RE2 – Optimization of Bioenergy Use GASIFICATION basics

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Research in gasification
Presentor's experience

- 1989-1995 Tampella Power Inc. and Enviropower Inc.
  - 15 MW_{th} pilot plant testing of coal gasification and gas cleanup
    - **Successful demonstration of the regenerative sulfur removal process**
  - 20 MW_{th} pilot plant testing of woody biomass gasification and gas cleanup
  - Engineering work for commercial-scale IGCC demonstration projects (USA: Clean Coal program, Finland: Summan voima)
- 1996-2006 Carbona Inc., (1999-2006 as consultant)
  - 20 MW_{th} pilot plant testing, result analysis and reporting of alfalfa gasification
  - **Engineering work for gasification plants (IGCC, Skive plant). Developing computer models and design tools.**
- 1999-2006 Åbo Akademi University
  - 2002-2004 research program called "Peruskaasu"
    - **Developing a gasification reactor simulation tool called "Carbon conversion predictor"**
    - Estimating the fate of heavy metals in gasification and gas cleanup processes
    - Fate of fuel nitrogen in combustion of product gas
- 2007-2008 Carbona Inc.
  - **UPM/Andritz/Carbona BTL-development project**
    - **Gasification and gas cleanup engineering calculations**
    - **Participation in the laboratory- and pilot-scale test run program in USA**
  - Engineering calculations and data estimation for commercial gasification plants (Skive, lime kiln gasification)
  - Participation in the board of the gasification R&D project for syngas production and cleanup, coordinated by VTT
- 2009 – Professor at the University of Jyväskylä
  - **Gasification reactivity GASIFREAC**, 2011-2014 , funded by Academy of Finland (partners VTT, ÅAU)
  - Modeling and pilot-scale testing of fixed-bed gasification, **HighBio2**, 2011 – 2013 (partners Kokkola Chydenius-centre, Luleå Technical University)
  - Consultant (Carbona Oy, Gasek Oy)

Gasification basics - CONTENTS

- Basic principles of gasification
  - Idea & opportunities
  - Gasification reactions
  - Gasification reactors
  - Gas cleaning
- Biomass-based Gasification applications for power & heat
  - IGCC
  - CHP plants
  - Lime kiln gasifiers
- Biorefineries based on gasification

Introduction

- The production of gaseous hydrogen (H_2) or a so called synthetic gas (syngas) – a mixture of H_2 and carbon monoxide (CO) – via gasification has been known technology since WW II
  - → Shortage of transport fuels: preparation of liquid fuels out of solid brown coal or coal (Germany, South Africa)

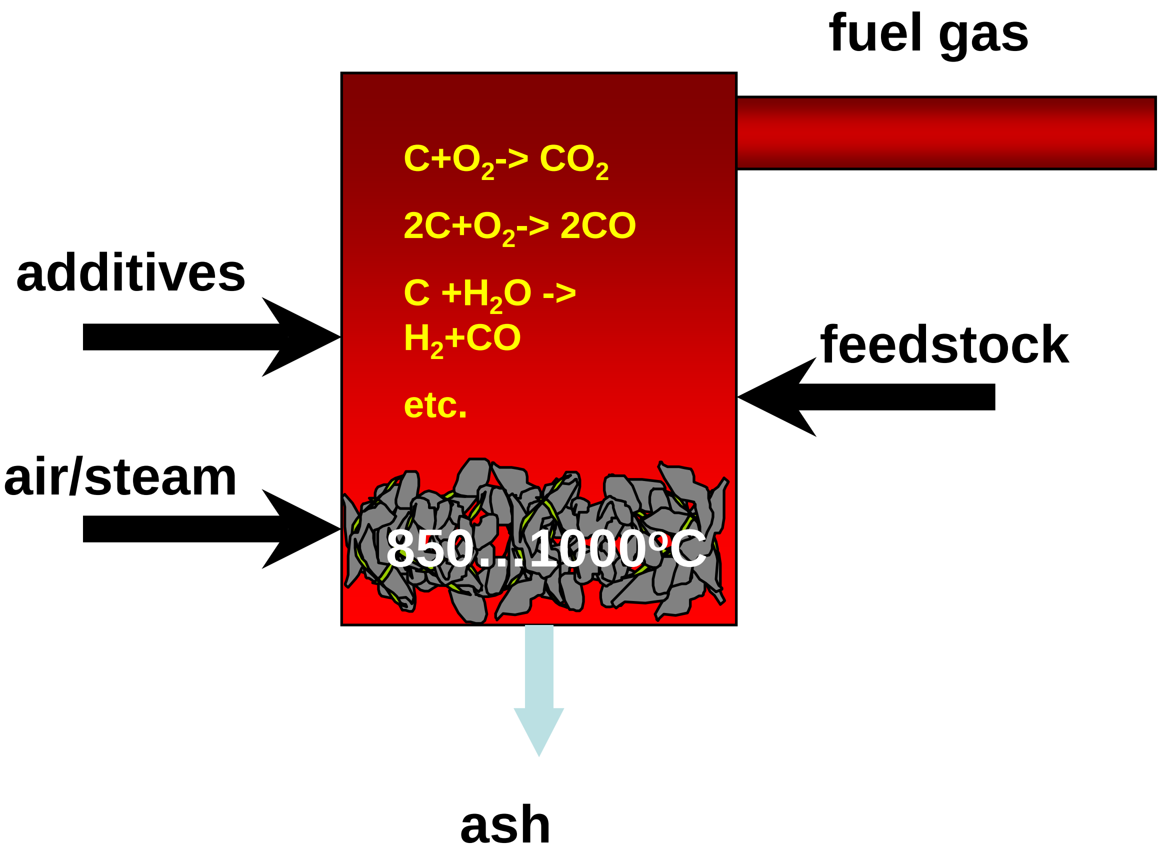
- Wood gas-fuelled cars – example application of Finland

- Fuel is combusted with substoichiometric oxygen (oxygen 30 – 50 % of the amount required for complete combustion)

THERMOCHEMICAL processing of solid (or liquid) fuel

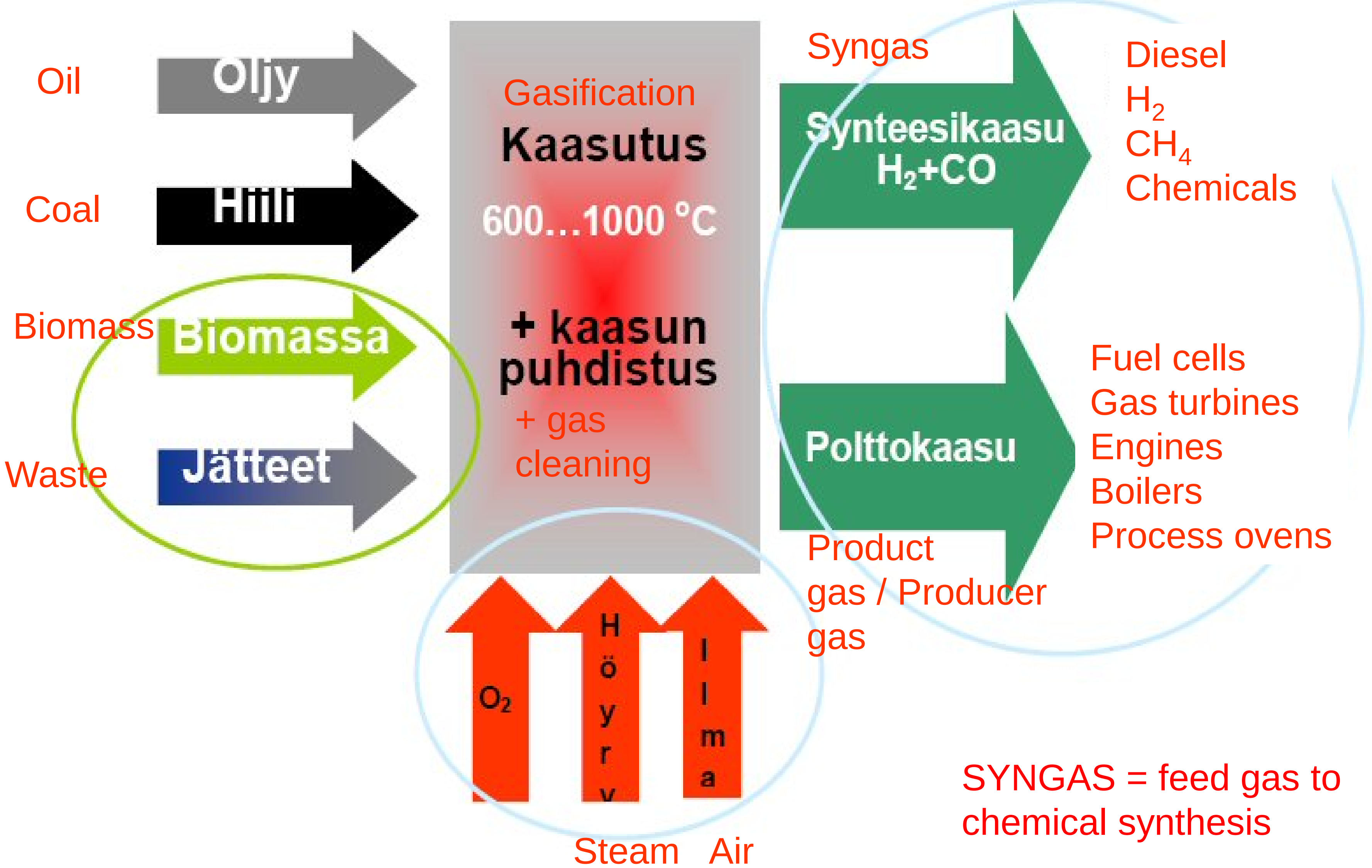
GASIFICATION

Gasification is an endothermic thermal conversion technology where a solid fuel is converted into a combustible gas.



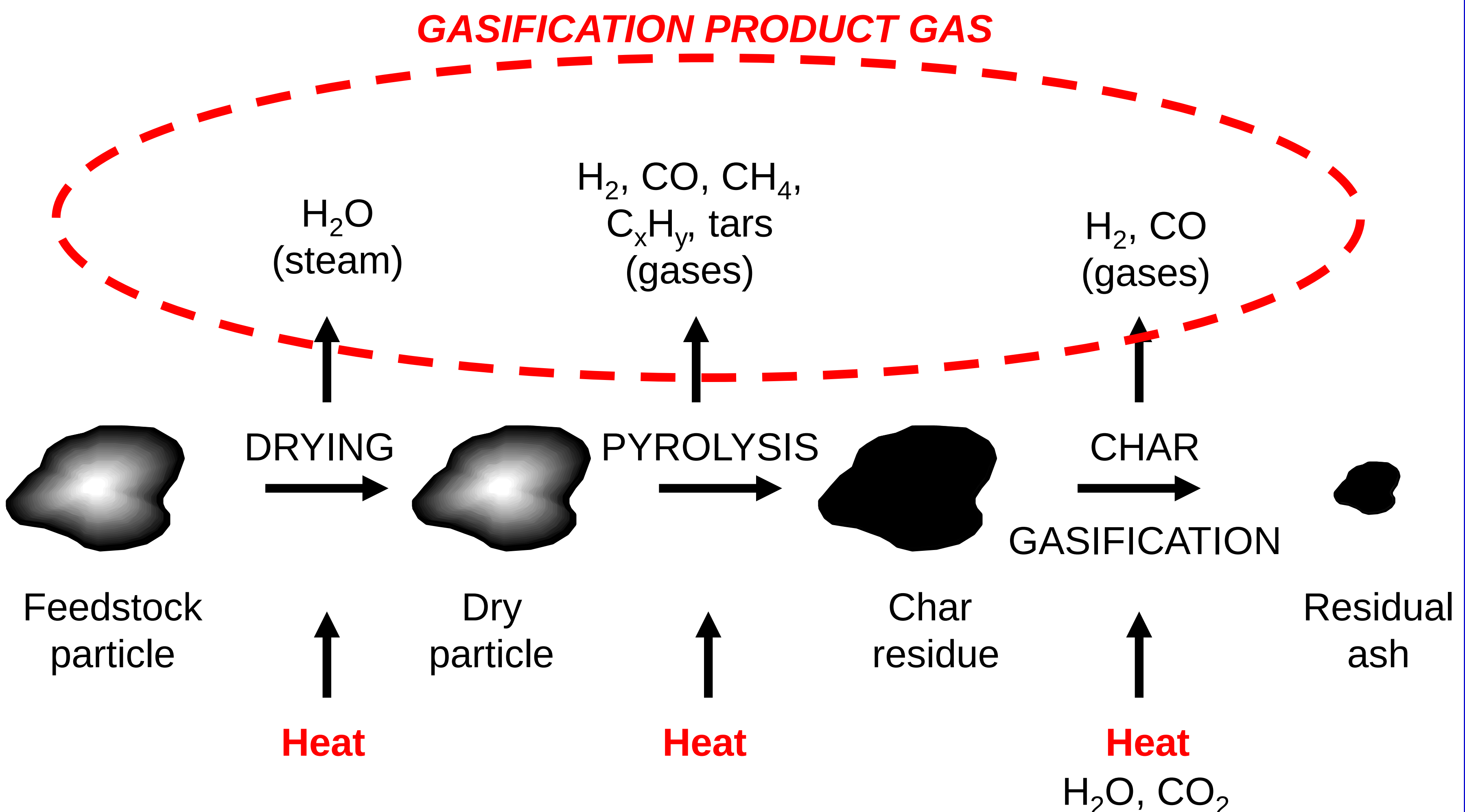
BIOMASSAN KAASUTUSTEKNIIKAN SOVELLUKSET

APPLICATIONS OF BIOMASS GASIFICATION



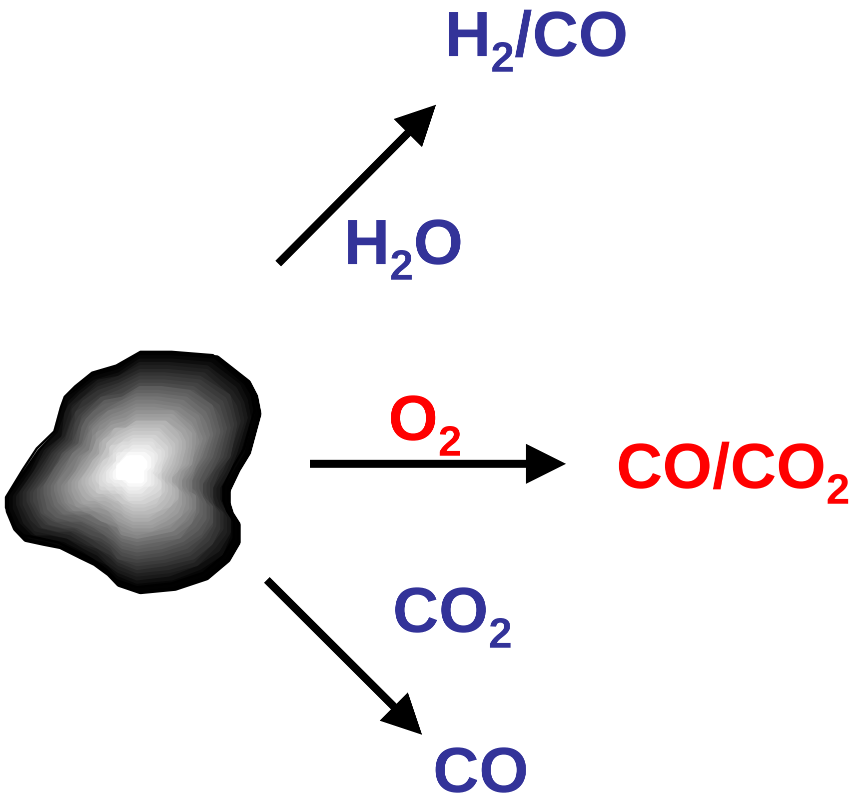
SYNGAS = feed gas to chemical synthesis

What happens in gasification?



Partial combustion of fuel with oxygen brings in the **heat**

Gasification reactions?



COMBUSTION ($C + O_2$) PROVIDES THE **HEAT** REQUIRED FOR GASIFICATION

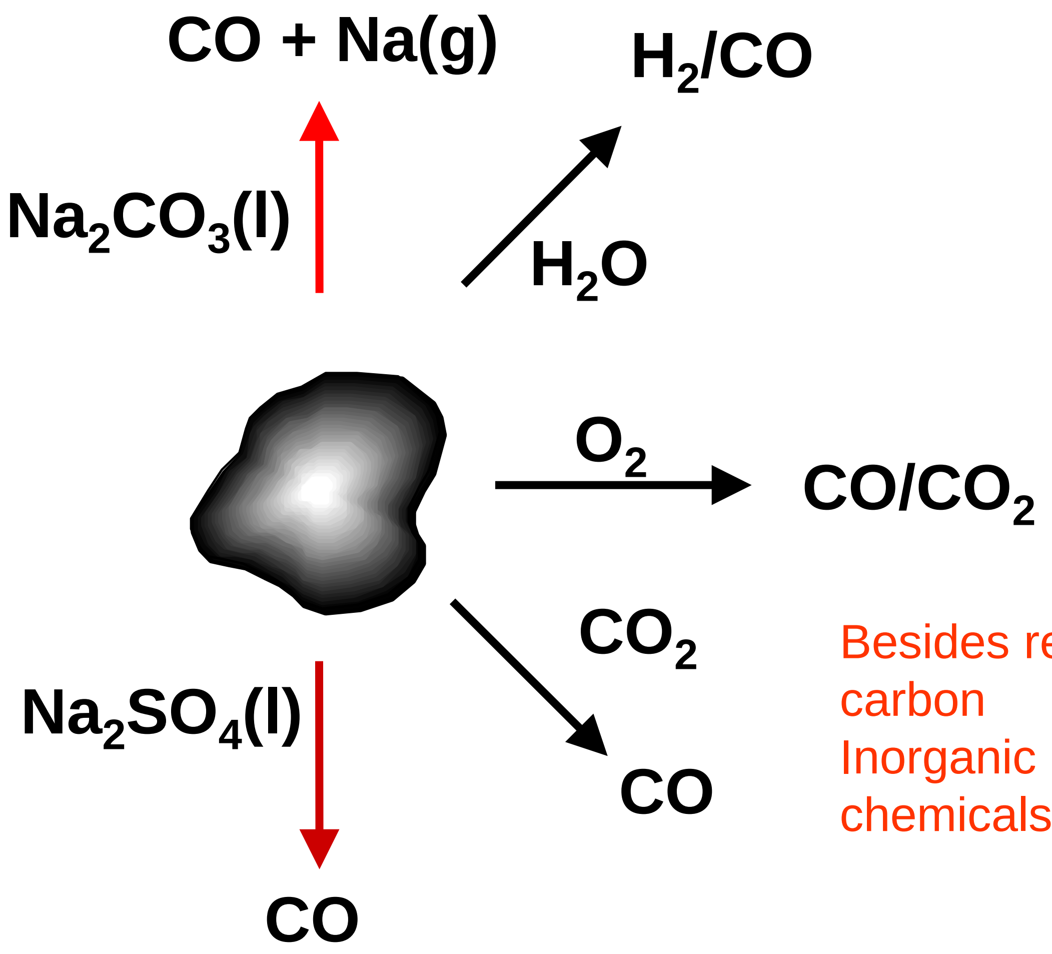
Char gasification:

$C(s) + CO_2 \Rightarrow 2\,CO$

$C(s) + H_2O \Rightarrow H_2 + CO$

$CO + H_2O \Leftrightarrow CO_2 + H_2$

Char reactions - Black liquor



Besides reactions with carbon
Inorganic cooking chemicals react also

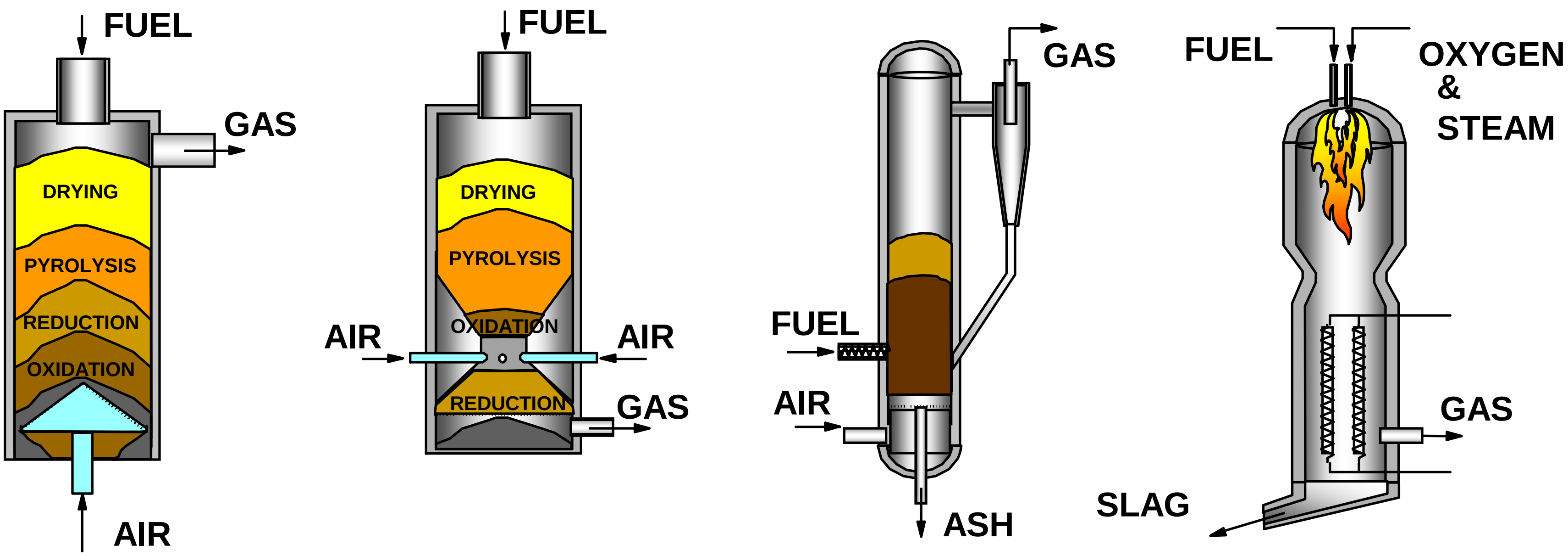
GASIFICATION TECHNOLOGIES

FIXED BED

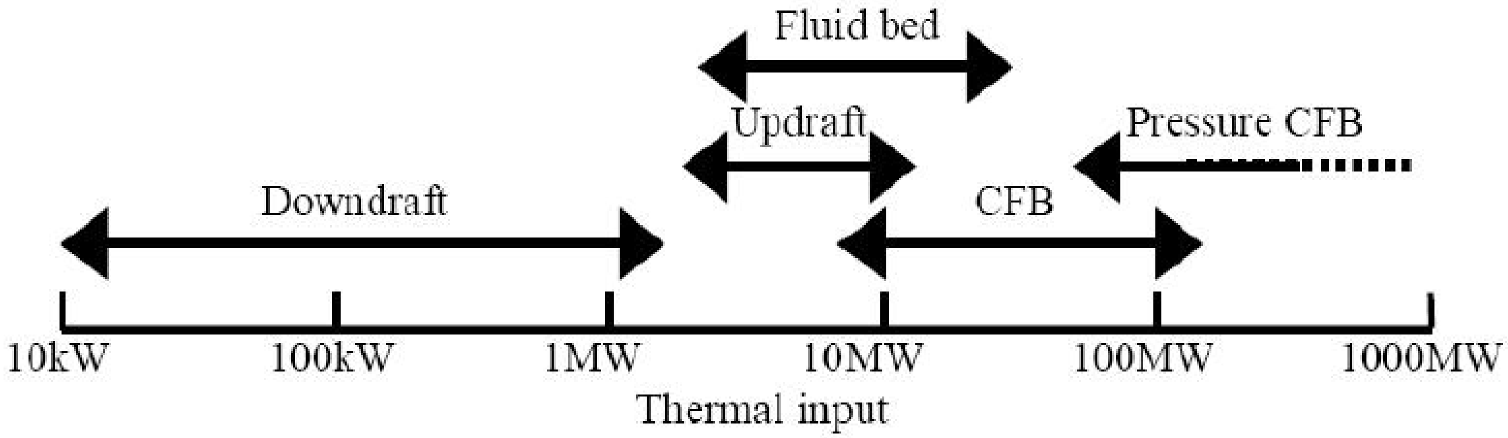
UPDRAFT | **DOWNDRAFT** | **FLUIDIZED BED** | **ENTRAINED FLOW**

CIRCULATING (CFB)

BUBBLING (BFB)



Suitability of different gasifier types



Bidgwater, A. W., 2002, The future for biomass pyrolysis and gasification: status, opportunities and policies for Europe. ALTENER report, University of Aston, November 2002, 27 p..

Fixed bed gasifiers

- At capacities below 10 MWt, updraft gasifiers are popular
- Gas leaves at relatively low temperatures
- Process has a high thermal efficiency
- Wet biomass up till 50% moist can be gasified without any pre-drying
- Produces lots of tar
- Bioneer counter-current gasifier is the classical design. Now with Foster Wheeler Energy Oy.
- More than 20 commercial references

- Downdraft gasifiers not commercially successful.
- They require dry ~20 % feedstock
- Prone to variations in fuel quality

Beenackers, A. A. C. M. and Maniatis, K., 1996, Gasification technologies for heat and power from biomass. Proceedings of EuroSun'96 Conference 1996, pp. 1311 - 1335.

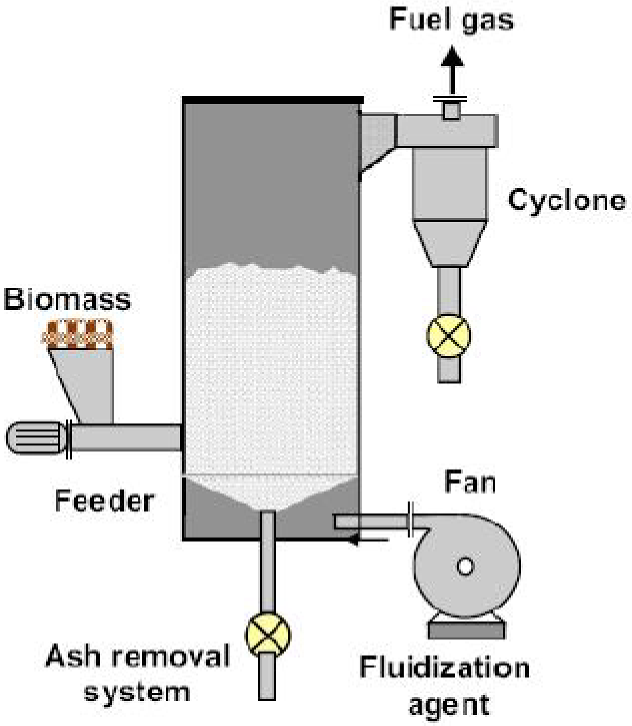
Fluidized bed gasifiers

- These reactors allow high rates of throughput, higher than fixed beds.
- They also result in good mixing, optimized kinetics, particle/gas contact and heat transfer as well as long residence time.
- High carbon conversion rates and, consequently, high yields.
- Tar content in the syngas is quite low
- Tolerant to particle size and fluctuations in feed quantity and moisture.
- The syngas is rich in particulates.
- There is danger of bed agglomeration when using biomass fuels.
- Large bubble size may result in gas bypass through the bed.

Olofsson, Ingemar ; Nordin, Anders and Söderlind, Ulf, 2005, Initial review and evaluation of process technologies and systems suitable for cost-efficient medium-scale gasification for biomass to liquid fuels. ETPC Report 05-02, Umeå University and Mid Swedish University, 2005-03-24, 95 p. ISSN 1653-

BFB gasifiers

- Wood pellet and woodchips of different size and moisture content
- Scale up limit, dry feed (t/h) 5 – 180t/day.
- Heating Value (MJ/Nm^3)
  - 4.5-7.9 (air),
  - 4-6 (Air and steam),
  - 5.5-13 (O_2 and steam)
- Typical gas composition (% volume)
  - 5-26 H_2, 13-27 CO, 12–40 CO_2,
  - 13-56 N_2, <18 H_2O, 3-11 CH_4
- Tar content of dry syngas (mg/Nm^3) 13500 *)
- Operating pressures (OP, bar) 1 – 35
- Operating temperatures (°C) 650 – 950



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*) depends on scale of the plant

CFB gasifiers

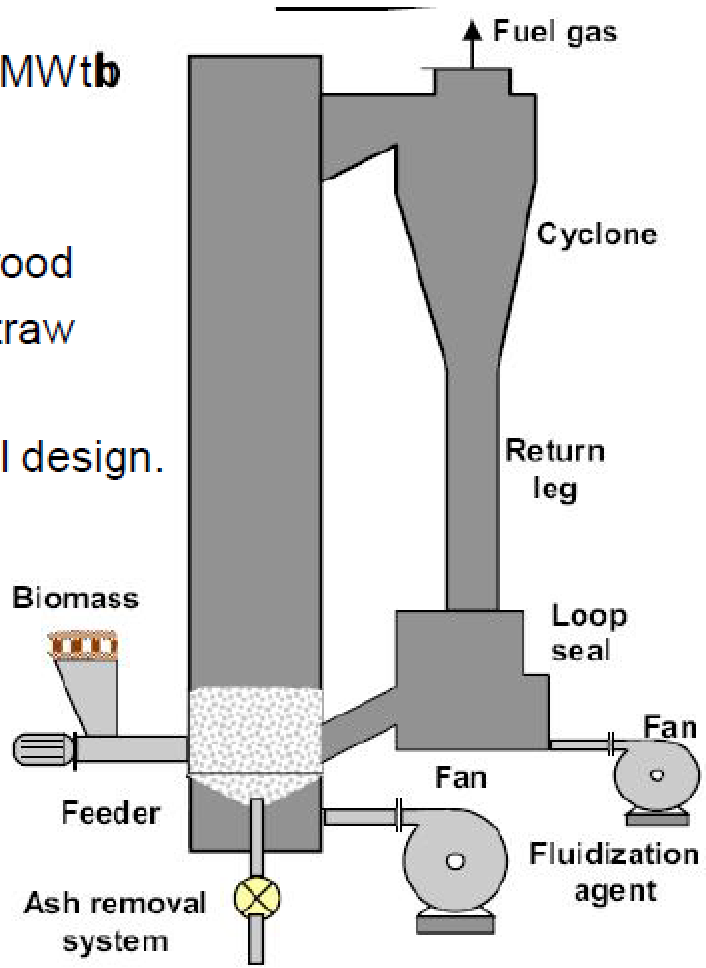
- Higher quality of syngas than BFBG
- Isothermal conditions, good mixing, optimized kinetics, particle/gas contact and heat transfer as well as long residence time
- High carbon conversion rates and consequently high yields.
- Low tar content in the syngas is quite low
- Tolerant to particle size and fluctuations in feed quantity and moisture
- Very fuel flexible technique.
- Syngas is rich in particulates.
- Significant danger of bed agglomeration when using biomass fuels.

- Foster Wheeler, Värnamo
- Babcock Borsig Power, Austrian Energy
- Andritz, Carbona Corp

Olofsson, Ingemar ; Nordin, Anders and Söderlind, Ulf, 2005, Initial review and evaluation of process technologies and systems suitable for cost-efficient medium-scale gasification for biomass to liquid fuels. ETPC Report 05-02, Umeå University and Mid Swedish University, 2005-03-24, 95 p. ISSN 1653-

CFB gasifiers

- Commercial biomass gasifiers up to 100 MWtb
- Requires dried biomass
- Produces tar ~10 g/Nm^3
- Operating temperature 900 -950 °C for wood
- Operating temperature 800 -850 °C for straw
- Produces rather even gas quality
- Ahlstrom Pyroflow gasifier is the classical design.
- Now with Foster Wheeler Energy Oy.
- More than 10 commercial references
- Currently Storea Cell Värö operating as
- lime kiln gasifier
- Current suppliers Metso, Andritz
  and Foster Wheeler



Entrained flow gasifiers

- Almost tar free syngas
- Leach-resistant molten slag
- A high percentage of energy is converted into sensible heat, requiring integration with steam user industry or electricity production, the latter associated with higher costs.
- The production of biomass powder suitable for entrained flow gasification from different feed stocks is an extra cost, but may be reduced by an initial torrefaction process.
- *Shell*
- *Texaco*
- *Destec*

- Challence with materials, due to high temperatures

Olofsson, Ingemar ; Nordin, Anders and Söderlind, Ulf, 2005, Initial review and evaluation of process technologies and systems suitable for cost-efficient medium-scale gasification for biomass to liquid fuels. ETPC Report 05-02, Umeå University and Mid Swedish University, 2005-03-24, 95 p. ISSN 1653-

Some basic things in the literature

- Air-blown gasification: Main gasification agent is ambient air (with O_2)
  - CHP and IGCC applications
- Oxygen-blown gasification: Gasification agent is oxygen
  - IGCC and BtL (Biomass to Liquids) applications

- Ambient operating pressure: Fixed-beds, fluidized beds
- Elevated operating pressures (> 10 bar): fluidized bed and entrained bed gasifiers
  - High pressure reactors well known in chemical industry
  - Can be challenging when processing materials with solid particulates

Examples of product gas/syngas compositions

Composition examples of gasification product gases (syngases) from different sources (volume %)/14, 15/.

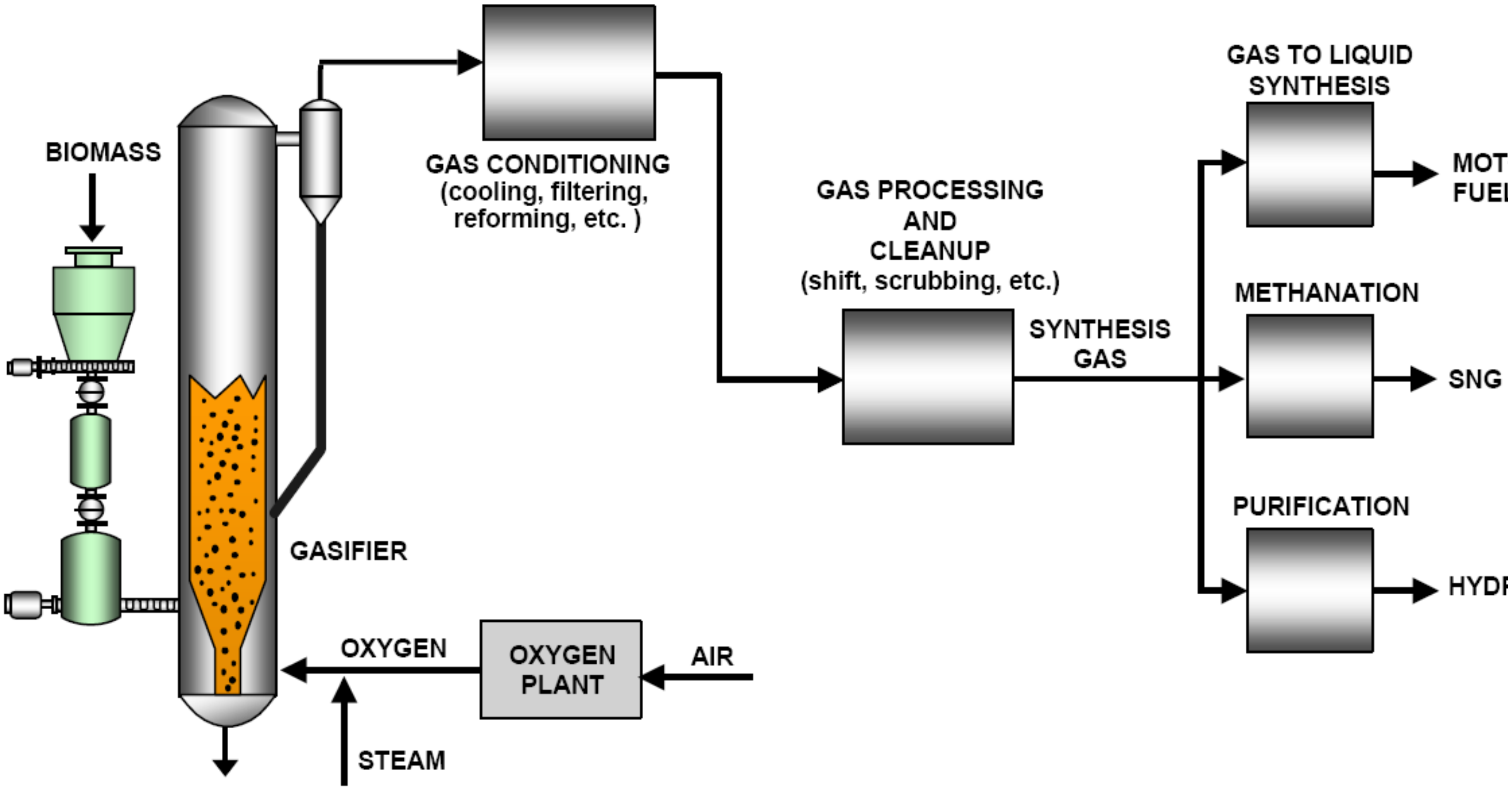
Composition	***Wood, air-blown (wet gas)***	***Wood, oxygen&steam-blown (dry gas)***	***Peat, oxygen&steam-blown (dry gas)***
CO	*12--14*	*20--22*	*15--16*
H_2	*9--11*	*23--25*	*16--28*
CH_4	*3--5*	*7--9*	*4--6*
CO_2	*12--13*	*25--35*	*20--28*
H_2O	*12--18*	*0*	*0*
N_2	*40--49*	*1--10*	*1--10*
LHV (MJ/m^3_n)	*4--6*	*8--11*	*7--10*

Source: Konttinen et al. (2011)

IMPURITIES IN GASIFICATION GAS

- always high amounts after gasifier
  - particulates, alkali- and heavy metals, tars, nitrogen compounds
- gas has to be cleaned before utilisation (expect when combusted directly in boiler in ditrict heating plants)
- **gas cleanup is the most crucial problem in the development of advanced gasification based processes**
  (engine, turbine, fuel cell, synthesis processes)

Gasification Product Gas/Syngas cleaning and processing



Syngas cleaning and processing

Contaminant	Examples	Problems	Cleanup method
Particulates	Ash, char, bed material	Erosion, plugging	Filtering, scrubbing
Alkali metals	Sodium (Na) and potassium (K) compounds	Hot corrosion, catalyst poisons	Cooling, absorbtion, condensation, filtering
Heavy metals and trace elements	Mercury (Hg), Arsenic (As), Cadmium (Cd), Lead (Pb), Tellurium (Te),…	Catalyst poisons	Condensation, filtering, guard beds, scrubbing ("ultra-cleaning")
Fuel-bound nitrogen	Mainly NH_3 and HCN	NO_x formation in gas combustion	Scrubbing, selective catalytic reduction
Tars	Reactive aromatics	Filter plugging, internal condensation and deposition	Tar cracking/reforming, scrubbing
Sulphur, chlorine	HCl and H_2S (and some COS)	Catalyst poisons, corrosion, gaseous sulphur emissions	Limestone or dolomite, zinc-based guard beds, scrubbing, absorption

Modified from the source: Bridgwater, A. et al.: An Assessment of the Possibilities for Transfer of European Biomass Gasification Technology to China. Part 1. Report of Mission to China. 1998, 65 p.

HOW DOES GASIFICATION PROCESS DIFFER FROM OTHER COMBUSTION PROCESSES?

- What is the same in all:
  - Renewable biomass and waste fuels can be used as feedstocks
  - Power and heat can be generated
    - Superheating steam with hot flue gases
  - Some gas cleaning steps are the same (dust removal)
- What is different:
  - Gasification is substoichiometric combustion → not enough oxygen is introduced for complete combustion
    - Combustible gases (CO, H_2, CH_4, C_xH_y,..) are generated
  - Gasification product gas/syngas can be used for many applications
    - Power and heat production
    - Production of chemicals
    - Production of liquid biofuels
  - In power and heat options, the ratio of power to heat, applying biomass and waste fuels can be increased
  - Gas cleaning more challenging (high temperatures & corrosive gases…)

SMALL-SCALE

CHP APPLICATIONS

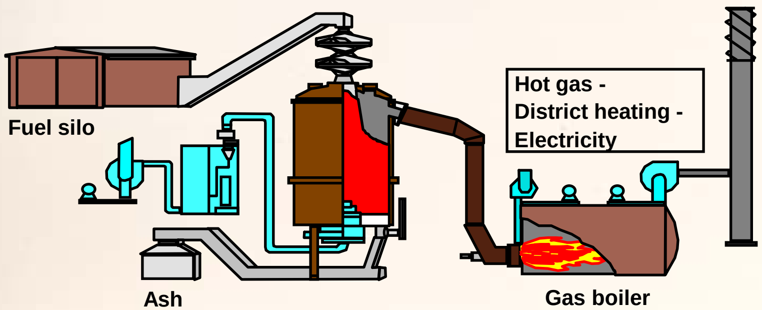
OF GASIFICATION

UPDRAFT GASIFIER
FOR BIOMASS AND WASTES

- 5 MW District heating plant, Kauhajoki Finland
- 9 commercial plants in operation in Finland and Sweden since 1986

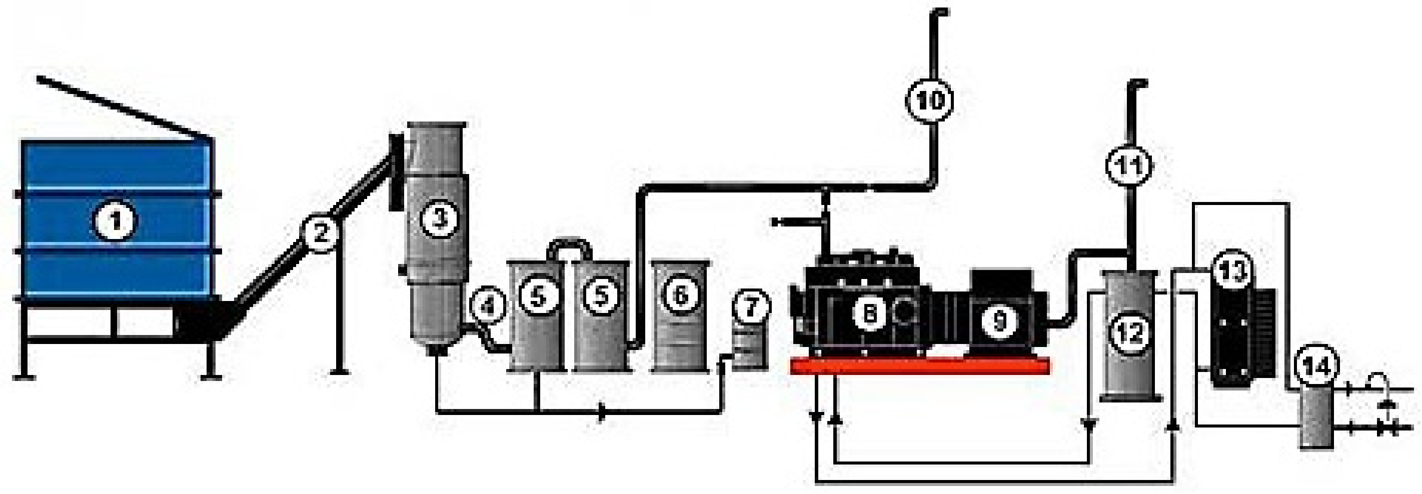
Applications:

- District heating 1 - 15 MW_{th}
- Small-scale CHP 1 - 3 MW_e
- Drying kilns and process ovens
- Diesel power plants after catalytic gas cleaning



Small-scale-CHP based on gasification

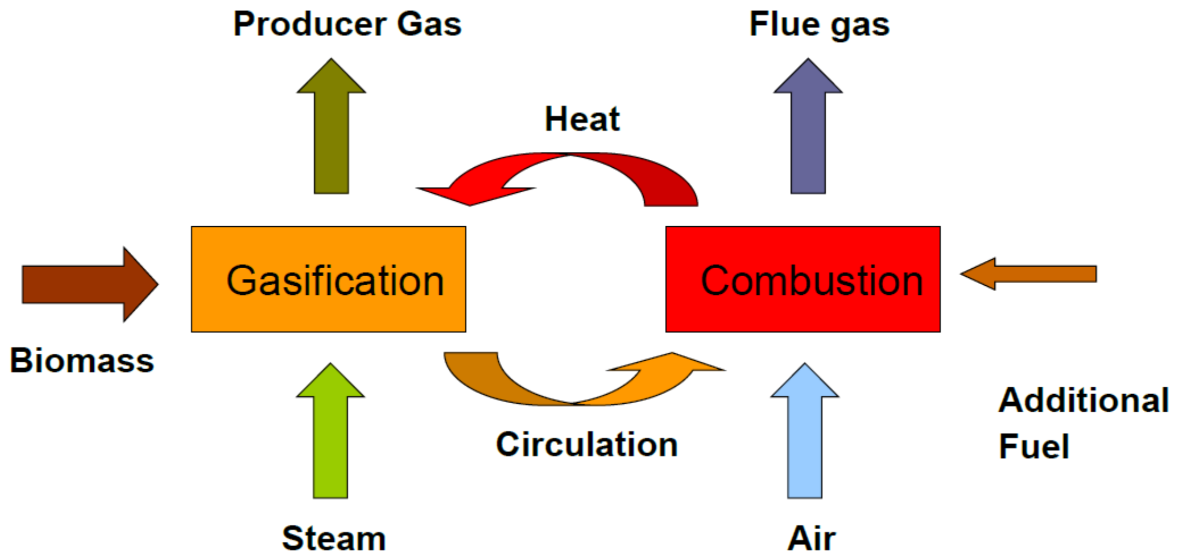
- Downdraft gasifier (150 kW_{th}) + gas cleaning + gas engine (< 50 kW_e)



1. Fuel silo	4. Raw gas	7. Ash bin	10. Ignition gas	13. Cooler
2. Feeding screw	5. Water scrubber	8. AGCO SISU POWER	11. Flue gas	14. Heat exhanger
3. Reactor	6. Water tank	9. Generator	12. Flue gas heat exhanger	

SOURCE: Gasek Oy www.gasek.fi

REPOTEC Güssing plant, Austria



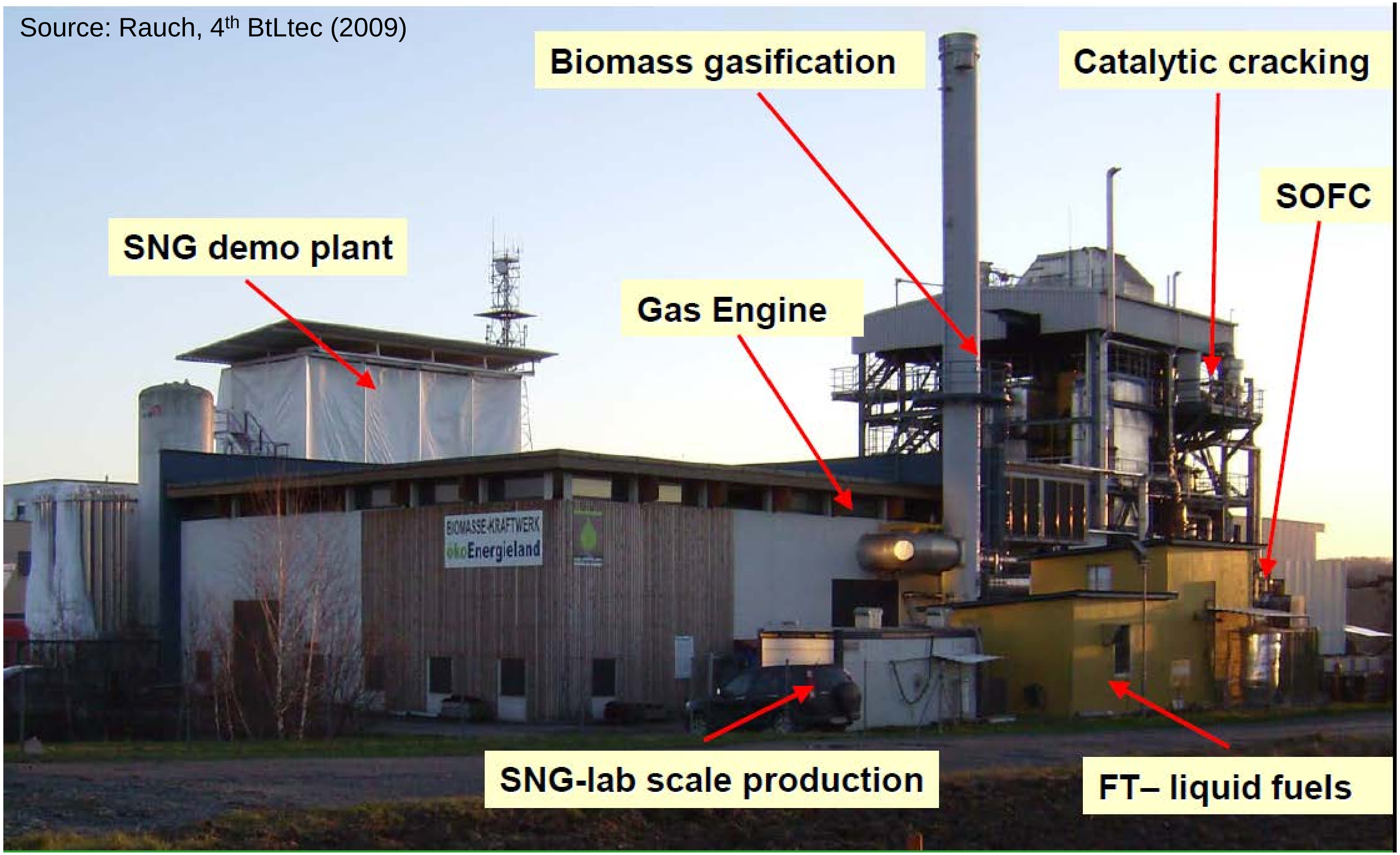
Source: Rauch, 4th BtLtec (2009)

- Production of power and heat (CHP) with wood fuels, 8 MW_{th} and more than 30 % power
- Availability of the plant 90 %
- Production of biodiesel has been demonstrate with Fischer-Tropsch-equipment
- Research on fuel cell applications under way
- SNG (Synthetic Natural Gas) demonstration: cars have been fuelled with the produced SNG

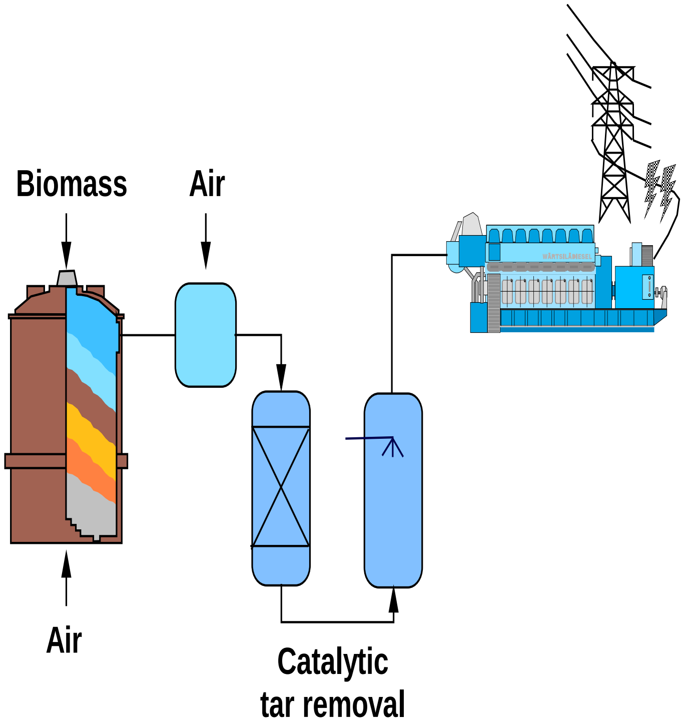
Why two side-by-side fluidized beds?

- One challenge in gasification is to convert all carbon in char to gases → maximize carbon conversion
- Idea: deliver the unconverted carbon to a nearby fluidized bed combustor and deliver the combustion heat back to the gasification fluidized bed

REPOTEC Güssing plant, Austria



Small-scale CHP-technique: Gasification of biofuels and gas engine



Applications:

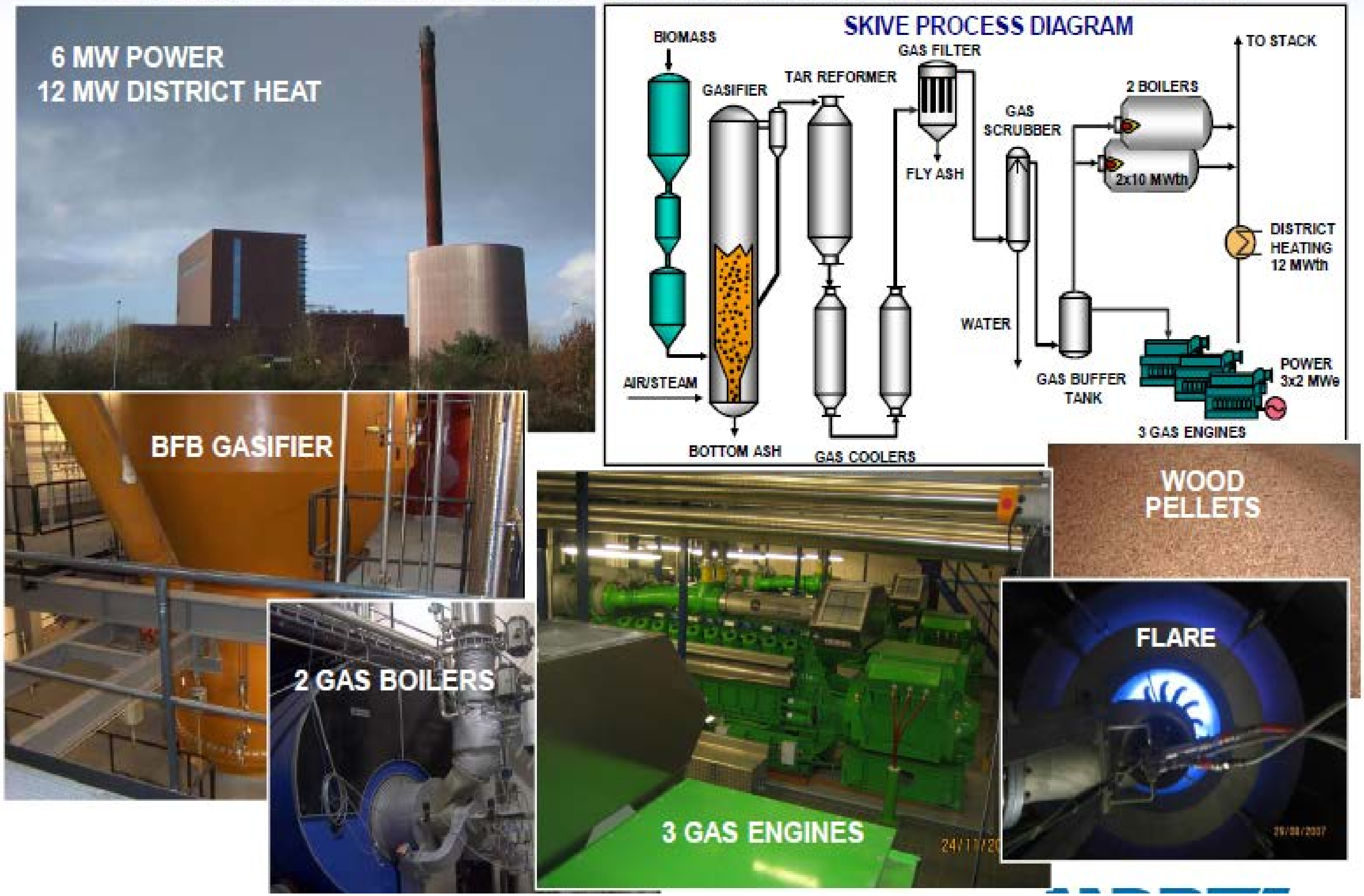
- Plant size 1- 20 MW_{th}, high potential
- Power 25-35 %, power + heat > 85 %
- Small-scale district heating plants
- Mixed combustion in turbines for natural gas
- Sawmills and other mechanical forest industry

R&D-work and different techniques (Finland)

- Novel-fixed-bed gasifier (Condens, **demonstration: serious drawbacks**)
- Fluidized bed gasification (Andritz/Carbona, **in operation (Skive plant)**)
- Entimos Oy co-current flow gasification
- Catalytic gas cleaning

Gasification CHP Plant, Denmark

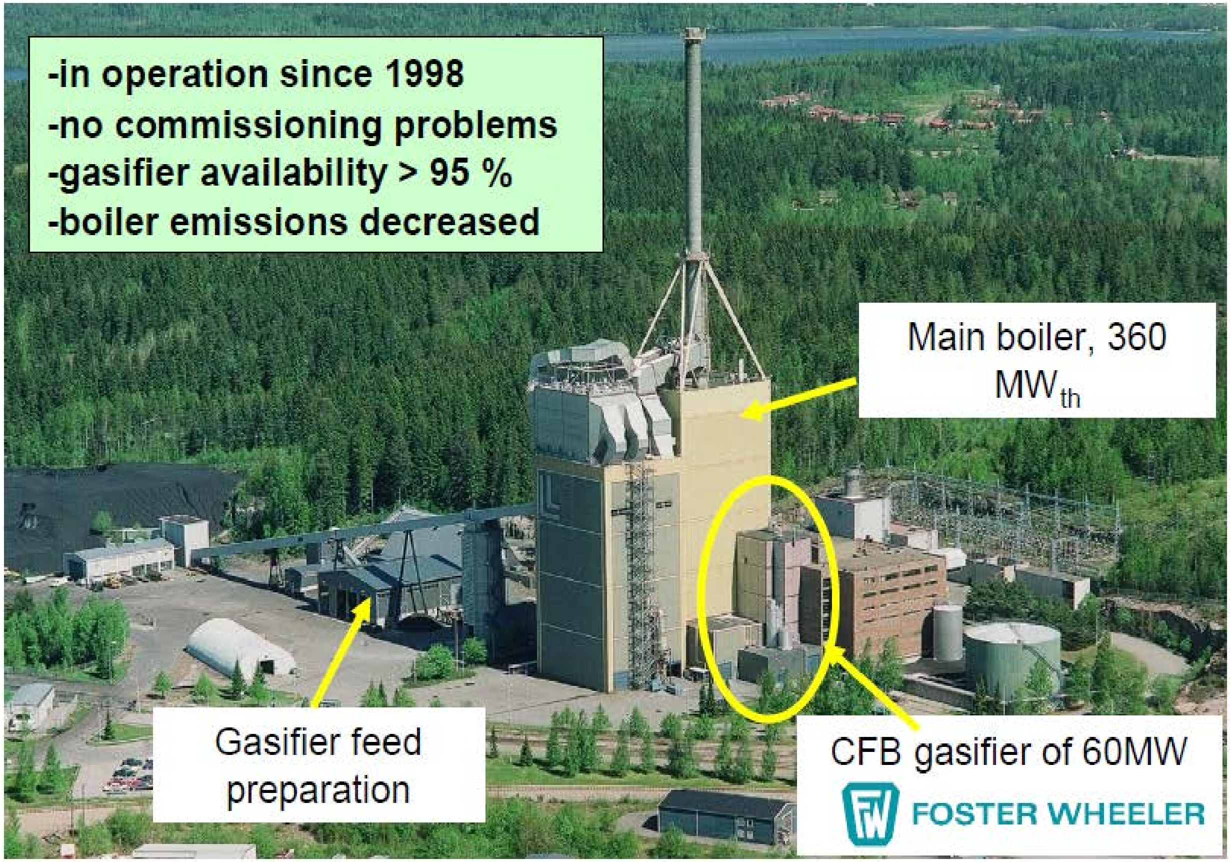
As result of Carbona's domestic and international R&D cooperation



Why gasification is good option to waste

- Makes it possible to use waste-derived fuels and biomass also in pulverised coal-fired boilers
- High power to heat ratio due to large-scale power plant technology (compared to small-scale biomass plants)
- Investments only to gasification and gas cleaning
- Effective emission control:
    - no dioxin formation in reducing atmosphere of gasifiers
    - 90...95 % of chlorine is removed before gas combustion
    - heavy metals (exept Hg) are removed before gas combustion.
    - effective flue gas cleaning after large-scale boiler
- Waste ash is not mixed with the coal ash of the main boiler

Proven reference: Lahti Energia (Kymijärvi power plant), Finland



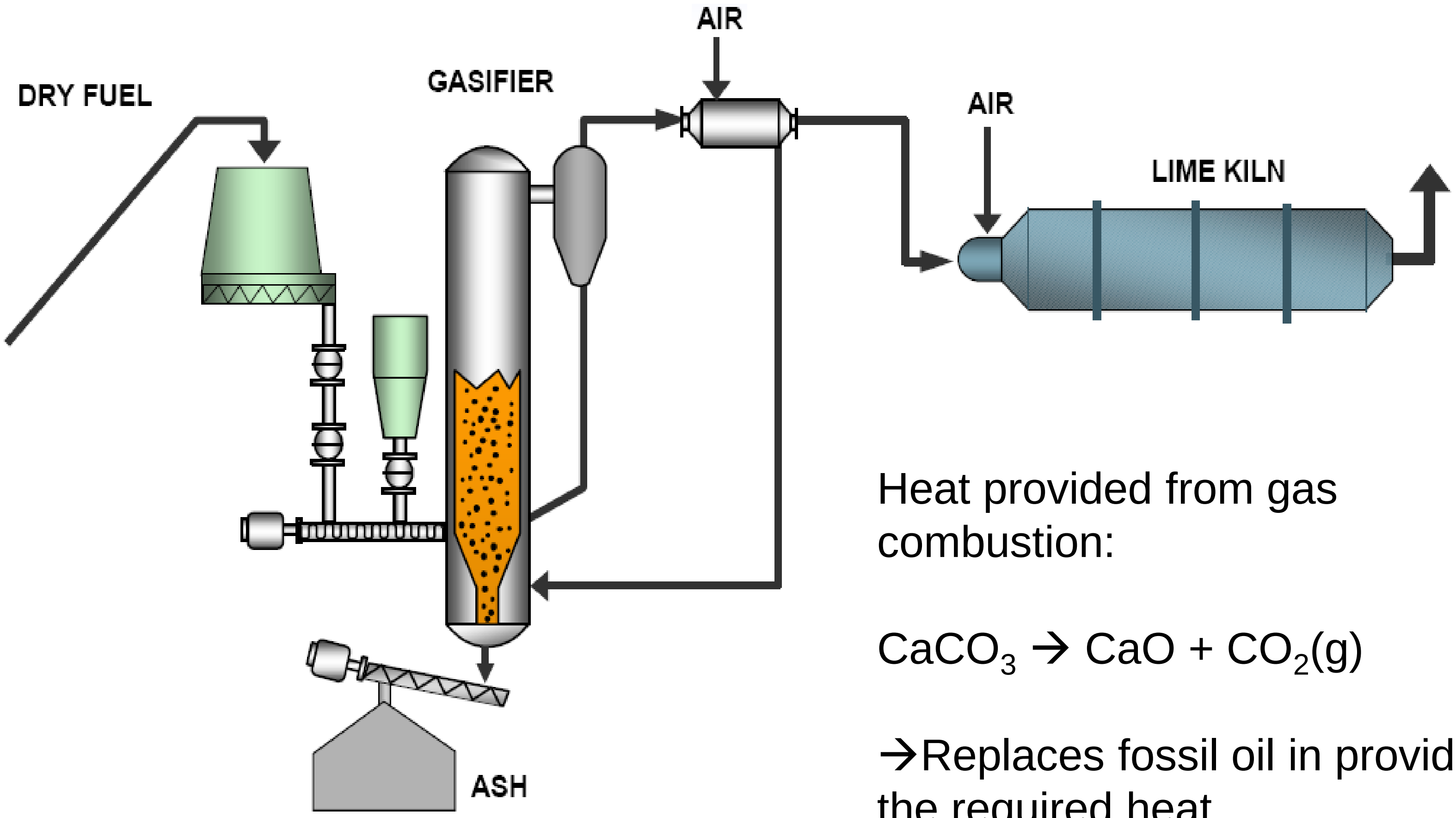
Source: VTT (M. Nieminen)

Year 2012:
Lahti Energia: Gasification plant of 160 MWth

- Project with international importance
- **Energy-containing waste** is the only fuel (from combustible material from households, shops and industry)
- The core of the plant is CFB gasifier equipped with gas cooling and cleaning
- New type of environmental technology, developed in Finland

www.lahtienergia.fi

Lime kiln gasifiers (Andritz/Metso/Foster Wheeler)



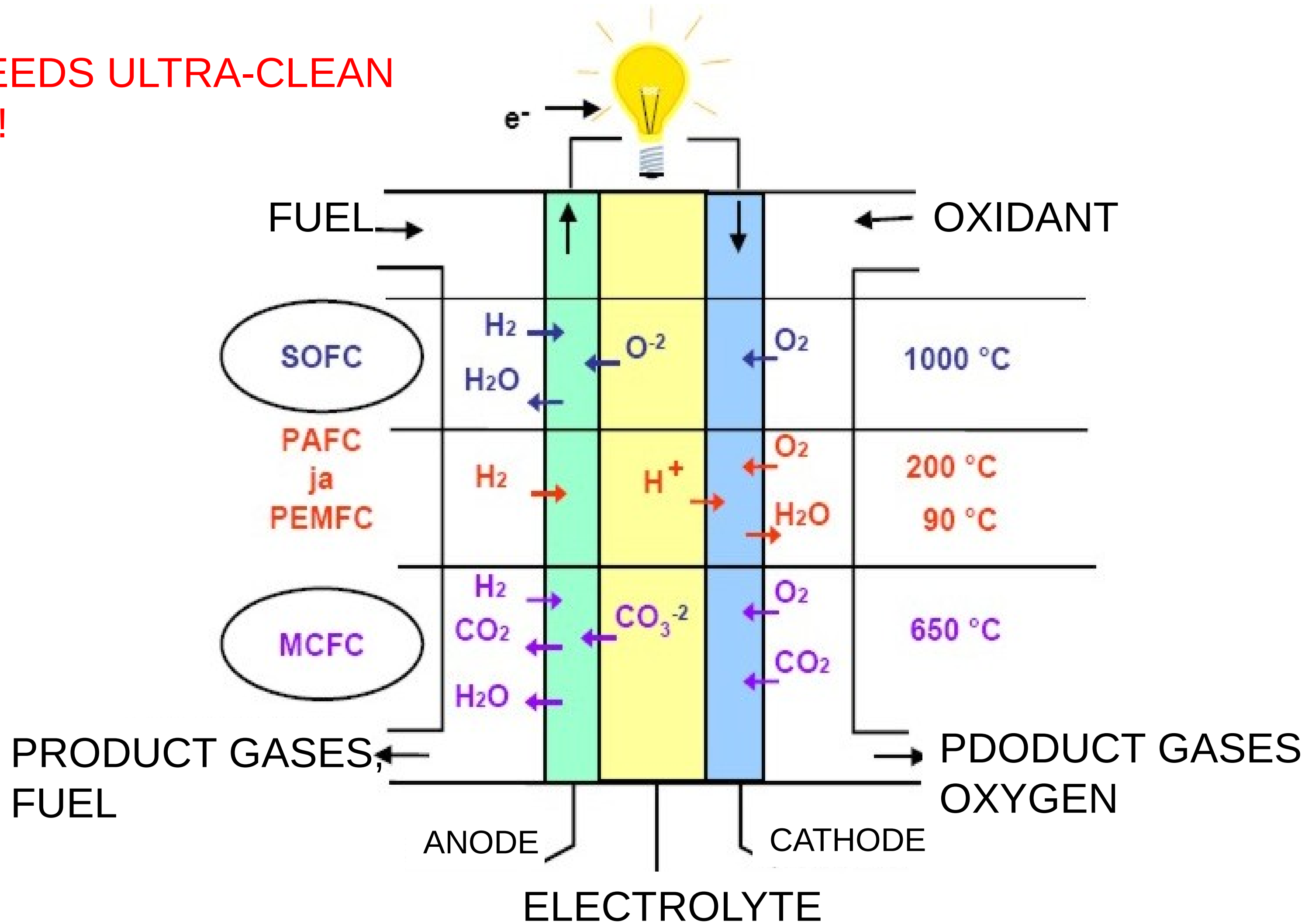
Heat provided from gas combustion:

$CaCO_3 \rightarrow CaO + CO_2(g)$

→Replaces fossil oil in providing the required heat

Fuel cell - combustion of H_2

NEEDS ULTRA-CLEAN H_2!

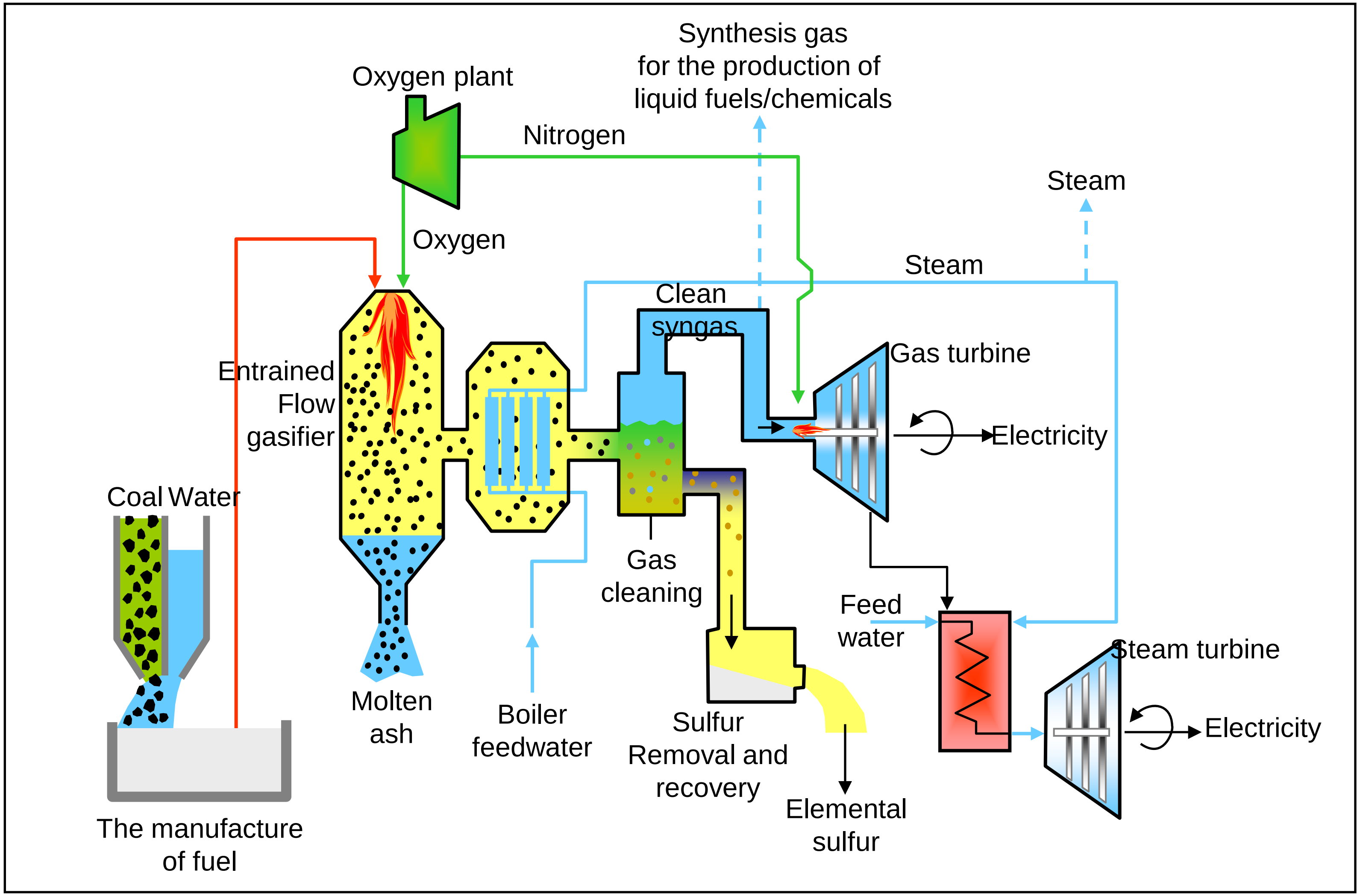


Hepola and Kurkela, VTT (2002)

Integrated Gasification Combined Cycle = IGCC

Gasification reactor (gasifier) + gas cleaning + power plant

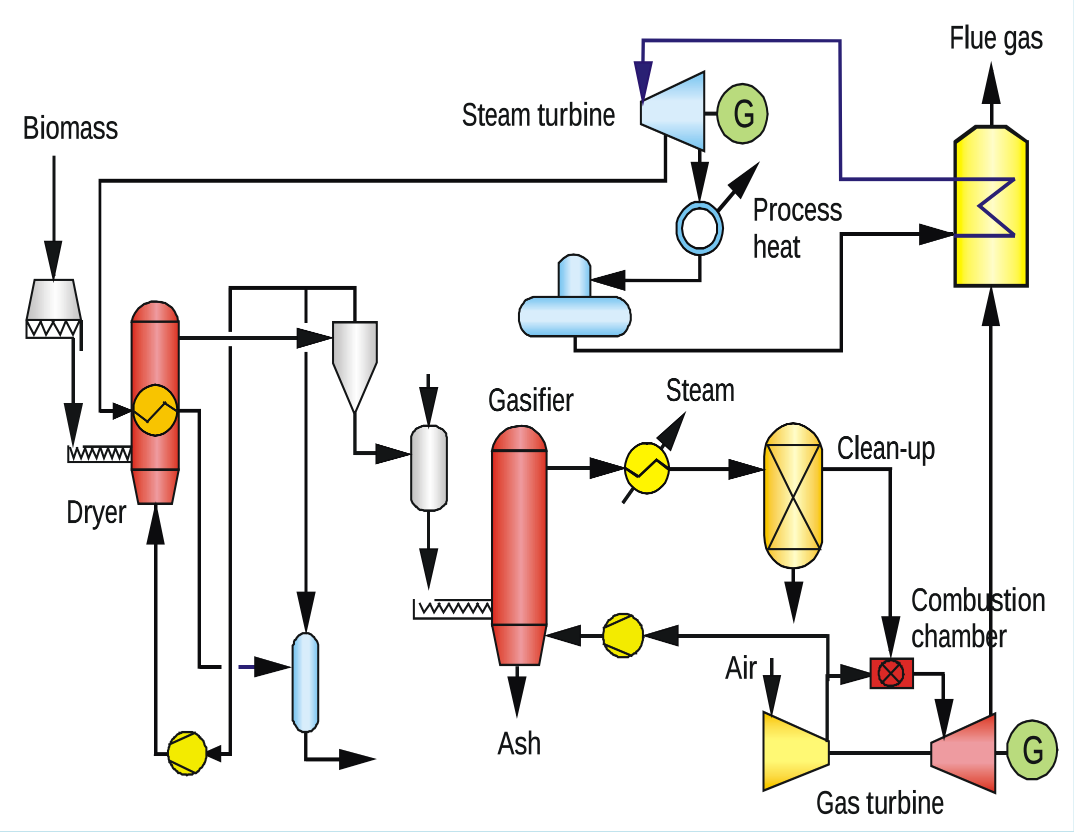
IGCC



TECO Power services mukaan

Biomass-based IGCC plant for industrial CHP production

(CHP = Combined Heat and Power)



Design parameters for a future plant

Wood input	150 MW
Power output	60 MW
Heat production	70 MW
Total efficiency	87%
Power-to-heat ratio	0.86

Specific investment 550 €/kW fuel

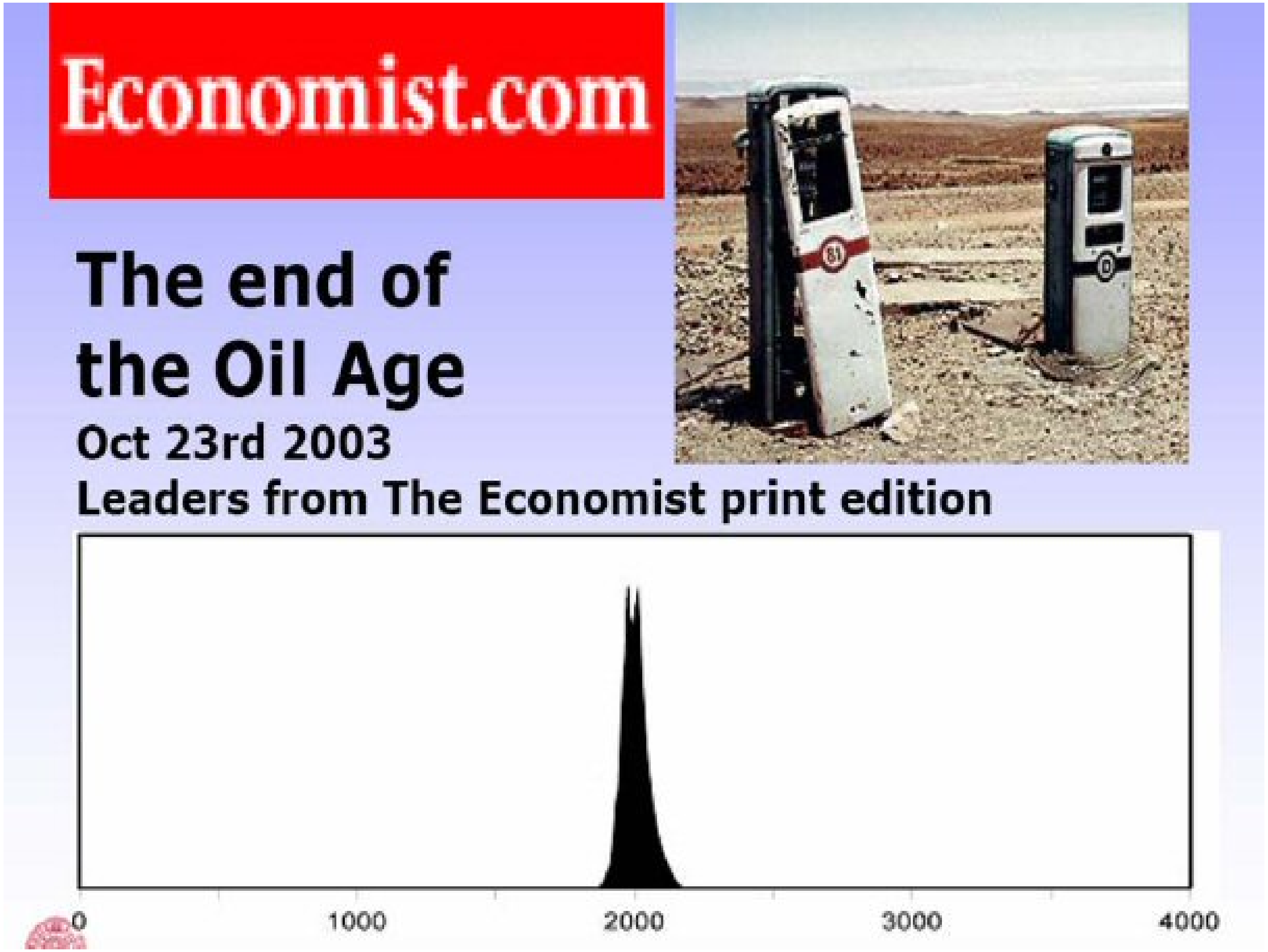
Power production cost 27 €/MWh

Assuming:

Price for heat	13 €/MWh
Fuel cost	7.5 €/MWh
Full-load operating time	6500 h/a
Economic lifetime	20 years
Interest rate	5%

Kurkela et al. (2003)

The end of oil age!?



Biorefinery?

- At one industrial plant, based on biomass (or biomass-containing waste) feedstocks to produce:
  - Food (from agro biomass raw material)
  - Chemicals
  - Liquid biofuels
  - Pulp & paper (from woody biomass raw material, IF integrated with a chemical pulp mill
  - Power
  - Heat

} Part of raw material which is not suitable for other products

→ ALL THE BIO-BASED RAW MATERIAL WILL BE USED

Biorefinery?

- VISION IN LONGER TERM
  - RAW MATERIAL: carbon from renewable biomass and waste
  - PRODUCT: value-added carbon-containing products (chemicals etc.)
  - ENERGY? Producing energy using other renewable methods (solar, wind, geothermal…)

→ chemicals are higher price products than energy

→ minimum release of carbon (in CO_2) to atmosphere

The USA – both the government and the private sector are heavily investing in biorefinery technology development

Major US DOE funded projects
About 1.1 billion USD invested by DOE

Source: US DOE, http://www1.eere.energy.gov/biomass

In Europe/EU:
-307 R&D projects around biorefinery
- Mostly in France, Finland, Belgium, the UK, Sweden, the Netherlands, Germany

Source: VTT/Mäkinen T., AEBIOM European Bioenergy Conference 2010

RECENT BOOK ABOUT BIOREFINERIES, including gasification

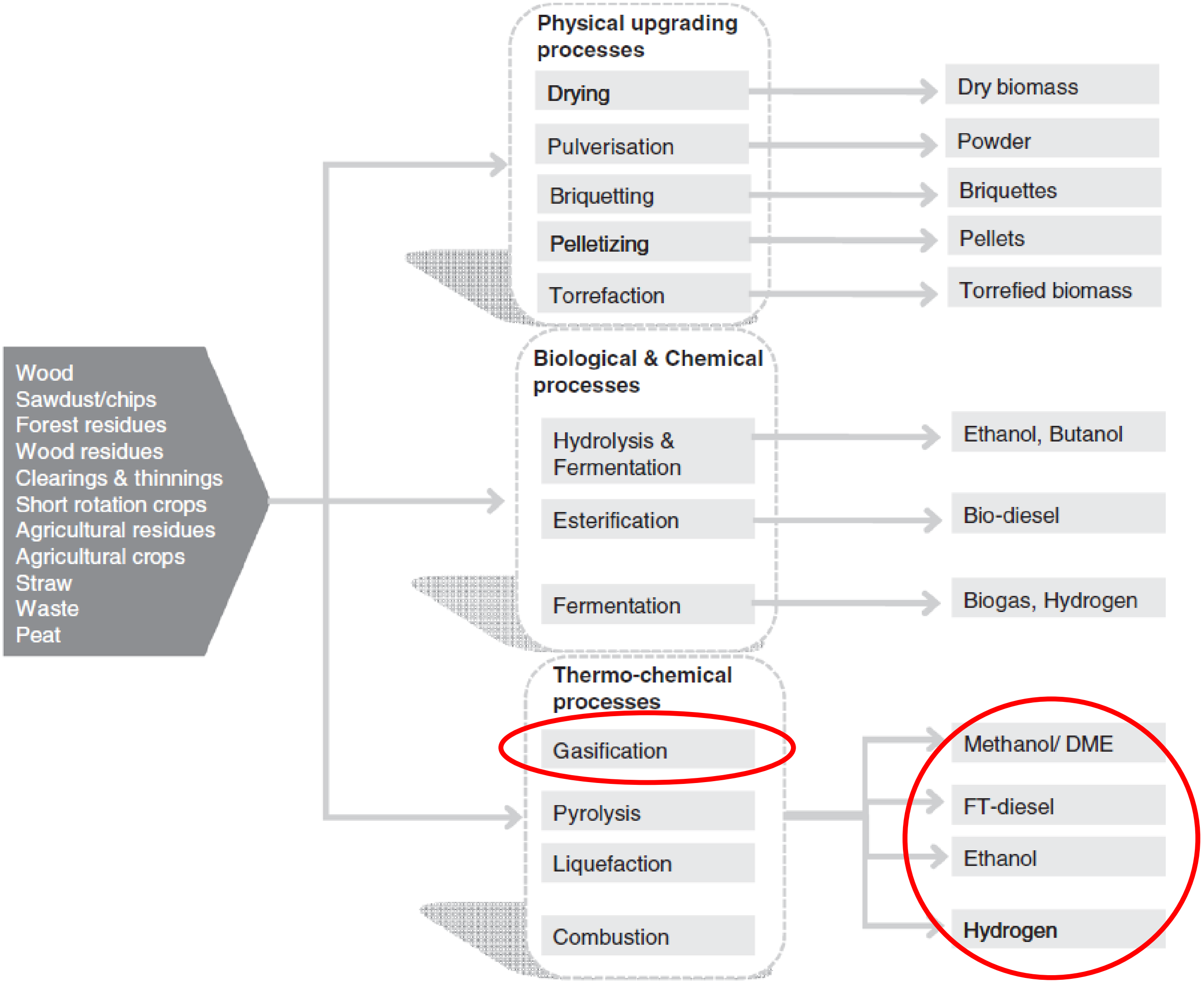
- Papermaking Science and Technology, Book 20: Biorefining of Forest Resources. Alén R. (ed.), Published by Paper Engineer's Association. Bookwell Oy, Porvoo, Finland 2011. ISBN 978-952-5216-39-4.
  - Chapter 8: Konttinen, J.; Reinikainen, M.; Oasmaa, A. and Solantausta, Y.: Thermochemical conversion of forest biomass Pp. 262-304

Definitions around biorefineries

First generation (1G) = starch/vegetable oils as raw material

Second generation (2G) = lignocellulosic raw material, more advanced processing, no effect on food production

Producing fuels from biomass



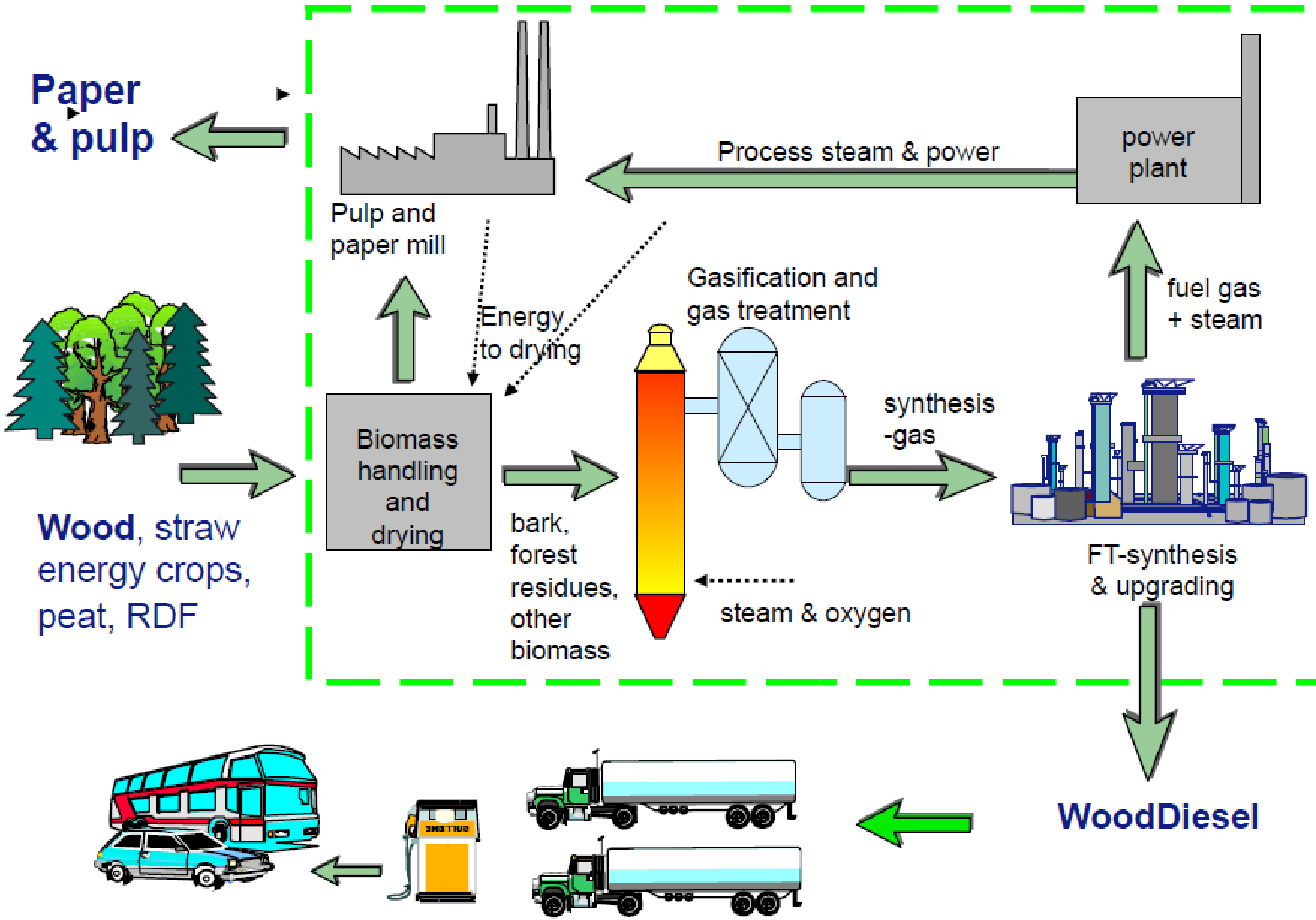
Source: Louhelainen J., University of Jyväskylä 2010

FINLAND: Large-scale Biomass to Liquids (BtL) production

- Many industrial companies activated (Forest industry)
- DRIVING FORCES
  - High crude oil price (→ may never decrease again & availability?) → decrease the dependence on fossil crude oil
  - Effect on CO_2-emissions (liquid biofuels vs.fossil-based mineral oil fuels)
  - The demand of paper will not necessary grow any more, paper prices decreasing → unloading the production overcapacity

    → alternative products to paper and paperboard
  - Better environmental image to customers

Finnish approach: Integration of renewable diesel-oil production to pulp and paper mills



Source: VTT/Mäkinen T., AEBIOM European Bioenergy Conference 2010

Gasification & production of liquid biofuels/Finland

- Stora Enso & Neste & Foster Wheeler & VTT
  - Partial refining at the biodiesel plants of Neste Oil
  - Gasification-based pilot-plant (5 MW) in Varkaus
- UPM-Kymmene & Andritz & Carbona
  - Biomass gasification, Fischer Tropsch-prosess for biodiesel production
  - Gasification-based pilot-plant (5 MW) near Chicago, USA
- VAPO/VapOil (& Metsäliitto)
  - Biomass gasification, F-T biodiesel production
    - PEAT will serve as reserve fuel for gasification
  - Commercial operation possibly in Äänekoski or in Kemi
- Metso: CoBiGas – gasifier (20 MW gas) in Gothenburg, Sweden

Liquid biofuels/Finland, present status

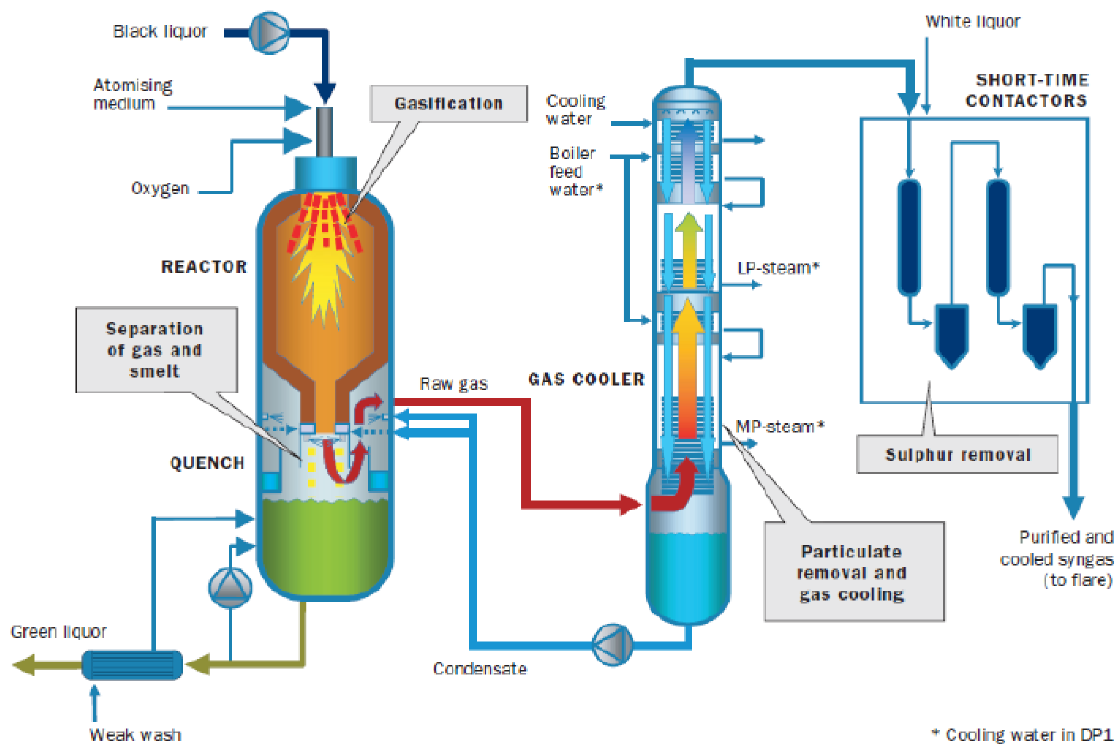
- 3 separate financing applications about gasification-based biodiesel demostration plants have been submitted in EU:
  - Converting power plants to chemical mills:
    - Large plants (100000 – 200000 ton/v.) have suitable economics → unrealistic in connection with smaller scale plants
    - Overall investment 400 – 800 million euros
    - Availability of fuel material
    - Integrating the gasification plant & FT-plant
  - Decisions can be expected towards the end of year 2012
    - KSML 9.1.2012: The planned subsidies by EU to NER-300 projects can decrease to one third of the original (6 → < 2 mrd. euros)
    - At least one demonstration project per EU member country will be financed
- Talouselämä 39/2010: Small role globally (compared with fossil oil) until year 2030

Chemrec development plant (DP-1) in Piteå, Sweden

- Oxygen-blown, pressurized black liquor gasification plant
  - recovery of cooking chemicals with simultaneous production of synthesis gas
  - entrained flow gasifier
  - operating conditions: 1000 °C, 30 bar (g)
- Nominal capacity:

  20 t BLS/d (3 MWth)
- In operation since 2005
- Black liquor, white liquor, water, steam and electricity supplied by the Smurfit Kappa Kraftliner mill

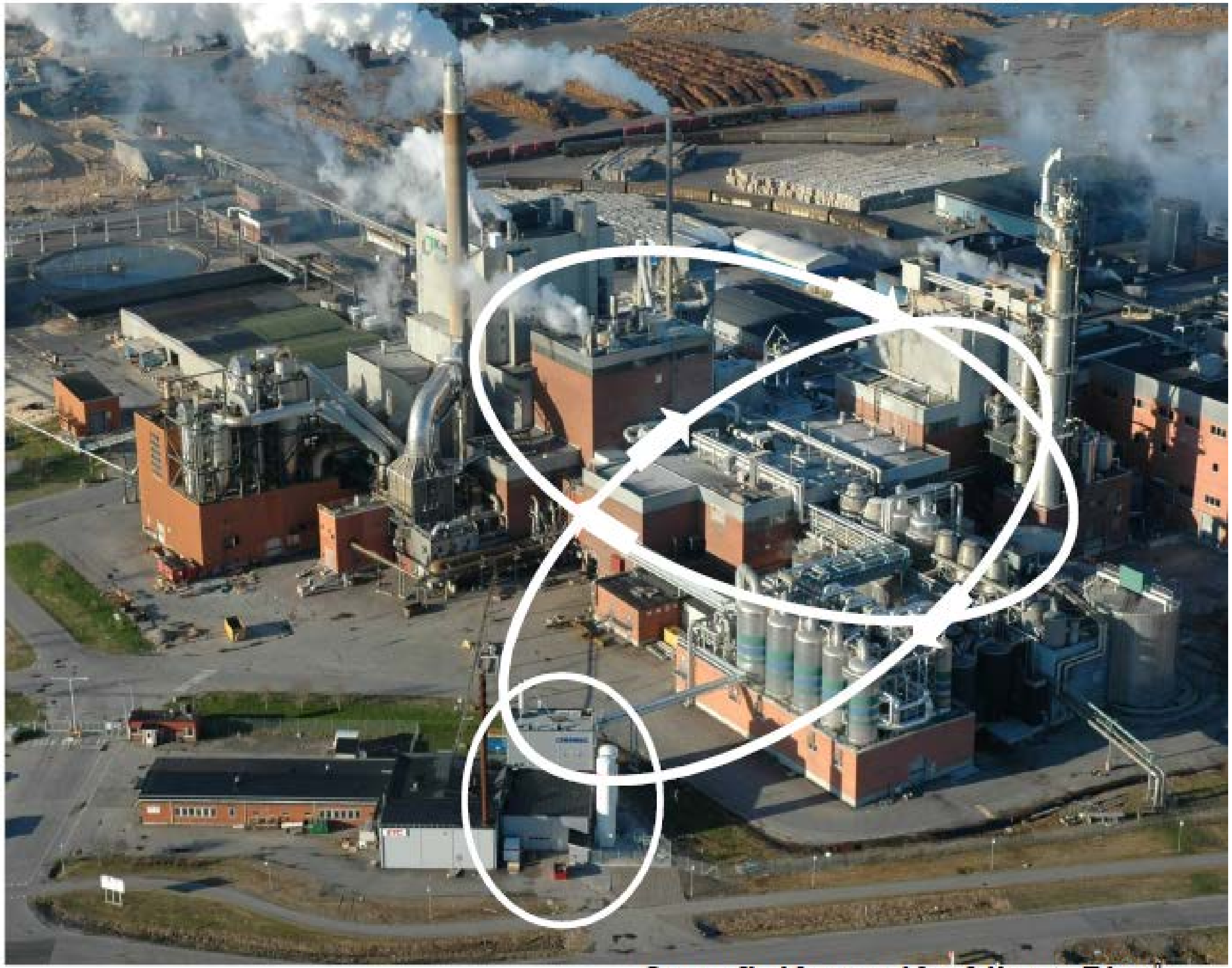
  (adjacent to the gasification plant)
- To be extended with a DME production plant
  - in operation from July 2010
  - capacity: 5 t DME/d



Source: www.chemrec.se

Source: VTT/Mäkinen T., AEBIOM European Bioenergy Conference 2010

Black liquor gasification



Smurfit Kappa Kraftliner, Piteå

Processing of synthetic gas into liquid biofuels

- In a so called Fischer-Tropsch process, synthesis occurs at the presence of a catalyst at 10-40 bar pressure and elevated temperature (200 – 400 °C), producing liquid hydrocarbons, such as BIODIESEL

  $nCO + 2nH_2 \rightarrow n(CH_2) + nH_2O$

- Syngas processing can also lead to:
  - Methanol (can be mixed with gasoline)
  - Ethanol (a part of gasoline)
  - Dimethyl ether (DME)
  - Other alcohols

  These technologies are not that commercially developed as Fischer-Tropsch

- ”2G” technology – the ”1G” transesterification process based on vegetable oils is a different method!

Gasification basics - summary

- Thermochemical processing of biomass and waste (and coal etc.) to generate gases which can be further processed into:
  - Heat
  - Power
  - Chemicals (CH_4, …)
  - Liquid biofuels (biodiesel, bioethane)

- Processing: introducing subtoichiometric amount of O_2 to produce gases H_2, CO, CH_4,…

- For energy production, the applications are:
  - Integrated Gasification Combined Cycle (IGCC)
  - CHP plants with gas engines/motors to produce power
  - Advantage: higher power to heat ratio than with conventional bioenergy processes

Gasification basics - summary

- For chemicals or liquid biofuels (separate presentation)
  - Biorefinery: can produce heat and power too to increase the overall efficiency
- Small-scale applications downdraft and updraft gasifiers (CHP)
  - Not easy to scale-up because of their operating principle (gas-solid contact)
- Large-scale industrial applications fluidized-bed and entrained-bed gasifiers
- Gas cleaning most crucial challenge for advanced applications (biomass to liquids, IGCC,…)
- Commercial demonstration still required
  - Some success (Lahti, Corenso, Skive, CHP plants)
  - IGCC and liquid biofuels production and fuel cell application still under demonstration