Biomass and biofuels

Implementation, role in the energy system

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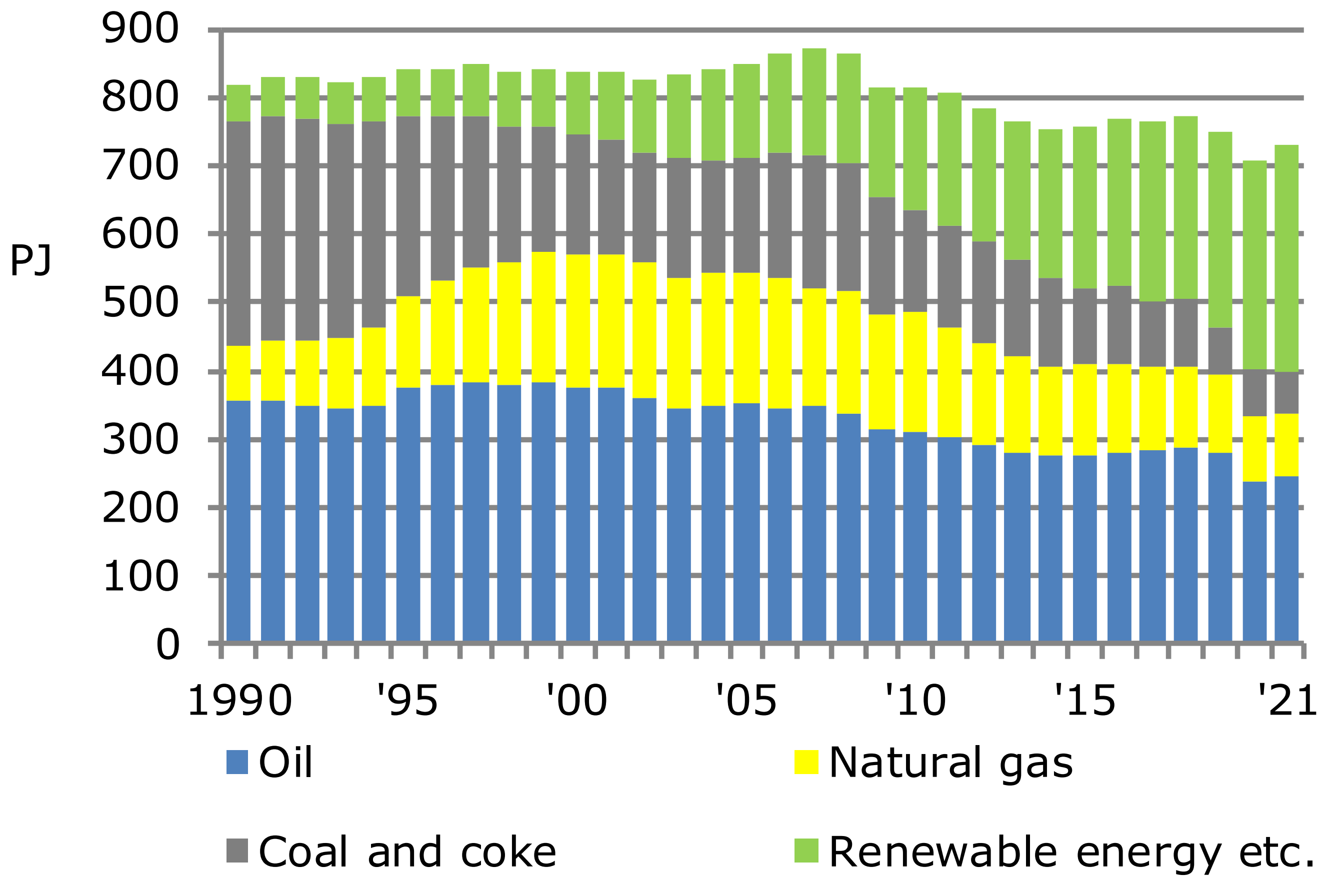
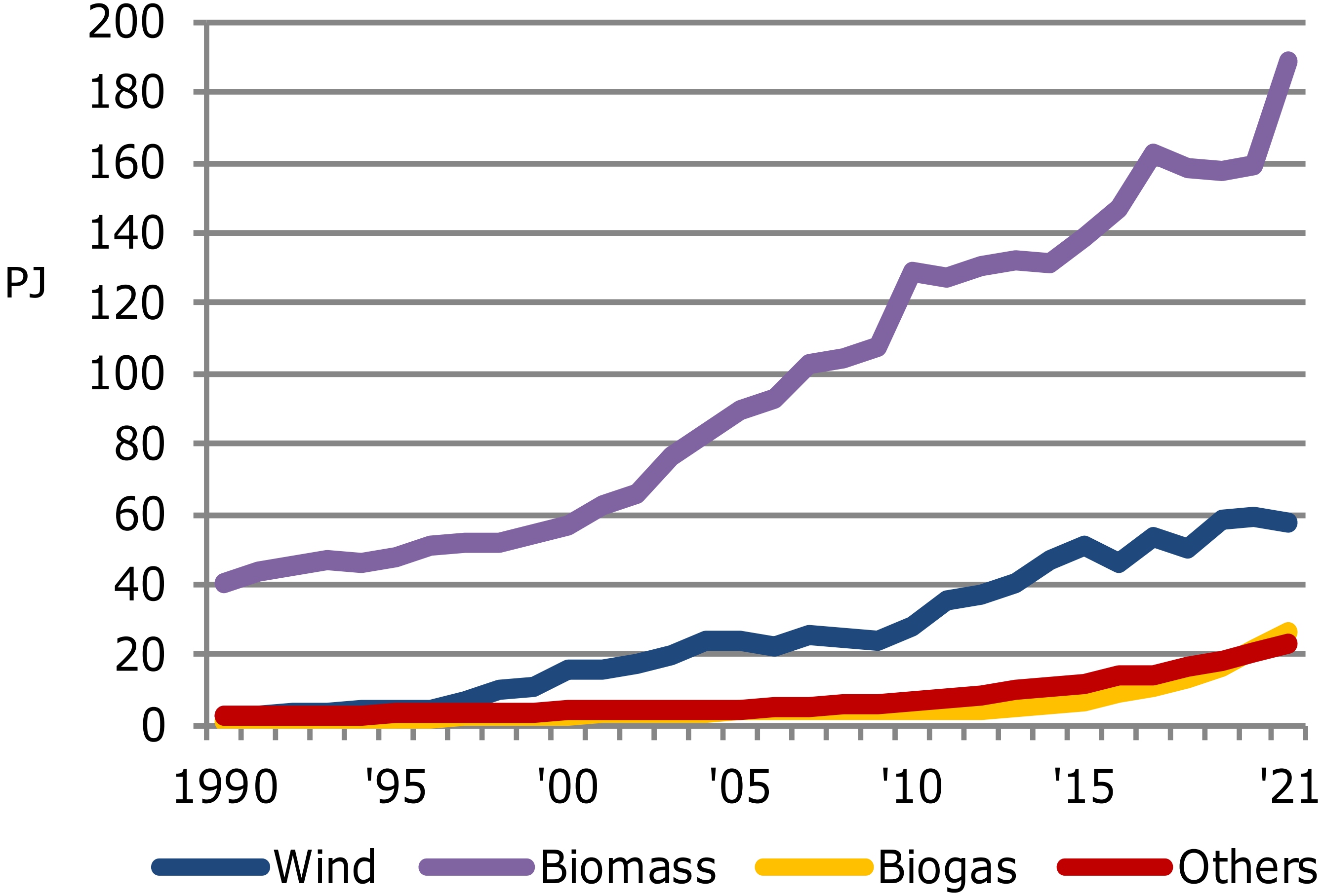
The Danish energy system

Gross energy consumption by fuel



from the Danish energy agency

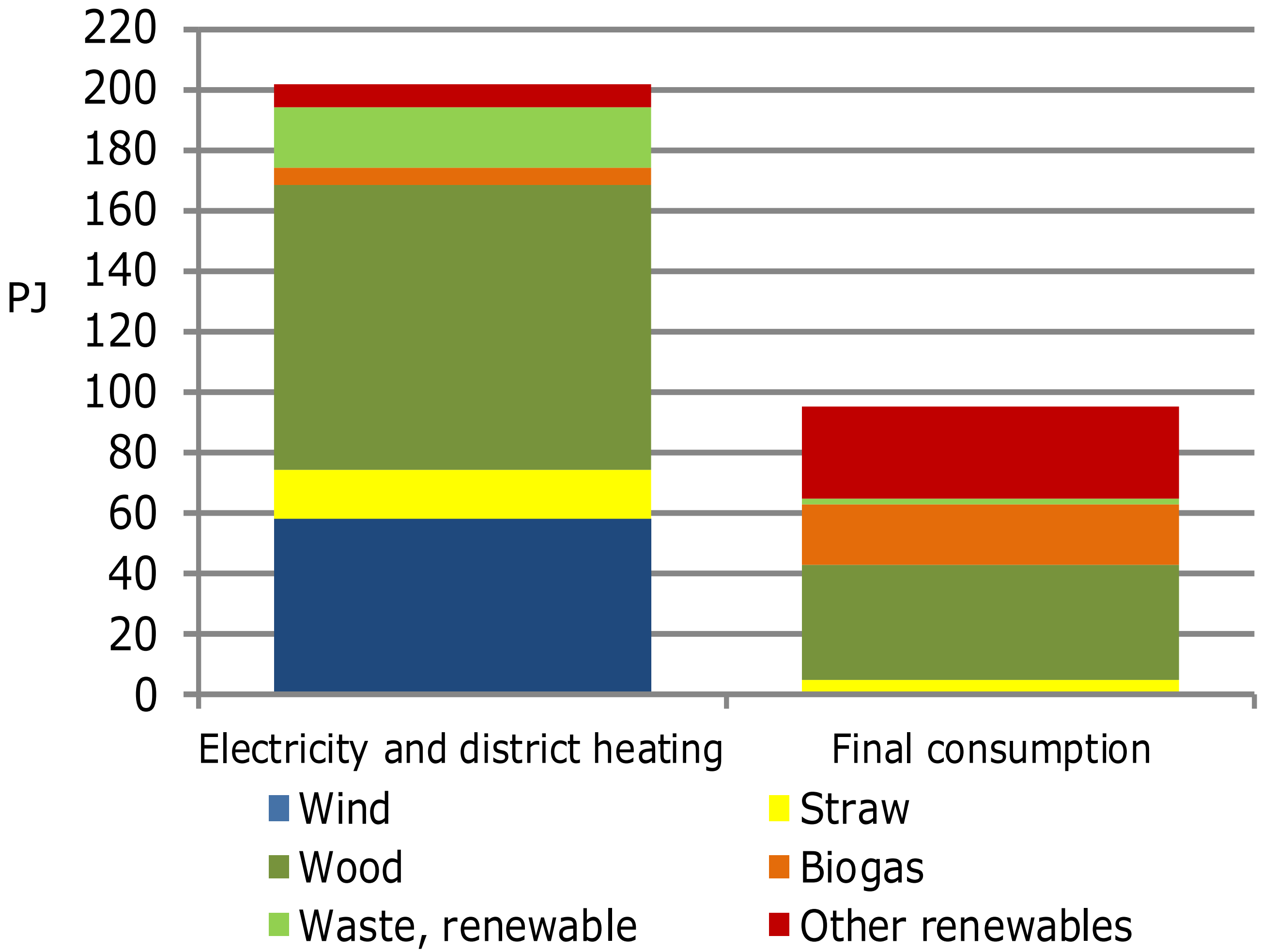
The Danish energy system
Renewable energy – consumption by energy product



from the Danish energy agency

The Danish energy system

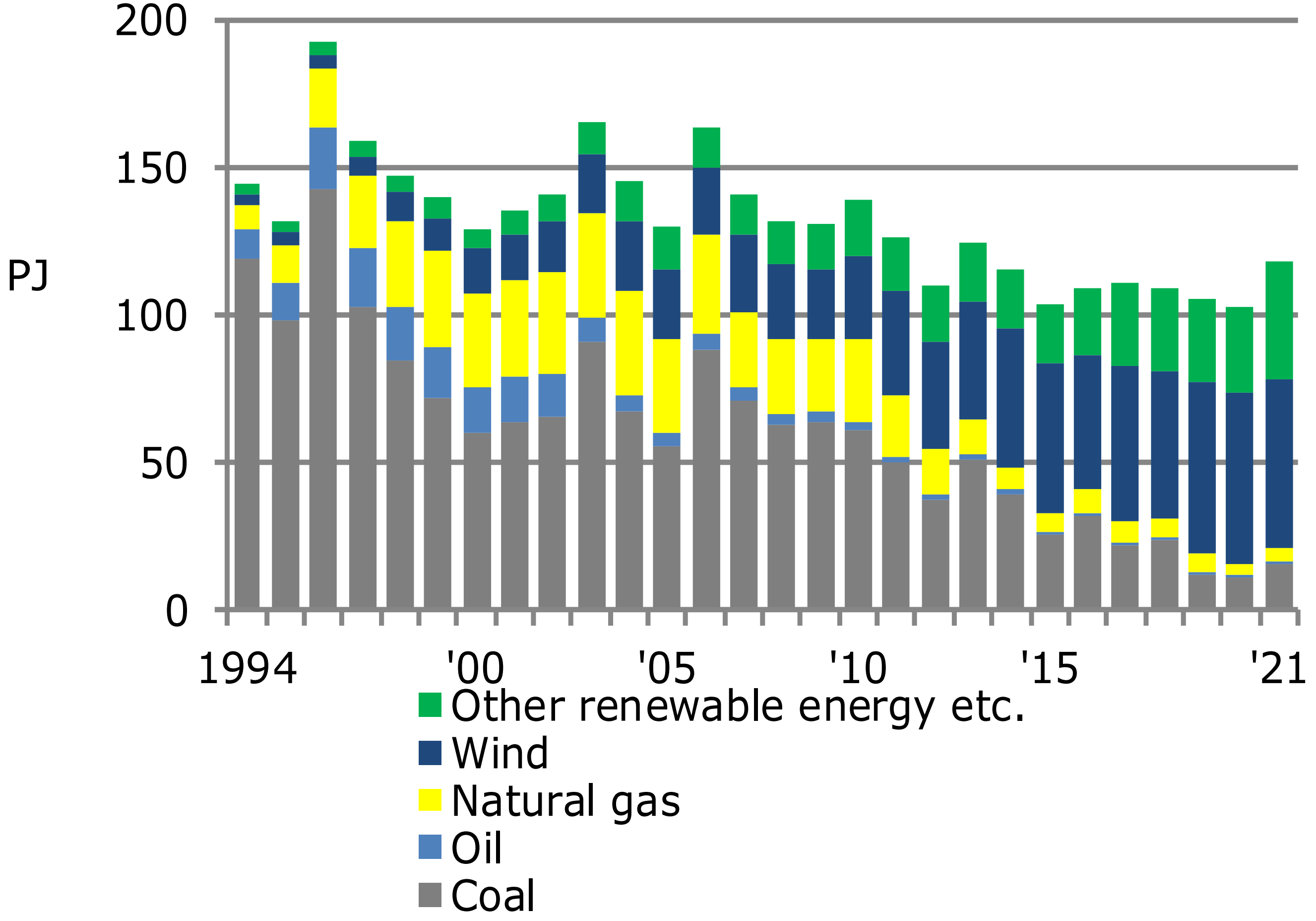
Use of renewable energy in 2021



from the Danish energy agency

The Danish energy system

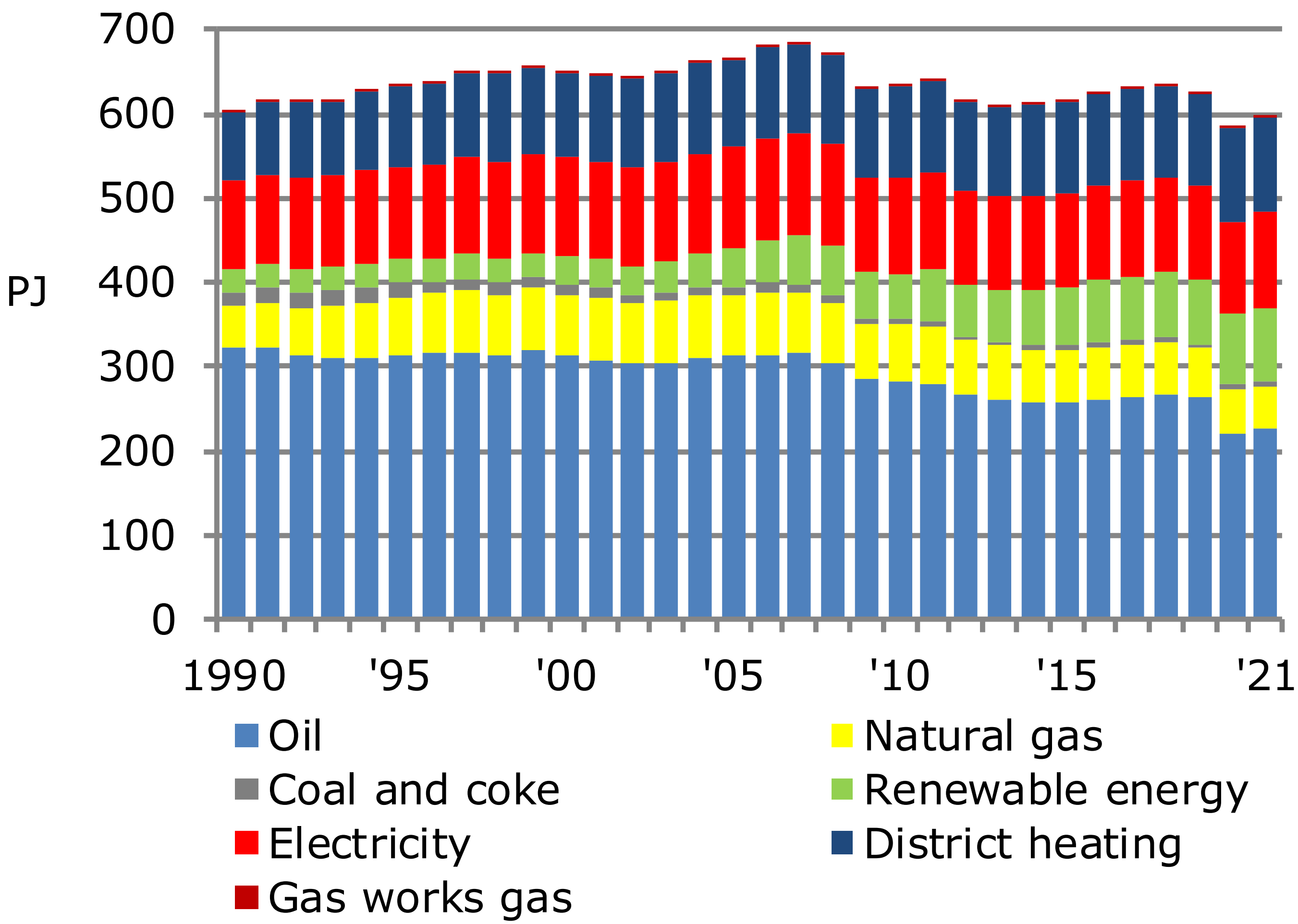
Electricity production by fuel



from the Danish energy agency

The Danish energy system

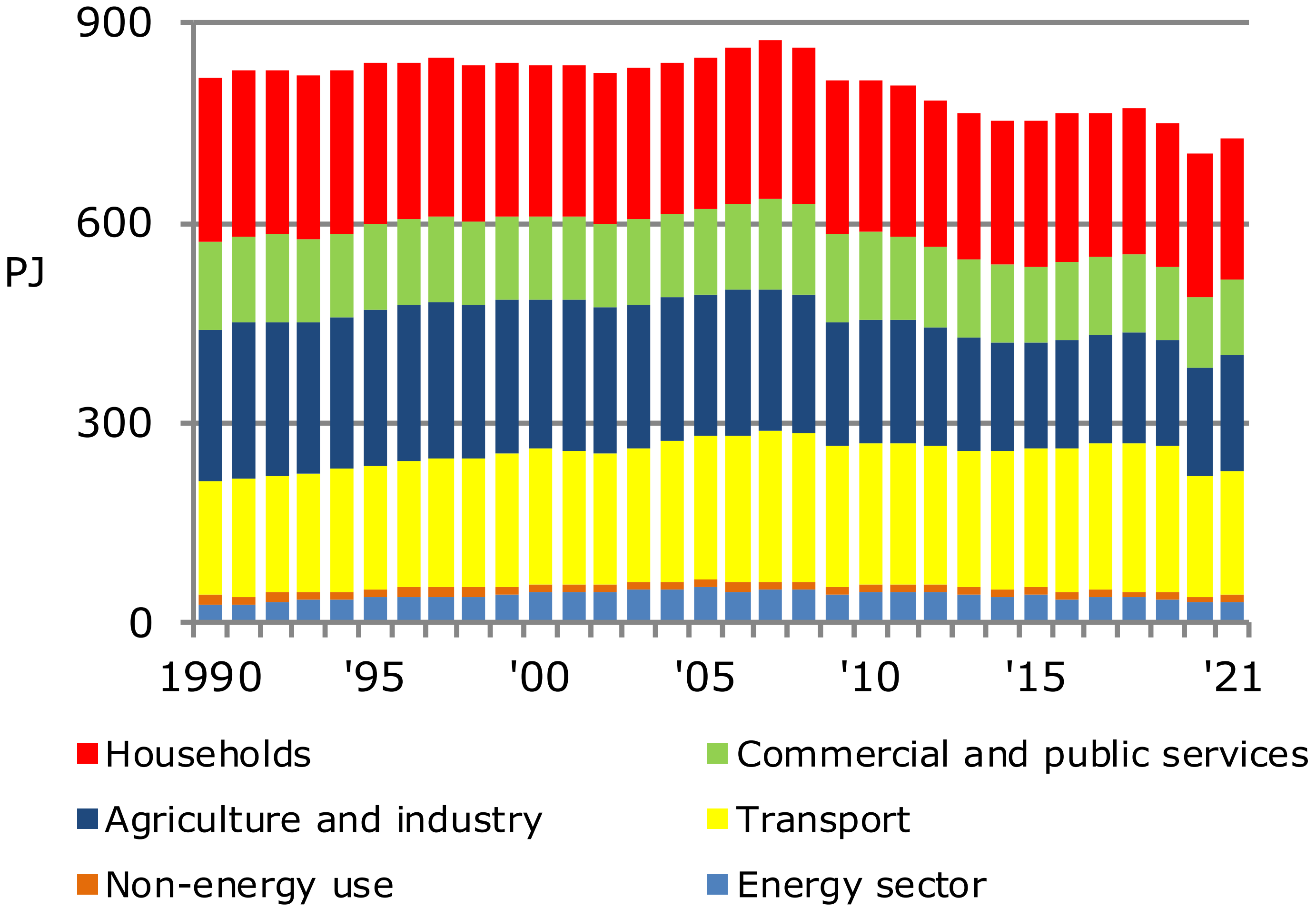
Final energy consumption by energy product



from the Danish energy agency

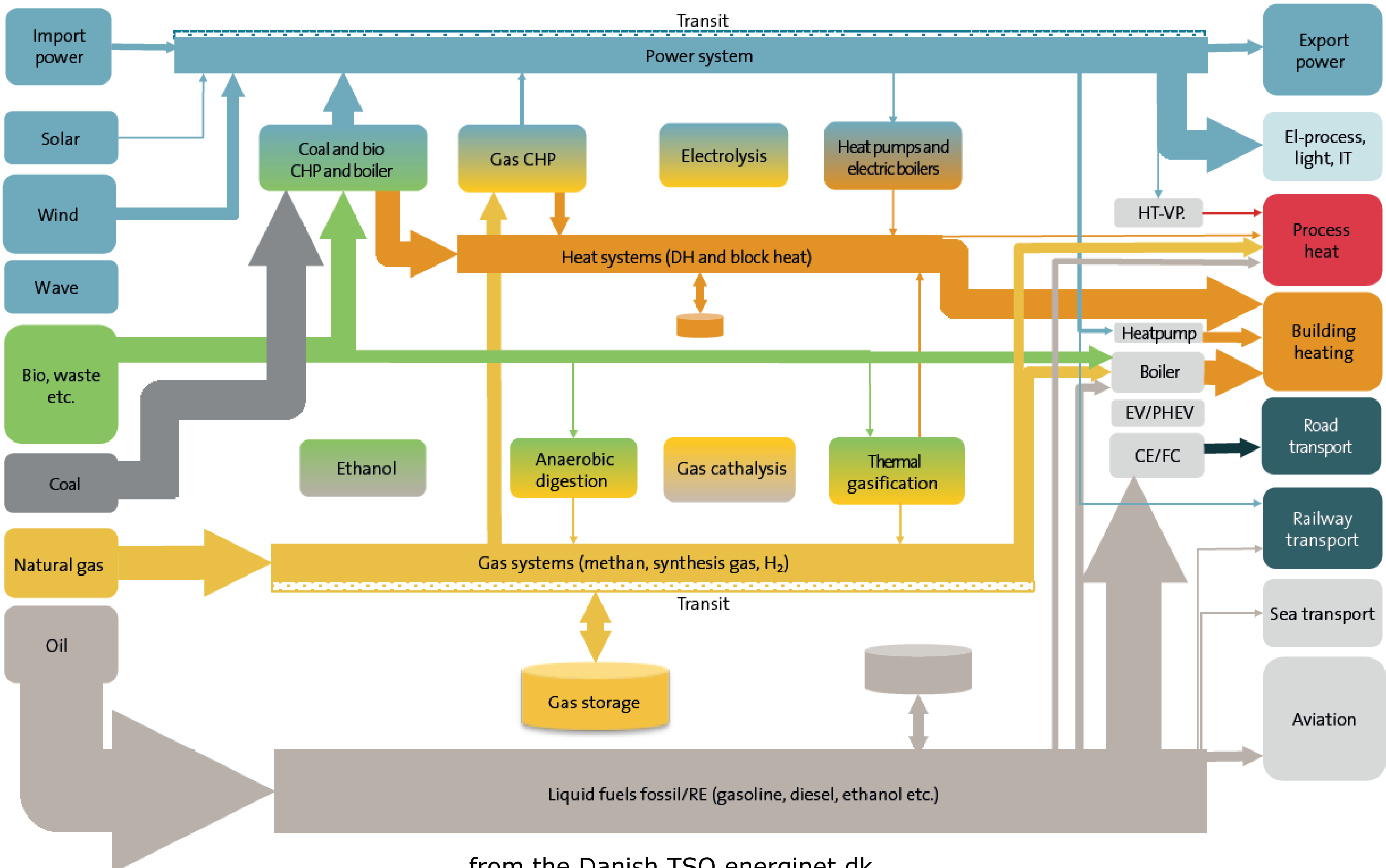
The Danish energy system

Gross energy consumption by use



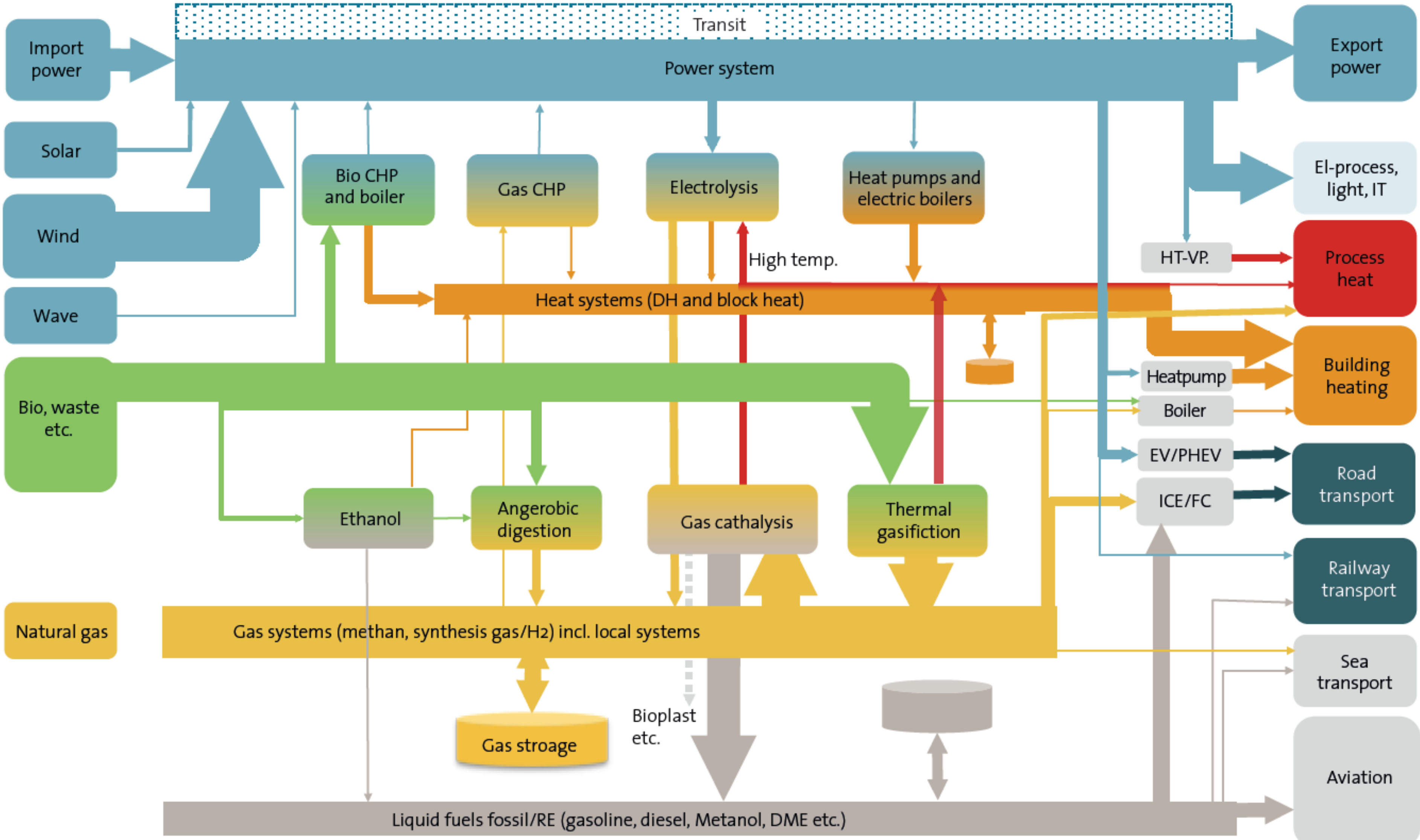
from the Danish energy agency

The energy system today (2014)



from the Danish TSO energinet.dk

Energy system scenario (2050)



from the Danish TSO energinet.dk

Questions

- What important differences is observed when comparing the Danish energy system from today, with the scenario for 2050?
- Try to come up with plausible explanations for the changes

Abbreviations used in slides:

CHP = Combined Heat and Power

EV = Electric Vehicle

PHEV = Plug-in Hybrid Electric Vehicle

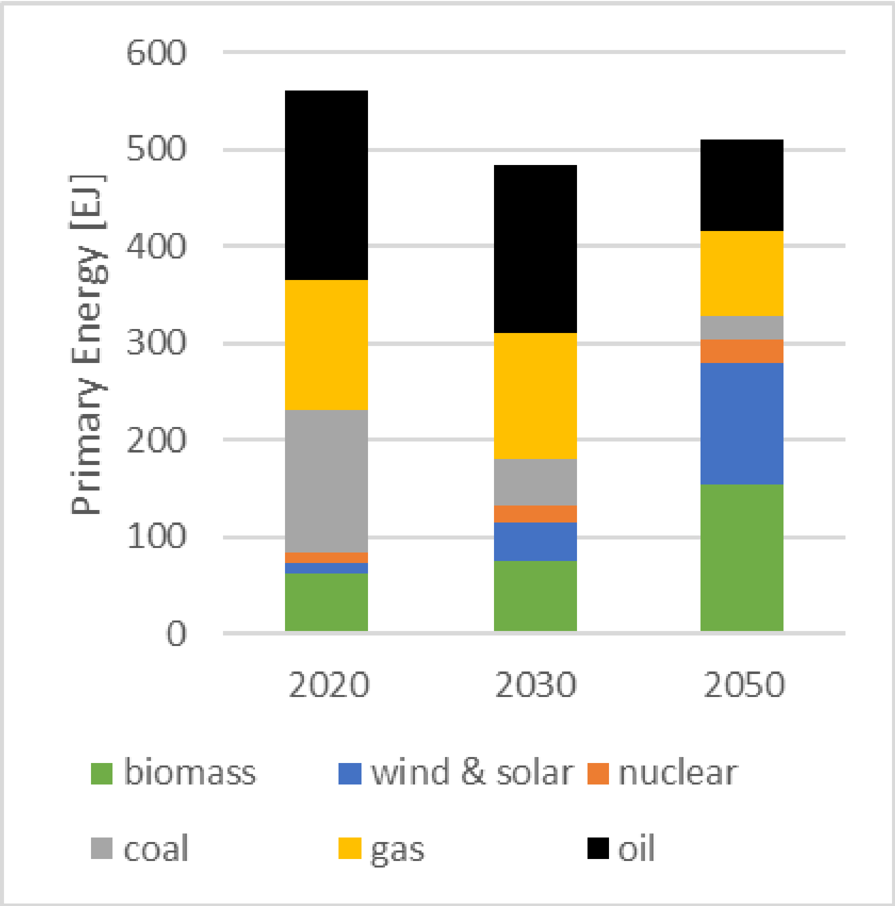
ICE = Internal Combustion Engine

CE = Combustion Engine (= ICE)

FC = Fuel Cell

HT-VP = High Temperature heat pump

IPCC 1.5°C pathways



- Biomass consumption for energy more than doubles by 2050

- The figure represents median values from 85 pathways

- Source: IPCC special report ”Global warming of 1.5 ºC”, 2018.

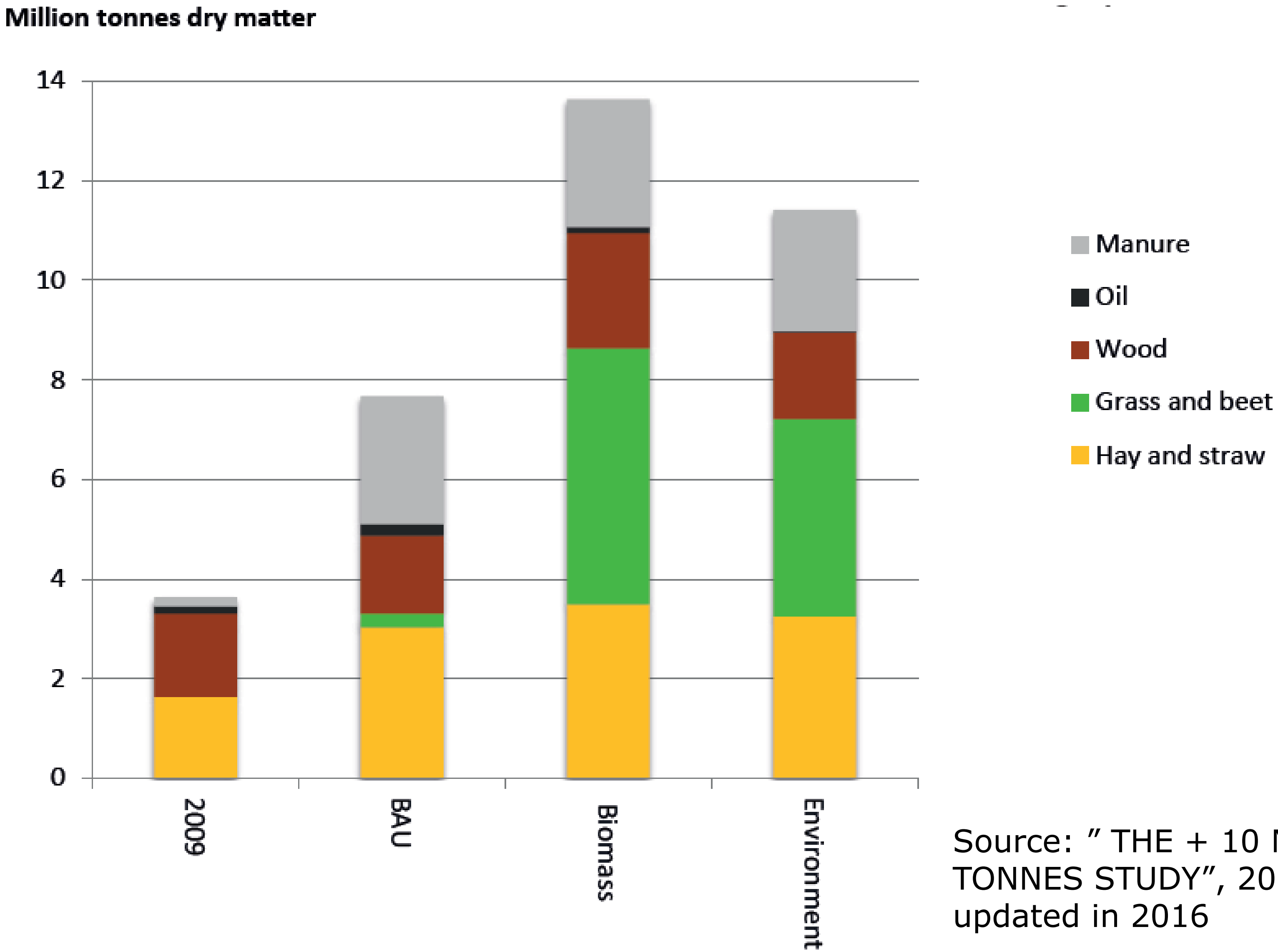
Sustainable biomass available for energy production

- How much sustainable biomass can be made available for energy production?

- Very difficult to answer. It depends on many different factors.

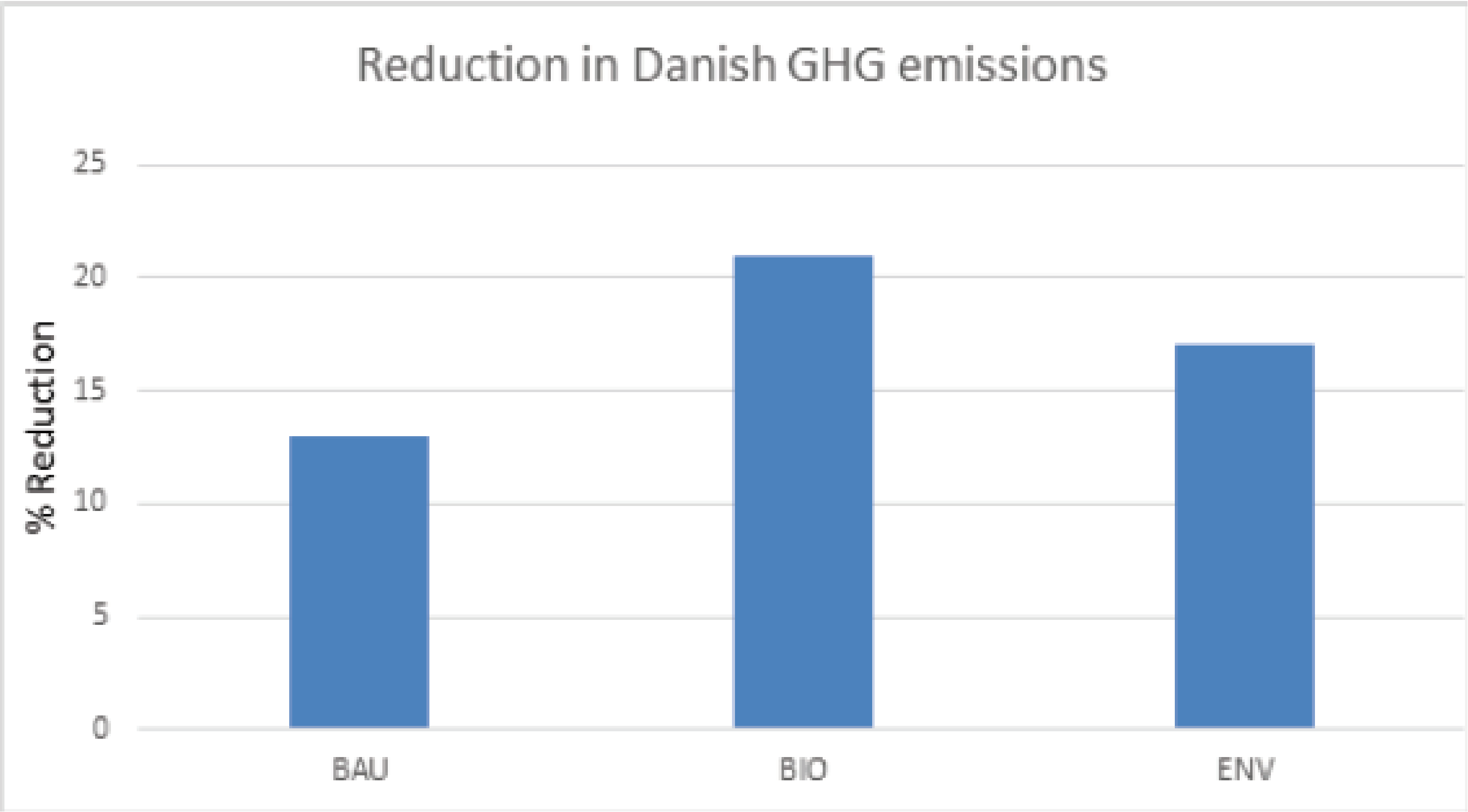
- A detailed study was made for the case of Denmark; ”THE + 10 MILLION TONNES STUDY”. It can be used to illustrate the complexity.

Biomass available for energy production
THE + 10 MILLION TONNES STUDY



Source: " THE + 10 MILLION TONNES STUDY", 2013, updated in 2016

Biomass available for energy production
THE + 10 MILLION TONNES STUDY



Source: " THE + 10 MILLION TONNES STUDY", 2013, updated in 2016

Biomass available for energy production
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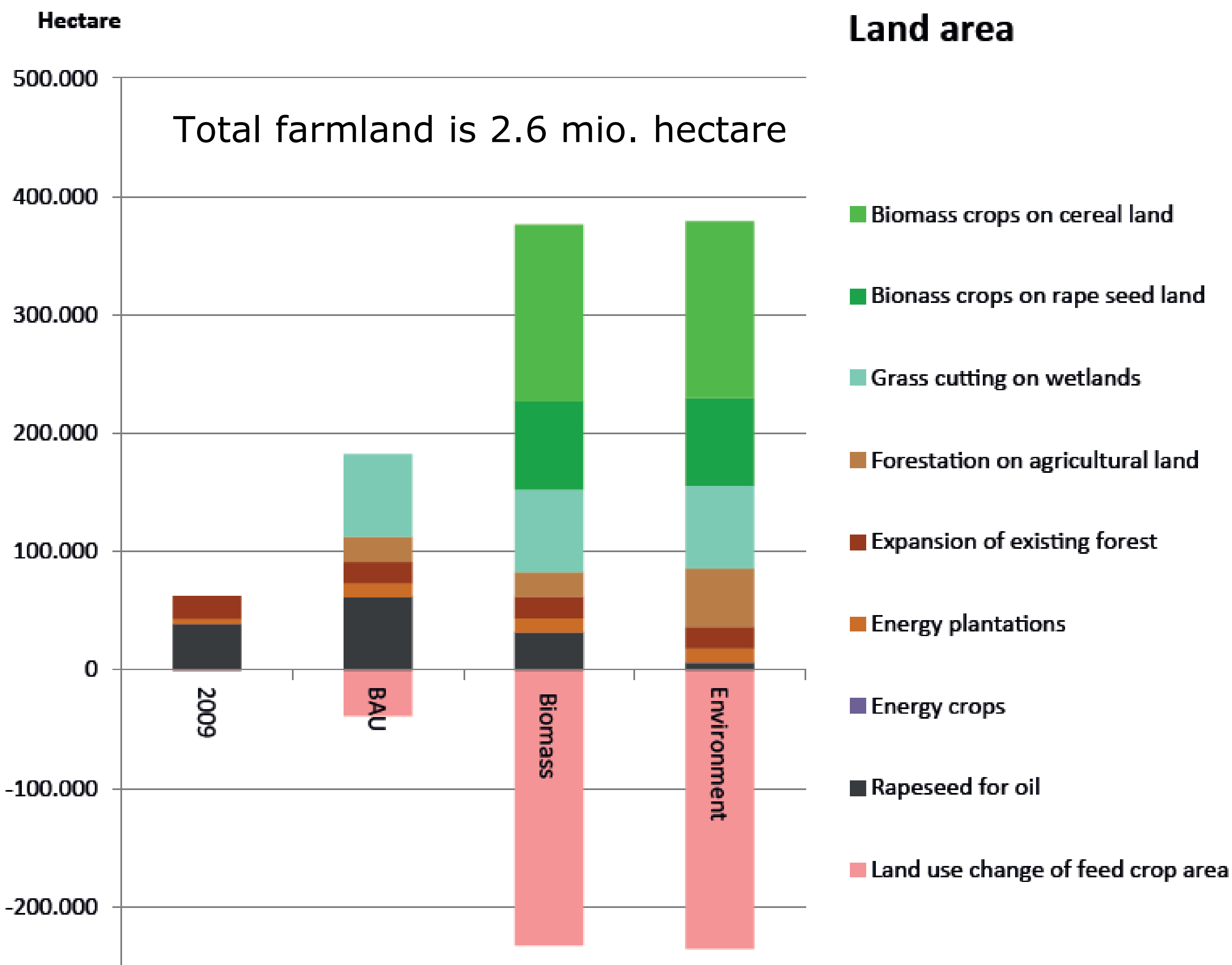
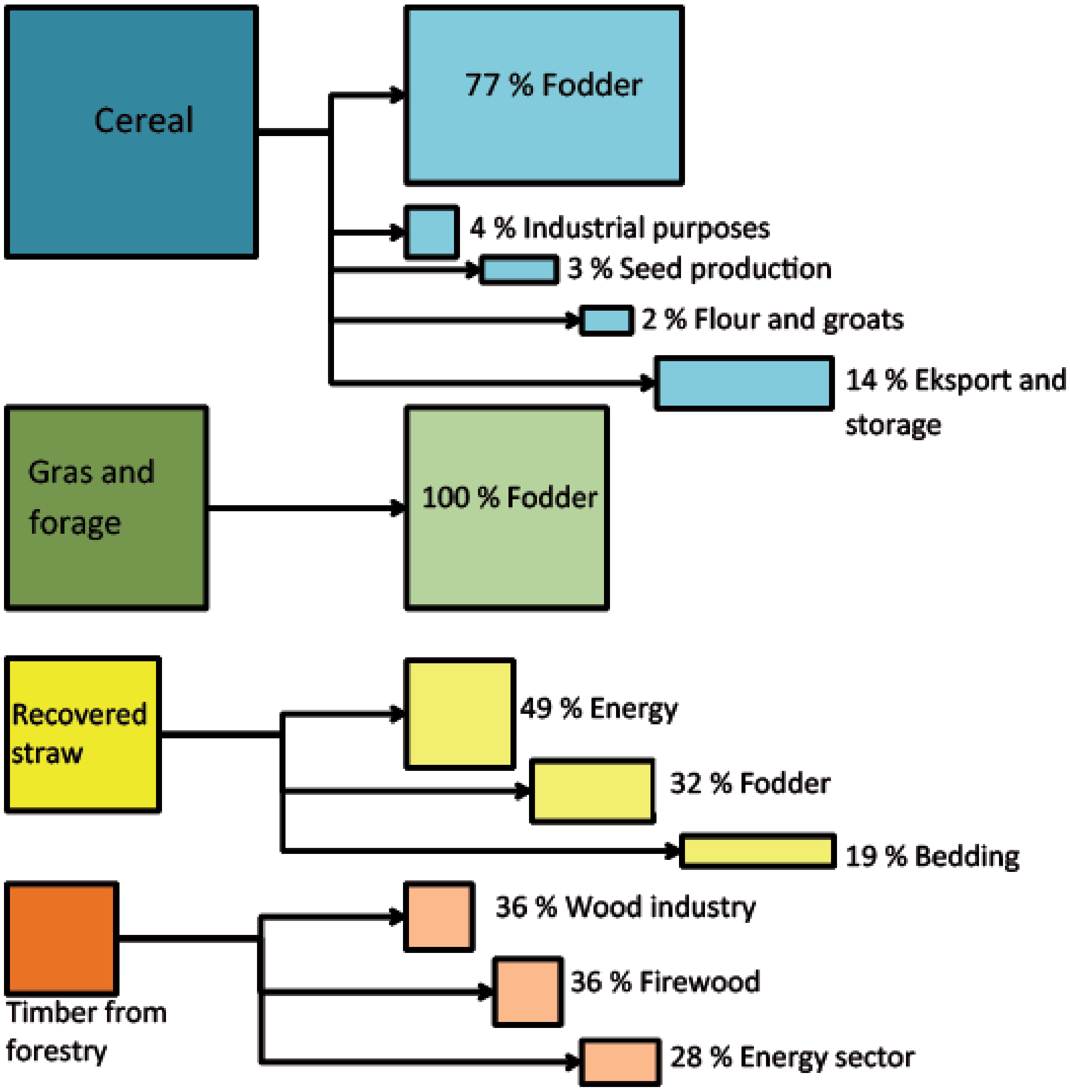


d biofuels

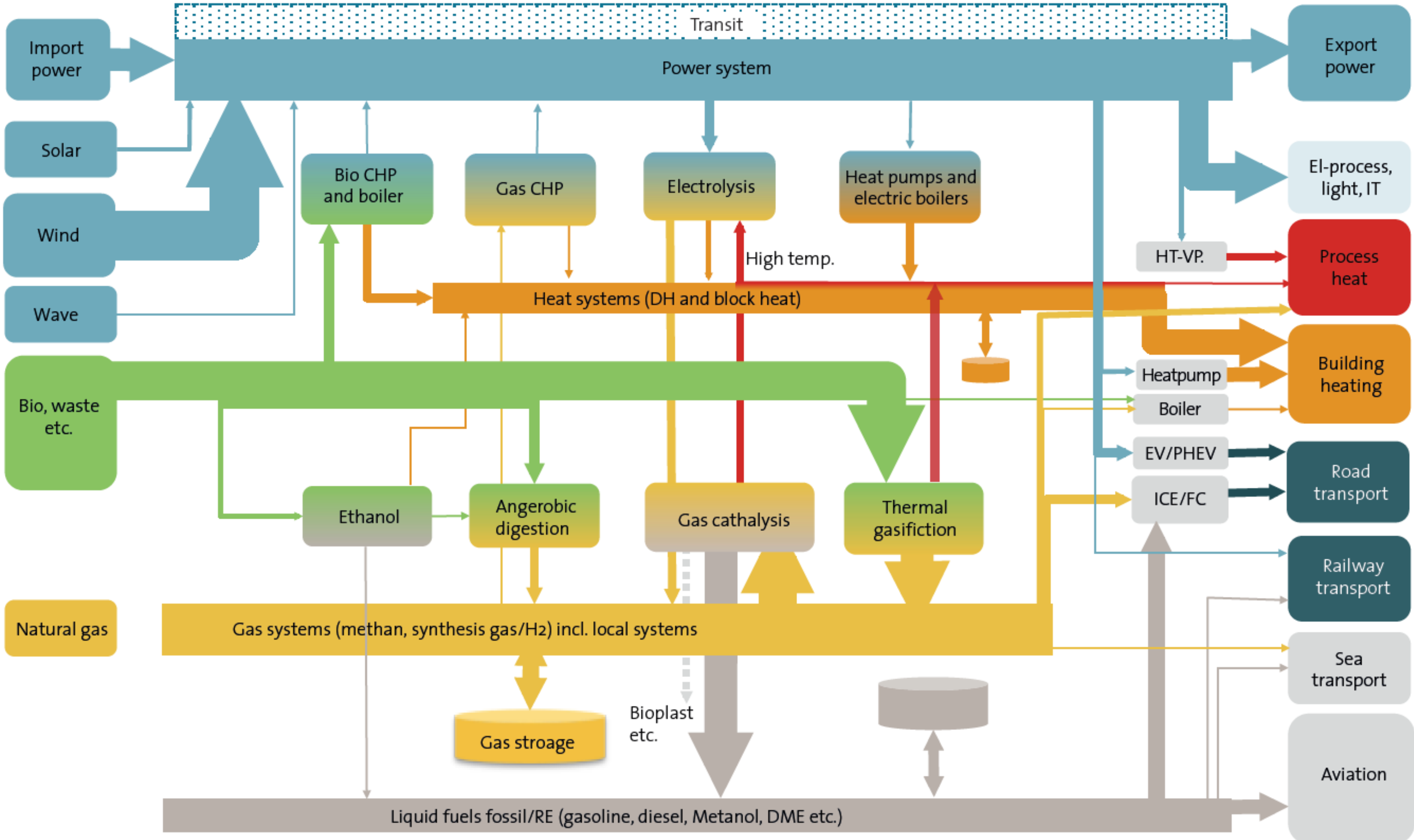
Biomass available for energy production



- Nearly all the farmland is currently used for fodder production instead of direct human consumption
- A more vegetarian diet would liberate a great amount of farmland

Source: ” THE + 10 MILLION TONNES STUDY”, updated in 2016

Energy system scenario (2050)

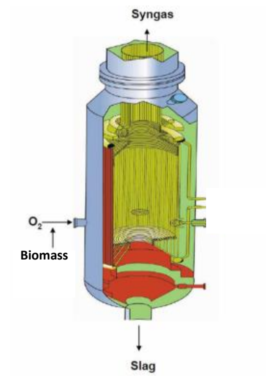


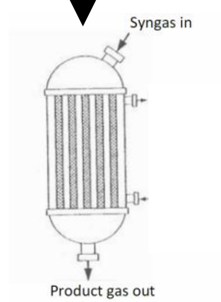
from the Danish TSO energinet.dk

Thermochemical biofuel production
Based on thermal gasification

Biomass

Gasifier

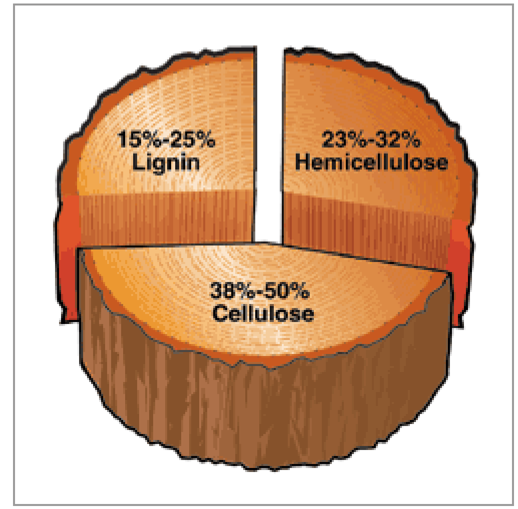




Synthesis reactor

Liquid fuel

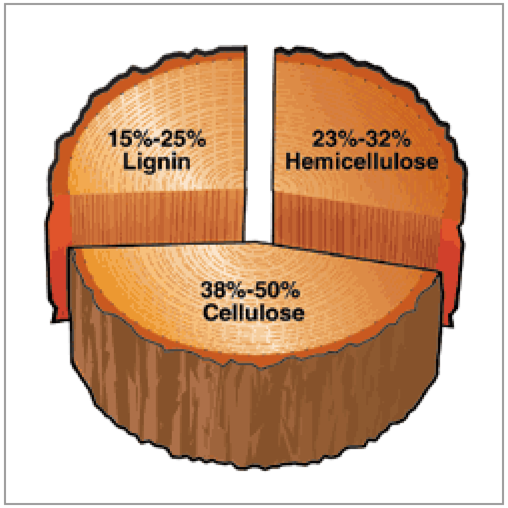
Biomass constituents:



Thermochemical processes convert all three parts.

Biochemical conversion (e.g. ethanol, biogas) cannot currently convert lignin.

<u>Biomass constituents:</u>



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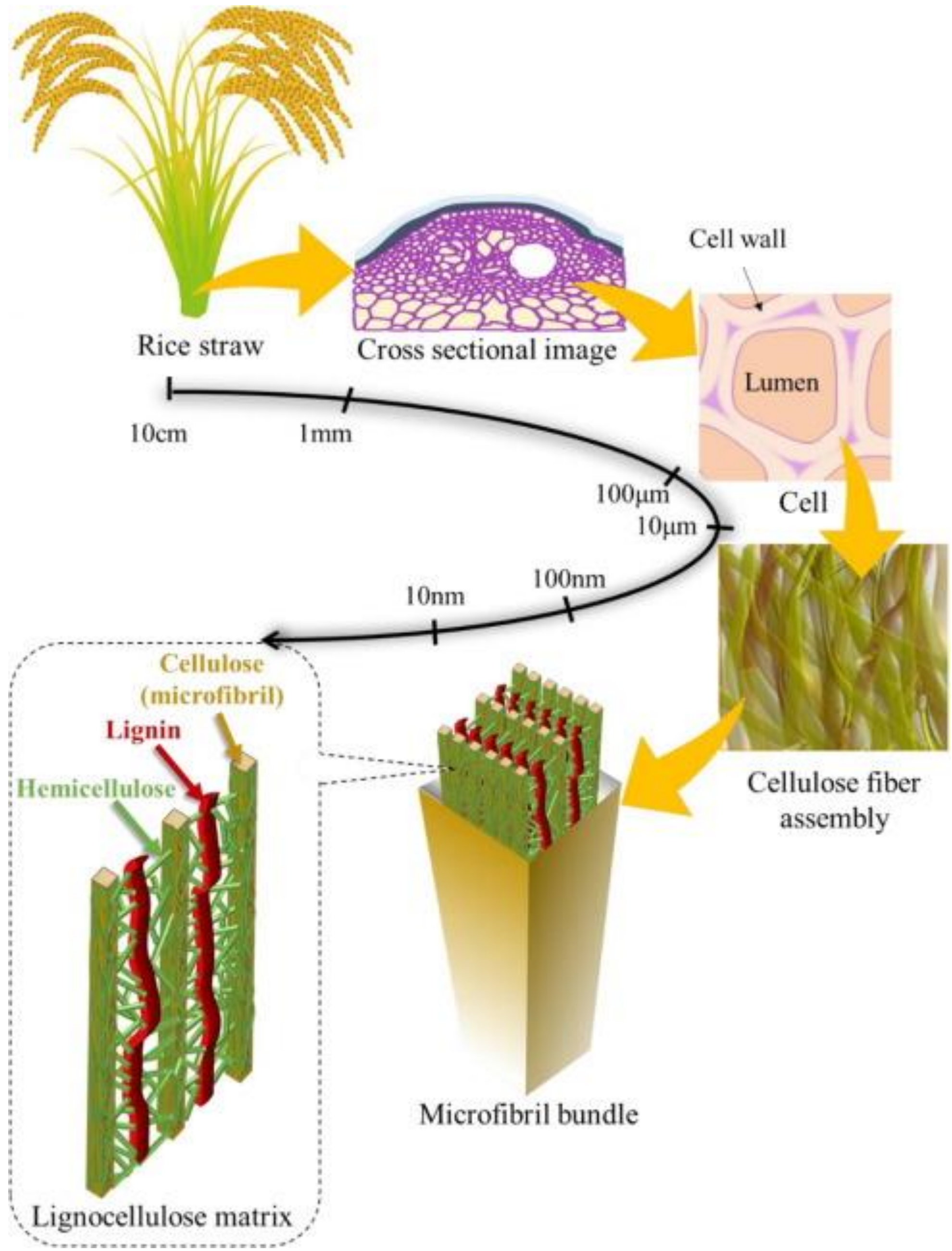
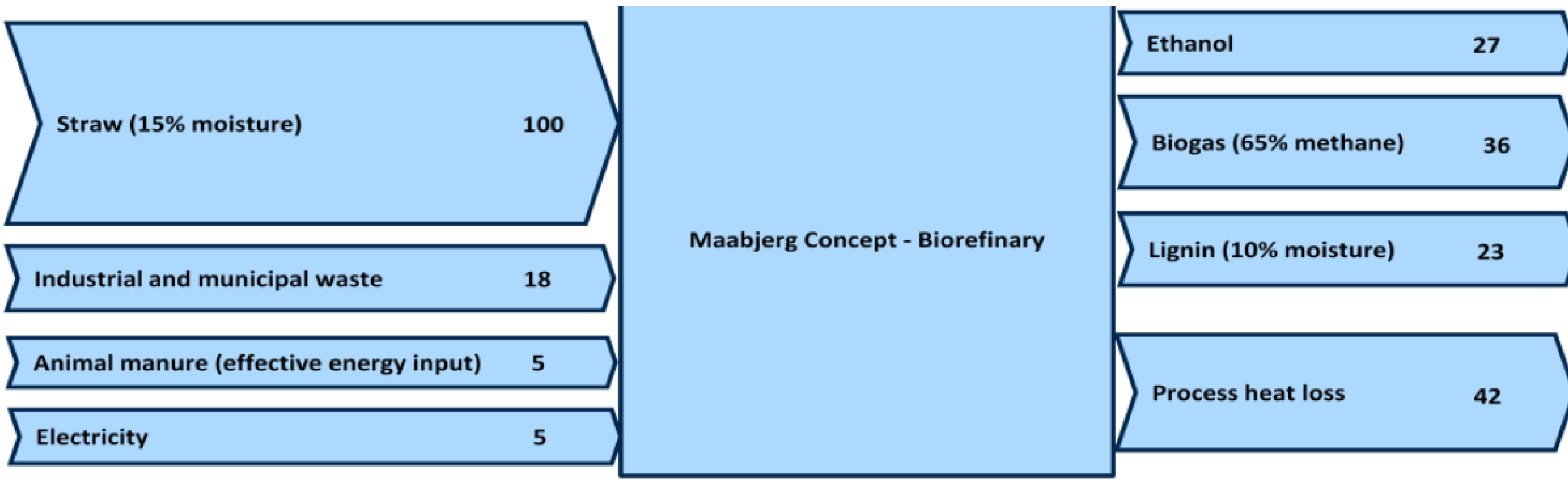


Biochemical biofuel production
The Maabjerg biorefinery



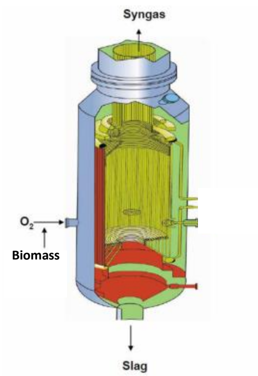
Technology data for advanced bioenergy fuels, Danish Energy Agency, 2013.

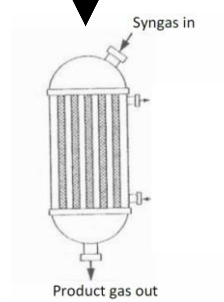
Efficiency: 49% (ethanol+biogas / inputs)

Thermochemical biofuel production
Based on thermal gasification

Biomass

Gasifier

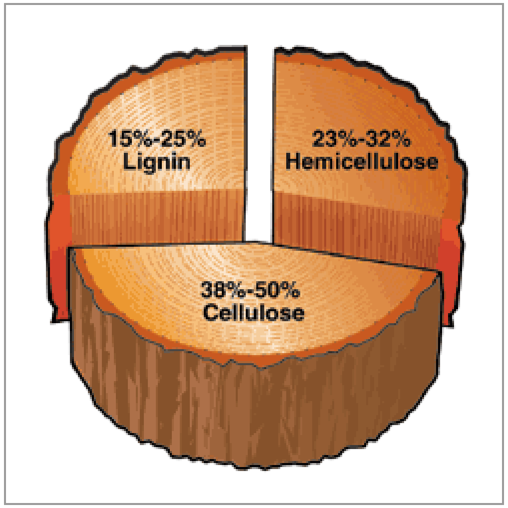




Synthesis reactor

Liquid fuel

<u>Biomass constituents:</u>



Thermochemical processes convert all three parts.

Biochemical conversion (e.g. ethanol, biogas) cannot currently convert lignin.

Thermochemical biofuel production
Agenda

- Gasification of biomass
  - Pyrolysis
  - Gasification reactions
  - Gasifier types
    - Fluidized bed gasifiers
    - Entrained flow gasifiers

Thermochemical biofuel production
Agenda

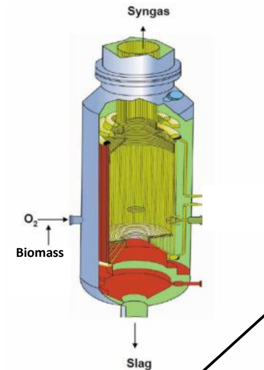
- Chemical synthesis
  - Synthesis of Dimethyl ether (DME), methanol, mixed alcohols Synthetic natural gas (methane), Fischer–Tropsch, synthetic gasoline, hydrogen

- Thermochemical biofuel production plants
  - The processes
  - Proposed plant designs
    - DME plant based on entrained flow gasification of biomass
  - Near commercial plants
  - Hurdles to overcome before biofuel plants are commercial

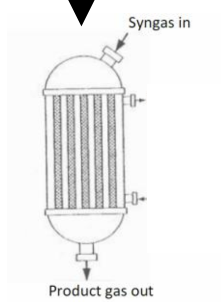
Thermochemical biofuel production
Based on thermal gasification

Biomass

Gasifier



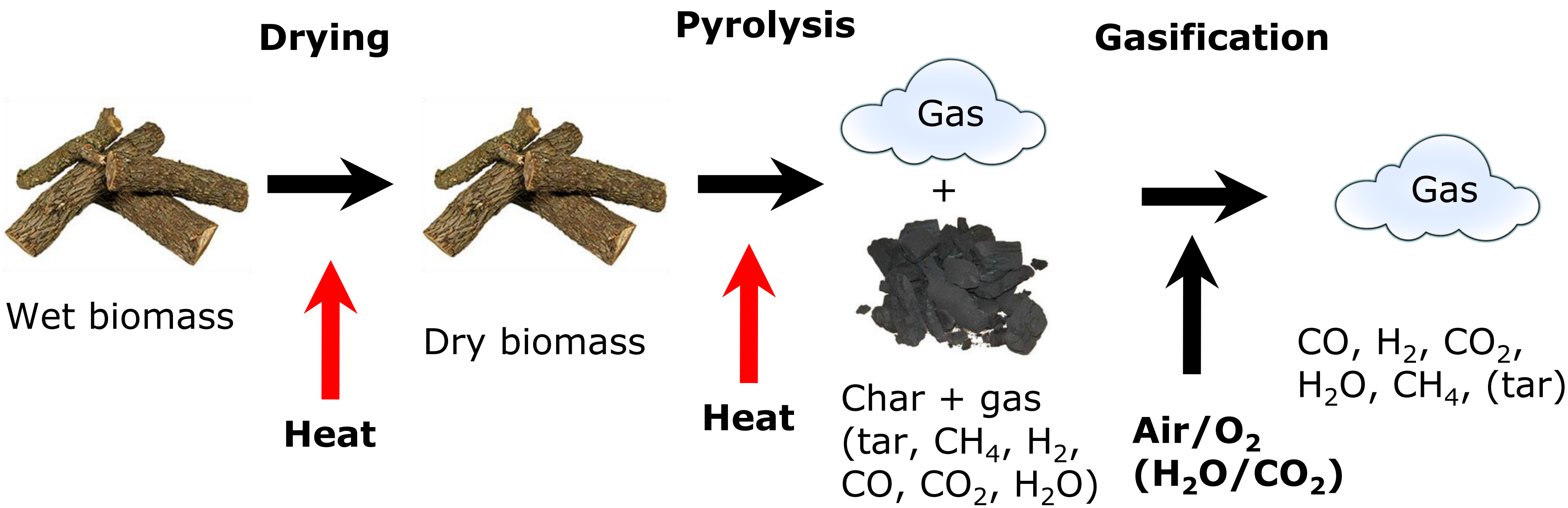
Syngas (synthesis gas)
- Consist of CO and H_2
  (the building blocks for chemical synthesis)



Synthesis reactor

Liquid fuel

Gasification of biomass

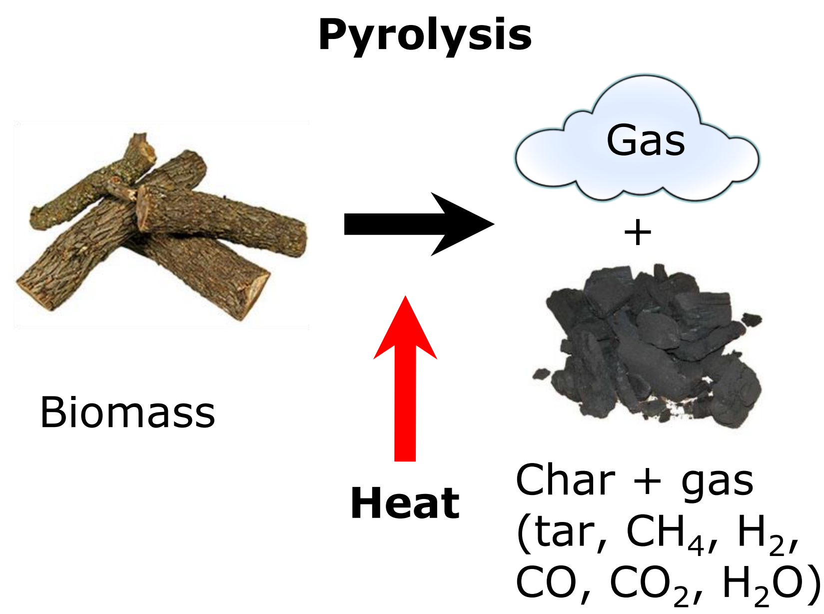


These 3 processes can be done in 1 reactor (gasifier), or can be split into 2 or 3 reactors

Gasification of biomass

Pyrolysis of biomass

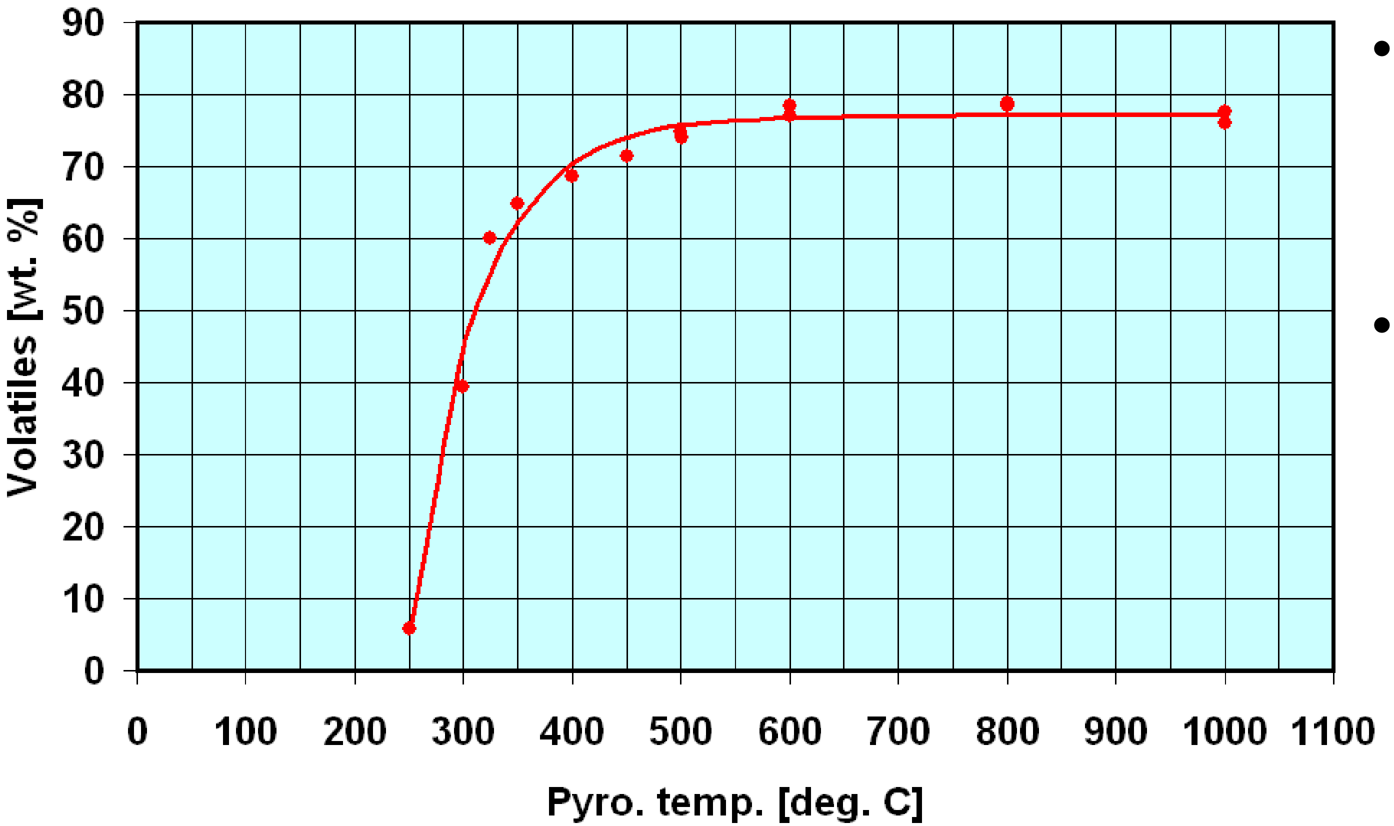
- Pyrolysis occurs when heating biomass to above 250°C in an oxygen-free environment
- Pyrolysis starts at 250°C and ends at about 600°C
- Up to 80% of the mass can be converted to gas (20% left as char)
- The char will contain more than 40% of the heating value



Gasification of biomass

Pyrolysis of biomass

Volatiles = Gas



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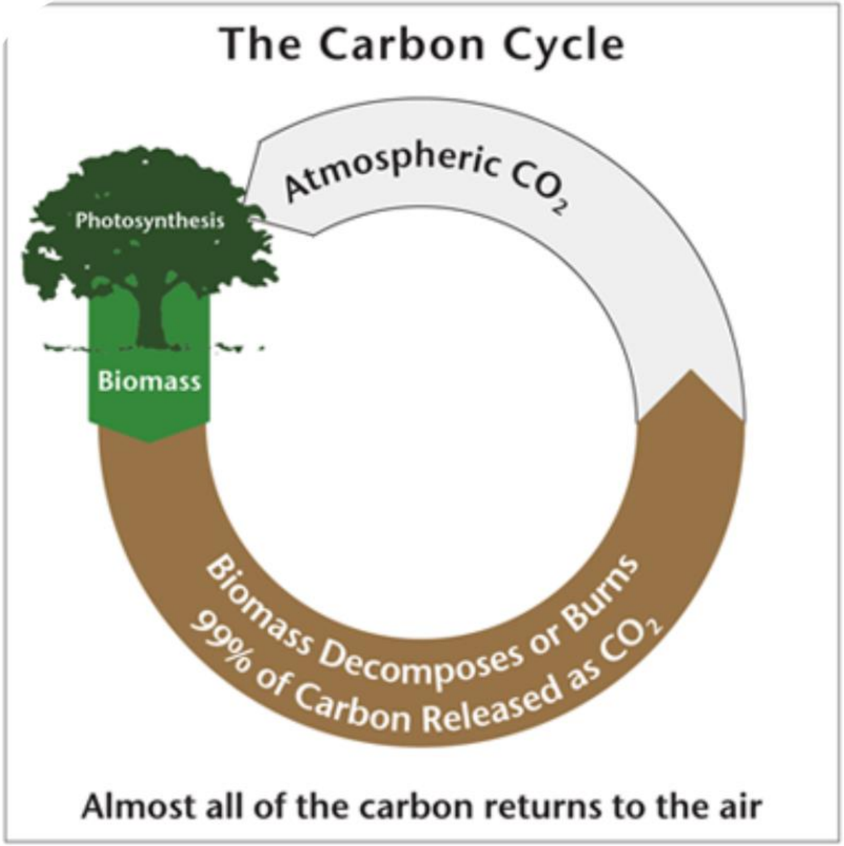
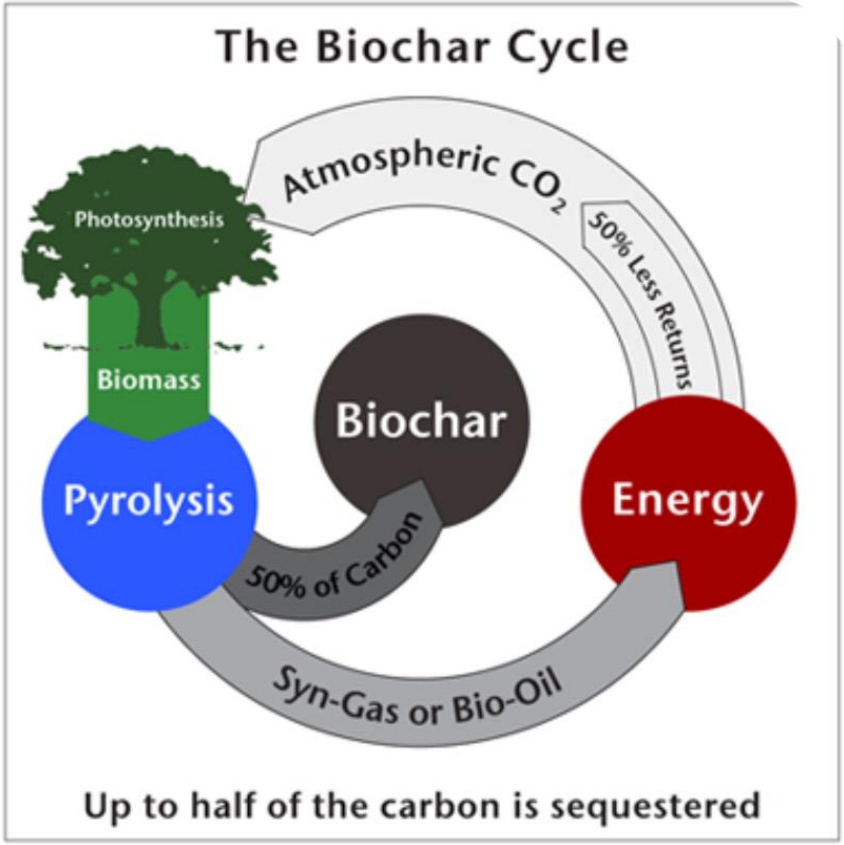
Gasification of biomass

Pyrolysis of biomass





Gasification of biomass

Gasification reactions

$C_{char} + H_2O \rightarrow H_2 + CO$

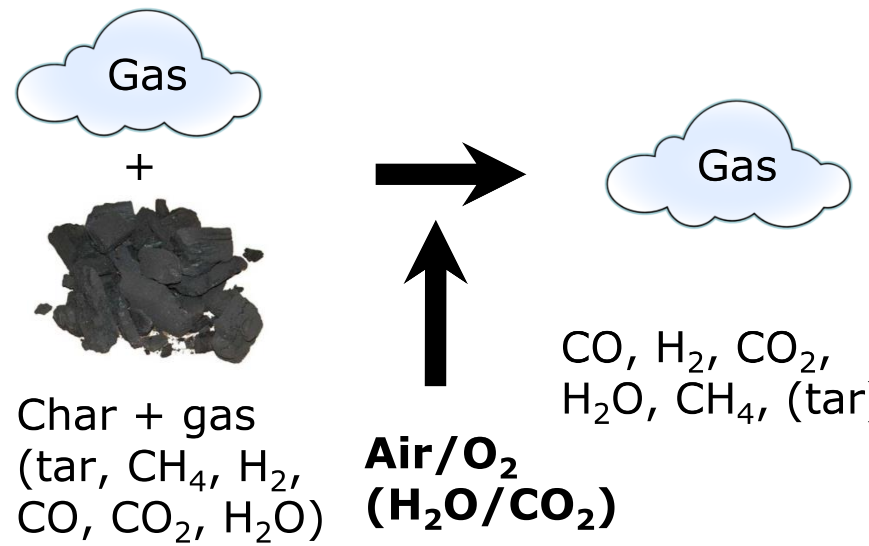
$C_{char} + CO_2 \rightarrow 2CO$

- The reactions above are both endothermic (requires heat)
- The heat required is typically supplied by adding air/O_2

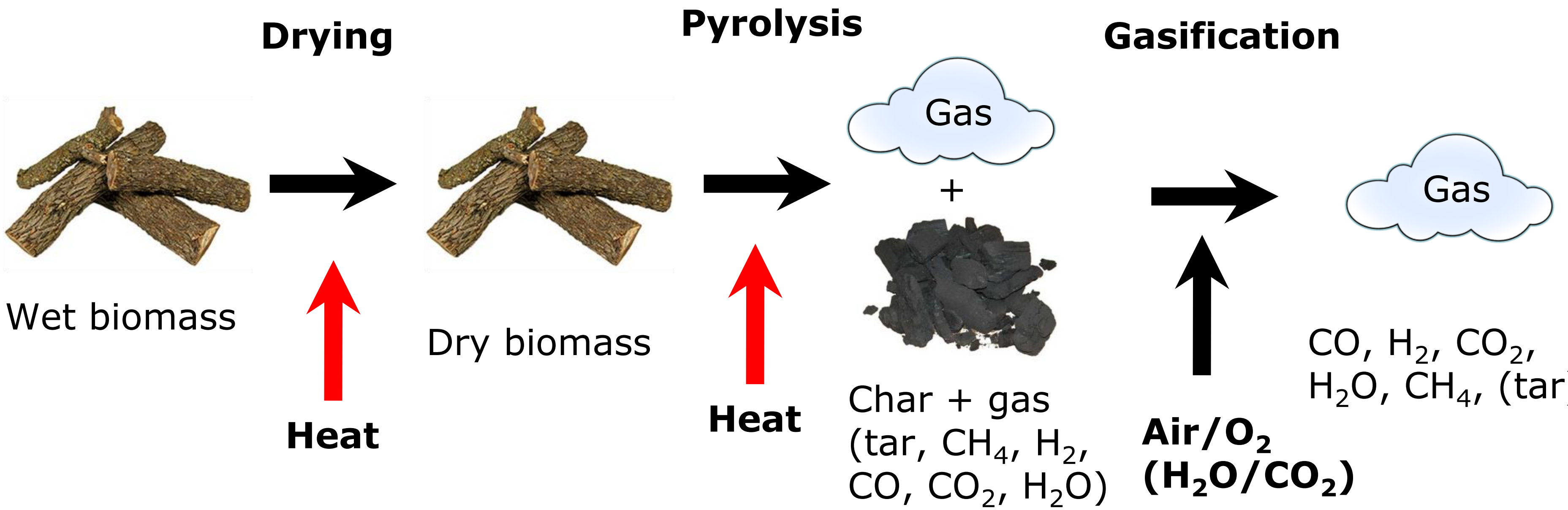
Water gas shift (WGS) reaction will typically be at equilibrium at temperatures above 750°C :

$H_2O + CO \leftrightarrow H_2 + CO_2$

Gasification



Gasification of biomass



High conversion:

Almost all the organic matter in the biomass ends up in the gas (some carbon in the ash)

High efficiency:

Up to 75-93% of the heating value in the biomass can end up as heating value in the produced gas

Thermochemical biofuel production
Agenda

- Gasification of biomass
  - Pyrolysis
  - Gasification reactions
  - Gasifier types
    - Fluidized bed gasifiers
    - Entrained flow gasifiers

Gasification of biomass

Gasifier types

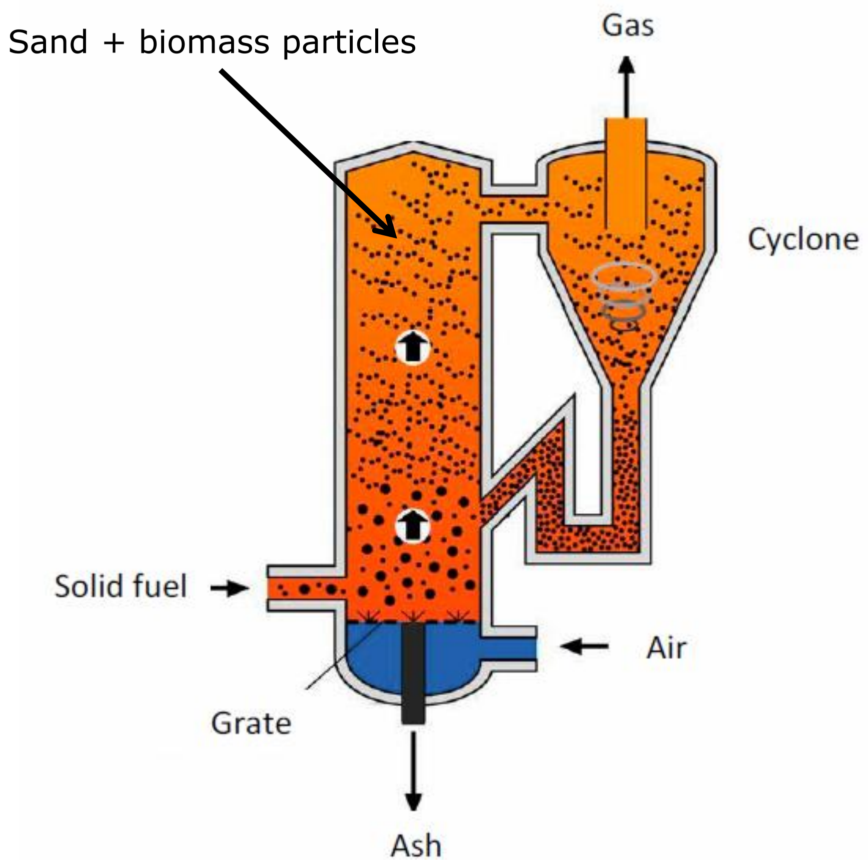
- Fluidized bed gasifiers
- Entrained flow gasifiers

Note: Batch processing do not occur in any of the gasifiers listed above. The processes happening in the gasifiers are all continuous processes.

$$\text{energy efficiency} = \frac{\text{Heating value in gas}}{\text{Heating value in biomass}} = \frac{\mathrm{LHV_{gas}} \cdot \mathrm{m_{gas}}}{\mathrm{LHV_{biomass}} \cdot \mathrm{m_{biomass}}}$$

Gasification of biomass

Gasifier types: Fluidized bed



Circulating fluidized bed

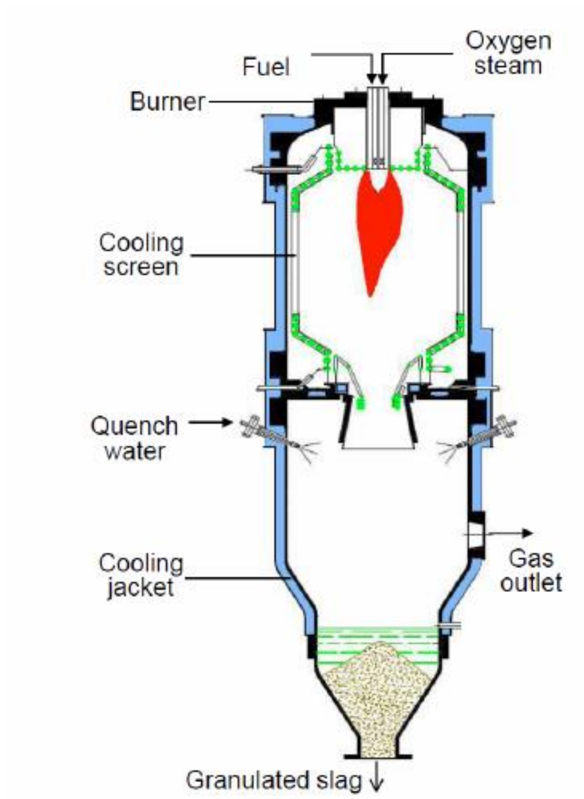
- Medium energy efficiency (~85%)
- Medium tar and CH_4 content in gas
- Temperature out: 730°C - 1000°C

- This gasifier type can handle many different types of biomass feedstocks

- Fast conversion of biomass because of extremely high heat transfer from sand to biomass

Gasification of biomass

Gasifier types: Entrained flow



- Low energy efficiency (~80%)
- No tar and CH_4 in gas (trace)
- Temperature out: 1200°C - 1600°C

- This gasifier type is typically used in commercial coal-to-liquids plants

Gasification of biomass

Gasifier types for biofuel production

The gas from the following gasifier type will need reforming of the tar and CH_4 (to $CO + H_2$)

- Fluidized bed gasifiers

The gas from the following gasifier type will not need reforming of the gas (no tar and CH_4 in gas)

- Entrained flow gasifiers

Thermochemical biofuel production
Agenda

- Chemical synthesis
  - Synthesis of Dimethyl ether (DME), methanol, mixed alcohols Synthetic natural gas (methane), Fischer–Tropsch, synthetic gasoline, hydrogen

- Thermochemical biofuel production plants
  - The processes
  - Proposed plant designs
    - DME plant based on entrained flow gasification of torrefied biomass
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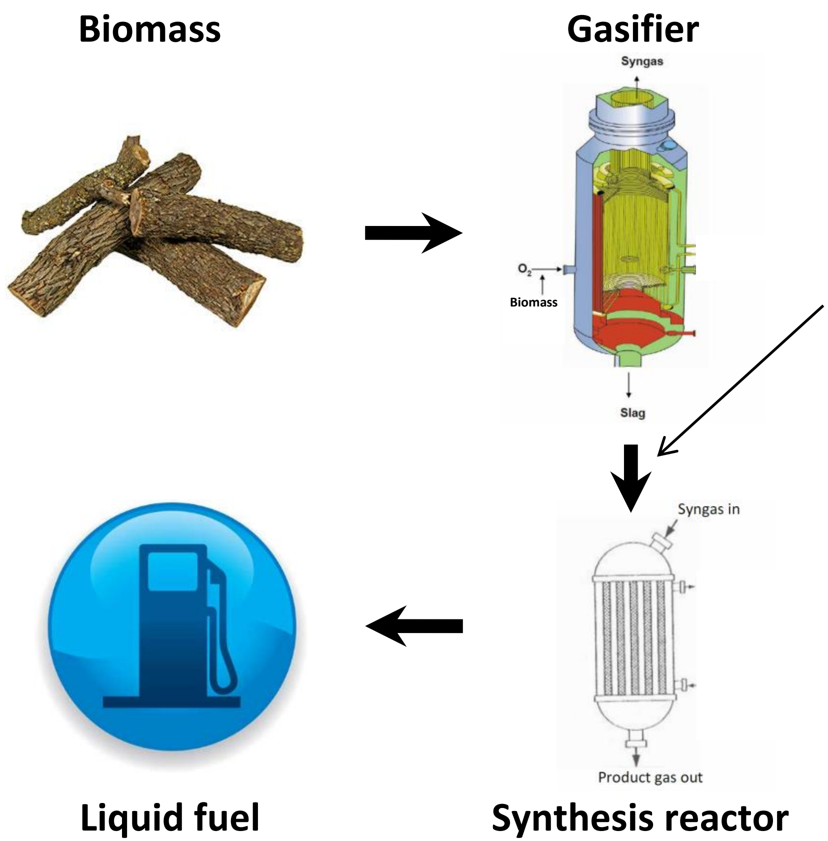
Thermochemical biofuel production
Based on thermal gasification



Syngas (synthesis gas)

- Consist of CO and H_2 (the building blocks for chemical synthesis)

Requirements for gasifier:

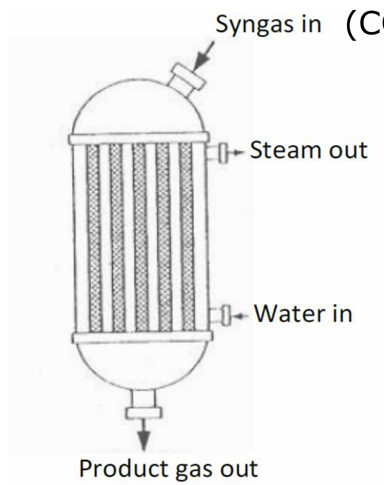
- High content of CO and H_2
- Low content of other combustible gasses - mainly CH_4 and tar

Chemical synthesis

Reactor:

7-150 bar

200-300 °C



(CO, H_2)

Catalyst in reactor:

(This is a catalyst for Fischer-Tropsch synthesis:

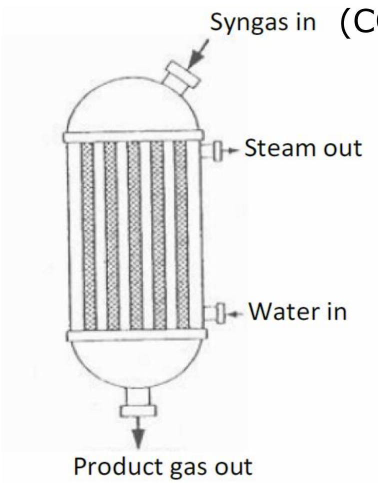
an iron catalyst made on an alumina support)

Fuel product
Dimethyl ether (DME)
Methanol
Synthetic natural gas (methane)
Mixed alcohols (~ethanol)
Fischer–Tropsch fuels
Synthetic gasoline
Hydrogen

Chemical synthesis

The H_2/CO-ratio can be adjusted by using the water gas shift (WGS) reaction:

$H_2O + CO \leftrightarrow H_2 + CO_2$



(CO, H_2)

Fuel product	Reaction	H_2/CO-ratio
Methanol	$CO + 2H_2 \rightarrow CH_3OH$	2
Dimethyl ether (DME)	$3CO + 3H_2 \rightarrow CH_3OCH_3 + CO_2$	1
	$2CO + 4H_2 \rightarrow CH_3OCH_3 + H_2O$	2
Synthetic natural gas (methane)	$CO + 3H_2 \rightarrow CH_4 + H_2O$	3
Mixed alcohols (~ethanol)	$3CO + 3H_2 \rightarrow C_2H_5OH + CO_2$	1
	$2CO + 4H_2 \rightarrow C_2H_5OH + H_2O$	2

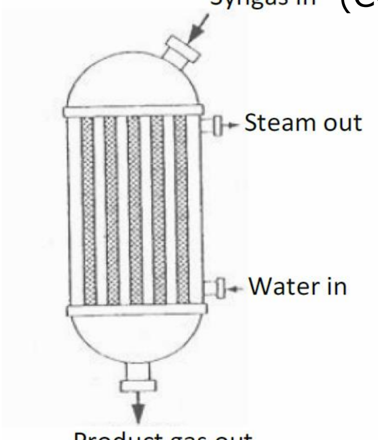
Reactor:

7-150 bar

200-300 °C

Other fuels: Fischer–Tropsch fuels, synthetic gasoline, hydrogen

Chemical synthesis
using CO_2



(CO, H_2)

Fuel product	Reaction
Methanol	$CO + 2H_2 \rightarrow CH_3OH$
	$CO_2 + 3H_2 \rightarrow CH_3OH + H_2O$
Synthetic natural gas (methane)	$CO + 3H_2 \rightarrow CH_4 + H_2O$
	$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O$

Reactor:

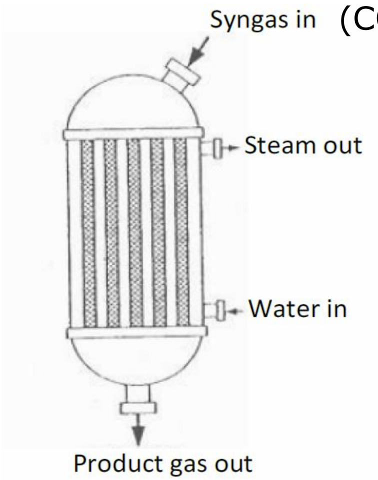
7-150 bar

200-300 °C

Chemical synthesis of DME

Fuel product	Reaction	H_2/CO-ratio
Dimethyl ether (DME)	$3CO + 3H_2 \rightarrow CH_3OCH_3 + CO_2$	1
	$2CO + 4H_2 \rightarrow CH_3OCH_3 + H_2O$	2

(CO, H_2)

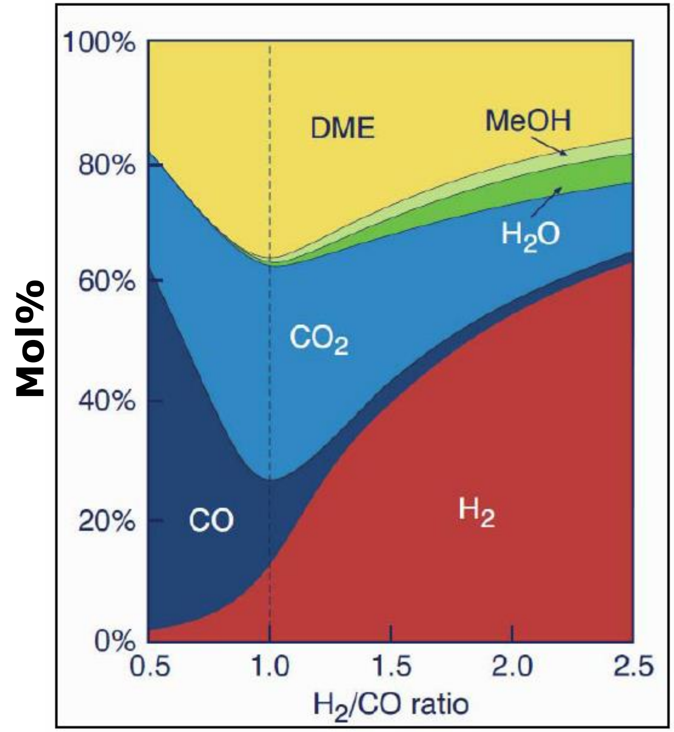


Reactor:

~50 bar

~260°C

Equilibrium composition from reactor



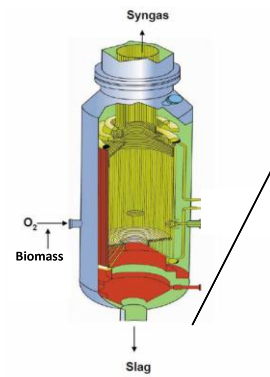
Dimethyl ether (DME)

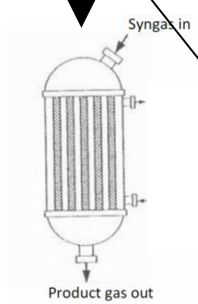
- DME is a gas at atm. pressure, but liquid at 5 bar. Chemical formula: CH_3OCH_3
- Is today used for: cooking and heating (like LPG), as a propellant gas in canisters, and as a transportation fuel (modified diesel engines).
- Low emissions from combustion: low NO_X-emission, zero SO_X and zero soot
- China has invested heavily in DME for transportation purposes and as a replacement for LPG. China is producing DME by gasification of coal. Today China has too much DME production capacity compared with the demand.

Thermochemical biofuel production
Based on thermal gasification

Biomass

Gasifier





Synthesis reactor

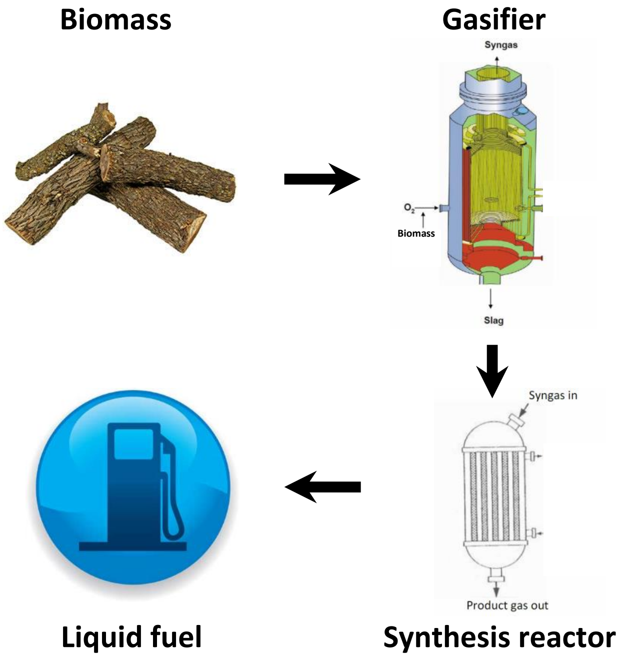
Liquid fuel

After the gasifier the gas needs to be cleaned and conditioned:

- The H_2/CO-ratio is adjusted to the requirements of the synthesis reaction
- Removing CO_2 to increase the conversion to biofuel and lower the size of downstream equipment
- Removing sulfur components (H_2S, COS) because they are poisonous to the catalytic material in the synthesis reactor

Thermochemical biofuel production

Exercise



If the cleaned and conditioned syngas from a gasifier consist of 2/3 of H_2 and 1/3 of CO (molar basis), and the energy efficiency from biomass to syngas is 80%, calculate:

- the energy efficiency from syngas to methanol
- the total energy efficiency (biomass to methanol).

Heating values:

H_2: 241.8 MJ/kmol

CO: 283.0 MJ/kmol

CH_3OH (Methanol): 638 MJ/kmol

Methanol reaction: $CO + 2H_2 \rightarrow CH_3OH$

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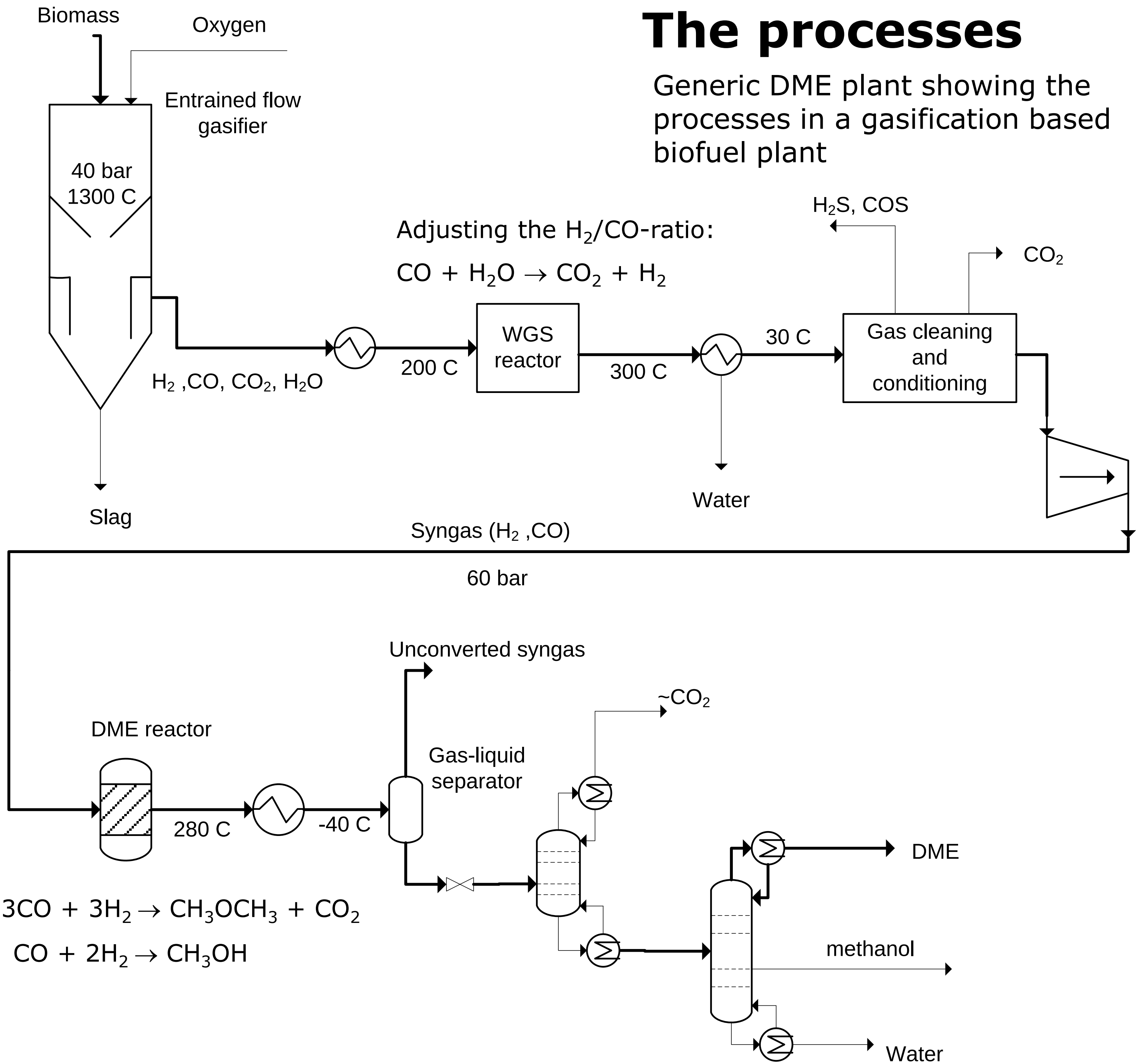
The processes

Generic DME plant showing the processes in a gasification based biofuel plant



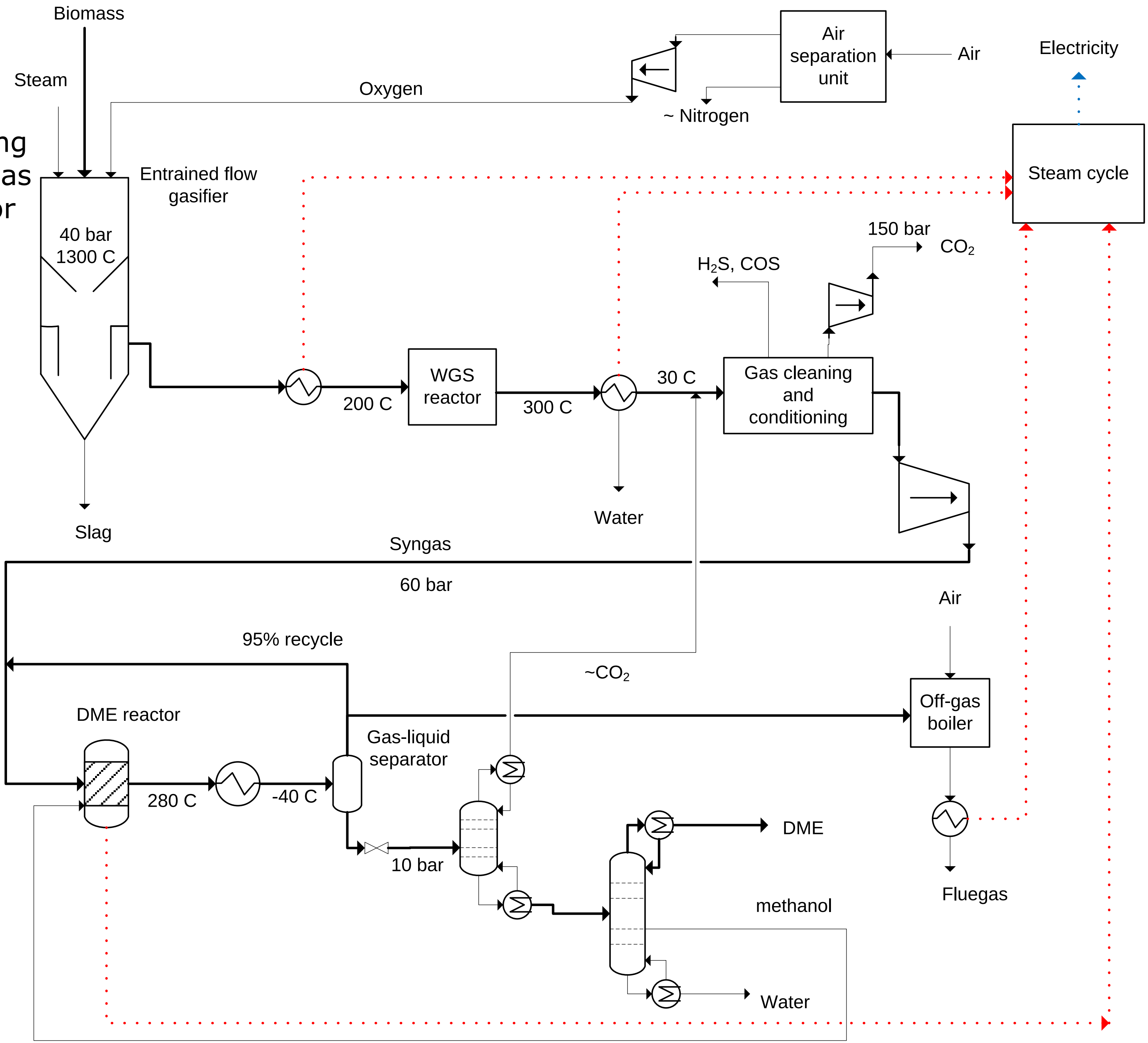
DME: $3CO + 3H_2 \rightarrow CH_3OCH_3 + CO_2$

Methanol: $CO + 2H_2 \rightarrow CH_3OH$

DME-RC

DME plant recycling unconverted syngas to the DME reactor

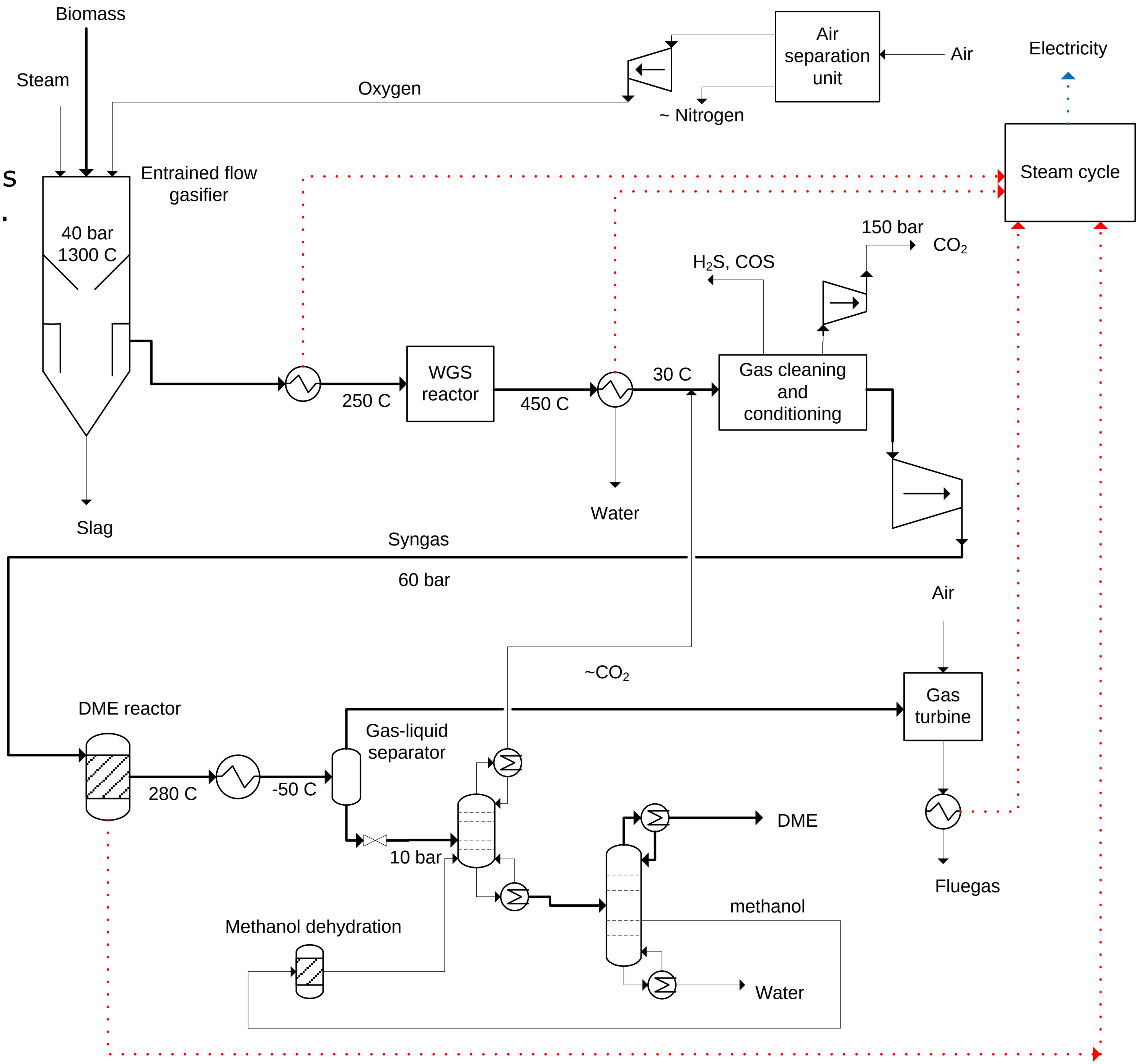
RC = recycle



DME-OT

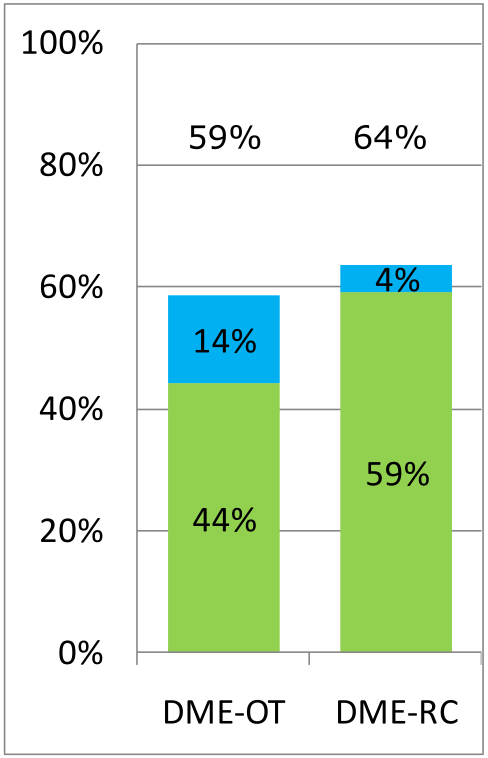
DME plant where the unconverted syngas is used in a gas turbine.

OT = once through



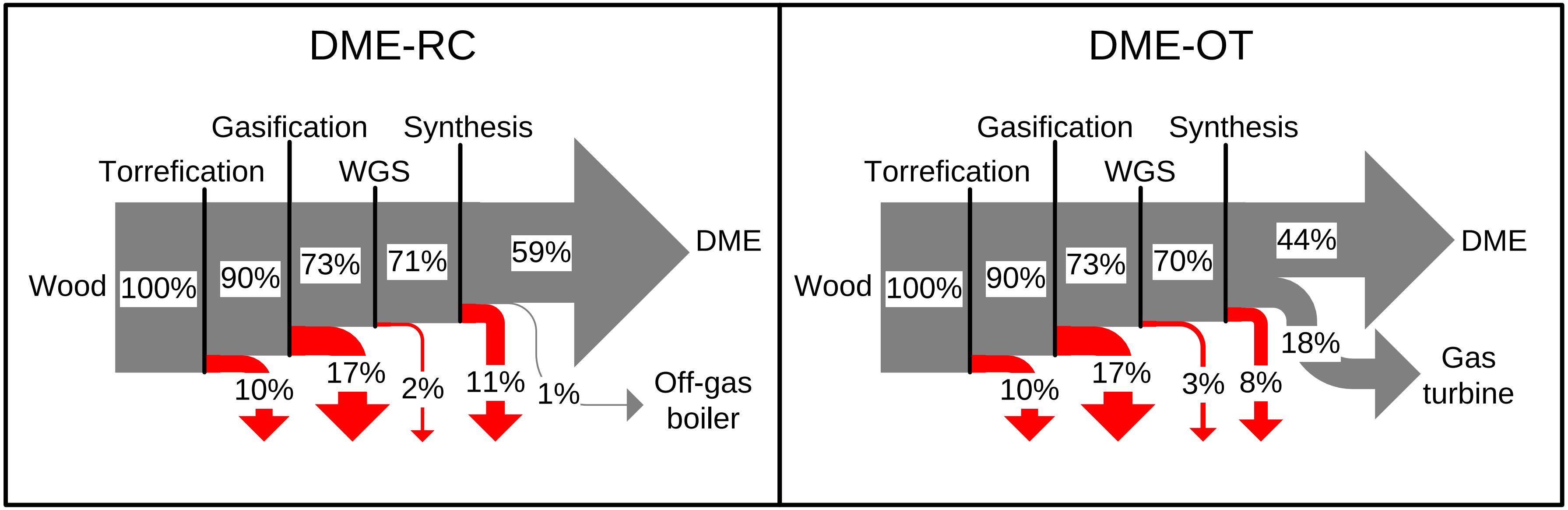
DME plants based on entrained flow gasification of torrefied wood

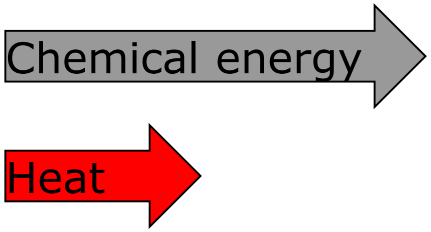
Energy efficiencies



DME plants based on entrained flow gasification of torrefied biomass

Chemical energy flows





Main features of the DME plants based on entrained flow gasification of torrefied biomass

- **High syngas to DME conversion** due to low content of inerts (CH_4, N_2 etc.) in the syngas (especially RC-plant). This was because of
  - Entrained flow gasification (no CH_4)
  - Oxygen-blown gasification (no N_2)

- **High total energy efficiency** due to a significant co-production of electricity. The electricity production was increased by having a highly integrated steam cycle (especially OT-plant)

- **Negative net CO_2 emissions** due to capture and storage of bio-CO_2
  - The CO_2 emissions were lowered even further by certain design changes (recycle of CO_2–rich mass flow, cooling the synthesis reactor product gas to capture CO_2 in the DME, increasing the H_2/CO ratio in the OT-plant)

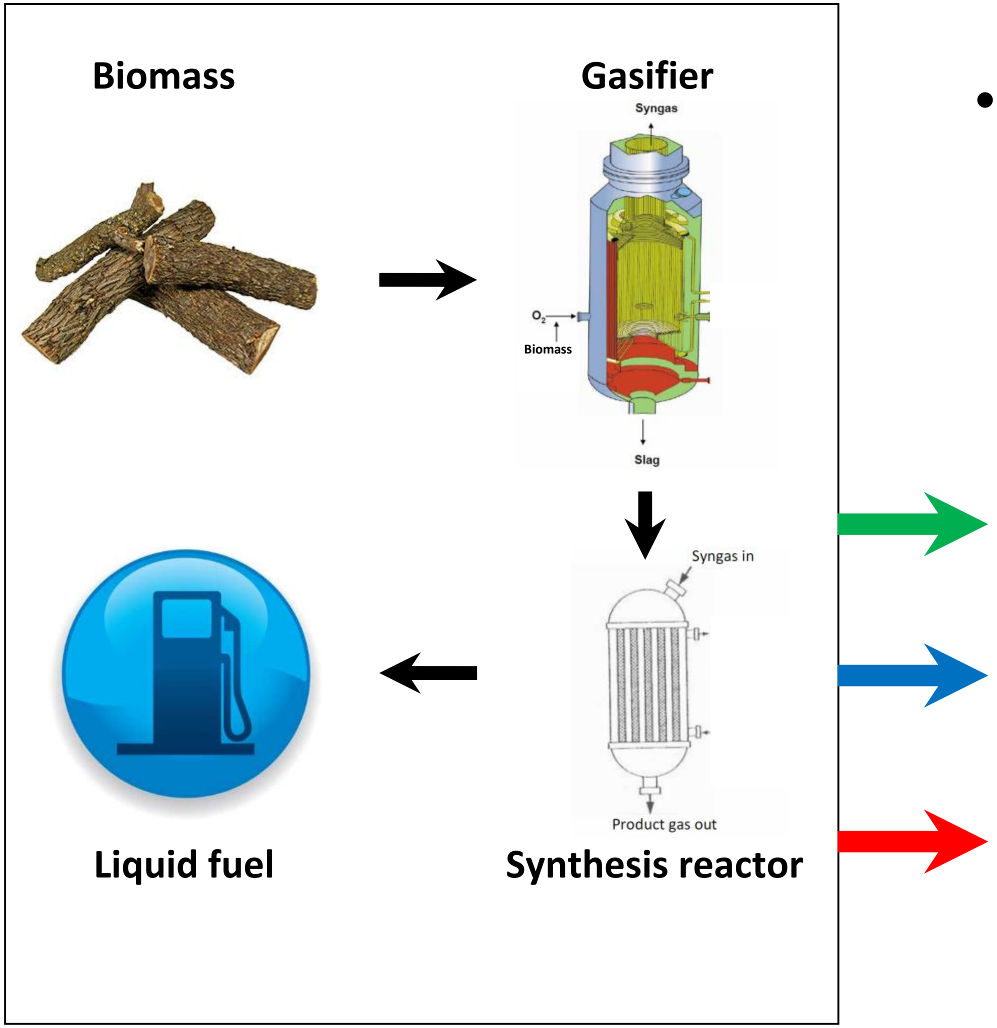
- **Low DME production cost**, especially if a credit is given for storing the bio-CO_2

Important aspects in the design of biofuel plants

		Pros	Cons
Gasification	Air	Low cost, simple design	N_2 in syngas $\Rightarrow$ lower conversion of syngas to fuel
	Oxygen	No N_2 in syngas $\Rightarrow$ higher conversion of syngas to fuel	Cost and electricity consumption of oxygen plant
	Atmospheric	Cost of gasifier, simple design	High electricity consumption for pressurization of syngas
	Pressurized	Low electricity consumption for pressurization of syngas	Cost of gasifier, complex design
Synthesis	Recycle of unconverted syngas (RC)	Higher conversion of syngas to fuel	Lower electricity co-production
	Once through synthesis (OT)	Higher electricity co-production	Lower conversion of syngas to fuel

Thermochemical biofuel production

Polygeneration



- The total efficiency of the BTL plant can be increased by co-production of:
  - Electricity
  - Heat
  - Biochar / bioash / fertilizer

Thermochemical biofuel production
Agenda

- Chemical synthesis
  - Synthesis of Dimethyl ether (DME), methanol, mixed alcohols Synthetic natural gas (methane), Fischer–Tropsch, synthetic gasoline, hydrogen

- Thermochemical biofuel production plants
  - The processes
  - Proposed plant designs
    - DME plant based on entrained flow gasification of torrefied biomass
  - Near commercial plants
  - Hurdles to overcome before biofuel plants are commercial

Near commercial plants

<u>Demonstration plants in operation:</u>

- The company Enerkem with one operating demonstration plant producing methanol/ethanol (28 MW) from waste. Several facilities planned

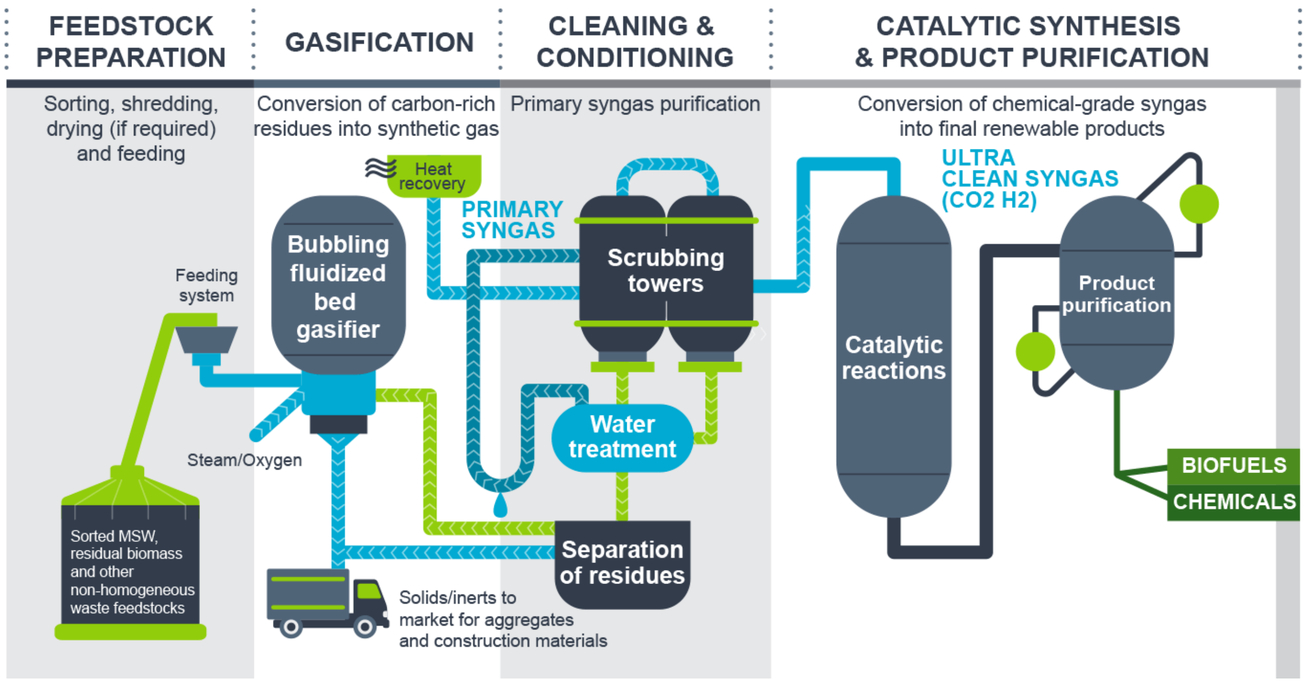
<u>Previous demonstartion plants:</u>

- GoBiGas in Sweden producing biomethane (SNG, 20 MW output)
- CHOREN in Germany producing Fischer-Tropsch diesel and gasoline (45 MW input)
- Chemrec in Sweden producing DME (3 MW input)

Gasification - Enerkem

Location: Edmonton, Canada
Type: single-line methanol-ethanol production commercial facility
Status: initiated production of methanol in 2015 and ethanol in 2017
Feedstock: post-sorted municipal solid waste (after recycling and composting)
Products: methanol, ethanol
Capacity: 38 million litres (0.9 PJ/y ethanol ~ 28 MW)

Gasification - Enerkem



Type: single-line methanol-ethanol production commercial facility
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Products: methanol, ethanol
Capacity: 38 million litres (0.9 PJ/y of ethanol ~ 28 MW of ethanol)

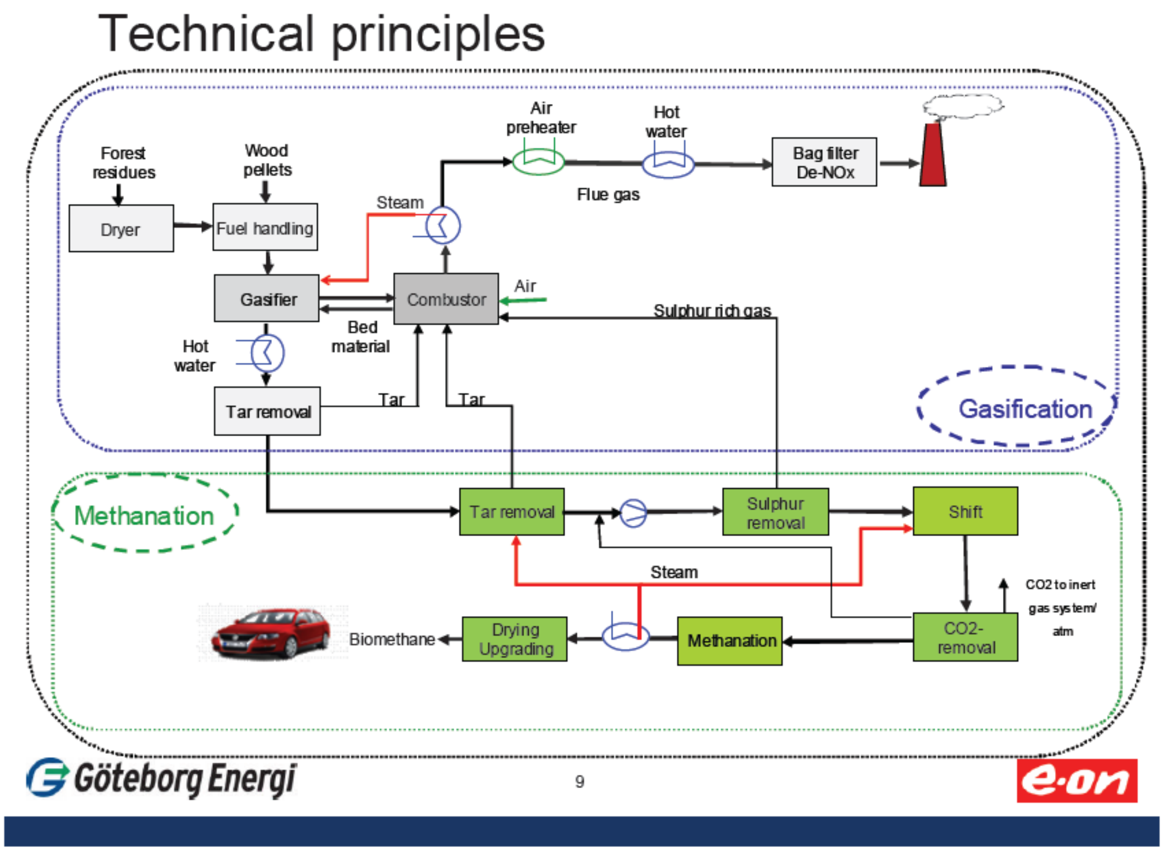
Gasification - Enerkem

New facilities

- Rotterdam: 270 M litres of methanol per year (= 9 PJ or about 156 MW).
  Pending final investment decision since 2019.
- Québec: half size as Rotterdam. Construction started
- $500 million secured investment for both facilities
- Tarragona, Spain: same size as Rotterdam. Pending final investment decision.
- Furthermore: $100million from Chinese partner with goal to build 100 plants in China

Near commercial plants

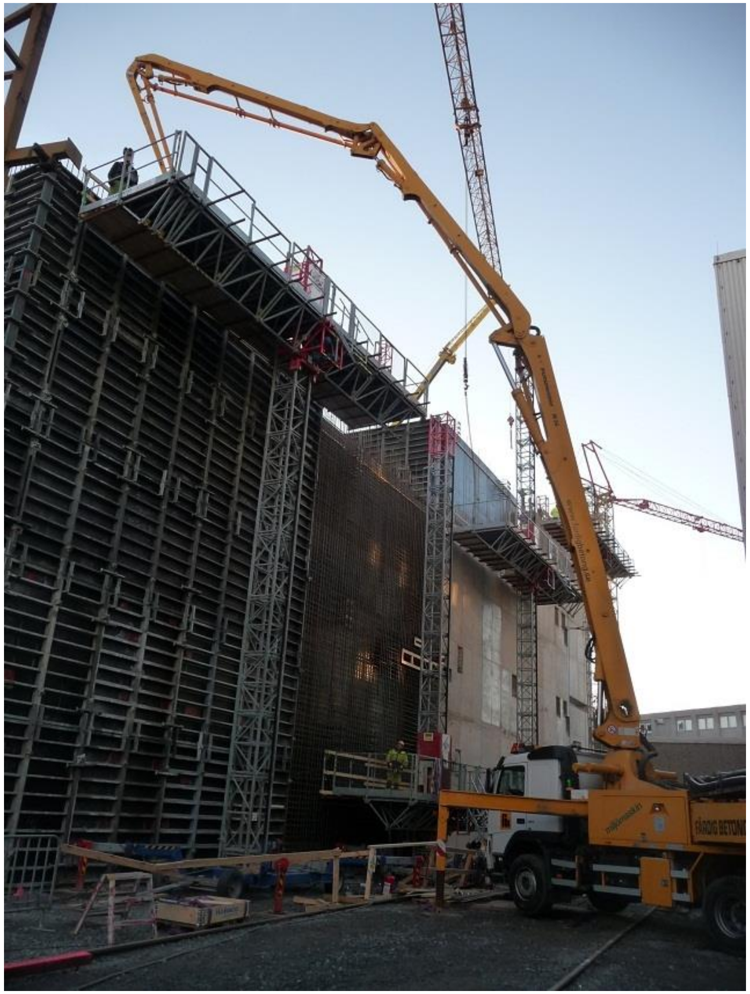
GoBiGas (Sweden)



- 32 MWth input of wood
- 20 MWth output of synthetic natural gas (methane)
- Inaugurated March 2014
- was one of the largest biomass to fuel plants in the world

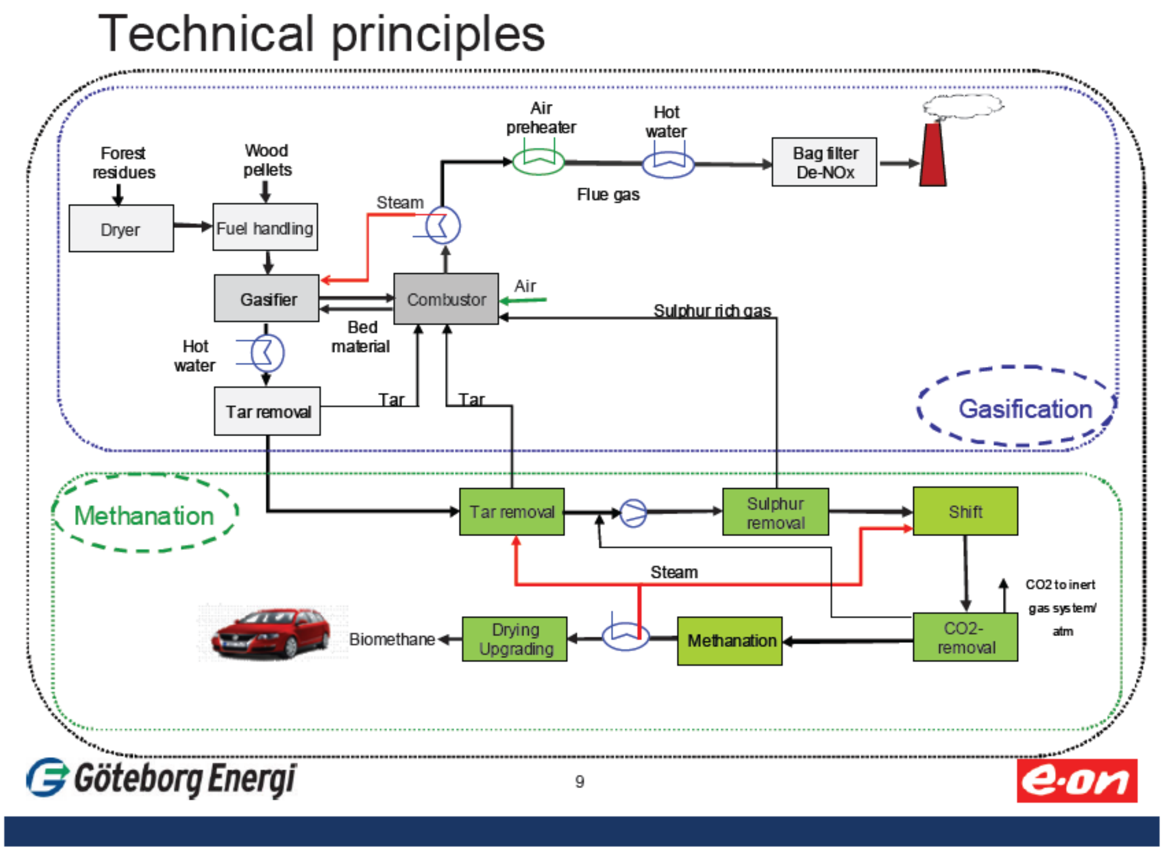
Near commercial plants

GoBiGas (Sweden)



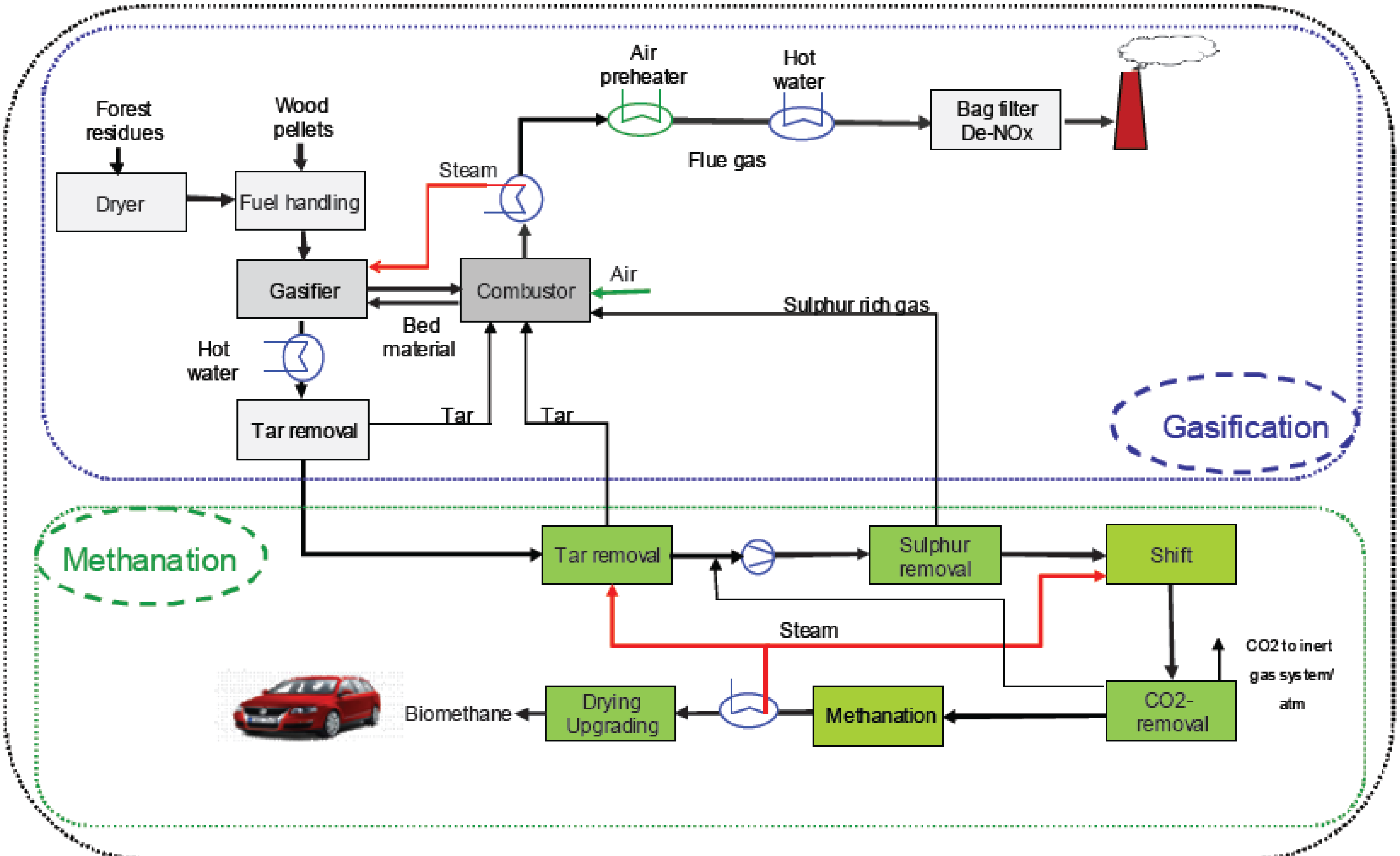
Near commercial plants

GoBiGas (Sweden)



- Based on technology from a demonstration plant in Austria (Güssing)
- Haldor Topsøe provides technology for the synthesis part

Technical principles



Göteborg Energi

e·on

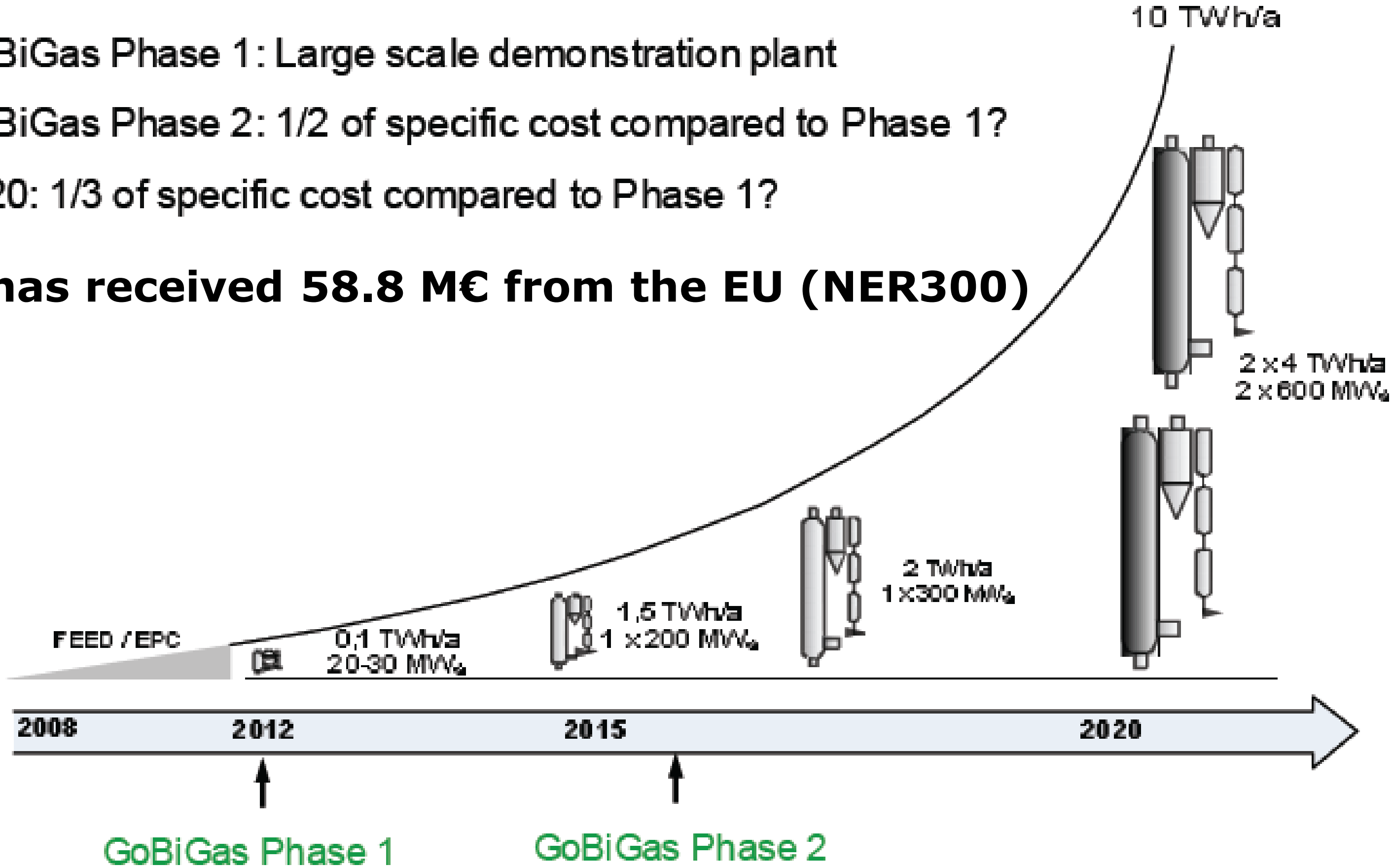
Commercial development of gasification technology in Sweden

GoBiGas Phase 1: Large scale demonstration plant

GoBiGas Phase 2: 1/2 of specific cost compared to Phase 1?

2020: 1/3 of specific cost compared to Phase 1?

Phase 2 has received 58.8 M€ from the EU (NER300)

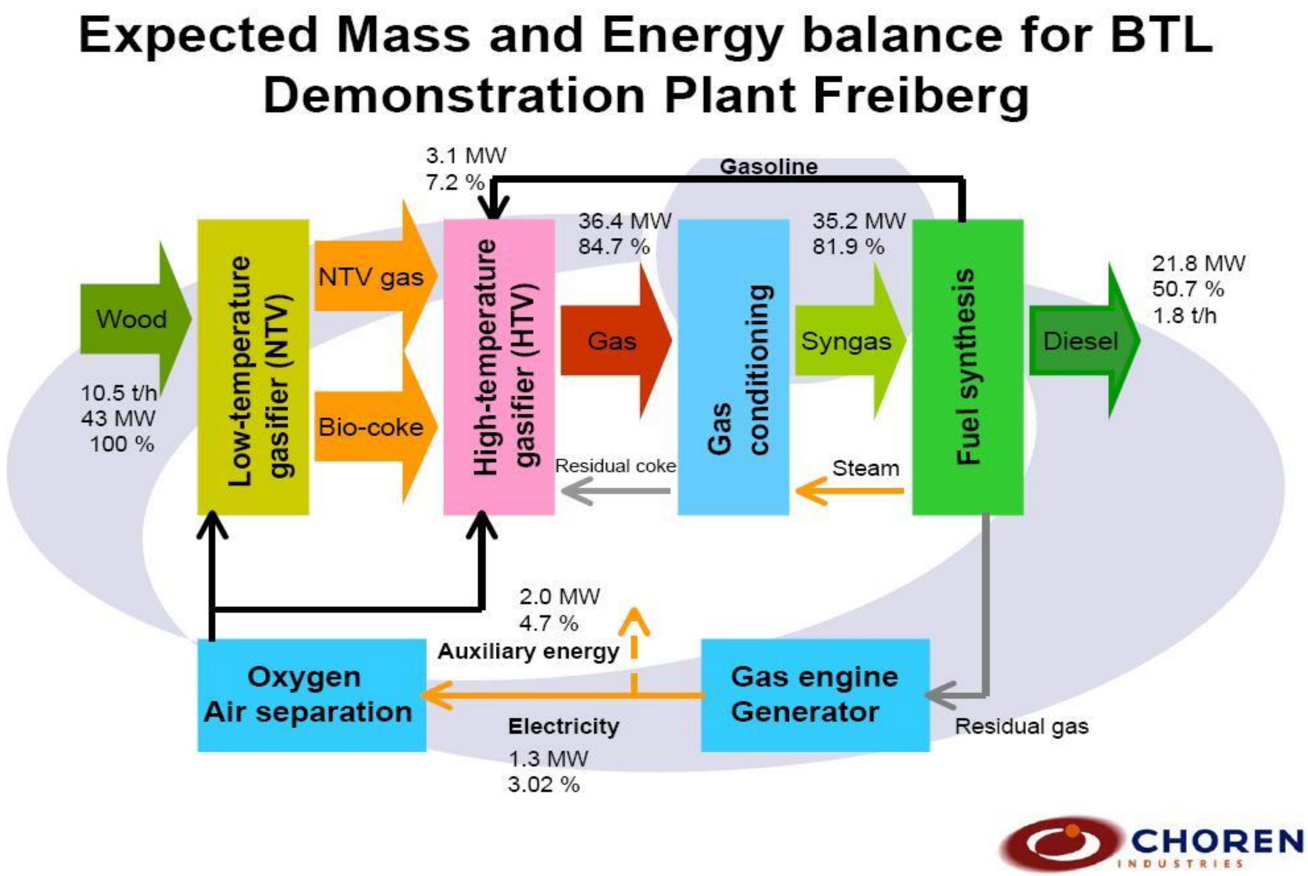


Göteborg Energi

e·on

Near commercial plants

CHOREN (Germany)



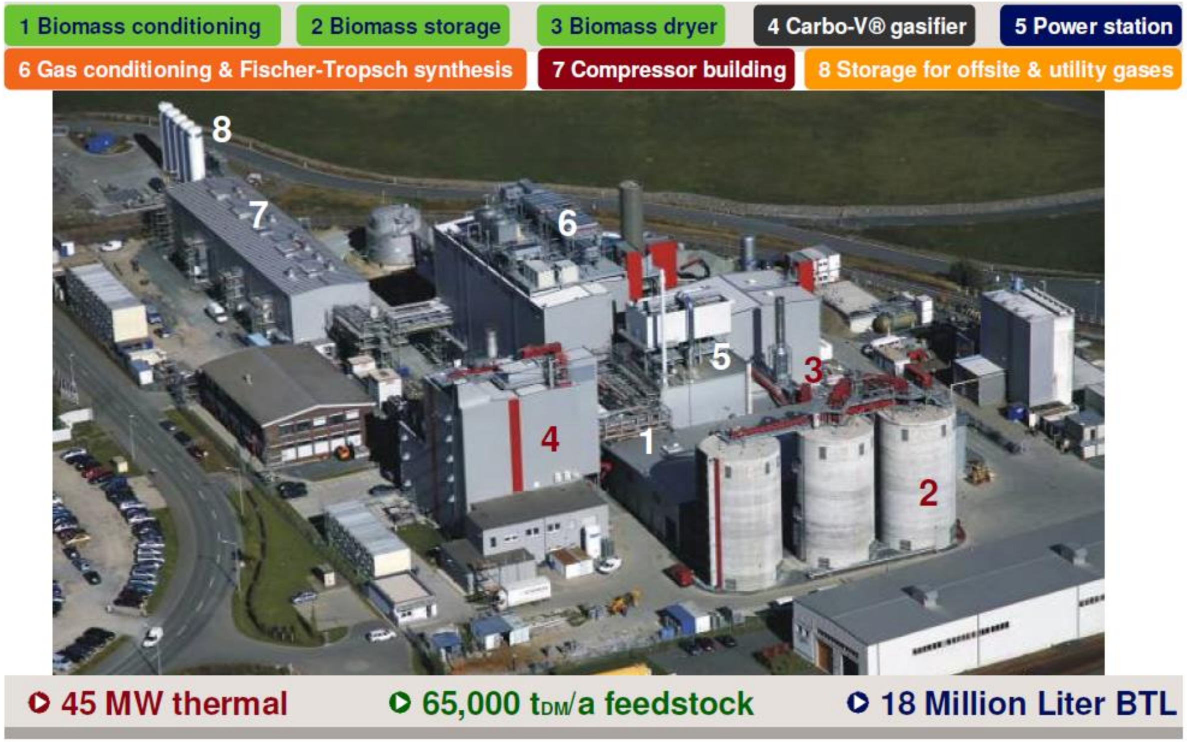
Near commercial plants

CHOREN (Germany)

Source:
www.choren.de

Near commercial plants

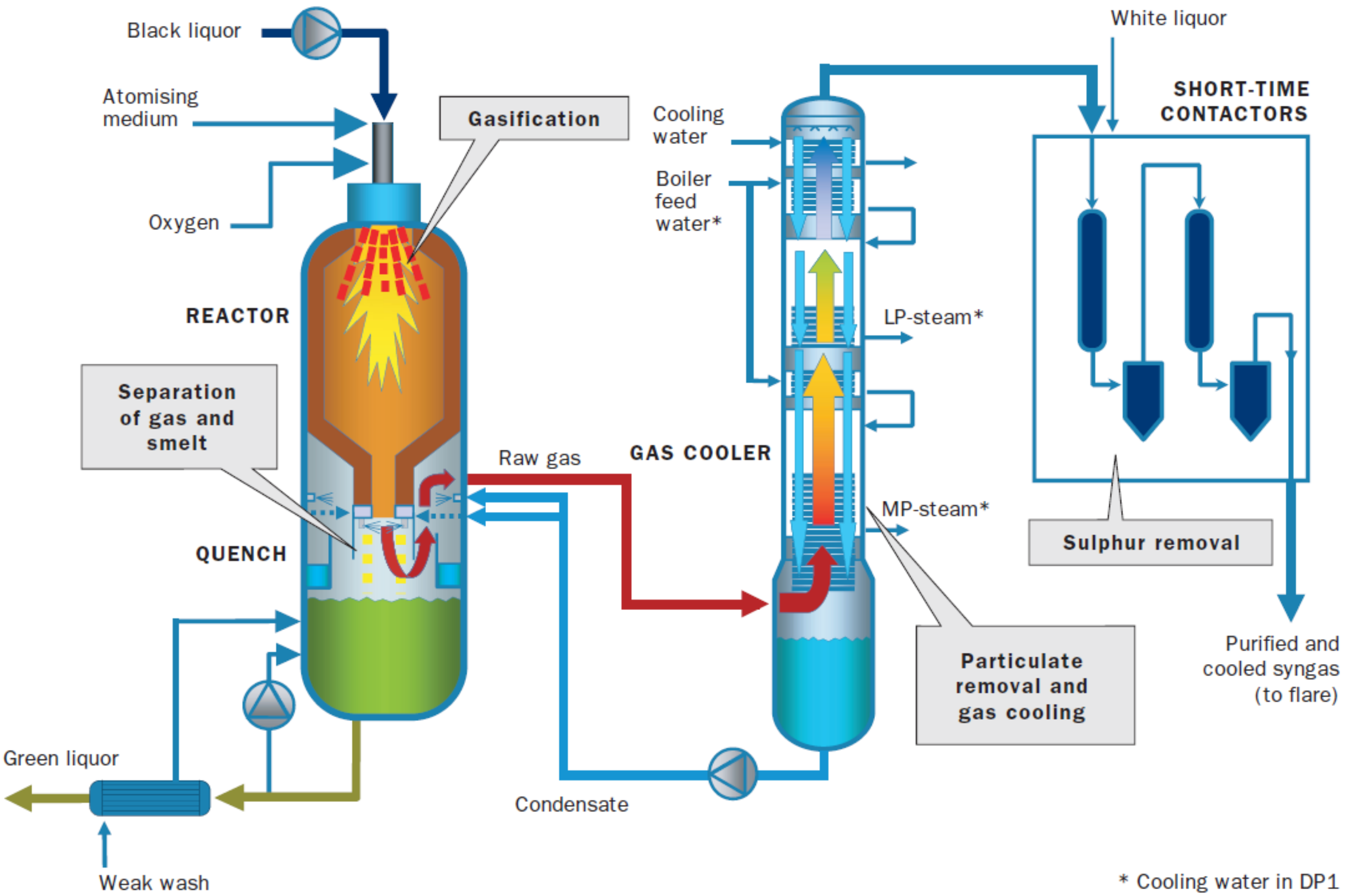
CHOREN (Germany)



- The technology is now owned by Linde Engineering
- The technology is planned to be used in a 480 MWth plant in Finland – the project is now on hold.

Near commercial plants

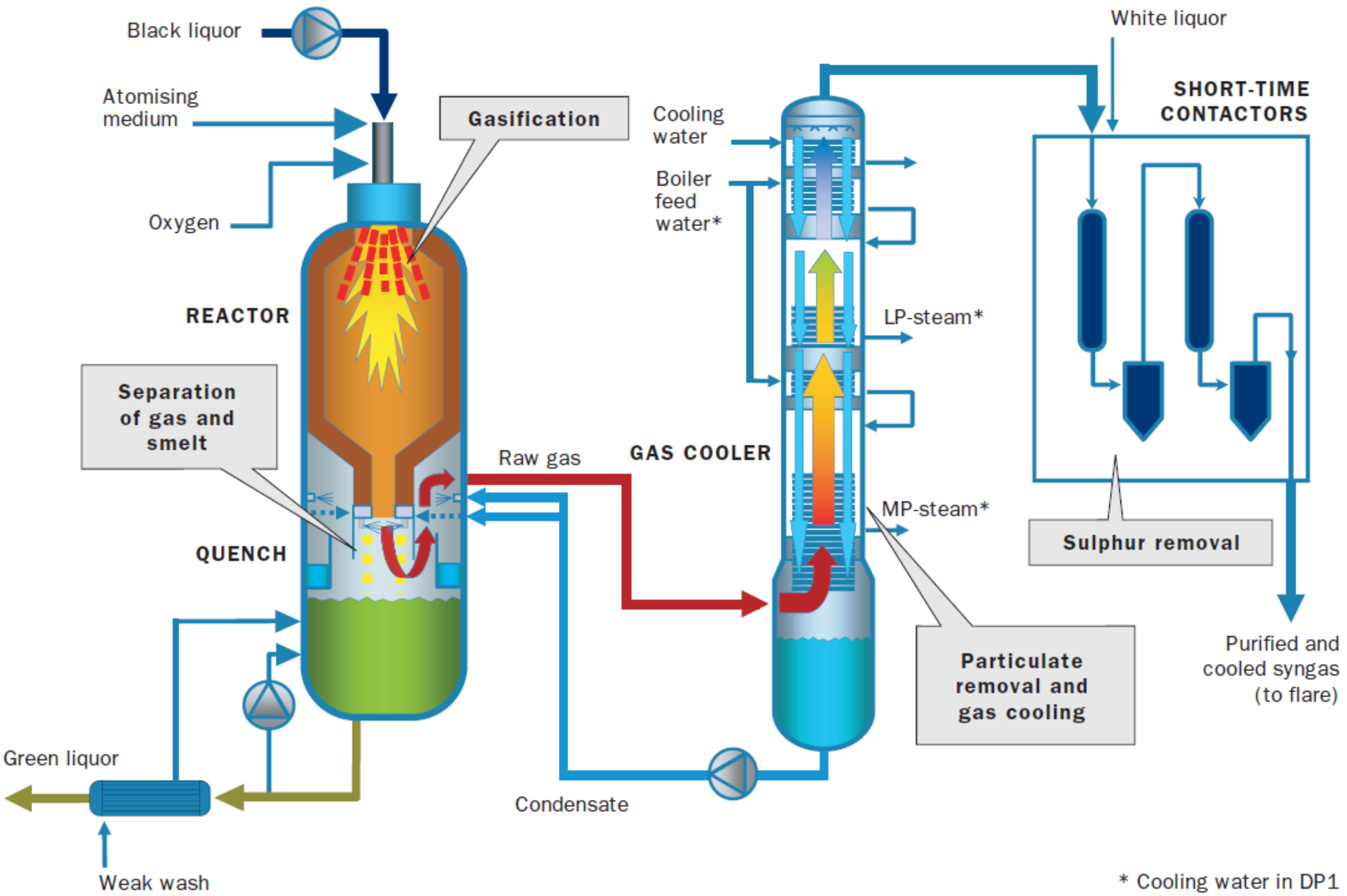
Plant based on the Chemrec gasifier (Sweden)



- Entrained flow gasification of black liquor
- Black liquor is a by-product from paper production
- A demonstration plant in Sweden has produced dimethyl ether (DME) based on the gas from this gasifier (3 MWth input)

Near commercial plants

Plant based on the Chemrec gasifier (Sweden)



- In April 2012, the company was ready to sell commercial plants together with a Chinese partner. Nothing has been sold.
- The company went bankrupt

Near commercial plants

Plant based on the Chemrec gasifier (Sweden)

- In April 2012, the company was ready to sell commercial plants together with a Chinese partner. Nothing has been sold.
- The company went bankrupt

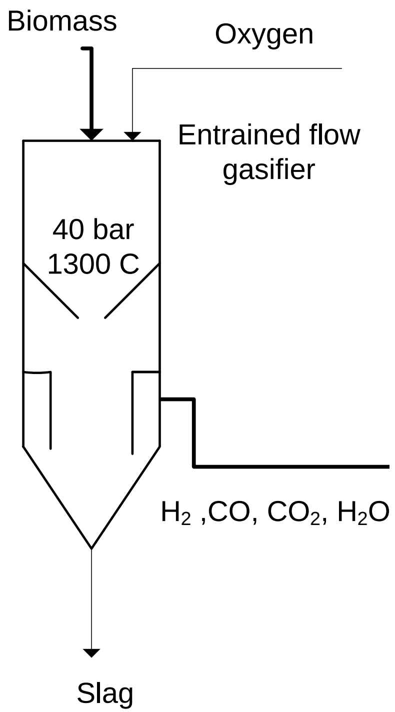
Hurdles to overcome before biofuel plants are commercial

- Economic
  - An incentive to produce green liquid fuels for the transportation sector is needed (EU). The current market is very small.
  - Competition with other green fuels.

- Technical
  - Upscaling the demonstrated small-scale gasifiers
  - Using wood on existing large-scale coal gasifiers
  - Efficient transport of biomass (many options: wood chips, wood pellets, torrefied wood pellets, pyrolysis oil)

- Environmental
  - The biomass used must be sustainable (not replace food/feed production, reduce net greenhouse gas emissions significantly compared to fossil alternatives, etc.)

Alternative thermochemical biofuel plants

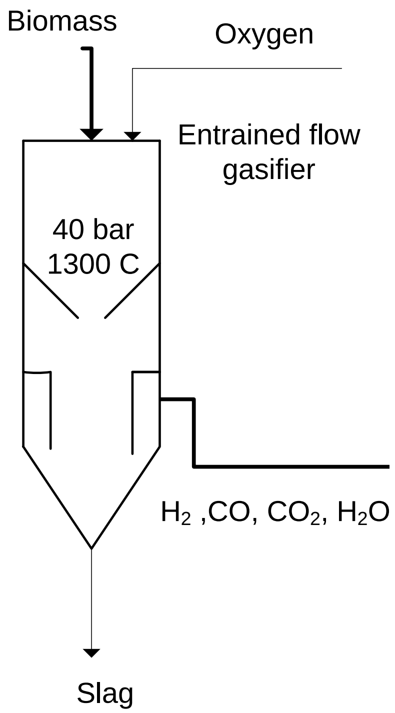


- **Typical gas composition (mol%):**
  26% H_2
  50% CO
  9% CO_2
  15% H_2O.

What can we do to make the syngas ready for methanol synthesis?

$H_2/CO = 2$ for methanol synthesis

Methanol plant integrating electrolysis of water



- **Typical gas composition (mol%):**
  26% H_2
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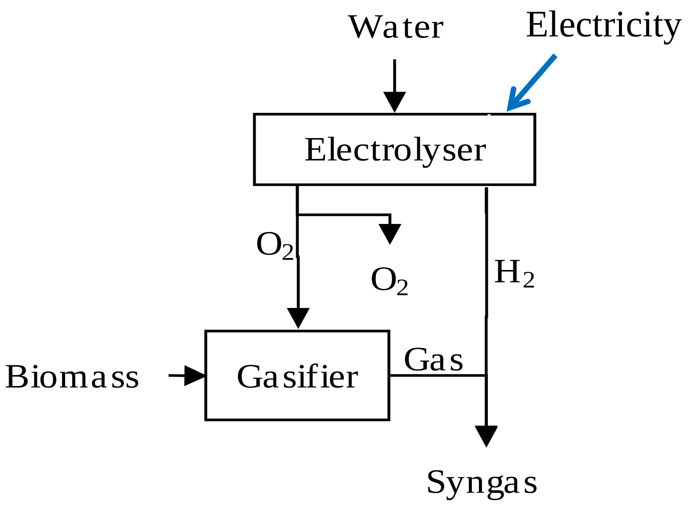


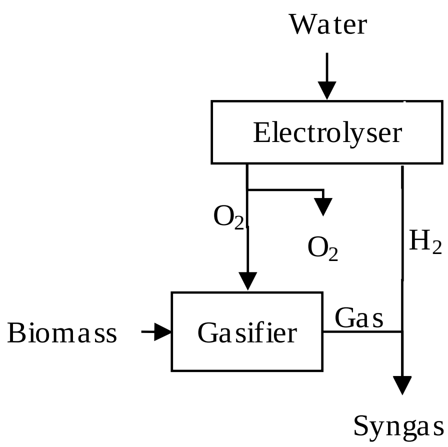
$$\frac{H_2 - CO_2}{CO + CO_2} = 2$$ for methanol synthesis

Thermochemical biofuel production

Exercise

By integrating electrolysis almost all the carbon in the biomass can be converted to fuel.

1. Calculate the potential output (kg) of methanol or CH_4 per kg of dry wood input.
2. Calculate the potential energy yield of methanol or CH_4 per energy input of dry wood.



Ultimate analysis of dry Wood (wt%): 47.2% C, 6.1% H, 45.1% O, 0.3% N, 0.02% S, 1.3% ash.

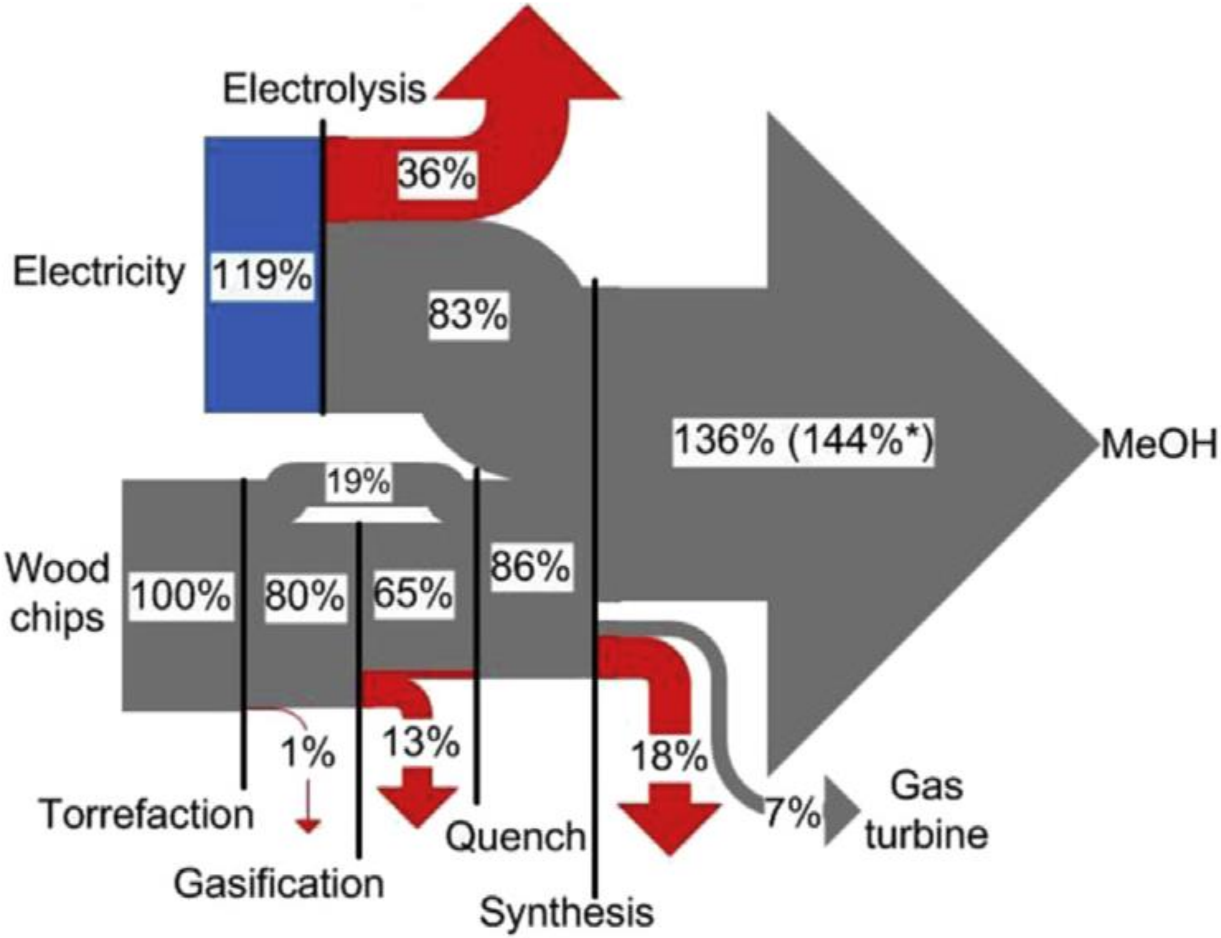
<u>Heating values:</u>

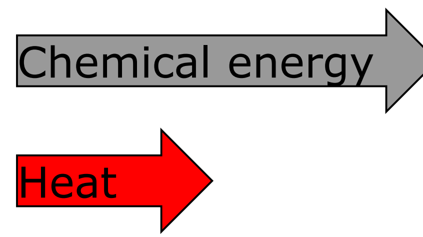
Wood (dry): 17.6 MJ/kg

CH_4 : 802.3 MJ/kmol

CH_3OH (Methanol): 638 MJ/kmol

Methanol plant integrating electrolysis of water

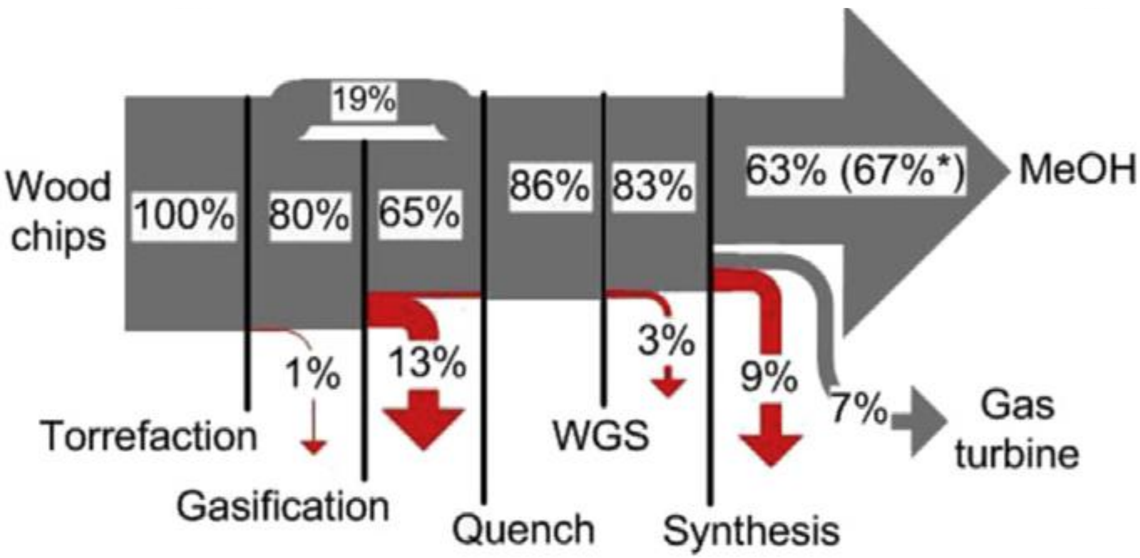


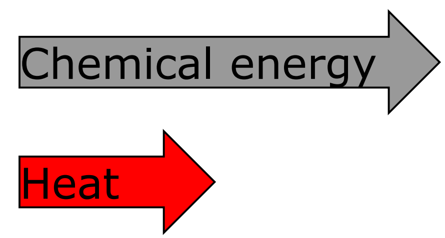


Energy efficiency: 62% (wood + electricity → methanol)

Energy efficiency with SOEC electrolysis (92% efficiency): 72%

Methanol plant without electrolysis of water



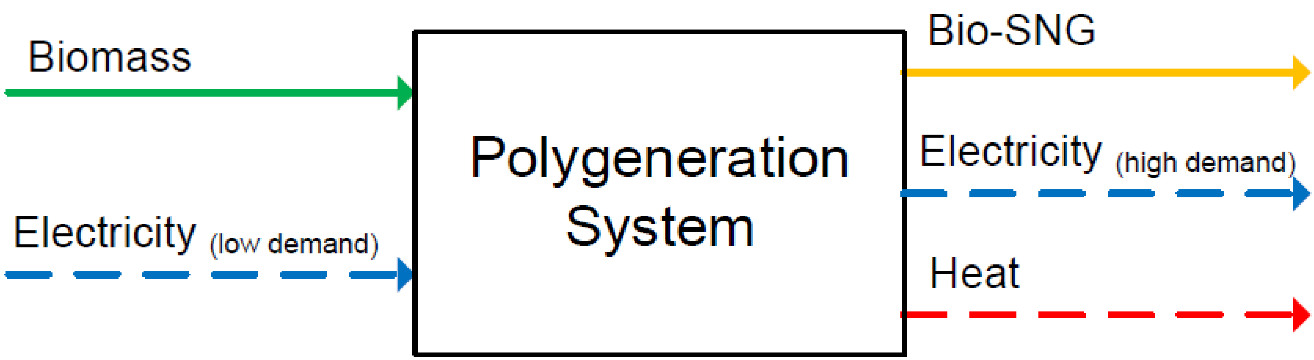


Main features of the methanol plant integrating electrolysis of water

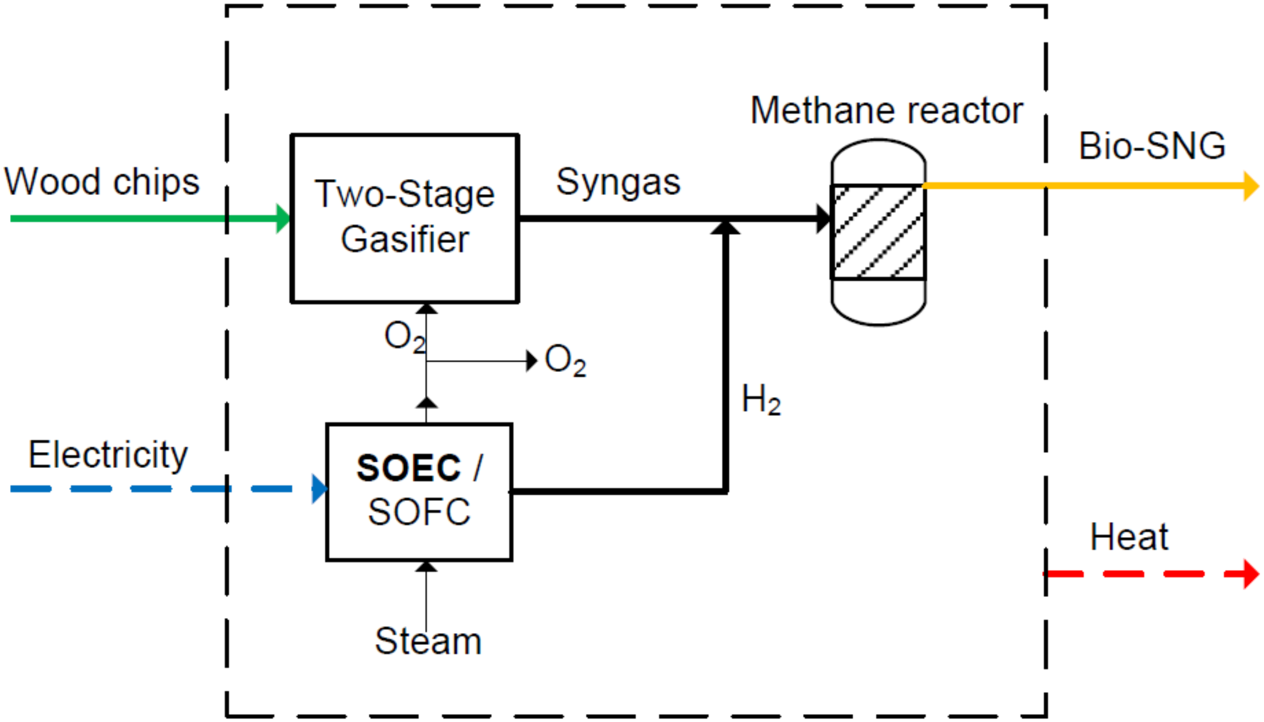
- Twice as high fuel output per biomass input compared to the DME plant based on entrained flow gasification of torrefied biomass
- Almost no CO_2 emission because almost all the carbon in the biomass is converted to a liquid fuel
- Can store surplus electricity from renewables (wind, solar)

Remaining slides if time allows

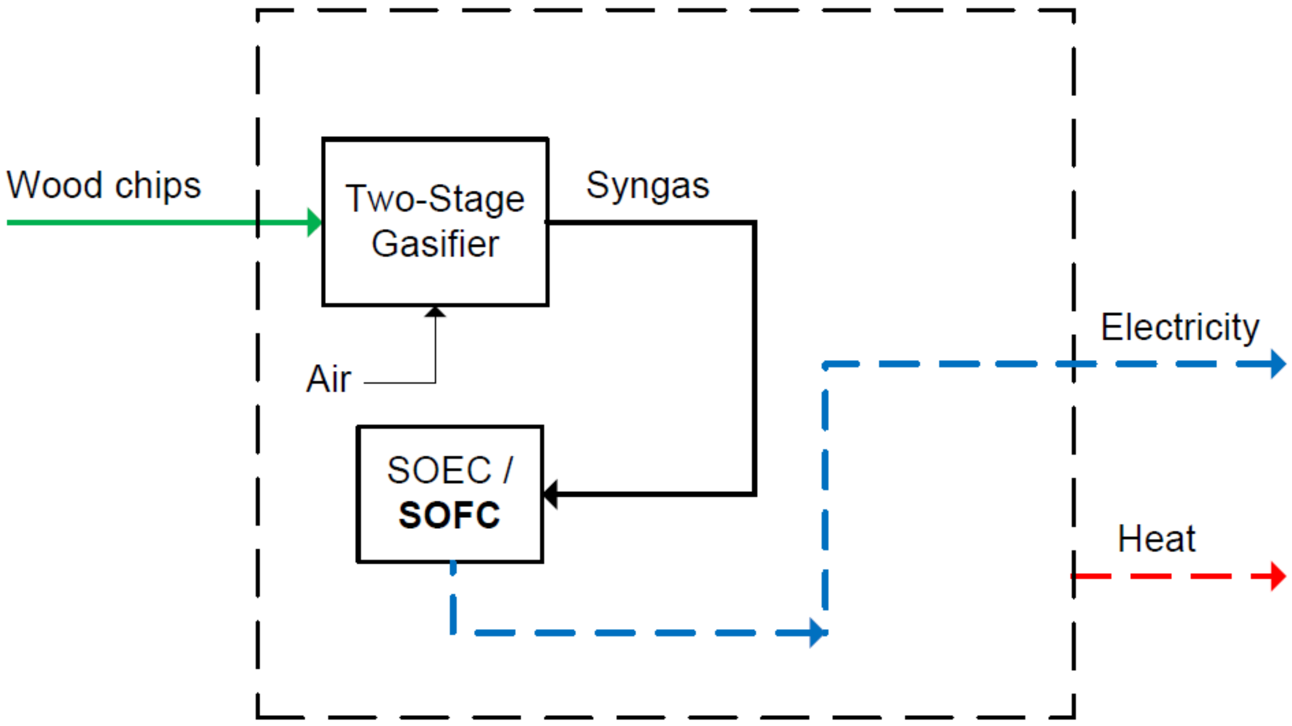
Polygeneration of heat, power and bio-SNG based on the Two-Stage Gasifier



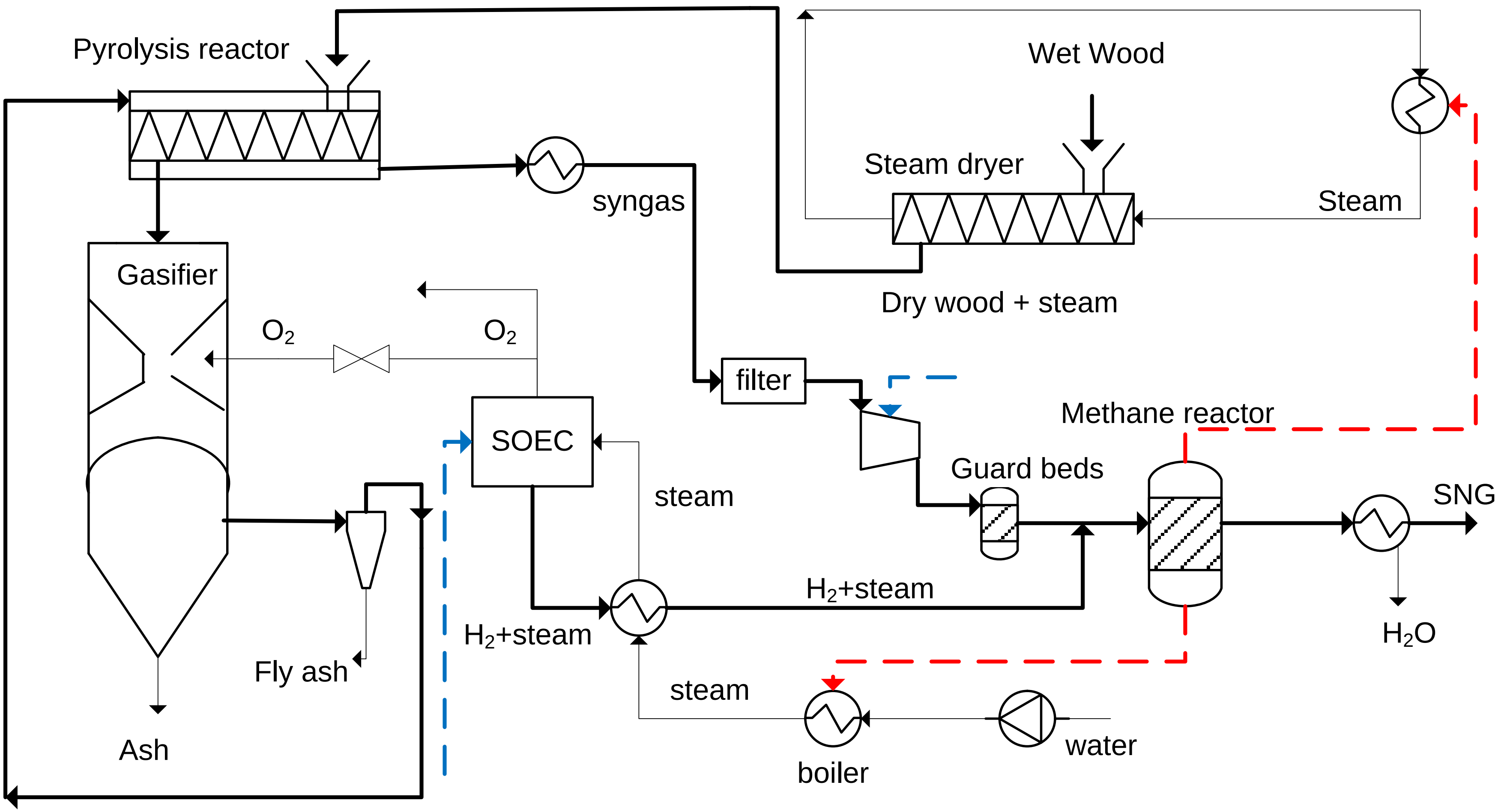
Plant in electricity storage mode



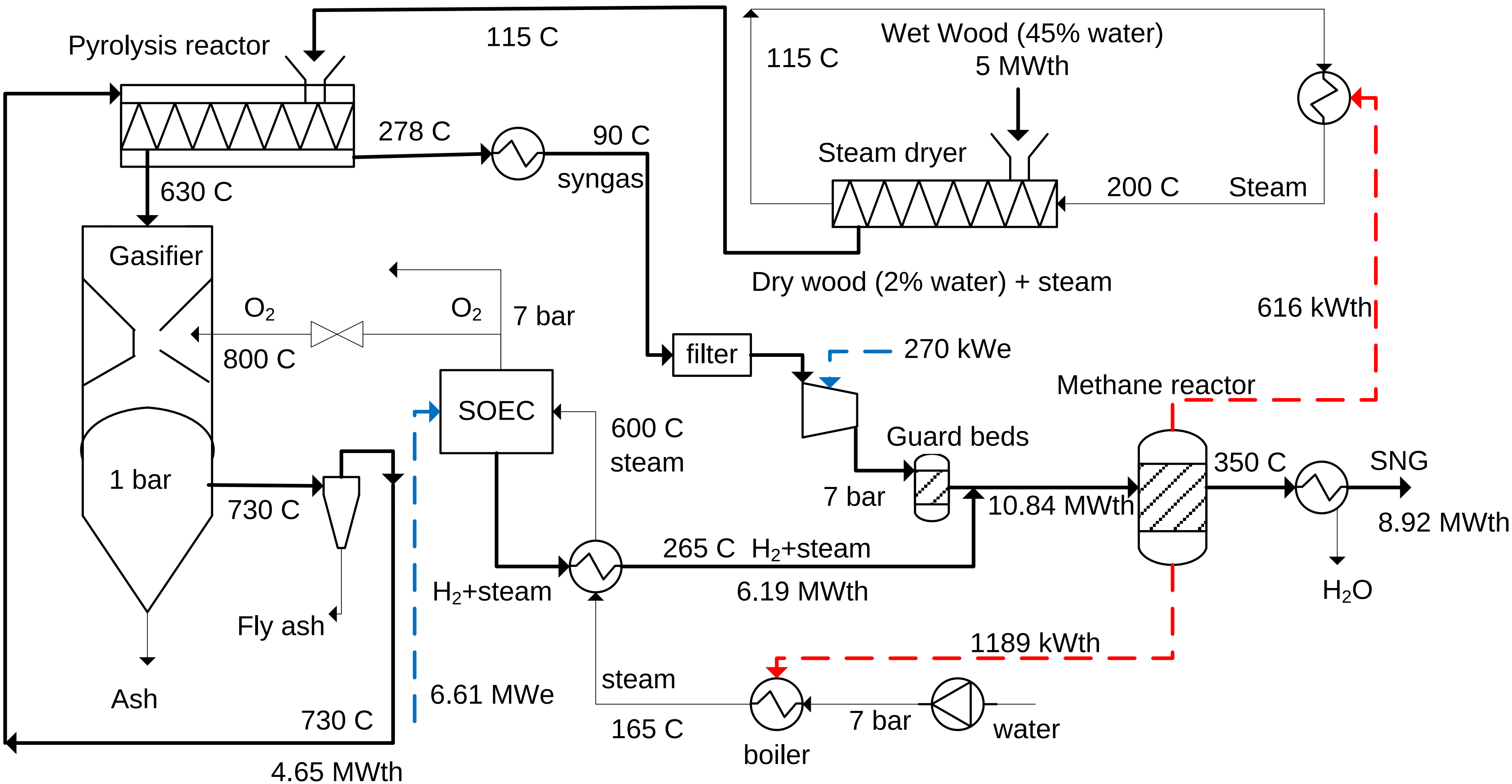
Plant in electricity production mode



Plant in electricity storage mode



Plant in electricity storage mode



Hydropyrolysis
The IH² system from GTI in Chicago

Figure 8—IH² Liquid Product from Wood -Top phase hydrocarbon, bottom phase water

Figure 9—Pyrolysis Oil – Picture from Ensyn Website

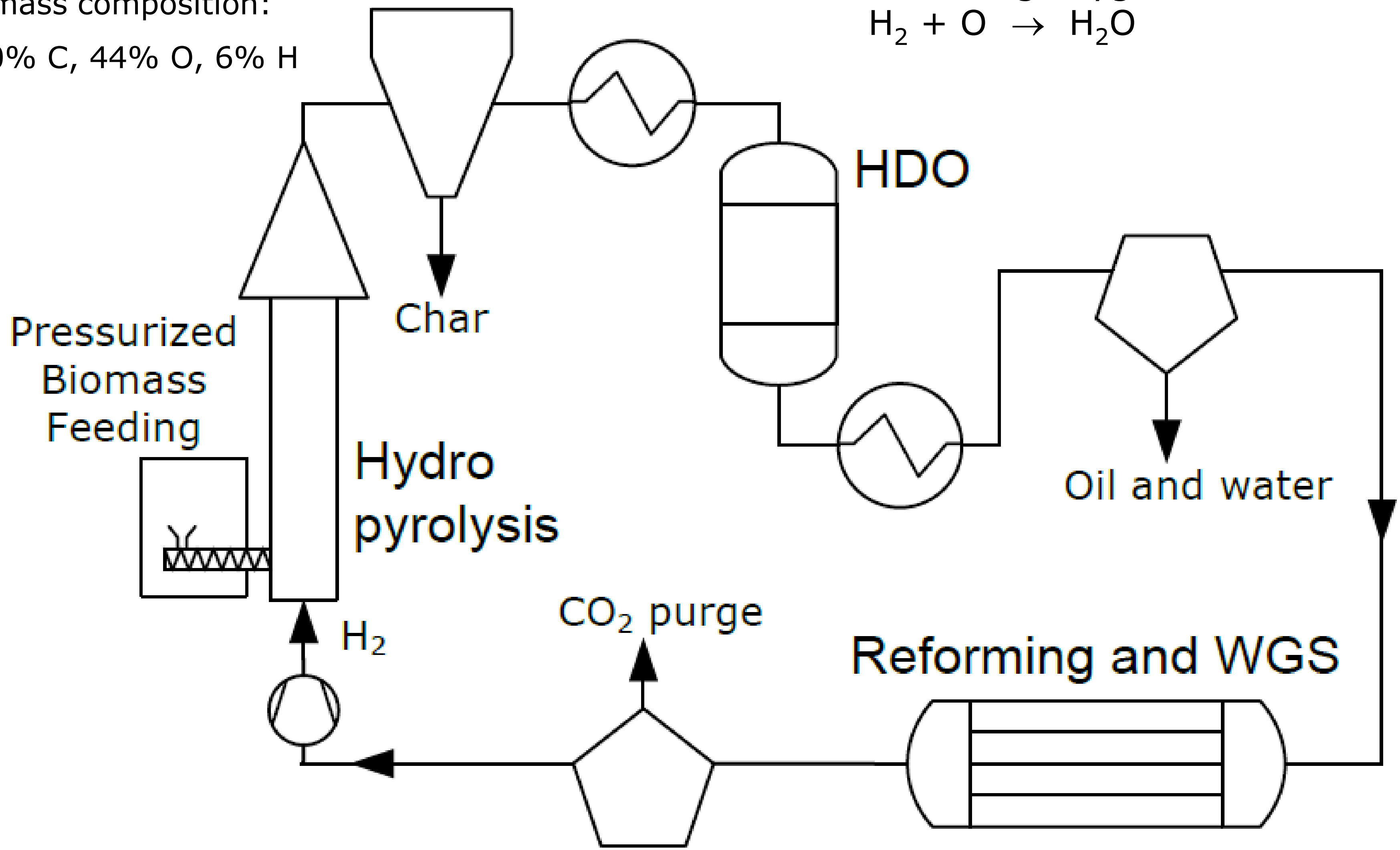
Hydropyrolysis

Biomass composition:

~50% C, 44% O, 6% H

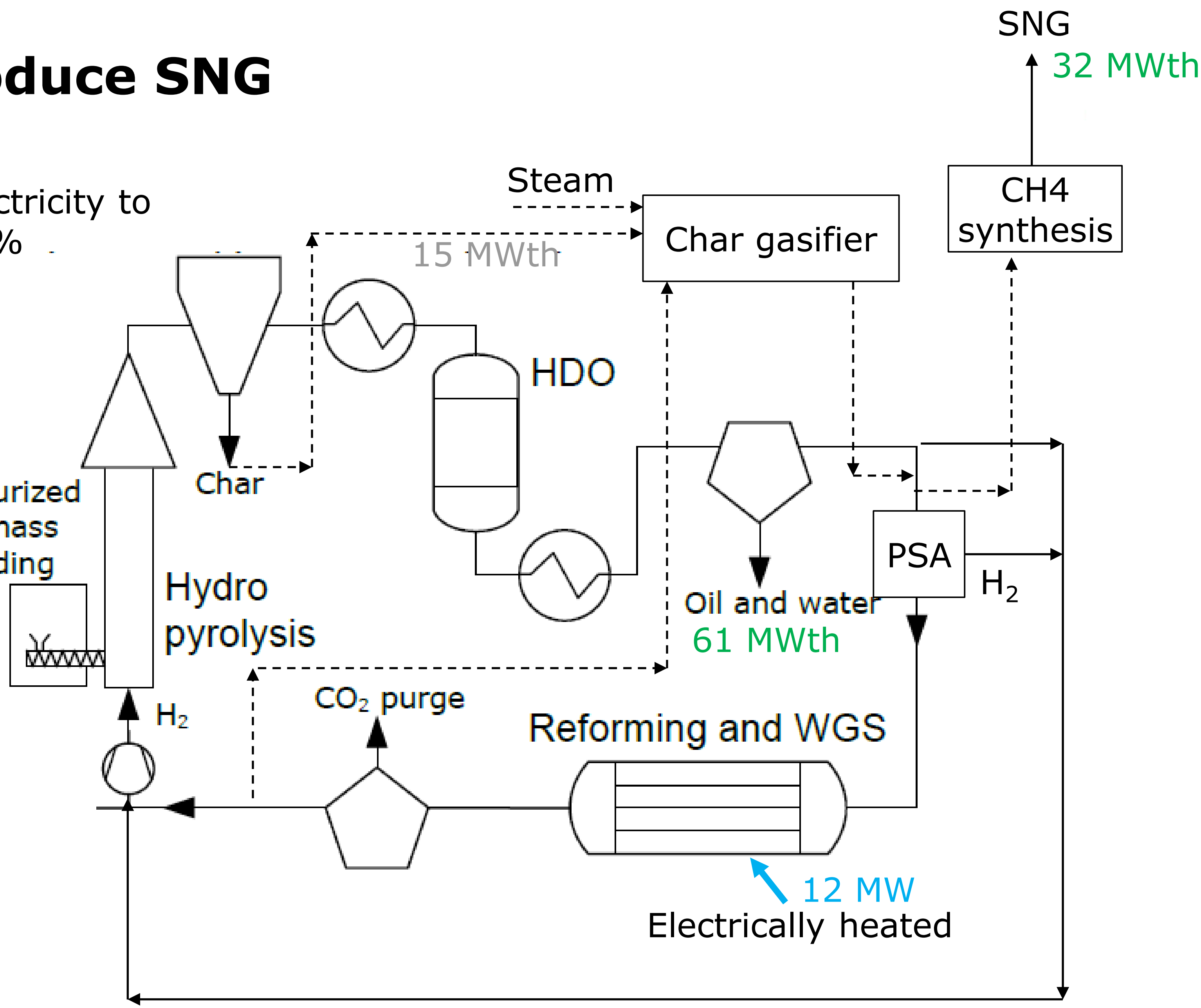
Removing oxygen from volatiles:

$H_2 + O \rightarrow H_2O$



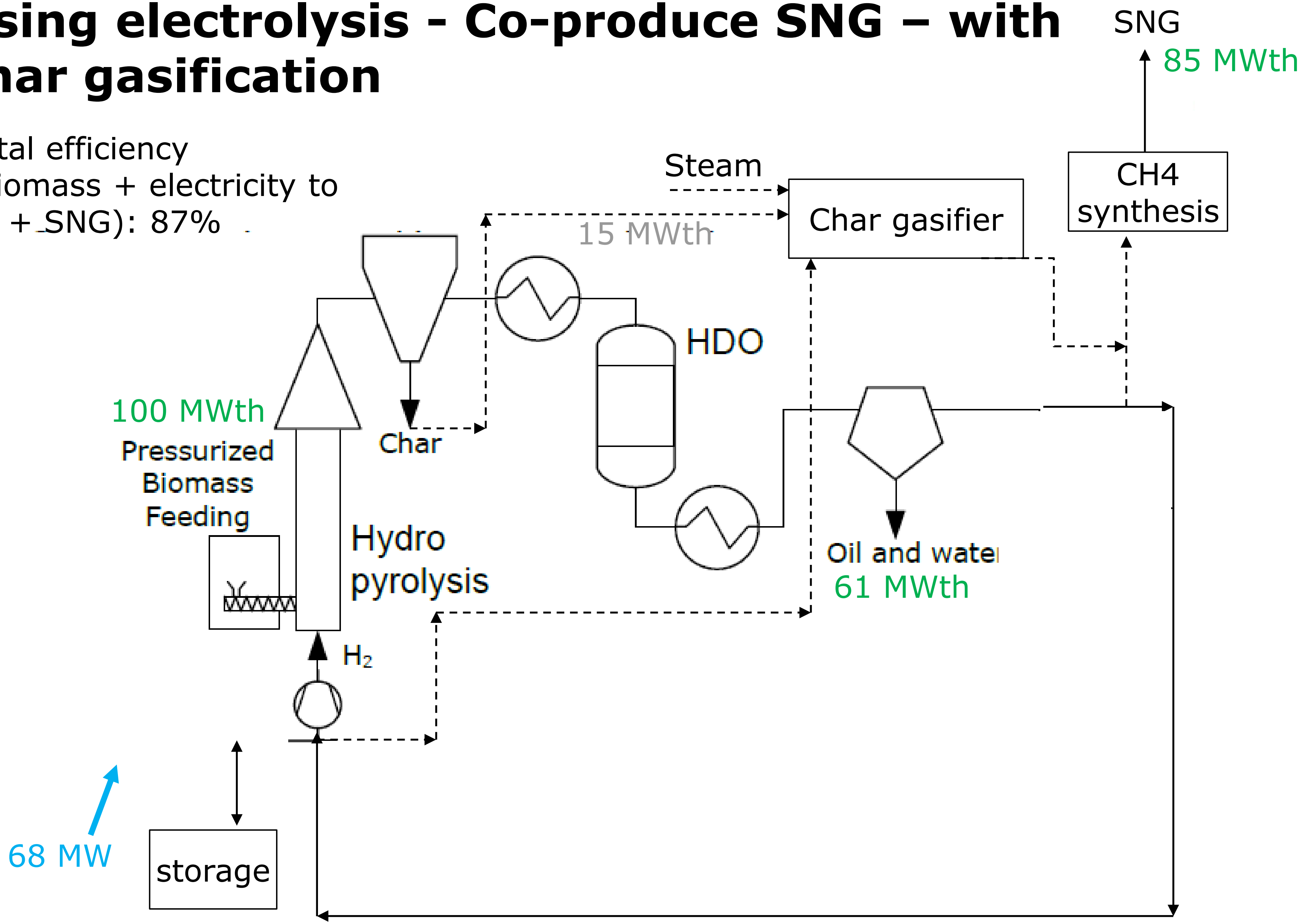
Co-produce SNG

Total efficiency (biomass + electricity to oil + SNG): 83%

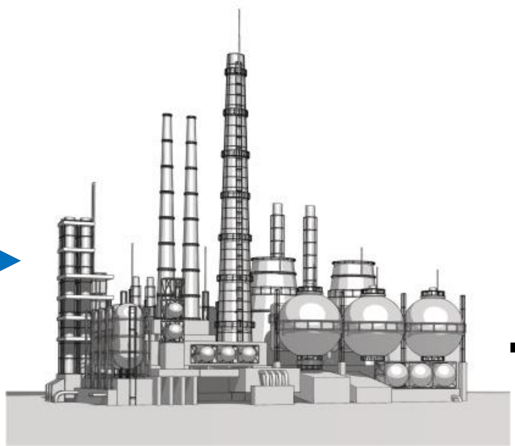


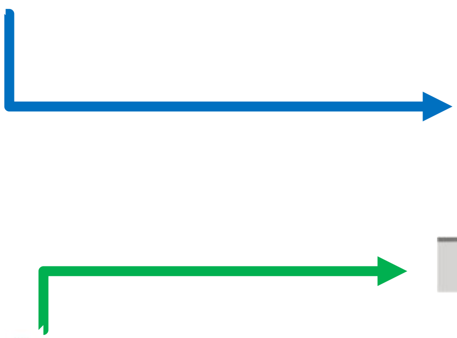
Using electrolysis - Co-produce SNG – with char gasification

Total efficiency (biomass + electricity to oil + SNG): 87%



Thermochemical biorefinery

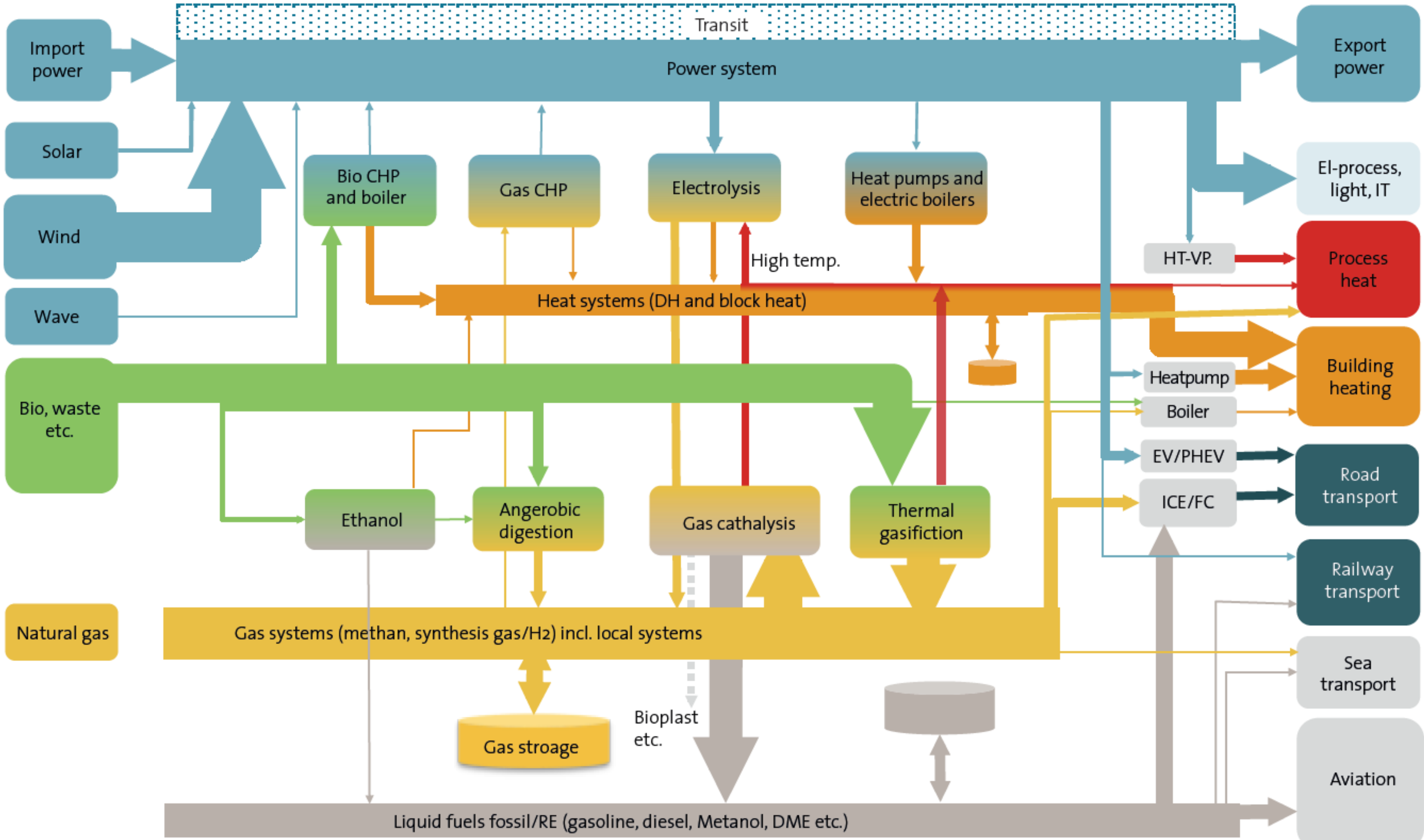




- Oil
- SNG
- H_2
- methanol

Pyrolysis oil or pyrolysis gas made from high ash biomasses such as straw

Energy system scenario (2050)



- Process integration between “thermal gasification” “gas catalysis” and “electrolysis” is very important to ensure efficient conversion.

- Coupling also with “CHP” production can give efficient and flexible polygeneration systems