Evaluating synthesis gas based biomass to plastics (BTP) technologies

SELIM NOURI
ANNE-MARIE TILLMAN

Department of Energy and Environment, Environmental Systems Analysis Division (ESA)
CHALMERS UNIVERSITY OF TECHNOLOGY
Göteborg, Sweden 2005

Evaluating synthesis gas based biomass to plastics (BTP) technologies

SELIM NOURI
ANNE-MARIE TILLMAN

ESA-report 2005:8
ISSN 1404-8167

Department of Energy and Environment, Environmental Systems Analysis Division (ESA)
CHALMERS UNIVERSITY OF TECHNOLOGY
SE-412 96 GÖTEBORG
Sweden 2005

http://www.esa.chalmers.se

CPM-report 2005:6
ISSN 1403-2694

CPM – Centre for Environmental Assessment of Product and Material Systems
CHALMERS UNIVERSITY OF TECHNOLOGY
SE-412 96 GÖTEBORG
Sweden 2005

http://www.cpm.chalmers.se

Chalmers reproservice
Göteborg, Sweden 2005

Abstract

Current efforts to mitigate climate change use renewable resources and reduce waste, drive the development of new processes. In this study we examine the technologies for conversion of biomass to conventional polymers such as polyolefins. Such process routes, based on gasification and syngas production, are potentially technically feasible, since all process units are currently either commercially available or in the pilot plant phase. In the study their economic and environmental feasibility are evaluated.

We evaluate the environmental attractiveness of this emerging technology using life cycle assessment (LCA) methodology. Economic evaluation is performed by combining and adapting existing financial data which could be further on being coupled with the LCA model. The expected out-comes of the study are the environmental and economic assessments as such, but also a contribution to the on-going efforts to integrate LCA with economic tools. We also expect to contribute to methodology development through the collection and documentation of experience from environmental assessments of new, emerging technologies.

Keywords: methanol-to-olefins; synthesis gas; biomass gasification; life cycle assessment; biopolymer

Preface

We would like to express our warmest gratitude to all people that in one way or another have contributed to the completion of this report.

We highly appreciated the participation and collaboration from all respondents in the CPM and AGS networks, as well as all engineers who helped us. Their supportive and kind efforts to enhance the content of our report are priceless and exclusive of their time, knowledge, experience and input, this report could not have been concluded. Finally, we would like to thank our supervisor, Anne-Marie Tillman, for her advice, insightful comments, constructive criticism and encouraging words throughout the entire process of creating this report.

Göteborg, November 2005

Selim Nouri

Nomenclature

APME: Association of Plastics Manufacturers in Europe

ASU: Air separation unit. Process that separate the air into its main compounds: oxygen, nitrogen, argon and rare gases if necessary.

Biofuels: organic materials, such as wood, waste, and alcohol fuels, burned for energy purposes

Biomass: material that are biological in origin, such as grasses, trees, municipal solid waste, etc.

Biorefinery: A biorefinery is a facility that integrates biomass conversion processes and equipment to produce fuels, power, and chemicals from biomass. The biorefinery concept is analogous to today's petroleum refineries, which produce multiple fuels and products from petroleum.

BTP: biomass to plastics.

BLG: black liquor gasification

CH4: methane.

CHP plant: combined heat and power plant.

CO: carbon monoxide.

CO2: carbon dioxide.

CO2eq: carbon dioxide equivalent; the amount of carbon dioxide by weight emitted into the atmosphere that would produce the equivalent radiative forcing as a given weight of another greenhouse gas. Carbon dioxide equivalents are the product of the weight of gas being considered and its global warming potential.

COP: cost of production

CSR: corporate social responsibility.

D.S: dry substance.

DME: dimethyl ether ($CH3-O-CH3$) is the simplest of all ether; DME is currently manufactured from methanol by dehydration.

DMFC: direct methanol fuel cell. Systems that convert the energy of a fuel (methanol) into electricity with high efficiency.

EJ: Exajoule (10^{18}J)

GHGs: green house gases.

GTL: gas to liquid, process that transform natural gas into a more transportable liquid fuel.

GTW: gas to wire, or an efficient way to transfer the energy of natural gas into electricity for effective distribution.

HDPE: high density polyethylene

IEA: international energy agency

IGCC plant: Integrated Gasification Combined Cycle plant.

LCA: life cycle assessment

LDPE: Low density polyethylene

LNG: liquefied natural gas. Process that liquefy natural gas for easier transportation using cryogenic process

MeOH: methanol

MeOH/DME: methanol/dimethyl-ether. Since DME is the "dehydrated version" of MeOH (2MeOH => DME + $H2O$) and that it is not still clear (studies are performed and industries are working on it) to assess whether it is better or not to produce directly one or the other. We will not judge this issue and will consider MeOH and DME as almost the same product at first. It is not that important for our first study of the BTP route since the MTO can be fed either with MeOH or DME.

MJ: megajoule

MTA: metric ton per annum

MTBE: methyl tertiary butyl ether

MTD: metric ton per day

MTO: methanol to olefins

MTP: methanol to propylene

NREL: US national renewable energy laboratory

PLA: Polylactic acid, degradable polyester commercially available

PP: polypropylene

SEK: Swedish Krona

TAME: Tert-Amyl Methyl Ether like MTBE is an oxygenated additive for green gasoline. TAME is currently catalytically produced in the liquid phase by the reaction of methanol and the isoamylenes 2-methyl-1-butene and 2-methyl-2-butene.

WTT study: well-to-tank study

WTW study: well-to-wheel study

Table of contents

1 Introduction

The interest for biomass based polymer processes has increased recently since the need to diversify the feedstock and to reduce emissions from industry is getting stronger. The recent increases of the cost of fossil fuel – especially oil – as well as its tendency to be more and more unforeseeable are also an important driver for the emergence of new a “flexi-fuel” economy and new material production processes, like the biomass-to-plastics route.

The biomass to plastics (BTP) process is an indirect - biomass is first converted to MeOH/DME - route for the conversion of biomass to olefins (ethylene and propylene). This process would convert biomass to clean syngas, then to methanol which will be converted to C_2-C_4 olefins, based on existing technology and finally polymerized in polyethylene and polypropylene. The supposed higher sustainability of the BTP process will have to be investigated as well as attributed low cost investments due to already developed technology for the expanding gas based petrochemistry.

In this report, a presentation of the thermo-chemical process steps to make conventional polymers (polypropylene and polyethylene) from biomass will be done. Moreover a preliminary environmental assessment of one production route will be performed.

Many process configurations are possible and have been technically assessed since the bio-refinery concept is not new. However dealing with both environmental impacts and cost advantages due to new technologies in this fields are very rare (compared for instance with the transport sector, where alternative fuels and power trains systems have been studied for a while). Therefore, the need of methodologies and integrated assessments (that take into account multiple parameters) is great for decision makers to identify sustainable material production alternatives.

1.1 Main goal

The BTP process inherently involves emerging technologies from natural gas petrochemistry as well as new biomass valorisation techniques. These new emerging technologies have been studied as well as their potential impact on environment.

The main aims of this study are:

- To collect data and make a screening of potentially viable BTP pathways.
- Taking the initiative, define and adapt assessment methods for estimating environmental and cost performance.

1.2 Background

There are basically two types of background for such a study. A scientific/academic background and an industrial one:

Most scientific publication about biomass based processes are dealing either with environmental or cost performance or purely engineering issues (MacLean, Lave 2002). Few of them are combining environmental and economic aspects in an engineering way of thinking. The life cycle implications of new technologies and production systems have been examined in the automotive industry - for instance in the well-to-wheel studies of alternative fuels (ex: EUCAR 2003) - and a similar approach could be adapted to the new sustainable material field.

LCA has long emerged from its “try to find its way” phase and is an established methodology. However, LCA does not include economic assessment neither does include technology development aspects.

Important progress has been made in examining the life cycles of a range of industrial systems for chemical production. One of the main contributions of these assessments is to show decision-makers the multitude of important aspects in, for instance, polymer production systems and in environmental impacts (Bauman, Tillman 2004). Indeed evaluating alternative polymer production systems is a multi-attribute decision problem. Developing such methodologies to improve our current awareness regarding new technologies adoption should avoid complete mistakes in new industrial strategies in terms of environment and public acceptance.

Industrially there are development patterns that indicate that there are many on-going technology developments that could contribute to a potential production of conventional polymers from biomass. Among those are:

- On-going effort to produce alternative fuels from multiple sources.
- Large investments for monetizing stranded natural gas and thus greatly

increasing the global methanol production capacity, leading to new methanol applications.
- Regulations and efforts to reduce waste volumes and especially plastic waste, thus leading to new recycling thinking.
- Methanol to Olefins process technology ready for commercialization.

1.3 Organization of work and report

The work reported here has been organized and financed within the Alliance for Global Sustainability and Chalmers University trough CPM (Centre for Environmental Assessment of Product and Material Systems).

The study comprises five phases. They are:

1. framing of case study
2. Identifying potentials of emerging technology
3. Characterizing market behavior
4. Characterizing Material sustainability
5. Synthesis

The current status of research is in phase four and reported here are preliminary green house gases (GHGs) emissions calculated with public data available. Moreover a mapping of the technological status as well as a compilation of financial data available have been conducted. Further collaboration with industry will hopefully lead to more results.

In this report, we will first examine the drivers for the development of bio-based process routes to polymers, and then a technical overview of the new production processes will be done as well as a first assessment of the GHGs emissions, energy use and production cost.

2 DRIVERS

Drivers for emergence of new material productions routes from biomass are numerous; among them are:

Climate change

Green house gases emissions are now being regulated and with the ratification of the Kyoto protocol, trading of those gases begin in 2005. The new CO2 trading system in E.U from January 2005 is an important driver for the biomass to polymer route.

Sustainable feedstocks

The oil feedstock has great chance to remain the main source of fuel and chemicals for the next 20 years. However, the strategy of having a multi-source based economy has not to be demonstrated anymore. The flexi-fuel or hybrid concept in cars is an example of the direct translation of this strategy. The industrial world is also implementing this strategy and processes dedicated to biomass and waste are emerging.

Indeed, oil price is very unsteady and being independent energetically is of great importance. Moreover having strategic energy reserves is crucial (for some countries like the USA it is a matter of national security) and the biomass based processes could help to keep those reserves untapped or save energy resources for next generations.

Sustainable thinking reaching industries

Awareness of environmental issues is no longer a marginal way of thinking and societies in general are sensitive to those issues. The effects of this awareness are multiple and in companies often take the form of active environmental programmes (cf. use of Environmental Management Systems, programmes for Design for Environment, programmes for Corporate Social Responsibility…).

Available and cheap feedstock

Biomass based plants – like pulp and paper ones – are already operating around the world with thermal inputs equivalent to 1000-2000 MW. Indeed, biomass is sometimes considered as the 4th largest source of energy worldwide and account for about 35% of consumption in developing countries currently (Bhattacharya 2001).

However, in industrialized countries, unused available biomass as well as the amount of waste produced remains today relatively untapped.

For instance, in Sweden the maximum amount of produced vehicle fuel - methanol for instance - that can be theoretically produced from untapped biomass fractions is 315.3 PJ per year (Hagström 2002) which is equivalent to almost half the worldwide actual (2003) production of methanol.

The following drivers are more inherent to the BTP route we are studying:

Technology push and synergy between gasifiers' technology and syngas processes.

The recent developments in gasification technologies and syngas processes are playing an important role in the consideration of a BTP route. Both the potential to make clean, cheap syngas and the potential chemical treatment of it to make fuel and chemicals are driving the biomass and waste based routes. Those processes, especially the syngas ones are more and more under the spotlights since they allow the production of alternative vehicle fuels (like Fisher-Tropsch, DME, and hydrogen…) and the demand in this sector is growing. Having those fuel processes ready will allow a further refinement to sustainable material production.

Waste monetization strategies

Syngas technology has been promoted for years by various companies. Although the specific processing steps vary, the goal is often the same, and is to convert a low value flow (ex: stranded natural gas, wood waste…) into a liquid, more transportable and valuable product.

The methanol φαίνομαι (phenomenon)

The methanol phenomenon is maybe one of the most interesting and strong driver for a potential BTP route. This phenomenon is quite new and lies in the strategy to monetize the stranded gas that used to be flared or re-injected on-site, due to remote location. One of the best way to monetize this stranded gas - in financial terms (cf. Newenham 2002) - is to build maximum scale methanol plants, and in recent year methanol technology has achieved unit capacities with 5000 metric tons per day (MTD) or higher.

This step change in maximum world scale capacity is beginning to be prominent. Before 2003, 35.2 million tons per year of methanol was produced with 95% in plants smaller than 2500 tons/day in size. After 2003, 12.7 million tons/year new announced methanol will be produced of which 80% will come from plants greater than 4500 tons/day in size (Intille

2004). Previsions are that by 2008 more than 30% of the global methanol capacity will be based on new plants with production capacities greater than 4500 tons/day.

Although these plants have a clear competitive advantage over conventional methanol plant, since they allow production cost to be drastically reduced (by three in certain cases with a stranded natural gas price at 0.5 $/million British thermal unit) their production cannot be totally absorbed by the conventional methanol chemical markets. Each mega-plant has a capacity equivalent to 5-10% of the global methanol demand that grow at rates between 2-4% per year (Andersen et al 2003). This opens other opportunities for methanol uses like power generation or light olefin production.

Moreover despite sagging end use markets, especially methyl tertiary-butyl ether, which represents about 30% of the US market (cf. Fig. 1), the market for methanol continues to hold firm (Brown 2003). In 2001 total demand was 29.4 million tons, of which MTBE/TAME accounted for 8.2 million tons. North America represented some 60% of the MTBE/TAME demand. Again, part of the methanol production won't be used anymore for the MTBE use in the USA letting opened new opportunities for methanol uses.

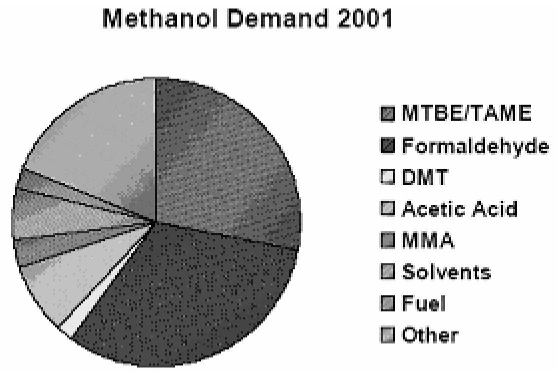


Figure 1 (Newenham 2002)

Two scenarios could appear:

- The methanol producers continue to sell methanol at a high price and make more profits.
- The market price drops and new methanol applications emerge.

Whatever happens, methanol is already playing a key role in many applications, from fuel cells to chemicals and some author like Nobel Prize laureate G. Olah see a future methanol based economy as more than possible (Olah et al 2005).

3 PRODUCTS AND MARKETS

The polymers produced via the BTP route are one of the many products that a BTP concept could theoretically produce. By producing several products, a BTP plant could take advantage of the differences in the production intermediates and maximize the value regarding the biomass input.

A BTP plant could, for instance, produce low-volume, but high-value, products like light olefins or polymers and a low-value, but high-volume intermediate fuel like methanol/DME, while generating electricity and process heat onsite with possible export of electricity. The high-value olefins and polymers would enhance profitability, the high-volume methanol/DME would help meet transportation energy needs, and the green power production would reduce costs and reduce substantially the GHGs emissions.

In the USA, the NREL (US national renewable energy laboratory) bio-refinery concept is built on two different "platforms" to promote different products (cf. fig 2). The "sugar platform" is based on biochemical conversion processes and focuses on the fermentation of sugars extracted from biomass feedstocks. The "syngas platform" is based on thermochemical conversion processes and focuses on the gasification of biomass feedstocks and by-products from conversion processes. This is the one, and the products it might deliver to the market, that we will further examine in our study.

However, since these two platforms deal with the same feedstocks and sustainable goals, sometimes even interconnected processes - for instance fermentation of synthesis gas to produce ethanol - it is essential to be aware of the technological and sustainable issues raised in both of the concepts.

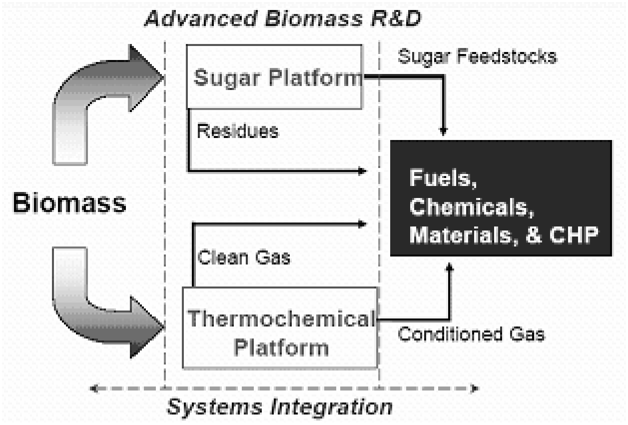


Figure 2 Biomass refinery platforms (Craig 2003)

3.1 *Type of products*

The possible products available from a thermochemical route depend largely on the production strategy choices - for instance focusing on one specific product like hydrogen - and the process integration level. A great number of products can be produced via syngas and existing routes are very numerous (Fig.3). Similar process routes already exist for the natural gas based petrochemistry.

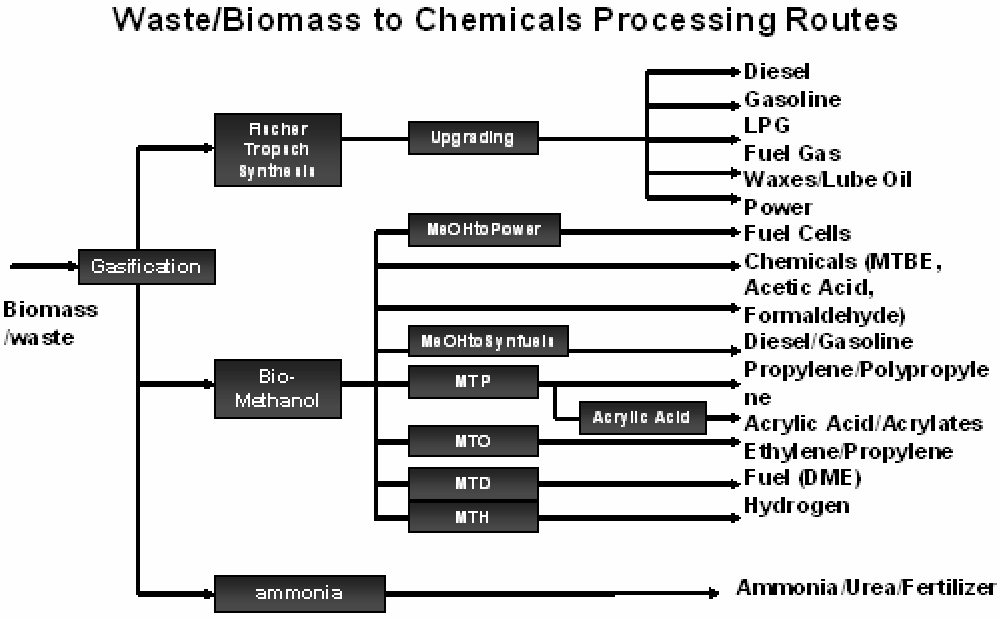


Figure 3 Biomass to chemicals routes (Wagner modified 2002)

Polymers production can be maximized and/or heat, electricity, fuels (MeOH/DME/H2) can also be produced along the process.

About olefins, they are the largest-volume chemicals produced by the petrochemical industries with a production of 140 million tons per year worldwide in 2001 (Andersen et al, 2003) and 590 000 tons per year in Sweden. Demand is driven mainly by polyolefin production but 40% is consumed for other derivatives. Today the majority of light olefins are produced by naphtha cracking, even if some low cost natural gas based processes are emerging, leading to a “flexi-feedstock” olefin production system. This flexible concept is interesting in those times of highly unpredictable oil price.

3.2 Present markets for products from a Biomass to plastics (BTP) route

In this section we will take a quick look at the different markets for intermediary products that could be produced along the BTP route.

A very common market for biomass and waste based plants is heat integration with district heating. It is very common in Sweden and Finland. This heat market in Sweden is quite mature and district heating from biomass is widely used. Combined heat and power applications are significant in Scandinavia. Electricity generation from biomass is common in Sweden, Finland and Denmark in Combined Heat and Power (CHP) plants. In Finland 12% of electricity is produced from biomass. Most of the biomass CHP facilities in Europe are operating in pulp and paper industries, followed by forest industry and CHP for large district heating systems. On a European level the largest producers of electricity from biomass are Finland, Sweden and Austria (EUROSTAT 1994).

The heat, electricity, methanol/DME/H2 markets in Europe/Sweden have been studied for a while. Markets for methanol are classic chemical markets (formaldehyde, acetic acid…) as well as water treatment and future fuel cells applications. Methanol is a very established commodity and applications are numerous.

DME is widely used as a propellant and commercialized by Akzo Nobel under the name Demeon® D. New applications are emerging, DME may be used in gas turbines for power generation, household purposes (cooking, heating) and for compression ignition or diesel engines (busses, trucks, taxi cabs, construction equipment, etc.), and also as a hydrogen source for fuel cells.

Hydrogen is mainly used in refineries, for instance for desulphurization. New applications for fuel cells as well as a future hydrogen economy are waiting for their time to come.

About the methanol market, it is changing due to industry restructuring, plants sizes increase and new emerging markets. There is what people call a “chemical to fuel” business transition (Fig. 4): the delivered MeOH/DME price is decreasing very fast and will no longer be the price of an intermediary chemical, but more of a fuel one. Moreover the volume of cheap methanol available will literally “fuel” new processes like methanol to olefins (MTO).

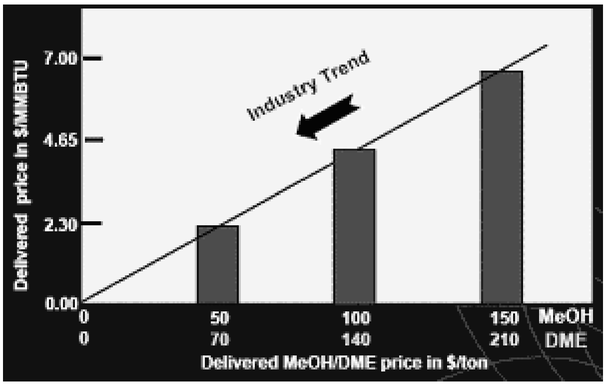


Figure 4 Chemical to fuel transition (Fleisch 2003)

If the high demand of new methanol market applications is pulling it, it could be worthy to produce methanol as a derivative of the BTP route. From a Scandinavian perspective, since Norway is already producing a huge amount of methanol from natural gas (915 518 tons in 2003 for Statoil, cf. WEBBOLT® 2004) and providing it to the market, there should be no technical problem to integrate the bio-methanol in the existing network.

4 RAW MATERIALS

4.1 Types of raw material from forest industry and agriculture

All organic material produced by living organisms is called biomass. Biomass can be produced by specific cultivation for the purpose of energy production. For this type of agriculture only fast growing plants, which give the best yield per hectare, are considered. Some examples are miscanthus, sweet sorghum and willow. Specific sustainable problems occurring with this type of crops are biodiversity – since after harvesting, similar plant growing is necessary – and ethical problems with energy production and food production interferences.

Waste from household and industry can also be considered as potential feedstocks. Wood residues examples consist of:

- sawdust
- wood chips
- wood waste: pallets, crate discards, wood yard trimming…

Agricultural residues examples are:

- corn residues
- rice hulls
- sugarcane bagasse
- animal waste

4.2 Availability

“Biomass can provide 6 to 7 times the energy now being used by humanity. In Japan there is a huge amount of biomass available, estimated at 190 million tons/yr” stated Hiroyuki Fujimura, Chairman of Ebara Corp in 2002 (Waseda University Lectures). However, such an optimist statement needs to be qualified.

Indeed, the earth receives 3 millions Exajoule (3.10^{24}J) per year from the sun. This solar energy can be accounted as 90 Exajoule (EJ) hydropower, 630 EJ as wind and 1250 EJ via biosynthesis. This can be compared to the global energy consumption of 400 EJ per year. However the 1250 EJ bound in biomass are only theoretically available. Even with a low factor of accessibility for those 1250 EJ, the useable potential remains interesting. Present state of the art technology should achieve an accessible potential of 120 EJ, but could increase quickly with evolution of the technology. The technical feasibility (120 EJ) is of the same magnitude as the global annual consumption of oil (150 EJ) which is about three times the global energy consumption from biomass (Source: Energy Research Center for the Netherlands 2004).

The available biomass potential has increased in almost all European countries since World War II (Ekbom 2003) and is now important (Fig. 5, 6). Biomass energy potential in Europe is about 8.9 EJ per year where wood fuels stands for 4 EJ per year. Only about 2 EJ per year (22 %) of the available biomass potential are currently used (Ekbom 2003). There is also a large potential in agricultural biomass potential (fig. 6) (Nikolaou et al 2003).

Forest biomass

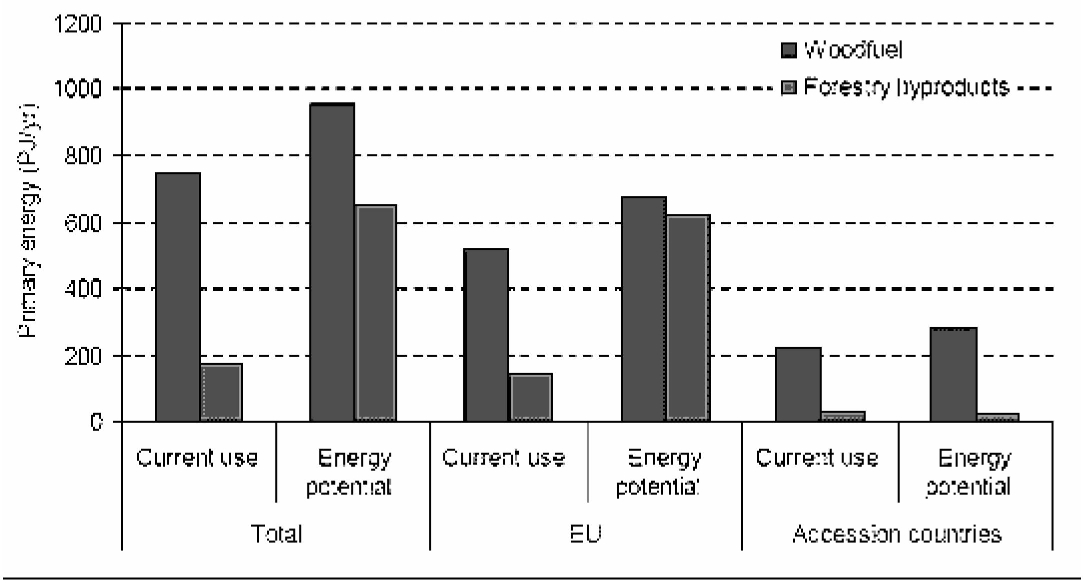


Figure 5 Current use and resource potential of forest biomass in Europe (Nikolaou et al 2003)

Agricultural Biomass

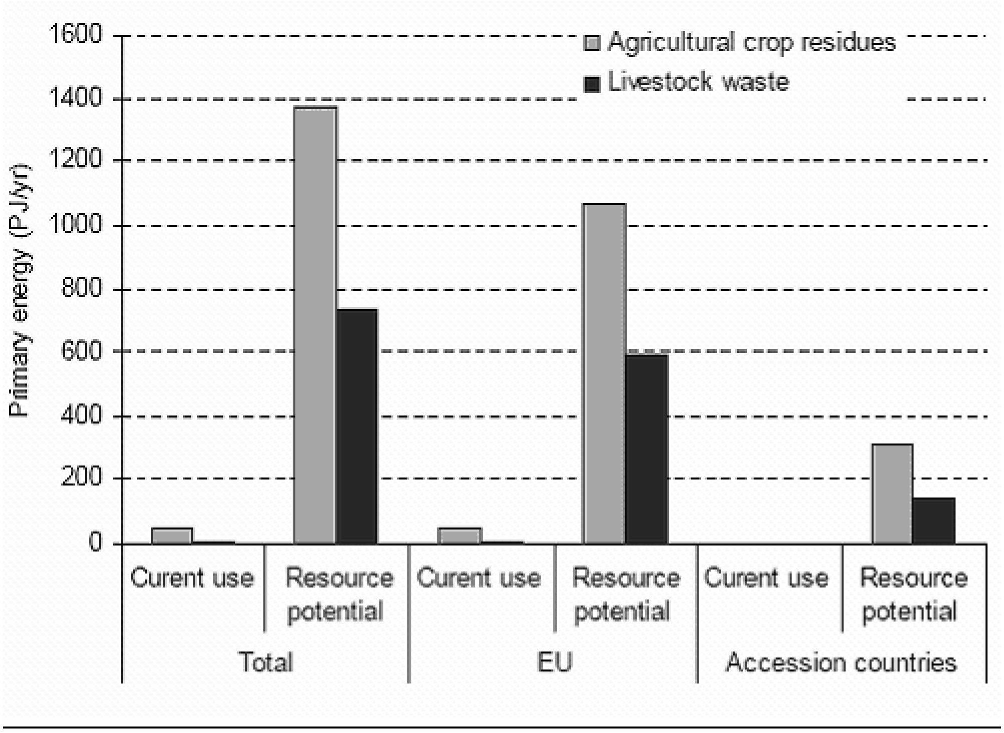


Figure 6 Current use and resource potential of agricultural crop residues and livestock waste in Europe (Nikolaou et al 2003)

4.3 The Swedish availability

Sweden has a great biomass available potential, about 330 PJ/year (Nikolaou et al 2003). It has even been claimed that if all its unused wood fuels and agro fuels fractions were transformed in methanol, it could theoretically produce half of the world methanol 2002 production (Hagström 2002).

4.4 Energy crops

Let’s see what the potential sources of energy crop in Europe could be. Switch grass, hybrid poplar, willow (Salix) are examples of energy crops or also called bio-energy crops. They are fast-growing crops that are grown for the specific purpose of producing energy: electricity or fuels. Their selection is based on their environmental performance like minimal fertilizer and pesticide consumption, erosion control and build-up of soil organic matter. There are many plant species which could be used for energy crops. Moreover, parts of traditional agriculture may be used for energy production (ex: the stems or stalks of alfalfa, corn or sorghum). In Sweden, in Västra Götaland studies have shown that if energy crops have to be planted, Salix production would be the most profitable (Ekbom 2003). There is no numbers in this section since many studies have been performed and are available about energy crops and their potential competition with agriculture or "ordinary" forestry (Keith, D.W. 2001). We deliberately chose in this report to focus on waste wood and how to use what is already available.

4.5 Municipal and industrial waste

If included in the potential feedstock, municipal and industrial waste represent a large potential (Fig. 7).

Waste potential

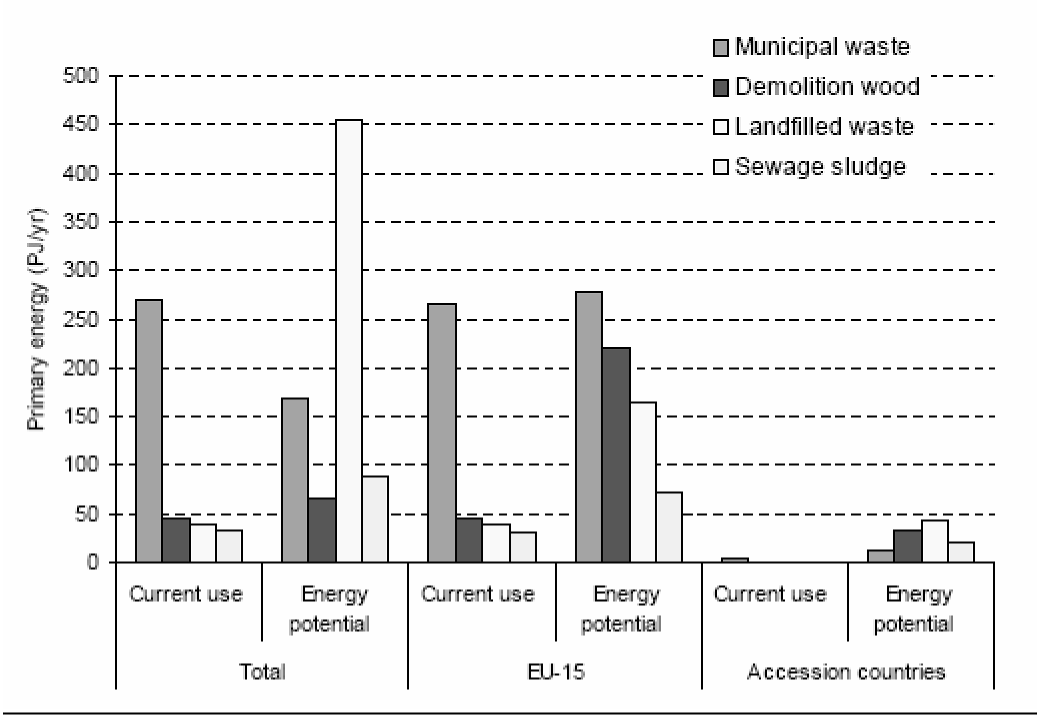


Figure 7 Current use and resource potential of waste in Europe (Nikolaou et al 2003)

One of the most interesting wastes that have been studied separately is plastics. Because of its high energy content and its high production volume it is an interesting feedstock for a waste-to-plastics route. Several companies like Hydro Polymers, Sumitomo and Nippon Steel have developed concepts or pilots for gasifying 100% plastic waste into syngas. Flexi-fuel concepts exist also in this field and SVZ plant in Schwarze Pumpe (Germany) was mixing plastic waste with coal to produce methanol via syngas.

The amount of plastic waste produced every year in Europe is 20 million tonnes - about 0.5 EJ (APME 2004) - with 13% recycling and 22% incineration. The major part of the rest is still landfilled; consequently the potential for plastic recovery through the thermochemical platform is great.

4.6 Waste market structure

The price of raw material as well as it stability is a key factor for the BTP route. The cost of biomass and waste depends on the local markets dynamics: agreements, contractors, user-producer interface mechanisms…The cost should also include all pre-treatment since feedstock cost is related to its readiness for processing. This cost is difficult to estimate since the markets are not very mature for fuel and chemical production. Changes occur rapidly so experience feedbacks from combined heat and power plants that use fuels like woods pellets and municipal waste could be very useful for a first analysis.

4.7 Environmental impact

4.7.1 WASTE BIOMASS COLLECTION

One of the main obstacles or challenges for biomass based process is logistics. The feedstock supply is limited by today’s logistic network and technologies. It may be one of the reasons why the studies (Ekbom et al 2003, Hamelinck, Faaij 2001…) which have been performed with different types of feedstocks (black liquor, wood residues…) all lead to production units – for methanol – with around 200 000 tons a year. Today, the environmental impact for feedstock and waste collection by trucks constitutes a main challenge for our bio-based process. Again the transport sector is a main pollutant and development of any sustainable activity is dependant on progress made in this field. Biodiversity and ecological impact from forest resources harvesting are also important, but most of the studies have been performed by forest industries (Stora enso 2004) and the main first resources used will be untapped biomass and waste (like plastic waste) that should not have more impact on the environment.

However, future energy crop strategies have to be carefully investigated since the impact on local environment could be important (biodiversity, disturbance of the mineral cycles - that will for instance lead to a recycling of the ashes and thus another logistic loop - , land use, incompatible ecosystems…).

5 THE BIOMASS TO PLASTICS ROUTE: POTENTIAL CONFIGURATIONS AND TECHNIQUES

There are many different potential process routes to produce polymers from biomass and waste. We will here try to present the one based mainly on the gasification of feedstocks to produce syngas that can be used for methanol/DME production and then olefins. First a basic design for the process will be examined with special interest for some interesting configurations and then the technological status of the different technologies involved and existing plants will be described.

The biomass to plastics route consists basically of 4 steps and a relatively simple flow sheet can be drawn (cf. fig 8). However due to its inherent sensibility to many drivers - pushes and pulls - there are many possible variations of this scheme.

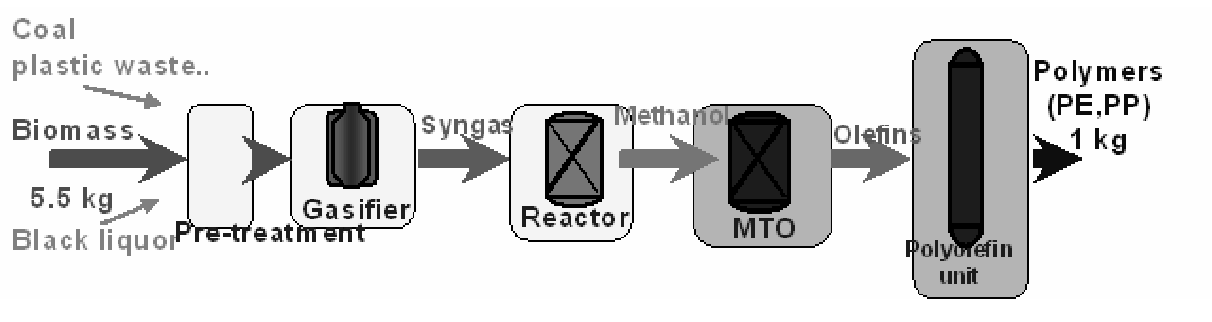


Figure 8 Biomass/waste to plastics flow steps

The different configuration options due to specific situations will be now overviewed.

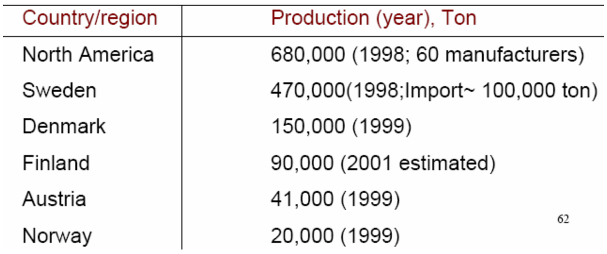
5.1 Pre-treatment

Before gasification, feedstock has to be pre-treated. This consists mainly in, screening, size reduction, drying. It is an important step since cost of this preparation could be about 5% of the total equipment investment costs (Ekbom 2003). Drying is generally the most important pre-treatment step. It reduces the moisture content to about 10% using generally steam or flue gas (Ekbom 2003).

The many feedstocks and ways to process biomass/waste could slightly change the basic BTP route. Processing biomass can lead to different possible feeding strategies. For instance “refining” the biomass to enhance its energy content (from drying to biooil or biocoke production) before entering the gasifier can lead to better results (i.e.: tar free syngas for the Choren system).

Densification is one of these ways to “refine” biomass before entering the BTP process. It consists in compacting low density material into a product of high density. Densification has aroused a great deal of interest worldwide in recent years as a technique of beneficiation of residues for utilization as energy source. Densified biomass is mostly found in the form of briquettes in developing countries and in the form of pellets in developed countries (Bhattacharya 2001).

Capacity of these plants is large, being in the range 1-30 tons per hour. Pelletizing was introduced in Sweden and USA in early and mid-1980s. In a number of countries it has a recent development, e.g. Germany, Norway (cf. table 1).



Country/region	Production (year), Ton
North America	680,000 (1998; 60 manufacturers)
Sweden	470,000(1998;Import~ 100,000 ton)
Denmark	150,000 (1999)
Finland	90,000 (2001 estimated)
Austria	41,000 (1999)
Norway	20,000 (1999)

Table 1 Pellets production (Bhattacharya 2001)

Another way is to go through an intermediate like biocoke (Choren GmbH) or biooil (BTG Biomass Technology Group BV 2003) via a first reactor and then gasifying it through an adapted gasifier, like the Carbo-V for Choren GmbH. The choice of making the two steps - production of the intermediate and gasification - in two different places could be motivated - or not - by a local heat and power production. Indeed, the Choren low temperature gasifier (first reactor) produces biocoke that can be gasified further on, and combustion gas that can be used on-site to produce decentralized heat and power (cf. fig 9).

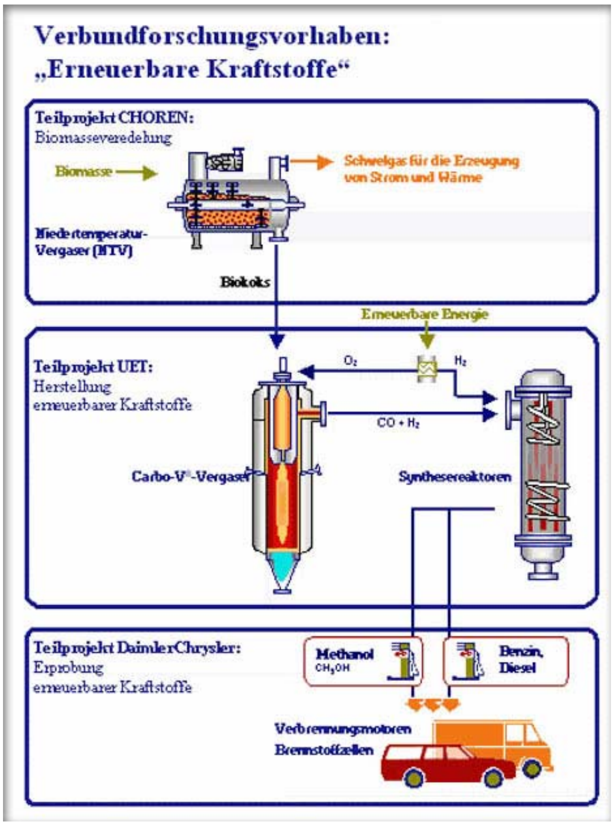


Figure 9 Decentralized-centralized concept (Choren GmbH 2004)

5.2 *Gasification and methanol production*

A biomass-to-methanol fuel plant via gasification comprises usually: an air separation unit (ASU), a gasification island (dryer, gasifier…), some gas-cleaning sections and a methanol synthesis (cf. fig 10).

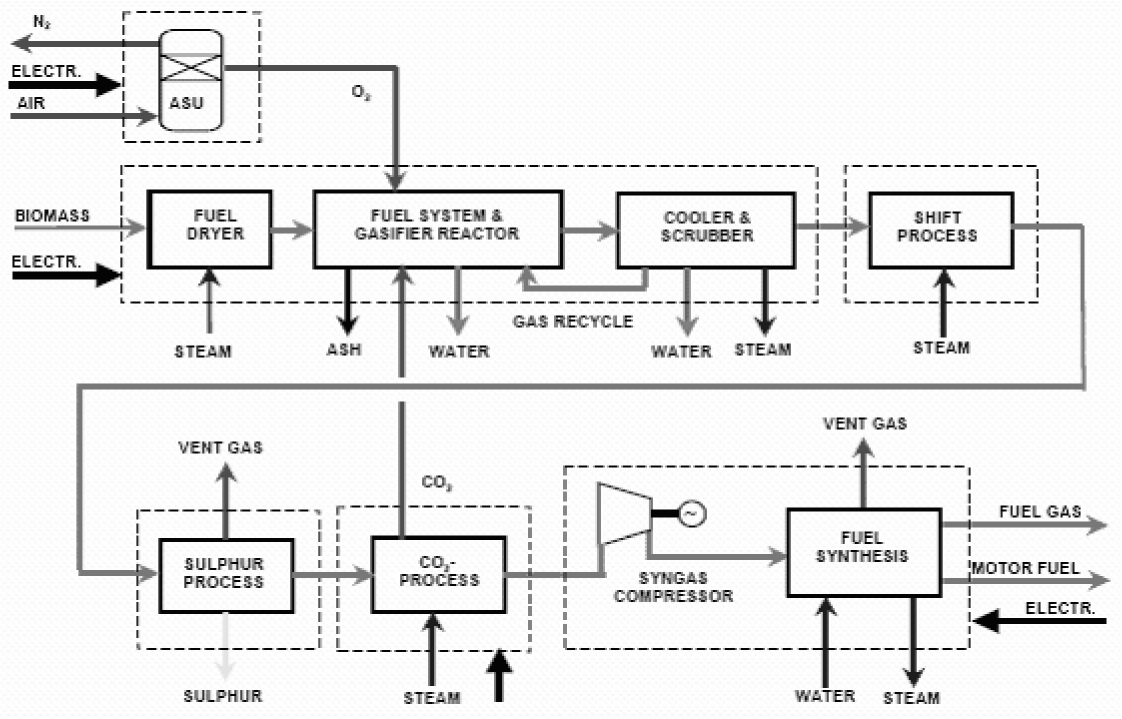


Fig. 10 Flow scheme of a biomass to methanol process (Ekbom 2003)

5.2.1 GASIFICATION TO CLEAN SYNGAS

Conversion of waste/biomass to synthesis gas (H2, CO2 and CO mixture) suitable for methanol synthesis takes place in the gasification unit. Circulating Fluidised bed gasifiers seems promising for forest residues feedstocks and there are existing demonstration projects for chemical production based on this type (Chrisgas project 2004)

The gas at the outlet of the gasification unit has to be cleaned before downstream processing. Indeed, the produced syngas contains tars, dust, alkalis, sulphur - biomass inherently contains sulphur in very low proportions, about 0.03 % (Scahill 2003), that can lead to sulphides formation - and halogens that can poison the catalyst or corrode the different units of the downstream process. Whereas conventional technology can be applied using gas cooling, low temperature filtration and water scrubbing, hot gas cleaning technology is not yet well proven. However due to strong investments and research – partly due to syngas process interests – hot gas cleaning is a very attractive and forthcoming cleaning concept (Hamelinck et al 2001).

Contaminant like tar and methane has also to be removed which may be done with new developed tar cracking and methane reforming catalysis.

Because of the flexibility of gasification regarding the feedstock (coal, biomass, plastic waste, black liquor, biooil, biocoke...etc...) several variations of the process exist. For instance, co-gasification of coal and waste is the way it was done to produce methanol in the Schwarze Pumpe plant configuration (Fig. 11).

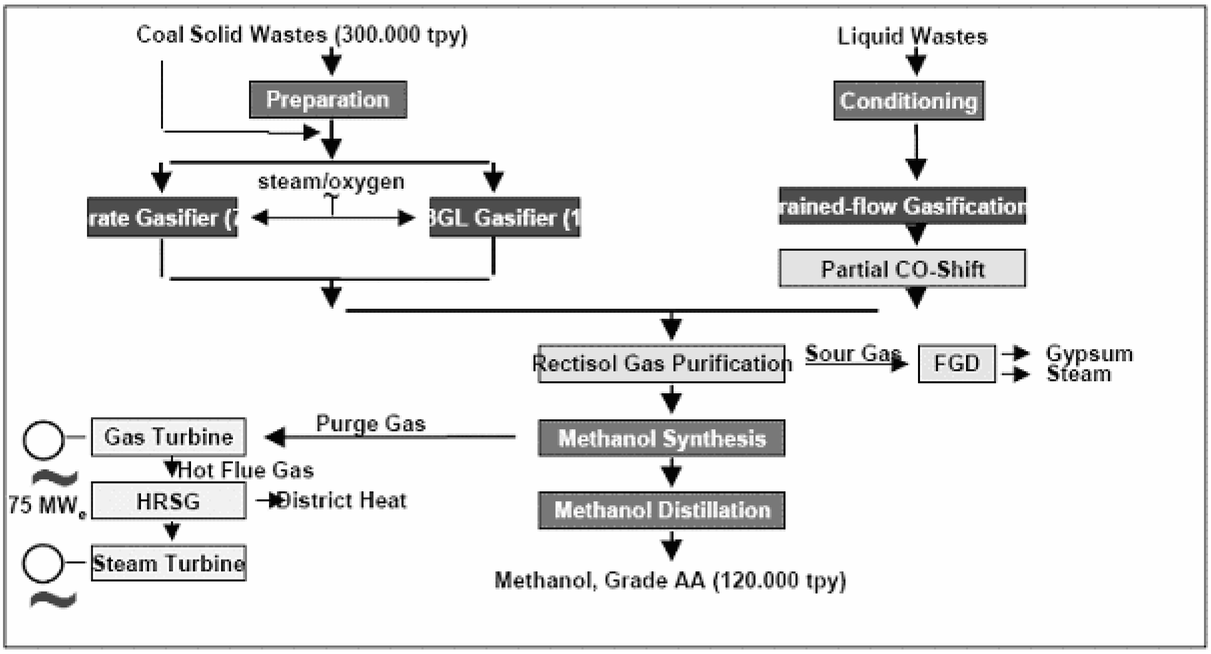


Figure 11 SVZ Plant (Hans Joachim Sander 2003)

Co-gasification of coal and biomass seems to have some advantages in case of co-production of methanol and electricity-energy like improving the economic flexibility of the system (Chmielniak 2002). The flexi-fuel concept seems to appear also in the chemical industry with plant running with different fuel inputs (Sander 2003).

Other biomass feedstock like black liquor can be used for the BTP process. The configuration will be a little bit different since the black liquor is a by-product of the pulp and paper industry. Consequently, production of methanol is possible via black liquor gasification (BLG) through pulp mill special integration (Fig.11) which also enables recovery of pulping chemicals. The conclusions of studies about BLG to produce electricity and/or fuels are very enthusiastic (Ekbom et al 2003).

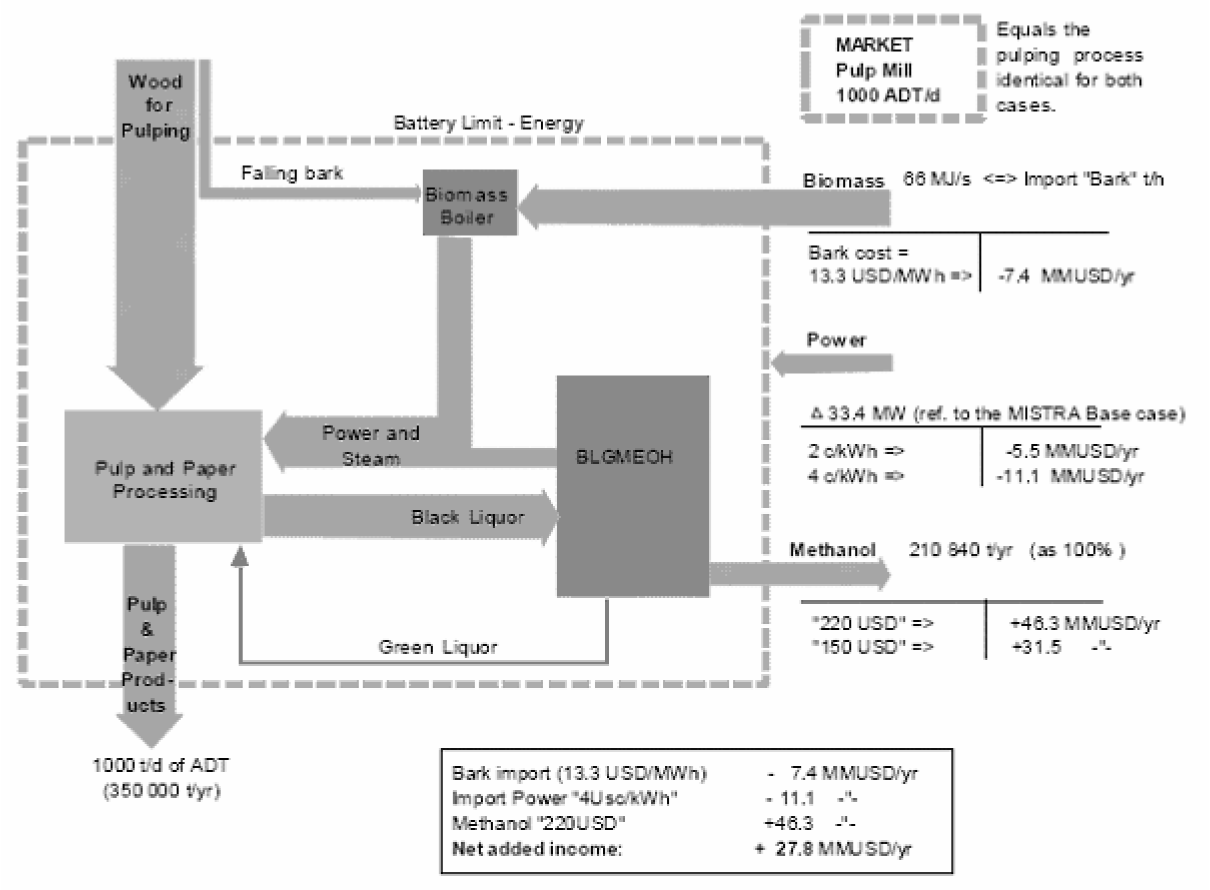


Figure 12 Black liquor gasification (BLG) with methanol production (Lindblom 1998)

Some power, heat and even electricity could be worthy to produce along the process. In Sweden, Finland and the Far East, biomass potential is great and thus allows possible integration of the methanol production process with combined heat and power (CHP) production (Fig. 13) with the aim to improve the total efficiency and the economics of the process. This requires some additional units (turbines, boilers…) and the process could change a little bit.

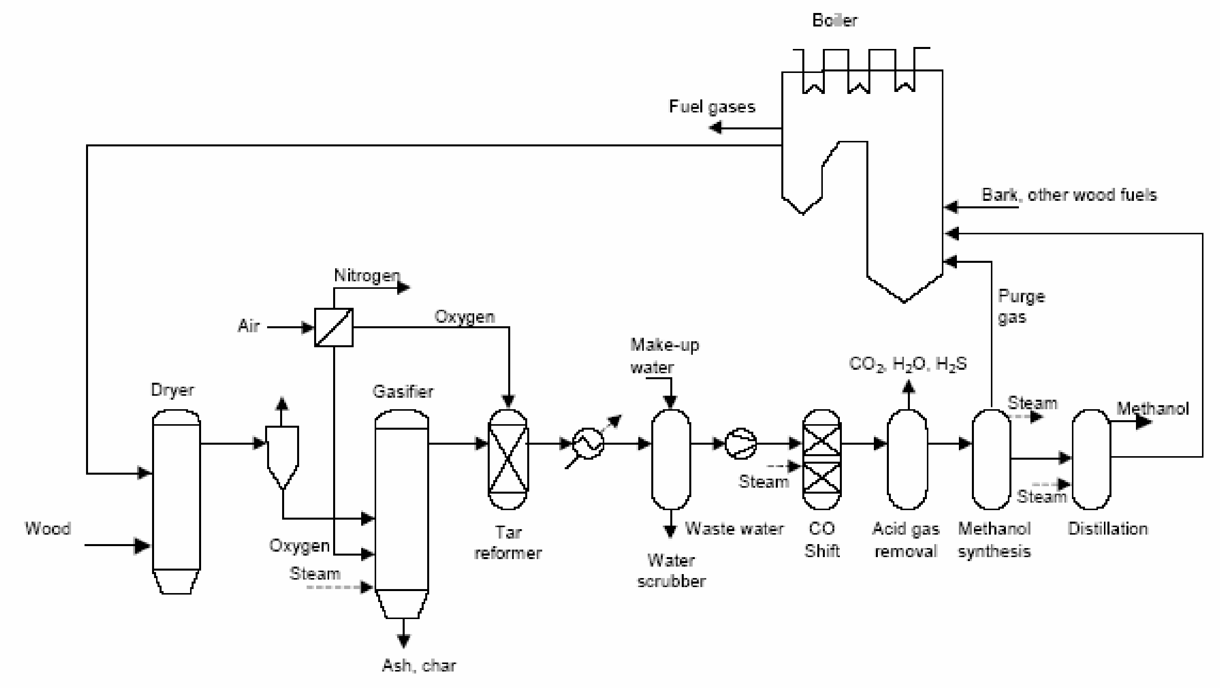


Figure 13 CHP-Methanol combination (Ohlström 1999)

Despite all those possible changes, the process configuration is still basically the same, all centered on gasification and methanol production.

5.2.2 METHANOL SYNTHESIS

Chemical reactions involved are:

- $CO + 2 H_2 = CH_3OH$

- $CO_2 + 3 H_2 = CH_3OH + H_2O$

Both reactions are exothermic and favored by high pressures. The standard operating condition (for low pressure synthesis) are 50 to 80 bar pressure, 210°C to 290°C temperature (reactor inlet/outlet), up to 7% mole methanol at reactor outlet, 3.5 to 7 recycle to make up, and a carbon monoxide conversion in the range of 90 to 97% depending on make-up gas quality and recycle rate. As always, the catalyst formulation is of prime importance. To reduce side reactions like methanation (strongly exothermic!), DME, ethanol, FT and heavier alcohol and ketones formation, temperature must be carefully controlled and reduced by appropriate catalyst formulation.

Many reactor configurations exist for methanol production; however Liquid Phase Methanol process (Air Products and Chemicals® Fig. 14) has shown a great performance in many already installed methanol plants.

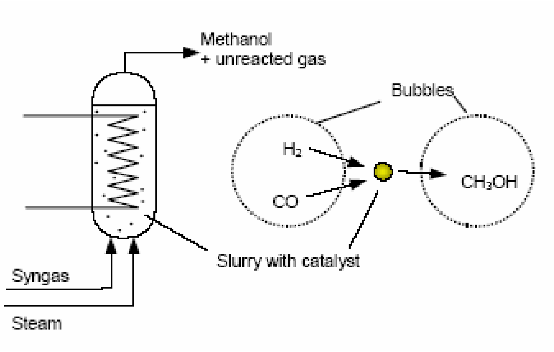


Figure 14 Liquid phase methanol synthesis (Hamelinck, Faaij 2001)

Some of the main advantages are:

- Excellent temperature control with smaller heat exchanger

- Faster mass transfer

- Higher conversion per pass

- Easy and rapid accommodation to changes in feed rate and composition

etc… (Faaij et al 2001).

5.3 Olefins production

A methanol to olefins plant exists as a demo plant in Porsgrunn, Norway, and is ready for commercialisation. It is able to convert methanol into lights olefins (ethylene and propylene). The feedstock is crude methanol (about 20% water) and the output is mainly ethylene, propylene, water and butenes. UOP/Hydro plant flow sheet is given (Fig 15). The main 3 major MTO process suppliers are UOP/Hydro, Lurgi and Exxon Mobil, with some variations among them. For instance the Lurgi process is producing only one olefin from methanol: propylene, so it is named methanol-to-propylene (MTP®).

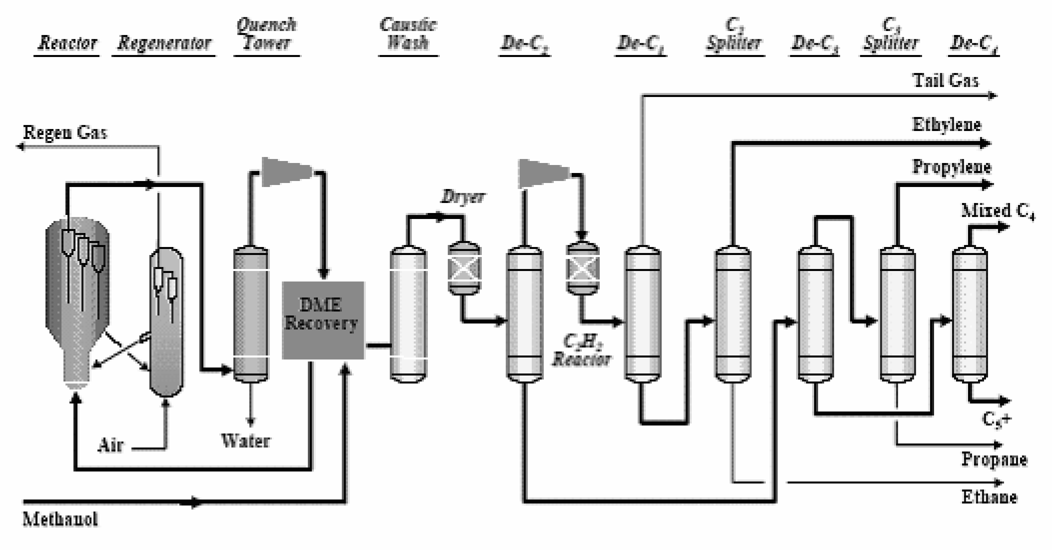


Fig. 15 Methanol to olefin process flow sheet (Andersen et al 2003)

5.4 Polyolefins production

The ethylene and propylene are then converted to polyethylene and polypropylene using polyolefin units.

Polyolefin unit are available on the market to polymerise olefins into polymers. Information is widely spread about this technology. Output depends on olefin input and mainly polyethylene and polypropylene are produced. There are some variation of the processes for producing LDPE or HDPE for instance, one requiring a more elevated pressure.

5.5 Technology status

An overview of the technological level of development of each technology involved in the BTP route will be now presented.

5.5.1 BIOFUEL/METHANOL PRODUCTION PLANT

Biofuel production via gasification is an emerging technology. It is still not mature but many pilot and demonstration plants exist around the world. The design of the process varies a lot depending on the feedstock and the gasifier choice. Gasification technology is strengthening from biopower to biofuel demand as well as need for new waste handling processes. The many types of gasifiers are adapted to the different growing applications. So far no gasifying reactor of choice seemed to have been selected and it is hard to say which technology is the best since few data is available (Knoef 2005).

Making fuel from syngas via gasification is not a new process. Methanol and FT (Fisher Tropsch) fuel have been made for a long time via gasification of coal. In Europe there are actually several plants making fuels (methanol, FT) from biomass, coal and waste. FT diesel is produced from biomass via gasification - biomass is first treated trough flash pirolysis - by Choren GmbH in Freiberg (Germany cf. fig 16) with a cumulative production of FT diesel around 9500 kg from 2003 to 2004.

Fig. 16: Industrial syngas production plant, Choren GmbH, 2003

Methanol was produced via gasification of mixed coal and waste in Schwartze Pumpe (Germany, methanol: 100.000 MTA, Fig. 17).

Figure 17 SVZ plant, 2003

In Sweden, the CHRISGAS project launched by the Växjö Värnamo Biomass Gasification Centre (VVBGC), has as its primary objective to demonstrate in the Värnamo plant (Fig. 18) the manufacture of a hydrogen-rich gas from biomass, suitable for fuel synthesis purposes.

Figure 18 Värnamo IGCC plant

Around the world, there are other projects oriented towards production of fuel from biomass or waste gasification.

In Japan, Mitsubishi Heavy Industries is developing a biomass gasification methanol synthesis system or BGMSS (Fig. 19).

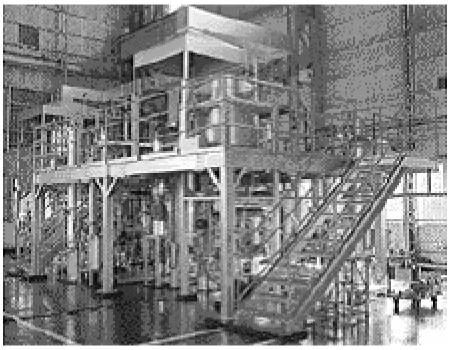


Figure 19 Biomass Gasification Methanol Synthesis System test equipments MHI LTD.

Another Japanese project is to convert plastic waste into methanol via gasification. An actual pilot plant is owned by Nippon Steel (Fig. 20).

Figure 20 Pilot plant 5 t/d Nippon Steel

A typical flowsheet for a waste biomass to biofuel plant (Fig. 21), showing the technology status of each step would be:

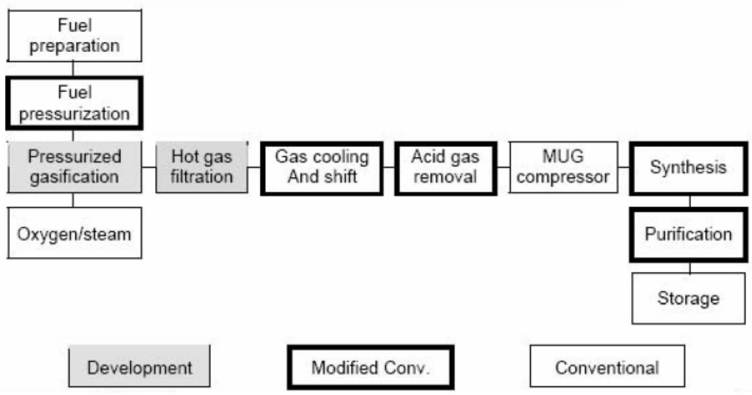
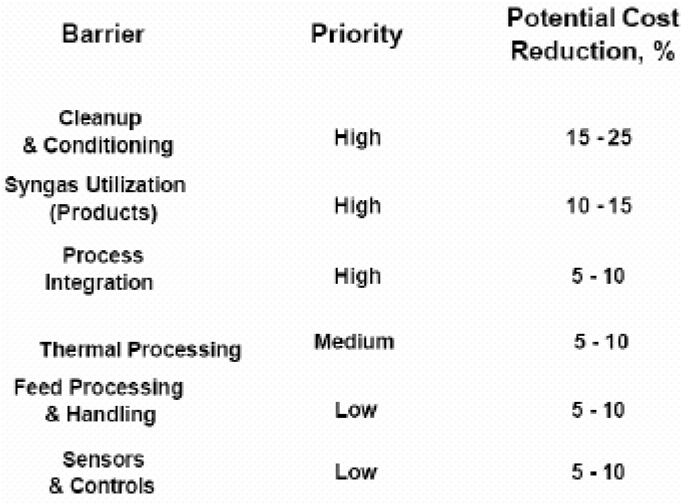


Figure 21 Biofuel plant flowsheet technological status (Ståhl et al 2004)

The status of technology development can also be illustrated by the potential cost reduction of syngas production, and the priority of overcoming barriers. Studies have shown (Craig 2003) that there is a cost reduction potential of 15-25% in gas clean up and conditioning which makes it a high priority barrier, whereas syngas utilisation potential cost reduction may be 10-15% and process integration 5-10%. Gas cleanup and conditioning is of high priority (Table 2) for the production of clean syngas to produce fuel/methanol:



Barrier	Priority	Potential Cost Reduction, %
Cleanup & Conditioning	High	15 - 25
Syngas Utilization (Products)	High	10 - 15
Process Integration	High	5 - 10
Thermal Processing	Medium	5 - 10
Feed Processing & Handling	Low	5 - 10
Sensors & Controls	Low	5 - 10

Table 2 Main technological barriers and cost reduction potential (Craig 2003)

Developing tar cracking, methane reforming catalysis as well as improved particulate removal techniques and gas cleanup testing is of prime importance for future industrial biofuel plants.

5.5.2 METHANOL TO OLEFINS

Methanol to olefins (MTO) is a well known process - though not yet realized at an industrial scale - and the chemical reactions which occur, though not well understood, have been studied for a while (Soundararajan 2000).

There is a planning for industrial realization in Nigeria for the UOP/Hydro MTO and in Iran for the MTP® for 2006. MTO technology is available and applicable.

There are currently 2 MTO demo plants in Norway, owned by UOP/Hydro and Lurgi/Statoil, respectively in Porsgrunn (Fig. 22) and Tjeldbergodden (Fig.24).

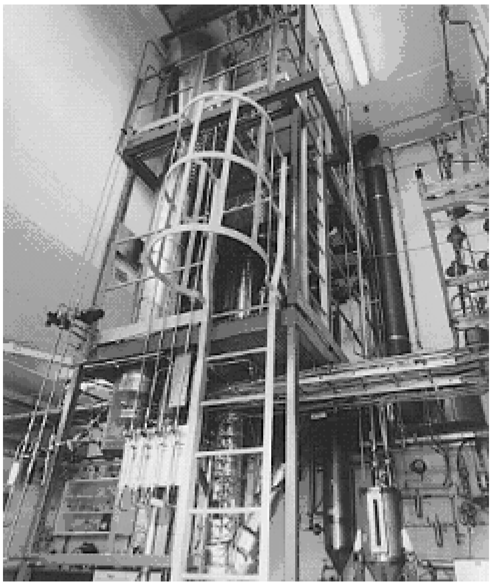


Figure 22 UOP/Hydro demo plant

The UOP/Hydro MTO demo plant is processing 1 ton per day of methanol (crude or high purity). Further development are planned such as integration of MTO with an olefin cracking unit (designed by a TOTAL SA subsidiary), leading to better yield (Fig. 23). Indeed, although the MTO reactions are quite selective, C4 + (butenes) by-product streams are produced. Achieving good valuation of these by-products can sometimes be difficult because MTO projects can be installed in remote locations. By integrating olefin cracking into an MTO complex the overall yield on feed to the complex can be greatly increased. The yield of methanol feed that goes to light olefins (carbon basis) for an MTO complex augmented with Olefin Cracking can approach 90%.

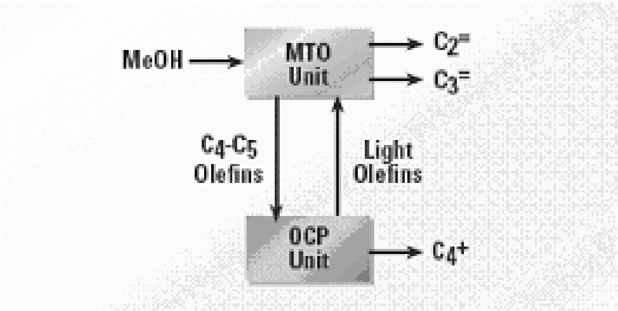


Figure 23 OCP-MTO integration (UOP 2004)

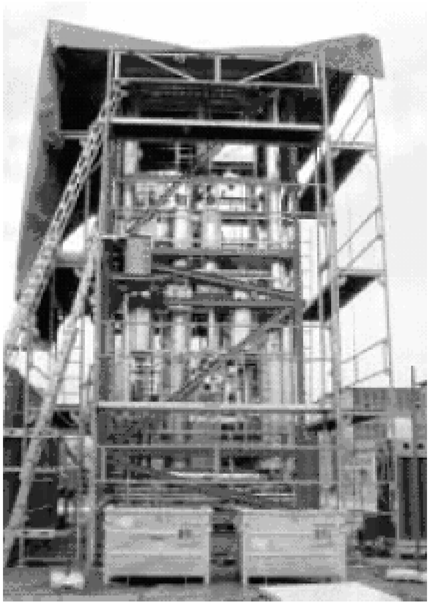


Figure 24 MTP Lurgi pilot plant with Statoil (Lurgi 2004)

6 TRANSPORT LOGISTICS

Since the transport issues is a very specific one and that the problems involved are not directly those related to the BTP route, we will try to deal with it separately.

6.1 Raw material supply

The BTP process needs a continuous and available inbound delivery of feedstocks. Supply chain management is crucial for this technically advanced process. The way buffer stocks of raw material, collection distance, plant site choices… are planned will have great impacts on the production cost and on the environmental impacts.

We assume that transport of feedstock will be done by trucks. However, other means of transportation like boats could be considered further on to reduce the transport intensity (Ekbom et al 2003). Moreover since the BTP route is supposed to emerge on a 20 year scheduled basis, emerging technologies in the transportation sector should be followed carefully.

Calculations show an optimum collection radius of about 50-70 km for various feedstocks when using truck transportation (Elam 2002).

The truck logistics leads to a feedstock input of biomass, for a reasonable bio-syngas route, of about 80 tons per hour (Ekbom et al 2003) which is about one truck - 40 ton capacity trucks - delivery to the plant every 30 minutes.

6.2 Syngas/Fuel/Methanol distribution

All along the process, syngas and methanol have to be distributed to the correct units in the most efficient way, depending on the configuration of the plant. If the location of the methanol production unit is different from the olefin production one, trucks, boats, trains or pipelines could be needed to transport methanol. The best and assumed situation is that both methanol production and olefins one are situated in an industrial park where process integration potential is important. Syngas from gasification could also be used as a complement of a natural gas reforming unit to produce methanol or partly be used in an integrated gasification combined cycle (IGCC) plant for energy purposes.

6.3 Ash transports

The ash content for pure wood is nearly 2% D.S (Ekbom 2003) which corresponds to about 7000 tonnes per year or one truck every 46 hours for a feed of 86t/h. Ash recycling has not been taken into account for this evaluation. However it is an important issue if extensive use of wood waste is done since ashes contains nutrients removed from the forest during wood waste collection.

7 PROJECT SCENARIO, ASSESSED ROUTE

We are now going to deal with one simple route from biomass to plastics. This first scenario is a very basic BTP route from biomass to polymer assumed to be situated in Sweden, preferably near an industrial park and with supply facilities like a harbour (for instance Stenungsund industrial park in Sweden). It has 5 steps: transport of biomass by truck, syngas production, methanol synthesis, MTO, and polymerisation.

We will, in the following sections, make a short assessment of the process performances of the BTP route. First we will make some material and energy balance, then we will make a rough life cycle assessment of the route and finally calculate some financial parameters (cost of production, product value…).

7.1 Material and energy balances

The material and energy balances depend of course on the configuration of the process and the different types of integration strategies. However a global pattern can be determined from a classic process base case.

Two examples of Sankey diagrams of biofuel plants are given for illustration of the main energy consuming part (with today's technology, Fig. 24, 25)

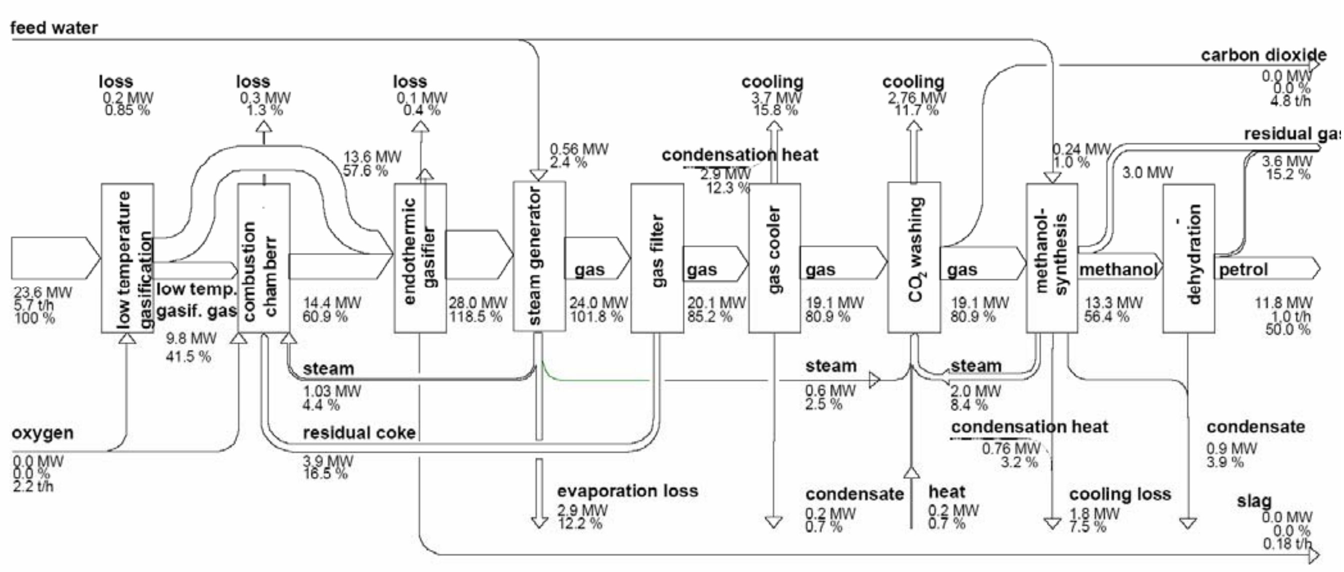


Figure 24 Sankey diag. for MeOH/Petrol synthesis using Carbo-V process (Wolf 2001)

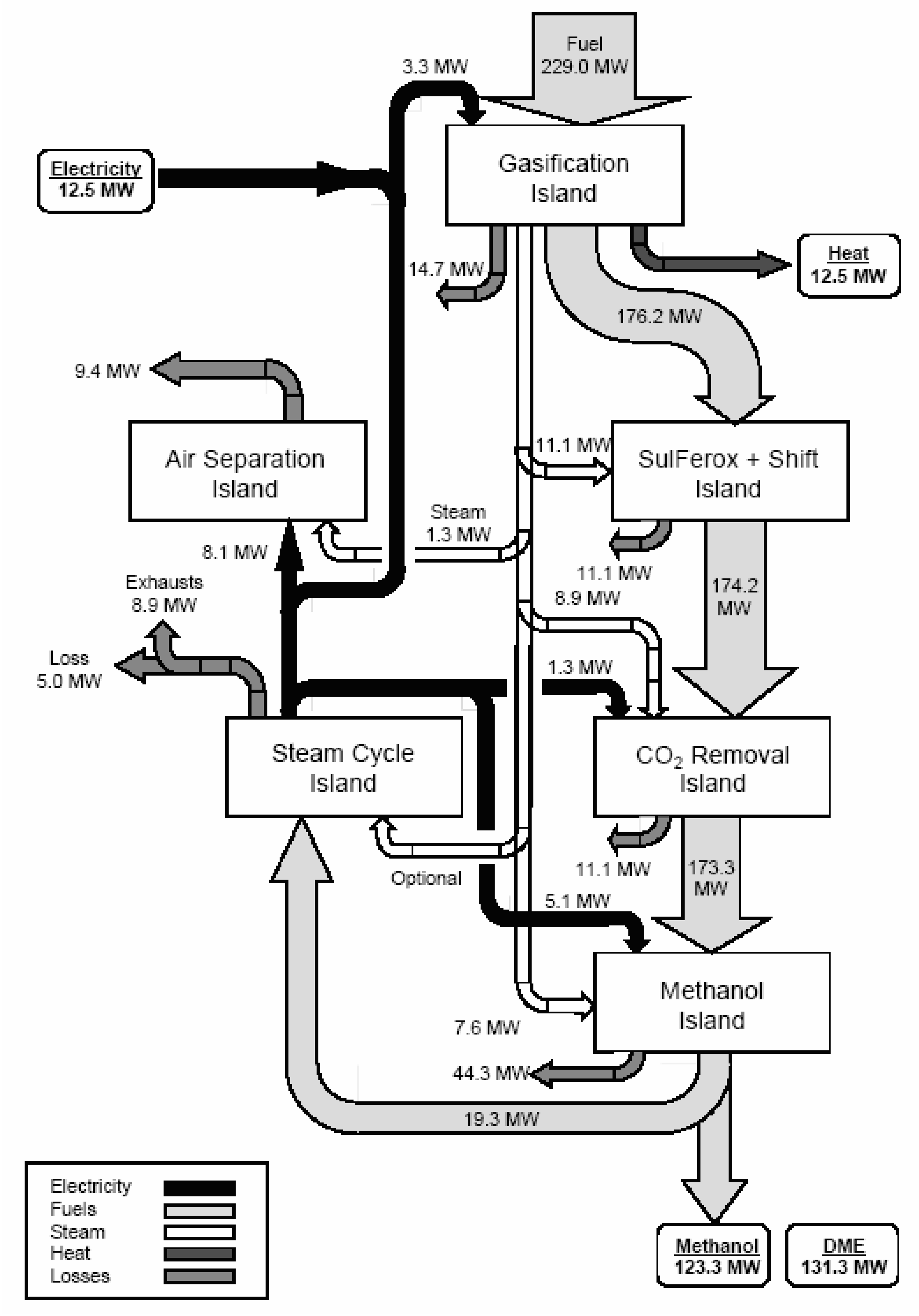
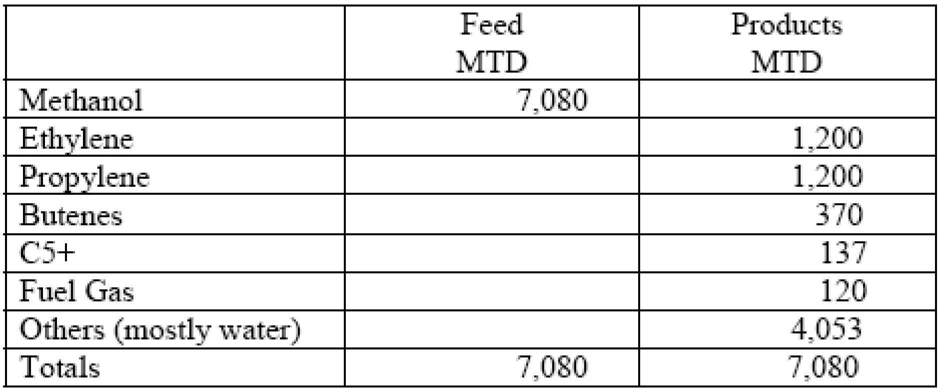


Figure 25 Sankey diagram of a bio-methanol plant (Ekbom 2001)

Despite differences in the reactors and process design, the global efficiency is still the same, and biomass may be transformed into methanol with an energy efficiency of about 50%. In terms of mass flowrates, it means roughly 3.7 tons of biomass (1.88 ton dry substance) is converted to 1 ton of methanol.

For a methanol to olefin unit, about 3 tons of methanol are needed to produce 1 ton of light olefins with equal amount of propylene and ethylene. An example of product distribution is shown table 3 for the production of 800 000 tons/year of olefins.



	Feed MTD	Products MTD
Methanol	7,080	
Ethylene		1,200
Propylene		1,200
Butenes		370
C5+		137
Fuel Gas		120
Others (mostly water)		4,053
Totals	7,080	7,080

Table 3 Example material balance for 800 000 tons/year MTO plant (Andersen et al 2003)

The conversion of propylene and ethylene to polypropylene and polyethylene is a matter of polymerisation and does really not affect the flow rate (polymerisation yield superior to 99%, Baumann, Tillman 2004).

This means that to produce 1 kg of polymer – 0.5 kg of polypropylene and 0.5 kg of polyethylene – about 11 kg of biomass is required (5.65 kg dry substance). To be more precise, the yield and composition of wood waste as well as the intermediate product yields and carbon balance can be calculated as in table 4, using the collected data.

	kg/kg biomass as received	**kg/kg biomass dry substance**	**Carbon efficiency (%)**
Dry material	**0.5**(a)	**1.**	**-**
Carbon content	**0.242 (sawdust** b**)**	**0.51**	**-**
Syngas	**0.77**(a)	**1.55**	**-**
Methanol	**0.265**	**0.53**	**90**(e)
Olefin (MTO)	**0.089**	**0.18**	**72**(c)
Polyolefin	**0.088**	**0.178**	**71.2**(d)
MTO by-products (C5+, Butenes c**)**	**0.019**	**0.037**	**-**

Table. 4 Product yield and carbon balance

(a) Source Ekbom 2003

(b) Biomass properties Scahill 2003

(c) Source: Andersen et al 2003

(d) Source Tillman, Baumann 2004

(e) Source: MHI power systems. Ed: The carbon efficiency displayed on the MHI website is quite high and do not match our basic carbon efficiency calculation which result is about 31% for the BTP process. We suppose that some assumptions or data used by MHI, that we are not completely aware of, were made.

The moisture content of wood waste is variable, but around 50% and its composition consists approximately of 24% carbon as received. Table 4 shows that the overall theoretical process yield 88 g polymer from 1 kg of wood waste as received (1 kg polymer/11.3 kg wood waste), leading to a carbon conversion efficiency of 71.2%.

A short comparison with polylactic acid (PLA) which is today one of the major biopolymer made via the sugar platform (cf. fig 2), could be interesting to perform, and using available sources, we will try to do so.

From Cargill™ (a major PLA producer) we know that approximately 2.5 kg of corn (15% moisture, Number 2 Yellow Dent) are required per kg PLA (Cargill™ 2004). We do not have the composition of the Number 2 yellow dent corn but the composition of red corn cob (Bain 2004), that we will use instead (16% moisture, 45% carbon content). The structure of PLA is shown fig. 26 and the molar mass of the monomer (lactic acid) is 72 g/mol of which 36 g/mol are due to carbon atoms.

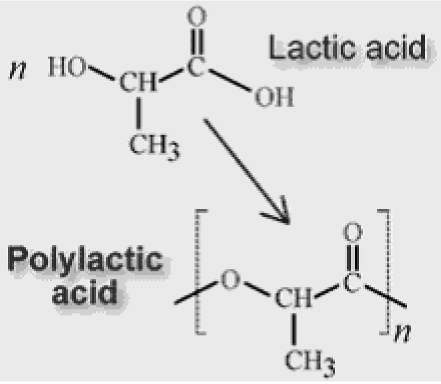


Fig 26 Polymerisation of lactic acid to PLA

This leads to 50% carbon content for PLA. Since 1 kg of corn is transformed in 0.4 kg PLA, it means that 0.45 kg of carbon from corn will be transformed into 0.2 kg of carbon in PLA. To conclude one can say that approximately 44% of total carbon in the corn will be recovered as PLA polymer.

About the first step to methanol, depending on the different feedstock compatible with gasification, the methanol yield could greatly vary (fig 30) and may orient the choice of one or another supply feeding options.

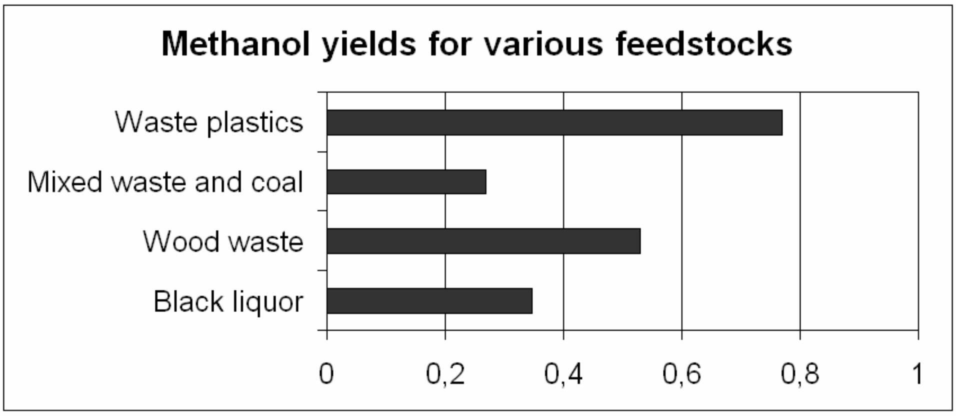


Fig 30 yield of methanol from residues generated from various activities.

Waste plastics are treated via gasification in a Japanese pilot plant owned by Nippon Steel. Waste plastics also used to be processed at SVZ plant in Germany. The yield reached for waste plastic is about 77% (Picard, Bröske 2004) which is high and quite understandable since the plastic waste stream has a high energy content. Wood waste has lower energy content and thus leads to a methanol yield of 53% (Ekbom et al 2003). For black liquor use, the yield is about 35% (and higher maybe due to the liquid form of the feedstock and the high efficiency of the dedicated gasifier. Mixed coal and waste was also used as a feedstock for methanol production at SVZ plant and the average yield was about 27%. This relatively low yield could be due to the very own configuration of SVZ plant that has been transformed to treat waste mainly, since the main goal was to process waste and not to produce methanol.

The process performance and balances - which still have to be assess although looking promising - thus greatly depend for instance on the different feedstock configurations. This parameter as well as some other major ones will be carefully taken into account in further studies.

7.2 Environmental performance – life cycle green house gases emissions and energy use

We will now try to assess the environmental performance of the BTP route by making some life cycle based calculations. First GHGs emissions and then the energy use will be accounted from a cradle to gate perspective. The LCA is a rough one, to a large degree on literature sources. The results should thus be seen only as a first estimation and are in no way final.

The general flow sheet assessed will look like the one in fig. 28:

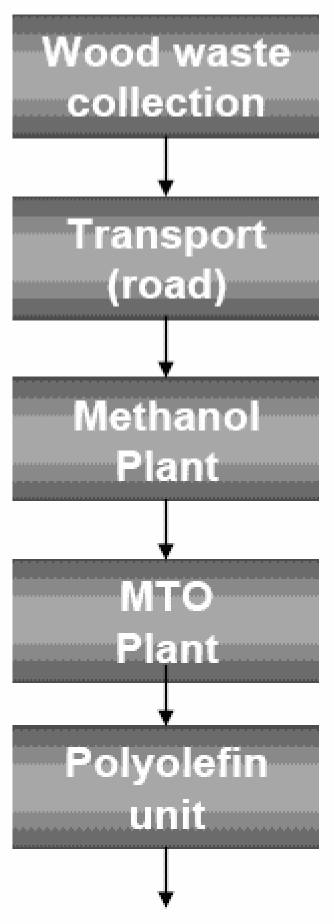


Figure 27: flow chart for the BTP route from cradle to gate base case

We will now account the green house gas balance for the BTP route. The CO2 figures represent the actual emissions occurring during each process. When CO2 emissions stem from biomass, only the net emissions are counted, i.e. CO2 of biomass origin is not accounted for.

Wood waste collection and chipping:

The wood waste considered is forest residual from commercial forestry (EUCAR 2003).

This gives net GHGs emissions (emissions from biomass sources not accounted) of 0.7 g CO2eq/MJf (MJf stands for MJ fuel, here MJ methanol, EUCAR 2003). Since methanol has a calorific value of 20 MJ/kg, the net GHG emitted are 0.7 x 20 = 14 g CO2eq/kgMeOH. Moreover, 3 kg of methanol are needed to make 1 kg of polymer, so 14 x 3 = **42 g CO2eq/kgPolymer** is emitted during collection and chipping of wood waste.

Transport to gasification plant:

The average transport distance for forest residual collection is about 50 km (EUCAR 2003). Assuming that road transport is chosen - worst case scenario since a combination of shipping and road transport is more likely to happen for a plant that size - emissions are 0.7 g CO2eq/MJf (EUCAR 2003) so **42 g CO2eq/kgPolymer** is emitted during transportation to the plant.

Methanol plant:

Emissions from the bio-methanol plant (gasification and methanol synthesis) have been assessed and are about 0.2 g CO2eq/MJf (EUCAR 2003). As a comparison, it could be mentioned that 11.7 CO2eq/MJf are emitted for methanol, from natural gas (EUCAR 2003).

It represents 4 g CO2eq/kgMeOH and thus about **12 g CO2eq** emitted per kg of polymer produced.

NB: in the literature, when people read "methanol" it is implicitly pure methanol (purity more than 99.9%) the author is talking about; so most of the data available are about pure methanol and thus include the purification step. However the purification of methanol is not needed for the MTO unit feeding. Indeed, in terms of process engineering, for a single train route - for any transportation of methanol, purification is of course needed since no one will pay for transporting water - from biomass to olefins, there is no need to purify the methanol up to 99% since the MTO process is running better with a feeding of crude methanol (20% water), so emissions from our methanol plant should not include the purification step of methanol. However such data are unavailable for the moment so we will approximate the emissions for crude methanol production to those of pure methanol one.

MTO plant:

Industrial data from UOP/Hydro give and estimation of GHG of about 200 gCO2eq/kg olefin produced. This data is corroborated by the extrapolated data for the Ifp's MTO process (Joosten 1998) with GHG emission of about 280 gCO2eq/kg olefin produced. Those CO2 emissions were calculated from the combustion of the process output fuels. CO2 emissions caused by the combustion of the extrafuel needed are excluded. Since all the carbon comes from biomass in the process, the only net emissions of GHG accounted are those from the combustion of extrafuel (assumed to be oil). The MTO required about 1.33 MJ extrafuel per kg of olefin produced (Joosten 1998), thus about the same per kg of polymer produced. The combustion of 1MJ of oil emits about 75.8 g of CO2 (Baumann, Tillman 2004) and the extraction/processing and transport 6 g of CO2, thus the MTO net CO2 emissions are about **107 g of CO2** emitted per kg of polymer produced.

Polyolefin unit:

The polyolefin unit global warming potential emissions can be found in the literature (Baumann Tillman 2004) and the total emissions are about 49.7 g CO2eq/kg of polymer produced for the air emissions and 8.6 g CO2/kg of polymer from the combustion of fossil fuel (assumed to be oil) needed and 6 g of CO2 for its production. The total global warming potential emissions are **64.3 g CO2eq/kg** of polymer produced. Here again we use a worst case scenario by taking the data for an HDPE polymerisation unit which consumes more energy than a PP one and by assuming that all the carbon from the flaring is from fossil origin, which may not be true.

The total net GHG emissions for the BTP route are 267 g CO2eq/kg for a Cradle-To-Gate (CTG) and worst case scenario cf. table 4.

Collection, chipping and transport	84
Gasification + MeOH synthesis	12
MTO	107
Polyolefin unit (HDPE)	64.3
Total net CTG GHGs emissions	**267 g CO2eq/kg**

Table 4 Net GHGs Emissions for polymer via BTP route

LCA studies compilations for polymers such as HDPE give an average GHG emission of 1.785 kg CO2eq/kg from cradle to factory gate (Vink et al 2002).

Bio-based polymers and particularly polymers from the BTP route seem to offer important environmental benefits regarding GHG emissions.

The energy use of the BTP process is distributed as follow:

Wood waste collection and chipping:

The total primary energy consumed for waste collection and chipping is 0.06 MJ/MJf of methanol produced (EUCAR 2003). Since methanol has a calorific value of 20 MJ/kg, the energy used is 0.06 x 20 = 1.2 MJ/kgMeOH. Moreover, 3 kg of methanol are needed to make 1 kg of polymer, so 1.2 x 3 = **3.6 MJ/kgPolymer** is used during collection and chipping of wood waste.

Transport to gasification plant:

Assuming that road transport is chosen, the total primary energy consumed is 0.01 MJ/MJ methanol (EUCAR 2003) so **0.6 MJ/kgPolymer** is consumed during transportation to the plant.

Methanol plant:

Total primary energy consumed for the bio-methanol plant (gasification and methanol synthesis) has been assessed and is 0.96 MJ/MJ methanol (EUCAR 2003).

It represents 19.2 MJ/kgMeOH, and thus about **57.6 MJ** total primary energy is consumed per kg of polymer produced. The process energy consumed is assumed to be electricity and is about 0.1 MJ/MJ methanol (cf. fig 26) or about 6 MJ electricity per kg of polymer produced.

MTO plant:

The MTO process uses roughly 0.3 MJ of electricity, 2.8 MJ of fuel and 1.1 MJ of high pressure steam to run and produce 2.11 kg of olefins (Joosten 1998) thus about 0.14 MJ of electricity, 1.33 MJ of fuel and 0.52 MJ hp-steam are used per kg of polymer produced. If electricity is generated with a 35% efficiency (E.U-Mix EUCAR 2003), the primary energy associated to 1 MJ of electricity is 2.86 MJ. The total primary energy associated to the process is then 2.25 MJ per kg of polymer produced.

Polyolefin unit:

The polyolefin unit energy consumption can be found in the literature (Baumann, Tillman 2004) and the total energy used is about 6.6 MJ electricity per kg and 2.2 MJ of fossil fuels per kg of polymer produced for LDPE, and 2.1 MJ electricity per kg and 0.11 MJ of fossil fuels per kg of polymer produced for HDPE. If electricity is generated with a 35% efficiency the primary energy associated to 1 MJ of electricity is 2.86 MJ. The total primary energy associated to the polymerisation process is then 2.1 x 2.86 + 0.11 = 6.12 MJ per kg of HDPE produced.

From a cradle-to-factory gate perspective, the total primary energy consumed for the BTP is 3.6 + 0.6 + 57.6 + 2.25 + 6.12 = **70.2 MJ/kg** of polymer produced (cf. table 5). Assuming that 85% of the electricity is from non renewable sources (EUCAR 2003) the non renewable energy use of the BTP process is thus 3.6 + 0.6 + 57.6x85% + 0.14x85% + 1.33 + 2.1x85% + 0.11 = **56.5 MJ** per kg of HDPE is non renewable energy.

Collection, chipping and transport	3.6 + 0.6
Gasification + MeOH synthesis	57.6
MTO	2.25

Polyolefin unit (HDPE)	6.12
Total primary energy consumed	**70.2 MJ/kg of polymer**

Table 5 Total primary energy consumed for polymer production via the BTP route

The total energy consumption to produce 1kg of polymer is divided into: 8.2 MJ electricity which with a 35% efficiency gives a total primary energy associated to electricity of about 23.6 MJ of which 85% i.e. 24.4 MJ are considered non renewable; 6.2 MJ fossil energy and about 115 MJ of biomass are also required.

A summary of the positioning of the BTP route compared to existing polymers routes can be seen in the figure 28

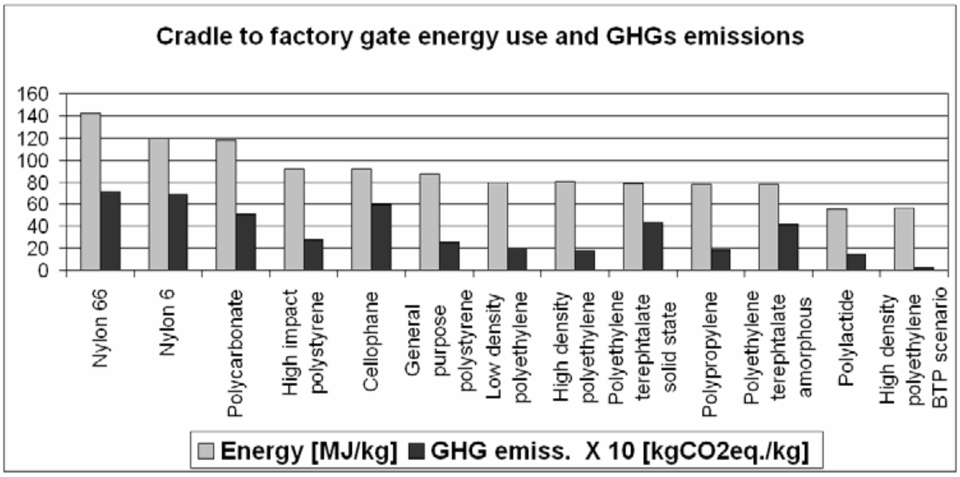


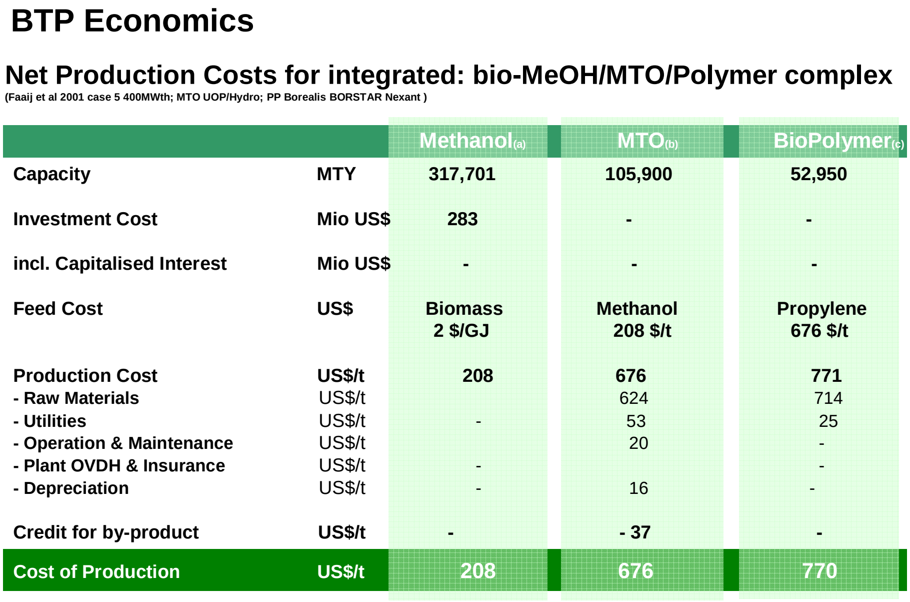
Figure 28 cradle to gate fossil energy and green house gases emissions for the BTP and other routes.

No conclusion could be written so far about the real environmental impact of BTP process. However from a qualitative perspective we can say that the BTP route seems promising regarding its positioning in the polymer production routes panel: with very low GHGs emissions and very competitive fossil fuel energy consumption.

The results from GHG emissions are encouraging but again based on one single technological configuration and without a real industrial context or strategy. Further assessments with clear goal and scope and with more accurate industrial data will be conducted.

7.3 Economics

The cost of production of biopolymer via the BTP route could be estimated by compiling and extrapolating financial data available from the main studies performed for biomass to methanol production routes and the major MTO concept designers (UOP/Hydro and Lurgi with its MTP). This leads to a cost of production for bio-polypropylene of about 770 $/ton cf. table 5.



BTP Economics

Net Production Costs for integrated: bio-MeOH/MTO/Polymer complex

(Faaij et al 2001 case 5 400MWth; MTO UOP/Hydro; PP Borealis BORSTAR Nexant)

		Methanol(a)	MTO(b)	BioPolymer(c)
Capacity	**MTY**	**317,701**	**105,900**	**52,950**
Investment Cost	**Mio US$**	**283**	**-**	**-**
incl. Capitalised Interest	**Mio US$**	**-**	**-**	**-**
Feed Cost	**US$**	**Biomass 2 $/GJ**	**Methanol 208 $/t**	**Propylene 676 $/t**
Production Cost	**US$/t**	**208**	**676**	**771**
- Raw Materials	US$/t		624	714
- Utilities	US$/t	-	53	25
- Operation & Maintenance	US$/t		20	-
- Plant OVDH & Insurance	US$/t	-		-
- Depreciation	US$/t	-	16	-
Credit for by-product	**US$/t**	**-**	**- 37**	**-**
Cost of Production	**US$/t**	**208**	**676**	**770**

Table. 6 Cost of production estimation for bio-polypropylene

(a) Production cost of methanol from biomass using data from methanol production concept 5 (Carlo N. Hamelinck, A. P. C. F.2001)

(b) production cost of propylene from methanol using MTO technology (Andersen et al 2003) assuming methanol feeding price at 208$/ton.

(c) Polypropylene unit economics (Lurgi Oel Gas Chemie 2002) assuming propylene feeding price at 676$/ton.

With US spot prices of about 1000 $/ton for polypropylene (ICIS-LOR 2005), the first cost estimation seem to show a potential for viability for the BTP route but further research has to be done to confirm it.

This 770 $/ton can be compared with the 590 $/t cost of production (2003 data) for non renewable polypropylene. We use the same presentation and calculation approach than with the gas to propylene concept presented for instance by Lurgi (Lurgi 2003).

It could also be interesting to see how far it is worthy to stop in the biomass monetization process. The value of the products from 1 ton of biomass dry substance depending on how far the biomass monetization process is conducted is shown in Figure 29.

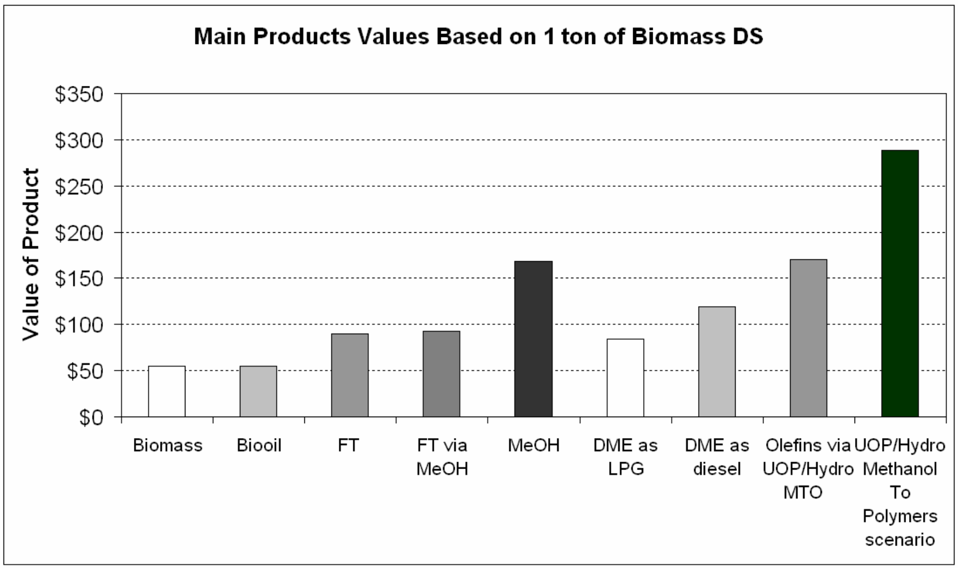


Figure 29: Biomass monetization products values

Basic conclusions from these charts could be that it seems worthy to go downstream and produce polyolefins than to stop at methanol. These charts depend on market prices and could change drastically in a near future.

8 Conclusions

The results and feedbacks of this preliminary study for new material and biopolymer production could be divided in 2 categories:

1. Identification of the potentials of the BTP route regarding economical, environmental and technical issues:
    - Rough estimates of COP, though higher than olefin production from naphtha cracking, looks interesting. Also a biomass monetisation analysis gives possible indication for the BTP route.
    - The BTP process is flexible regarding the feedstock and the products. Moreover strong push/pull drivers exist that can facilitate its implementation.
    - The green house gases emissions are considerably lower than those from conventional polyolefins production. Also the fossil energy consumption is lower compared to other polymer routes.
    - On a general level, all the different sub-processes that constitute the BTP route exist either on a commercial level or as pilot plants. However, no pilot BTP process was ever constructed. Many of the individual processes such as biomass feeding into a pressurised reactor and polymerisation are industrially implemented. Key processes to the BTP route, the gasification to clean syngas followed by methanol synthesis and the MTO process are however only demonstrated at pilot plant and demonstration plant respectively.

2. Methodology learning :
    - It is useful to look at a broader picture, including technical status, market potentials, potential production cost and environmental performance but difficult and done at the expense of accuracy in individual data.
    - Combining LCA and technology screening allows a better identification of the environmental potentials and thus a possibility to produce technically, as well as environmentally, based future scenarios.
    - The integrated assessment was based on a life cycle perspective, focused on finding the main environmental and resources issues as well as economics and technical ones of polymer material; however a more stringent analytic framework is needed.

9 *REFERENCES*

Andersen Jim, Bakas S, Foley T, Gregor J,Vora B, Kvisle S, Reier Nilsen H, Fuglerud T, Grønvold A (2003). MTO: MEETING THE NEEDS FOR ETHYLENE AND PROPYLENE PRODUCTION. ERTC Petrochemical Conference, Paris, France, UOP, HYDRO.

APME (2004), plastics in Europe, an analysis of plastics consumption and recovery in Europe.

http://www.apme.org/dashboard/business_layer/template.asp?url=http://www.apme.org/media/Public_documents/20040813_143314/2002_20022003.pdf

Bain, R. L. (2004). Biomass gasification overview. US. DOE. Battelle, NREL.

Baumann Henrikke, Tillman Anne-Marie (2004). The hitch hiker's guide to LCA, studentlitteratur.

Berglin, N., M. Lindblom, et al. (2003). Preliminary economics of black liquor gasification with motor fuels production. Park city Utah USA, colloquium for black liquor combustion and gasification.

Bhattacharya, S. C. (2001). A review of biomass energy technologies, Energy Field, Asian Institute of Technology.

Brown, R. (2003). "Methanol market remains flat on soft MTBE demand and high feedstock costs (petrochemicals). (industry overview)." Chemical Market Reporter May 12, 2003.

Cargill™, www.natureworksllc.com

Chmielniak. T, M. S. (2002). "Co-gasification of biomass and coal for methanol synthesis." Applied Energy 74: 393-403.

Chrisgas project (2004), www.chrisgas.com

Craig, K. (2003). Thermochemical Platform Overview. Second Meeting of S-1007, Washington, DC USA.

Ekbom, T., H. Boding, et al. (2003). BioMeetII Stakeholders for Biomass based Methanol/DME/Power/Heat energy combine Final Report Altener Project AL/2000/367. N. S. Ecotraffic. Trollhättan Municipality, Altener.

Ekbom, T., M. Lindblom, et al. (2003). Cost-competitive, efficient biomethanol production from biomass via black liquor gasification. Stockholm, altener.

Elam, N. (2002). The bio-DME project phase 1 Report to Swedish National Energy Administration (STEM), Atrax Energi AB.

Erwin T.H. Vink, K. R. R., David A. Glassner, Patrick R. Gruber (2002). "Applications of life cycle assessment to NatureWorksTM polylactide (PLA) production." Polymer Degradation and Stability 80: 403-419.

EUCAR, CONCAWE, et al. (2003). Well-to-Wheels analysis of future automotive fuels and powertrains in the European context. Brussels, EU commission.

EUROSTAT EU Commission web site : http://europa.eu.int/comm/energy_transport/atlas/htmlu/bioepot1.html

Fleish, T. (2003 oct). Gas to products (GTP): more options for remote gas monetization. SPE Meeting, Denver, BP.

Fujimura, H. (2002). The 21st century - Age of the biomass-based industrial structure in the 21st century. Business leaders on the environment, Waseda University.

Hagström, P. (2002). BIOENERGY POTENTIAL FOR HEAT, ELECTRICITY AND VEHICLE FUELS IN THE SWEDISH ENERGY SYSTEM. Uppsala, SWEDEN, Swedish University of Agricultural Sciences.

Hamelinck, C. N. and A. P. C. Faaij (2001). Future prospects for production of methanol and hydrogen from biomass, Universiteit Utrecht, Copernicus Institute, Science Technology society.

MacLean Heather L, L. B. Lave. (2002). "Evaluating automobile fuel/propulsion system technologies." progress in energy and combustion science 29: 1-69.

ICIS-LOR Global commodity price reporting and market intelligence http://www.icislor.com/il_shared/Samples/SubPage144.asp

Intille, G. M. (2004). Profitability and Cyclicality in the Chemical Industry Technology Solutions for the Coming Decade. Asian Petrochemical Industry Conference, Kuala lumpur, SRI consulting.

Keith, D.W., Sinks, Energy Crops and Land Use: Coherent Climate Policy Demands on Integrated Analysis of Biomass. Climatic Change, 2001. **49**: p. 1-10

Knoef Harrie, personal communication, BTG group 2005

Lindblom, M. and N. Berglin (1998). Efficient production of methanol from biomass via black liquor gasification. Stockholm, Sweden.

Lurgi-Oel-Gas-Chemie, http://www.lurgi.de/lurgi_headoffice_kopie/deutsch/nbsp/menu/produkte/gas_to_chemicals/mtp.pdf

http://www.lurgi.de/lurgi_headoffice_kopie/deutsch/nbsp/menu/produkte/gas_to_chemicals/methanol_to_synfuels.pdf

Maniatis, K. (2001). Progress in biomass gasification: an overview. Brussels, European commission.

Mitsubishi Heavy Industries Ltd, 2005

http://www.mhi.co.jp/power/e_power/techno/idx_biomass.html

Newenham, R. (2002 October). “Methanol and the MTBE Issue or Should I Build a Methanol Plant”, Jacobs Consultancy.

Nikolaou. A, M. R., Ilian Jeliazkov (2003). Biomass availability in Europe. Lot 5: Bioenergy's role in the EU Energy Market, Centre for Renewable Energy Sources.

Nippon steel corp, 2003. Recycling Technology of waste PVC by gasification (2003).

OHLSTRÖM, M., J. LAURIKKO, et al. (1999). "GREENHOUSE IMPACT OF BIOMASS-BASED METHANOL USE IN FUEL CELL VEHICLES." VTT.

Olah, G. A., Alain Goeppert, Surya Prakash (2005). Beyond Oil and Gas: The Methanol Economy, Wiley-VCH.

Patel, M. (2001). Lessons to be learnt from LCAs for biodegradable polymers. Review of LCAs for bioplastics. Utrecht, Universiteit Utrecht.

Picard, L. and H. Bröske (2004). from plastic bag to methanol, report of SVZ schwarze pumpe, germany. Plastretur day, O-slo, SVZ.

Sander, H.-J., G. Daradimos, et al. (2003). Operating Results of the BGL Gasifier at Schwarze Pumpe. Gasification Technologies 2003, San Fransisco, California, ENVIROTHERM GmbH.

Scahill, J. (2003). Biomass Resources and Technology Options. 2003 Tribal Energy Program Project Review Meeting, Golden, CO USA, Midwest Research institute.

Soundararajan. S, A. K. D., F. Berruti (2000). "Modeling of MTO process in a circulating bed reactor." fuel 80: 1187-1197.

Ståhl, K., L. Waldheim, et al. (2004). Biomass IGCC at Värnamo, Sweden - Past and Future. GCEP Energy Workshop, Frances C. Arrillaga Alumni Center, Stanford University, CA, USA, Stanford university.

Stora Enso sustainability 2004, http://www.storaenso.com/CDAvgn/showDocument/0,,2919,00.pdf

UOP, Jim Andersen personal communication, 2004

United states Department of Energy (1991). Assessment of Costs and Benefits of Flexible and Alternative Fuel Use in the US Transportation Sector. Technical Report No. 7: Environmental, Health, and Safety Concerns., US DOE.

Wagner, J. (2002). Technologically Advanced Natural Gas Monetization: Opportunities for Chemicals & Petrochemicals. Gas To Chemicals, New Delhi, Lurgi Oel gas chemie.

Wolf, M. (2001). BIO-METHANOL AS A FUEL AVAILABLE FROM REGIONAL SOURCES. C. I. GmbH. Freiberg, Choren Industries GmbH.

WEBBOLT® 2004, Global Business News, Research & Intelligence http://webbolt.ecnext.com/coms2/description_19620_Statoil2-200104_PET