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THERMAL BIO-REFINERY; HIGH-EFFICIENT INTEGRATED PRODUCTION OF RENEWABLE CHEMICALS, (TRANSPORTATION) FUELS, AND PRODUCTS FROM BIOMASS

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Thermal Bio-Refinery

High-efficient integrated production of renewable chemicals, (transportation) fuels, and products from biomass

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Thermal Bio-Refinery

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- Motivation
- Biological and Thermal Refineries
- Concept development of Thermal Bio-Refinery
- Ultimate goal
- Product amounts
- Economics
- Conclusion

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Thermal Bio-Refinery

Motivation

Humanity consumes fossil resources for:

Heating — household, cooking, tap water, industrial processes, etc.
⇨ *in all kinds of boilers*

"Devices" — lighting, all electronics (tv, airco, computer), etc.
⇨ *electricity;*

Transport — cars, trucks, buses, planes.
⇨ *gasoline, diesel, kerosene, in the future hydrogen*

Materials — plastics, fertiliser, clothing, additives, etc.
⇨ *intermediates: syngas, base and fine chemicals, mostly refinery fractions*

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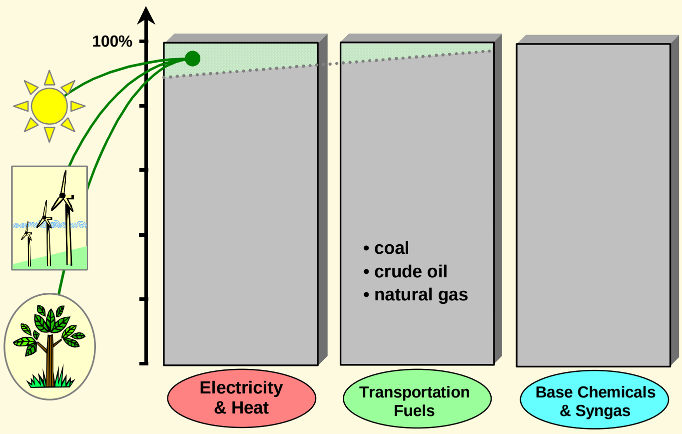
Current Role of Renewables

Dominant position of fossil fuels



Contribution of renewables Solar, Wind, and Biomass is limited.

Almost all energy and chemicals are produced from *fossil resources*.

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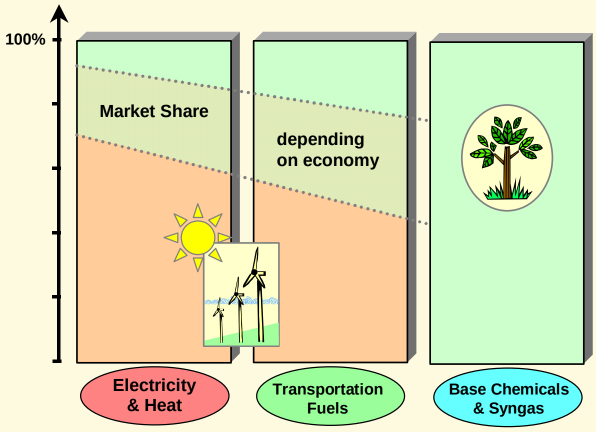
Future role of Renewables

Assuming the end of fossil fuels



Biomass is the only source of renewable carbon;

chemicals & syngas can only be produced from biomass:

preferred application.

All energy and chemicals are produced from *renewables*.

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Products from Biomass

Biological and Thermal Refinery

Biological Refinery

- Advantages = biomass structures can be maintained to yield complex products • relatively simple processes
- Disadvantages = limited number of biomass materials is suitable • each requiring different processes • typically 30-50 wt% of the biomass is not converted

Not competing, but complementary

Thermal Refinery

- Key-step (universal) = conversion of biomass into a product gas by gasification
- Advantage = all biomass materials can be used as feed
- Work-up of product gas = similar to crude oil refinery

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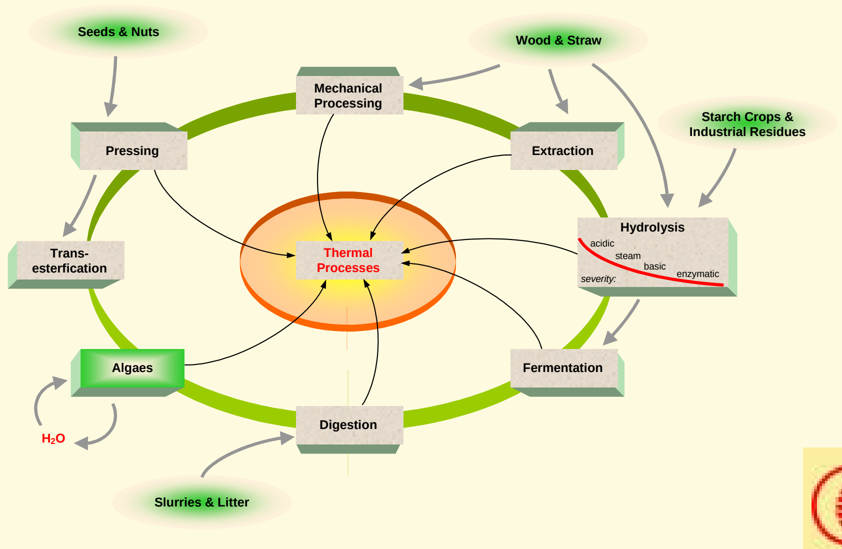
Biological Refinery

Examples of feedstocks and processes



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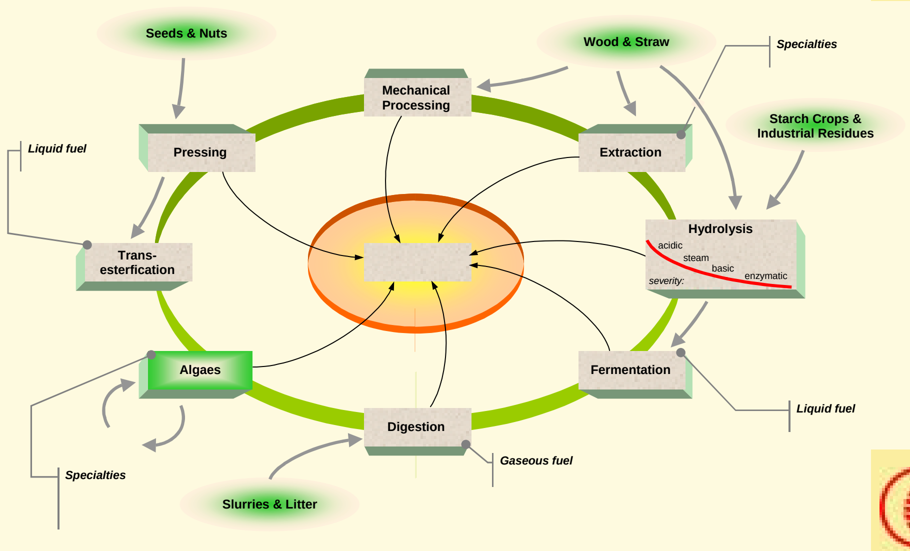
Biological Refinery

Examples of products



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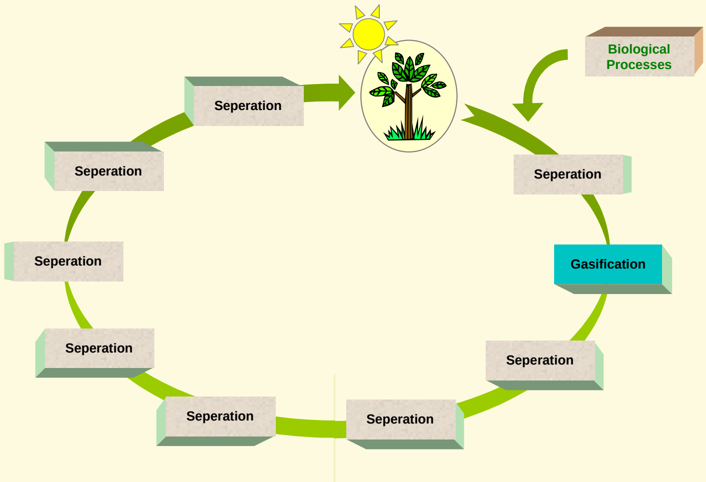
Thermal Bio-Refinery

Concept: one integrated process



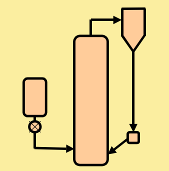
Gasification
=
key-step

Product gas
=
feedstock for
Refinery

The 'Circle' illustrates the sustainable principle of closing the CO_2 cycle upon using biomass-derived chemicals

Thermal Bio-Refinery Feed

Example of product gas composition



PRODUCTION	[vol%,dry]
H_2O (relative to dry gas)	22.40
CO	34.23
H_2	20.93
CO_2	26.17
CH_4	11.62
N_2	0.52
ethylene (C_2H_4)	3.87
acetylene (C_2H_2)	0.39
ethane (C_2H_6)	0.26
benzene	0.97
toluene	0.14
xylenes	0.09
NH_3	0.47
tar total	0.35
TOTAL	*100.00*

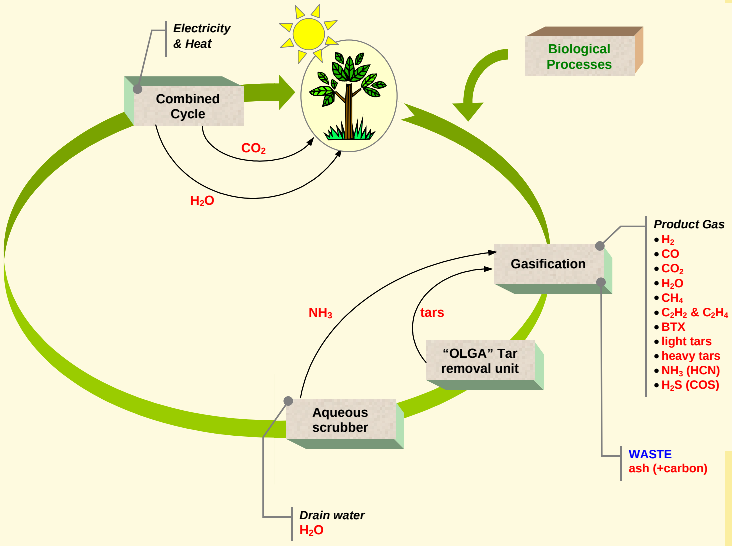
Composition of product gas from oxygen/steam-blown circulating fluidised bed (CFB) gasifier operated at 850°C with wood feed

Important products/chemicals:

- Syngas (H_2/CO)
- Methane
- Ethylene
- BTX
- Tar compounds (*e.g.* naphthalene)

Concept Development

Base case = Bio-CHP



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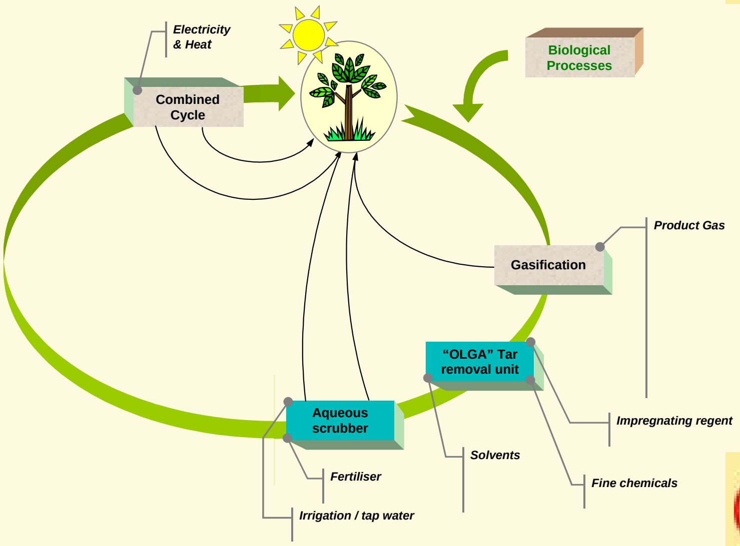
Concept Development

Products from Bio-CHP



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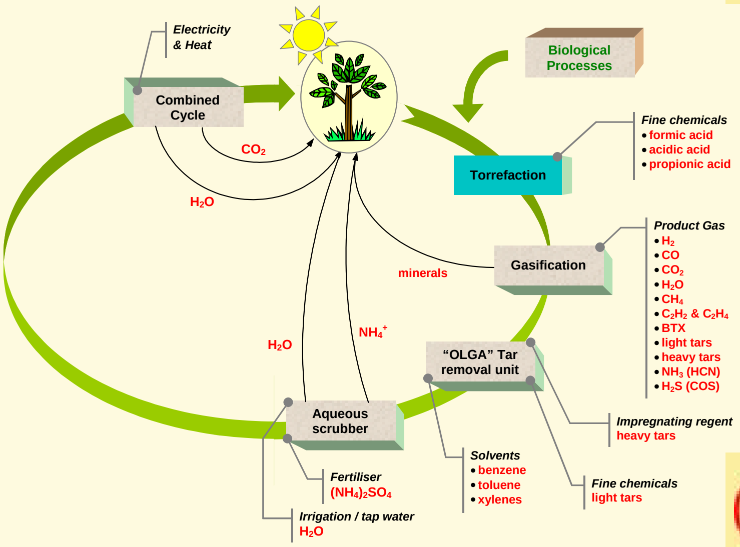
Concept Development

Upstream products: Torrefaction



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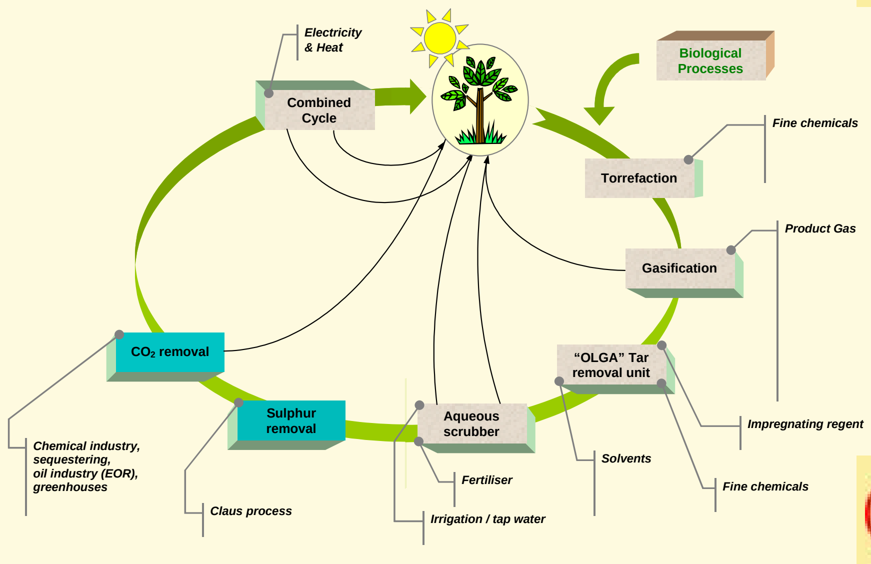
Concept Development

Down-stream products: gas work-up



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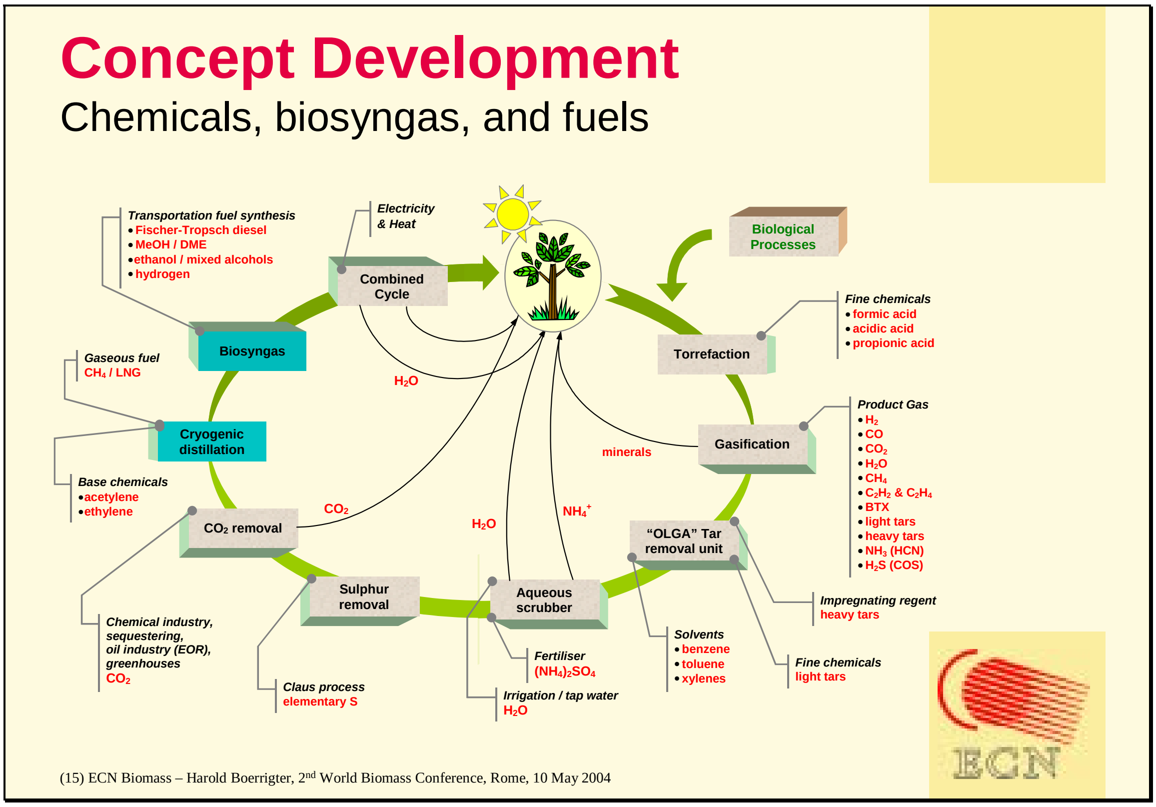
Concept Development
Chemicals, biosyngas, and fuels
Transportation fuel synthesis
• Fischer-Tropsch diesel
• MeOH / DME
• ethanol / mixed alcohols
• hydrogen
Electricity & Heat
Combined Cycle
Biological Processes
Biosyngas
Gaseous fuel
CH_4 / LNG
H_2O
Torrefaction
Fine chemicals
• formic acid
• acidic acid
• propionic acid
Cryogenic distillation
Base chemicals
• acetylene
• ethylene
minerals
Gasification
Product Gas
• H_2
• CO
• CO_2
• H_2O
• CH_4
• C_2H_2 & C_2H_4
• BTX
• light tars
• heavy tars
• NH_3 (HCN)
• H_2S (COS)
CO_2 removal
CO_2
H_2O
NH_4^+
"OLGA" Tar removal unit
Sulphur removal
Aqueous scrubber
Impregnating regent
heavy tars
Chemical industry, sequestering, oil industry (EOR), greenhouses
CO_2
Fertiliser
$(NH_4)_2SO_4$
Solvents
• benzene
• toluene
• xylenes
Fine chemicals
light tars
Claus process
elementary S
Irrigation / tap water
H_2O
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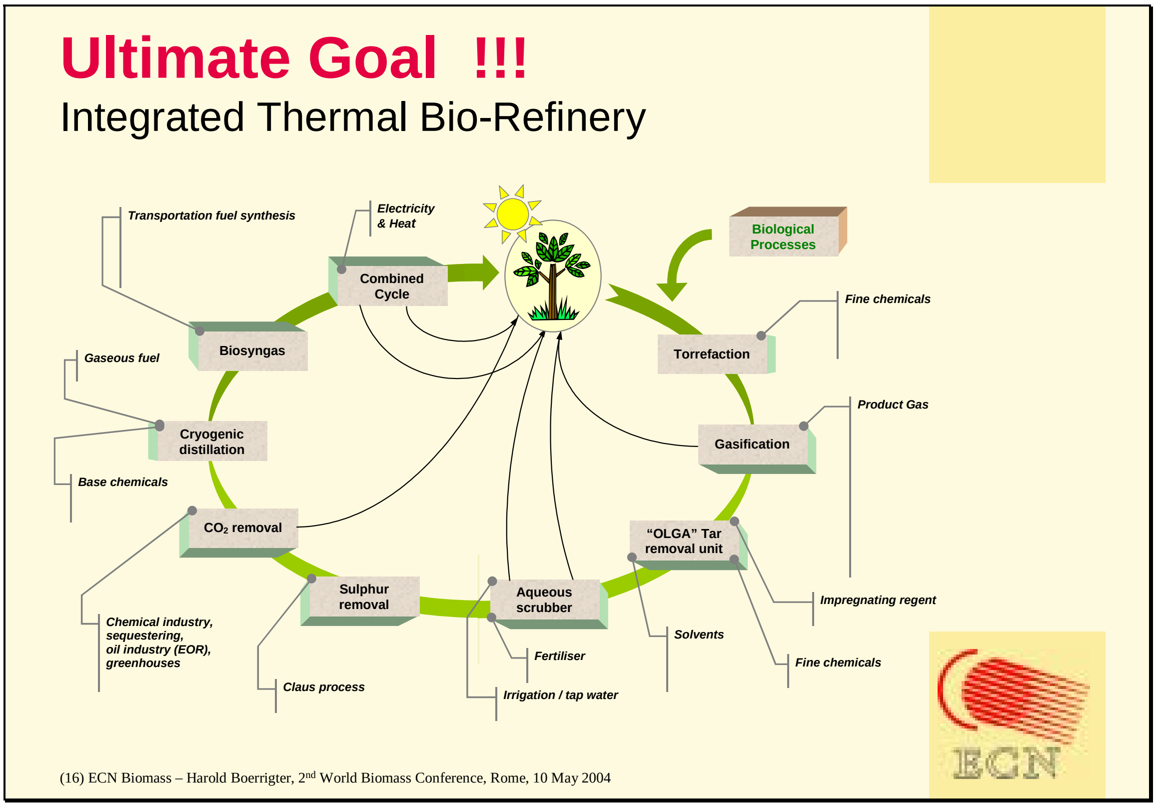
Ultimate Goal !!!
Integrated Thermal Bio-Refinery
Transportation fuel synthesis
Electricity & Heat
Combined Cycle
Biological Processes
Biosyngas
Gaseous fuel
Torrefaction
Fine chemicals
Cryogenic distillation
Product Gas
Base chemicals
Gasification
CO_2 removal
"OLGA" Tar removal unit
Sulphur removal
Aqueous scrubber
Impregnating regent
Chemical industry, sequestering, oil industry (EOR), greenhouses
Fertiliser
Solvents
Fine chemicals
Claus process
Irrigation / tap water
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Product amounts

Thermal Bio-Refinery of 500 MW_{th}

Compound	composition [vol%]	yield [kg/tonne]	annual yield [ktonne]
CO	34.2	364	309
H_2	20.9	16	13
CO_2	26.1	438	372
CH_4	11.6	71	60
N_2	0.52	5.6	4.7
ethylene (C_2H_4)	3.87	41	35
acetylene (C_2H_2)	0.39	3.8	3.2
ethane (C_2H_6)	0.26	3.0	2.5
benzene	0.97	29	24
toluene	0.14	4.8	4.1
xylenes	0.09	3.6	3.0
NH_3	0.47	3.0	2.5
tars (sum)	0.35	17	14
- heavy tars	~	*6.4*	*5.4*
- light tars	~	*10*	*8.9*
- phenol	~	*1.8*	*1.54*
- indene	~	*1.5*	*1.24*
- naphthalene	~	*2.7*	*2.27*
- antracene	~	*0.5*	*0.46*
TOTAL	100	1000	850
furfural	~	30	25
acetic acid	~	65	55
formic acid	~	40	34

The scale of the Bio-Refinery, and the amount of chemicals produced, match with typical chemical processes as currently in operation.

- Yield per tonne dry ash-free wood
- 8000 operational hours
- With preceding Torrefaction plant

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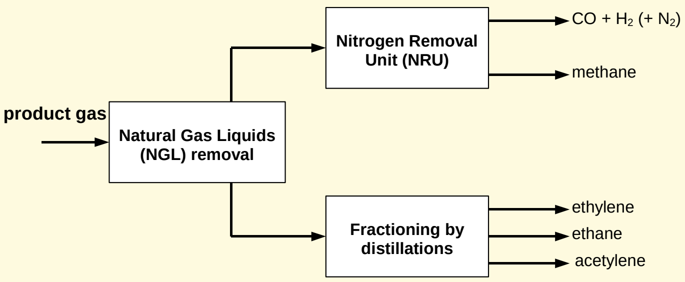
Economics

Case: Cryogenic distillation - process

- Product work-up of CO_2-free product gas to recover C_2-compounds and syngas (and methane)
- Process is comparable to 'NGL' with subsequent 'NRU' and distillation



Compounds	boiling point (°C)
acetylene (C_2H_2)	-84*
ethane (C_2H_6)	-89
ethylene (C_2H_4)	-104
methane (CH_4)	-162
carbon monoxide (CO)	-192
nitrogen (N_2)	-196
hydrogen (H_2)	-253

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Economics

Case: Cryogenic distillation – product value

Added value of products	+167 M€
Energy costs	-86 M€
Capital costs	-26 M€
Operational costs	-26 M€
Annual net added value	+30 M€

Compounds	Reference	Value [€/GJ]
crude oil		15 \$/bbl
natural gas (NG)	crude oil (in NL)	1.8
methane	NG	1.8
ethane (C_2H_6)	NG + 10%	1.98
ethylene (C_2H_4)	1.8 × NG	3.24
acetylene (C_2H_2)	products from C_2H_4	12.2
syngas ($CO+H_2$)	1.5 × NG	2.7
Product gas	NG	1.8

Cryogenic separation is economic very attractive as product value is much higher than value as energy fuel

Thermal Bio-Refinery (large-scale); 8000 MW_{th} input; investment costs 225 M€; 7000 operational hours; 8% interest rate; 15 years depreciation; 4 ct€/kWh electricity price.

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Conclusion

- Biomass can be fractioned in a Thermal Bio-Refinery, in analogy with refining of crude oil.
- Key-step is gasification, upon which biomass is converted into a product gas, containing a variety of interesting compounds that can be recovered.
- Product recovery is economic attractive, as the product value is (much) higher than the energy value as fuel (illustrated for cryogenic distillation).
- The Thermal Bio-Refinery allows the development of a completely sustainable chemical industry.

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www.ecn.nl/biomass

Visit also: "Phyllis" - *internet database for biomass, coal, and residues:* *www.phyllis.nl*

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ECN Biomass

Mission

Contributing to the implementation of biomass (and waste) in the Dutch and global (energy) infrastructure by means of short-term, mid-term, and long-term research, technology development, and knowledge dissemination.

ECN Biomass is a business unit of the Energy research Centre of the Netherlands (ECN)

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ECN Biomass

Research Clusters

Power Generation

➔ Slagging, fouling, co-combustion, co-firing, ash-quality

Combined Heat and Power

➔ gasification, combustion, gas clean-up, prime-movers

Fuels and Products

➔ liquid fuels, gaseous energy carriers, syngas, bio-refinery, co-generation

Implementation time

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THERMAL BIO-REFINERY; HIGH-EFFICIENT INTEGRATED PRODUCTION OF RENEWABLE CHEMICALS, (TRANSPORTATION) FUELS, AND PRODUCTS FROM BIOMASS

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ABSTRACT: The renewable and CO_2-neutral nature is the major motivation to use biomass for energy generation and the production of chemicals, raw materials, and fuels. In the Thermal Bio-Refinery, biomass is converted by (fluidised bed) gasification, where the resulting product gas contains a variety of valuable products that are recovered in analogy with crude oil refinery. Prior to gasification, a torrefaction step is included to produce fine chemicals. In the downstream OLGA tar removal unit the tars and BTX are removed, which have product value as impregnating agent, fine chemicals, and solvents, respectively. Aqueous scrubber yields NH_3 for fertiliser production, sulphur removal yields elementary sulphur, and CO_2 is removed for application in chemical industry, enhanced oil recovery, or in greenhouses. Ethylene and acetylene, present in over 4 vol% in the product gas, are very important raw materials in chemical industry and can be recovered by cryogenic distillation. Preliminary economic assessments show that the difference between the fuel and product value of the compounds allows profitable product recovery. The resulting biosyngas (H_2/CO mixture) can be used for liquid fuels synthesis or upgraded to pure hydrogen. In conclusion, the thermal bio-refinery opens new routes to synthesize products from biomass and it allows the development of a sustainable chemical industry.
Keywords: chemicals from biomass, biorefining, innovative concepts.

1 INTRODUCTION

Biomass is a general term to describe all organic carbon-containing material produced by photosynthesis in plants. Biomass is available in many forms, comprising products as well as residues from agriculture, forestry, and the agro-industry. By definition, biomass is a renewable material as during growth of the plants, crops, and trees, CO_2 is withdrawn from the atmosphere (the carbon source) and stored in the biomass as chemical energy. The CO_2 cycle is closed again when the CO_2 is released during conversion of the biomass and the use of the derived products. The renewable and CO_2-neutral nature of biomass is the major motivation to use the material for energy generation (*e.g.* green electricity) and the production of chemicals, raw materials, and transportation fuels.

2 CHEMICALS AND RAW MATERIALS FROM BIOMASS

To date, all transportation fuels and most materials and chemicals are produced from crude oil or natural gas. At a certain moment in the future, the decreasing reserves of these fossil materials will give rise to increasing prices. To maintain the same production levels, an alternative carbon source is required and biomass is the only renewable carbon source available. Therefore, biomass will be the future feedstock for the production of transportation fuels and chemicals. This is not an illusion, as the annually amount of biomass available (*i.e.* not used as food or otherwise) equals about six times the total global energy consumption. In two ways chemicals can be produced from biomass, *i.e.* via biological and thermal refining. Both conversions routes are complementary as (typically) different feedstocks are used and another spectrum of chemicals is produced.

2.1 Biological refining

In the biological refining (or *C5/C6 chemistry*) advantage is taken from the C5 and C6 sugar structures present in the original biomass. Via fermentation these sugar structures are converted in products like ethanol and methane. Alternatively, by extraction processes the complex structures from the original biomass are maintained and fine-chemical products can be isolated. Disadvantage of the biological route is that only a limited number of biomass materials are suitable for biological conversion and, furthermore, suitable micro-organisms are required for fermentation. Typically, 30 up to 50 wt% of the feedstock is not converted in the biological process and this residue has to be treated in a thermal conversion process (*e.g*. combusted or gasified) for CHP production or alternatively used as feed for a thermal refining process.

2.2 Thermal refining

In the thermal conversion (or *C1 chemistry*) gasification of the biomass and conversion into a product gas is the key step. The advantage of this route is that almost all biomass materials are suitable for gasification. The gasification gas contains CO/H_2 as main products and, in addition, raw materials for chemicals production as well as a number of valuable chemicals products that can be directly separated. With the gasification conditions the amounts of raw materials and chemicals produced can be controlled. Due to the analogy with crude oil refinery, the fractioning and recovery of products after thermal conversion of biomass is called thermal refinery of biomass, or **Thermal Bio-Refinery**.

In Figure 1 the overall concept of the Thermal Refinery of Biomass is shown. The refinery is illustrated as a circle to express the CO_2 cycle that is closed when biomass is used.

3 THERMAL BIO-REFINERY CYCLE

3.1 Gasification

Gasification is the key-step in the Thermal Bio-refinery; biomass materials of various shapes and origins are converted into a product gas of more consistent quality. Also residues from biological processes can be used as feedstock. Typical constituents of a product gas are indicated in Figure 1. Besides the product gas, the gasification step also affords an *ash* fraction containing all the minerals from the biomass, which is very suitable as fertiliser. The gasification product gas is the actual 'feed' of the 'refinery'.

Although all products are present, the recovery of each individual or group of chemicals from the gas is a choice to be made depending on the specific plant conditions and economic aspects. For example, when biosyngas is the desired product high temperature gasification (*i.e*. in an entrained flow gasifier) is preferred as this affords the highest biosyngas yield and almost no side products [1]. However, in that case the process is not considered as a thermal refinery. In the Thermal Bio-refinery concept low temperature gasification is always assumed as key-step (*i.e*. below 1000°C).

3.2 Torrefaction

Optional is a low-temperature torrefaction step preceding the gasification, either on techno-economic grounds as pre-treatment to homogenise the biomass or with the purpose to produce specific acids and solvents. Typical examples of important torrefaction products are *furfural*, *formic acid*, and *acetic acid*. The incorporation of a torrefaction step will have little effect on the gasification product gas composition.

3.3 OLGA tar removal

In the OLGA unit [2,3] three groups of chemicals are separated from the gas by scrubbing with a special organic solvent, *i.e*. the *heavy tars*, the *light tars*, and the *BTX (benzene, toluene, and xylenes)* fraction. By regenerating the scrubbing liquid these products are recovered. Typically, the heavy or condensable tar compounds with three or more aromatic rings are recovered as one product. The light tars (with two and three aromatic rings) can be recovered as one product or further fractioned leading to the recovery of several groups of products or even pure compounds. A typical example of the latter is naphthalene. The one-ring aromatic compounds of the BTX fraction are isolated in a similar way.

Generally, tar removal is always required for every gas application other than co-firing or direct combustion in a boiler. Therefore, tar removal can be considered as a required gas cleaning step. Alternative to isolate the tars as products, the separated tars can be recycled to the gasifier where they are destructed.

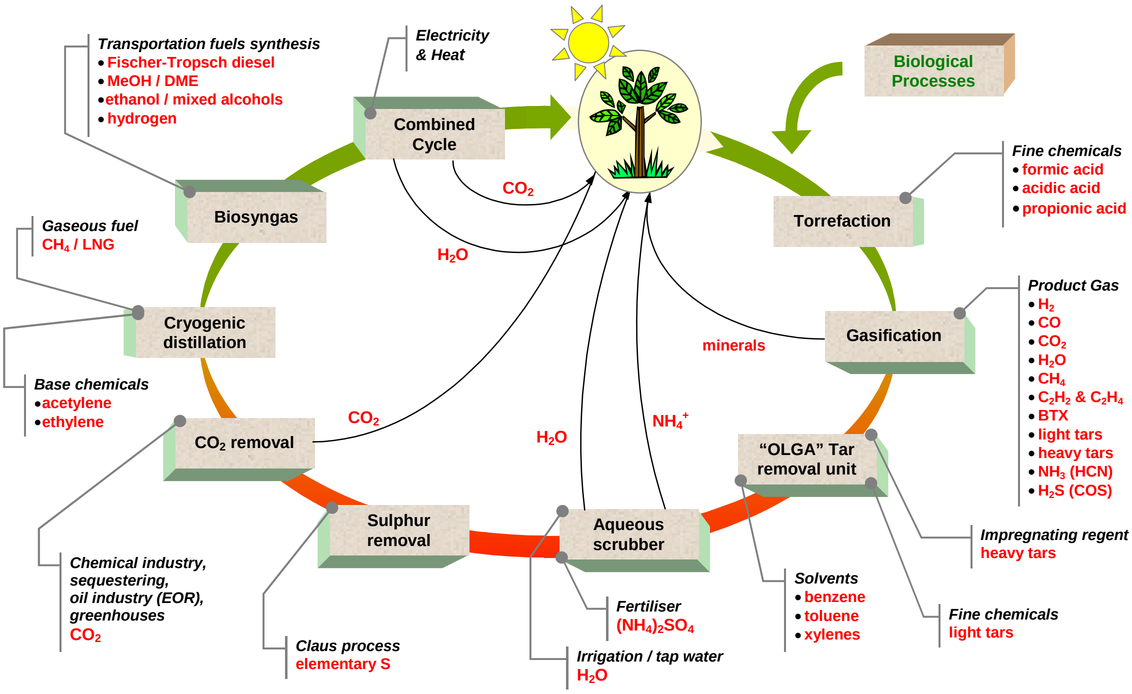

Figure 1: Thermal Refinery of biomass, visualizing the cycle of CO_2, water, and nutricients (*i.e.* minerals and ammonia), and the variety of chemicals, products, and fuels that can be isolated from biomass.

3.4 Aqueous scrubber

The gas after the OLGA unit is tar-free with only gaseous constituents. In an aqueous scrubber the inorganic compound *ammonia* (NH_3) is removed. When significant amounts of HCN are present in the gas, this compound can be converted into NH_3 in an upstream hydrolysis step. Alternatively, the HCN is removed from the gas by adsorption with filters. Typically, the NH_3 is recovered from the scrubber water solution by precipitated as ammonium salt, *e.g.* as ammonium sulphate $(NH_4)_2SO_4$ with sulphuric acid. Ammonia is an important ingredient for fertilisers and the existing production processes are very energy intensive. Most biomass materials contain only small amounts of nitrogen and the concentration of NH_3 is usually very low, therefore, the NH_3 production capacity in a Thermal Bio-Refinery is limited. However, when chicken manure is used feedstock, the concentration of NH_3 in the gas can rise to several volume percentages.

3.5 Sulphur removal

Similar to nitrogen, most biomass materials contain only very small amounts of sulphur that after gasification will be present in the gas mainly in the form of H_2S with minor amounts of COS. When desired COS can be converted into H_2S in an upstream hydrolysis step. Typically, isolation of sulphur will not be economic interesting and sulphur removal is achieved as part of the gas cleaning with adsorption on filters. When large amounts are present, the H_2S can be separated from the gas and converted into *elementary sulphur*, which has value as industrial base material.

3.6 CO_2 removal

Biomass product gas generally contains 10 to 30% of CO_2. For application to generate electricity and heat the presence of CO_2 is no problem. However, CO_2 removal is strongly recommended as gas conditioning step, before further cryogenic distillation of the gas or for biosyngas production. CO_2 is a problematic compound in the cryogenic processes and is an undesired inert diluent in the synthesis processes for which the biosyngas is used. The removed CO_2 is can be applied for pressurising oil wells (Enhanced Oil Recovery), in green houses, for chemical synthesis, or sequestered.

3.7 Cryogenic distillation

The next step in the refinery is deep cooling of the product gas and separation of gaseous products by cryogenic distillation. The first products recovered are *ethane*, *ethylene (C_2H_4)* and *acetylene (C_2H_2)*; the last two are very important raw materials in the chemical industry. Upon further cooling *methane (CH_4)* is recovered. Methane can be supplied to the natural gas grid as Substitute Natural Gas (SNG) for stationary and mobile applications, used as fuel on site for steam generation, or used as raw material.

3.8 Biosyngas applications

After all the described refinery steps, *i.e.* removal of the chemicals and raw materials as products, the gas only contains CO and H_2, making it a renewable syngas or *biosyngas*. Syngas, a product by itself, is an important and generic raw material in the chemical industry. Within the objective to produce transportation fuels from biomass, the gas can be used to synthesise *Fischer-Tropsch diesel*, *methanol* (or DME), or *ethanol* (or mixed alcohols) for use in combustion engines. The gas can also be shifted to produce pure *hydrogen* for use in fuel cell vehicles, which is considered as a long-term option.

3.9 Combined Cycle

The remaining unconverted syngas and off-gases from the different processes can be used to generate *electricity* and *heat* in a Combined Cycle (CC). Typically, a chemical production plant will generate its own energy needs in this way, or even a surplus that can be delivered to the grid (as green electricity). Upon combustion in the combined cycle, CO_2 and H_2O are formed and released to the atmosphere. Herewith the CO_2 cycle is closed

4 INDICATIVE AMOUNTS

The compounds and chemicals discussed are <u>always</u> formed upon gasification of biomass (with oxygen/steam). However, the relative amounts depend largely on the gasification temperature. An exception is the amount of ammonia formed, which depends mainly on the amount of nitrogen present in the feed. In Table I, this is illustrated by a representative product gas composition calculated for oxygen/steam-blown gasification of woody biomass at 850°C in a fluidised bed gasifier. The gas compositions are also translated into production numbers. Firstly, expressed as yield per ton of biomass and secondly, as annual yield based on a representative medium-size biomass gasifier (500 MW_{th}).

Table I: Typical product gas composition for gasification of woody biomass at 850°C in a fluidised bed gasifier (second column), yield of the individual compounds per tonne of biomass (third column), and the annual yield based on a 500 MW_{th} gasifier (fourth column).

Oxygen/steam-blown gasification at 850°C			
Compound	composition[a] [vol%]	yield[b] [kg/tonne]	annual yield[c] [ktonne]
CO	34.2	364	309
H_2	20.9	16	13
CO_2	26.1	438	372
CH_4	11.6	71	60
N_2	0.52	5.6	4.7
ethylene (C_2H_4)	3.87	41	35
acetylene (C_2H_2)	0.39	3.8	3.2
ethane (C_2H_6)	0.26	3.0	2.5
benzene	0.97	29	24
toluene	0.14	4.8	4.1
xylenes	0.09	3.6	3.0
NH_3	0.47	3.0	2.5
tars (sum)	0.35	17	14
- heavy tars	~	*6.4*	*5.4*
- light tars	~	*10*	*8.9*
- phenol[d]	~	*1.8*	*1.54*
- indene[d]	~	*1.5*	*1.24*
- naphthalene[d]	~	*2.7*	*2.27*
- antracene[d]	~	*0.5*	*0.46*
TOTAL	100	1000	850
furfural[e]	~	30	25
acetic acid[e]	~	65	55
formic acid[e]	~	40	34

a) on dry gas basis; b) yield of gases products per ton of dry and ash-free biomass (wood); c) based on 8000 hours operation; d) examples of selected tar compounds; e) in case of a preceding torrefaction plant.

5 ECONOMICS

The economic perspectives of a Thermal Bio-Refinery depend on the specific conditions for each location. Detailed economic assessment of the complete integrated concept is ongoing. In this paper the economic potential is illustrated focussing solely on the cryogenic distillation step to recover C_2 hydrocarbons.

5.1 Cryogenic recovery of C_2 hydrocarbons

The CO_2-free product gas fed to the distillation contains CO, H_2, CH_4, ethane, ethylene, acetylene, and a small amount of nitrogen. The boiling points of these compounds at 1 bar are indicated in Table II. The separation of the C_2 hydrocarbons can be compared to the recovery of 'natural gas liquids', whereas the separation of CH_4 from H_2/CO is comparable to the removal of N_2 from natural gas to increase the calorific value of the gas. The C_2 compound product stream needs further distillation to recover the pure products.

Table II: Boiling points at 1 bar.

Compounds	boiling point (°C)
acetylene (C_2H_2)	-84*
ethane (C_2H_6)	-89
ethylene (C_2H_4)	-104
methane (CH_4)	-162
carbon monoxide (CO)	-192
nitrogen (N_2)	-196
hydrogen (H_2)	-253

* acetylene has no boiling boint; it sublimates at the given temperature.

5.2 Product prices

The prices of the products depend on the oil and gas prices. A conservative crude oil price of 15 $/bbl is assumed. In the Netherlands the natural gas (NG) price is coupled to the crude oil price, which in that case costs 1.8 €/GJ (1$ = 1 €). Methane is valued equal to NG as the typical application will be fuel. Ethane is valued 10% higher, being a raw material for chemical industry. Ethylene is typically produced from crude oil or NG, and is 1.8 times more expensive compared to NG [4]. The applications of acetylene are similar to those for ethylene and with a price of 12.2 €/GJ the costs of the products (*e.g.* vinyl acetate and vinyl chloride) are competitive with routes using ethylene as feed [5]. Syngas is typically produced by partial oxidation of NG. Therefore, the price of the product biosyngas is taken 1.5 times the price of NG, *i.e.* 2.7 €/GJ [6].

5.3 Investment and operational costs

The investment costs of a cryogenic product gas distillation unit are estimated with natural gas liquids and nitrogen separation units as reference. For a large-scale thermal bio-refinery of 8000 MW input (for motivation of scale see [7]), the investment costs are estimated to be 225 M$ and the operational costs are taken equally to the annual capital costs (with 7000 h/y operation, 15 year depreciation period, and an interest rate of 8%). The electricity costs used are 0.04 €/kWh.

5.4 Economic perspectives

The purpose of the economic assessment is to illustrate that fractioning of the product gas into chemicals and raw materials in economically more attractive than direct use of the gas in a combined cycle. Therefore, it is assumed that the product gas on energy basis has the same value as NG, *i.e.* 1.8 €/GJ. The product value of the gas should be higher than the energetic value plus the costs of the cryogenic separation.

The added value of the products, compared to the fuel value is 167 M€. The annual cost for energy, capital, and the operational costs are 86, 26, and 26 M€, respectively. Therefore, the net added value of the system is 30 M€ per year, making cryogenic separation economically a very attractive step.

6 CONCLUSIONS

In analogy with the refining of crude oil, biomass can be fractioned in a thermal bio-refinery. Upon gasification the biomass is converted in a product gas containing a variety of interesting compounds that can be isolated by fractioning of the gas. For the cryogenic distillation step of the integrated refinery, the economic attractiveness was illustrated.

7 OUTLOOK

To date, the whole chemical industry is based on crude oil and optimised to use by and side products from the refining and synthesis as feedstock for other processes. The thermal bio-refinery opens new routes to synthesize products from other biomass-derived raw materials. More important, the thermal bio-refinery allows the development of a sustainable chemical industry.

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