the factors playing a role in the competitiveness of a particular chain and their relative weight. We have concentrated our attention on the cases where the biomass feedstock, or biomass-based F-T liquids, is to be transported to the importing country by ship. The following section presents the details.

## 4.2 Costs and energy consumption for long-distance transportation of bioenergy

### 4.2.1 *Scenario outline*

Costs and energy consumption for two scenarios of bioenergy import to Japan are examined. In the first scenario, the biomass is produced in North America as forest residues and delivered to Japan (an international transport distance of 8000 km) either in the forms of logs, bales, chips, pellets or biomass-derived F-T liquids via ship. In the second scenario, energy crops (Eucalyptus) produced in Latin America are transported to Japan in the forms of bales, chips, pellets or F-T liquids via ship (an international transport distance of 15000 km). Figure 10 presents the transport chains considered here. The chains are named after the form of the bioenergy in their ship transport.

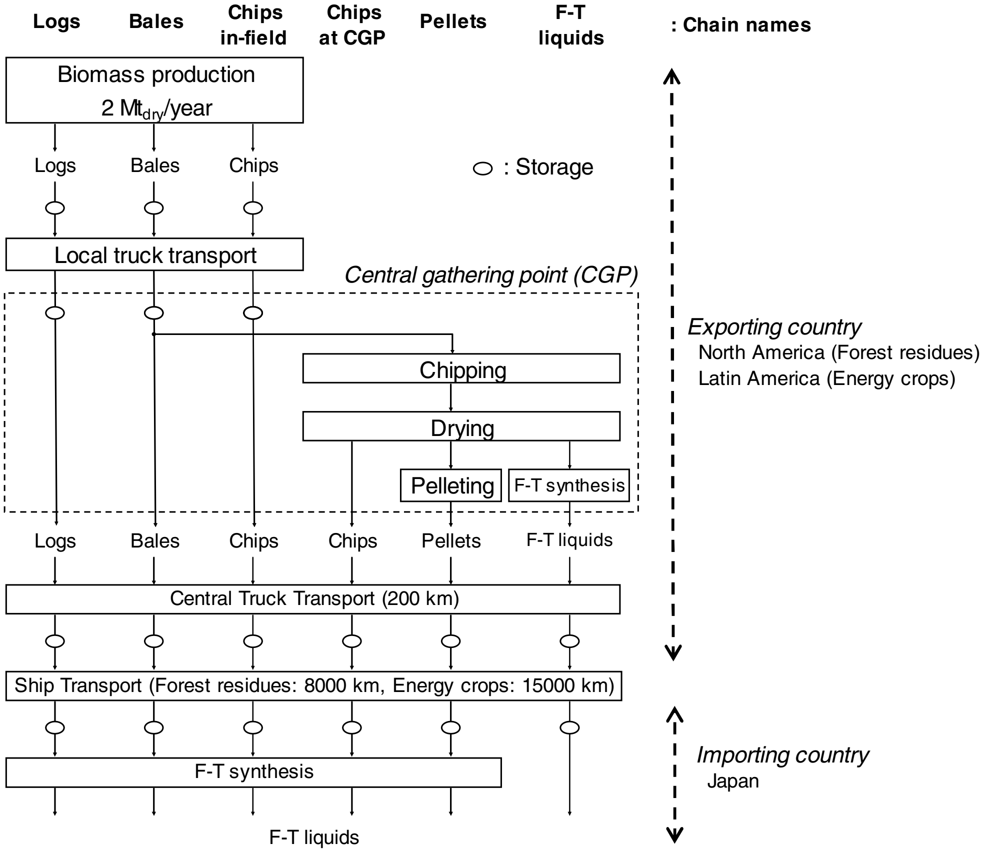

Figure 10: Bioenergy chains examined. The logs chain is used only for forest residues.

It is assumed that the biomass is taken from production sites in the form of logs, bales or chips, and transported to a central gathering point (CGP) of the exporting country using trucks (named 'local truck transport' in this study). After storage at a CGP, logs, bales and chips are transported via truck to a harbor, which is assumed to be located 200 km away from a CGP (named 'central truck transport' in this study). Bales can be converted to chips, pellets or F-T liquids at a CGP. For all chains, biomass is assumed to be converted to F-T liquids finally, either at a CGP or at an energy conversion plant in the importing country.

The data sets used for this scenario analysis are shown in Table 5, Table 6 and Table 7 for 'biomass production', 'pretreatment and conversion' and 'storage and transport' respectively. Most of these figures are based on Suurs (2002) and Hamelinck *et al* (2003b), in which a comprehensive investigation of the bioenergy chain has been conducted. For costs and performance of a F-T synthesis plant, the data of the BCL gasifier case with ATR (i.e., BCLa in section 3) was used, in which case the production cost is relatively low and less electricity is produced. It is assumed that the plant size is 1500 GJ/h and the co-produced electricity is assumed to be sold at a price of 0.04 US$/kWh. Ship size is determined so as to minimize the total cost (see 4.2.3 for details).

The average distance of local truck transport from biomass production sites to a CGP is assumed to be expressed by 1/√2 times the radius of a circle with the same surface A [$km^2$], which is given by dividing biomass yield (Y [$t_{dry}/km^2/year$]) into size of a CGP (S [$t_{dry}/year$]). Consequently, the average distance (L[km]) is expressed by the following equation; $L = 1/\sqrt{2} * \sqrt{(A/\pi)} = \sqrt{(S/(2\pi Y))}$. This assumption means that production sites are large, or at least adjacent to each other, and enough to fulfill the biomass demand of a CGP, which is set to be 2 $Mt_{dry}/year$ (see section 4.2.3 and 4.2.3.6 for details).

Table 5: Costs and characteristics of biomass production used for this scenario estimation. These figures are based on Suurs (2002) and Hamelinck *et al.* (2003b).

| Biomass type | | Forest residues | | | Energy crops | |
|---|---|---|---|---|---|---|
| | | Logs | Bales | Chips in-field | Bales | Chips in-field |
| Production costs | $US\$/GJ_{biomass}$ | 0.84 | 1.10 | 1.94 | 0.90 | 1.00 |
| Energy use for production | $GJ_{prim}/GJ_{biomass}$ | 0.019 | 0.019 | 0.067 | 0.010 | 0.020 |
| Harvest yields | $t_{dry}/km^2/year$ | 375 | 375 | 375 | 22400 | 22400 |
| Initial moisture | % | 50 | 50 | 50 | 60 | 60 |
| Moisture after local storage | % | 45 | 45 | 40 | 35 | 40 |

Table 6: Costs and characteristics for treatment and conversion of biomass used in the scenario estimation. It is assumed that interest rate is 10%. These figures are based on Suurs (2002) and Hamelinck *et al.* (2003b).

| | | Central chipping | Drying | Pelleting | F-T synthesis |
|---|---|---|---|---|---|
| Capacity (base) | GJ/h | 832 | 1144 | 60 | 1500 |
| | $t_{dry}/h$ | 40 | 55 | 2.9 | 72 |
| Investment costs (base) | million US$ | 0.50 | 5.0 | 0.27 | 300 |
| Scale factor | | 0.70 | 0.70 | 1.00 | 0.74 |
| Energy use | $GJ_{prim}/t_{dry}$ | 0.28 | 1.21 | 0.32 | - |
| Dry matter loss | % | 2 | 1 | 0 | - |
| Efficiency (F-T synthesis) | % | - | - | - | 35 |
| Efficiency (Electricity) | % | - | - | - | 5 |
| Load factor | % | 80 | 100 | 83 | 90 |
| Annual O&M costs | % of capital cost | 20 | 3 | 40 | 4 |
| Economic lifetime | Year | 15 | 15 | 10 | 15 |

Table 7: Costs and characteristics of storage and transport used for this scenario estimation. It is assumed that economic life time is 25 years for all storage and transport facilities. An interest rate of 10% is used in the calculation. These figures are based on Suurs (2002) and Hamelinck *et al* (2003b).

| Forms of bioenergy | | Logs | Bales | Chips | Pellets | F-T liquids |
|---|---|---|---|---|---|---|
| ***General*** | | | | | | |
| Energy content | GJ/$t_{dry}$ | 20.8 | 20.8 | 20.8 | 20.8 | 47.9 |
| Bulk density | $t_{dry}/m^3$ | 0.30 | 0.23 | 0.15 | 0.55 | 0.75 |
| ***Local storage (at roadside)*** | | | | | | |
| Capacity | $m^3_{biomass}/m^2$/year | 2.0 | 2.0 | 2.0 | - | - |
| Land costs | US\$/$m^2$/ear | 2.2 | 2.2 | 2.2 | - | - |
| ***Central storage (at CGP, outside)*** | | | | | | |
| Capacity (base) | $m^3_{biomass}$ | 3000 | 3000 | 3000 | - | - |
| Investment costs (base) | thousand US\$ | 25 | 25 | 25 | - | - |
| Scale factor | | 1.0 | 1.0 | 1.0 | - | - |
| Annual maintenance costs | % of investment | 3 | 3 | 3 | - | - |
| ***Central storage (at harbors, inside or covered)*** | | | | | | |
| Capacity (base) | $m^3_{biomass}$ | 3000 | 3000 | 25000 | 25000 | 3000 |
| Investment cost (base) | thousand US\$ | 108 | 108 | 1900 | 1900 | 3805 |
| Scale factor | | 0.9 | 0.9 | 0.7 | 0.7 | 0.7 |
| Annual maintenance costs | % of investment | 3 | 3 | 3 | 3 | 3 |
| ***Truck transport*** | | | | | | |
| Truck capacity (weight) | T | 40 | 40 | 40 | 40 | 25 |
| Truck capacity (volume) | $m^3$ | 130 | 130 | 130 | 130 | 33 |
| Km-costs | US\$/km | 0.80 | 0.80 | 0.80 | 0.80 | 1.17 |
| Transfer costs | US\$/$m^3$ | 0.47 | 0.47 | 0.47 | 0.47 | 0.47 |
| Fuel use for truck | Liter $_{diesel}$/km | 0.45 | 0.45 | 0.45 | 0.45 | 0.45 |
| Fuel use for transfer | $MJ_{prim}$/t | 2.75 | 2.75 | 2.75 | 2.75 | 2.75 |
| ***Ship transport*** | | | | | | |
| Maximum ship size | thousand dwt[(a)] | 170 | 170 | 170 | 170 | 250 |
| Capacity (cargo volume) | $m^3$/dwt | 0.70 | 0.70 | 0.70 | 0.83 | 0.92 |
| Vessel costs | million US\$ | Bulk: 10.5 + 0.000212 * (ship size in dwt)<br>Liquid: 14.1 + 0.000232 * (ship size in dwt) | | | | |
| Fuel use Heavy Fuel Oil | kg $_{HFO}$/km | 11.0 + 0.001 * (ship size in dwt) | | | | |
| Fuel use of empty cargo | % of loaded ship | 65 | 65 | 65 | 65 | 65 |
| Ship speed | km/h | 27.8 | 27.8 | 27.8 | 27.8 | 27.8 |
| Transfer speeds | t/h | 180 | 120 | 463 | 550 | 1000 |
| Transfer costs | US\$/t | 4.4 | 6.2 | 3.0 | 3.2 | 1.5 |
| Energy use for transfer | $GJ_{prim}$/t | 0.04 | 0.04 | 0.04 | 0.04 | 0.04 |
| Port charge | US\$/t | 0.64 | 0.64 | 0.64 | 0.64 | 0.64 |
| Price of HFO | US\$/t | 202 | 202 | 202 | 202 | 202 |
| Moisture content | % | 45 | 45 | 10 | 8 | 0 |
| Annual O&M costs | % of capital cost | 10 | 10 | 10 | 10 | 10 |

(a) Deadweight tonne (dwt) is the carrying capacity of a ship when fully loaded, expressed in metric tones. It includes cargo, bunkers, water, stores, passengers and crew.

### 4.2.2 *Results*

#### *4.2.2.1 Costs*

The cost estimates are summarized in Figure 11 for the forest residues scenario and Figure 12 for the energy crops scenario.

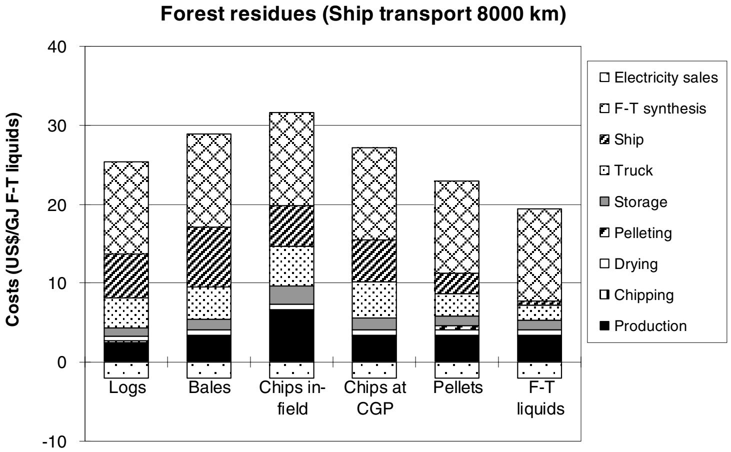

Figure 11: Costs of F-T liquids from forest residues (US$/GJ of F-T liquids). Biomass is transported by ship (8000 km) in the form of logs, bales, chips (locally or centrally chipped), pellets or F-T liquids. For every case, biomass is converted to F-T liquids, where co-produced electricity is sold at a price of 0.04 US$/kWh. It is assumed that biomass yield is 2 $Mt_{dry}$/year and a central gathering point (CGP) is located 200 km away from a harbor. For the case with locally chipping, i.e., ‘Chips in-field’, chipping costs are included in production costs.

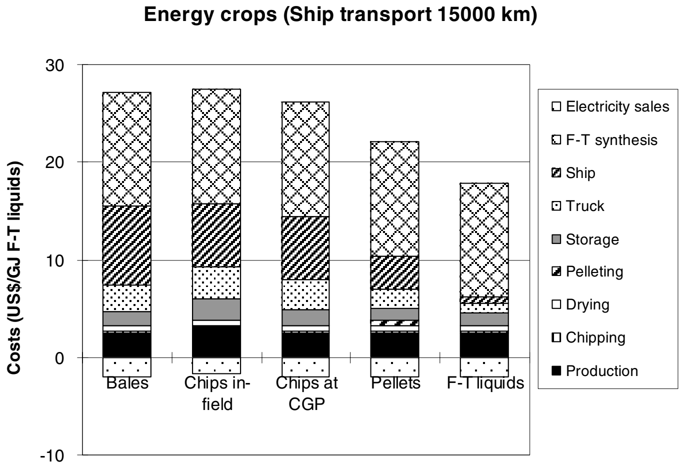

Figure 12: Costs of F-T liquids from energy crops (US$/GJ of F-T liquids). Biomass is transported by ship (15000 km) in the form of bales, chips (locally or centrally chipped), pellets or F-T liquids. For every case, biomass is converted to F-T liquids, where co-produced electricity is sold at a price of 0.04 US$/kWh. It is assumed that biomass yield is 2 $Mt_{dry}$/year and a central gathering point (CGP) is located 200 km away from a harbor. For the case with locally chipping, i.e., ‘Chips in-field’, chipping cost is included in production cost.

For both scenarios, the F-T liquids chain, where biomass is transported in the form of F-T liquids, is the most attractive from the economic point of view, followed by the pellets and logs chains. Bales and chips chains appear more expensive. The main differences between these chains are found in transport costs (both by truck and ship). This is mainly due to the different values of bulk density (i.e., energy content per unit of volume) for each form in which bioenergy is transported. A lower bulk density causes a lower amount of energy to be delivered per trip, resulting in more trips of trucks or ships and consequently higher costs. In addition, for the F-T liquids chain, the total volume (also the weight) of transported biomass is reduced significantly because of the matter and energy losses during the conversion to F-T liquids. Table 8 depicts the difference in the amounts of bioenergy transported by ship for the forest residues scenario, which are expressed in volume ($10^6$ $m^3$/year) and weight ($10^6$ t/year).

Table 8: Annual amounts of bioenergy transported by ship for the forest residues scenario (expressed in volume and weight).

| | Logs | Bales | Chips in-field | Chips at CGP | Pellets | F-T liquids |
|---|---|---|---|---|---|---|
| Total volume ($10^6$ $m^3$/year) | 6.5 | 8.5 | 10.9 | 12.7 | 3.4 | 0.4 |
| Total weight ($10^6$ t/year) | 3.6 | 3.6 | 1.8 | 2.1 | 2.1 | 0.3 |

The total costs of these two scenarios (forest residues scenario and energy crops scenario) are roughly in the same level despite the large difference in the ship transport distance. This is partly because costs of ship transport are not very sensitive to the distance.[6] This results in slightly higher costs for the energy crops scenario than for the forest residues scenario. On the other hand, costs of truck transport are lower for energy crops than for forest residues. The reason for this is that the average distance of local truck transport from biomass production sites to a central gathering point (CGP) is much shorter for energy crops than for forest residues due to the much higher harvested yields (i.e., annual biomass production per unit of area) of energy crops.

#### *4.2.2.2 Energy consumption*

For the same two scenarios, Figure 13 and Figure 14 present the energy consumption along the transport chain. Figures are expressed in GJ of primary energy ($GJ_{prim}$) by unit of energy contents of F-T liquids at the importing country. That is, it is assumed that the energy use is equal to the primary-energy equivalent of the amount of final-energy carrier consumed in each step of the chain. Electricity which is co-produced at a F-T liquids plant is assumed to substitute for fossil-based electricity which would have been generated at a electrical efficiency of 40%.

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[6] This will be explained in more detail in section 4.2.3

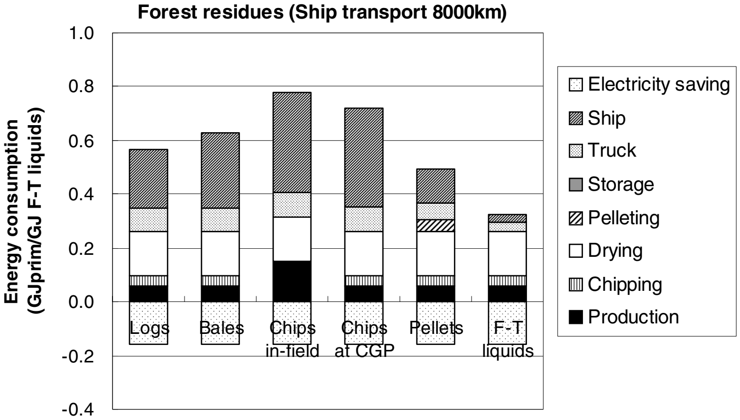

Figure 13: Energy consumption along the transport chains of forest residues ($GJ_{prim}$/GJ of F-T liquids). Biomass is transported by ship (8000 km) in the forms of logs, bales, chips (locally or centrally chipped), pellets or F-T liquids. It is assumed that biomass yield is 2 $Mt_{dry}$/year and a central gathering point (CGP) is located 200 km away from a harbor. For the case with local chipping, i.e., ‘Chips in-field’, the energy consumption of chipping is included in that of production.

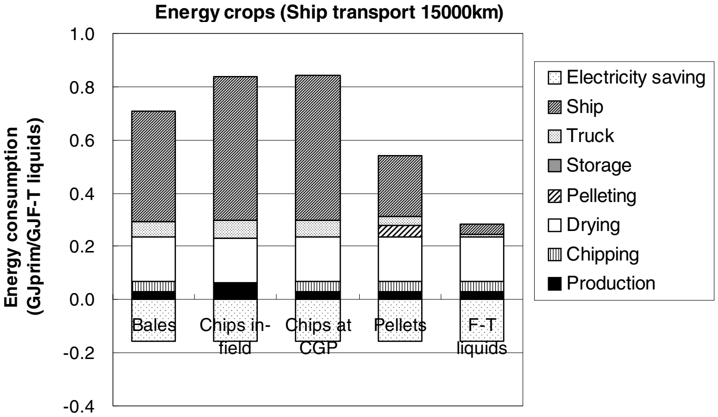

Figure 14: Energy consumption along the transport chains of forest residues (GJprim/GJ of F-T liquids). Biomass is transported by ship (15000 km) in the forms of bales, chips (locally or centrally chipped), pellets or F-T liquids. It is assumed that the biomass yield is 2 $Mt_{dry}$/year and that a central gathering point (CGP) is located 200 km away from a harbor. For the case with local chipping, i.e., ‘Chips in-field’, the energy consumption of chipping is included in that of production.

For both scenarios, the ranking among the alternative chains for total energy consumption is similar to those ranking for costs shown above. The F-T liquids chain is the least energy consuming, followed by the pellets and logs chains. For the chips and bales chains, significant amount of energy (equivalent to more than 50% of F-T liquids obtained) is consumed, where ship transport contributes the largest share to the total energy consumption. This is because, as mentioned in the cost analysis above, the lower bulk density of these forms of biomass requires more trips of ship transport, resulting in a higher amount of fuel use. Besides ship transport, energy consumption in truck transport and drying of biomass are noticeable. Although pelleting operations require a certain amount of energy input, this can be compensated by energy savings in other steps of the transport chain.

These results suggest that an early conversion of biomass to F-T liquids before it is exported is most favorable for long transport of bioenergy on economic and energy-consumption grounds. The transport of chips appears as a highly unfavorable alternative. Logs chain is a more favorable alternative but its availability for bioenergy purposes may be limited due to competition from the timber and pulp industry. The transport of pellets appears to be a better alternative than chips or logs, because they have a higher energy density and this greatly facilitates transport, thus reducing the corresponding costs.

### 4.2.3 *Sensitivity analysis*

In order to gain insights into the relative influence of different variables on costs, this section presents a sensitivity analysis for the scenarios examined above. Assumptions and parameters described in section 4.2.1 were used, except for the parameter which sensitivity is examined. The results are shown only for costs but similar trends were observed for energy consumption.

#### *4.2.3.1 Size of F-T liquids plant*

Figure 15 presents the F-T liquids production costs as a function of the size of F-T liquids plant for the two scenarios. Economies of scale from F-T liquids plant have a considerable influence on overall production costs, but scale effects start to level off at a capacity of around 2000 GJ/h.

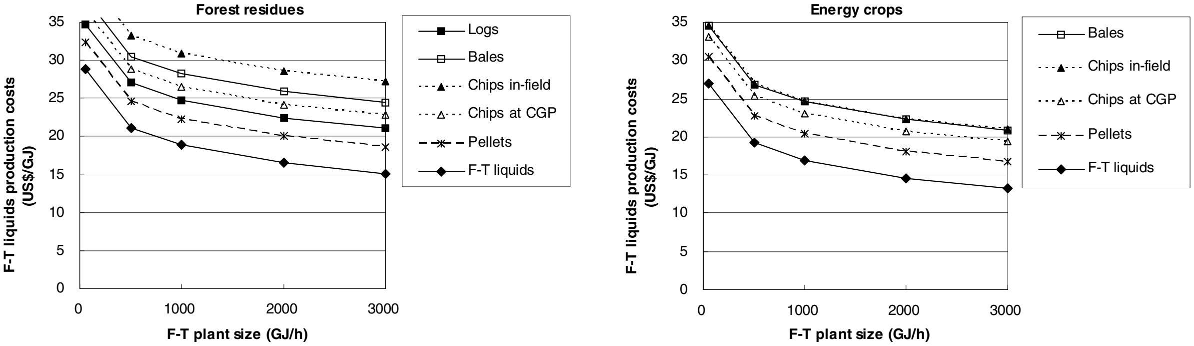

Figure 15: Influence of F-T plant size on F-T liquids production costs by form of biomass when using ship transport (Above: Forest residues in North America with ship transport of 8000 km, Below: Energy crops in Latin America with 15000 km). Assumptions for other parameters are as described in section 4.2.1.

#### *4.2.3.2 Ship size*

Ocean ships exist in a wide capacity range, from less than one thousand to several hundred thousand tonnes deadweight (Hamelinck *et al.,* 2003b). Ship size affects various factors such as capital cost, fuel consumption rate, storage capacity and loading and unloading time. The suitable size of a ship is determined by these factors, between which there is a trade-off.

Figure 16 presents the F-T liquids costs as a function of ship size for the two scenarios examined above. Up to a certain level of ship size, the costs decrease as the ship size increases. But when the ship size is large enough, the costs remain constant or increase as the ship size increases. This is because the scale merits of the ship become smaller. Moreover, the amount of bioenergy that one ship can deliver during a unit of time period decreases due to the longer time needed for loading and unloading of cargo.

This influence appears explicit for the logs and bales chains, because the loading and unloading (transfer) speeds are very low as shown in Table 7. For the F-T liquids chain, the trend is similar to those of the logs and bales chains although the speed of loading and unloading is much higher. This is because ship's capacity is not fully utilized when the ship size exceeds a certain level. In other estimations in this study, ship sizes are determined so as to minimize the total costs.

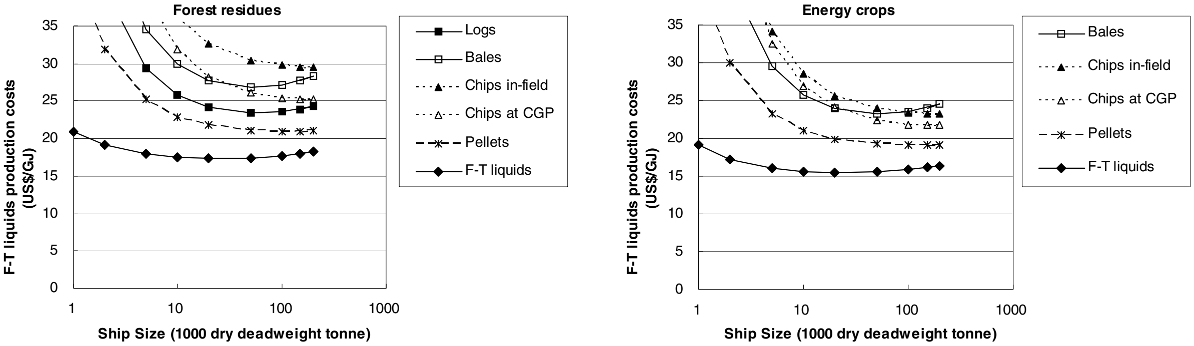

Figure 16: Influence of ship size on F-T liquids production costs by the form of biomass in ship transport (Above: Forest residues in North America with ship transport of 8000 km, Below: Energy crops in Latin America with 15000 km). Assumptions and parameters described in section 4.2.1 were used, except for ship size.

### *4.2.3.3 Distance of ship transport*

Figure 17 presents the F-T liquids costs as a function of transport distance via ship for the two scenarios. Shipping distance has an influence on the total cost, but this influence does not appear significant because of relatively low variable costs and a low energy use per tonne-km compared to other transport means. For the F-T liquids chain, the cost are less sensitive to the distance due to the very small share of total costs that ship transport costs represent (as mentioned in section 0).

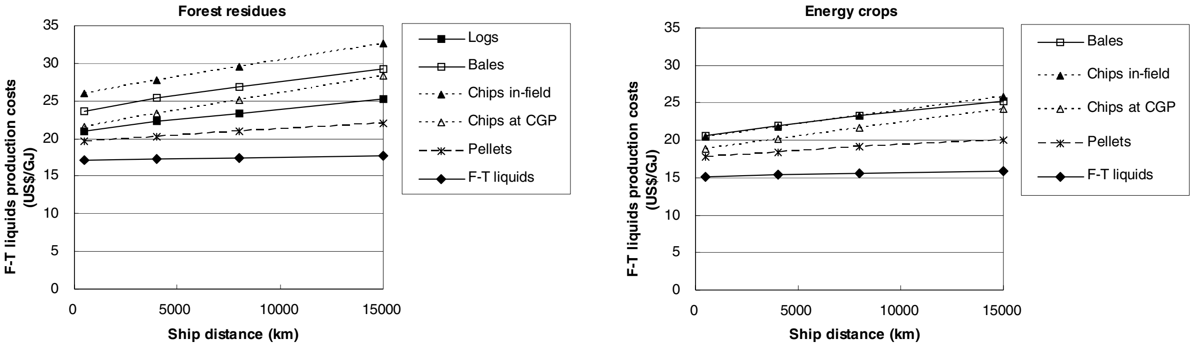

Figure 17: Influence of distance for ship transport on F-T liquids production costs by the form of biomass in ship transport (Above: Forest residues in North America, Below: Energy crops in Latin America). Assumptions for other parameters are as described in section 4.2.1.

### 4.2.3.4 Distance of central truck transport from CGP to harbor

Figure 18 depicts the influence of distance for central truck transport, i.e., truck transport from a CGP to a harbor, on the costs for the two scenarios. Truck distance appears to have a larger influence on the total cost compared to ship transport. This is due to relatively high variable costs and a higher energy use per tonne-km. Central truck transport would actually be needed in various points along the chain. But, for simplification, only the truck transport component in the exporting country is considered in this study. The distance of truck transport is considered to be one of the most important factors in selecting suitable sites for biomass production and conversion.

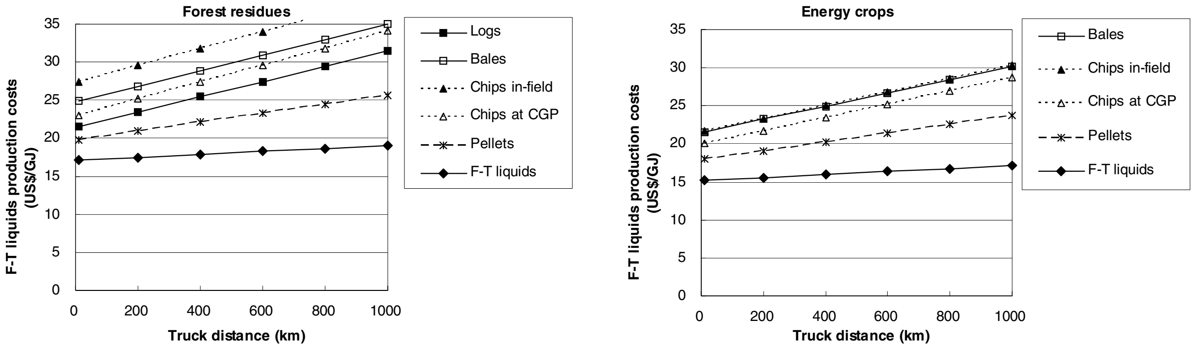

Figure 18: Influence of distance for central truck transport on F-T liquids production costs by form of biomass in ship transport (Above: Forest residues in North America with ship transport of 8000 km, Below: Energy crops in Latin America with 15000 km). Assumptions for other parameters are as described in section 4.2.1.

### 4.2.3.5 Spatial distribution of biomass

Spatial distribution of biomass determines the average distance of local truck transport from biomass production sites to a central gathering point (CGP), which in turn determines its cost. For the base cases above, as mentioned in section 4.2.1, it is assumed that the area from where biomass is collected to a CGP equals S/Y, where S is size of CGP ($t_{dry}$/year) and Y is biomass yield ($t_{dry}$/km$^2$/year). This assumption means that production sites are large, or at least adjacent to each other and enough to fulfill the biomass demand. In practice, however, it might be needed to deliver biomass from more distant sites to gather the required amount of biomass.

To examine the influence of the spatial distribution of biomass, we introduce an indicator of biomass density $\delta$, where biomass is to be collected from biomass production sites which disperse in a surface A' ($km^2$) which is $100/\delta$ times the area for the base case (i.e., S/Y). Here a biomass density $\delta$ of 100 gives the base case, and as a $\delta$ decreases a wider area is needed to be accessed. The average distance (L [km]) is expressed by the following equation; $L = 1/\sqrt{2} * \sqrt{(A'/\pi)} = \sqrt{(S/(2\pi Y\delta/100))}$, where S is size of CGP ($t_{dry}$/year), Y is biomass yield ($t_{dry}/km^2$/year).

The results are presented in Figure 19. The influence of spatial distribution appears larger for the forest residues scenario than for the energy crops scenario. This is because the former has much lower biomass yields as mentioned above. A smaller range of biomass density in these figures might seem impractical, but it can be reasonable when a certain amount of biomass is to be collected.

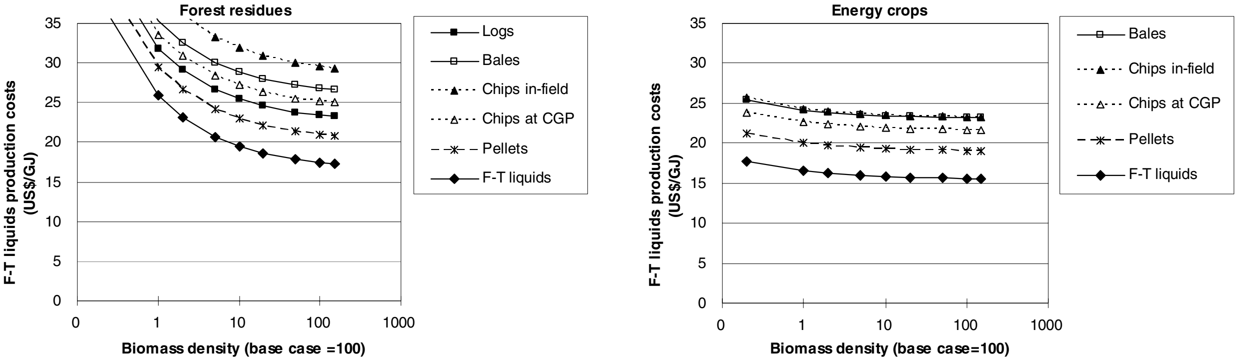

Figure 19: Influence of spatial distribution of biomass on F-T liquids production costs by the form of biomass in ship transport (Above: Forest residues in North America with ship transport of 8000 km, Below: Energy crops in Latin America with 15000 km). Assumptions for other parameters are as described in section 4.2.1.

### *4.2.3.6 Size of central gathering point*

The size of the central gathering point (CGP) has an influence on many economic determinants along the chain. A larger size of the CGP leads to a longer average distance of local truck transport, as mentioned in section 4.2.3, which results in higher costs. On the other hand, it allows larger sizes of ships and F-T liquids plants within their plausible ranges, which can offer economies of scale.

Figure 20 presents the influence of the size of the CGP on the total costs. For the F-T liquids chain, it is assumed that the size of the F-T liquids plant at the CGP is the same as the size of the CGP up to a maximum size, which is set to 1500 $GJ_{biomass}$/h. For the other chains, where F-T liquids conversion takes place in the importing country, the size of the F-T liquids plant is assumed to be 1500 $GJ_{biomass}$/h regardless of the CGP size. The ship size was determined as mentioned in section 4.2.3.

For the two scenarios, within the smaller range of the CGP size, the total cost decreases as the CGP size increases due to economies of scale for ship transport. For the F-T liquids chain, this tendency is conspicuous since it has a scale effect of F-T liquids plant as well as ship. In other words, disadvantages could arise if early conversion to F-T liquids cannot take place at a sufficiently large scale. On the other hand, as the CGP size exceeds a certain level, the larger CGP size brings the higher cost because the cost of local transport becomes more significant.

A larger CGP size would require a larger access area, resulting in the lower biomass density defined in section 4.2.3. In this study, however, this relation between CGP size and biomass density is not considered because it lacks in information and highly depends on the condition of each site. Inclusion of this relation could lift up the cost curves in Figure 20 especially in the higher range of CGP size.

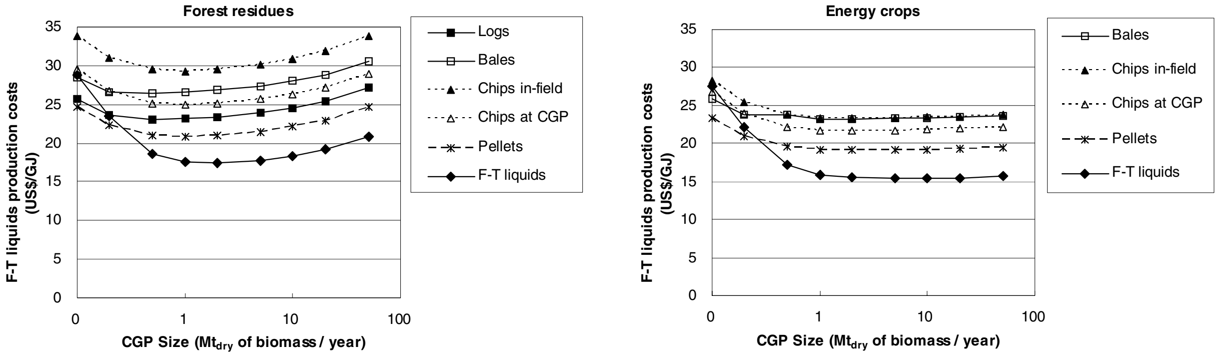

Figure 20: Influence of size of central gathering point (CGP) on F-T liquids production costs by the form of biomass in ship transport (Above: Forest residues in North America with ship transport of 8000 km, Below: Energy crops in Latin America with 15000 km). Assumptions and parameters in section 4.2.1 were used except for sizes of CGP and F-T liquids plant at CGP.

# 5 Conclusions

In this report, the co-production of Fischer-Tropsch liquids and electricity using biomass gasification is examined, highlighting its promising potential as an option to supply high-quality energy carriers in the medium term. In addition, costs and energy consumption for selected long-distance transport chains of bioenergy to Japan has been examined using two illustrative cases, namely forest residues in North America and energy crops in Latin America.

F-T liquids and electricity derived from biomass gasification are attractive alternatives for meeting energy needs in the medium-term and could be good candidates for policies supporting the introduction of renewable-based energy carriers currently in force (e.g., European Parliament, 2001; 2003) or to be imposed in the future. They could bring environmental benefits and pave the way for the introduction of other biomass-based energy carriers in the long run.

Specifically, biomass-derived F-T diesel could provide a low-carbon option for the transportation sector, which is compatible with current and advanced (e.g., electric-hybrid) vehicle technologies and with the fuel-delivery infrastructure available today (Woods and Bauen, 2003). Thus, it could have a key contribution to a cleaner fuel-mix in the transportation sector in the medium term, while facilitating a transition towards more advanced technologies and energy carriers, such as fuel cells and hydrogen, in the long run.

The biomass-based co-production system examined here highlights the important role that the so-called “energyplexes” could play in the medium and long term energy supply at the global level. “Energyplexes” are integrated energy systems that could facilitate the co-production of several high-quality commodities, energy carriers and chemicals, among others, while facilitating control of $CO_2$ and other pollutants. These systems could substantially contribute to increase the flexibility of energy companies to respond to ever-changing market needs and that of the energy system to respond to increasingly stringent requirements in terms of cost-effectiveness and environmental standards, among others.

We examined co-production configurations of F-T liquids and electricity using three different biomass gasifiers, namely the BCL, IGT and TPS gasifiers, which can be considered representative of a variety of biomass gasification technologies currently available. Our study indicates that an indirectly-heated gasifier (e.g., the BCL gasifier) could be one of the promising biomass gasification technologies for a co-production scheme of F-T liquids and electricity. This is due to its capability to produce a syngas mixture that contains less inert gases (e.g., carbon dioxide and nitrogen) without using a costly air-separation unit, thus resulting in the lower production cost of F-T liquids.

The potential benefits that the sales of the co-product electricity could have on the economics of F-T liquids have been illustrated. Such benefits, however, depend on the system configuration and the type of gasifier, among others. In addition, the effects of the prices of the biomass feedstock on the production costs of F-T liquids have been quantified. Under our assumptions, if the price of biomass feedstock is less than 3 US$/GJ, F-T liquids from biomass gasification could be competitive with petroleum-derived diesel with the tax levels currently imposed in many countries.

Moreover, the impact of a carbon tax on their competitiveness has been analyzed as well. The imposition of a carbon tax could increase the competitiveness of carbon-neutral F-T liquids. If their production is combined with $CO_2$ capture and storage (CCS), they could become an attractive option in a severely $CO_2$-constrained world. However, since a large carbon tax would be required for a sizeable effect, a combination of carbon tax and some other taxes might be needed for making the biomass-derived F-T liquids with $CO_2$ capture competitive with petroleum-derived diesel. This, of course, presupposes that CCS systems can turn out technically and economically feasible, environmentally sound and socially accepted.

Some world regions appear to have a much larger bioenergy potential than others and could become net exporters. International trade of bioenergy may foment the utilization of bioenergy at the international level, particularly in those countries without indigenous biomass resources, and could have stabilizing effects on biomass prices. It could help importing countries to meet environmental constraints such as caps on $CO_2$ emissions.

On the other hand, it could be difficult to ensure that the biomass is grown in a sustainable manner in the producing countries. If demand is large enough, bioenergy production for exports could impose a substantial burden on their resources and enter in conflict with competing uses of land such as food production or with the use of water resources, eventually affecting poor segments of the population (Faaij *et al.* 2000a). If the bioenergy potential could be tapped in a sustainable and effective manner, an international system for trade of energy from biomass could be effective way to utilize the bioenergy.

We also examined the costs and energy consumption associated with the long-distance international transport of biomass using two scenarios where forest residues produced in North America and energy crops produced in Latin America are transported to Japan via ship. A variety of supply chains were compared, including transport in the forms of logs, bales, chips, pellets and F-T liquids.

For all situations considered here, early conversion to F-T liquids in advance of long-distance transport via ship is the most favorable option to obtain F-T liquids from biomass on economic and energy-consumption grounds. This is mainly due to the low cost and energy consumption for truck and ship transport as a result of considerably low volume of bioenergy, i.e., F-T liquids, to be delivered. However, our sensitivity analysis shows that disadvantages might arise if this process cannot take place at a sufficiently large scale. If the final commodity is not F-T liquids but biomass itself, the transport in the form of pellets appears the most favorable alternative. The transport of chips appears as a highly unfavorable alternative for long-distance transport.

The sensitivity analysis performed in this study suggests that the distance of inland transport appears to have a substantial influence on the total cost. Central truck transport would be needed in various points along the chain and can be considered to be one of the most important factors in selecting suitable sites for biomass production and conversion. The optimal size of the bioenergy chain, which corresponds to the CGP size, appears several $Mt_{dry}$/year for forest residues and several tens of $Mt_{dry}$/year for energy crops. But these figures might be lowered if the spatial density of biomass production sites is smaller.

It should be noticed that the estimates in this study do not include the effects of technology learning, i.e., the cost reductions and performance improvements in a technology or cluster of technologies that result from the accumulation of experience in the marketplace and the acquisition of new knowledge through R&D efforts (Argote and Epple, 1990; McDonald and Schrattenholzer, 2001). Stimulating the technology learning in biomass gasification technologies could lead to increased competitiveness of this option. Moreover, these technologies could benefit from learning spillovers from related or complementary technologies.

Increasing the share of energy carriers derived from biomass in the global energy supply requires, among others, a reliable, sustainable and cost-effective chain for the production, transport and conversion of the biomass feedstock. Although there may be considerable potential for bioenergy, its development requires a number of actions if this is to constitute a sound option in the long term (Sims, 2003). On the one hand, the production and transport of the biomass feedstock should fulfill stringent sustainability criteria, ranging from carbon emissions to biodiversity and competition with food production and other land and water uses, and be cost-effective. On the other hand, the technologies that allow the conversion of biomass into high-quality energy carriers should be cost-effective, efficient, environmentally sound and flexible.

Regarding the latter, biomass gasification offers a considerable potential. It could act as a key enabling technology for the development of integrated and flexible bioenergy strategies. Biomass gasification allows the production or co-production of, among others, electricity, hydrogen and clean liquid fuels. Thus, it has an inherent flexibility that could be an important asset in liberalized energy markets. Gasification could improve the competitiveness of biomass-fired electricity production, bringing efficiency improvements and flexibility in the size of plants, among other benefits. It would also facilitate the incorporation of $CO_2$ capture and storage systems.

The technology is currently in the demonstration phase and a number of R&D needs must still be addressed. However, significant progress has been made so far and there is significant potential for cost reductions and efficiency improvements in the future (Faaij *et al*., 2000b). Moreover, the technology is in a phase of development where a diversity of approaches and technical configurations co-exist and the important goal is basically the demonstration of technical feasibility. In a later stage, as development progresses, some of these variants may be chosen over others and a diffusion process could begin.

In order to stimulate such diffusion process, a strategic management of niche markets, where the technology may be attractive due to specific advantages or particular applications, is necessary (Kemp, 1997). Valuable experience could be accumulated there, from which performance/cost improvements may result. Also, a successful introduction of the technology in niche markets would contribute to build up the confidence of potential users, equipment manufacturers and other social actors, such as policy makers, on the biomass gasification option.

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# Appendix A: Characteristics of syngas from a variety of biomass gasifiers

| Data Name | | I-Atm-Air-CFB (BCL) | I-Atm-Air-BFB (MTCI) | I-Atm-Air-CFB (VUT) | D-Pre-O2-BFB (IGT) | D-Pre-O2-CFB | D-Atm-O2-CFB | D-Pre-O2-BFB (IGT+) | D-Pre-Air-BFB (IGT) | D-Pre-Air-CFB | D-Atm-Air-CFB | D-Pre-Air (EP) | D-Atm-Air-CFB (TPS) | D-Atm-Air-CFB (Lurgi) | D-Atm-Air-BFB (SEI) | D-Atm-Air-BFB (EPI) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Developer | | Battelle Columbus Laboratory (BCL) | Manufacturing and Technology Conversion International (MTCI) | Vienna University of Technology (VUT) | Institute of Gas Technology (IGT) | n.a. | n.a. | Institute of Gas Technology (IGT) | Institute of Gas Technology (IGT) | n.a. | n.a. | Enviro Power | Termiska Processor AB (TPS) | Luigi Energy | Southern Electric International (SEI) | Energy Products of Idaho (EPI) |
| Heat supply | | Indirectly | Indirectly | Indirectly | Directly | Directly | Directly | Directly | Directly | Directly | Directly | Directly | Directly | Directly | Directly | Directly |
| Pressure | | Atmospheric | Atmospheric | Atmospheric | Pressurized | Pressurized | Atmospheric | Pressurized | Pressurized | Pressurized | Atmospheric | Pressurized | Atmospheric | Atmospheric | Atmospheric | Atmospheric |
| Type | | CFB | BFB | CFB | BFB | CFB | CFB | BFB | BFB | CFB | CFB | n.a. | CFB | CFB | BFB | BFB |
| Oxidation medium | | Air | Air | Air | $O_2$ | $O_2$ | $O_2$ | $O_2$ | Air | Air | Air | Air | Air | Air | Air | Air |
| $H_2$/CO ratio | | 0.45 | 1.45 | 1.48 | 1.39 | 1.39 | 1.64 | 2.09 | 1.33 | 0.75 | 0.86 | 0.73 | 0.77 | 1.03 | 0.82 | 0.33 |
| Gas composition (mol%) | $H_2O$ | 19.9 | dry | dry | 31.8 | 36.8 | 38.6 | 48.0 | 39.9 | 12.9 | 12.6 | 13.6 | 13.6 | dry | dry | dry |
| | $H_2$ | 16.7 | 35.1 | 37.0 | 20.8 | 15.0 | 19.8 | 24.0 | 8.9 | 11.0 | 14.1 | 10.0 | 13.3 | 20.1 | 12.7 | 5.8 |
| | CO | 37.1 | 24.3 | 25.0 | 15.0 | 10.8 | 12.0 | 11.5 | 6.7 | 14.6 | 16.3 | 13.8 | 17.2 | 19.6 | 15.5 | 17.5 |
| | $CO_2$ | 8.9 | 20.8 | 25.0 | 23.9 | 23.4 | 20.8 | 16.0 | 13.5 | 15.1 | 12.9 | 15.4 | 12.2 | 13.5 | 15.9 | 15.8 |
| | $CH_4$ | 12.6 | 10.4 | 10.0 | 8.2 | 12.4 | 7.3 | 0.5 | 6.5 | 8.3 | 4.7 | 7.3 | 2.8 | 0.0 | 5.7 | 4.7 |
| | C2+ | 4.8 | 9.4 | 0.0 | 0.3 | 1.0 | 1.0 | 0.0 | 0.1 | 1.0 | 1.0 | 0.5 | 1.0 | 3.8 | 2.3 | 2.6 |
| | Tar | 0.0 | 0.0 | 0.0 | 0.0 | 0.1 | 0.1 | 0.0 | 0.2 | 0.1 | 0.1 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| | $N_2$ | 0.0 | 0.0 | 3.0 | 0.0 | 0.5 | 0.5 | 0.0 | 24.2 | 37.0 | 38.5 | 38.9 | 39.2 | 42.9 | 47.9 | 51.9 |
| Conversion Efficiency | % HHV | 78.3 | 77.9 | n.a | 76.2 | n.a. | n.a. | 71.9 | 81.4 | n.a. | n.a. | 84.3 | 72.2 | 83.0 | 21.8 | 67.9 |
| Steam input | kg/kg dry feed | 0.02 | 1.37 | n.a | 0.30 | 0.32 | 0.42 | 0.80 | 0.28 | n.a. | n.a. | 0.17 | 0.30 | n.a. | n.a. | n.a. |
| Oxygen input | kg/kg dry feed | 0.00 | 0.00 | 0.00 | 0.30 | 0.21 | 0.26 | 0.38 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Source | | Williams *et al.*, 1995 | Ciferno and Marano, 2002 | Hofbauer *et al.*, 2002 | Williams *et al.*, 1995 | Hamelinck *et al.*, 2003 | Hamelinck *et al.*, 2003 | Hamelinck and Faaij, 2001 | Craig and Mann, 2002 | Hamelinck *et al.*, 2003 | Hamelinck *et al.*, 2003 | Tijimensen *et al.*, 2002 | Tijimensen *et al.*, 2002 | Ciferno and Marano, 2002 | Ciferno and Marano, 2002 | Ciferno and Marano, 2002 |

# Appendix B: System modeling assumptions

**Oxygen production:** Electricity consumption rate in MWh/tonne $O_2$ is 0.3 for separation and 0.168 for compression (Hamelinck *et al.*, 2003a).

**Gas cleaning:** To supply heat for cracking tar, 2% of the fuel gas is combusted.

**Biomass gasification:** The BCL, IGT and TPS gasifiers are selected for this study (Detailed characteristics are shown in Appendix A).

**Auto-thermal reforming (ATR):** Auto-thermal reforming (ATR) combines steam reforming with partial oxidation. Since steam reforming is a highly endothermic process, part of the feed is oxidized to supply the necessary heat. Total efficiency for ATR is assumed to be 90%. $O_2$ needed for partial oxidation is supplied by an $O_2$ production unit. The reactions are:

[Steam reforming] $CH_4 + H_2O \rightarrow CO + 3\ H_2$

$C_2H_6 + 2\ H_2O \rightarrow 2\ CO + 5\ H_2$

[Partial oxidation] $C_xH_{2x+2} + (1.5x+0.5)\ O_2 \rightarrow x\ CO_2 + (x+1)\ H_2O$, where x=0, 1, 2

**Water gas shift:** In a shift reactor, the $H_2/CO$ ratio is changed via the following reaction; $CO + H_2O \rightarrow H_2 + CO_2$

In this study, the fraction of syngas sent to a shift reactor is determined in such way that the $H_2/CO$ ratio of the input gas to the F-T reactor is 2:1, where production of liquid F-T products (C5+) is maximized.

**F-T synthesis:** In F-T synthesis, hydrocarbons with chains of different length are produced from CO and $H_2$.

$n\ CO + (2n+1)\ H_2 \rightarrow C_nH_{2n+2} + n\ H_2O$

The variety of chain lengths is determined by the Anderson-Schulz-Flory (ASF) distribution (Schulz, 1999), which describes the molar yield in carbon number as: fraction $C_n = \alpha^{n-1}(1-\alpha)$, where α is chain growth probability and n the length of the hydrocarbon, which makes (1-α) the chance that the chain growth terminates.

Following Hamelinck *et al* (2003a), the chain growth probability, i.e., α, is determined as follows;

$S_{C5+} = 1.696 - 0.00241\ T - 0.0876\ [H_2]/[CO] + 0.181\ ([H_2]+[CO]) + 0.00781\ p_{total}$

$\alpha = 0.75 + 0.25\ S_{C5+} - 0.373\ \sqrt{-\log(S_{C5+})}$

with $S_{C5+}$ : liquid selectivity

T, $p_{total}$ : temperature, pressure of the F-T reactor (500K and 45 bar are assumed.)

$[H_2]$, $[CO]$: partial pressure for $H_2$ and CO entering a F-T reactor

**Hydrocracking:** Following Hamelinck *et al* (2003a), it is assumed that all C20+ chains are hydrocracked to a length of preferable $C_{10}$ and maximal $C_{19}$ as the equations below;

$C_{20}H_{42} + H_2 \rightarrow 2C_{10}H_{22}$

$C_{25}H_{52} + H_2 \rightarrow C_{10}H_{22} + C_{15}H_{32}$

$C_{48}H_{98} + 3\ H_2 \rightarrow 3C_{10}H_{22} + C_{18}H_{38}$ etc.

Hydrogen for hydrocracking is assumed to be supplied by a pressure swing adsorption after a water gas shift reactor.

**Power generation:** Off gas from the F-T reactor is burned in a gas turbine (combined cycle), if its heating value is above 5 MJ-LHV/$Nm^3$. Otherwise, only the steam turbine is used for electricity production. The rationale behind this assumption is that it is not suitable to use low calorific gas in a commercial gas turbine from the viewpoints of combustion stability, pressure loss through the fuel injection system and limits to the increasing mass flow through a turbine. The electrical efficiency is set to be 52% for a combined cycle and 30% for a steam turbine.

**Auxiliary Power:** Based on the estimation in Hamelinck *et al* (2003a), the auxiliary power use except for $O_2$ production (separation and compression), which is mainly for gas compression at each stage, is assumed 0.053 for BCL, 0.028 for IGT and 0.94 for TPS in $MWh_e/MWh_{th}$-biomass input.

# Appendix C: Costs of components for F-T liquids production via biomass gasification

Table C: Costs of biomass gasifiers

| Name | | Developer | Heat supply method | Gasifier type | Pressure | Reactant | $H_2$/CO ratio | Feedstock | Efficiency (%) | Capacity ($GJ_{biomass\ feed}$/h) | Investment cost (million US$2000) | Source |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Biomass Gasifier | BCL | Bettelle Columbus Laboratory | Indirect | Circulating Fluidized Bed | Atmospheric | Air | 0.32 | Wood | 74.6 | 730 | 25.2 | Ciferno and Marano, 2002 |
| Biomass Gasifier | BCL | Bettelle Columbus Laboratory | Indirect | Circulating Fluidized Bed | Atmospheric | Air | n.a. | Wood | 70.7 | n.a. | n.a. | Larson and Jin, 1999 |
| Biomass Gasifier | BCL | Bettelle Columbus Laboratory | Indirect | Circulating Fluidized Bed | Atmospheric | Air | 0.45 | Wood | 78.3 | 667 | 8.6 | Williams *et al.*, 1995 |
| Biomass Gasifier | BCL | Bettelle Columbus Laboratory | Indirect | Circulating Fluidized Bed | Atmospheric | Air | 0.45 | Wood | 78.3 | 1440 | 13.2 | Tijimensen *et al.*, 2002 |
| Biomass Gasifier | BCL | Bettelle Columbus Laboratory | Indirect | Circulating Fluidized Bed | Atmospheric | Air | 0.49 | Wood | 72.9 | 1221 | 17.4 | Craig and Mann, 2002 |
| Biomass Gasifier | BCL | Bettelle Columbus Laboratory | Indirect | Circulating Fluidized Bed | Atmospheric | Air | 0.49 | Wood | n.a. | 1769 | 13.6 | Mann, 1995 |
| Biomass Gasifier | BCL | Bettelle Columbus Laboratory | Indirect | Circulating Fluidized Bed | Atmospheric | Air | 0.45 | Wood | 81.2 | 1542 | 16.3 | Hamelinck and Faaij, 2001 |
| Biomass Gasifier | BCL | Future Energy Resource Corporation | Indirect | Circulating Fluidized Bed | Atmospheric | Air | 0.35 | Wood | 78.0 | 666 | 7.8 | Weyerhaeuser, 2000 |
| Biomass Gasifier | BCL | Bettelle Columbus Laboratory | Indirect | Circulating Fluidized Bed | Atmospheric | Air | n.a. | Wood | n.a. | 36 | 0.7 | Amos, 1998 |
| Biomass Gasifier | MTCI | Manufacturing and Technology Conversion International | Indirect | Bubbling Fluidized Bed | Atmospheric | Air | 1.45 | Pulp | 77.9 | 40 | 1.1 | Ciferno and Marano, 2002 |
| Biomass Gasifier | MTCI | Manufacturing and Technology Conversion International | Indirect | Circulating Fluidized Bed | Pressurized | Air | 2.26 | Wood | 107.8 | 65 | 4.5 | Williams *et al.*, 1995 |
| Biomass Gasifier | IGT | Institue of Gas Technology | Direct | Bubbling Fluidized Bed | Pressurized | O2 | 1.39 | Wood | 76.2 | 1620 | 37.5 | Williams *et al.*, 1995 |
| Biomass Gasifier | IGT | Institue of Gas Technology | Direct | Bubbling Fluidized Bed | Pressurized | O2 | 1.39 | Wood | 76.2 | 1440 | 30.6 | Tijimensen *et al.*, 2002 |
| Biomass Gasifier | IGT | Institue of Gas Technology | Direct | Bubbling Fluidized Bed | Pressurized | $O_2$ | 1.39 | Wood | 81.9 | 1548 | 39.2 | Hamelinck and Faaij, 2001 |
| Biomass Gasifier | IGT+ | Institute of Gas Technology | Direct | Bubbling Fluidized Bed | Pressurized | $O_2$ | 2.09 | Wood | 71.9 | 1548 | 39.2 | Hamelinck and Faaij, 2001 |
| Biomass Gasifier | IGT | Institute of Gas Technology | Direct | Bubbling Fluidized Bed | Pressurized | Air | 1.33 | Wood | 81.4 | 1356 | 57.4 | Craig and Mann, 2002 |
| Biomass Gasifier | IGT | Institute of Gas Technology | Direct | Bubbling Fluidized Bed | Pressurized | Air | 0.73 | Wood | 84.3 | 1440 | 30.6 | Tijimensen *et al.*, 2002 |
| Biomass Gasifier | IGT | Institute of Gas Technology | Direct | Bubbling Fluidized Bed | Pressurized | Air | n.a. | Wood | n.a. | 751 | 40.5 | DOE and EPRI, 1997 |
| Biomass Gasifier | IGT | Institute of Gas Technology | Direct | Bubbling Fluidized Bed | Pressurized | Air | n.a. | Black liquor | n.a. | 1364 | 36.3 | Larson *et al.*, 2000 |
| Biomass Gasifier | IGT | Institute of Gas Technology | Direct | Bubbling Fluidized Bed | Pressurized | $O_2$ | n.a. | Black liquor | n.a. | 1372 | 18.2 | Larson *et al.*, 2000 |
| Biomass Gasifier | IGT | Institute of Gas Technology | Direct | Bubbling Fluidized Bed | Pressurized | $O_2$ | n.a. | Wood | 76.1 | n.a. | n.a. | Larson and Jin, 1999 |
| Biomass Gasifier | TPS | Termiska Processor AB | Direct | Circulating Fluidized Bed | Atmospheric | Air | n.a. | Wood | 70.0 | n.a. | n.a. | Larson and Jin, 1999 |
| Biomass Gasifier | TPS | Termiska Processor AB | Direct | Circulating Fluidized Bed | Atmospheric | Air | 0.77 | Wood | 72.2 | 250 | 3.3 | Tijimensen *et al.*, 2002 |
| Biomass Gasifier | TPS | Termiska Processor AB | Direct | Circulating Fluidized Bed | Atmospheric | Air | 0.73 | Wood | n.a. | 201 | 27.5 | Ciferno and Marano, 2002 |
| Biomass Gasifier | TPS | Termiska Processor AB | Direct | Circulating Fluidized Bed | Atmospheric | Air | 0.80 | Wood | 66.0 | 1199 | 26.9 | Craig and Mann, 2002 |
| Biomass Gasifier | Lurgi | Luigi Energy | Direct | Circulating Fluidized Bed | Atmospheric | Air | 1.03 | Bark | 83.0 | 87 | 8.7 | Ciferno and Marano, 2002 |
| Biomass Gasifier | SEI | Southern Electric International | Direct | Bubbling Fluidized Bed | Atmospheric | Air | 0.82 | Wood | 21.8 | 284 | 11.1 | Ciferno and Marano, 2002 |
| Biomass Gasifier | EPI | Energy Products of Idaho | Direct | Bubbling Fluidized Bed | Atmospheric | Air | 0.33 | Wood | 67.9 | 73 | 2.1 | Ciferno and Marano, 2002 |

## Table C2: Costs of other components

| Name | Capacity | | Investment cost (million US$2000) | Source |
|---|---|---|---|---|
| $O_2$ separation (99.5%) | 1008 | tonne $O_2$/day | 35.0 | Tijimensen *et al.,* 2002 |
| $O_2$ separation (99.5%) | 576 | tonne $O_2$/day | 23.0 | Tijimensen *et al.,* 2002 |
| $O_2$ separation (99.5%) | 576 | tonne $O_2$/day | 21.9 | Hamelinck *et al.,* 2003 |
| $O_2$ separation (99.5%) | 2037 | tonne $O_2$/day | 30.9 | Hamelinck *et al.,* 2003 |
| $O_2$ separation (99.5%) | 1000 | tonne $O_2$/day | 48 | Williams *et al.,* 1995 |
| $O_2$ separation (99.5%) | 500 | tonne $O_2$/day | 29 | Williams *et al.,* 1995 |
| $O_2$ separation (99.5%) | 1100 | tonne $O_2$/day | 28 | Larson *et al.,* 2000 |
| Biomass pre-treatment | 274 | $GJ_{biomass\ feed}$/h | 10 | Tijimensen *et al.,* 2002 |
| Biomass pre-treatment | 554 | $GJ_{biomass\ feed}$/h | 8.4 | Hamelinck *et al.,* 2003 |
| Biomass pre-treatment | 1471 | $GJ_{biomass\ feed}$/h | 22 | Williams *et al.,* 1995 |
| Biomass pre-treatment | 59 | $GJ_{biomass\ feed}$/h | 1.7 | Williams *et al.,* 1995 |
| Biomass pre-treatment | 600 | $GJ_{biomass\ feed}$/h | 8.9 | Williams *et al.,* 1995 |
| Biomass pre-treatment | 36 | $GJ_{biomass\ feed}$/h | 1.3 | Amos, 1998 |
| Biomass pre-treatment | 1557 | $GJ_{biomass\ feed}$/h | 21 | Hamelinck and Faaij, 2001 |
| Biomass pre-treatment | 666 | $GJ_{biomass\ feed}$/h | 8.2 | Weyerhaeuser, 2000 |
| Biomass pre-treatment | 1221 | $GJ_{biomass\ feed}$/h | 12 | Craig and Mann, 2002 |
| Biomass pre-treatment | 1356 | $GJ_{biomass\ feed}$/h | 12 | Craig and Mann, 2002 |
| Biomass pre-treatment | 1199 | $GJ_{biomass\ feed}$/h | 10 | Craig and Mann, 2002 |
| Biomass pre-treatment | 505 | $GJ_{biomass\ feed}$/h | 8.3 | Larson *et al.,* 2000 |
| Biomass pre-treatment | 1022 | $GJ_{biomass\ feed}$/h | 12 | Larson *et al.,* 2000 |
| Biomass pre-treatment | 6381 | $GJ_{biomass\ feed}$/h | 46 | Borgwardt, 1997 |
| Biomass pre-treatment | 751 | $GJ_{biomass\ feed}$/h | 8.8 | DOE and EPRI, 1997 |
| Biomass pre-treatment | 1307 | $GJ_{biomass\ feed}$/h | 38 | Simbeck and Chang, 2002 |
| Gas cleaning | 250 | $GJ_{biomass\ feed}$/h | 13 | Tijimensen *et al.,* 2002 |
| Gas cleaning | 666 | $GJ_{biomass\ feed}$/h | 2.9 | Weyerhaeuser, 2000 |
| Gas cleaning | 1221 | $GJ_{biomass\ feed}$/h | 10 | Craig and Mann, 2002 |
| Gas cleaning | 2093 | $GJ_{biomass\ feed}$/h | 18 | Hamelinck *et al.,* 2003 |
| Gas cleaning | 1548 | $GJ_{biomass\ feed}$/h | 20 | Hamelinck and Faaij, 2001 |
| Gas cleaning | 1548 | $GJ_{biomass\ feed}$/h | 8.7 | Hamelinck and Faaij, 2001 |
| Auto-thermal reformer | 441 | kmol-feed/h | 1.0 | Mann, 1995 |
| Auto-thermal reformer | 7859 | kmol-feed/h | 30 | Tijimensen *et al.,* 2002 |
| Auto-thermal reformer | 127068 | kmol-feed/h | 205 | Borgwardt, 1997 |
| Auto-thermal reformer | 1390 | kmol-feed/h | 4.7 | Hamelinck *et al.,* 2003 |
| Auto-thermal reformer | 18955 | kmol-feed/h | 24 | Hamelinck *et al.,* 2003 |
| Auto-thermal reformer | 15795 | kmol-feed/h | 23 | Hamelinck *et al.,* 2003 |
| Auto-thermal reformer | 3720 | kmol-feed/h | 21 | Hamelinck and Faaij, 2001 |
| Steam methane reformer | 6250 | kmol-feed/h | 41 | Simbeck and Chang, 2002 |
| Steam methane reformer | 2156 | kmol-feed/h | 23 | Hamelinck and Faaij, 2001 |
| Steam methane reformer | 124 | kmol-feed/h | 0.22 | Amos, 1998 |
| Water shift reactor | 8819 | kmol-H2,CO/h | 11 | Williams *et al.,* 1995 |
| Water shift reactor | 14600 | kmol-H2,CO/h | 33 | Hamelinck *et al.,* 2003 |
| Water shift reactor | 4265 | kmol-H2,CO/h | 11 | Hamelinck and Faaij, 2001 |
| Water shift reactor | 102208 | kmol-H2,CO/h | 42 | Borgwardt, 1997 |
| Water shift reactor | 87 | kmol-H2,CO/h | 0.047 | Amos, 1998 |
| Water shift reactor | 891 | kmol-H2,CO/h | 0.14 | Mann, 1995 |
| Water shift reactor | 2400 | kmol-H2,CO/h | 0.45 | Tijimensen *et al.,* 2002 |
| $CO_2$ removal (Selexol) | 810 | kmol-$CO_2$/h | 16 | Williams *et al.,* 1995 |
| $CO_2$ removal (Selexol) | 1544 | kmol- $CO_2$/h | 26 | Lange *et al.,* 2001 |
| $CO_2$ removal (Selexol) | 9909 | kmol- $CO_2$/h | 48 | Hamelinck *et al.,* 2003 |
| $CO_2$ removal (Selexol) | 819 | kmol- $CO_2$/h | 37 | Kreutz *et al.,* 2002 |
| Pressure swing adsorption | 14123 | kmol-feed/h | 36 | Williams *et al.,* 1995 |
| Pressure swing adsorption | 356 | kmol-feed/h | 1.1 | Mann, 1995 |
| Pressure swing adsorption | 9600 | kmol-feed/h | 26 | Hamelinck *et al.,* 2003 |
| Pressure swing adsorption | 4440 | kmol-feed/h | 14 | Lange *et al.,* 2001 |
| Pressure swing adsorption | 6397 | kmol-feed/h | 19 | Hamelinck and Faaij, 2001 |
| Pressure swing adsorption | 118651 | kmol-feed/h | 198 | Borgwardt, 1997 |
| F-T reactor (solid phase) | 360 | $GJ_{F\text{-}T\ liquids}$/h | 17 | Tijimensen *et al.,* 2002 |
| F-T reactor (solid phase) | 360 | $GJ_{F\text{-}T\ liquids}$/h | 19 | Hamelinck *et al.,* 2003 |
| F-T reactor (solid phase) | 7901 | $GJ_{F\text{-}T\ liquids}$/h | 119 | Gray and Tomlinson, 2001 |
| F-T reactor (solid phase) | 11115 | $GJ_{F\text{-}T\ liquids}$/h | 227 | Gray, 2002 |
| F-T reactor (liquid phase) | 472 | $GJ_{F\text{-}T\ liquids}$/h | 27 | Hamelinck *et al.,* 2003 |
| F-T upgrading | 473 | $GJ_{F\text{-}T\ liquids}$/h | 6.0 | Tijimensen *et al.,* 2002 |
| F-T upgrading | 10973 | $GJ_{F\text{-}T\ liquids}$/h | 171 | Hamelinck *et al.,* 2003 |
| F-T upgrading | 7901 | $GJ_{F\text{-}T\ liquids}$/h | 120 | Gray and Tomlinson, 2001 |
| F-T upgrading | 11115 | $GJ_{F\text{-}T\ liquids}$/h | 118 | Gray, 2002 |

# Acronyms

| | |
|---|---|
| ASF | Anderson-Schulz-Flory distribution |
| ATR | Auto-thermal reformer |
| BCL | Batelle Columbus Laboratory gasifier |
| BFB | Bubbling fluidized bed gasifier |
| CFB | Circulating fluidized bed gasifier |
| CCS | $CO_2$ capture and storage |
| CGP | Central gathering point |
| CO | Carbon oxide |
| $CO_2$ | Carbon dioxide |
| DFB | Downward fixed bed gasifier |
| dwt | Deadweight tonnes |
| EJ | Exajoule ($10^{18}$) |
| F-T | Fischer-Tropsch |
| GHG | Greenhouse gas |
| GJ | Gigajoule ($10^{9}$) |
| HHV | High heating value |
| HRSG | Heat recovery steam generator |
| $H_2$ | Hydrogen |
| IGT | Institute for gas technologies gasifier |
| kMol | $10^{3}$ Mol |
| MJ | Megajoule ($10^{6}$) |
| MMol | $10^{6}$ Mol |
| $Mt_{dry}$ | Megatonnes ($10^{6}$) on dry basis |
| NETL | National Energy Technology Laboratory (United States) |
| O&M | Operation and maintenance |
| PSA | Pressure swing adsorption |
| ST | Steam turbine |
| TPS | Termiska Processor AB gasifier |
| UFB | Upward fixed bed gasifier |
| WGS | Water gas shift |