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The feasibility of integrating biomass steam gasification and syngas biomethanation to store renewable energy as methane gas

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High-quality fuels from biomass gasification

A glance at future renewable energy systems

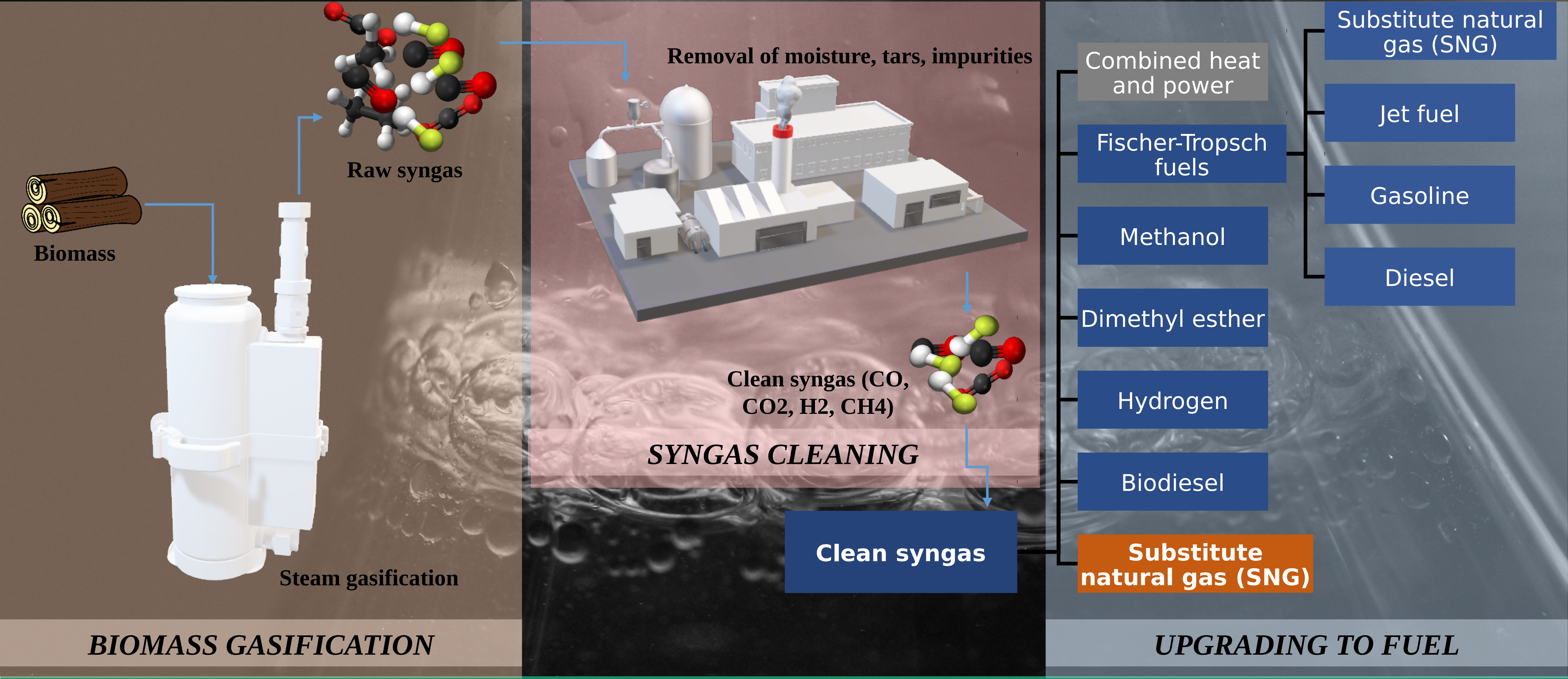
- Multiple sectors will require **diverse renewable fuels**

and

- Fuels with **high storage capacity** will be required to grant temporal flexibility

Thus, sole **heat and power** production from biomass will not be appropriate: biomass conversion has to shift towards the synthesis of **versatile, storable, transportable fuels**

High-quality fuels from biomass gasification



Why Methane?

- High **volumetric energy content** :
  LHV_{CH_4}: 33 MJ/Nm^3 vs LHV_{H_2}: 10 MJ/Nm^3

- Existing transport and storage **infrastructure**

- Established combustion and conversion **technologies** across sectors

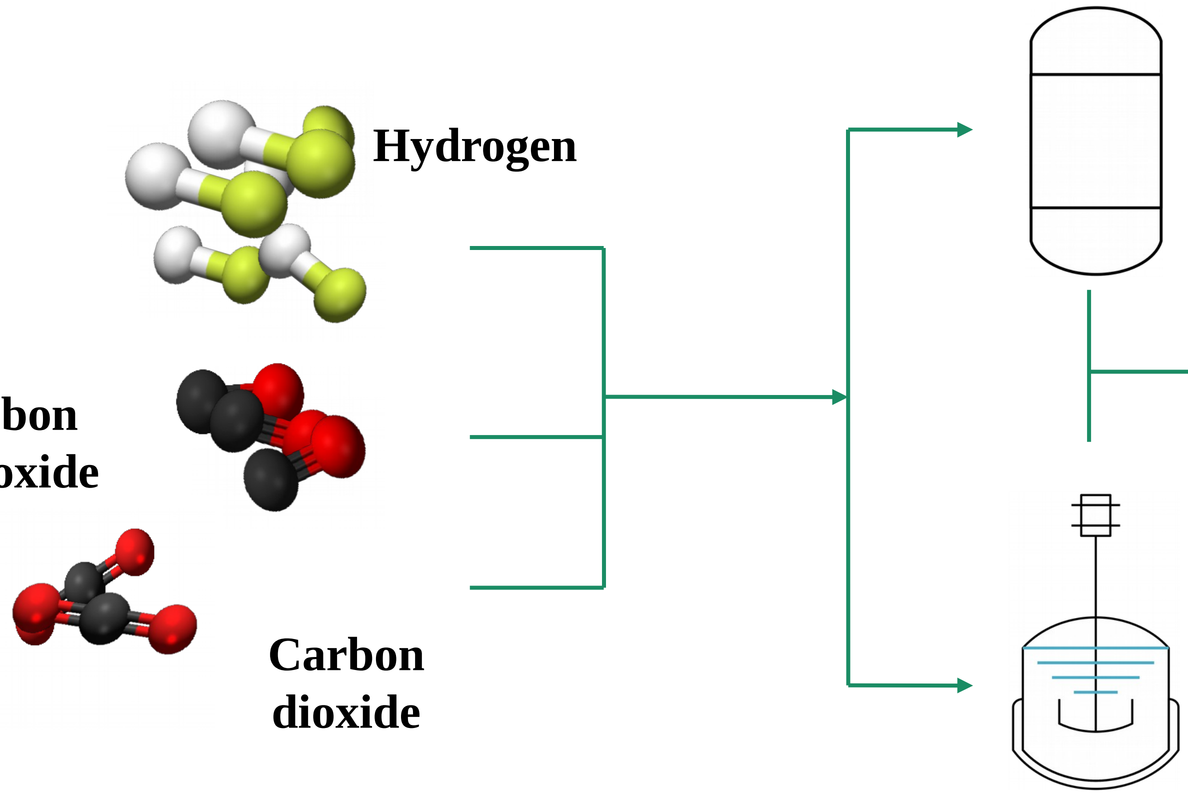


«*Natural gas offers many potential benefits [...] given limits to how quickly renewable energy options can **scale up** and that cost-effective zero-carbon options can be **harder to find in some parts of the energy system**. The **flexibility** that natural gas brings to an energy system can also make it a good fit for the rise of **variable renewables** such as wind and solar PV*»

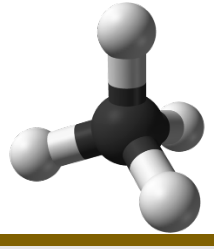
- International Energy Agency, 2017

Methanation processes

$$CO_2 + 4H_2 \leftrightarrow \boldsymbol{CH_4} + H_2O$$
$$CO + 3H_2 \leftrightarrow \boldsymbol{CH_4} + H_2O$$
$$4\,CO + 2\,H_2O \leftrightarrow \boldsymbol{CH_4} + 3\,CO_2$$



Catalytic methanation
- Operating temperatures: 300-550 °C
- Operating pressures: 1-100 bar
- Risk of catalyst poisoning

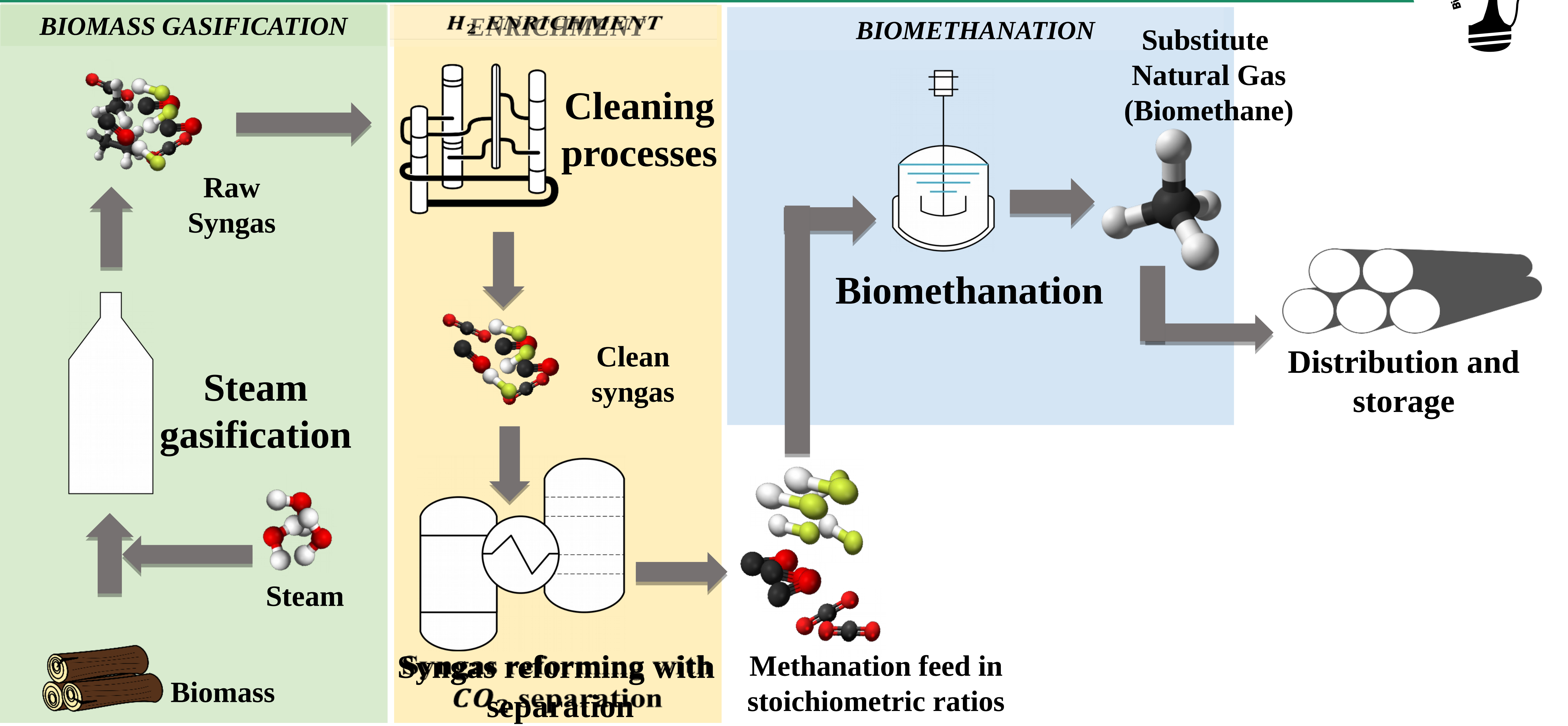


Biological methanation
- Operating temperatures: **35-70 °C**
- Operating pressures: **atm or higher**
- Tolerance to feed **impurities**

CO, CO_2, H_2 IN STOICHIOMETRIC RATIOS

CATALYTIC OR BIOLOGICAL METHANATION

Biomethanation of syngas: Substitute Natural Gas from biomass



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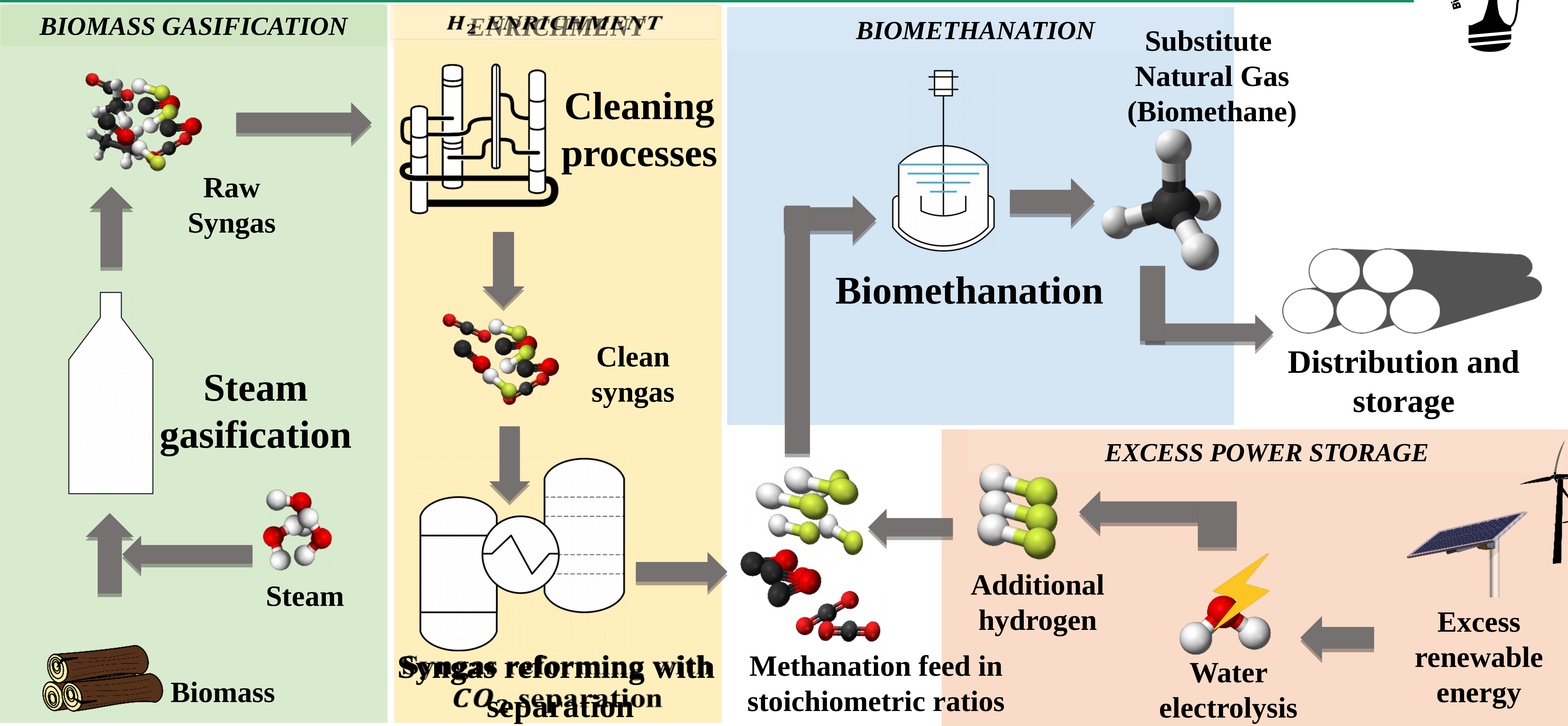
Biomethanation of syngas: Substitute Natural Gas from biomass and Power-to-Gas services



Key feasibility questions

1. **Yield of biomethane**?
2. **Overall production capacity**?
3. **Energy efficiency**?
4. Product **minimum selling price**?
5. Desirability of **biomethane** compared to **hydrogen**?

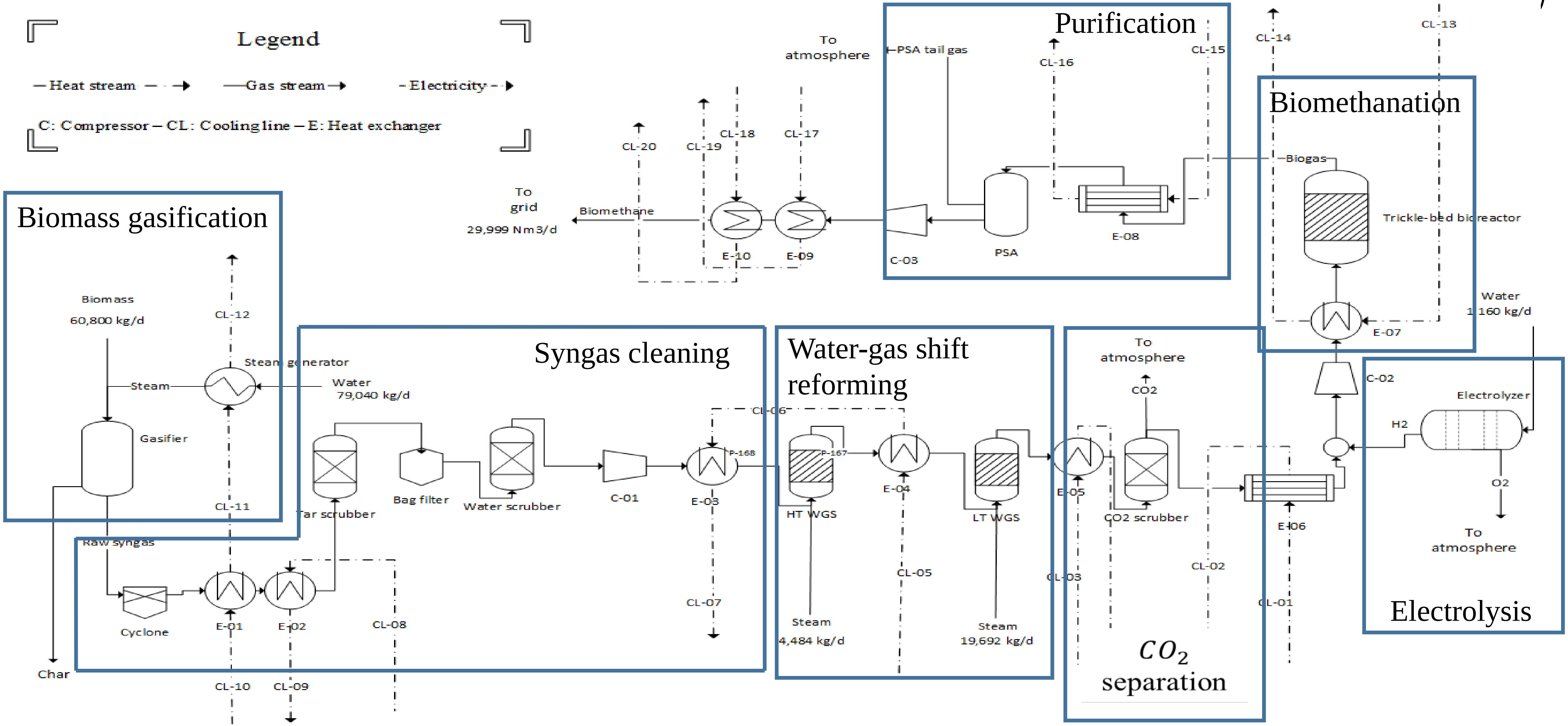
Study objectives

Define a **Biomass-to-Biomethane** system (A) and a **Biomass-to-Hydrogen** system (B), both supplemented by **water electrolysis**.

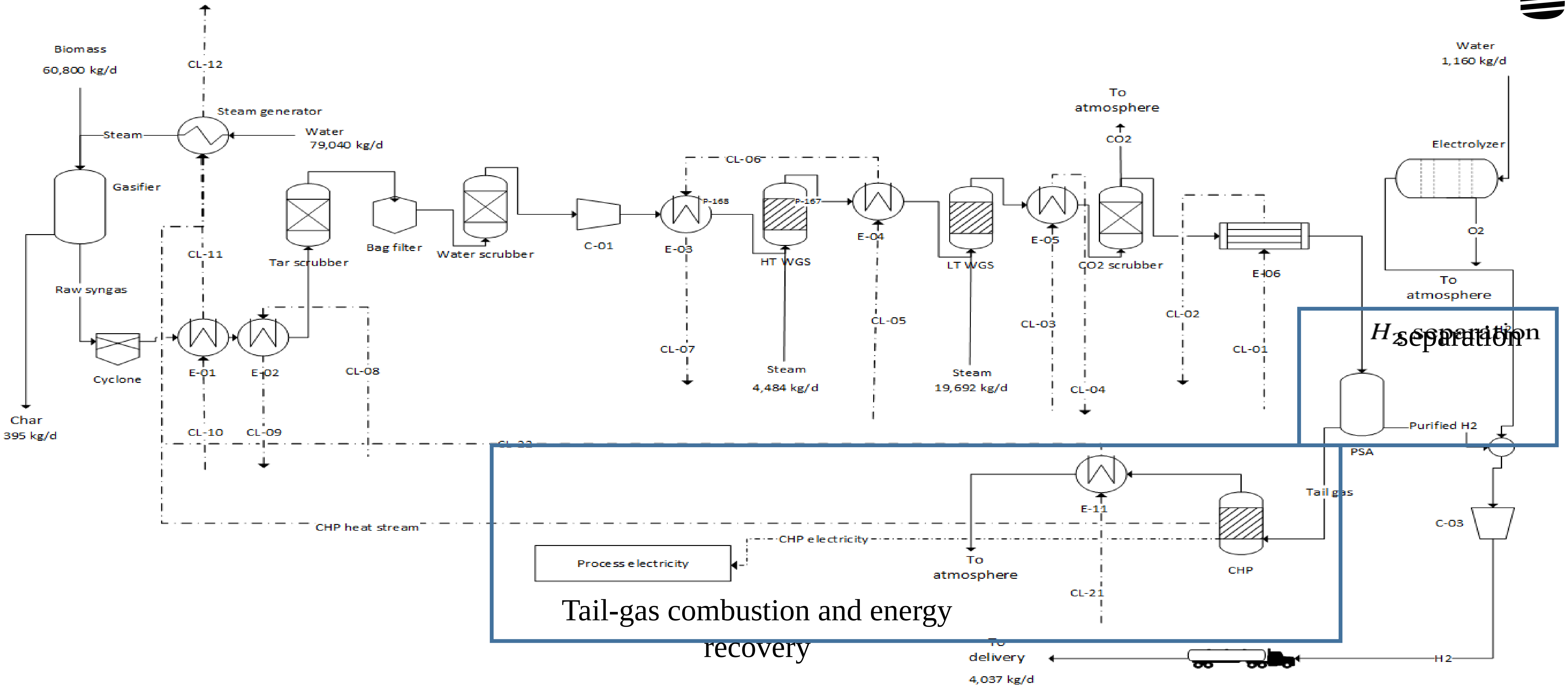
And for both systems:

1. Estimate the **system mass balance and production capacity**
2. Estimate the **system energy balance and efficiency**
3. Estimate the **minimum selling price** of the products
4. Identify system **optimization requirements**

System A: Biomass-to-Biomethane



System B: Biomass-to-Hydrogen



Process techno-economic parameters

Process section	Parameter	Value	Reference
Dual fluidized bed gasifier	Cold gas efficiency calculated on syngas lower heating value	72%	Ptasinski (2015)
Alkaline water electrolysis	Share of excess electricity input	30%	Technical assumption
	Share of grid electricity input	70%	
	Specific electrical consumption	4.6 kWh/Nm^3 H_2	Guillet and Millet (2015)
Biomethanation	Hydrogen conversion rate	97%	Rachbauer *et al*. (2016)
Pressure swing adsorption	Methane recovery rate	90%	Augelletti *et al*. (2017)
	Hydrogen recovery rate	85%	Yao *et al*. (2017)
Water-gas shift reforming	Low-temperature carbon monoxide conversion rate	47%	Thermodynamic model in Matlab with empirical correlations based on literature data
	High-temperature carbon monoxide conversion rate	59%	

Process financial assumptions and parameters

Parameter	Value
General financial assumptions	
Plant lifetime	20 years
Tax rate	35%
Discount rate	7%
Materials, utilities, labor	
Biomass cost	100 €/t
Char disposal cost	150 €/t
Labor	24.87 €/man-hour
Natural gas	0.03 €/kWh
Full-price electricity	0.09 €/kWh
Surplus renewable electricity	0.05 €/kWh

System mass balance and production capacity

System ID	Product type	Input			Output	
		Biomass	Liquid water	Steam	Biomethane	Hydrogen
		kg/day			Nm^3/day	kg/day
A	Biomethane	60,800	1,160	103,217	**26,999**	-
B	Hydrogen	60,800	1,160	103,217	-	**4,037**

Important comparisons

Typical production of European anaerobic digestion biomethane plant: 12,000 - 14,000 Nm^3/day of biomethane

Typical H_2 consumption of European ammonia production plant: 160,000 - 315,000 kg/day
Typical H_2 consumption of European oil refinery: 20,000 - 300,000 kg/day

System mass balance and conversion efficiency

System ID	Product type	Hydrogen utilization	Yield on dry biomass	Yield on carbon or hydrogen
			Nm^3 SNG/kg biomass	mol CH_4/mol C
A	Biomethane	97.5%	**0.44**	0.45
			kg H_2/kg biomass	mol H_2/mol H_2
B	Hydrogen	85.0%	**0.07**	0.35

Major conversion limitations with respect to carbon (A) and hydrogen (B) inputs

Process A: - carbon losses in CO_2 scrubbing

Process B: - hydrogen losses in PSA tail gas

- steam conversion limitations in gasification and water-gas shift reforming
- moisture removal

System energy balance and efficiency

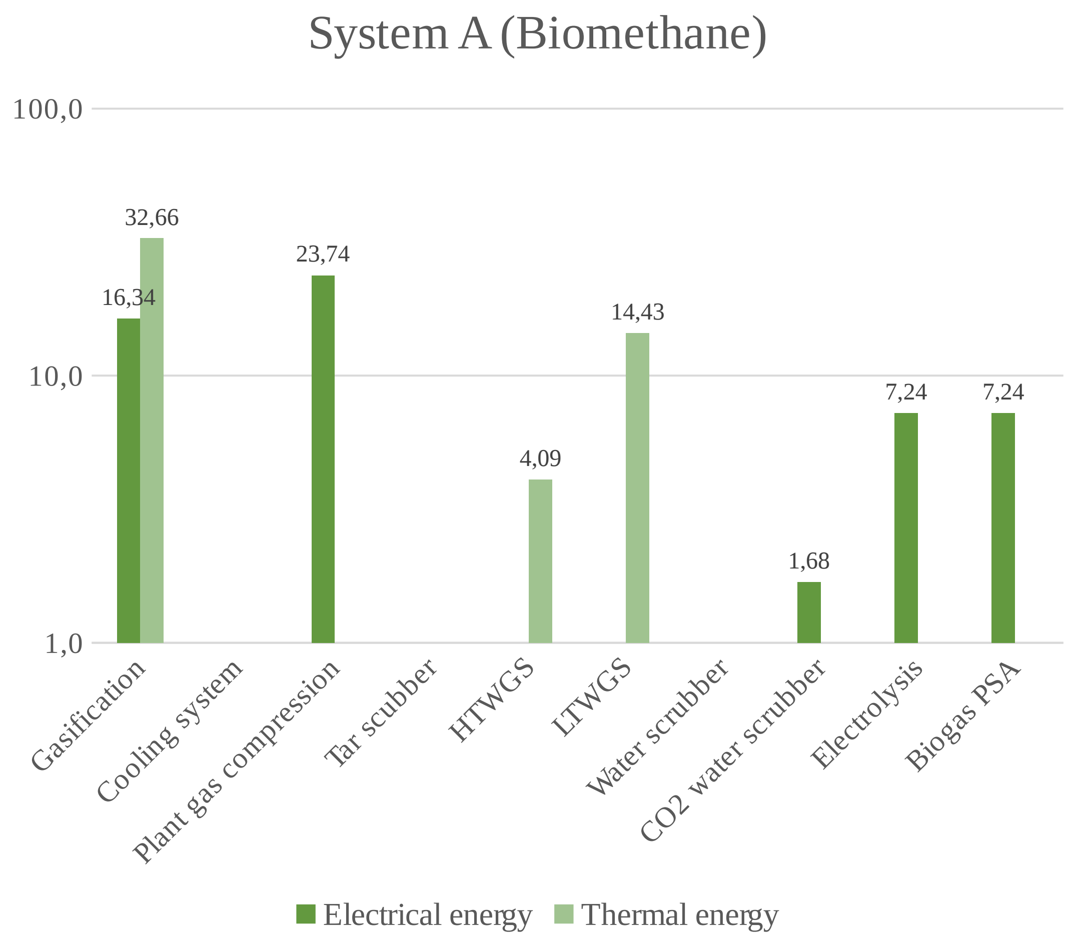
System ID	Product type	Energy input			Energy output	Efficiency
		Biomass	Thermal	Electrical	Product LHV	Cold gas efficiency
		MW				-
A	Biomethane	13	2.1	2.3	10.2	58.4%
B	Hydrogen		**0.8**	**1.5**	5.6	36.6%

Energy recovery from PSA tail-gas combustion in Process B

Electricity: 1.39 MW
High-temperature heat: 2.91 MW

Breakdown of process energy requirements

Energy consumption (MWh/day)



Greatest electrical energy requirements

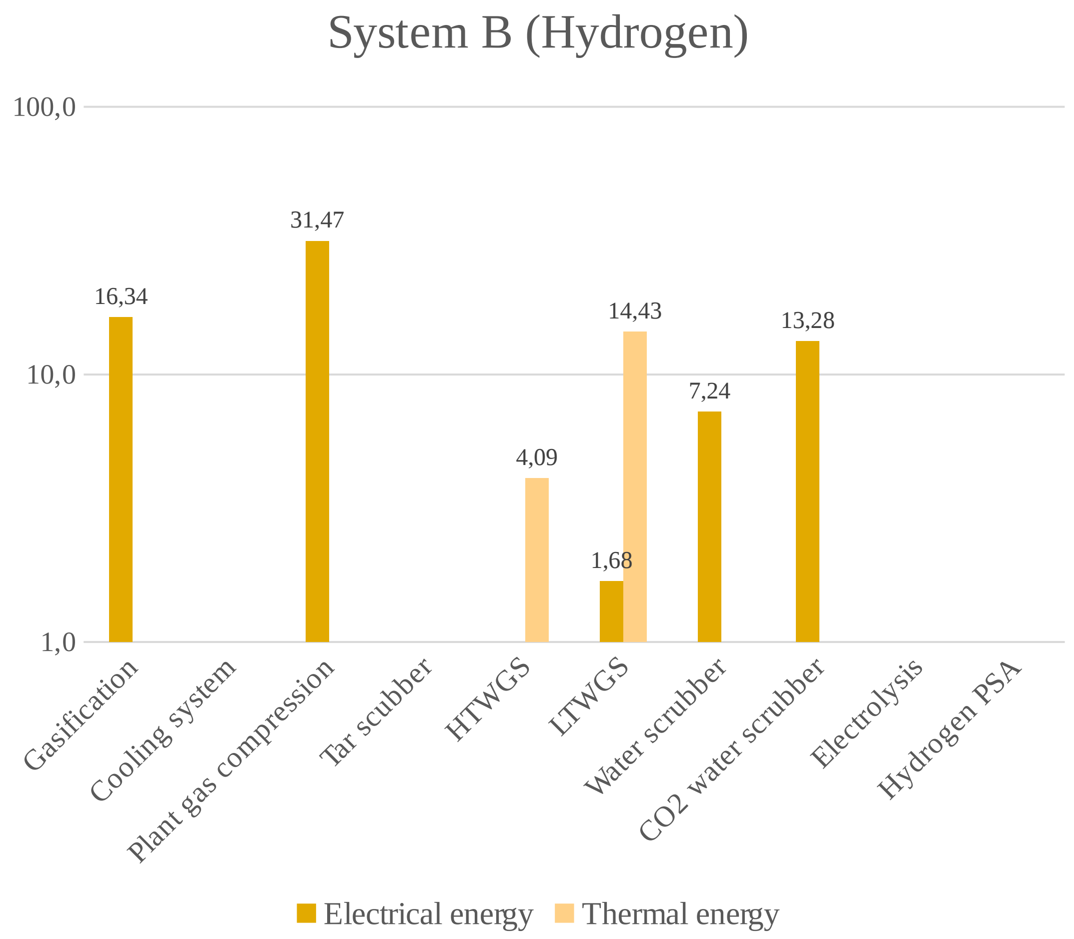
1. Gas compression (42%)
2. Gasification (29%)
3. Pressure Swing Adsorption (13%)

Greatest thermal energy requirements

1. Gasification steam (64%)
2. Water-gas shift steam (28%)

Breakdown of process energy requirements

Energy consumption (MWh/day)



Greatest electrical energy requirements

1. Gas compression (45%)
2. Gasification (23%)
3. Pressure Swing Adsorption (19%)

Thermal energy requirements

Water-gas shift units are only source of heat demand, thanks to PSA tail-gas combustion and heat integration

Product minimum selling price and current market prices

		Minimum selling price		Current market prices	
System	Product	Product unit	Energy unit	Product description	Product unit price
A	Biomethane	**2.37 €/Nm³**		Biomethane from AD of waste and by-products	0.83 €/Nm³
B	Hydrogen				

(1) Through biomass gasification and CHP production; (2) Before delivery

Product minimum selling price and current market prices

		Minimum selling price		Current market prices	
System	Product	Product unit	Energy unit	Product description	Product unit price
A	Biomethane	**2.37 €/Nm³**	0.26 €/kWh	Biomethane from AD of waste and by-products	0.83 €/Nm³
				Biomass-derived(1) renewable electricity	0.16 €/kWh – 0.27 €/kWh
B	Hydrogen				

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				Biomass-derived[1] renewable electricity	0.16 €/kWh – 0.27 €/kWh
B	Hydrogen	**15.45[2] €/kg**	0.46 €/kWh		

[1] Through biomass gasification and CHP production; [2] Before delivery

Product minimum selling price and current market prices

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				Biomass-derived[(1)] renewable electricity	0.16 €/kWh – 0.27 €/kWh
B	Hydrogen	**15.45[(2)] €/kg**	0.46 €/kWh	Technical grade hydrogen (before delivery)	8.54-10.98 €/kg
				Technical grade hydrogen (after mid-range delivery)	11 – 13 €/kg

[(1)] Through biomass gasification and CHP production; [(2)] Before delivery

Conclusions

Among the two systems analyzed:

1. Biomass-to-Biomethane (system A) shows
   a) a **higher yield on biomass**
   b) a **more efficient utilization of the hydrogen input**
   c) an overall **higher cold gas efficiency production capacity**

2. Biomass-to-Hydrogen (system B) offers **better heat integration opportunities**, thanks to PSA tail gas combustion

Conclusions

3. The **renewable energy subsidies** required to make syngas biomethanation feasible are **comparable with those currently in place** for on-site syngas combustion for CHP in Italy

4. Biomass-to-Biomethane provides **higher production capacities and lower delivery costs** than hydrogen purification: better option for biomass gasification

5. Key process optimization areas include:
   a) **Steam-to-hydrogen conversion** in gasification and syngas reforming processes
   b) Process operation at **lower pressures** to reduce power inputs
   c) Better **heat integration** in Biomass-to-Biomethane processes

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Thank you

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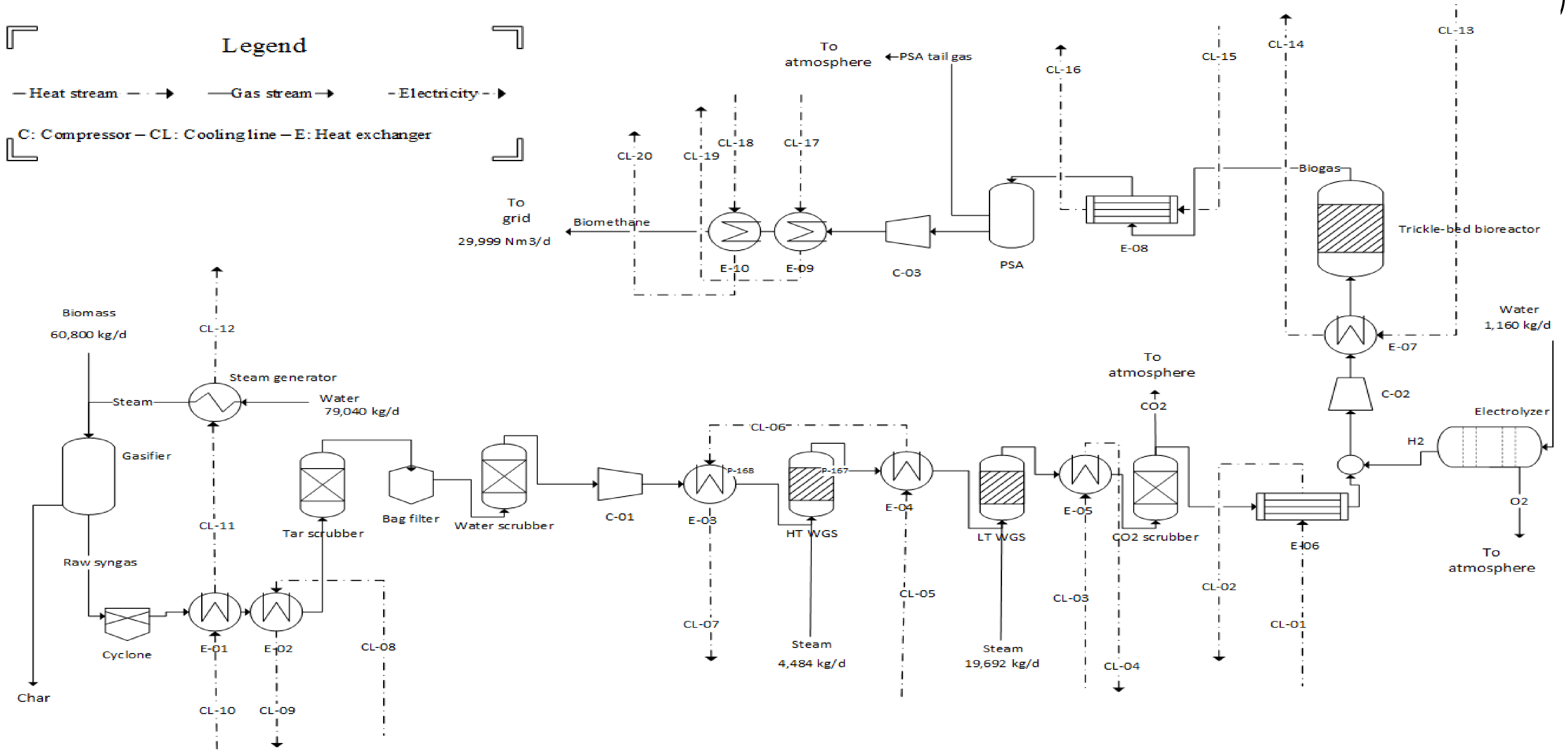
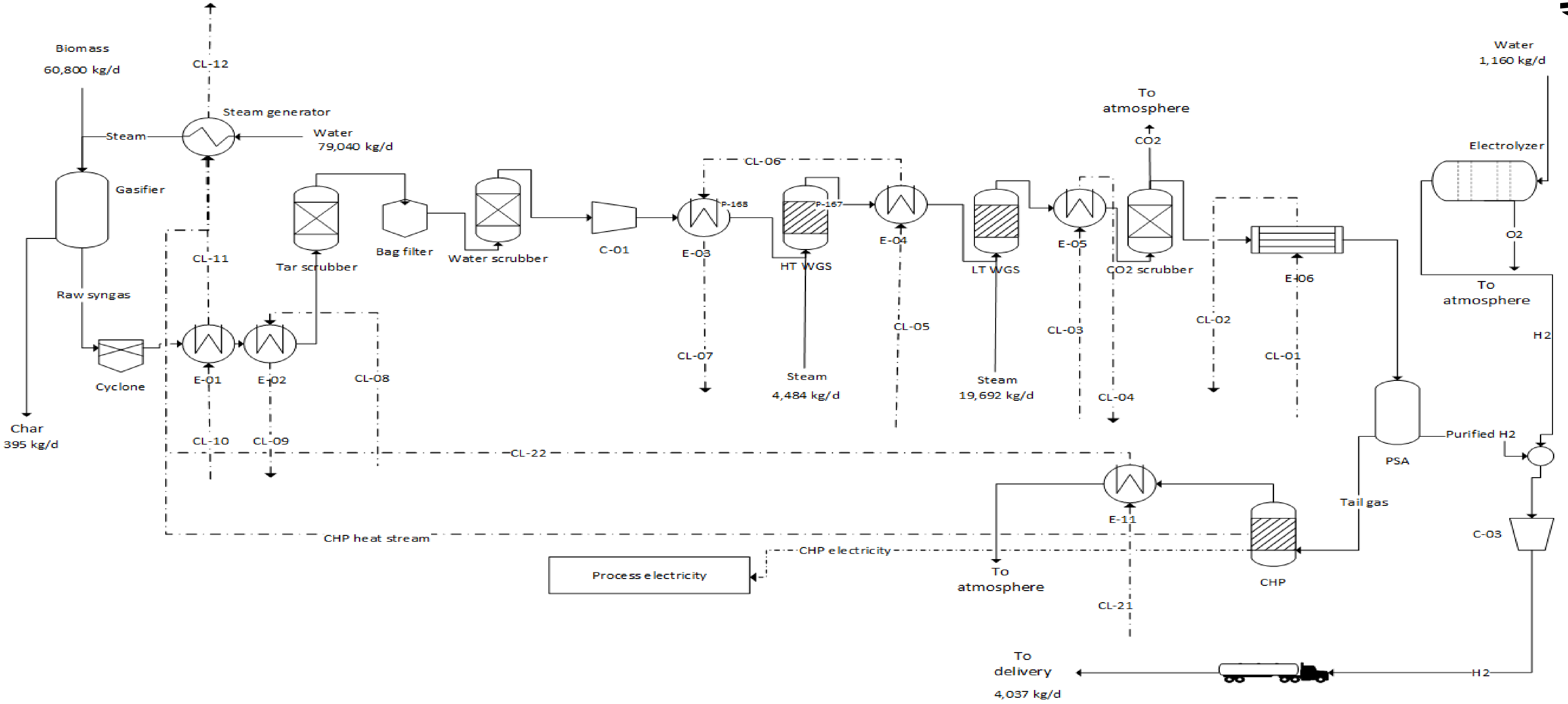
System A: Biomass-to-Biomethane



System B: Biomass-to-Hydrogen



Product minimum selling prices in similar systems

This study		Previous studies			
Process	Minimum selling price	Process	Adapted unit prices	Ref.	Notes
Biological methanation	2.37 €/Nm^3	Catalytic methanation	0.5 €/Nm^3	Gassner and Maréchal (2008)	
			0.65 €/Nm^3	Rivarolo and Massardo (2013)	• Surplus electricity cost: 0.01 €/kWh vs. 0.05 €/kWh • Biomass cost 40 €/t vs. 100 €/t
Hydrogen purification	15.45 €/kg	Hydrogen purification	3.71 €/kg	Hulteberg and Karlsson (2009)	Biomass cost 30% of biomass cost in this study
			3.1 – 3.4 $/kg	Salkuyeh *et al*. (2017)	Biomass cost 90% of biomass cost in this study

Water-gas shift modeling

Model assumptions:

- Single adiabatic reactors at 15 bar pressure
- Water-gas shift is only reaction taking place: $CO + H_2O \leftrightarrow CO_2 + H_2$
- High-temperature WGS: 350 °C; Low-temperature WGS: 200 °C

Iteration set-up in Matlab with Cantera thermodynamic database

Adiabatic process assumption: $H_{feed} = H_{product}$

Set Matlab iteration

Find temperature T that satisfies adiabatic assumption

Calculate corresponding CO equilibrium conversion

$$\frac{K}{K_{ref}} = \exp\left[\frac{\Delta H_0}{R}\left(\frac{1}{T} - \frac{1}{T_{ref}}\right)\right]$$

T = adiabatic reactor temperature
$\chi_{eq}(T)$ = equilibrium conversion

BUT $\chi_{real}(T) < \chi_{eq}(T)$

Correct by means of empirical correlations as function of reaction temperature:

$$\Delta\chi = \chi_{eq} - \chi_{real} = f(T)$$

Reaction type	Correlation function	Ref.
High temperature WGS	$\Delta\chi = 745.8 \exp(-0.02\ T)$ $(R^2 = 0.99)$	Rauch *et al.* (2015)
Low temperature WGS	$\Delta\chi = 6.26 \exp(-0.01\ T)$ $(R^2 = 0.97)$	Jeong *et al.* (2014)