



FLEXIBLE AND ADVANCED BIOFUEL TECHNOLOGY THROUGH AN
INNOVATIVE MICROWAVE PYROLYSIS & HYDROGEN-FREE
HYDRODEOXYGENATION PROCESS

Early Stage Life Cycle Sustainability Assessment of Advanced Biofuel Production from a flexible feedstock system

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flexby

Flexible and advanced Biofuel technology through an innovative microwave pYrolysis & hydrogen-free hydrodeoxygenation process

Valorising microalgae cultivated in urban wastewater as well as sludge from the dairy industry as feedstocks

HORIZON -CL5 -2023 - D3 -02 -07 - Development of next generation advanced biofuel technologies

48 months (2024 to 2028)



GreenDELTA



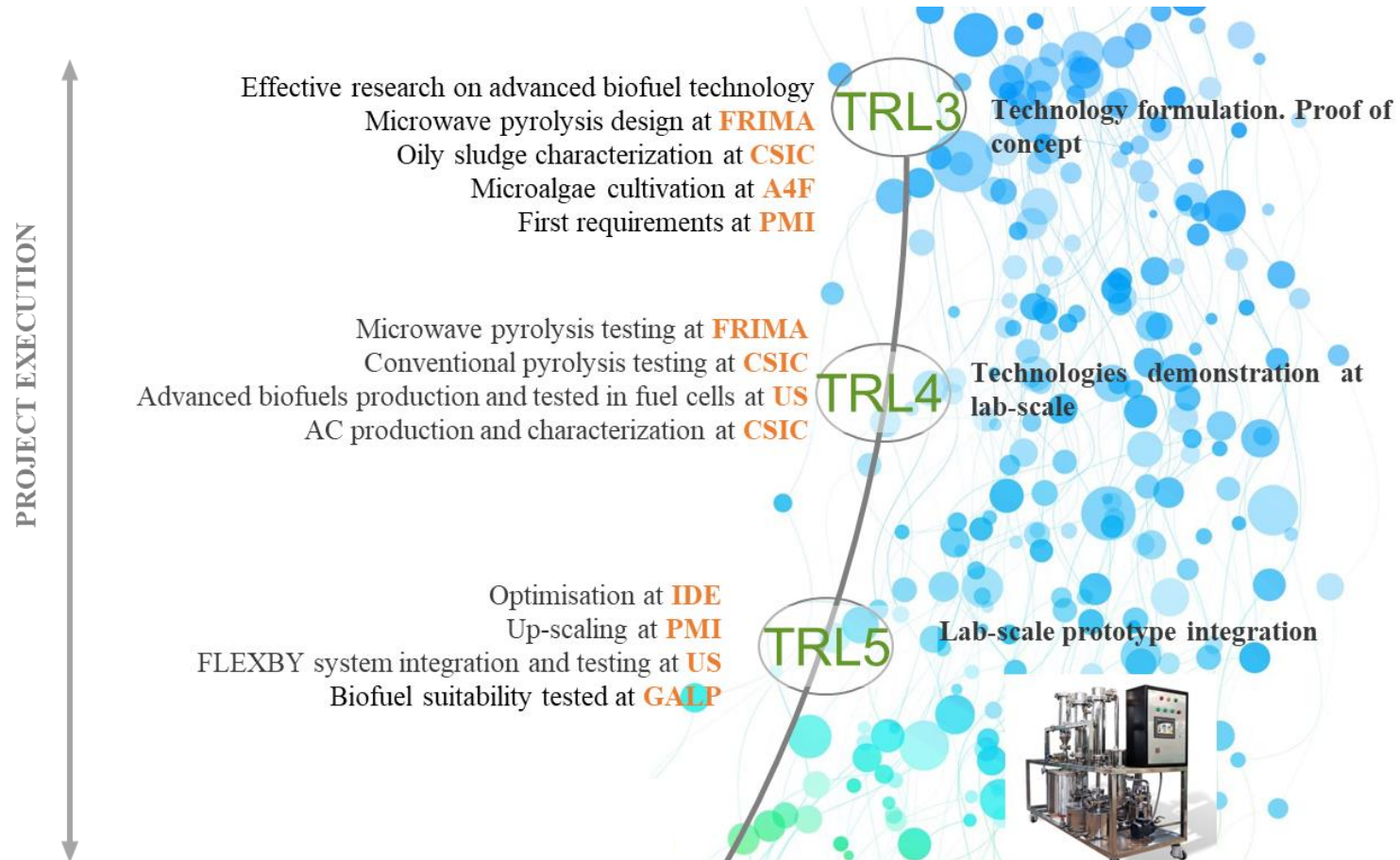
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galp



flexby TRL evolution



Early stage LCSA

- What are the potential environmental and economic hotspots in the life cycle?
- Which process parameters, methodological choices most influence the potential impacts of the FLEXBY pathway?
- How do the processes (or intersecting sectors) affect **human well-being**?

The current discussion is based on built lab scale setups and simulations, these questions are still being explored, as the system is optimised

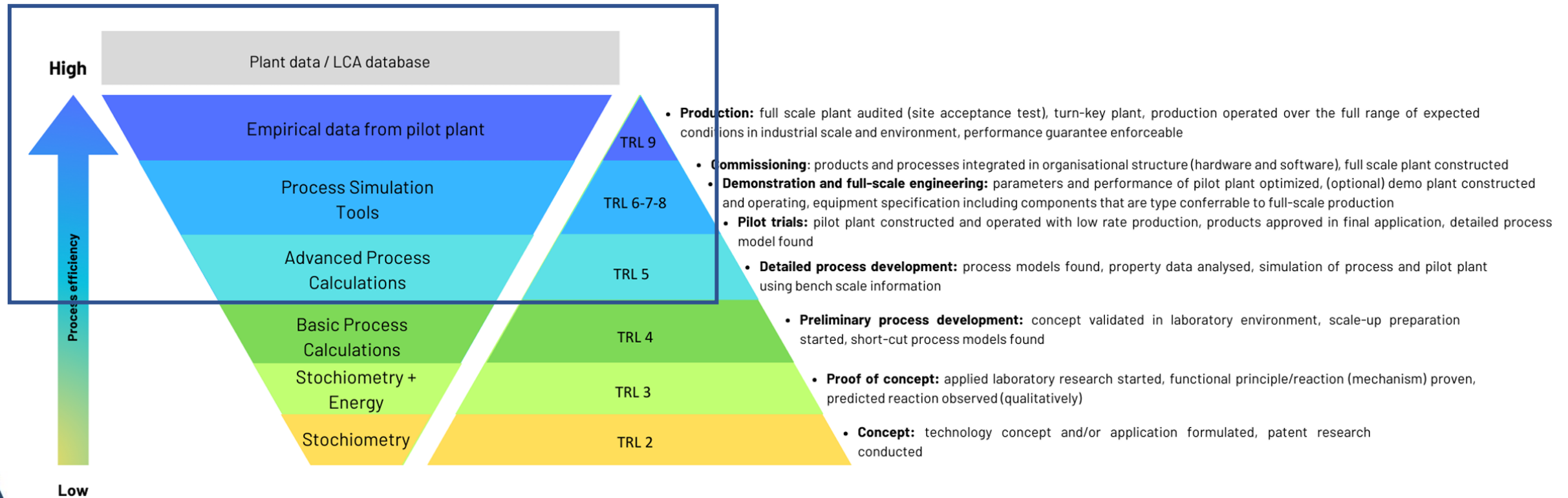
Preliminary LCSA

The **attributional LCSA** study considers three dimensions of environment, economy and society using harmonised process structure and shared inventory data with the **SOCA v4 database** (*ecoinvent with social indicators add-on*)

- **eLCA:** environmental impact hotspots with the **Environmental Footprint Method (EF3.1)**
- **LCC:** CAPEX, OPEX and replacement-related cost drivers to estimate costs
- **sLCA:** social hotspot screening across supply chains and process stages using **SOCA V4** with the **social impact weighting method** to assess the social hotspots based on risk levels as well as a literature review and stakeholder discussions
- Functional unit = **1 MJ of biofuel**

Impacts were also calculated for 1 kWh of electricity produced by the fuel cell and 1 kg of biochar

Data assumptions at different TRLs



[1] A. G. Parvatker and M. J. Eckelman, *ACS Sustainable Chemistry & Engineering* **2019**, 7(1).

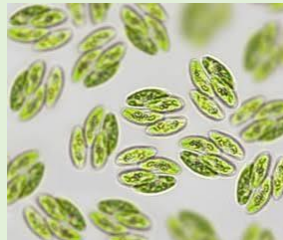
[2] R. Hischer et. al., *International Journal of Life Cycle Assessment* **2005**, 10(1).

Microalgae and Dairy sludge as feedstocks

- Cultivated in municipal secondary effluent. The *Scenedesmus* microalgal growth provides tertiary treatment for advanced removal of nutrients¹
- Primary cultivation data.

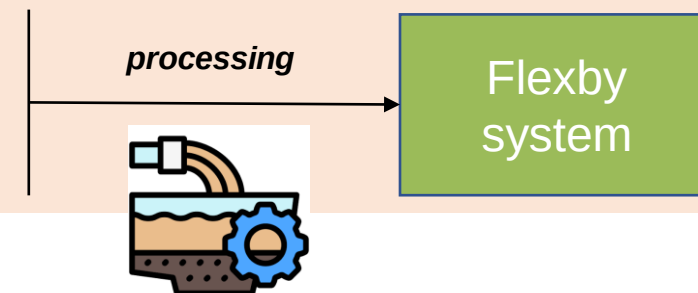
The reference can therefore be:

- Treatment of 1 m³ of wastewater or
- Production of 1 kg of microalgae



- Residue from dairy wastewater treatment, supplied as a waste feedstock
- No upstream production burden. Collection, deodorization and drying included inside the boundary.
- *Avoided sludge-treatment or other avoided applications will be included only after confirming the current management route.*

Cut off

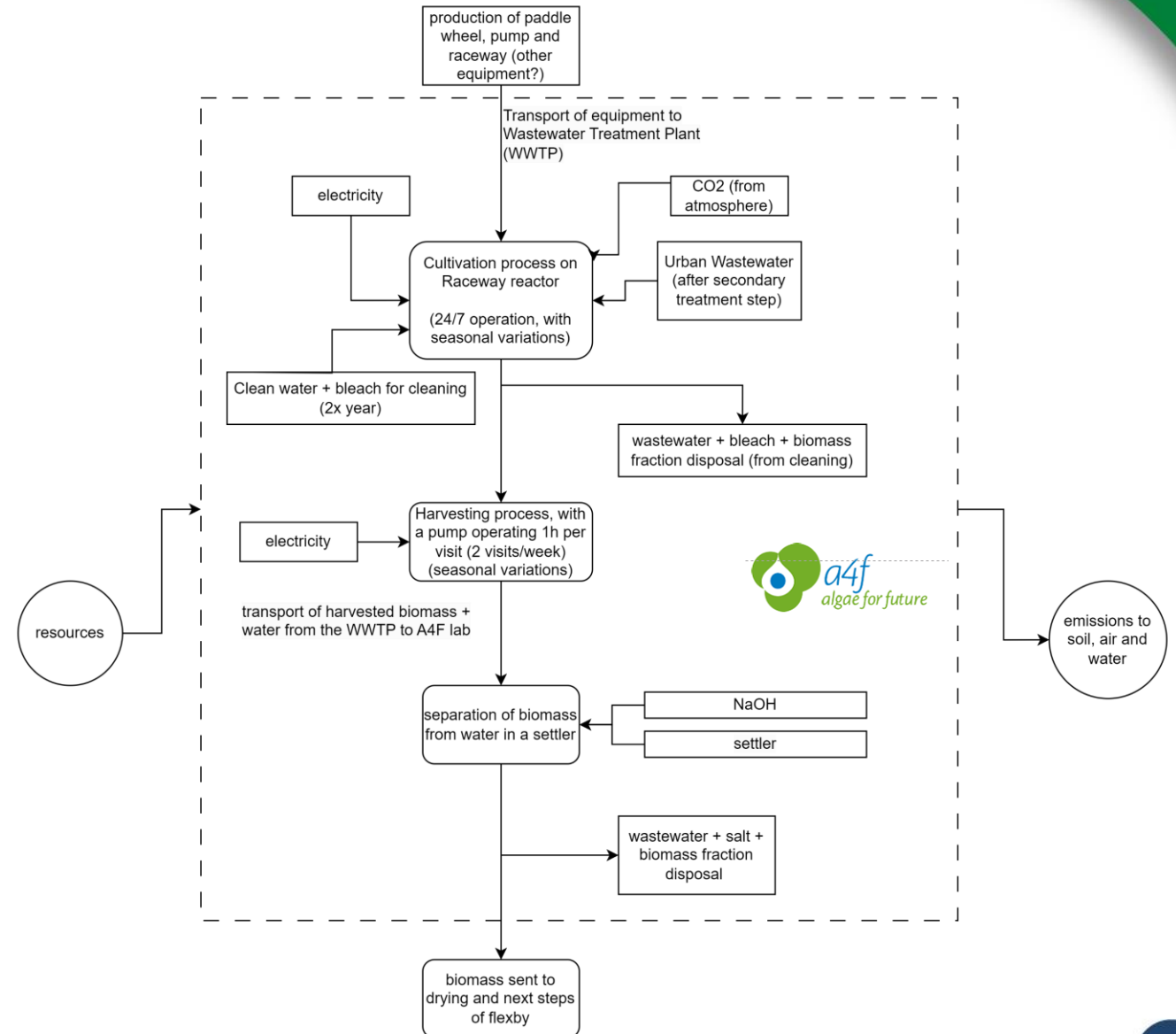


1. Vaz, S., Martins, R. C., Pinheiro, H. M., & Monteiro, L. (2026). A comparative study of mechanistic and hybrid model structures for microalgae-based tertiary wastewater treatment systems. *Journal of Water Process Engineering*, 93, 110971. <https://doi.org/10.1016/j.jwpe.2026.110971>

Microalgae – primary data

- Harvested biomass is subsequently used as FLEXBY feedstock,
- Raw materials, internal transport and machinery data were provided and post-treatment steps were considered

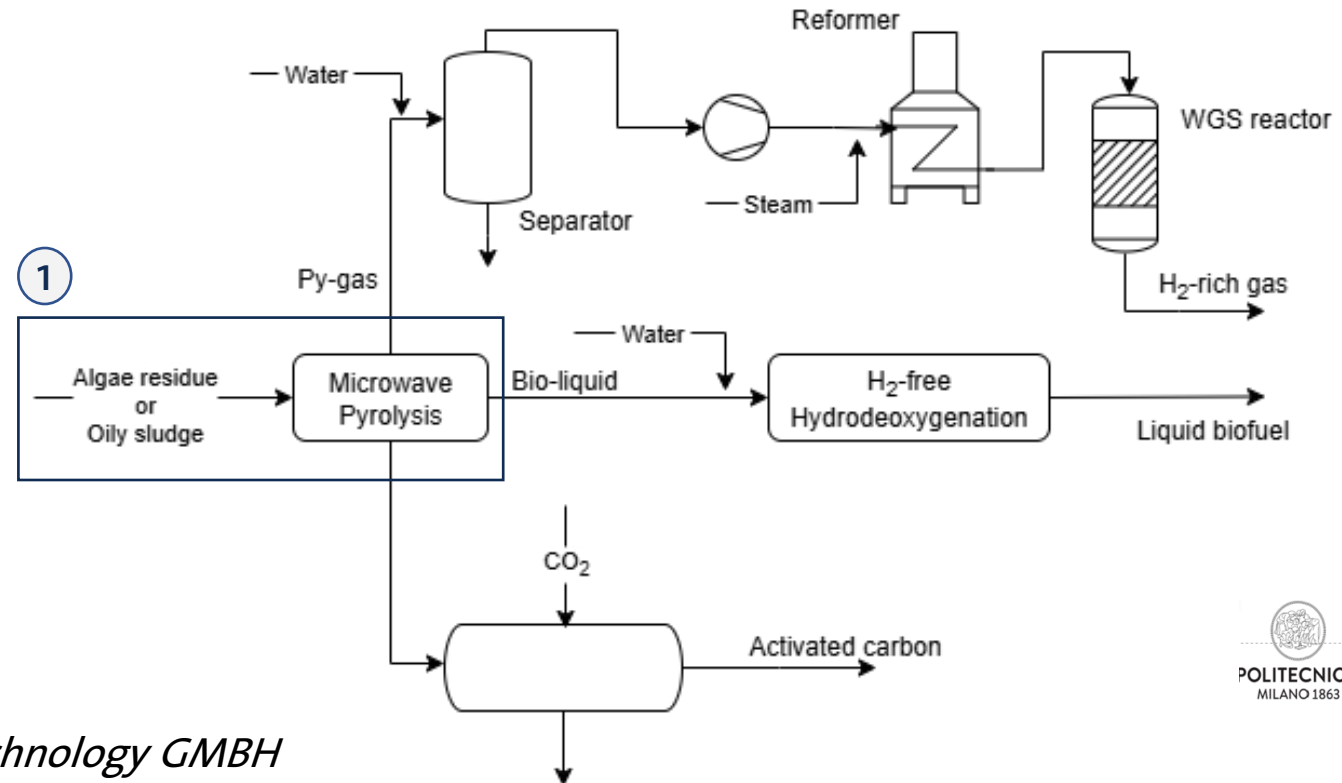
- How to allocate burdens between the microalgae and the treated wastewater?
 1. Wastewater as quantitative waste reference with microalgae as a by-product (handled with allocation)
 2. Microalgae as a reference with credits to avoided tertiary wastewater treatment



Process Layout

- Performance assessment of the process for industrial applications

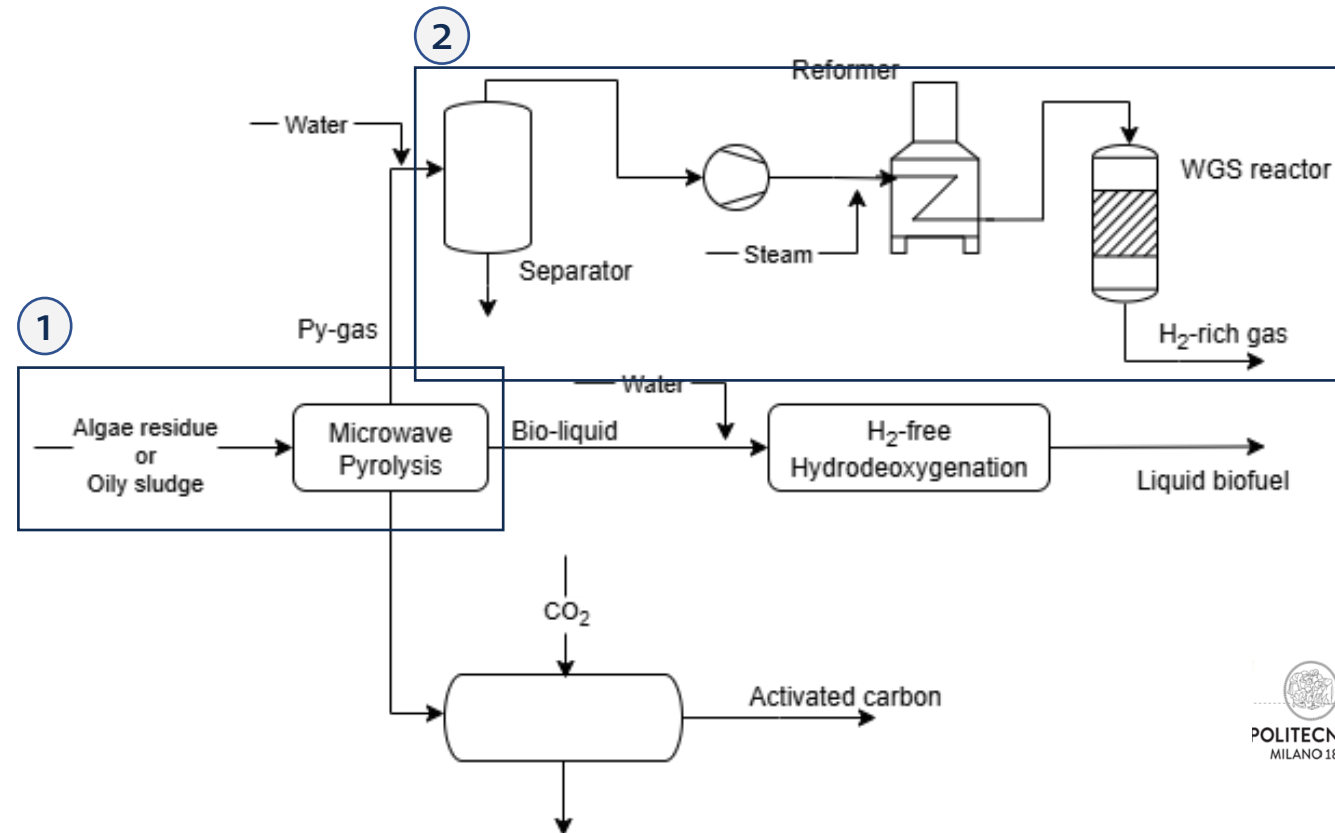
1. Microwave pyrolysis **reduces** reaction time and **increases** the quality of the product.



Process Layout

- Performance assessment of the process for industrial applications

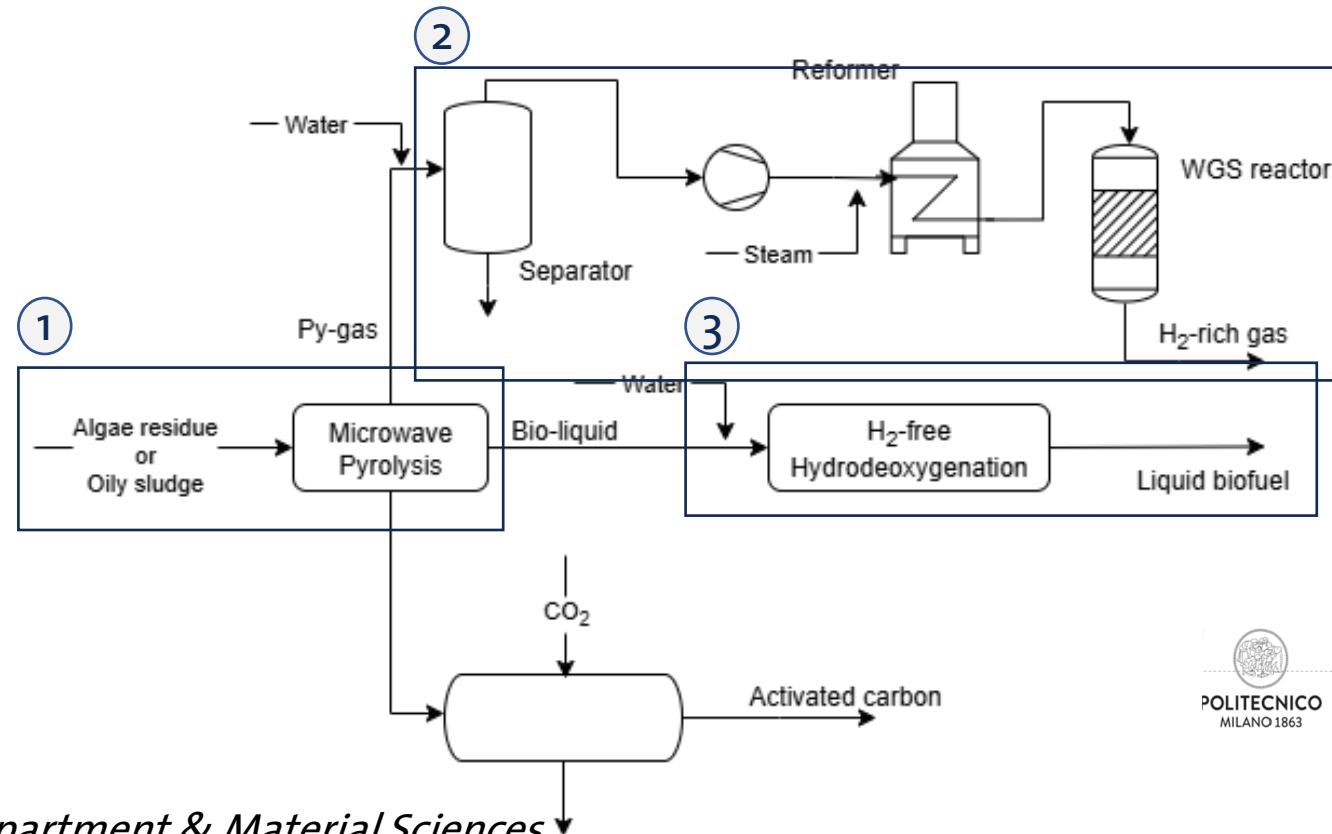
1. Microwave pyrolysis **reduces** reaction time and **increases** the quality of the product.
2. Py-gas post processing is performed with technologies that are **well documented** in literature.



Process Layout

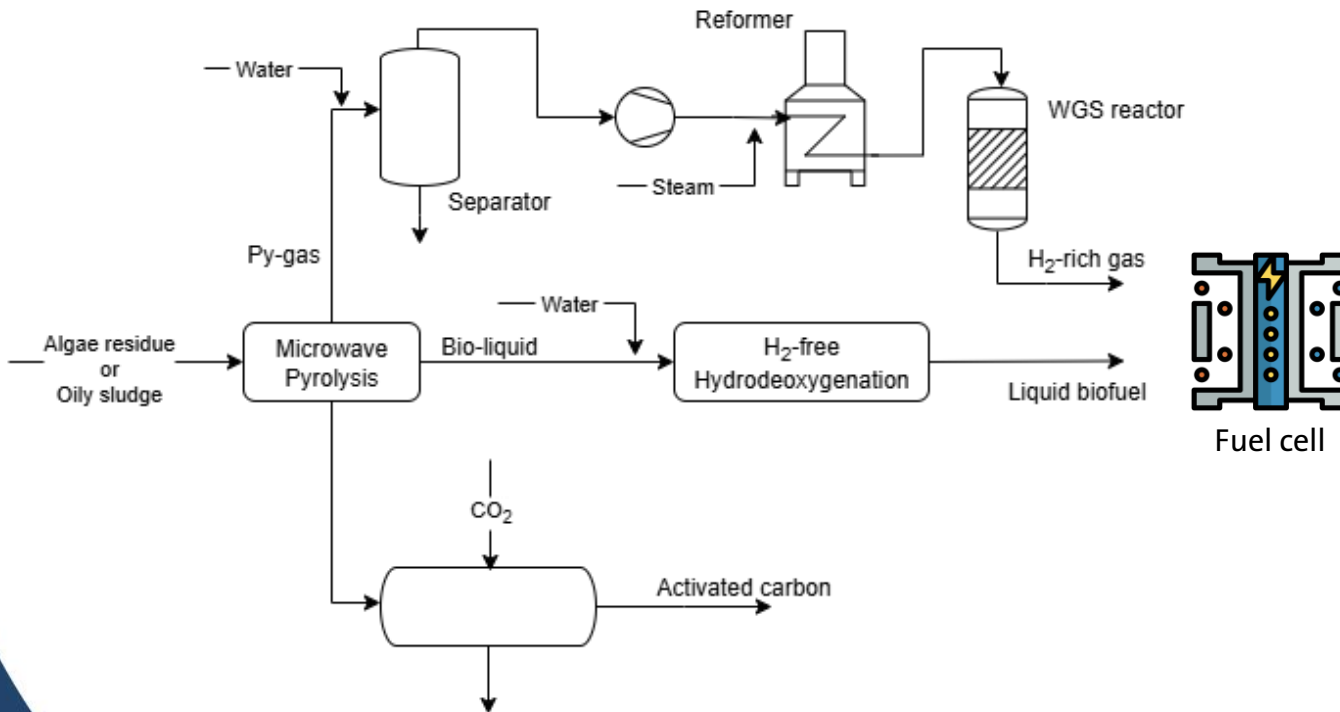
- Performance assessment of the process for industrial applications

1. Microwave pyrolysis **reduces** reaction time and **increases** the quality of the product.
2. Py-gas post processing is performed with technologies that are **well documented** in literature.
3. Hydrodeoxygenation uses water as primary reactant to **reduce** the overall energy demand of the process.



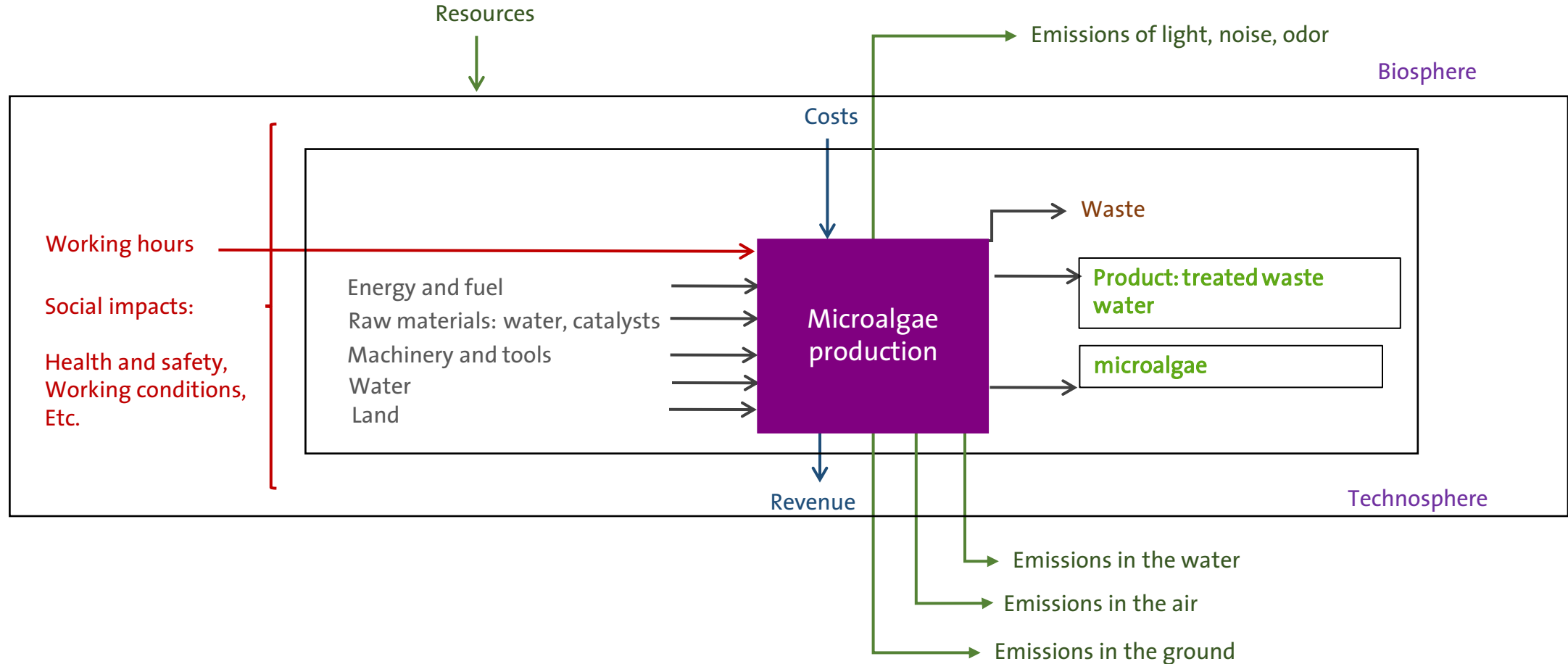
Process Layout

- Performance assessment of the process for industrial applications



- The final hydrogen enriched stream and liquid bio-fuel are supplied to two different **fuel cells** to be converted in electric energy

Unit process with LCSA data in the study



Modelling inputs

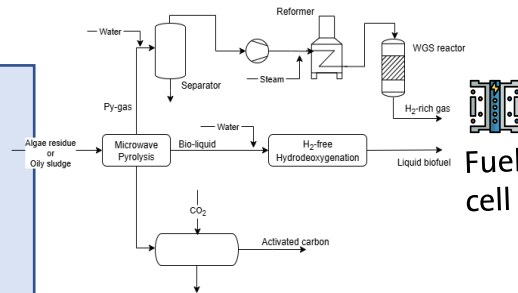
Process simulation for mass and energy flows

- All mass flows and product yields
- Electricity, heat, water and utility requirements
- Material and energy balances for pyrolysis, HDO, reforming, WGS and the fuel cell
- OPEX estimated

Machinery inventory

- Primary equipment data where available
- Secondary literature and database data for remaining machinery
- Equipment mass, materials, lifetime and replacement assumptions
- CAPEX estimated

Cost data from: IEA
Ecoinvent 3.11
BusinessAnalytiq



Map to processes in SOCA
(and sectors in PSILCA)

Obtain social risk data for
similar processes and
sectors

Parameterised exchanges
updated in openLCA to run
multiple scenarios

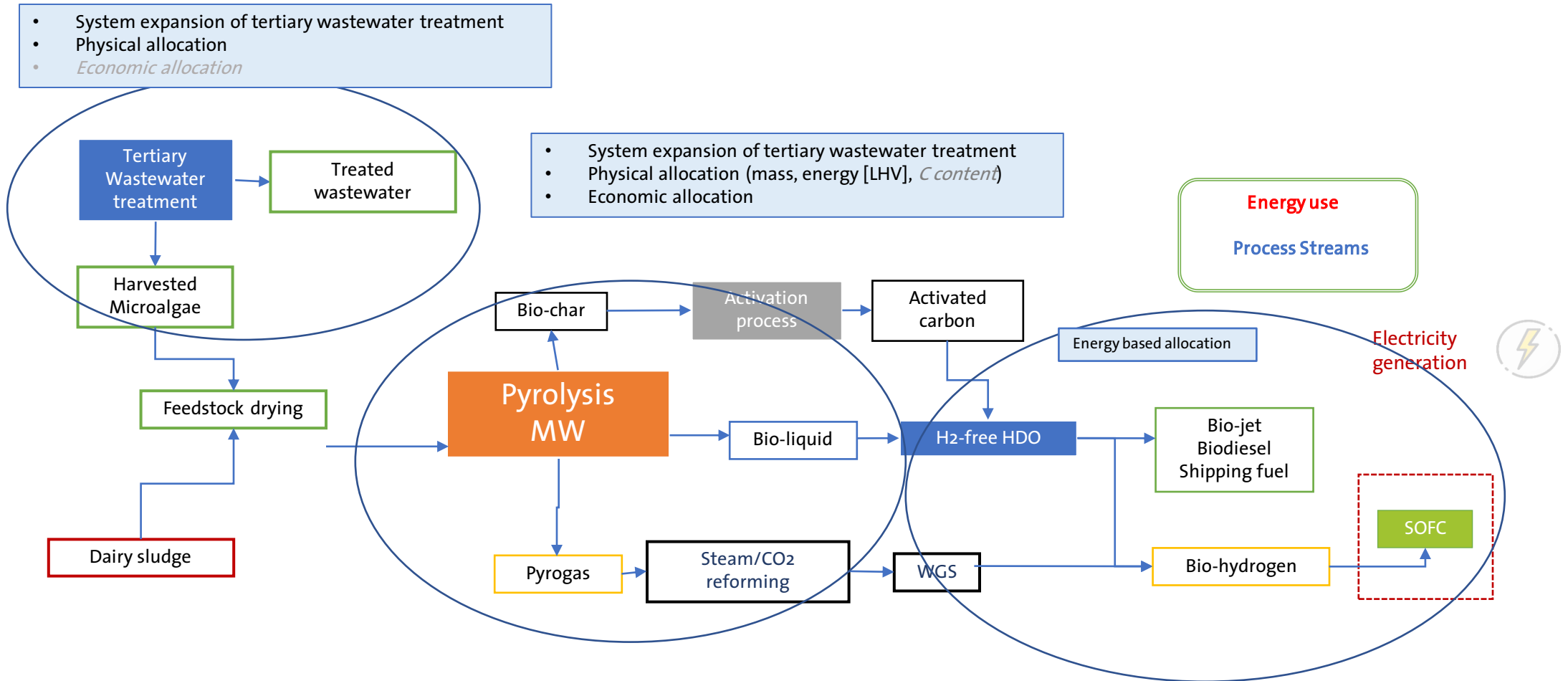


Manenti, F., & Bozzini, M. M. (2026). *D2.3: Requirement list for the TRL4 FLEXBY system* [Project deliverable]. FLEXBY Consortium. <https://doi.org/10.5281/zenodo.19048409>

Social indicators from initial stakeholder discussions

Foreground	Stakeholder worker – social indicators	Data to be considered
Algae cultivation and harvesting	<ul style="list-style-type: none"> Local water quality for release Odours 	<ul style="list-style-type: none"> Operating and safety records Exposure controls odour management practices
Dairy-sludge collection and conditioning	<ul style="list-style-type: none"> Worker exposure to VOCs and odours Handling and transport 	<ul style="list-style-type: none"> Exposure controls odour management practices
Pyrolysis, bioliquid processing, pyrogas processing	<ul style="list-style-type: none"> Process safety Emissions and particulate matter exposure 	<ul style="list-style-type: none"> H&S procedures monitoring and training

Multifunctionality in pyrolysis and further processing



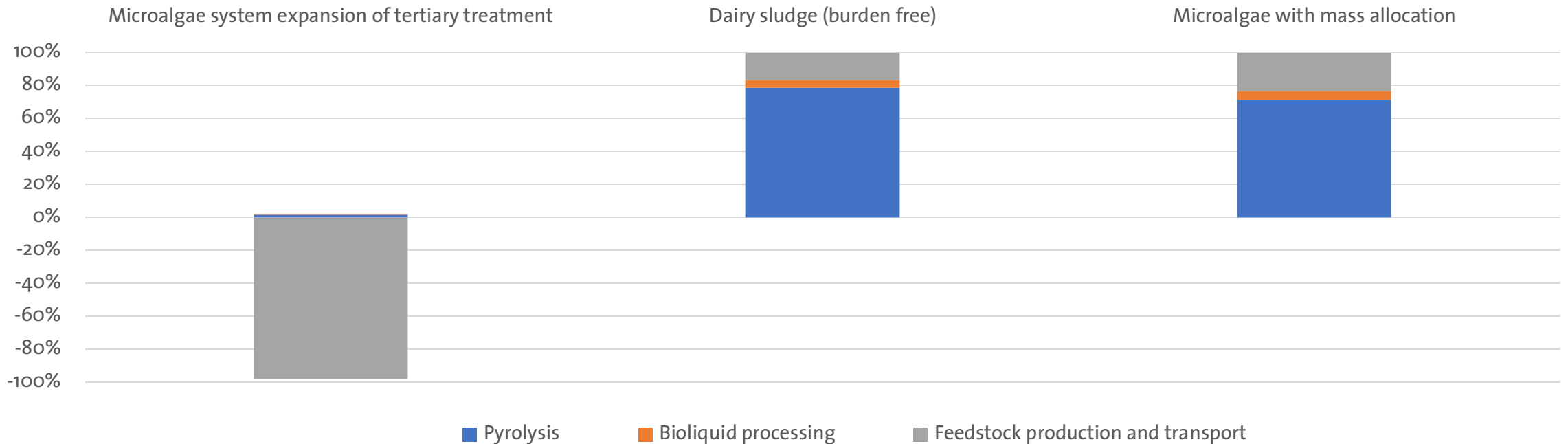
Preliminary results

Subject to change as project evolves and new data is available

Preliminary LCIA Results 1 MJ of biofuel

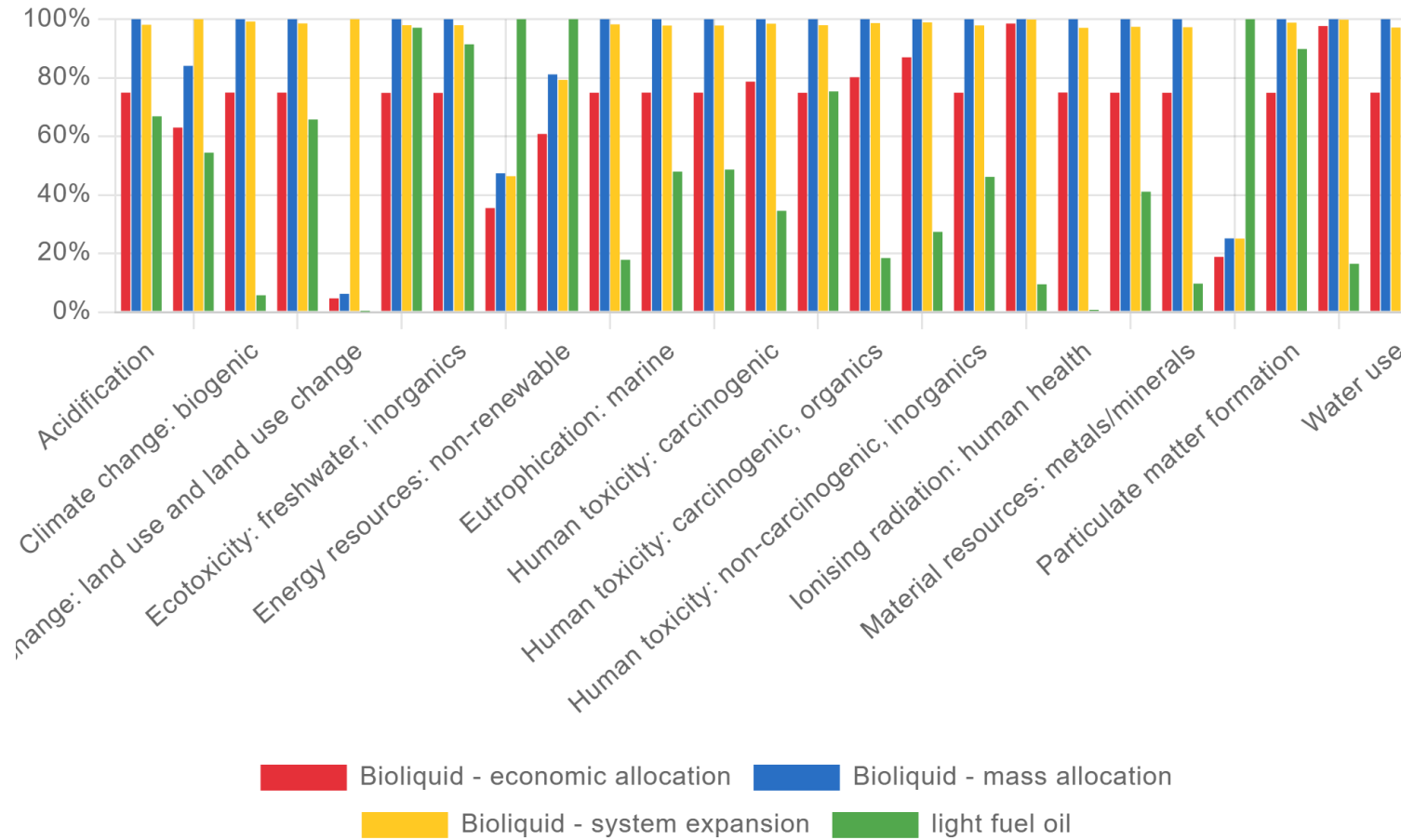
EF 3.1 - (mass allocation vs system expansion for the microalgae feedstock cultivation)

Sensitivity analysis - feedstocks



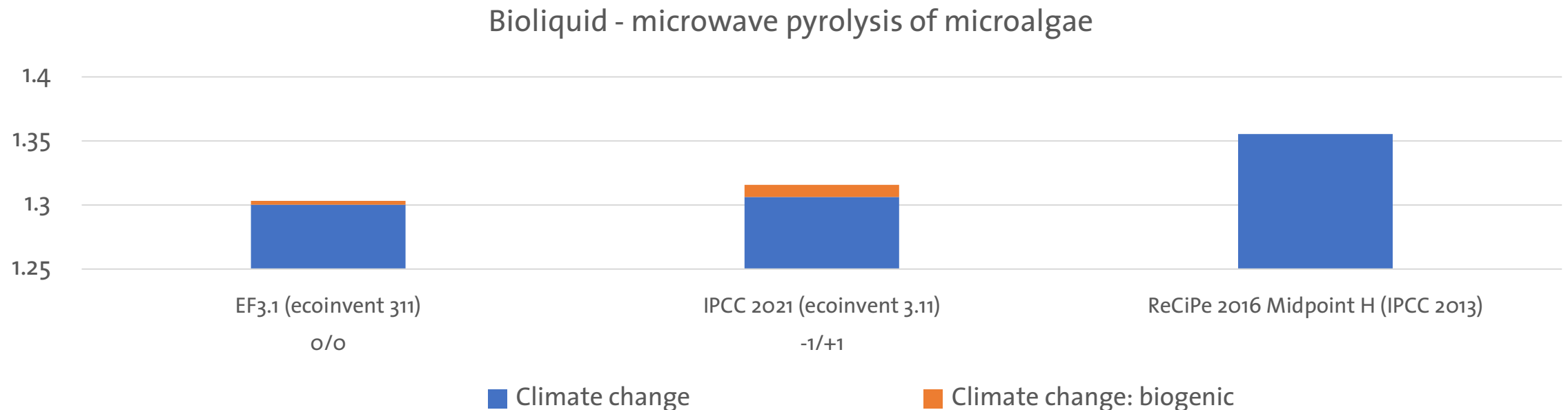
LCIA Results 1 MJ of biofuel - high uncertainty

EF 3.1 - (mass allocation vs economic allocation vs system expansion for the pyrolysis process)

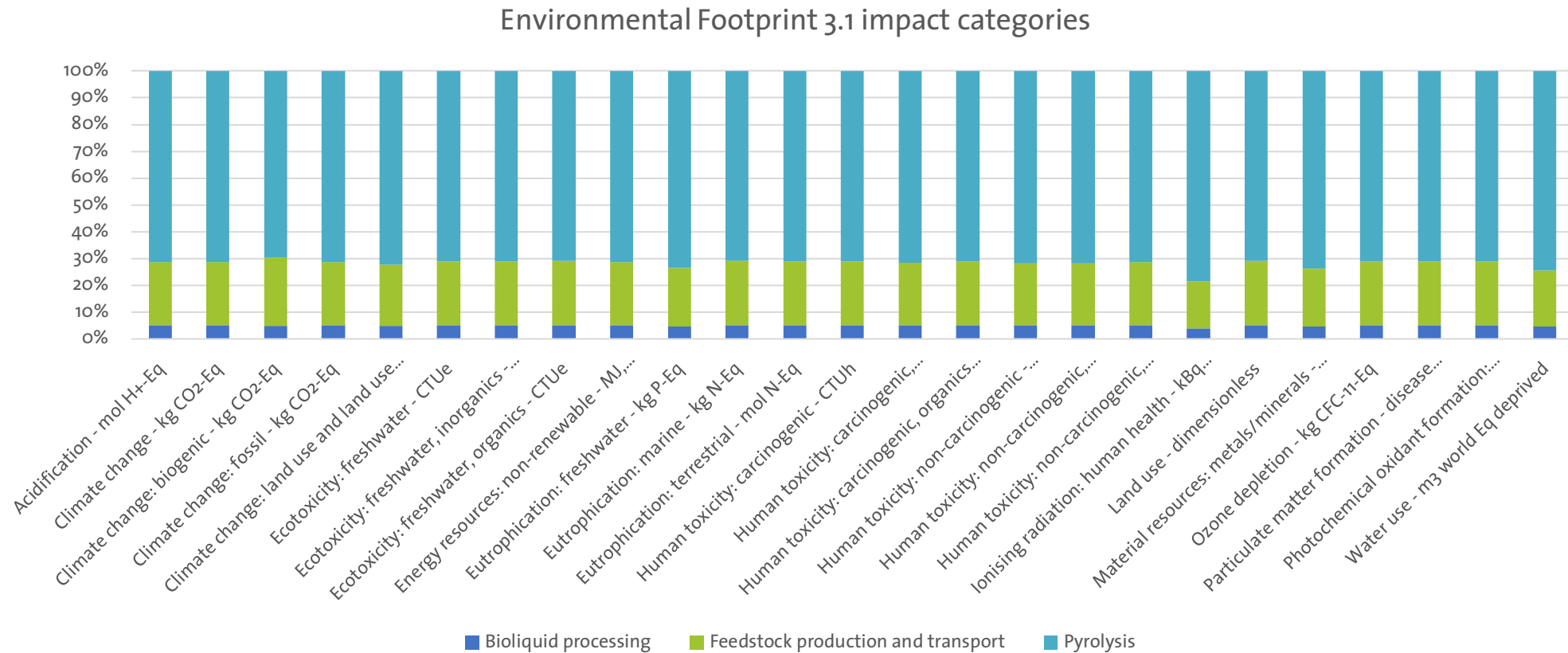


Biogenic carbon consideration in different standards

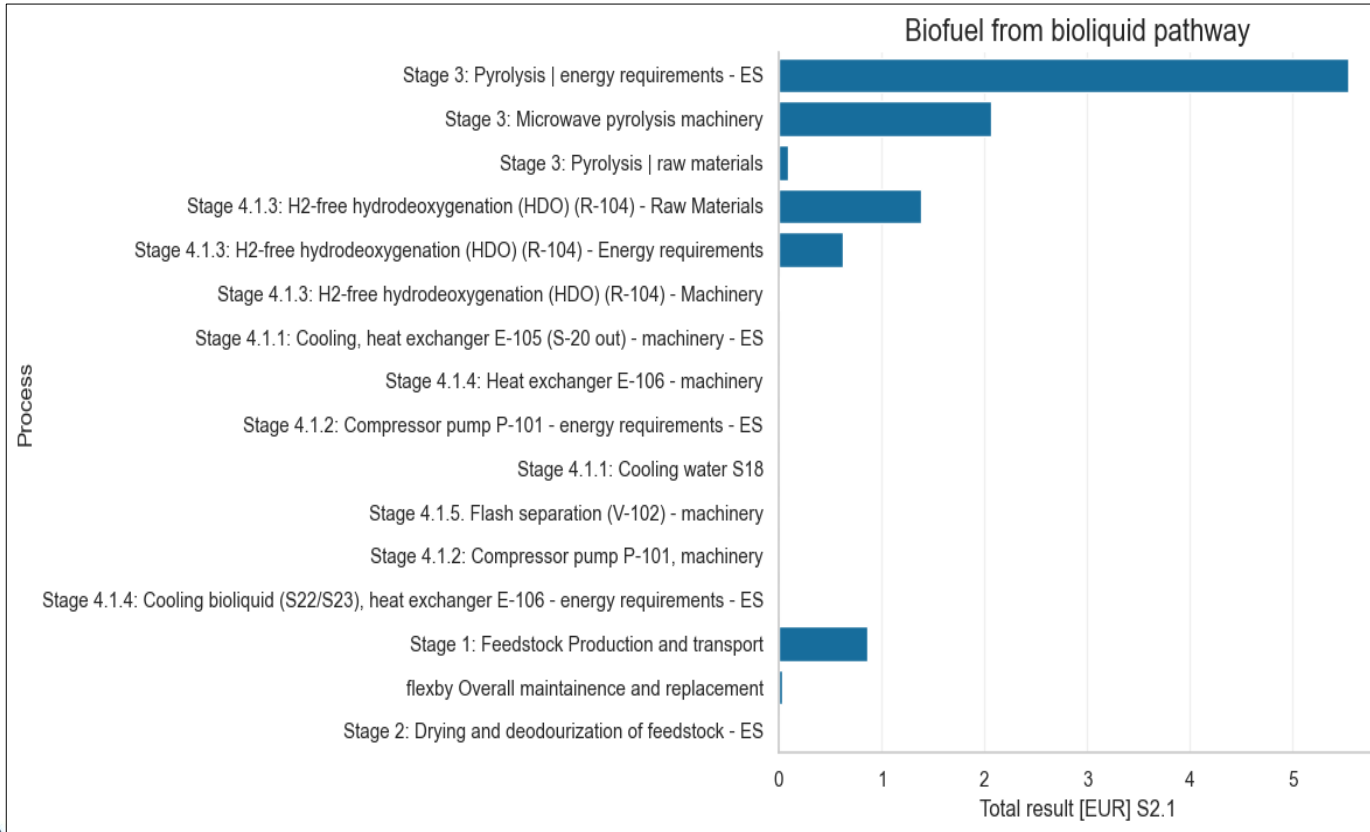
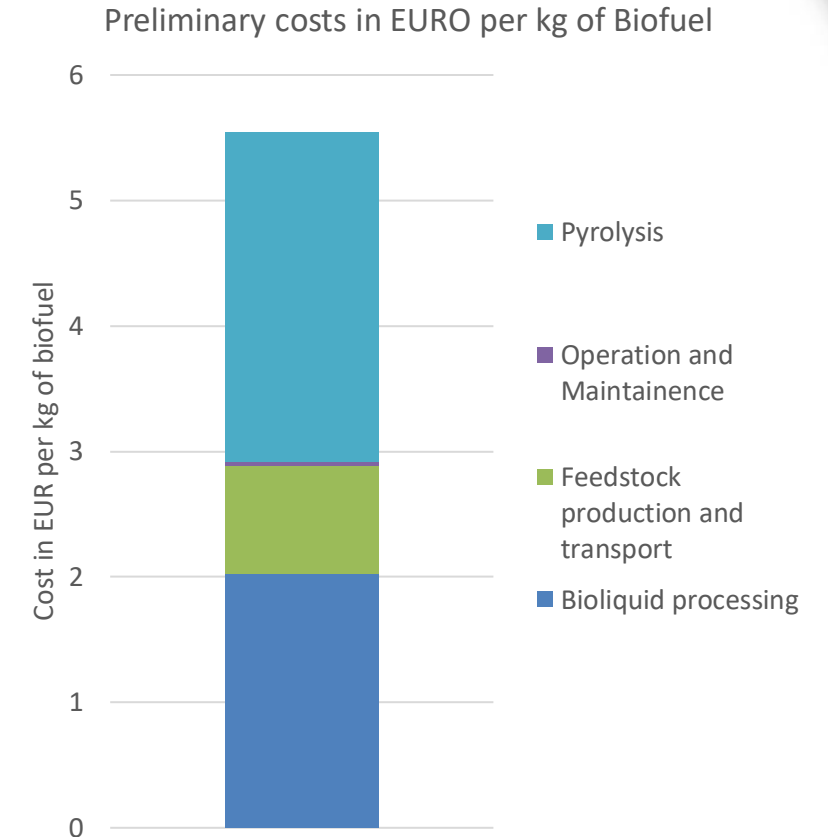
- **ISO 14044** allows both 0/0 approach and +1/-1 approach
- **PEF, Renewable Energy Directive (RED III) , ReCiPe 2016** – 0/0 approach



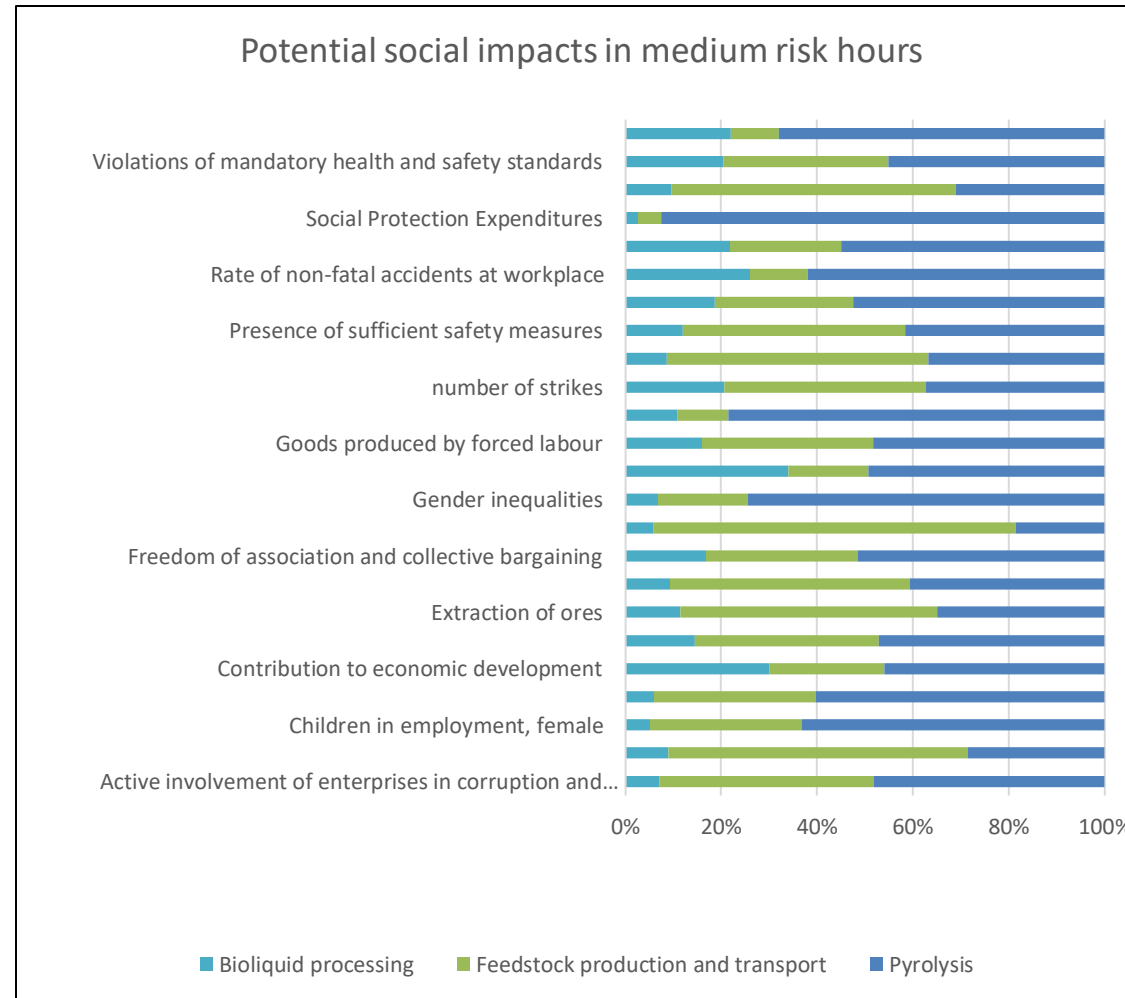
Environmental LCIA Impacts with EF 3.1 (*mass allocation*)



LCIA results and LCC results (*mass allocation*)



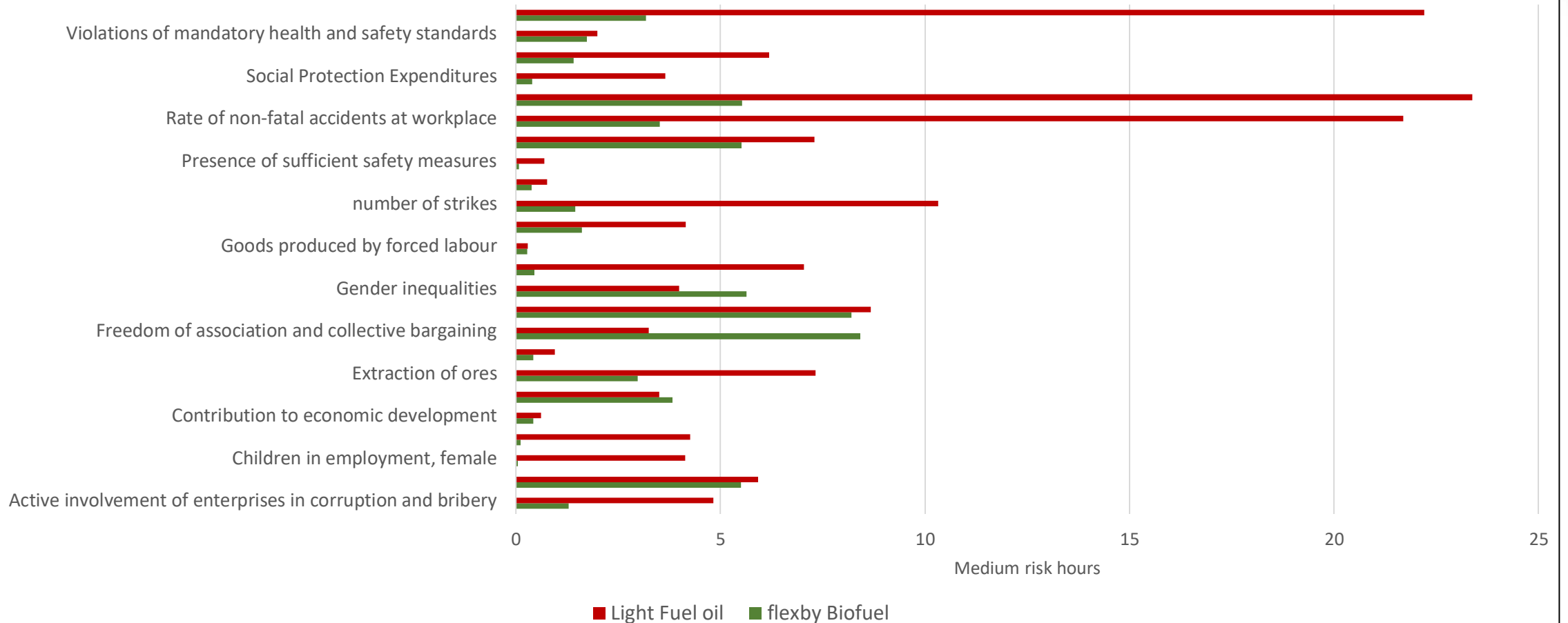
Preliminary Social Life Cycle Assessment results in medium risk hours per MJ of fuel (*mass allocation*)



Distribution of risk levels across the life cycle(*mass allocation*)



Preliminary comparison of potential social risks (in medium risk hours) between flexby biofuel and light fuel oil (*mass allocation*)



Key takeaways

- Process simulation allows the early assessment of LCSA to detect hotspots, in this case electricity requirements have a significant impact
- Reducing process energy demand has the highest potential for optimization rather than machinery/material at early stage
- occupational safety, fair employment, gender equality and worker representation as the principal foreground risks. Risks related to minerals, forced labour and geographically dispersed supply chains require procurement-based mitigation (which may not always be possible) rather than direct operational control.
- Researcher's everyday experiences when working with bio-products and chemicals, provides some insights for considerations of future workers
- Uncertainty of results:
 - Scale-up of energy and material demand
 - Product yields and efficiencies at TRL5
 - Multifunctionality scenarios influence results strongly
 - Current fate and treatment of dairy sludge
 - Future electricity and supply-chain backgrounds

Further References

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Acknowledgments

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