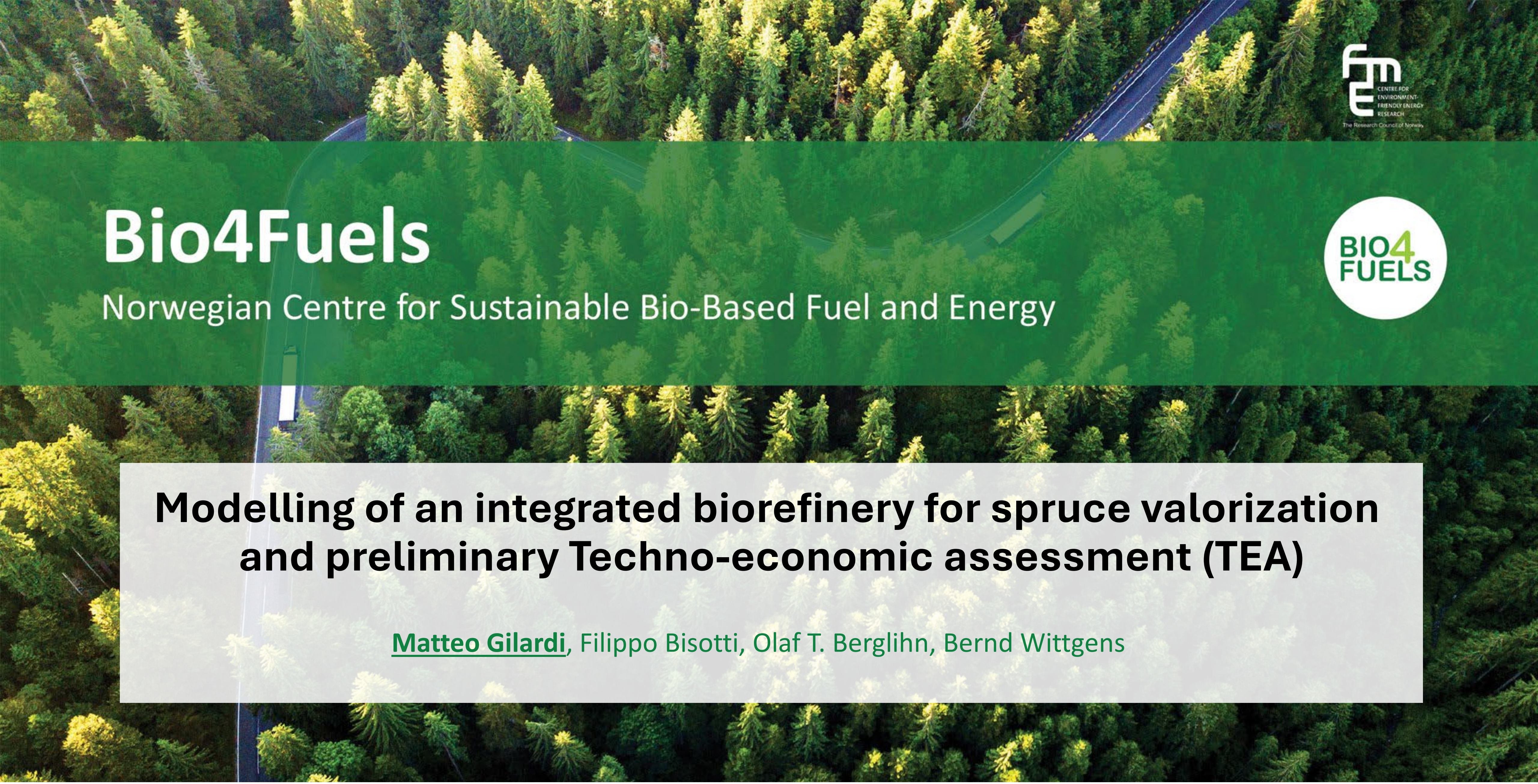


Bio4Fuels

Norwegian Centre for Sustainable Bio-Based Fuel and Energy

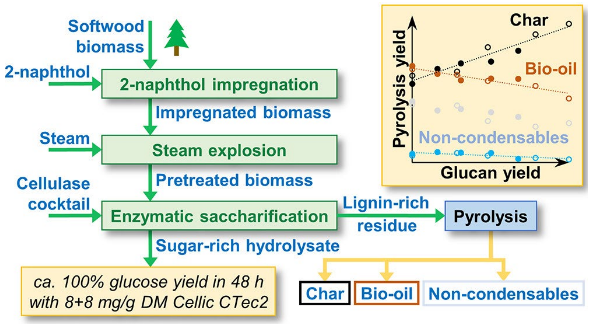
Modelling of an integrated biorefinery for spruce valorization and preliminary Techno-economic assessment (TEA)

Matteo Gilardi, Filippo Bisotti, Olaf T. Berglihn, Bernd Wittgens

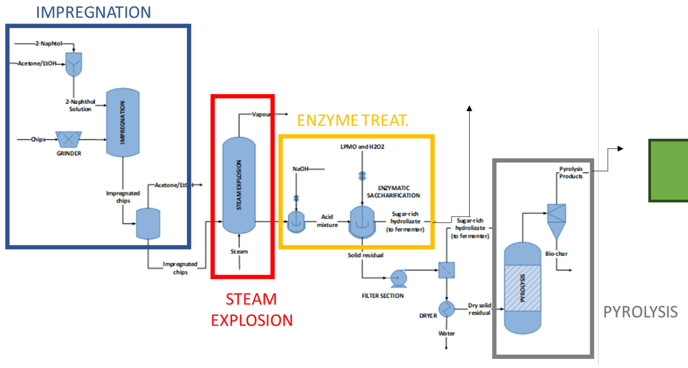
From lab-scale to industrial facility

We target process **design and scale-up** of a **biorefinery for the valorization of spruce chips**:

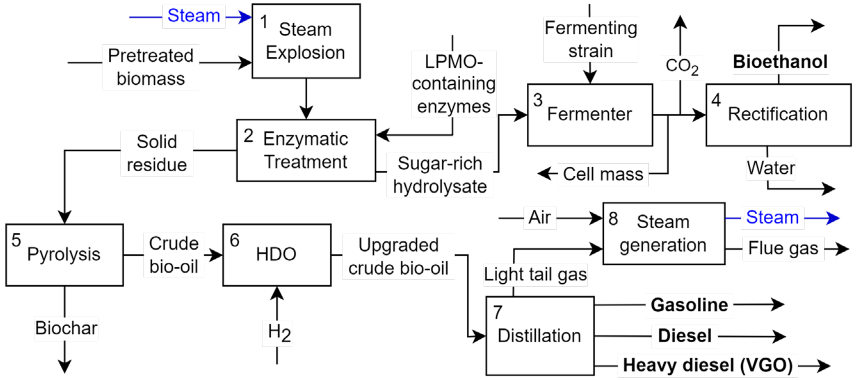
- Remove lab-scale steps that cannot be replicated on an industrial scale
- Identify missing steps and **design a comprehensive process**
- Identify a feasible and **valuable path** to **convert biomass into added-value chemicals**


Softwood biomass
2-naphthol
2-naphthol impregnation
Impregnated biomass
Steam
Steam explosion
Pretreated biomass
Cellulase cocktail
Enzymatic saccharification
Lignin-rich residue
Pyrolysis
Sugar-rich hydrolysate
ca. 100% glucose yield in 48 h with 8+8 mg/g DM Cellic CTec2
Char
Bio-oil
Non-condensables

1. Tested lab-scale concept

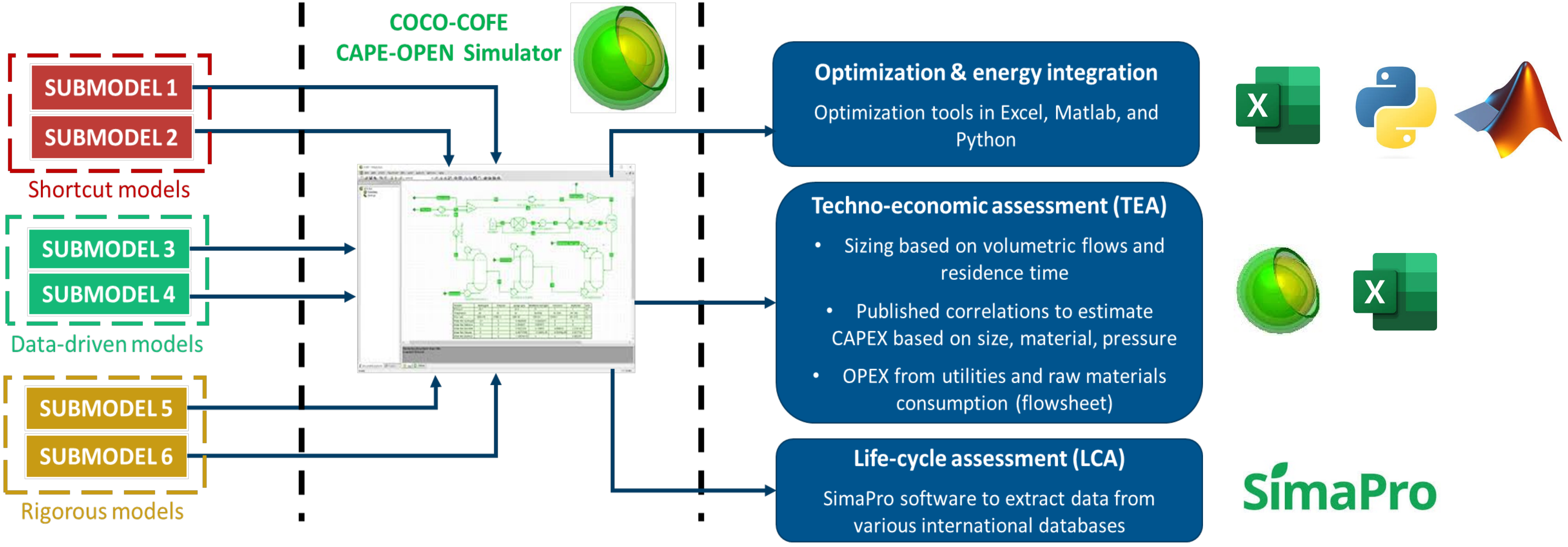

IMPREGNATION
STEAM EXPLOSION
ENZYME TREAT.
PYROLYSIS

2. Translation into a feasible industrial plant


Steam
Pretreated biomass
1 Steam Explosion
2 Enzymatic Treatment
LPMO-containing enzymes
Solid residue
Sugar-rich hydrolysate
Fermenting strain
3 Fermenter
Cell mass
CO_2
4 Rectification
Bioethanol
Water
5 Pyrolysis
Biochar
Crude bio-oil
6 HDO
H_2
Upgraded crude bio-oil
Air
8 Steam generation
Steam
Flue gas
Light tail gas
7 Distillation
Gasoline
Diesel
Heavy diesel (VGO)

3. BFD completed with missing steps/units

Approach: from plug-in models to TEA



Optimization & energy integration

Optimization tools in Excel, Matlab, and Python

Techno-economic assessment (TEA)

- Sizing based on volumetric flows and residence time
- Published correlations to estimate CAPEX based on size, material, pressure
- OPEX from utilities and raw materials consumption (flowsheet)

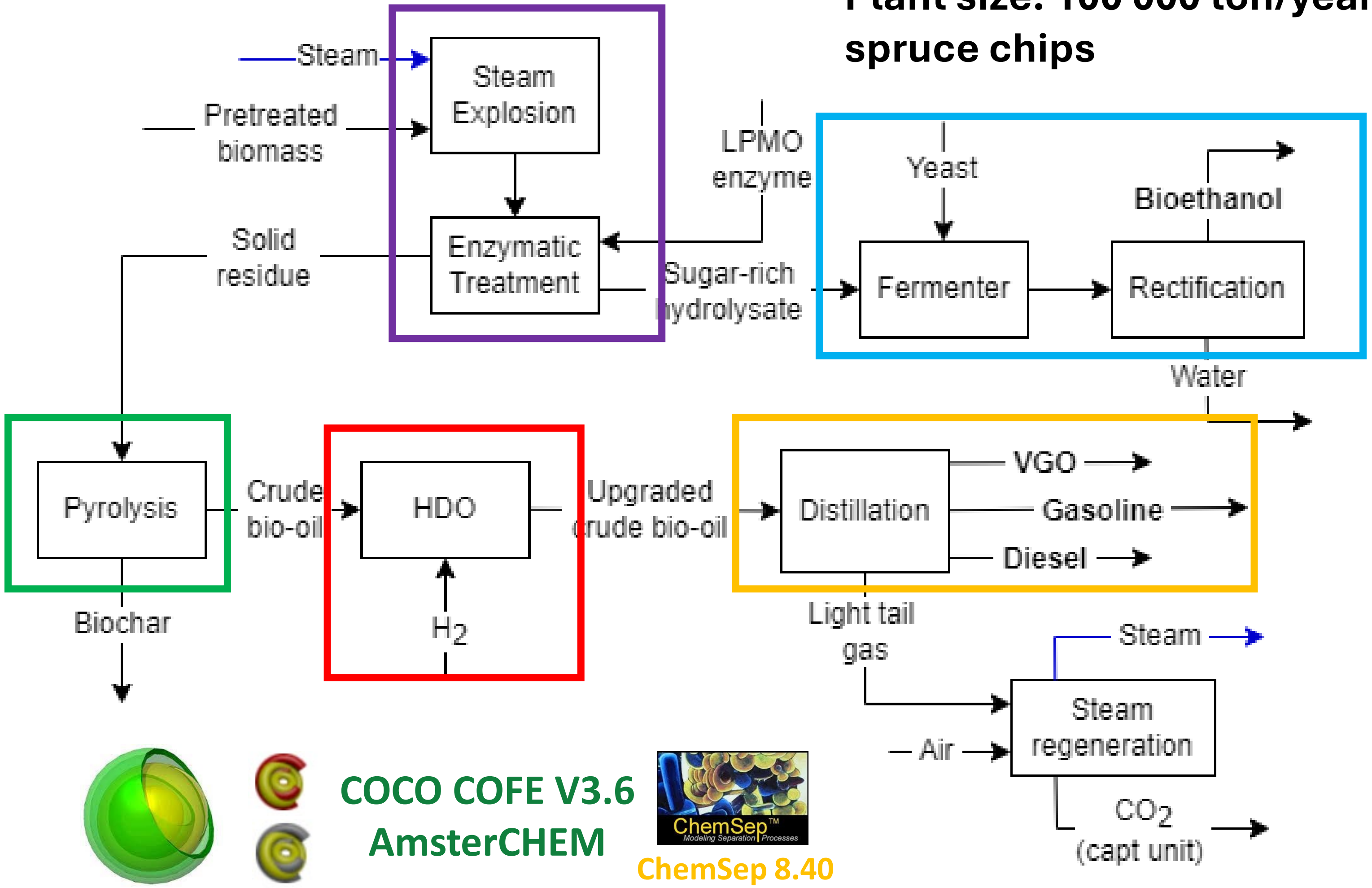
Life-cycle assessment (LCA)

SimaPro software to extract data from various international databases

Block Flow Diagram and Simulation tools

- **Spruce chips** are converted into **bio-oil** and **bioethanol** in an integrated biorefinery.
- Cellulose and hemicellulose chains are broken by **enzymatic treatment**. **Sugars are fermented to bio-ethanol**, which is purified by **rectification**.
- **Lignin** is converted into **bio-oil** through **pyrolysis**. Oil is **stabilized by hydrodeoxygenation** and **distilled in different cuts**.

Plant size: 100 000 ton/year spruce chips



COCO COFE V3.6
AmsterCHEM

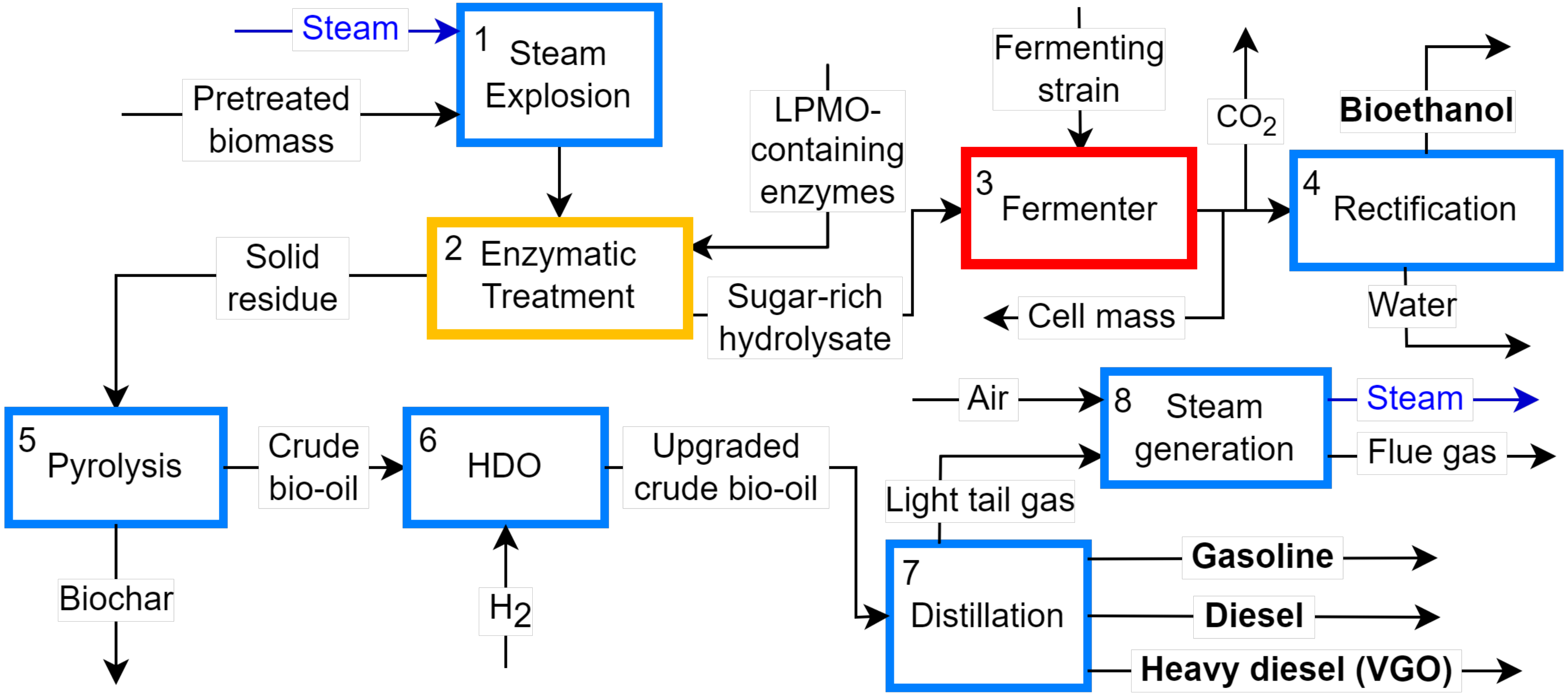
ChemSep 8.40

Model implementation

RIGOROUS MODELS

DATA-DRIVEN MODELS

BLACK-BOX MODEL



Simulation results: KPIs productivity

KPIs (Key Performance Indicators)		Notes
Process weight yield (including biochar)	0.593 $\mathrm{kg_{product}/kg_{BM}}$	Light gas is excluded. The mass yield refers to the treated biomass
Process weight yield (excluding biochar)	0.457 $\mathrm{kg_{product}/kg_{BM}}$	Light gas is excluded
Bioethanol yield	0.21 $\mathrm{ton_{ethanol}/ton_{BM}}$	Water/moisture is not included in the mass used to calculate these yields
Bio-oil yield	0.24 $\mathrm{ton_{bio\text{-}oil}/ton_{BM}}$	
Biochar yield	0.14 $\mathrm{ton_{biochar}/ton_{BM}}$	
Light gas yield	0.11 $\mathrm{ton_{tail\ gas}/ton_{BM}}$	

Simulation results: KPIs energy

KPIs (Key Performance Indicators)		Notes
Total specific steam demand	2.43 ton_{steam}/ton_{BM}	
Cooling water demand	32.4 ton_{CW}/ton_{BM}	
Pyrolysis specific energy	1.65 $MJ/kg_{dry\ BM}$ 0.46 MWh_{th}/ton_{BM}	In line with Daugaard and Brown (2003)
Total specific thermal duty	0.98 MWh_{th}/ton_{BM}	Includes all the thermal duties (supplied heat)
Specific cooling duty	0.56 MWh_{th}/ton_{BM}	Includes all cooling duties (removed heat)
Specific electricity	1.45 MWh_{el}/ton_{BM}	Simulations assume 70% efficiency for pumps and compressors. Spare pumps are neglected.

Integration & Optimization

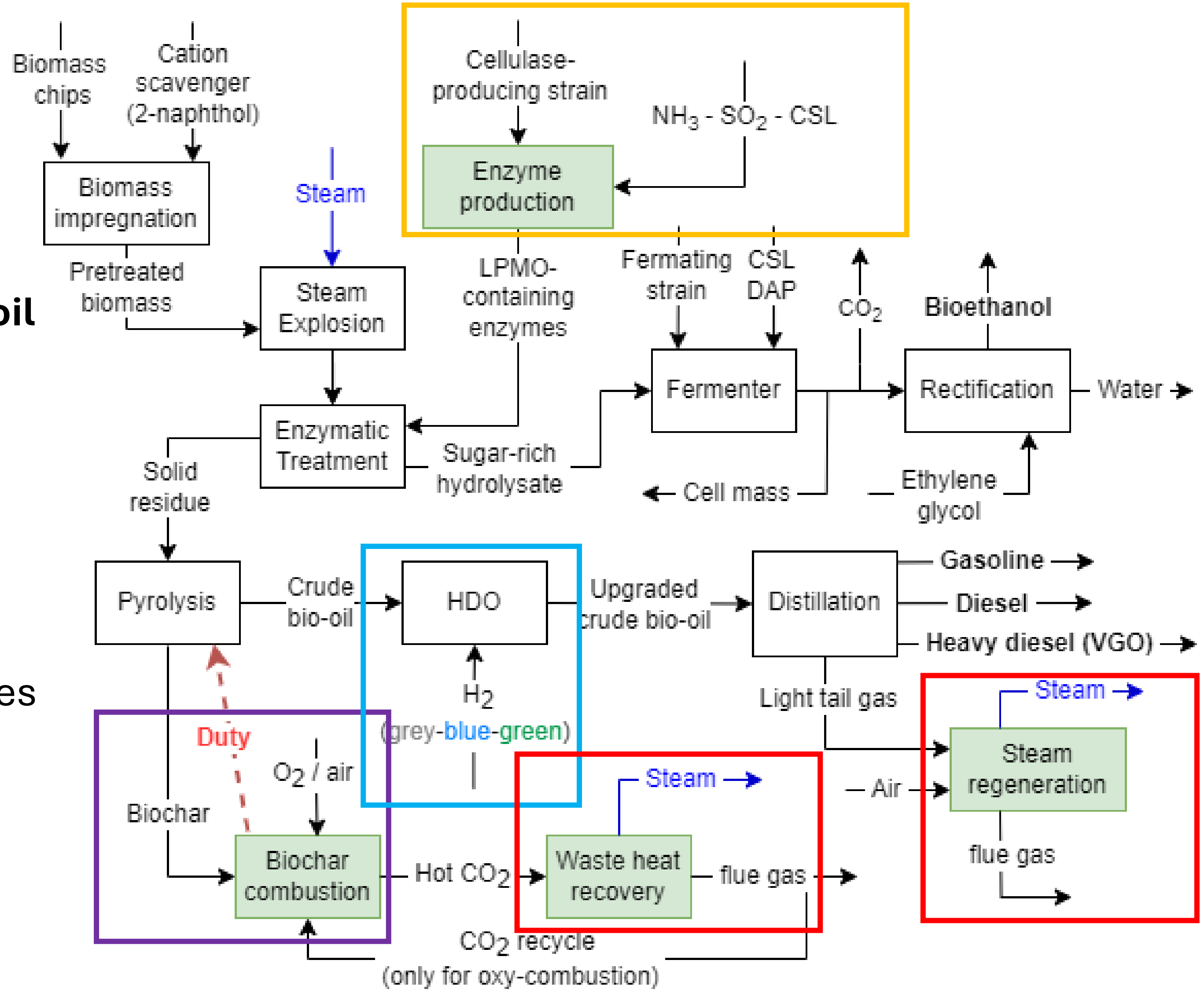
- ☐ **On-site enzyme production**

- ☐ **Heat recovery from hot stabilized oil**

- ☐ **Different H_2 sources**
  - ✓ Green H_2 production can cover also the O_2 demand for char oxy-fuel combustion

- ☐ **Steam generation** from hot flue gases

- ☐ **Biochar combustion in air/O_2** to provide the **thermal energy for the pyrolysis chamber**



Unit sizing and investment cost

The **sizing** of **upscaled reactors from batch lab scale data** is obtained based on the **residence time** and **circulating volume flow (Q)**.

$$Vol = Q \cdot \tau_{res}$$

The total investment cost is obtained by summing the **base equipment costs**, the **installation costs**, and **indirect investment costs** using **correction factors** (*f*).

$$C_{tot} = \boldsymbol{C_{equipment}} + \boldsymbol{C_{install}} + \boldsymbol{C_{indirect}}$$

The **base equipment cost** is calculated as a function of the unit size using correlations by Guthrie, Ulrich, and Navarrete[1-3].

Costs are **actualized to 2023 with CEPCI** index.

$$C_{install} = C_{equipment} \cdot (f_{installation} + f_{piping} + f_{instrumentation} + f_{auxiliary} + f_{electrical} + f_{building} + f_{yard\ improv} + f_{infrastructure})$$

$$C_{indirect} = C_{equipment} \cdot (f_{engin\ \&\ superv} + f_{construction} + f_{legal\ fees} + f_{contractor\ fees} + f_{contingency})$$

---

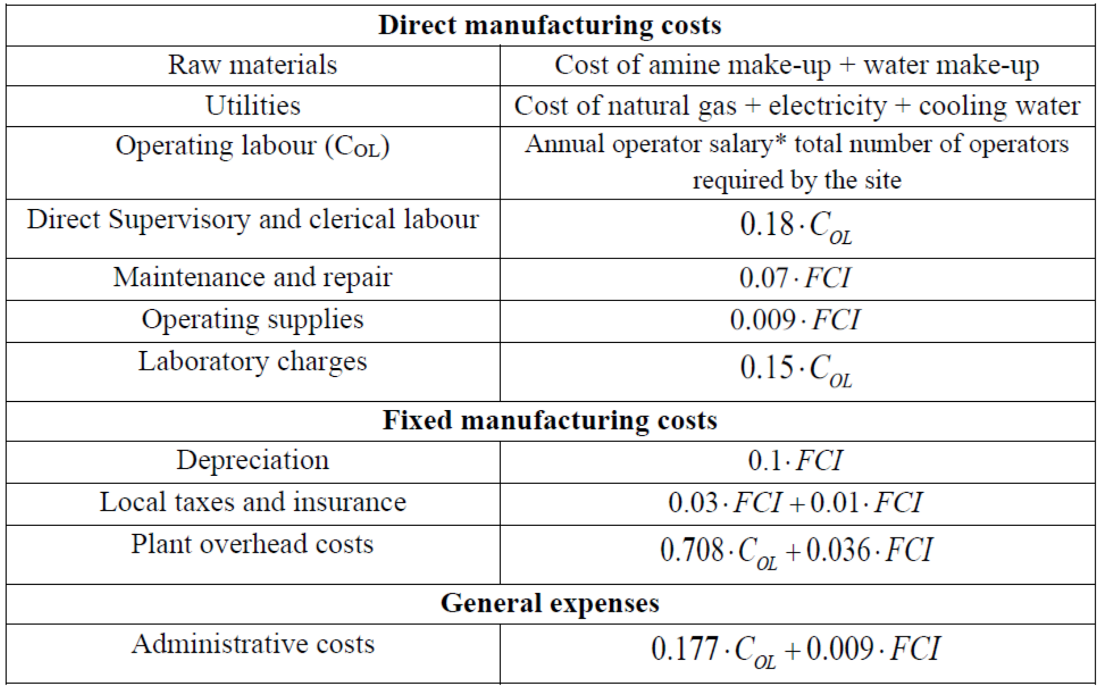
[1]. Guthrie, 1974. Process Plant Estimating, Evaluation and Control

[2] Ulrich, G. D., 1984. A Guide to Chemical Engineering Process Design and Economics. John Wiley and Sons.

[3] Navarrete, P. F., 1995. Planning, Estimating, and Control of Chemical Construction Projects. Marcel Dekker, Inc.

Operating costs

Operating costs are estimated according to Turton[1].



Direct manufacturing costs	
Raw materials	Cost of amine make-up + water make-up
Utilities	Cost of natural gas + electricity + cooling water
Operating labour (C_{OL})	Annual operator salary* total number of operators required by the site
Direct Supervisory and clerical labour	$0.18 \cdot C_{OL}$
Maintenance and repair	$0.07 \cdot FCI$
Operating supplies	$0.009 \cdot FCI$
Laboratory charges	$0.15 \cdot C_{OL}$
Fixed manufacturing costs	
Depreciation	$0.1 \cdot FCI$
Local taxes and insurance	$0.03 \cdot FCI + 0.01 \cdot FCI$
Plant overhead costs	$0.708 \cdot C_{OL} + 0.036 \cdot FCI$
General expenses	
Administrative costs	$0.177 \cdot C_{OL} + 0.009 \cdot FCI$

Raw material	Specific cost ($/ton)	Source
Spruce chips	56.7	[4]
2-Naphtol	3500	[5]
Hydrogen blue green grey	 3500 7250 1500	[6]
NH_3	410	[5]
SO_2	276	[5]
Corn steep liquor (CSL)	50	[5]
DAP	895	[5]
Ethylene glycol	860	[5]
Oxygen from ASU	250	[6]

Average over last 10 years (data by Statistisk sentralbyrå)

Utility	Specific cost	Source
Natural gas	20 $/MWh	[2]
Electricity	61.3 $/MWh	[3]
Cooling water	0.354 $/GJ	[1]

---

[1] Turton, R. Analysis, Synthesis and Design of Chemical Processes. 5th Edition, Prentice Hall
[2] https://tradingeconomics.com/commodity/eu-natural-gas;
[3] SSB Electricity prices. https://www.ssb.no/en/energi-og-industri/energi/statistikk/elektrisitetspriser
[4] NMBU. https://publikasjoner.nve.no/rapport/2012/rapport2012_32.pdf.
[5] D. Bbosa, M. Mba-Wright, R.C. Brown, 2018, Biofuels, Bioproducts & Biorefining, 12, 497–509
[6]] J.M.M Arcos and D.M.F. Santos, 2023, Gases, 3, 25–46.

Sensitivity analysis on H_2 source

Sensitivity analysis on hydrogen source (for HDO) **and air/oxyfuel combustion** has been performed.

Case	H_2 source	Combustion type
CS1	**Grey**	Air
CS2	**Grey**	Oxy-fuel (O_2 from Air Separation Unit)
CS3	**Blue**	Air
CS4	**Blue**	Oxy-fuel (O_2 from Air Separation Unit)
CS5	**Green**	Oxy-fuel (integrated H_2 and O_2 production via electrolysis)

Assumption for oxy-fuel combustion: the **boiler volume is reduced by ¾** due to the absence of nitrogen.

Cash flow

- We investigate the **MSPR (Minimum Selling Price Ratio)** for bio-oil and bio-ethanol to target an **Internal Rate of Return (IRR) equal to 10% or 15%**.
- MSPR is obtained using the actual selling prices of the corresponding fossil-based product as a reference.

MSP (same): same price ratio assumed for both bio-oil and bio-ethanol

MSP (oil) and MSP (ethanol): price **ratio calculated only for the commodity in brackets**. The price for the other product is fixed to the current value.

Three options for hydrogen: **grey**, **blue**, and **green**.

Fossil-based Product	Selling price ($/liter)	Source
Ethanol	0.80	[1]
Gasoline	0.79	
Diesel	0.86	

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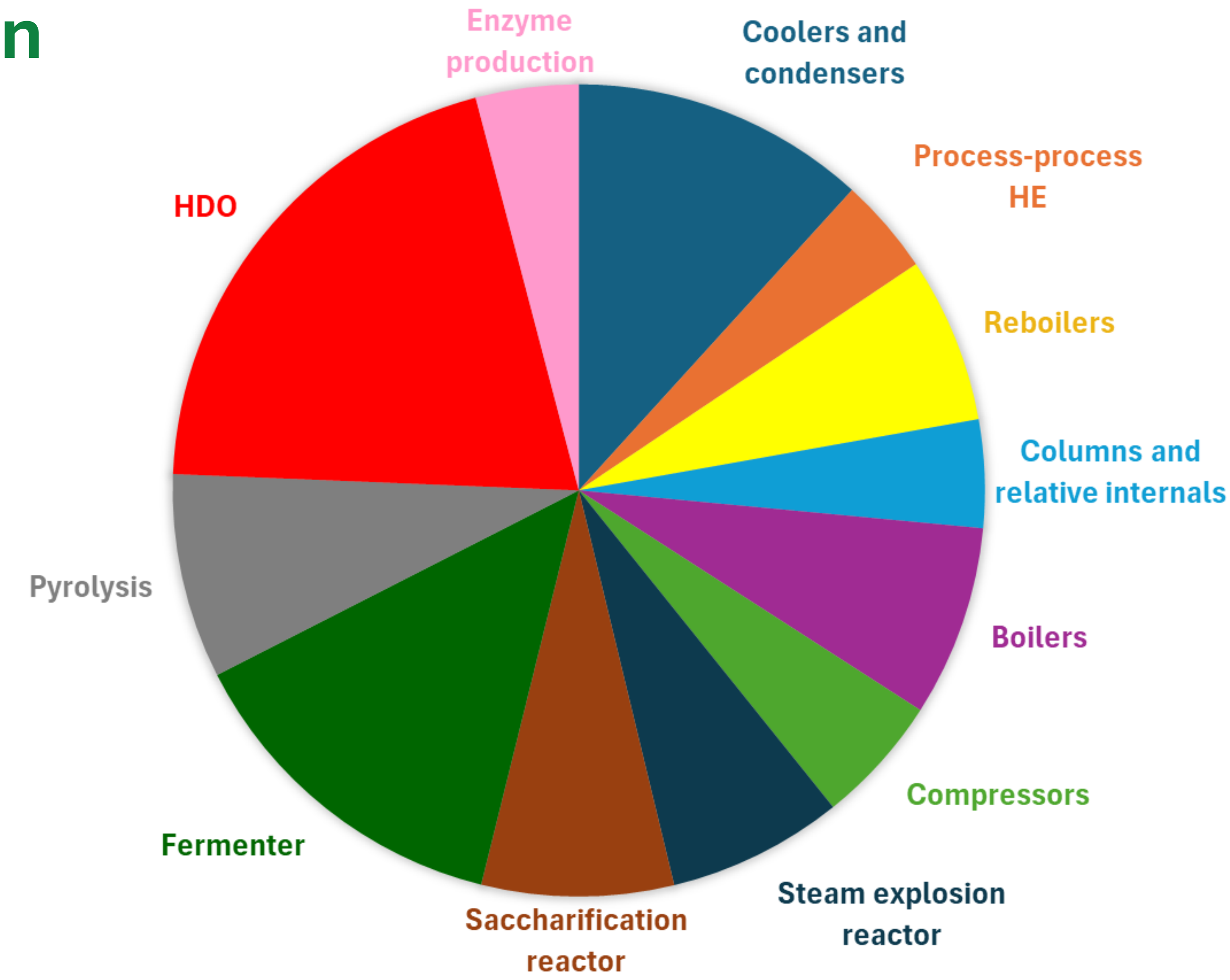
[1] SSB Norway. https://www.ssb.no/en/energi-og-industri/olje-og-gass/statistikk/sal-av-petroleumsprodukt

Reference case-study: green H_2 and air combustion

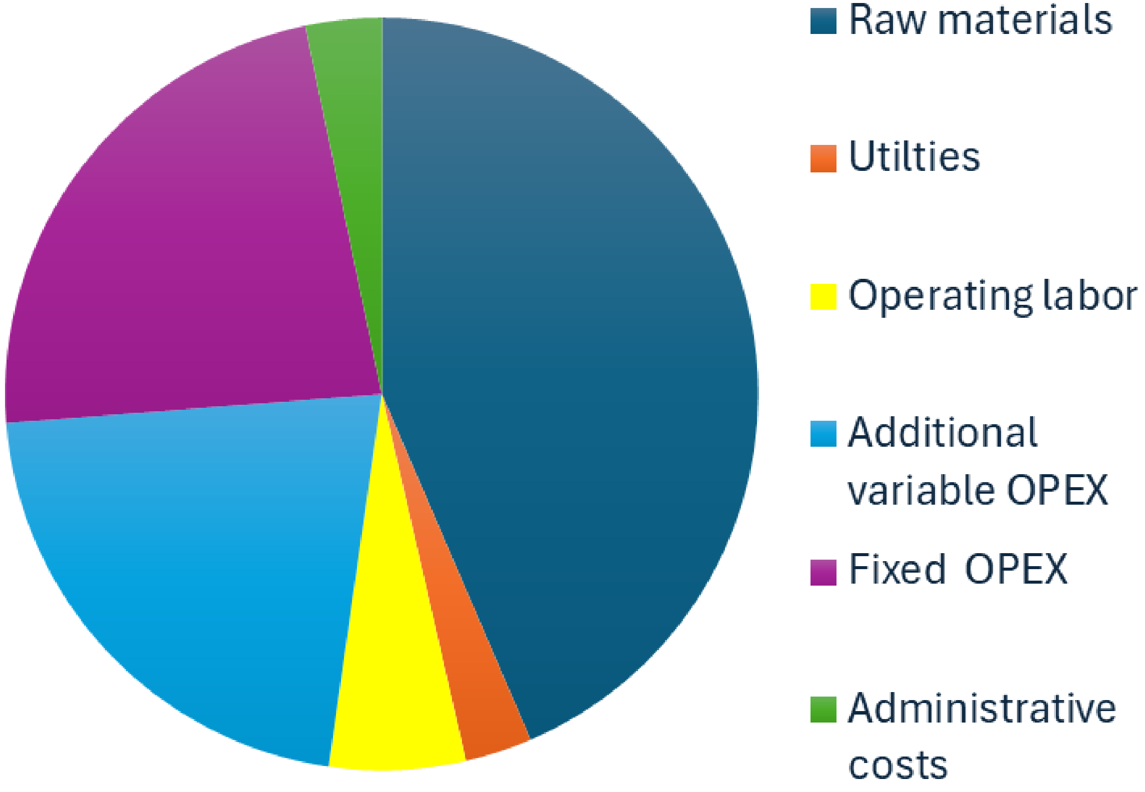
CAPEX breakdown

- Saccharification, fermentation, and pyrolysis are associated with **high large CAPEX** due to the **high required residence time**.
- **HDO** is a major contribution being a **high-pressure catalytic chamber**.



OPEX breakdown

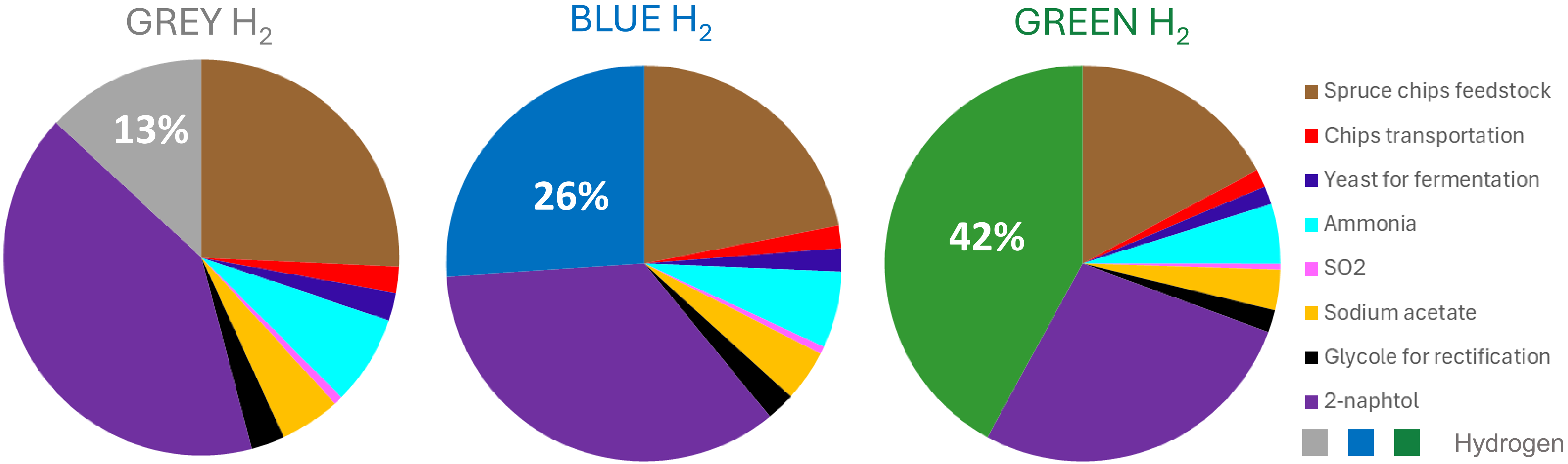
Reference case-study: green H_2 and air combustion



Raw materials are the **key contribution** to the operating costs.

Thanks to the proposed energy integrations, the **demand for external utilities is minimized**.

OPEX breakdown: raw materials



- The share of raw materials cost associated with H_2 significantly increases when blue or green H_2 are used.
- **2-naphtol can be potentially replaced with phenolics** to be recovered from the produced bio-oil.

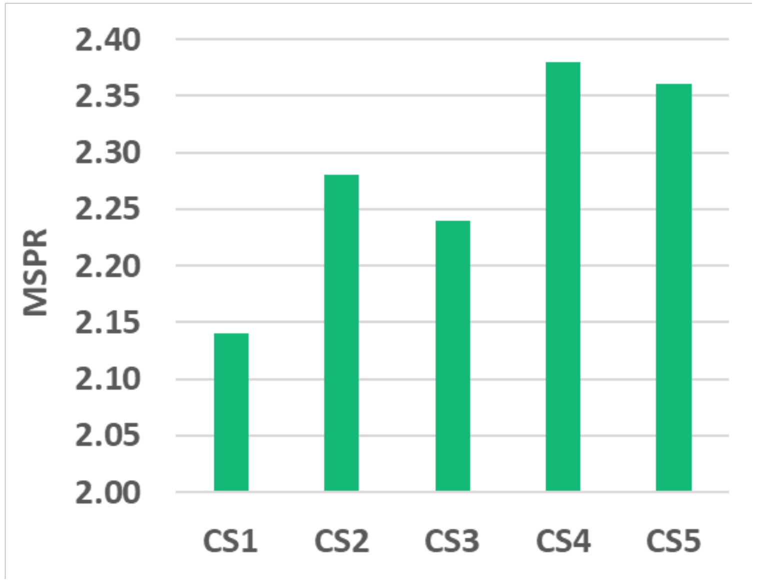
Results: CAPEX and OPEX

Case study	Hydrogen color	Combustion	CAPEX [M$]	Raw materials [M$/year]	Utilities [M$/year]	Total OPEX [M$/year]
CS1	Grey	Air	179	22.04	1.96	76.48
CS2		Oxy-fuel	169	29.73	1.96	83.99
CS3	Blue	Air	179	25.89	1.96	81.22
CS4		Oxy-fuel	169	33.58	1.96	88.73
CS5	Green	Oxy-fuel	179	33.02	1.96	88.04

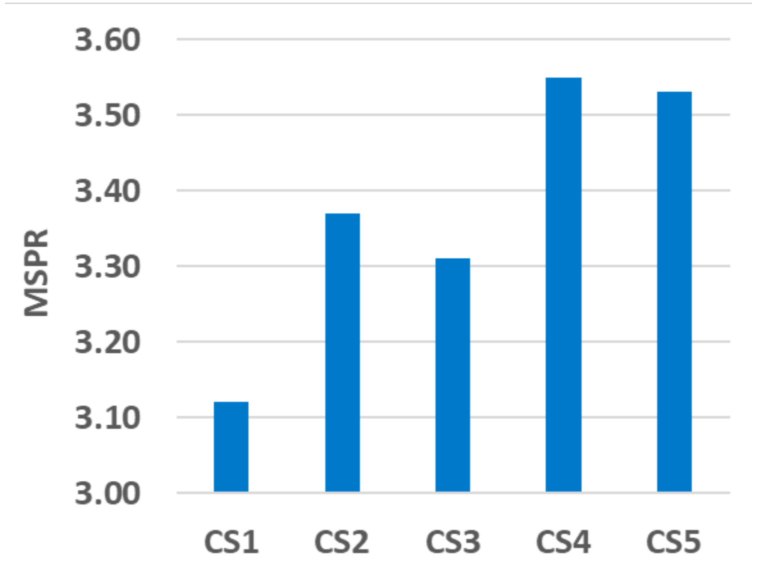
- **Oxy-fuel combustion** provides a **5% reduction in the total CAPEX** due to the lower boiler volume.
- **Oxygen for ASU** results in a **10% increase in the total OPEX** compared to air combustion.
- **Green hydrogen** results in a **15% increase in the total OPEX** with respect to grey hydrogen and air combustion.
- CS5 provides slightly better results than CS4.

Results: MSPR

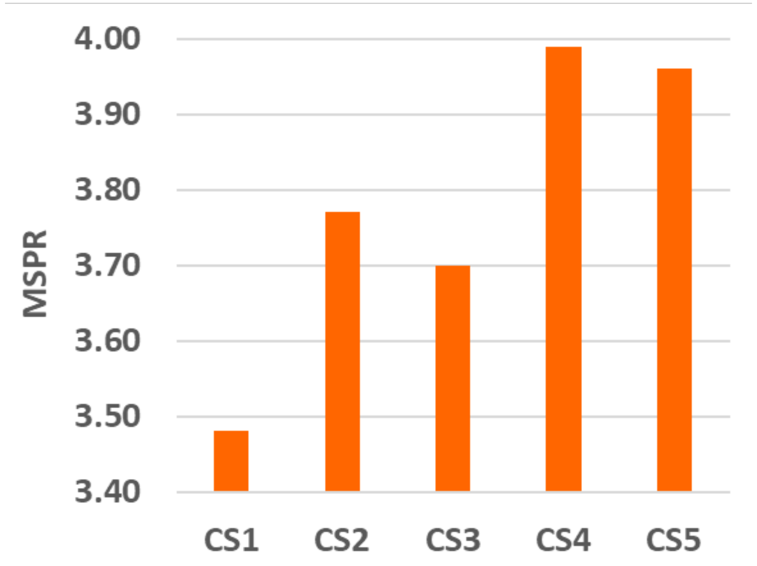
Target: IRR= **10%**



MSPR (same)



MSPR (ethanol)



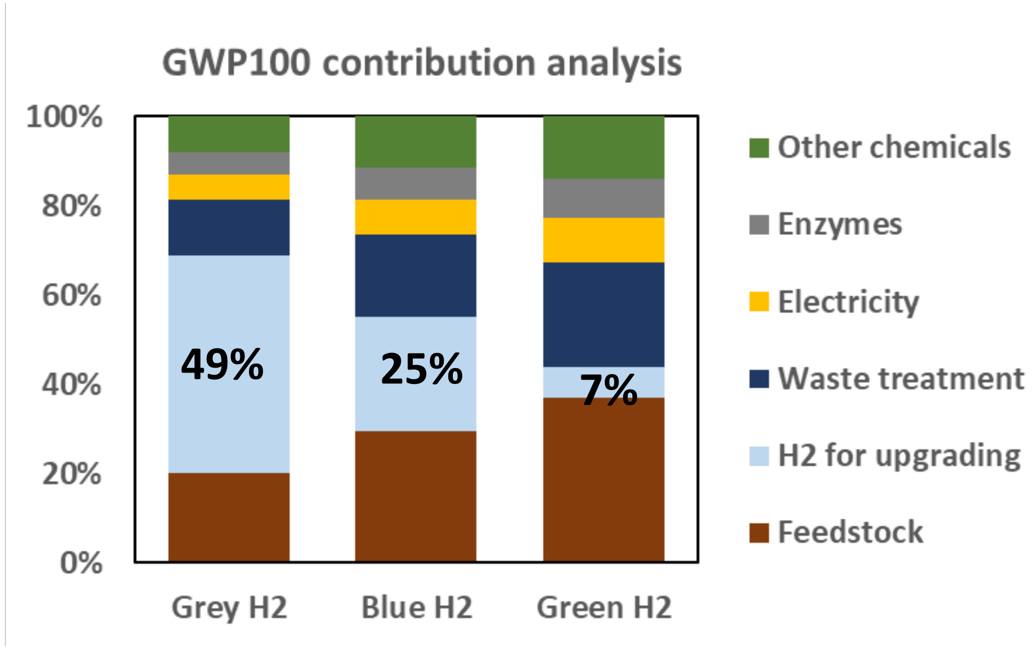
MSPR (oil)

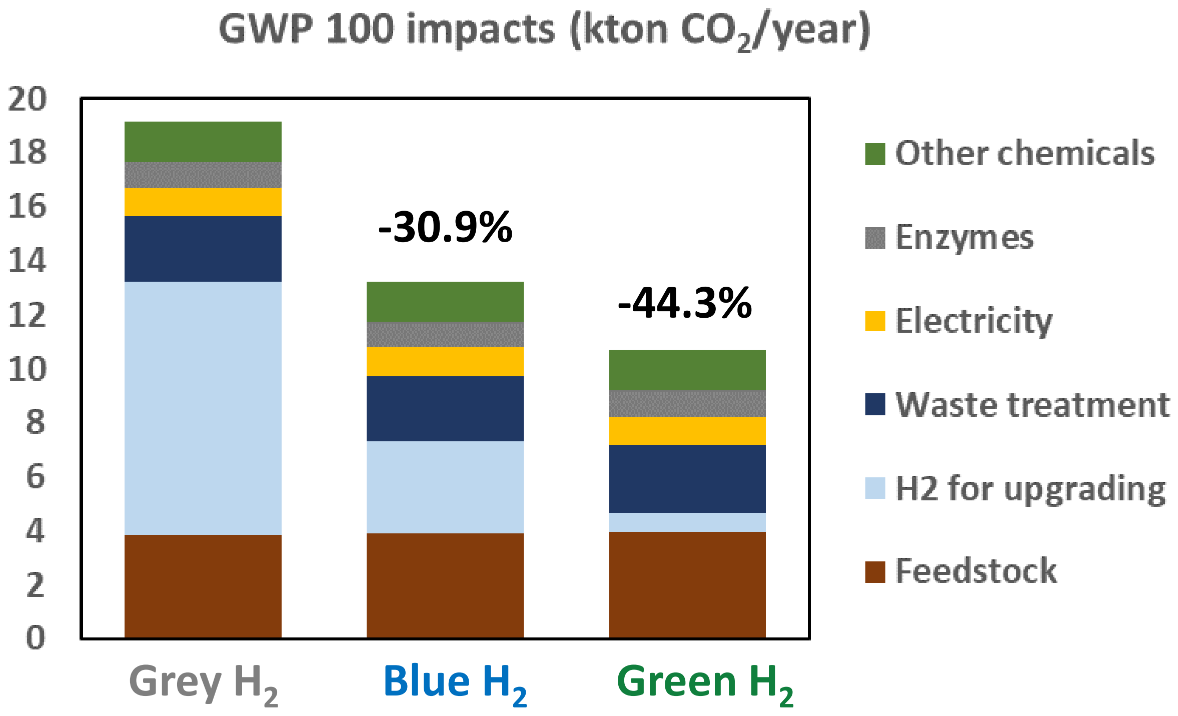
- All scenarios require a **MSP for both bio-ethanol and bio-oil over two times the actual prices of the corresponding fossil-derived products**.
- Using green hydrogen requires a 9% and 4.5% higher MSPR with respect to grey and blue hydrogen, respectively.
- **Green hydrogen** is currently much less economically viable, but **what about the effect on CO_2 eq. emissions**?

Environmental assessment

An environmental analysis (GWP100 impact category only) of the process was performed in cooperation with Prof. Cherubini and Dr. Ballal.

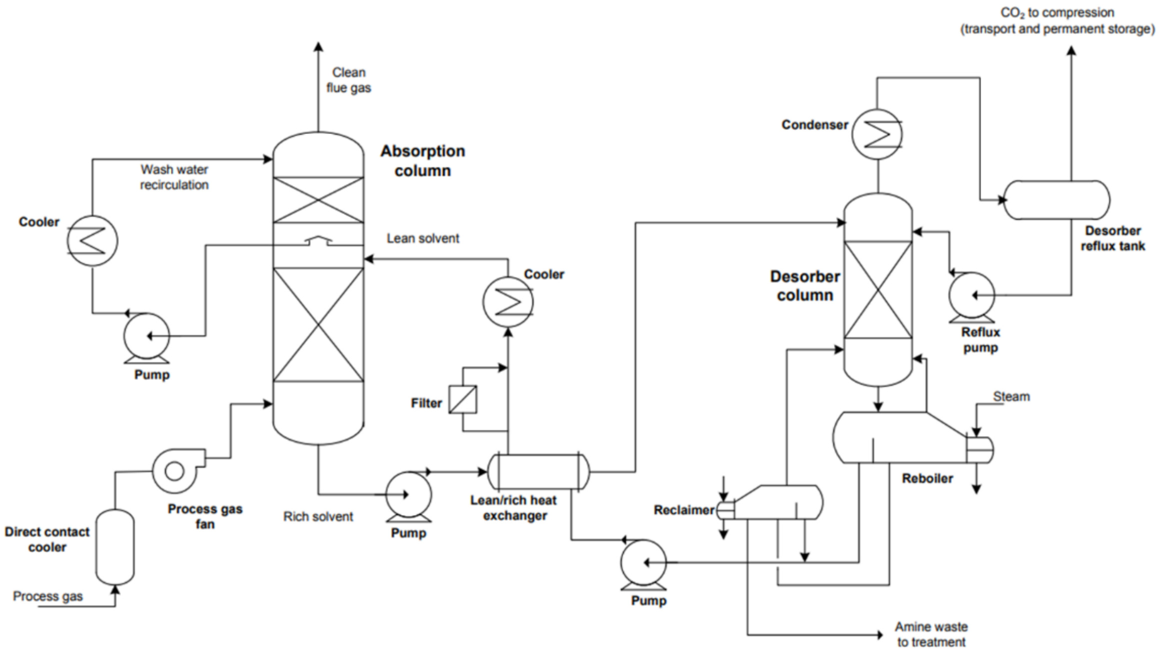
KEY ASSUMPTIONS
- System boundaries set to the process itself (gate-to-gate)
- Electricity source: Norwegian National electricity mix
- Grey hydrogen: SMR of natural gas
- Green hydrogen: offshore wind energy for electricity production





CO_2 capture: towards negative CO_2 emissions

- **CO_2-rich streams** from light gas combustion (6 vol%) and char combustion (14.5 vol%) have potential for CO_2 capture.
- The two stacks have been mixed and **conveyed to a conventional amine absorption plant**.
- Two solvents have been considered: **MEA** and **CESAR-1**



Simulation software: **CO2SIM**

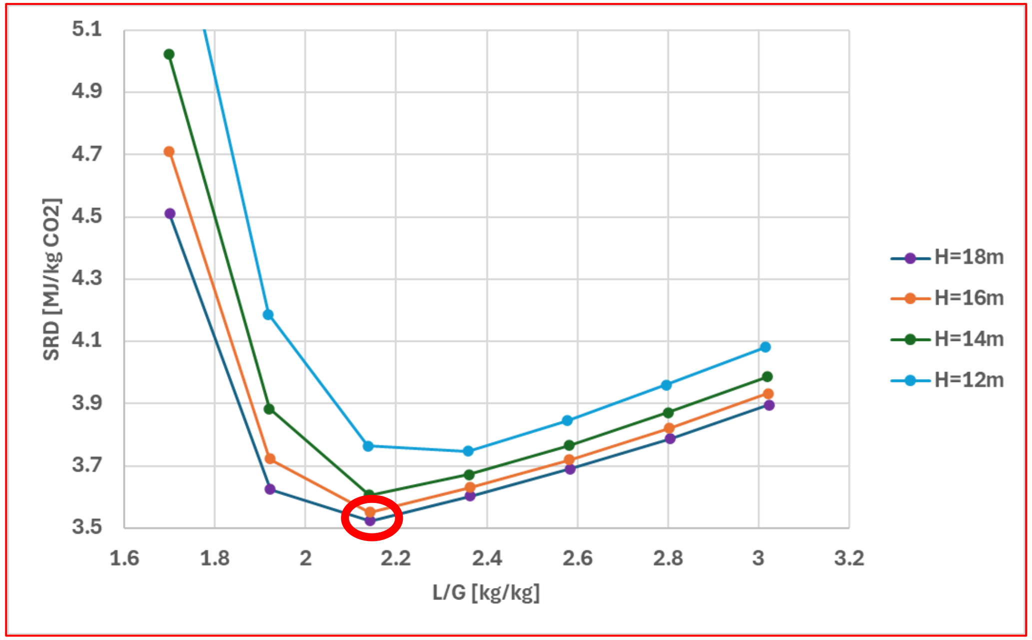
SINTEF

ASSUMPTIONS

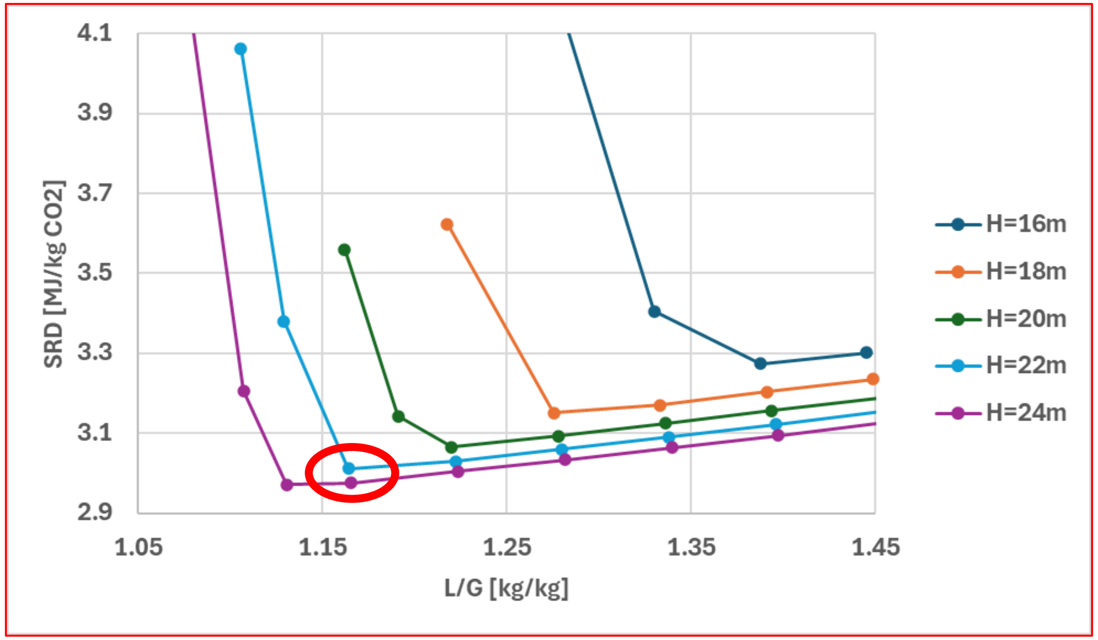
- 90% CO_2 capture
- Packing: Mellapak 2X
- Sensitivity analysis to determine optimal L/G ratio and absorber packing height to minimize the Specific Reboiler Duty (SRD)

CO_2 capture plant optimization

MEA



CESAR-1

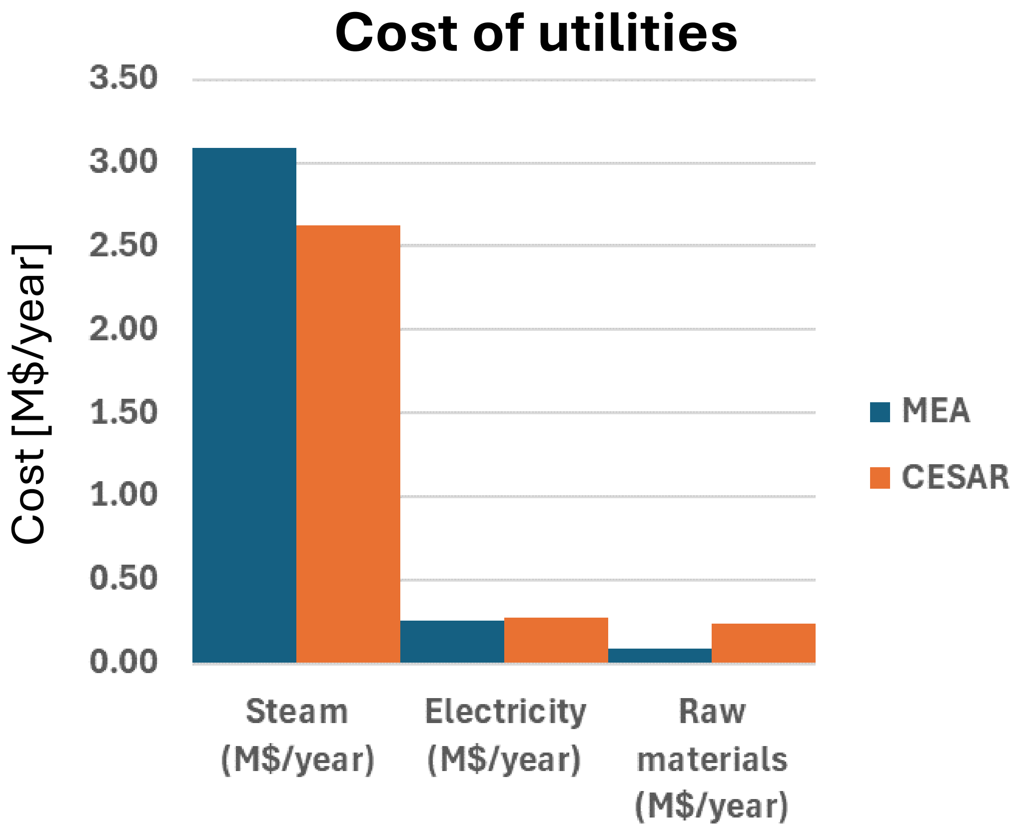


Using **CESAR-1**:

- the **SRD of the optimized capture plant** reduces from 3.55 down to **3.01 MJ/kg CO_2 capt. (-15%)**
- The required **solvent flow** is also **reduced by** a factor of **45%**
- Conversely, a higher packing is needed due to slower kinetics (22m versus 16m)

CO_2 capture plant costs

Index	MEA	CESAR	CESAR vs MEA
FCI (M$)	**23.05**	**22.69**	**-1.5%**
Total OPEX (M$/year)	**12.61**	**12.16**	**-3.5%**
Utilities (M$/year)	3.43	2.97	-13.2%
Steam (M$/year)	3.09	2.62	-15.2%
Electricity (M$/year)	0.25	0.28	+10.0%
Raw materials (M$/year)	0.09	0.24	2.61 times
Total cost (M$/year)	**12.61**	**12.16**	**-3.5%**

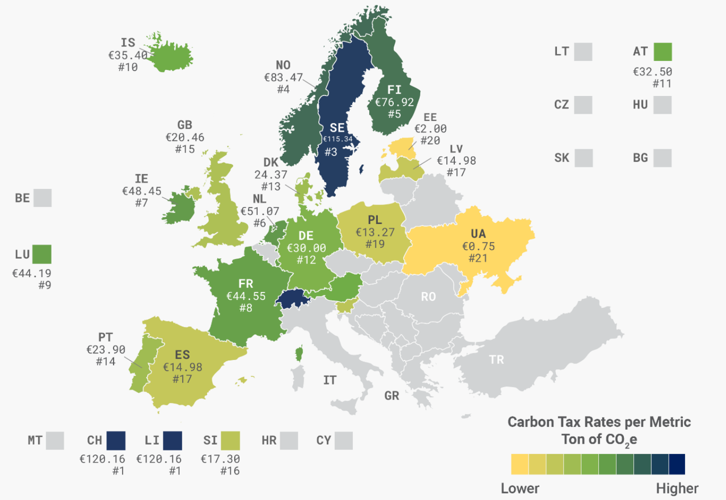


Is the cost of CO2 capture sustainable for the designed biorefinery?

- **Biorefinery CAPEX increase** when integrating the capture plant: **+ 12.7%**
- **Biorefinery OPEX increase** when integrating the capture plant: **+ 15.9%**

Carbon Taxes in Europe

Carbon Tax Rates per Metric Ton of CO_2e, as of March 31, 2023



Note: The carbon tax rates were converted using the EUR-USD currency conversion rate as of August 31, 2023 (USD 1 = EUR 0.9186).
Source: World Bank, "Carbon Pricing Dashboard."

TAX FOUNDATION @TaxFoundation

Breakeven carbon tax: 240 $/ton CO_2

- The high specific CO_2 capture cost in this application is due to the limited volume of treated flue gas (economy of scale)
- Integrated capture plant with flue gases from other facilities at close distance is a great option to enhance viability (**industrial symbiosis**)

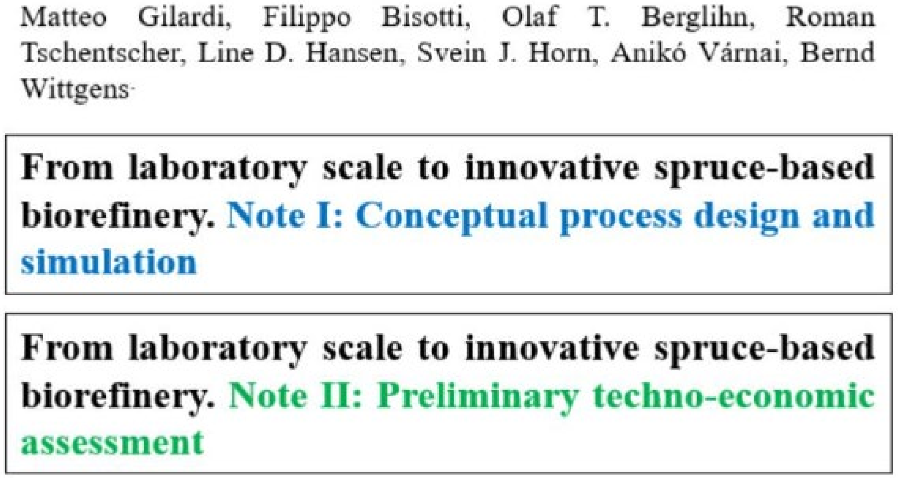
Conclusions

- **Successful scale-up modelling** of an integrated biorefinery for combined bioethanol and bio-oil production from spruce chips.
- The proposed **integrated biorefinery** **minimizes biomass waste** through the complete **valorization of all biomass constituents**, including lignin, and promoting **energy recovery**.
- If grey hydrogen is exploited, the **Minimum Selling Price** required for **ethanol and bio-oil** to achieve a IRR=10% is **2.14 times the actual price for fossil-derived sources**.
- Cooperation with SP1 to **combine economic and environmental considerations**.
- Good potential for **CO_2 capture integration** toward **negative CO_2 emissions**.
- Need to discuss the potential for **industrial symbiosis**: how to **effectively link this biorefinery with other plants?**

BIO4 FUELS

Conferences and publications

Strategies and approaches for the modelling of a biorefinery



Matteo Gilardi, Filippo Bisotti, Olaf T. Berglihn, Roman Tschentscher, Line D. Hansen, Svein J. Horn, Anikó Várnai, Bernd Wittgens

From laboratory scale to innovative spruce-based biorefinery. Note I: Conceptual process design and simulation

From laboratory scale to innovative spruce-based biorefinery. Note II: Preliminary techno-economic assessment

Upcoming presentations

EUBCE
32nd European Biomass Conference & Exhibition

Economic and environmental assessment

ghgt-17

CO_2 capture integration

Bio4Fuels

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CENTRE FOR ENVIRONMENT-FRIENDLY ENERGY RESEARCH

The Research Council of Norway