IPESE
Industrial Process and Energy Systems Engineering

Biomass Technologies and Carbon Flows

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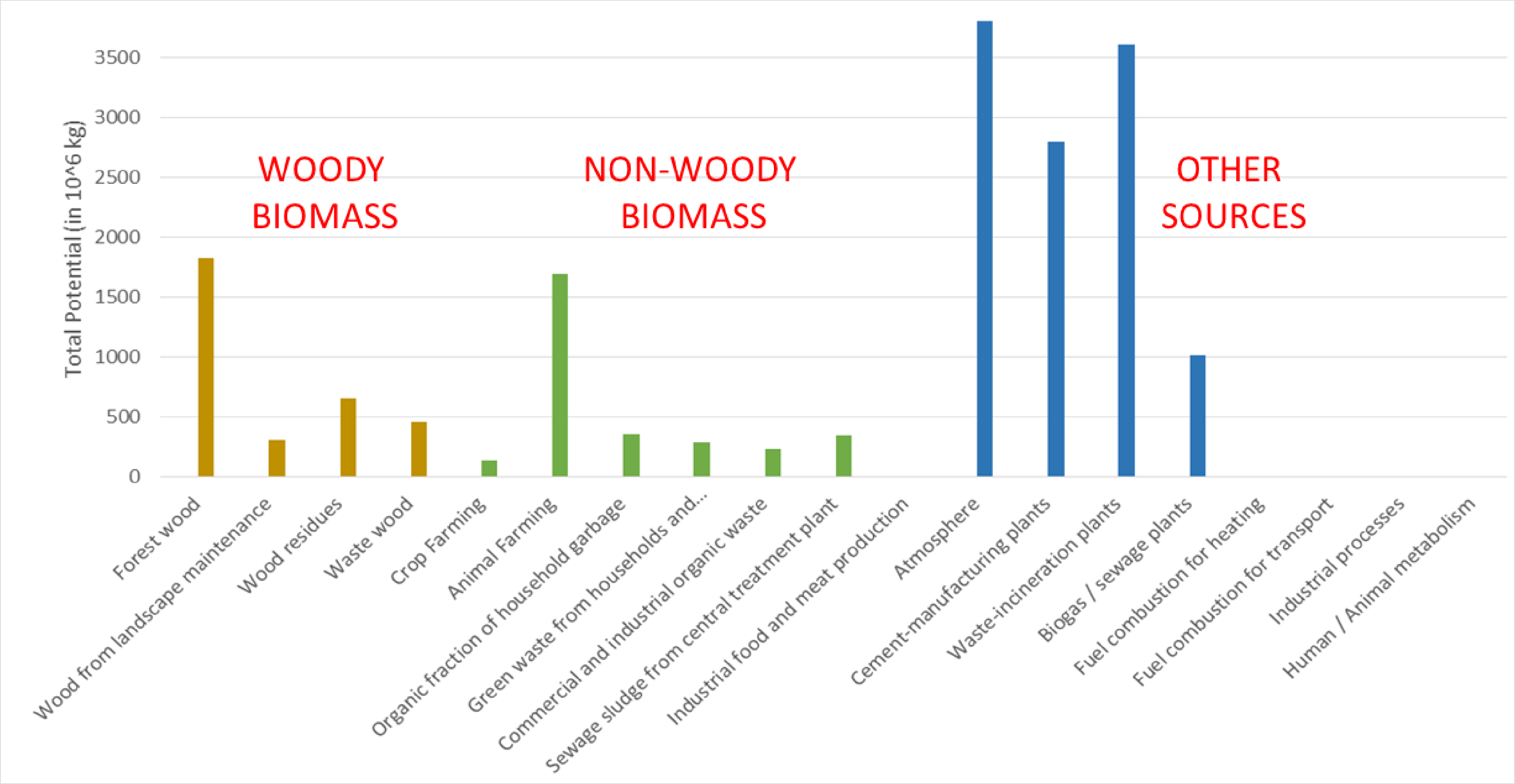
Carbon Sources in Switzerland

Sustainable carbon potential from various identified sources in Switzerland in mass (ktons/y)[1,2].



CO_2: cement and waste incineration plants, sewage treatment and biogas plants: 8.64 Mt_{CO2}/a[1], atmosphere is regarded as an unlimited source with 410 ppm.
Import: Fuels for transport and heating, plastics, chemicals.

[1]B. Meier, F. Ruoss, M. Friedl, Investigation of Carbon Flows in Switzerland with the Special Consideration of Carbon Dioxide as a Feedstock for Sustainable Energy Carriers. Energy Technology. 2017, pp. 5:864-876.

[2]O. Thees, V. Burg, M. Erni, G. Bowman, R. Lemm, Biomassenpotenziale der Schweiz für die energetische Nutzung, WSL Berichte, Heft 57, 2017.

Biomass potentials in Switzerland

Biomass potentials have been collected based on Thees et al. (2017)[1]

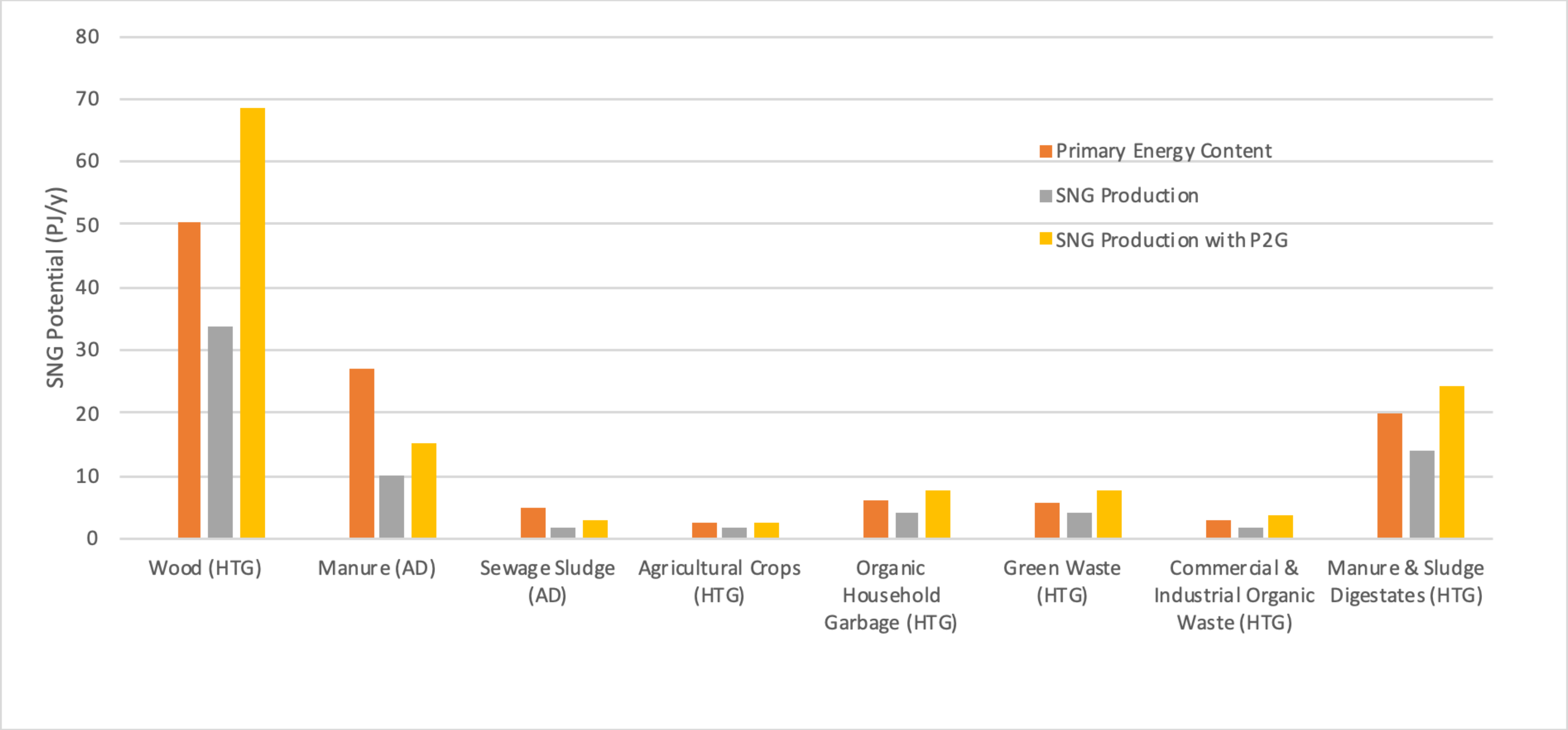
Theoretical potential: energy contained in the biomass available.
Sustainable potential: amount that can actually be used for energy purposes, after deduction of environmental and techno-economic restrictions.
Already used potential: amount already used for energy purposes.

Additional sustainable potential: the extra amount that can be used supplementary for energy purposes.

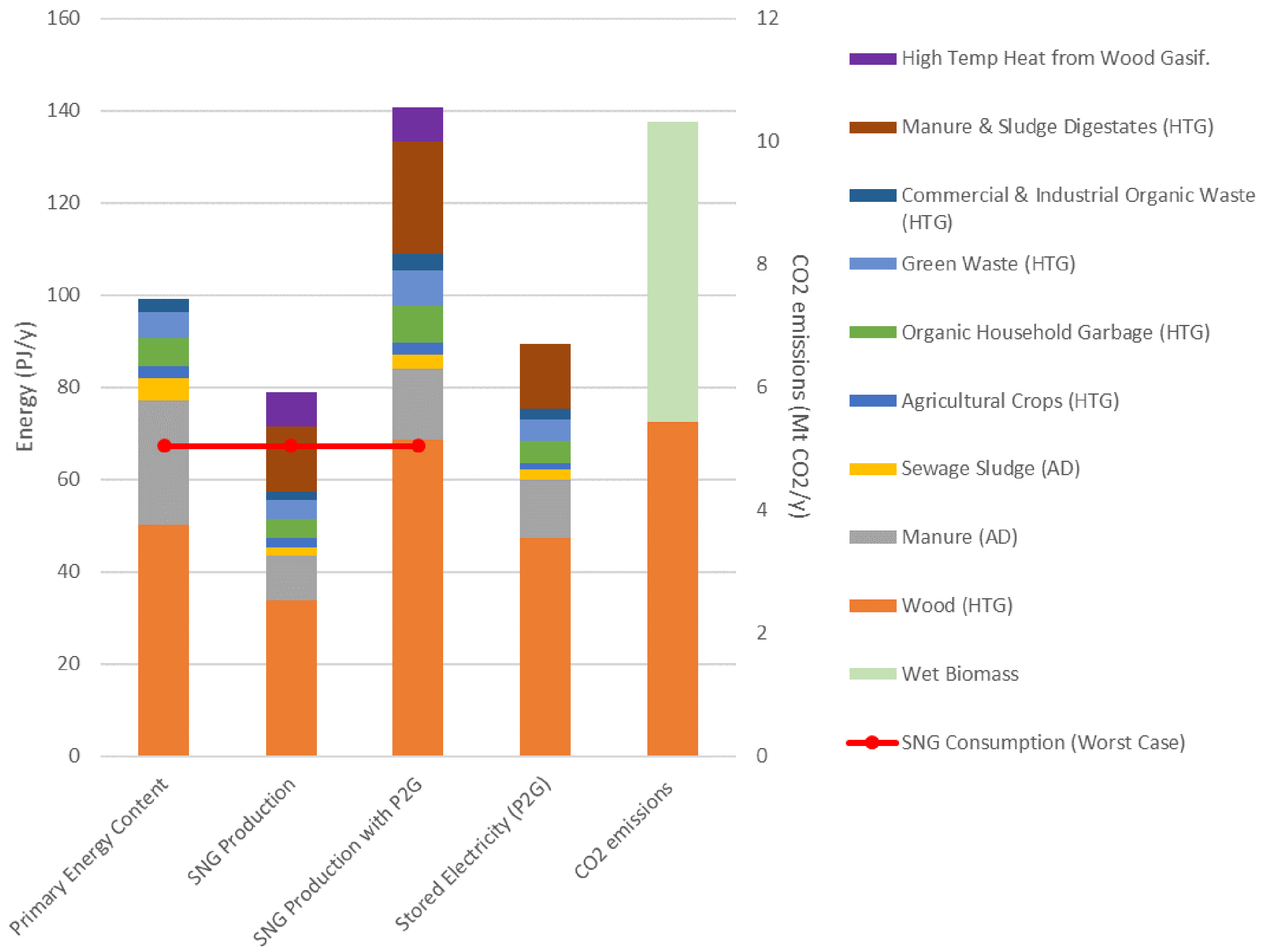
$$\textbf{Additional sustainable} = \underbrace{\textbf{Theoretical} - \textbf{Restrictions}}_{\textbf{Sustainable}} - \textbf{Already Used}$$

[1]O. Thees, V. Burg, M. Erni, G. Bowman, R. Lemm, Biomassenpotenziale der Schweiz für die energetische Nutzung, WSL Berichte, Heft 57, 2017.

SNG Potentials for Biomass with Power Storage



SNG Potentials for Biomass with Power Storage



Hypothetical complete conversion of biomass to SNG is more than enough to supply the annual natural gas needs.

Application of P2G using captured (stored) CO_2 and renewable H_2 increases the final SNG potential by 78%.

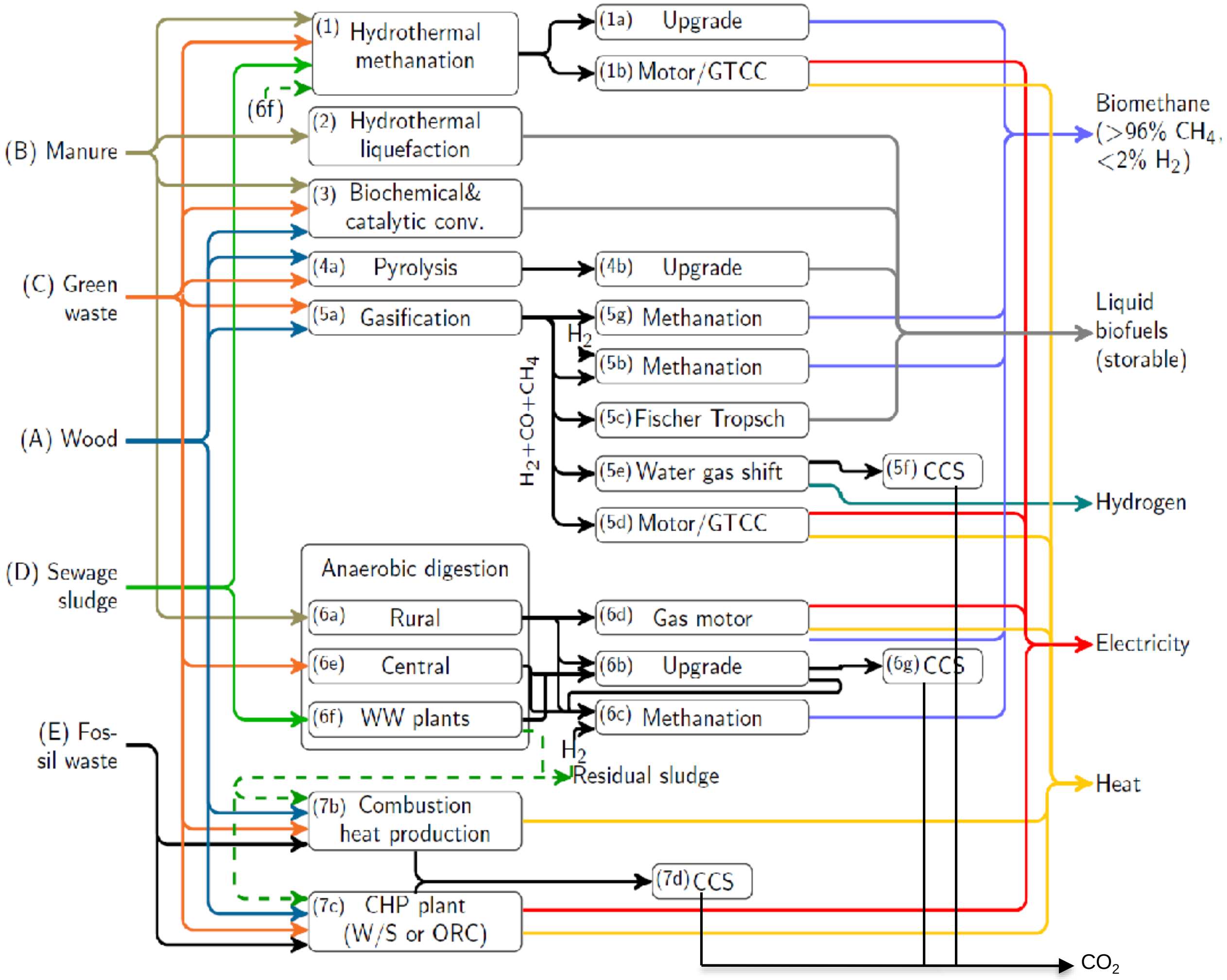
Solid biomass (wood) is used in gasification, wet biomass is either processed in HTG or anaerobic digestion + HTG

Biomass to X technologies

Biomass to fuels (and heat):
- Anaerobic digestion
- Methanation
- Power-to-Gas
- Biomass to hydrogen
- Pyrolysis
- Gasification/HTG
- Fischer-Tropsch
- Biomass to ethanol
- Methanol synthesis

Heat Production:
- Combustion
- CHP
- Fuel Cells
- Gas engines/CCGT
- CHF

Power Production:
- CHP
- Fuel Cells
- Engines
- BECCS



Adapted from C. Bauer, E. Panos, R. Sacchi, X. Zhang, T. Damartzis, X. Li, F. Maréchal“ Technology characteristics”, SCCER JAS&M Report, 2020

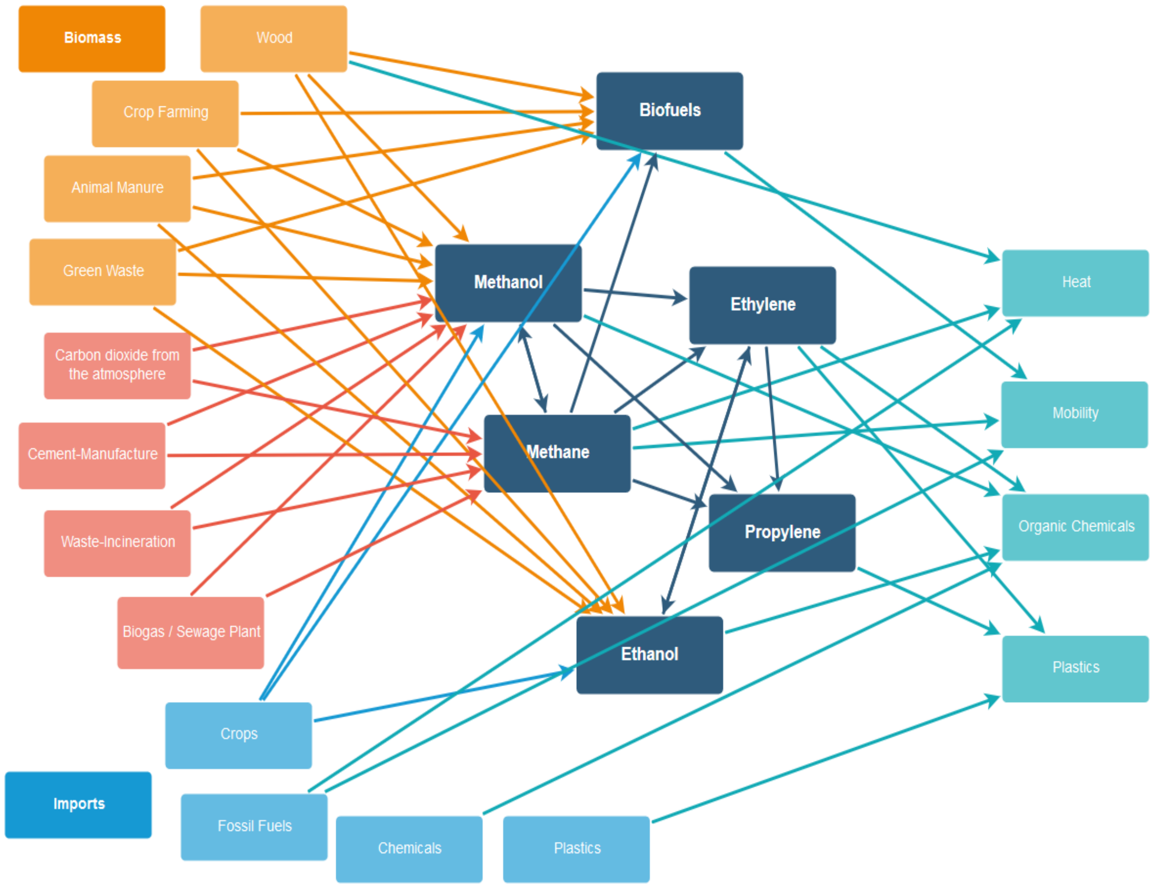
Heat recovery - Energy management

CO_2 to X technologies

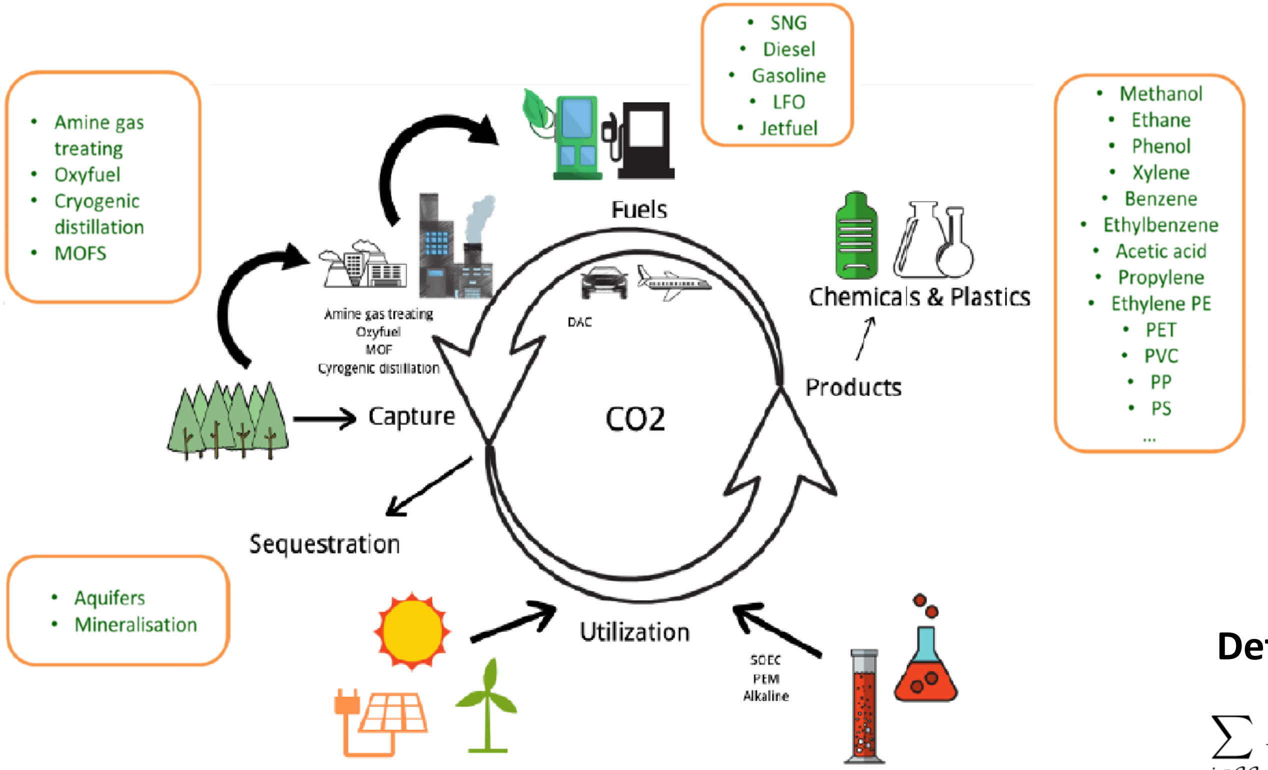
CO_2 capture:
- Pre-combustion
- Oxy-combustion
- Post-combustion

CO_2 Sequestration:
- Deep Saline
- Unmineable coal seams
- Storage in mines

(bio-)CO_2-to-X:
- Ethylene/propylene synthesis
- Methanol/ethanol
- Benzene
- Xylene
- Acetic acid
- DME
- Bio-SNG
- Plastics from chemicals (PE, PP, HDPE, PS, PET, PVC)



Carbon Flows in Energyscope



Modeling of carbon flows

CO_2 from biogenic and non-biogenic resources captured and used for fuel and bio-product synthesis.

Biomass Energy Content

Wood: 50.2 PJ/y

Wet biomass: 46.8 PJ/y

Biogenic Carbon

Wood: 5.43 Mt CO_2/y

Wet biomass: 4.89 Mt CO_2/y

Define initial CO_2 balance

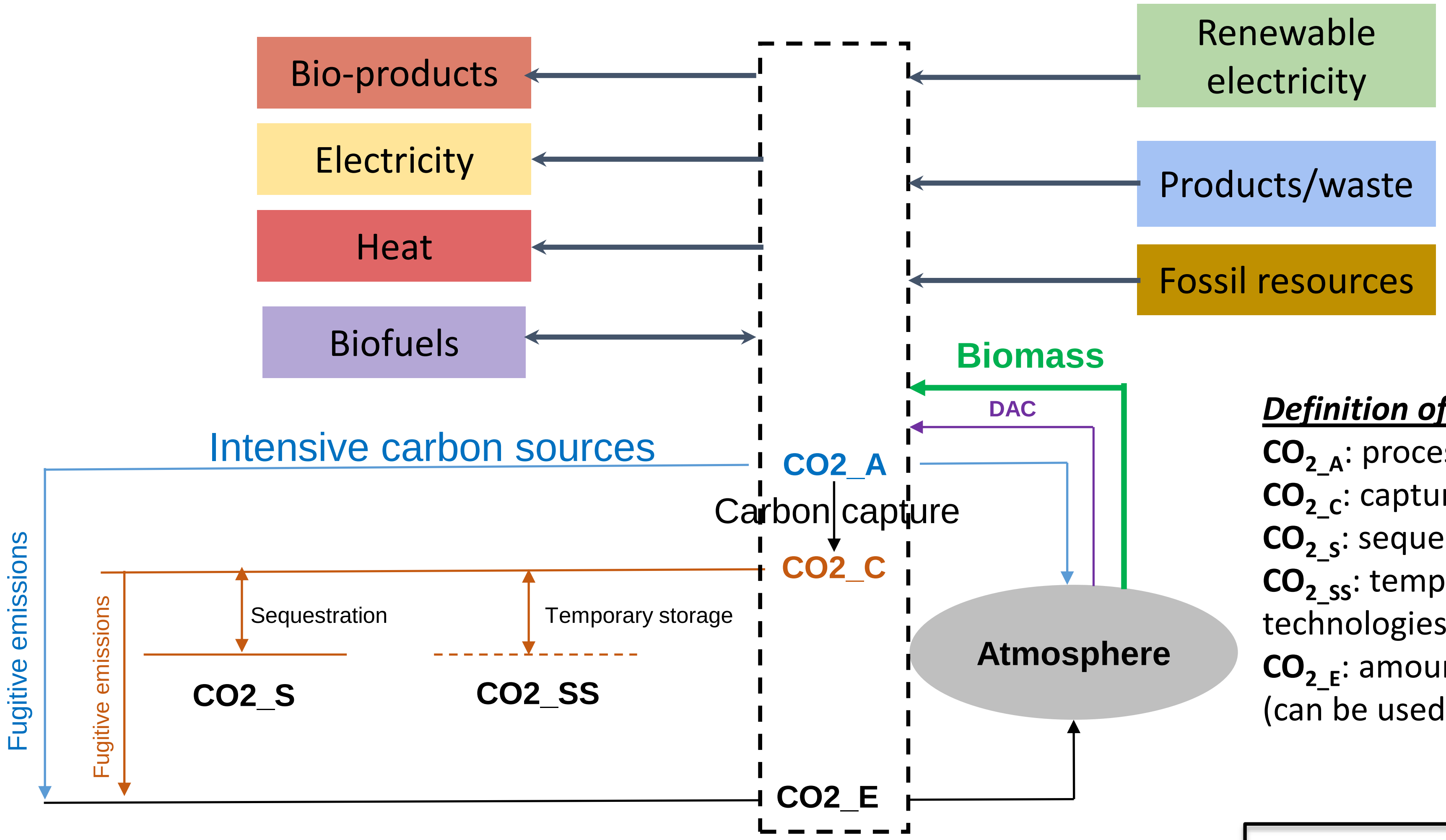
$$\sum_{j \in \mathcal{CC}} F(j,t) = \sum_{j \in \mathcal{CCS}} F(j,t) + \sum_{j \in \mathcal{CCU}} F(j,t) \quad \forall t \in \mathcal{T}$$

CC: carbon capture
CCS: carbon sequestration
CCU: carbon utilization
t: time period
j: technology

Define carbon content of resources/products

$$Carbon\ content_i = \frac{C\ mass\ fraction_i}{LHV_i} \quad \left[\frac{kt.C}{GWh}\right]$$

Carbon Flows in Energyscope



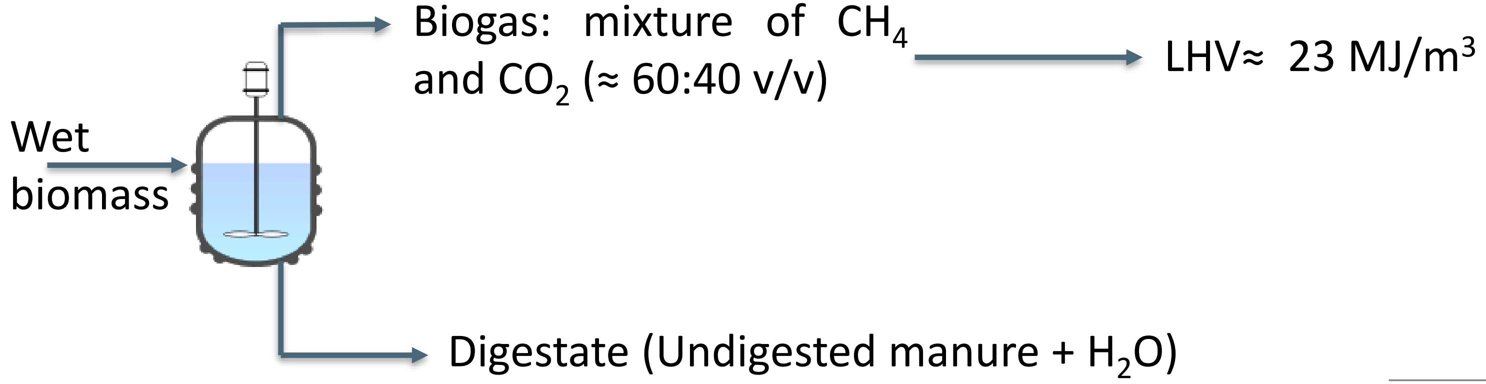
Definition of CO_2 layers:

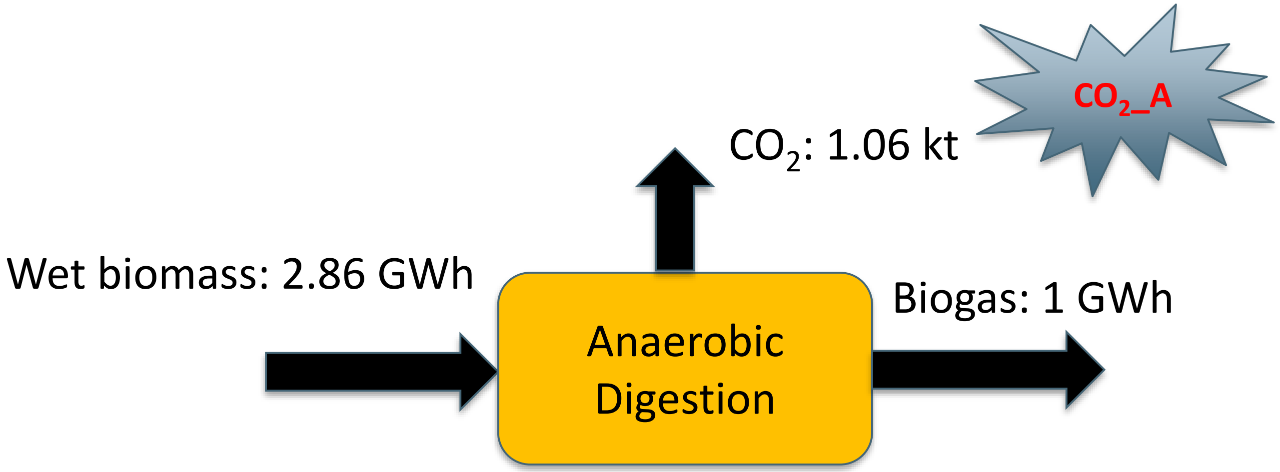
CO_{2_A}: process emitted CO_2 (can be captured)
CO_{2_C}: captured CO_2 using relevant technologies
CO_{2_S}: sequestrated CO_2 using relevant technologies
CO_{2_SS}: temporarily stored CO_2 using relevant technologies
CO_{2_E}: amount of CO_2 finally entering atmosphere (can be used to grow biomass)

$$\boxed{F_{CO2,A} + F_{CO2,C} + F_{CO2,S} + F_{CO2,SS} + F_{CO2,E} = 0}$$

Example – Anaerobic Digestion

A set of biochemical reactions that break the biogenic carbon of wet biomass and release it as biogas.





$$Carbon\ content_i = \frac{C\ mass\ fraction_i}{LHV_i} \quad \left[\frac{kt.C}{GWh}\right]$$

Carbon content of selected resources and products

Resource	*C mass fraction (kg C / kg)*	*LHV (kWh / kg)*	*Carbon content (kt C / GWh)*
Gasoline	0.83	12.06	0.0688
Diesel	0.861	11.83	0.0728
Wood	0.50	4.50	0.111
Natural Gas	0.704	13.10	0.0537
Coal	0.90	8.00	0.1125
Waste	0.40	2.71	0.1476
Wet Biomass	0.40	3.90	0.1025
Bioethanol	0.522	8.25	0.0633
Biodiesel	0.861	11.83	0.0727
LFO	0.855	12.22	0.0699
LNG	0.704	15.33	0.0459
Biogas	0.44	5.31	0.0828

Hydrothermal Gasification

A catalytic high-pressure conversion process, able to convert wet feedstock to CH_4 and/or H_2

Used to process most types of wet biomass.

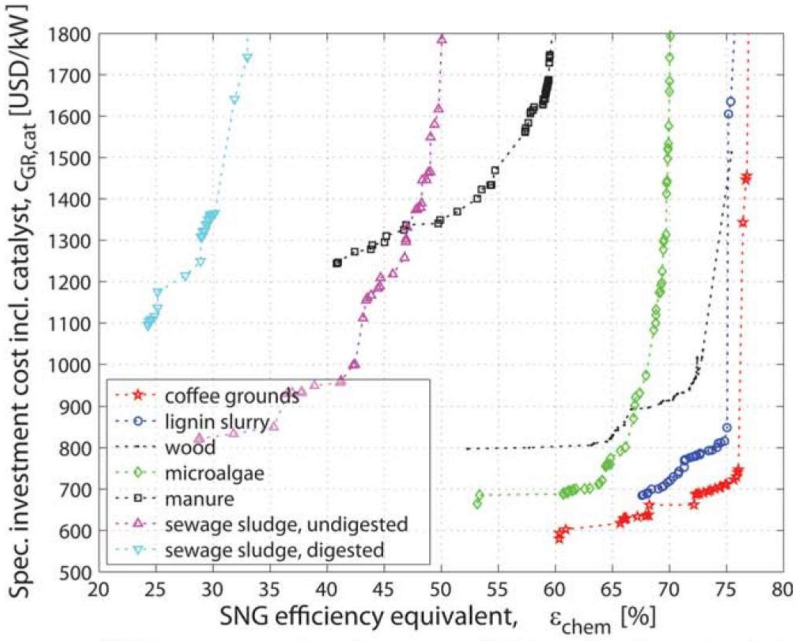
Avoids the energy intensive drying step.

Supercritical water conditions (> 25 - 30 MPa, > 270 °C) ensure:

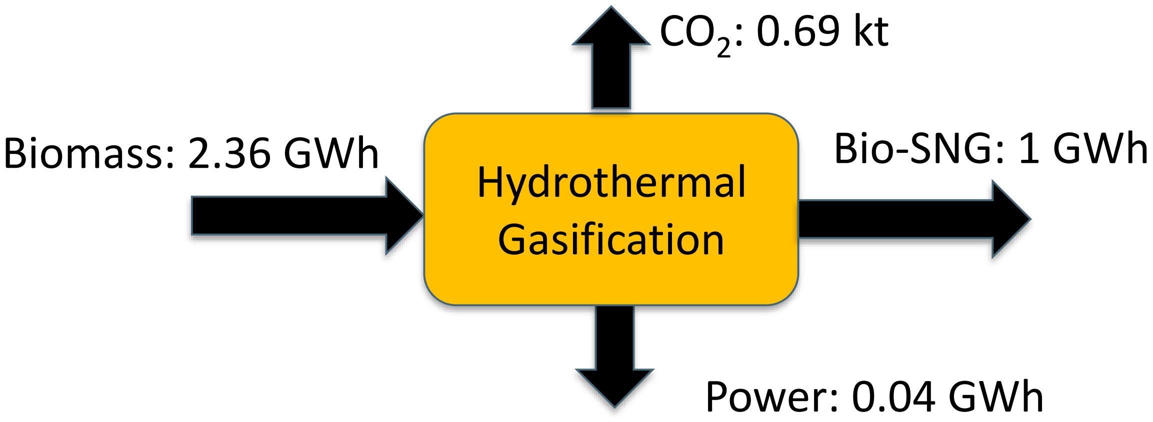
- The dissolution of organic matter in water.
- The preservation of the minerals contained in the biomass (K, P, N).

Able to achieve high CH_4 yield but high investment costs.

Cleaning and maintenance issues due to the use of catalyst.



M. Gassner, F. Vogel, G. Heyen, F. Maréchal, Energy Environ. Sci., 2011, 4, 1742-1758

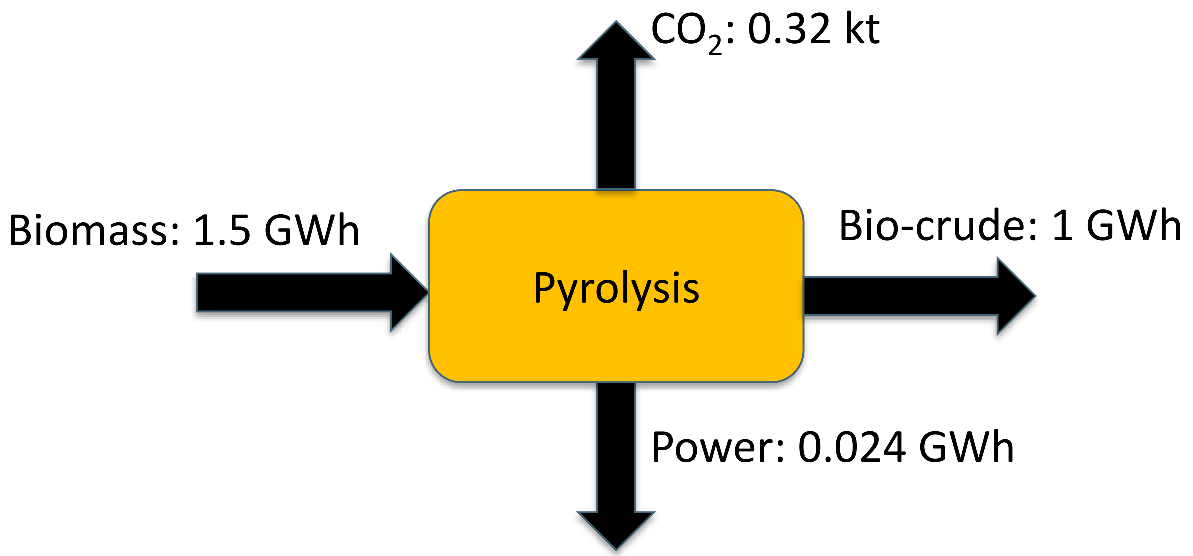


Wood Pyrolysis

The thermal decomposition of dry biomass in the absence of any oxidizing medium.

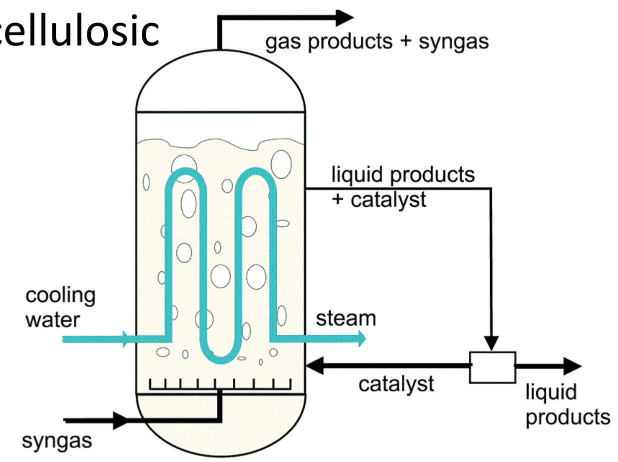
- Converts dry biomass into gaseous and liquid products and bio-char.
- Products dependent on the heating rate.
- Mainly used for the production of bio-crude.

A mature technology with applications based on different reactor designs (etc. fixed bed, fluidized bed, ablative reactors etc.), depending on the desired product.



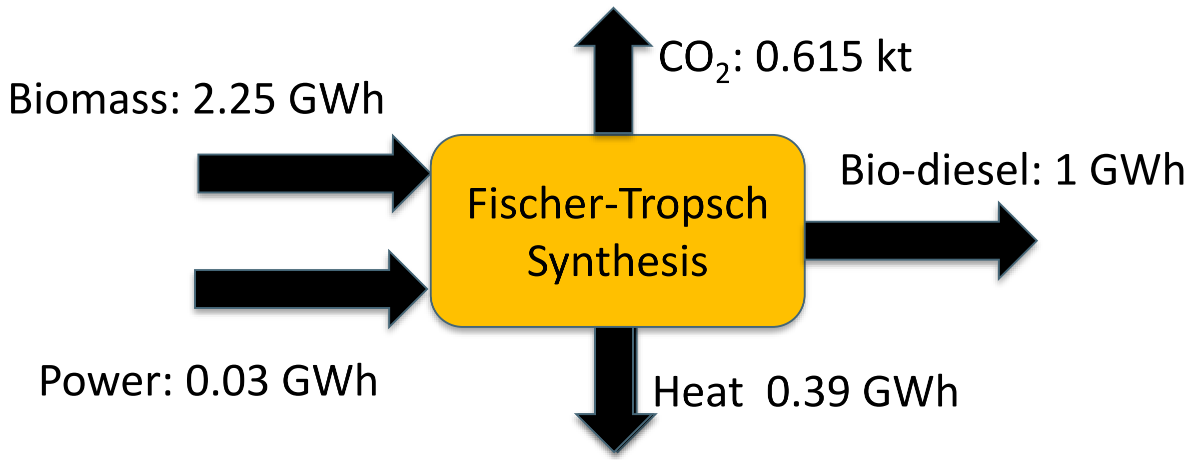
Biomass to Liquid Fuels (Fischer – Tropsch Synthesis)

The Fischer-Tropsch (F-T) process is used to synthesize bio-diesel from lignocellulosic biomass-derived syngas.



F-T synthesis is a catalytic polymerization reaction that takes place at 250-300 ^{o}C and 20-30 bars in slurry reactors.
The final product is a mixture of paraffins, depending on the ***operating conditions and H_2/CO input ratio***.

Fischer-Tropsch requires high purity input streams due to the sensitive nickel or cobalt catalysts.
Products must undergo hydrotreatment to adjust the final hydrocarbon blend.



CO_2 to Biomethane

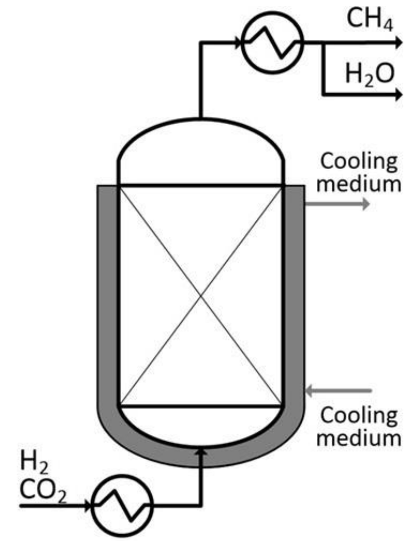
Captured carbon dioxide can be converted to methane using renewable hydrogen (e.g. water electrolysis) in the process known as Power-to-Gas

By using the Sabatier process

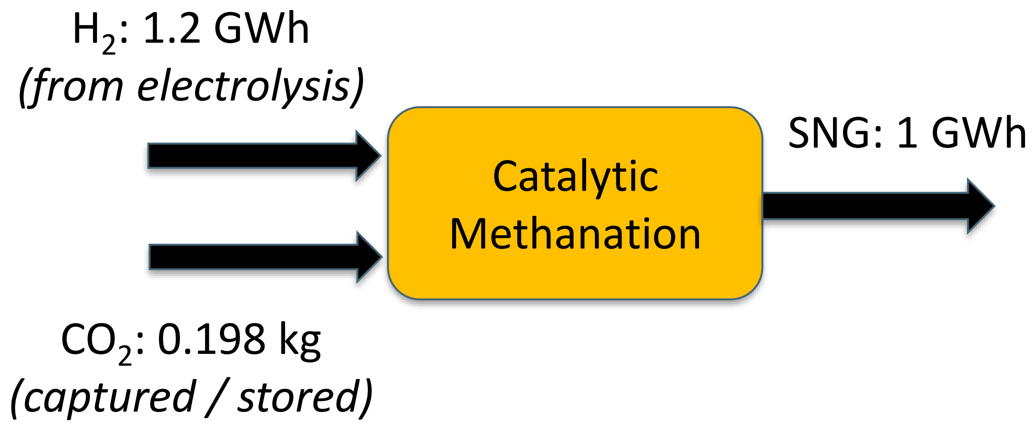
$$CO_2 + 4H_2 \rightleftharpoons CH_4 + 2H_2O$$

$$CO + 3H_2 \rightleftharpoons CH_4 + 2H_2O$$

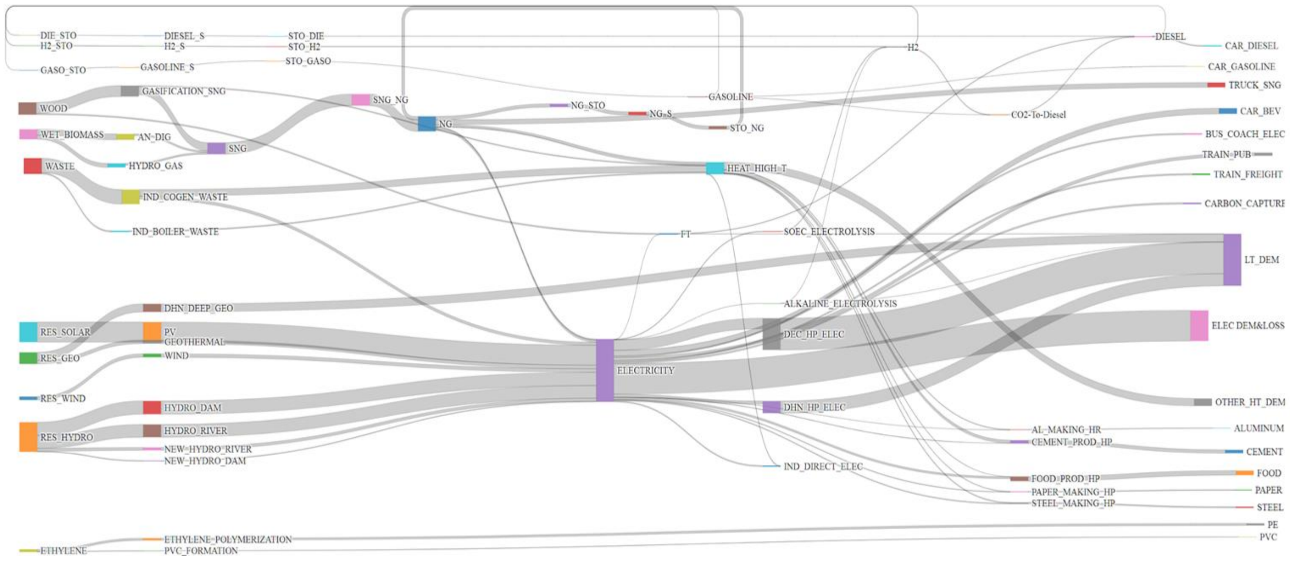
In a catalytic (nickel, alumina) reactor at 300-400 ^{o}C and 20-30 bar.



adapted from M. Held, D. Schollenberger, S. Sauerschell, S. Bajohr, T. Kolb, Power-to-Gas: CO2 Methanation Concepts for SNG Production at the Engler-Bunte-Institut, Chemie Ingenieur Technik, 92(5), 2020, doi:10.1002/cite.201900181

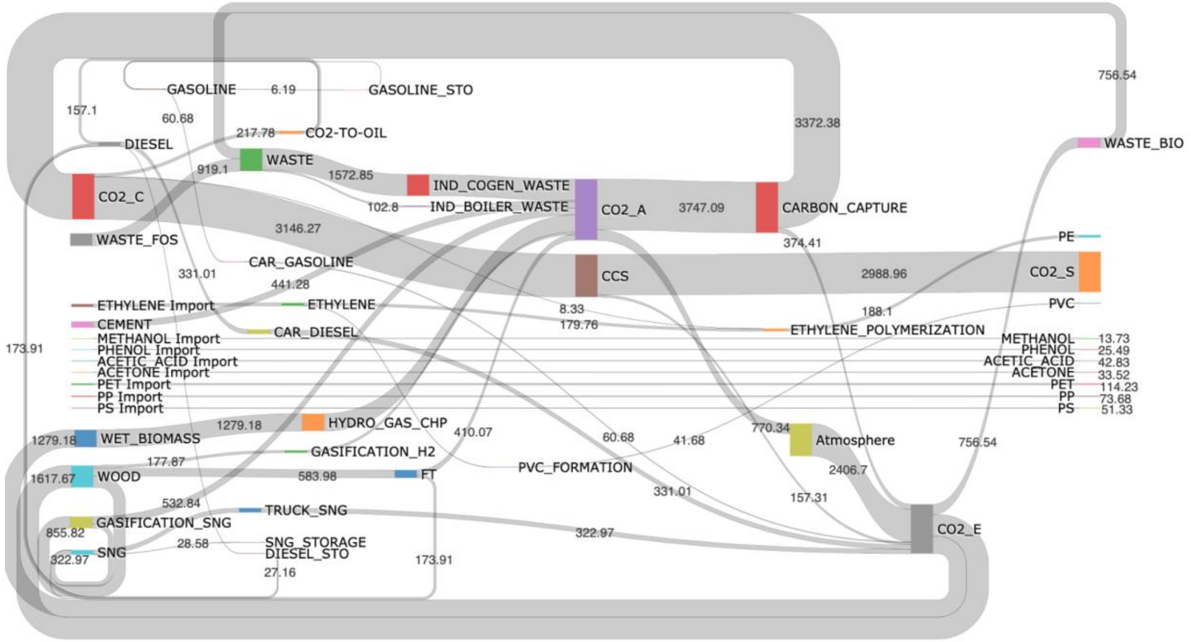


Energyscope Output



Energy Sankey diagram: flows of energy (TWh/y)

Carbon Sankey diagram: flows of carbon (kt C/y)



Take Home Messages

- Biomass is both a source of energy and carbon.
- Existing biomass potentials are sufficient to cover a large part of the Swiss energy demand.
- Available carbon has to be efficiently used in the energy system to maximize efficiency and minimize CO_2 emissions.
- Carbon flow representation within the boundaries of the energy system is feasible using multiple interacting layers with different physical meanings.
- Integration of the carbon flows into Energyscope results in an additional graphical representation (carbon Sankey) which has to be analyzed together with the energy one to derive conclusions on the energy system.
- Biomass / carbon conversion technologies always yield at least one carbon / CO_2 flow that has to be accounted for.