TriFluorium
safe fluorine circularity

Green Metrics or Life Cycle Assessment? A Sustainability Evaluation of Tribochemical Fluoride Recycling from Waste Fluoropolymers

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GreenDelta

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European Innovation Council

Fluoropolymers

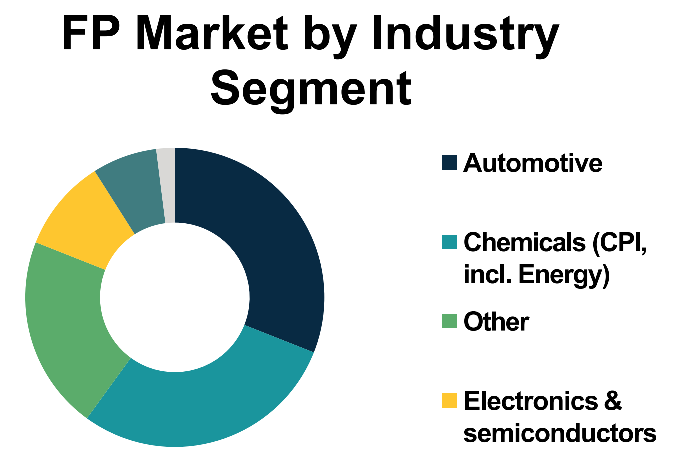
- Fluoropolymers (FPs) are used throughout all industries

Tubing (PVDF)

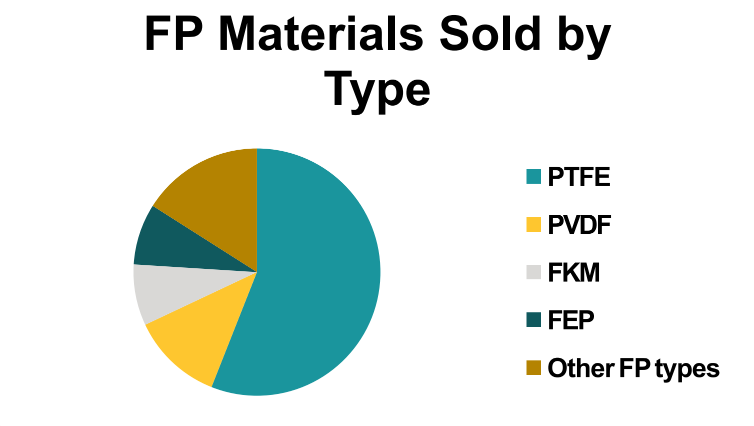
Membrane Syringe Filter (PTFE)

Architecture (ETFE)

Frying Pan Coatings (PTFE)



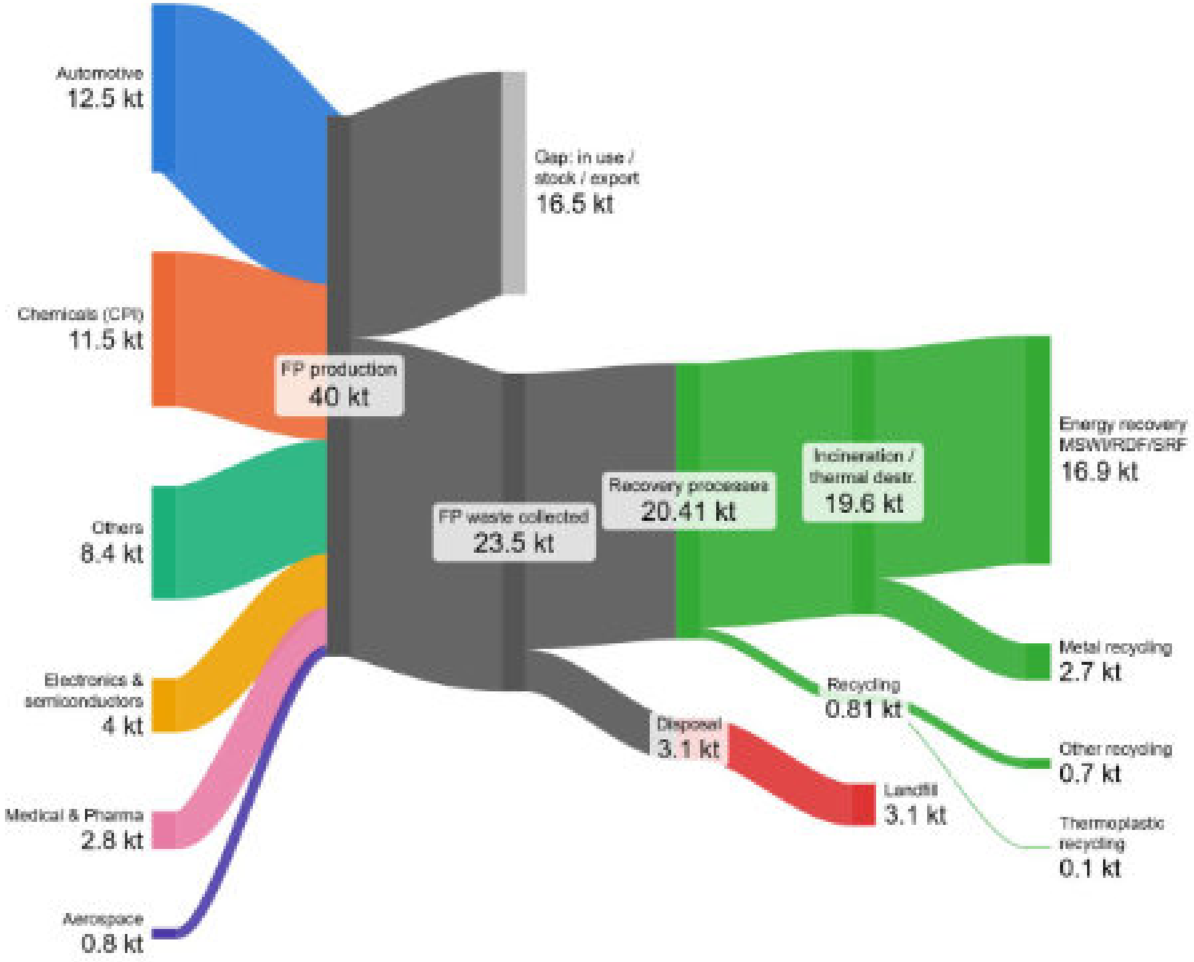
FP Market by Industry Segment



FP Materials Sold by Type

Fluoropolymer waste in Europe 2020, Conversion for Pro Kunstoff

Fluoropolymers - Circularity



- **Production of FP** is associated with problematic **emissions (HFCs, PFAS)** and **use of CRM (CaF_2)**
- **Only 0.81 kt (3.4%) of 23.5 kt FP waste collected in 2020 was recycled**
- Recycling limited to "clean" pre-consumer scrap from manufacturers; post-consumer FP waste too dilute (<0.01% by mass) for economical sorting
- **Waste treatment might be associated with release of PFAS** (OECD report, 2024)
- **CaF_2 dependency** makes **circularity a feedstock security issue**, not just waste management

Fluoropolymer waste in Europe 2020, Conversion for Pro Kunstoff

Mission

"**TriFluorium** will expand **circular economy** capabilities

by pioneering a **novel mechanochemical recycling process**

for **safe, sustainable, and efficient regeneration of fluorine**

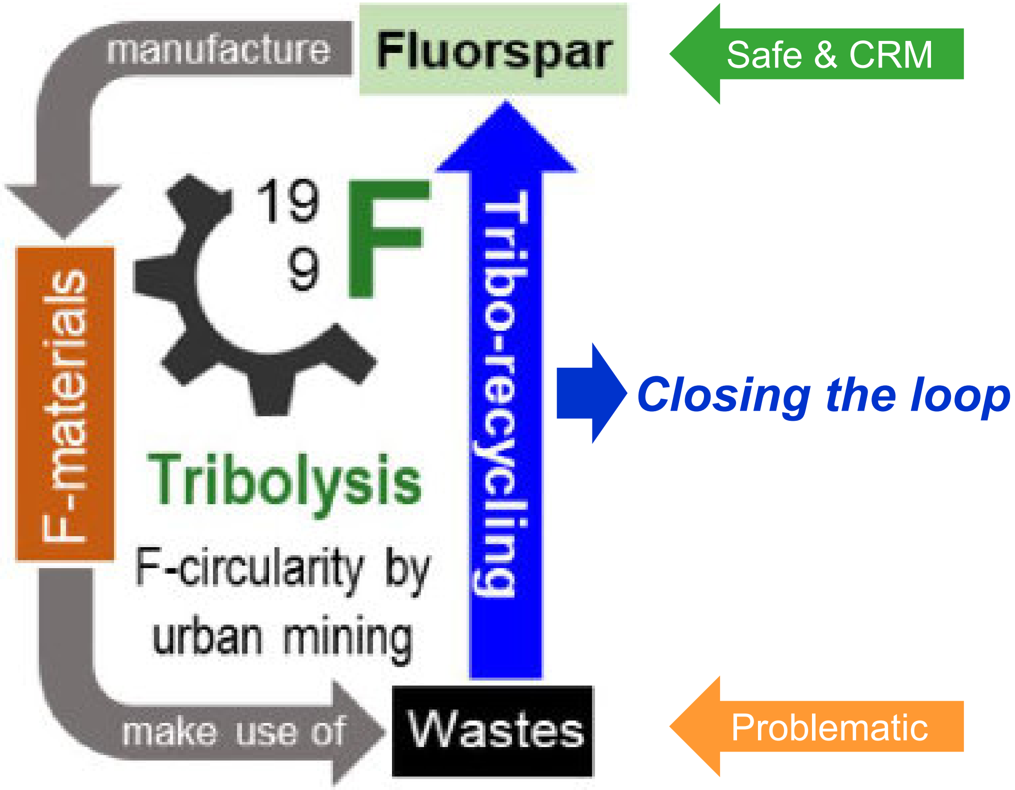
from **persistent high-value fluoropolymer waste**

into **valuable industrial and CRM resources.**"

TriFluorium at glance

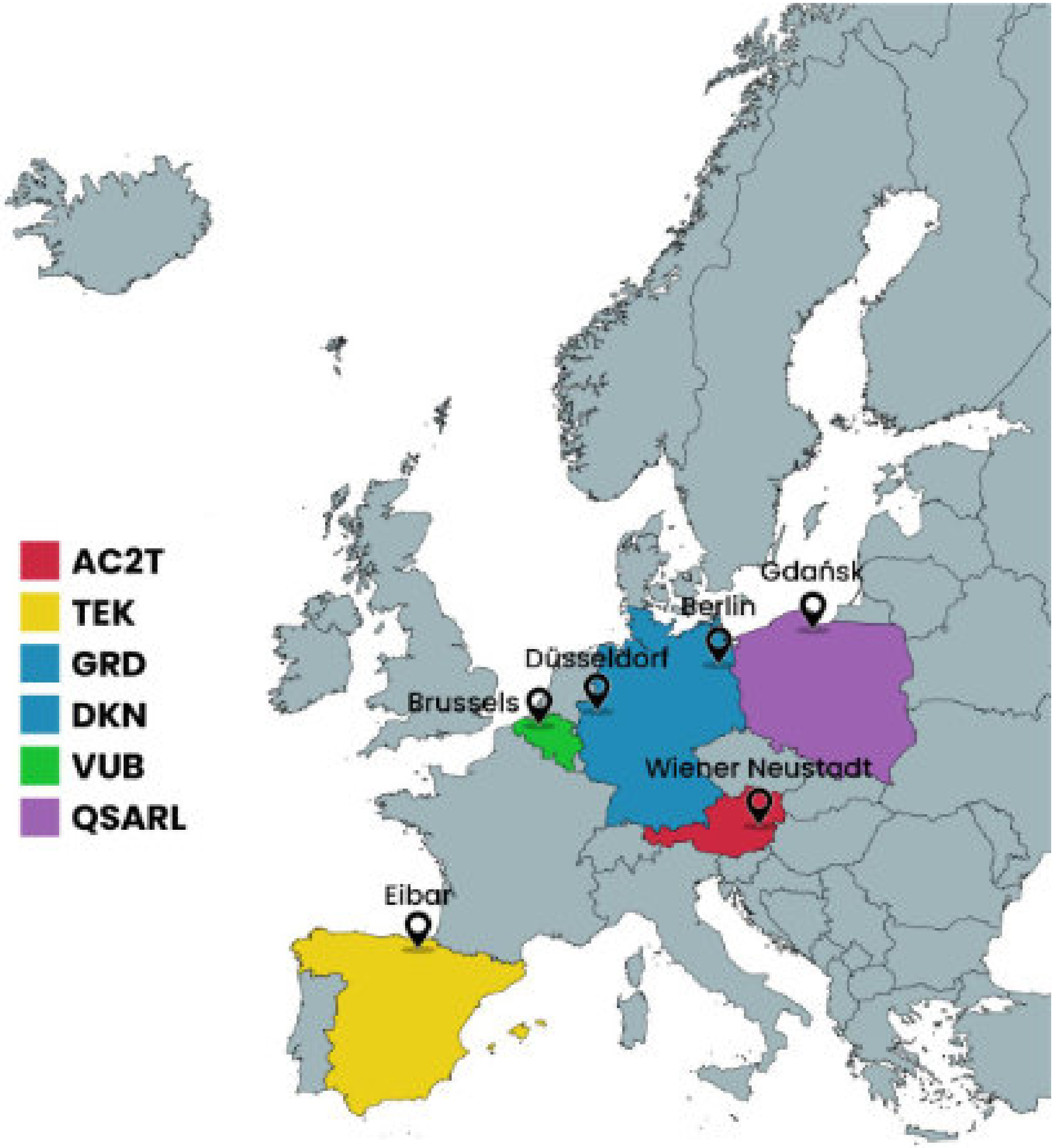
- **TriFluorium –** Tribo-Reactor for **fluorine circularity** by urban mining
    - Call allocation: HORIZON-EIC-2024-**PATHFINDER-OPEN**-01
        - **Enabler of circular economy for stable high F-containing waste**

- **Actual project figures**
    - Grant agreement ID: 101187492
    - Duration: **48 months**
    - Time frame: February 2025 – January 2029
    - Total funding: **€ 3 355 038.75**
    - Efforts: 359 PMs, 8 WPs, 37 Tasks

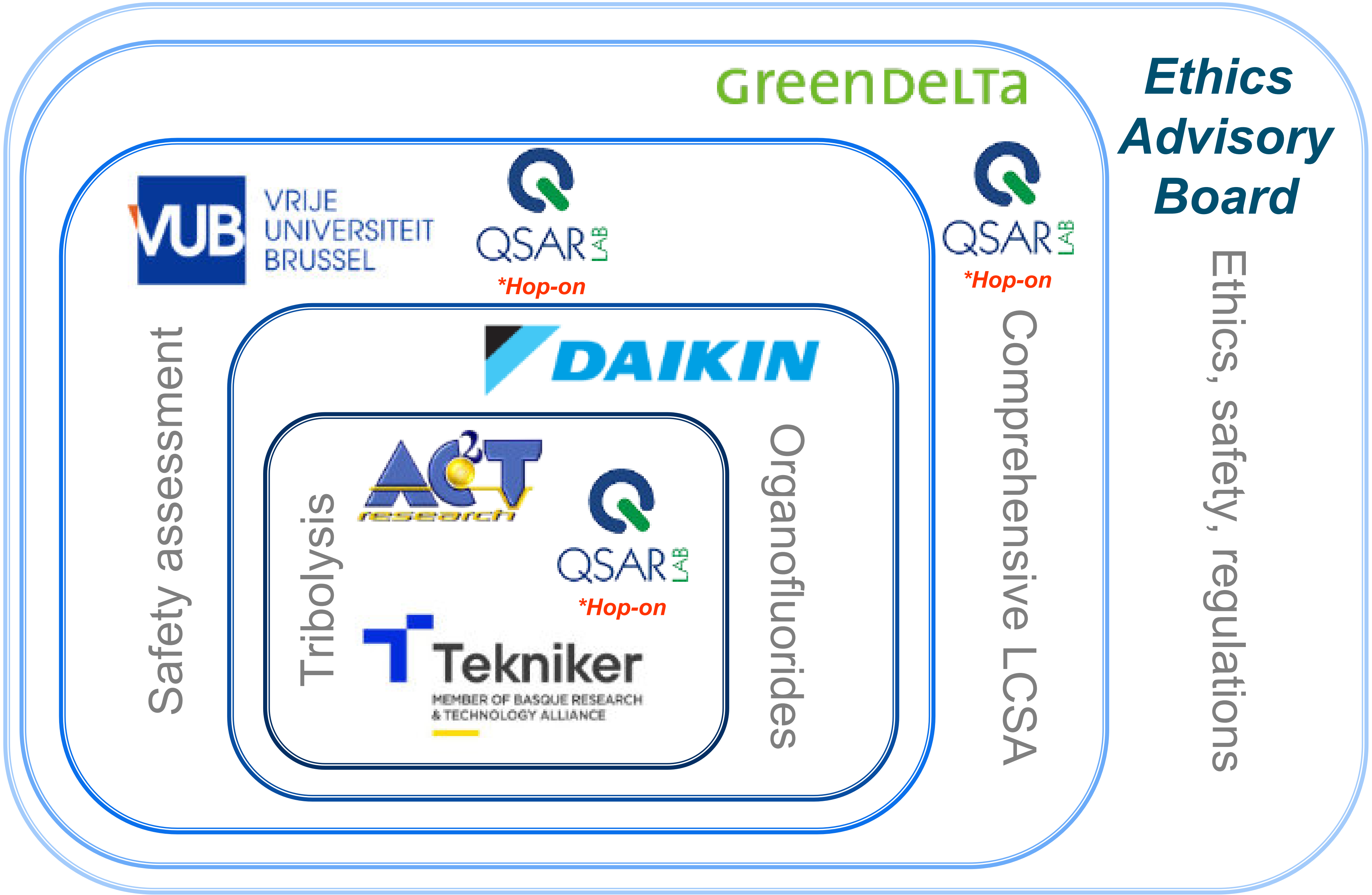


Consortium

- **6 beneficiaries from 5 EU countries**
  - 2 research centers
    - **AC2T research GmbH** (AC2T)
      - **COORDINATOR**
    - ***Fundación Tekniker*** *(TEK)*
  - 3 industrial partners
    - **Daikin Chemical Europe GmbH** (DKN)
    - **GreenDelta GmbH** (GRD)
    - **QSAR Lab Sp. z o.o.** (QSARL)
  - 1 higher education institution
    - **Vrije Universiteit Brussel** (VUB)



Complementary competences



Ethics Advisory Board

*Hop-on

*Hop-on

*Hop-on

Safety assessment

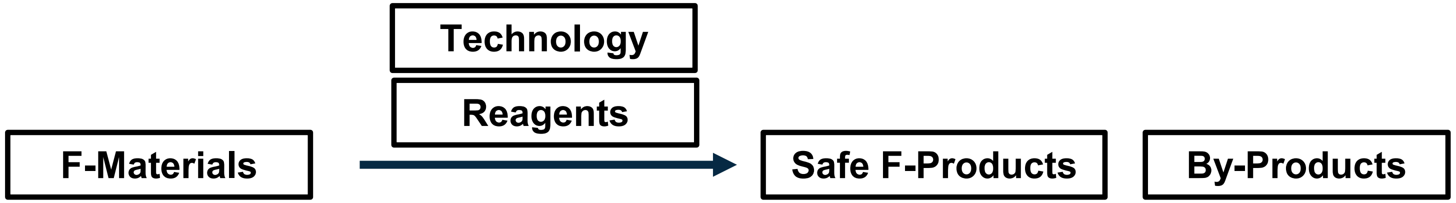
Tribolysis

Organofluorides

Comprehensive LCSA

Ethics, safety, regulations

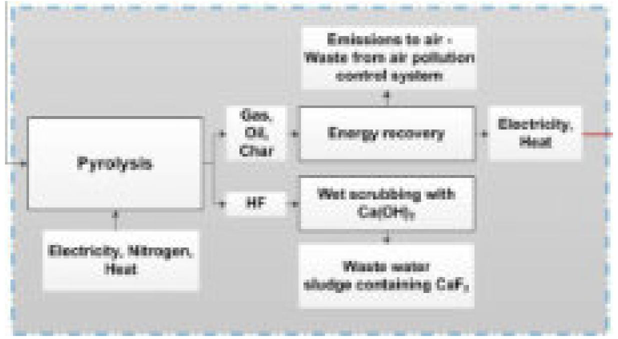
Literature Overview: FP Recycling



Pyrolysis without F recovery

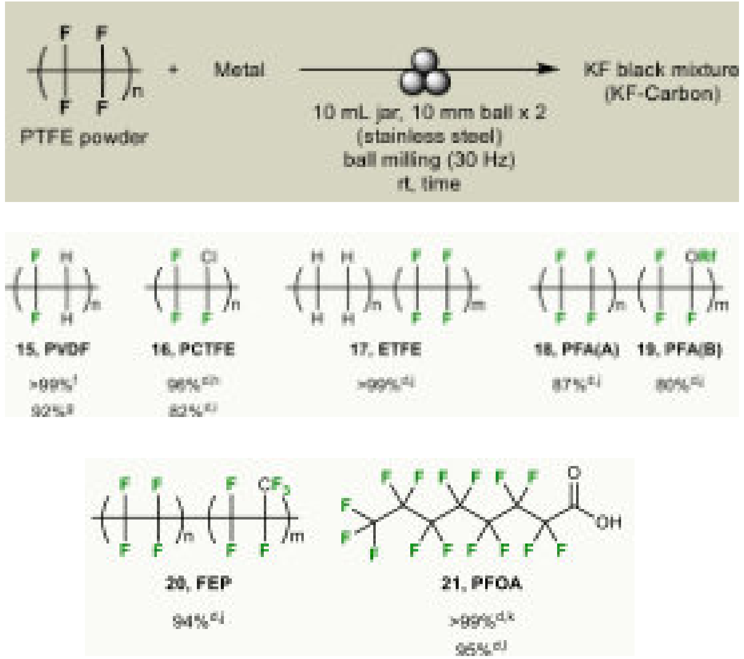
TABLE 1 List of EoL scenarios considered in this study

Scenario	No.	Description
Incineration	1.1	Incineration of fluorine-free backsheet (PET)
	1.2	Incineration of fluorinated backsheet (PVDF)
Pyrolysis	2.1	Pyrolysis of fluorine-free backsheet (PET)
	2.2	Pyrolysis of fluorinated backsheet (PVDF)



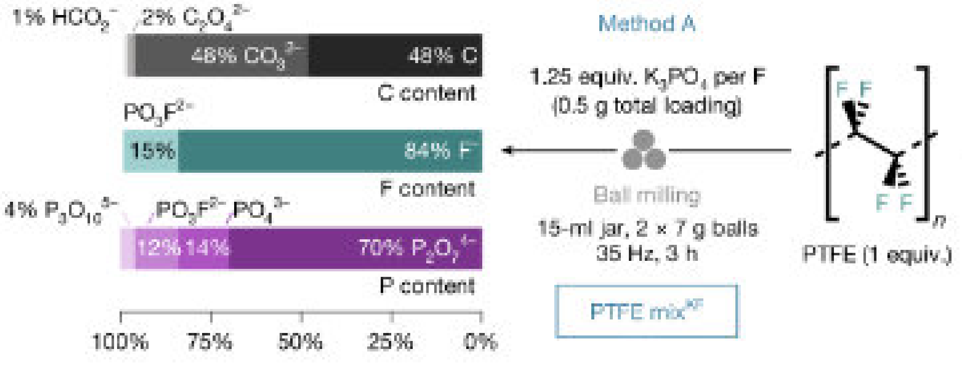
Aryan et al., *Prog. Photovolt. Res. Appl.* **2018**; 26, 443–459

Ball milling with reactive metals



Hattori et al., *Nat. Comm.* **2026**, *669*

Ball milling with phosphate salts



Upcycling of PFAS from consumer items and adsorbed pollutants

Yang et al., *Nature* **2025**, *640*, 100–106

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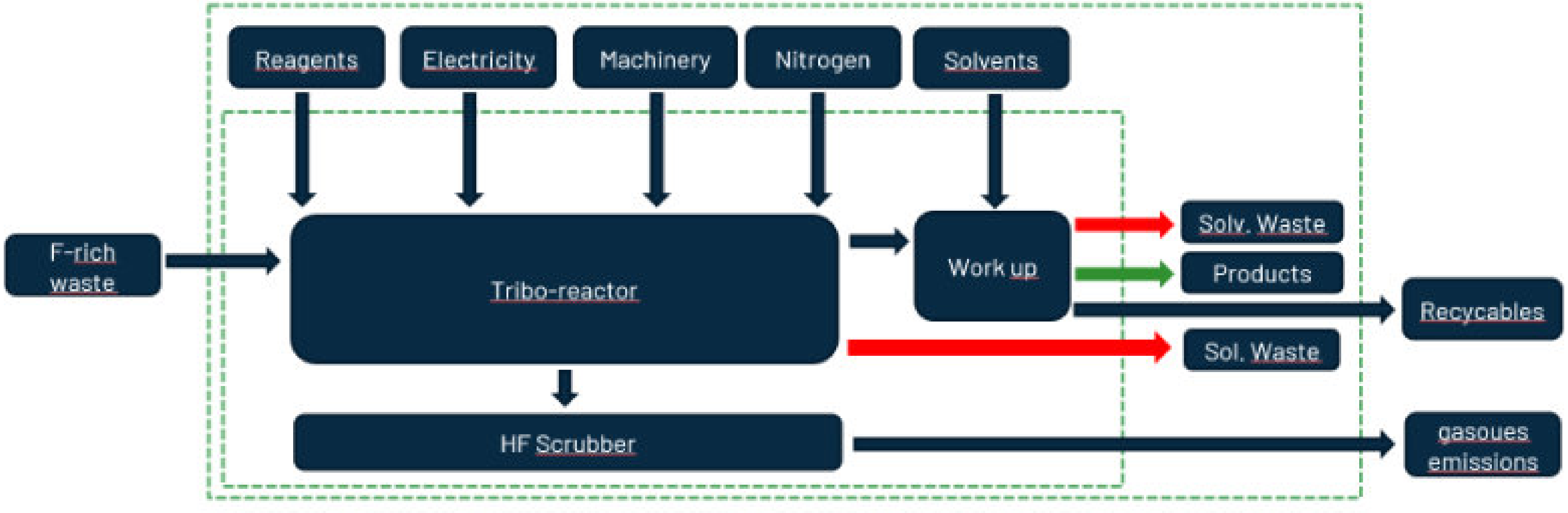
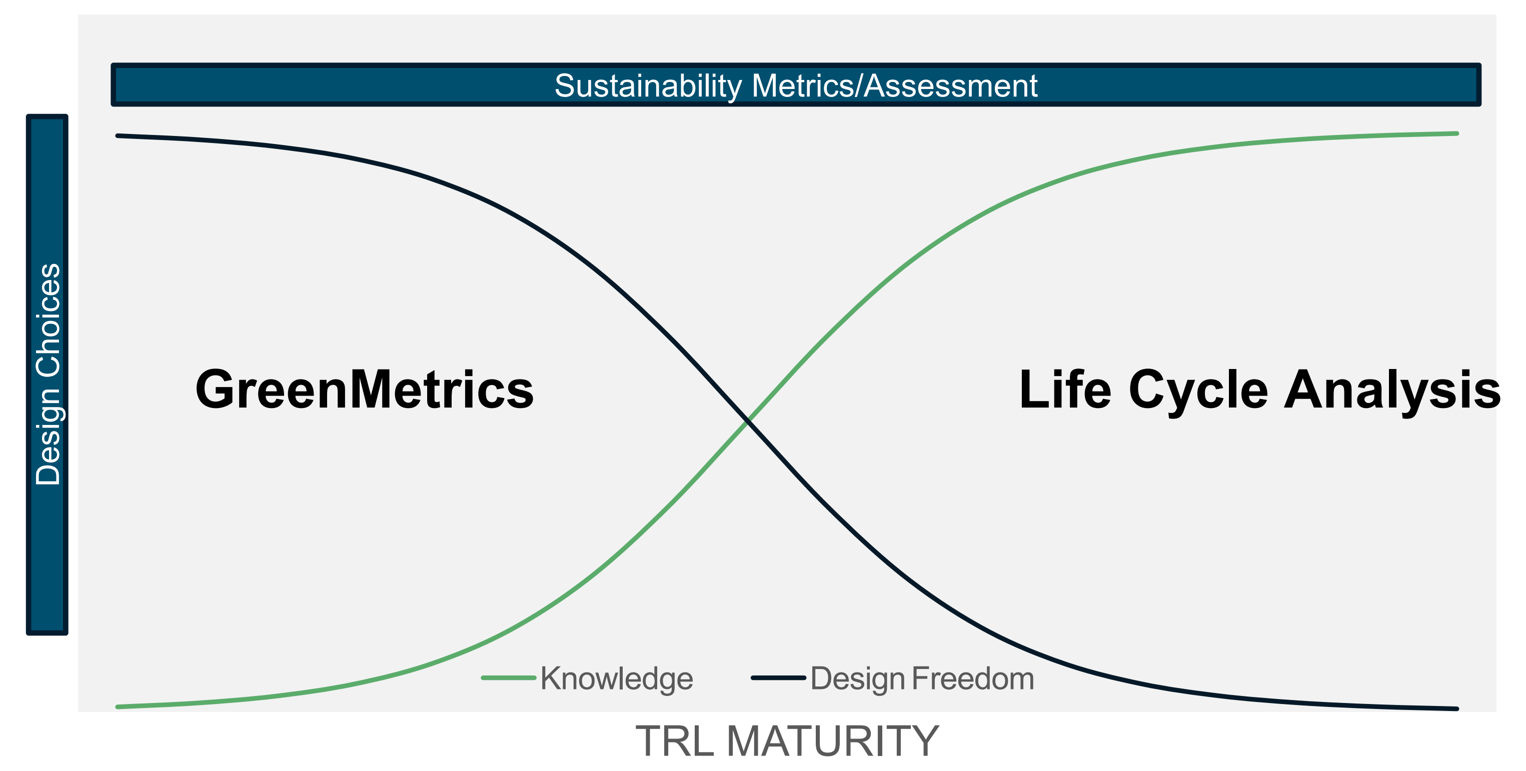


Reagents
Electricity
Machinery
Nitrogen
Solvents
F-rich waste
Tribo-reactor
Work up
Solv. Waste
Products
Recycables
Sol. Waste
HF Scrubber
gasoues emissions

But how sustainable is such a process and how can we guide with sustainability principles?

Sustainability of a tribolysis process



See Blöomer et al. 2024

Green Metrics

$$A + B \rightarrow C$$

$$\text{Atom economy} = \left(\frac{\text{m.w. of product C}}{\text{m.w. of A} + \text{m.w. of B}} \right) \times 100$$

$$\text{Mass intensity (MI)} = \frac{\text{Total mass used in a process or process step (kg)}}{\text{Mass of product (kg)}}$$

$$\text{Reaction mass efficiency} = \left(\frac{\text{mass of product C}}{\text{mass of A} + \text{mass of B}} \right) \times 100$$

$$\text{Carbon efficiency} = \frac{\text{no. of moles of product} \times \text{no. of carbons in product} \times 100}{(\text{moles of A} \times \text{carbons in A}) + (\text{moles of B} \times \text{carbons in B})}$$

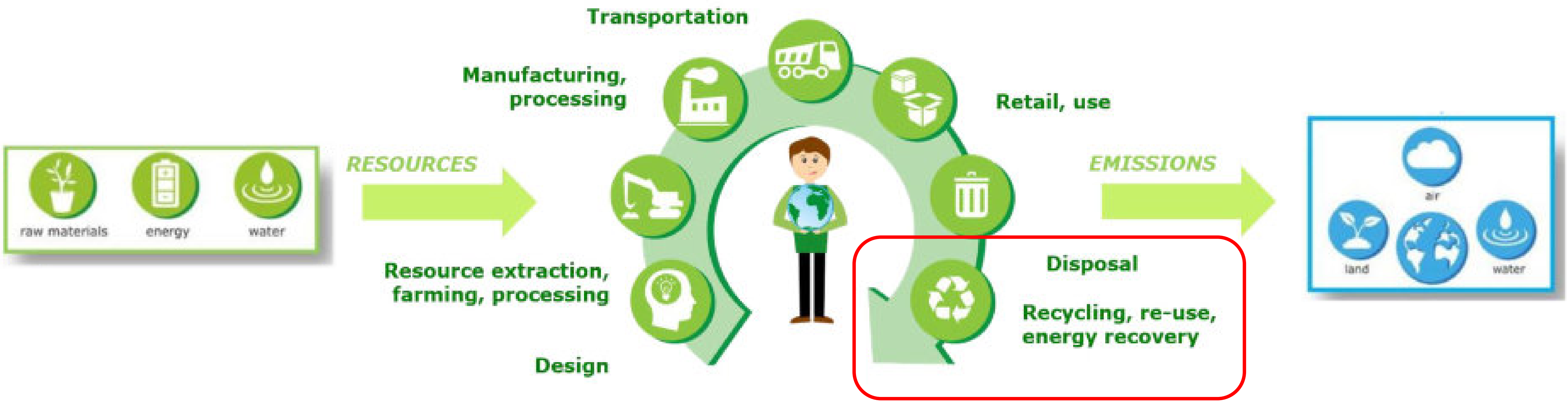
$$\text{E Factor} = \frac{\text{Total waste (kg)}}{\text{kg product}}$$

Category	Metrics
Overview	Conversion, Fluoride recovery, Carbon recovery, Yield, Mass balance
Mass-based efficiency	Atom Economy (AE), Mole Efficiency (ME), Reaction Mass Efficiency (RME), Process Mass Efficiency (PME), Mass Productivity (MP), Carbon Efficiency (CE)
Mass intensity and waste generation	Reaction Mass Intensity (RMI), Process Mass Intensity (PMI), Mass Intensity (MI), E-Factor (simple, complete, total), Waste Intensity (AI)
Solvent and water use	Solvent Intensity (SI), Water Intensity (WI), Wastewater Intensity (WWI)
Energy screening	Process Energy Intensity (PEI, foreground only)
Neglected for TriFluorium	Renewable Resources Percentage (RP), Renewable Resources Intensity (RI), Effective Mass Yield (EMY)

Cunningham *et al.*, *Green Chemistry*, **2002**, *4*, 521–527

Life Cycle Assessment

- **Definition (DIN 14044)**: *'Life Cycle Assessment (LCA) is a compilation and evaluation of inputs, outputs and the potential environmental impacts of a product system through its life cycle.'*



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European Commission, Joint Research Centre, Cristobal-Garcia, J., Pant, R., Reale, F. et al., Life cycle assessment for the impact assessment of policies, Publications Office, 2016, https://data.europa.eu/doi/10.2788/318544

Life Cycle Assessment: Structure

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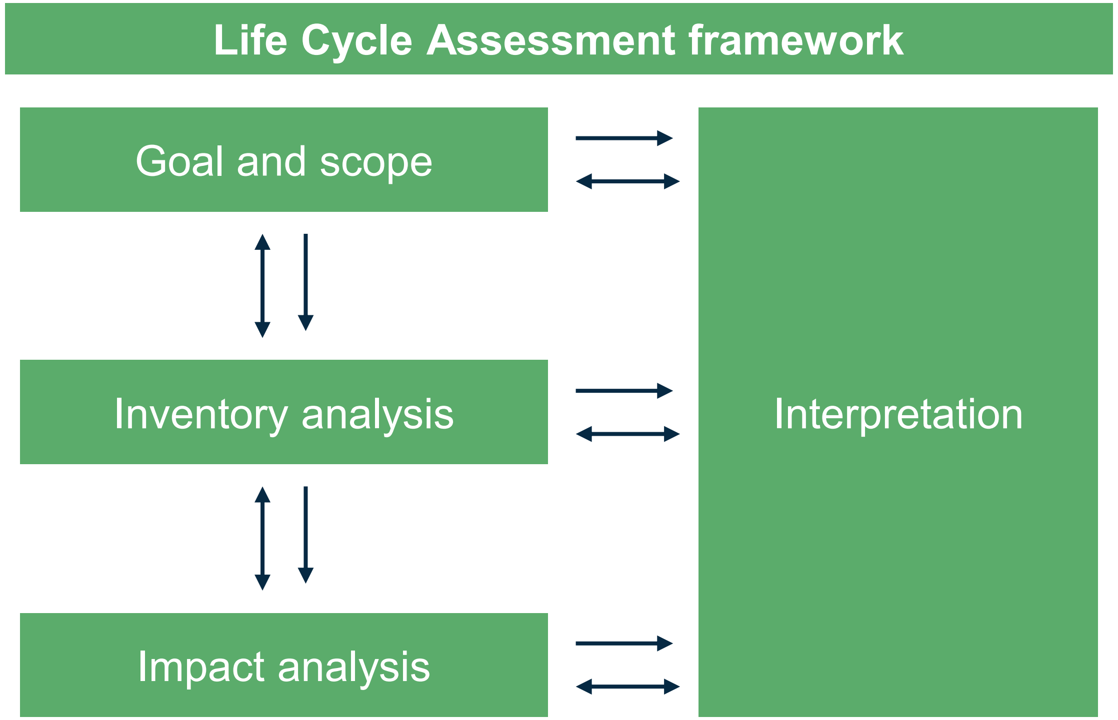
- LCA approach is mainly based on two standards: **ISO 14040:2006 and ISO 14044:2006**
- LCA is performed in **four steps:**
    1. Goal and Scope definition
    2. Life Cycle Inventory
    3. Life Cycle Impact Analysis
    4. Life Cycle Interpretation

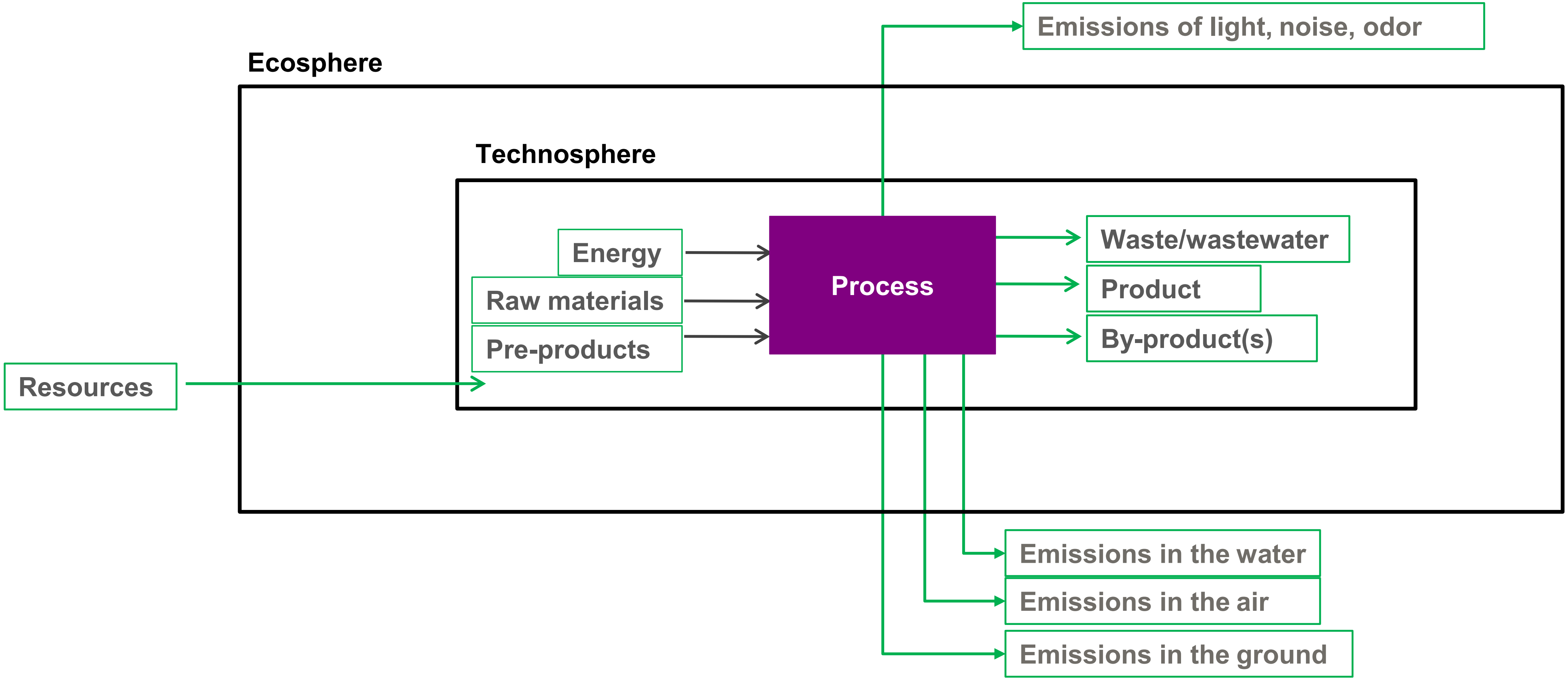
- **Functional unit**:

“Provision of 1 kg of XY”; “Treatment of 1 m^3 water” “Management of 1 tonne of sorted packaging waste bales with defined composition”



Life Cycle Assessment framework

Life Cycle Assessment: Inventory



Emissions of light, noise, odor

Ecosphere

Technosphere

Energy

Raw materials

Pre-products

Process

Waste/wastewater

Product

By-product(s)

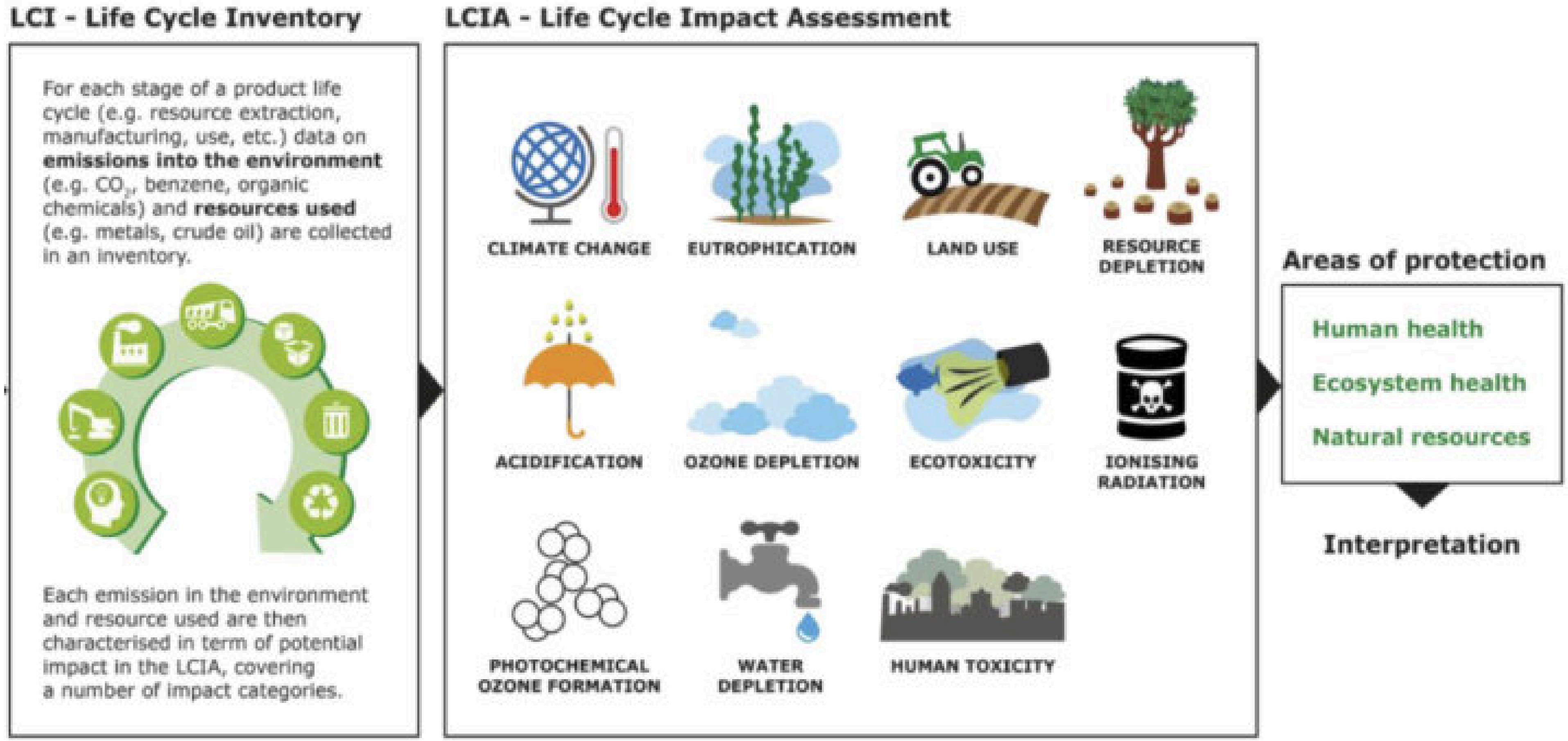
Resources

Emissions in the water

Emissions in the air

Emissions in the ground

Life Cycle Assessment: Impact Assessment



LCI - Life Cycle Inventory

For each stage of a product life cycle (e.g. resource extraction, manufacturing, use, etc.) data on **emissions into the environment** (e.g. CO_2, benzene, organic chemicals) and **resources used** (e.g. metals, crude oil) are collected in an inventory.

Each emission in the environment and resource used are then characterised in term of potential impact in the LCIA, covering a number of impact categories.

LCIA - Life Cycle Impact Assessment

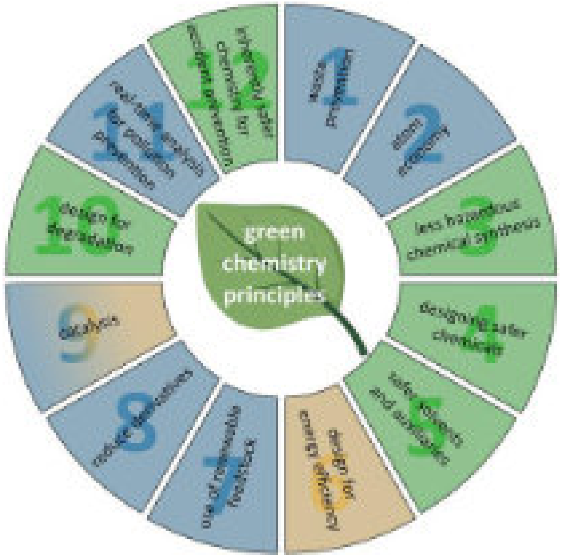
Areas of protection

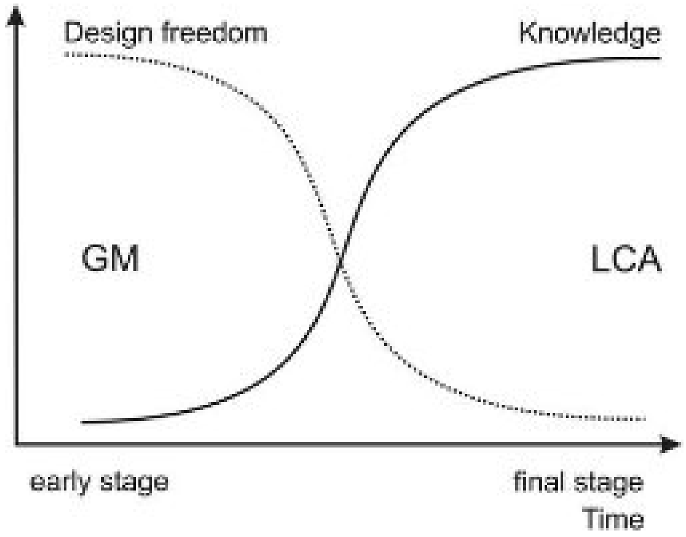
- Human health
- Ecosystem health
- Natural resources

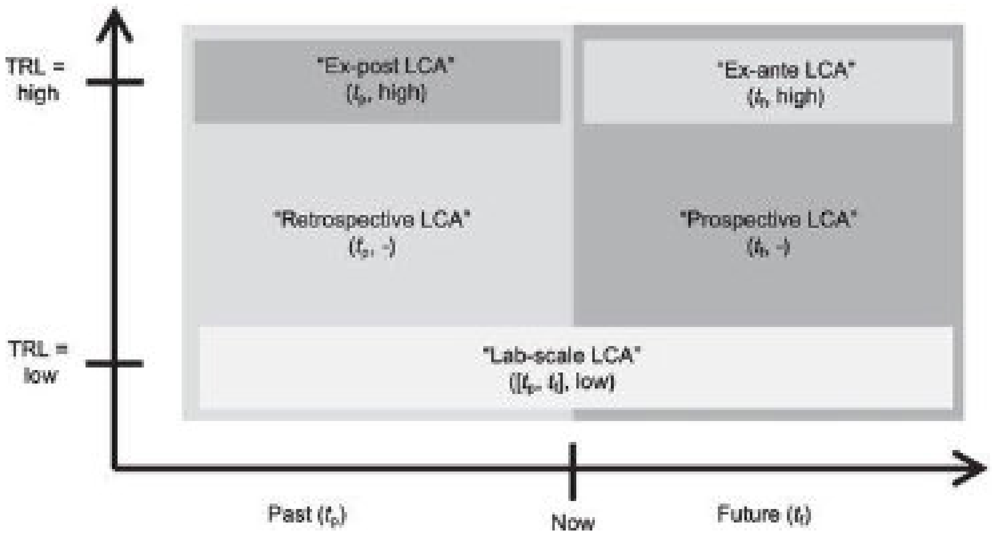
Interpretation

Sala S., Cerutti A.K., Pant R., Development of a weighting approach for the Environmental Footprint, Publications Office of the European Union, Luxembourg, 2018, ISBN 978-92-79-68042-7, EUR 28562, doi:10.2760/945290

Prospective LCA and methodology for tribolysis at design







- As LCA itself is commonly performed once a stable system is developed (retrospective)
- However, there are lab-scale LCA and prospective LCA as methods
- To allow early stage design decision of a chemical reaction, Green Metrics can be used which assesses the process metrics in detail following green chemistry principles
- **In TriFluorium, we are trying both concepts and highlight their different aspects**

Blöomer et al. **2024**, Arvidsson et al. **2024**

Inventory for Tribolysis

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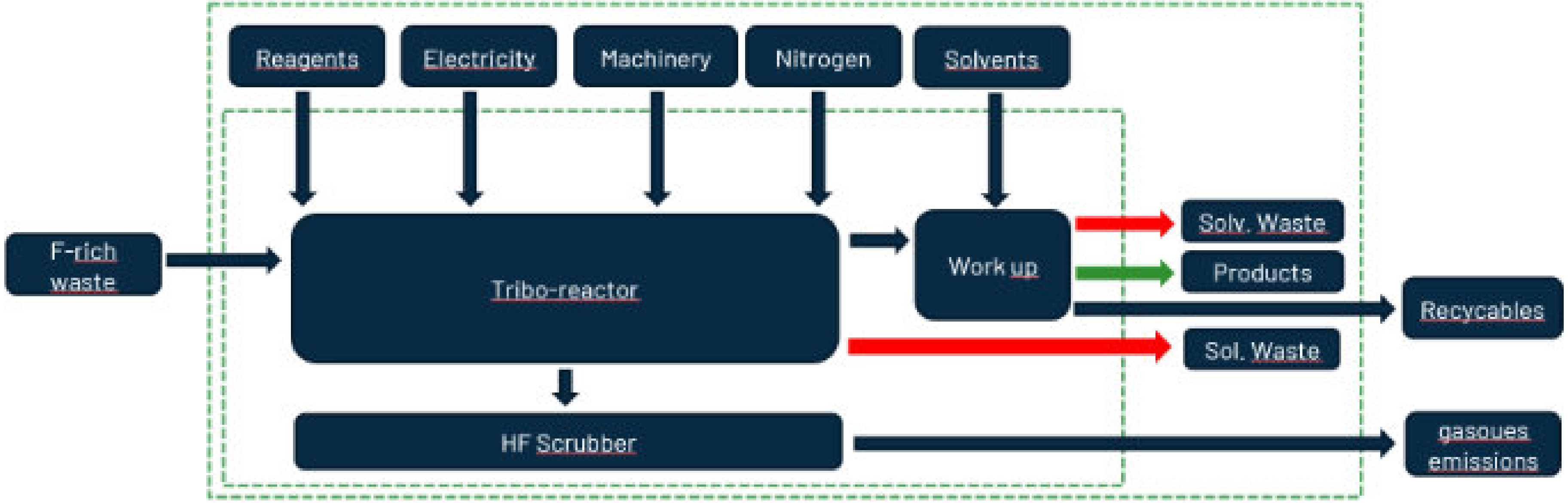

Process Inputs

- Fluoropolymer waste, fluoride scavenger, electricity for triboreactor, nitrogen, water (solvent & cleaning)
- Lubricant as **dual trapping agent:** assumed suitable for 1000 runs (n = 1000)
- Tribometer parts - **assumed lifetime n = 100**

Process Outputs

- **Products:** inorganic fluoride, iron scrap, carbon black
- **Waste:** municipal solid waste; wastewater average from reaction effluent and cleaning
- **Direct emissions:** fossil CO_2 and evaporated water; potentially HFC gases

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Scenarios Considered

G
M

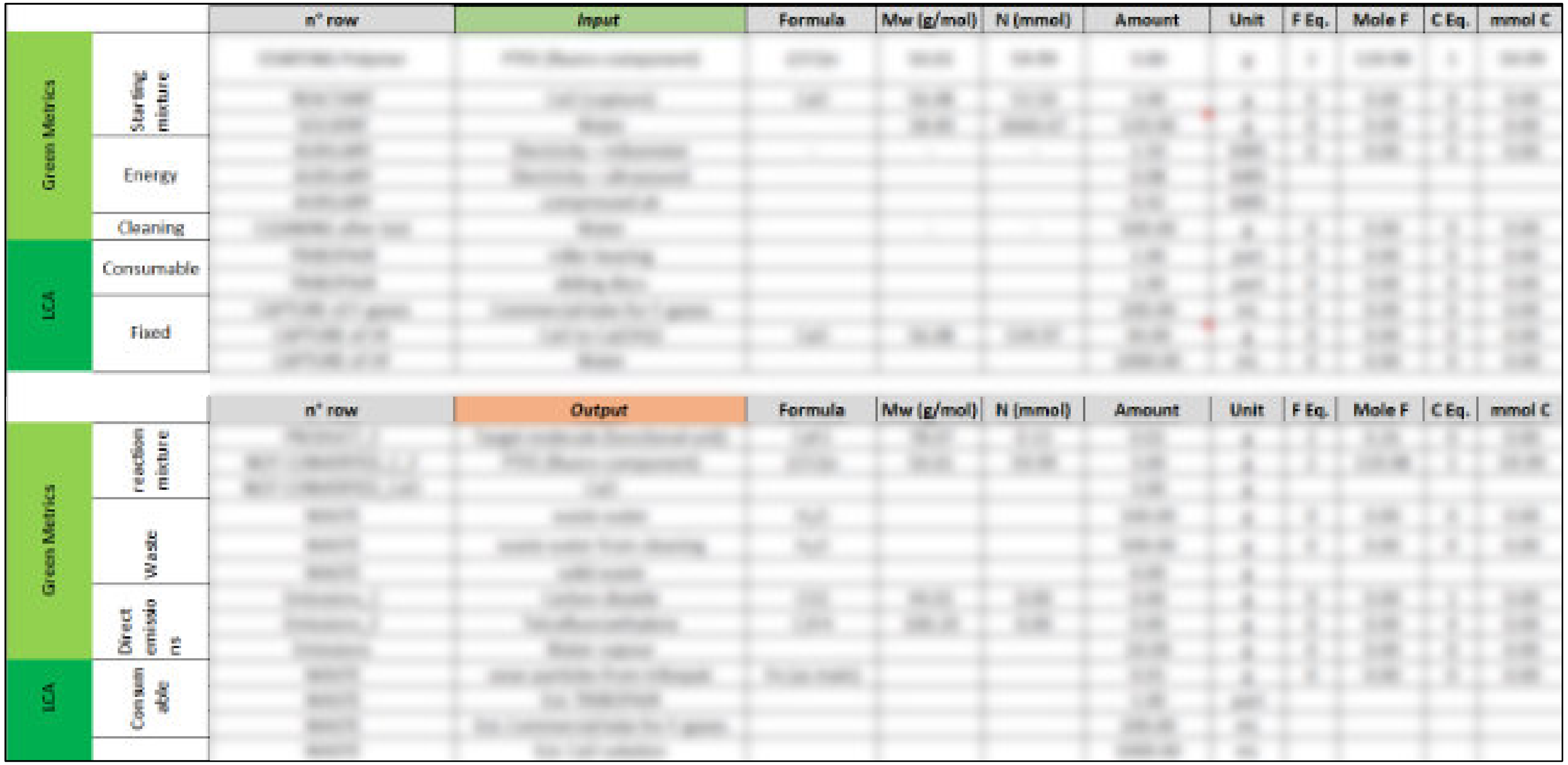
A) Yield & process boundary

A1) 100% yield, direct CO_2 emission, with solvent, with washing; **A2)** no solvent; **A3)** no washing

A4) no direct emissions, 3 kWh/kg electricity, no nitrogen (optimal)
A5) 50% yield, direct CO_2 emission, remainder treated as waste (realistic)

Realistic values: 500 kWh/kg Planetary Mill, 34 kWh/kg Twin Screw; 8-16 kWh/t Grinding

Green Metrics/LCA: Excel Template



		n° row	*Input*	Formula	Mw (g/mol)	N (mmol)	Amount	Unit	F Eq.	Mole F	C Eq.	mmol C
Green Metrics	Starting mixture											
	Energy											
	Cleaning											
LCA	Consumable											
	Fixed											

		n° row	*Output*	Formula	Mw (g/mol)	N (mmol)	Amount	Unit	F Eq.	Mole F	C Eq.	mmol C
Green Metrics	reaction mixture											
	Waste											
	Direct emissions											
LCA	Consumable											

Mass-based Metric	Value	Optimal	Unit
Atom Economy AE	67%	100%	%
Mole efficency (ME)	1%	100%	%
E-Factor (Simple) sEF	0.00	0	g/g
E-Factor EF	21.41	0	g/g
E-Factor (Complete) cEF	25.70	0	g/g
Reaction Mass Intensity RMI	26.70	1	g/g
Reaction Mass Efficiency RME	100%	100%	%
Process Mass Intensity PMI	26.70	1	g/g
Process Mass Efficiency PME	4%	100%	%
Mass Productivity MP	100%	100%	%
Mass Intensity MI	1.00	1	g/g

Visual guidance on improved foreground process parameters

Green Metrics: Results

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Reagents

F-Materials → **Safe F-Products** **By-Products**

Case	A1	Opt.	
Decription	Full conversion, Real Condition	Best Case	Unit
Yield	100%	100%	%
Fluoride recovery	100%	100%	%
Carbon Efficiency CE	0%	100%	%
Atom Economy AE	67%	100%	%
Mole efficency (ME)	1%	100%	%
E-Factor EF	21.41	0.00	g/g
Reaction Mass Intensity RMI	26.70	1.00	g/g
Reaction Mass Efficiency RME	100%	100%	%
Process Mass Intensity PMI	26.70	1.00	g/g
Process Mass Efficiency PME	4%	100%	%
Mass Intensity MI	1.00	1.00	g/g
Solvent Intensity	25.70	0.00	g/g
Water Intensity WI	25.70	0.00	g/g
Waste Water Intensity WWI	128.48	0.00	g/g
Waste Intensity AI	0.80	0.00	g/g
Process Energy Intensity PEI	63.15	0.00	MJ/kg

SSbD compliant parameter

Life Cycle Assessment: Goal and Scope

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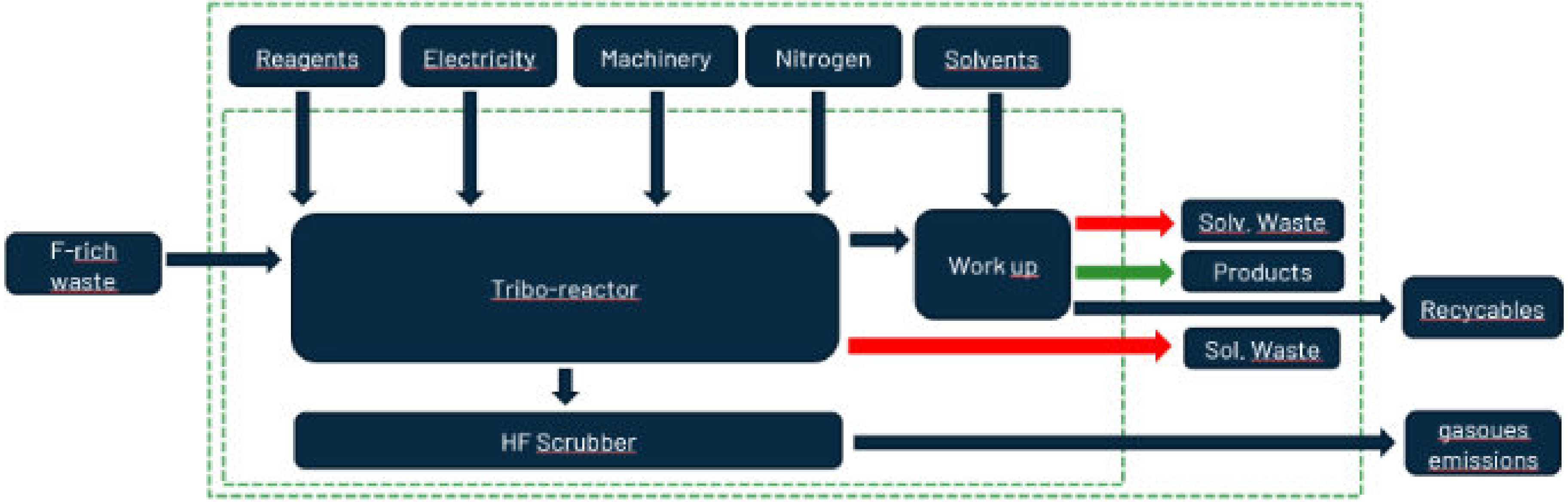
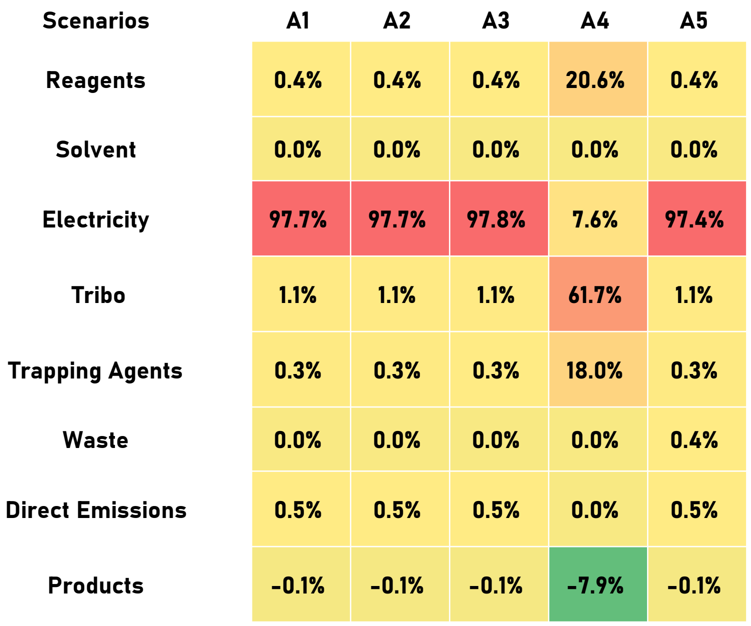


openLca

free and open-source, by GreenDelta

Element	Description
Goal	• To assess and quantify the environmental sustainability of the tribolytic decomposition • The focus is on the conversion of FP into inorganic fluorides and potential for energy recovery during treatment
Functional unit // RF	• **End of life treatment of 1 kg fluoropolymer waste under European conditions** • **Reference Flow:** 1 kg of fluoropolymer waste, treated
Scope	• Gate to gate, focusing specifically on the tribolysis process in Europe.
Boundaries	• **Includes all inputs and outputs** of the tribolysis process such as **energy use, reagents, emissions, and recovery of by-products; excludes upstream production of fluoropolymers** (cut-off approach)
Allocation	• Byproducts of market-equivalent quality **receive substitution credits** • Recyclable materials requiring **further purification are treated as burden-free inputs**

Life Cycle Assessment: Impact Assessment



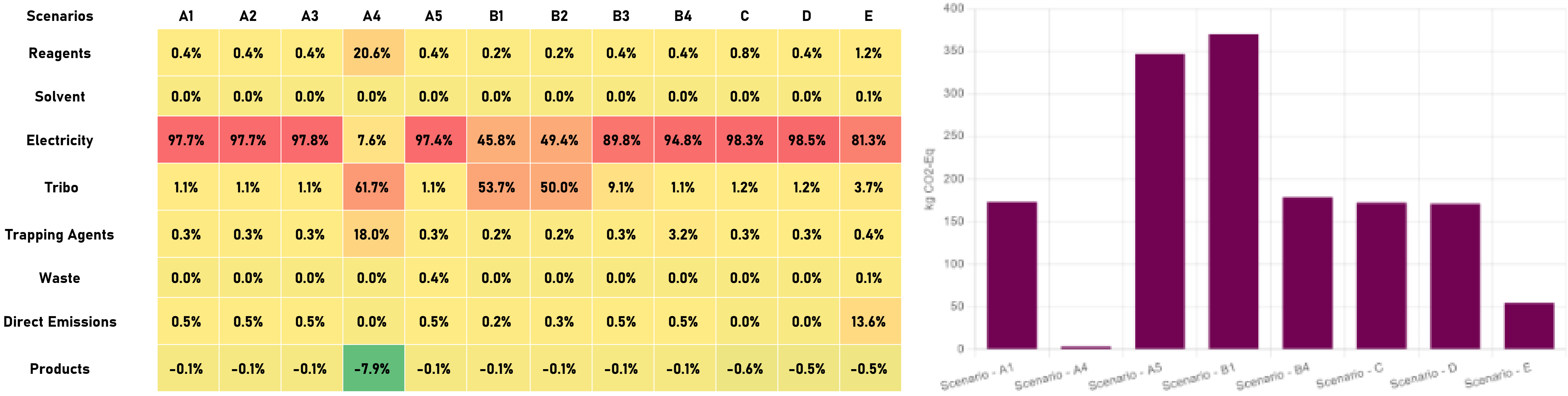
Scenarios	A1	A2	A3	A4	A5
Reagents	0.4%	0.4%	0.4%	20.6%	0.4%
Solvent	0.0%	0.0%	0.0%	0.0%	0.0%
Electricity	97.7%	97.7%	97.8%	7.6%	97.4%
Tribo	1.1%	1.1%	1.1%	61.7%	1.1%
Trapping Agents	0.3%	0.3%	0.3%	18.0%	0.3%
Waste	0.0%	0.0%	0.0%	0.0%	0.4%
Direct Emissions	0.5%	0.5%	0.5%	0.0%	0.5%
Products	-0.1%	-0.1%	-0.1%	-7.9%	-0.1%

Scenario(s)	Key variation from baseline
A1	Baseline: 100% yield; direct CO_2 emissions; solvent included; washing included; product is substituted
A2–A3	Removal of individual process steps: A2: no solvent; A3: no washing
A4	No direct CO_2 emissions; electricity reduced to 3 kWh/kg; no nitrogen use
A5	50% yield; direct CO_2 emissions; remaining material treated as waste

Relative and absolute climate change impacts using EF 3.1 LCIA method and ecoinvent 3.11

- **Electricity** dominates impacts (>97%) in the baseline scenario (A1) (tribolysis and N_2)
- **Limiting solvent use or cleaning does not influence the LCA results**
- With **optimised conditions** (A4; 1 kWh/kg), the impact is mostly on the tribo equipment (n = 100)

Life Cycle Assessment: Impact Assessment



Scenarios	A1	A2	A3	A4	A5	B1	B2	B3	B4	C	D	E
Reagents	0.4%	0.4%	0.4%	20.6%	0.4%	0.2%	0.2%	0.4%	0.4%	0.8%	0.4%	1.2%
Solvent	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.1%
Electricity	97.7%	97.7%	97.8%	7.6%	97.4%	45.8%	49.4%	89.8%	94.8%	98.3%	98.5%	81.3%
Tribo	1.1%	1.1%	1.1%	61.7%	1.1%	53.7%	50.0%	9.1%	1.1%	1.2%	1.2%	3.7%
Trapping Agents	0.3%	0.3%	0.3%	18.0%	0.3%	0.2%	0.2%	0.3%	3.2%	0.3%	0.3%	0.4%
Waste	0.0%	0.0%	0.0%	0.0%	0.4%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.1%
Direct Emissions	0.5%	0.5%	0.5%	0.0%	0.5%	0.2%	0.3%	0.5%	0.5%	0.0%	0.0%	13.6%
Products	-0.1%	-0.1%	-0.1%	-7.9%	-0.1%	-0.1%	-0.1%	-0.1%	-0.1%	-0.6%	-0.5%	-0.5%

Relative and absolute climate change impacts using EF 3.1 LCIA method and ecoinvent 3.11

- **Electricity** dominates impacts (>97%) in the baseline scenario (A1) (tribolysis and N_2)
- **Limiting solvent use or cleaning does not influence the LCA results**
- With **optimised conditions** (A4; 1 kWh/kg), the impact is mostly on the tribo equipment (n = 100)
- **Short tribo equipment lifetimes raise impacts** due to steel replacement (B1 and B2)
- **Substitution** gives only small credits vs. total burden (C and D) **besides in optimised (A4)**
- **Renewables (scenario E)** reduced climate change

➢ **Lowering electricity use and extending lifetime most effectively cut impacts**

Life Cycle Assessment: Impact Assessment

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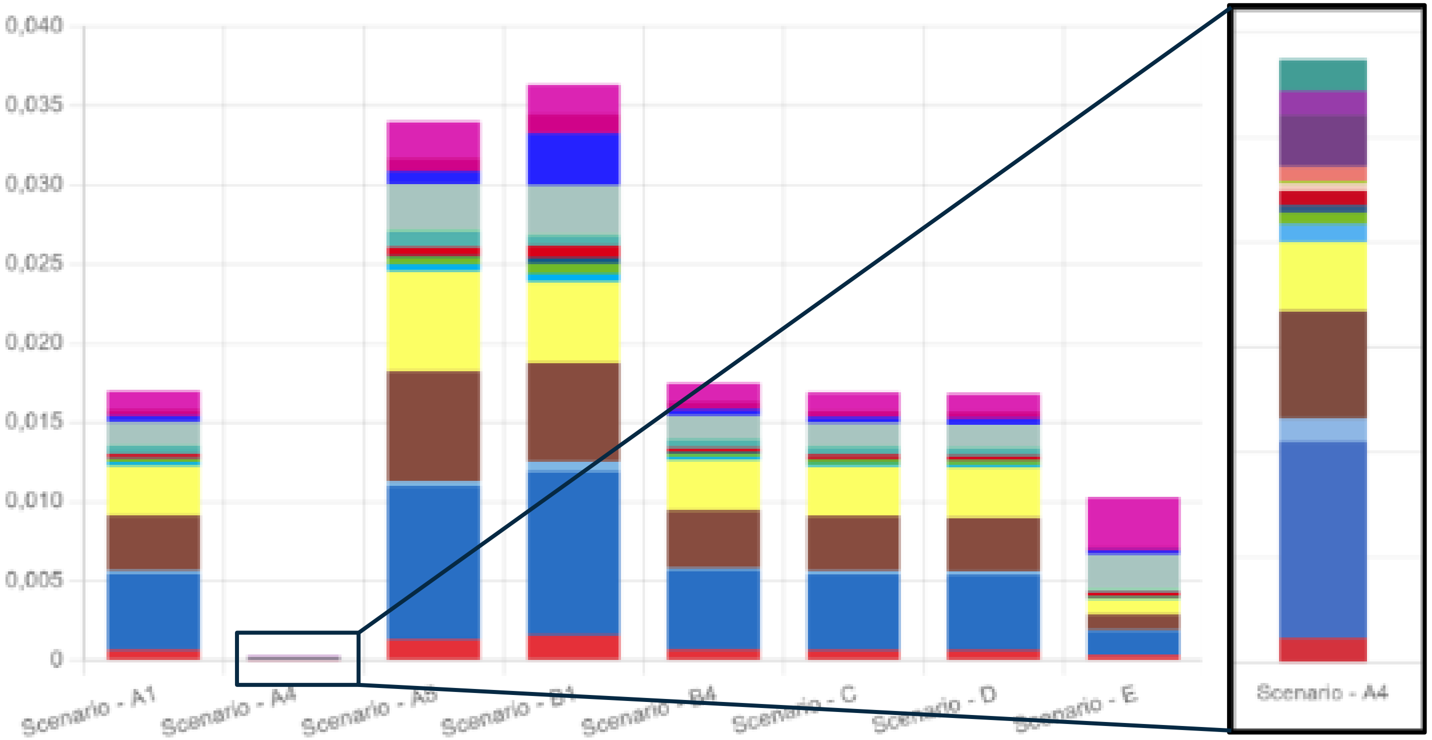
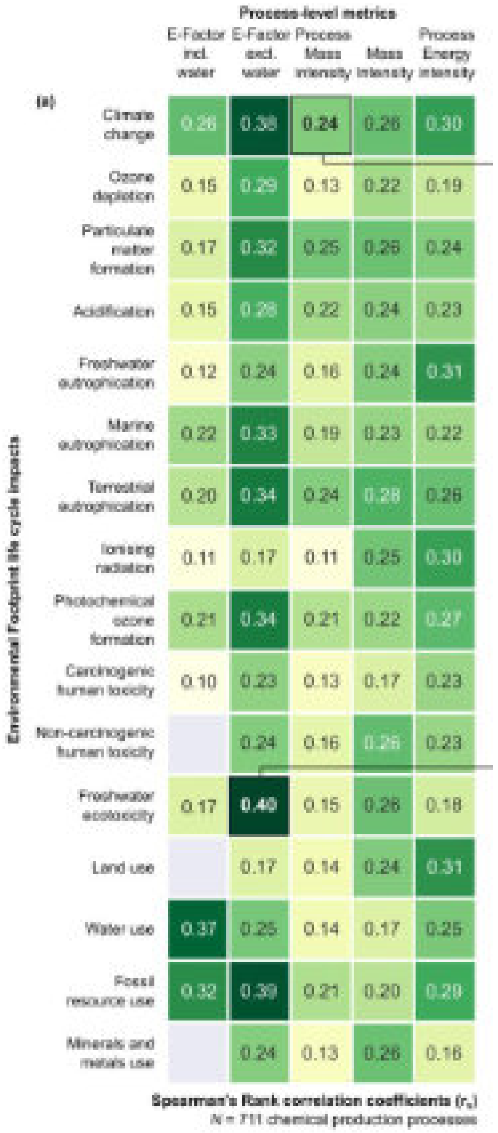


Single scores using normalization and weighting from the EF 3.1 LCIA method and ecoinvent 3.11

- **A5/B1: Highest overall impacts** (low yield, short tribo equipment lifetime)
- **Electricity dominates impacts** across most scenarios
- **Substitution and lifetime changes** have limited influence
- **Renewables (E):** −33% single score but higher water impacts
- **A4: Lowest impacts** (high efficiency, high yield)
- **Lower electricity use is the most effective improvement strategy**

Conclusion



(a)

	Process-level metrics				
Environmental Footprint life cycle impacts	E-Factor incl. water	E-Factor excl. water	Process Mass intensity	Mass intensity	Process Energy intensity
Climate change	0.26	0.38	0.24	0.26	0.30
Ozone depletion	0.15	0.29	0.13	0.22	0.19
Particulate matter formation	0.17	0.32	0.25	0.26	0.24
Acidification	0.15	0.28	0.22	0.24	0.23
Freshwater eutrophication	0.12	0.24	0.16	0.24	0.31
Marine eutrophication	0.22	0.33	0.19	0.23	0.22
Terrestrial eutrophication	0.20	0.34	0.24	0.28	0.26
Ionising radiation	0.11	0.17	0.11	0.25	0.30
Photochemical ozone formation	0.21	0.34	0.21	0.22	0.27
Carcinogenic human toxicity	0.10	0.23	0.13	0.17	0.23
Non-carcinogenic human toxicity		0.24	0.16	0.26	0.23
Freshwater ecotoxicity	0.17	0.40	0.15	0.26	0.18
Land use		0.17	0.14	0.24	0.31
Water use	0.37	0.25	0.14	0.17	0.25
Fossil resource use	0.32	0.39	0.21	0.20	0.29
Minerals and metals use		0.24	0.13	0.26	0.16

Spearman's Rank correlation coefficients (r_s)
N = 711 chemical production processes

- **Fluoropolymer recycling is highly relevant:** current recycling rates are low, while production relies on **critical raw materials** and generates significant emissions — motivating to new recycling routes such as **tribolysis and their sustainability**
- **Green metrics enable rapid process assessment**, while LCA provides the full environmental picture and identifies the true impact drivers **before scale-up**
- **LCA provides an overall picture**, especially when comparing synthesis with **emerging technologies** such as **tribolysis** (by-products, wear of materials)
- **Main reduction potentials for tribolysis:** lowering energy demand and extending equipment lifetime — **not** reagents or solvents
- **Takeaway for process design:** mass and energy metrics alone tell you a process is efficient, not whether it's actually sustainable

Lucas *et al.*, *Green Chemistry*, **2024**, **26**, 9300–9309

TriFluorium

safe fluorine circularity

Funded by
the European Union

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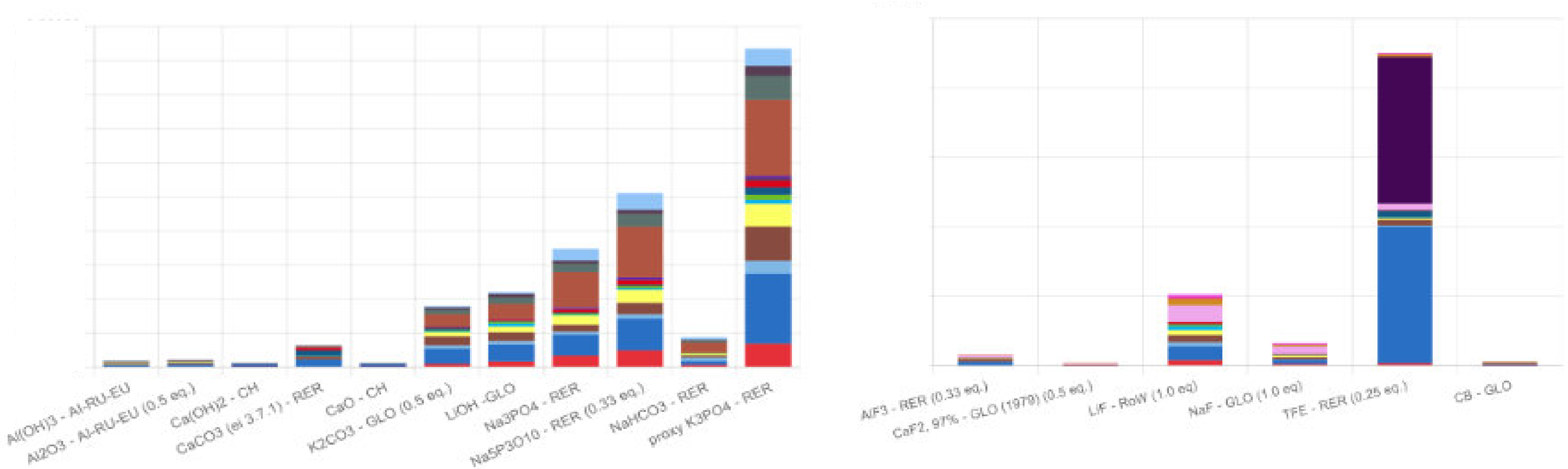
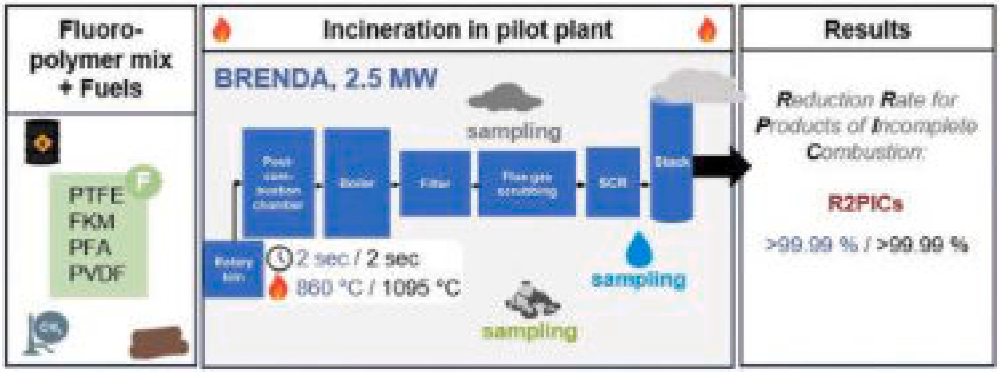
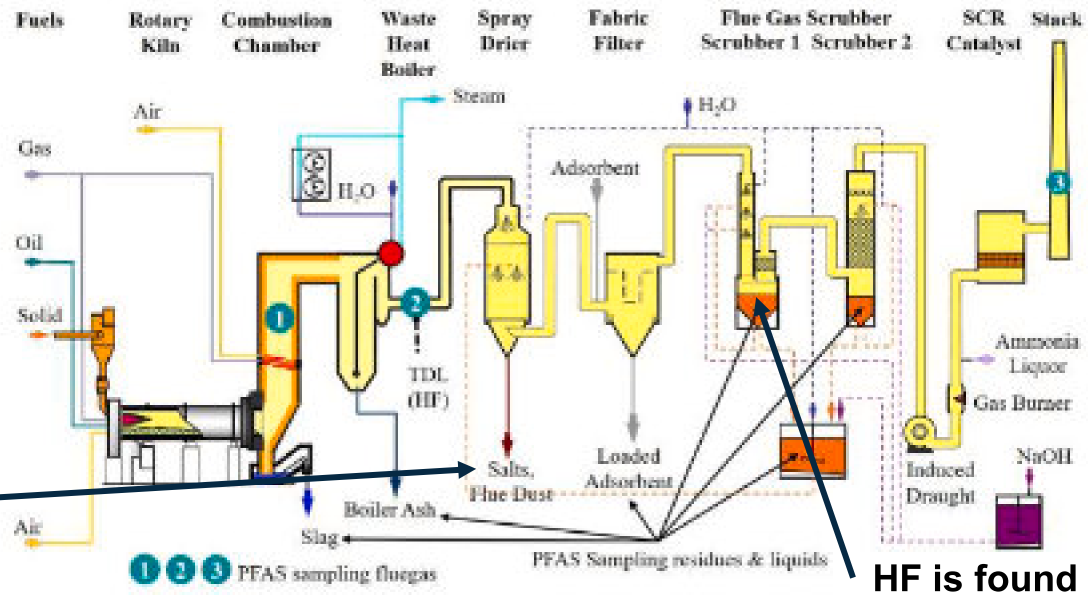
LCA for reagent and product selection



Single scores using normalization and weighting from the EF 3.1 LCIA method and ecoinvent 3.11

Reference case for tribolysis





Inorganic fluorides (NaF) end here

HF is found here

- Findings indicate that under standard European conditions, see European Industrial and Livestock Rearing Emissions Directive (2024) or the corresponding German regulation (17. BImSchV), **fluoropolymers should be mineralized**
- However, at lower temperatures due to open incineration of municipal incineration plants in developing the emission of potentially harmful HFCs might occur or remains in the bottom
- According to OECD report, the **PFAS contamination around incineration plants is rather high**. How so?
- In all cases, **carbon and fluoride are not recovered** in the processes in contrast to what is possible with tribolysis

Gehrmann *et al.*, *Chemosphere* **2024**, 365, 143403.