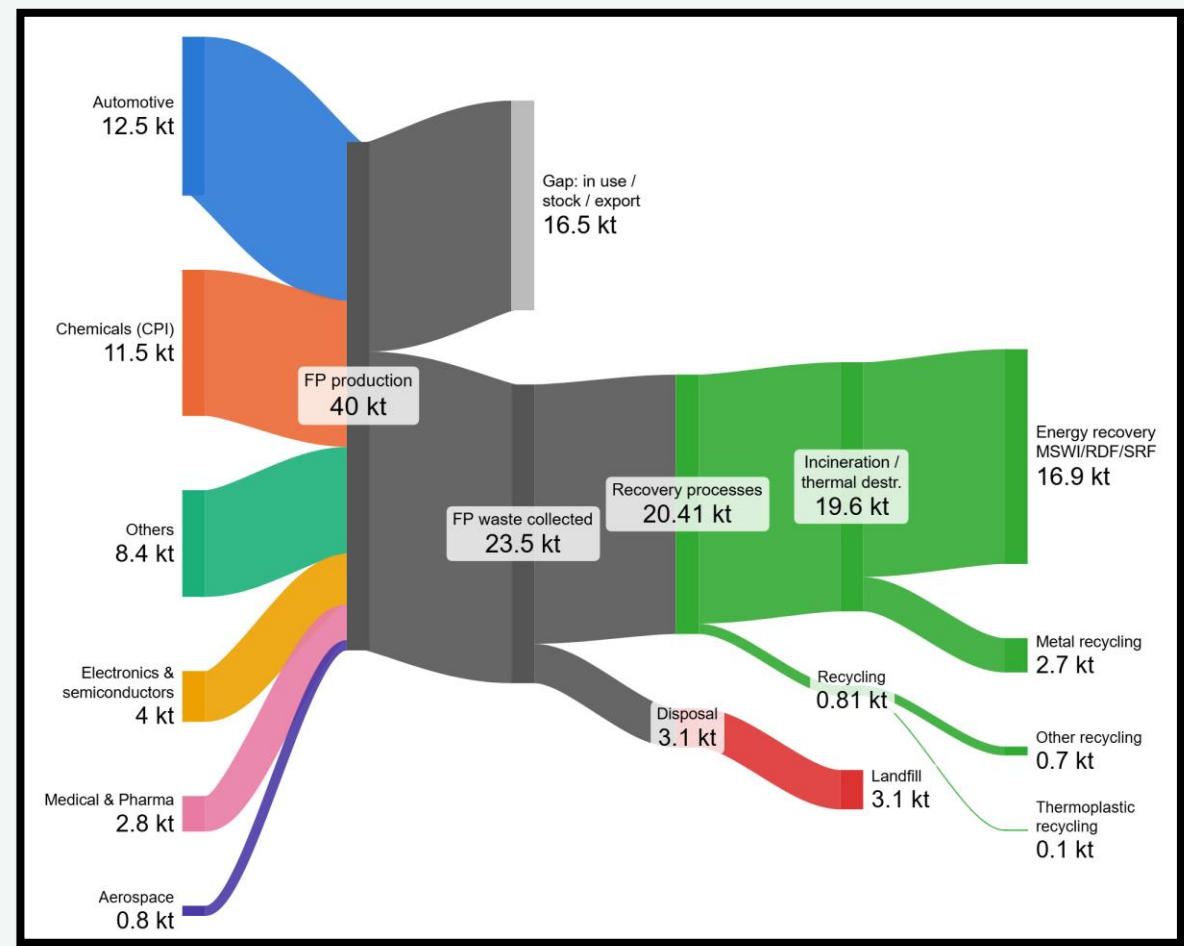
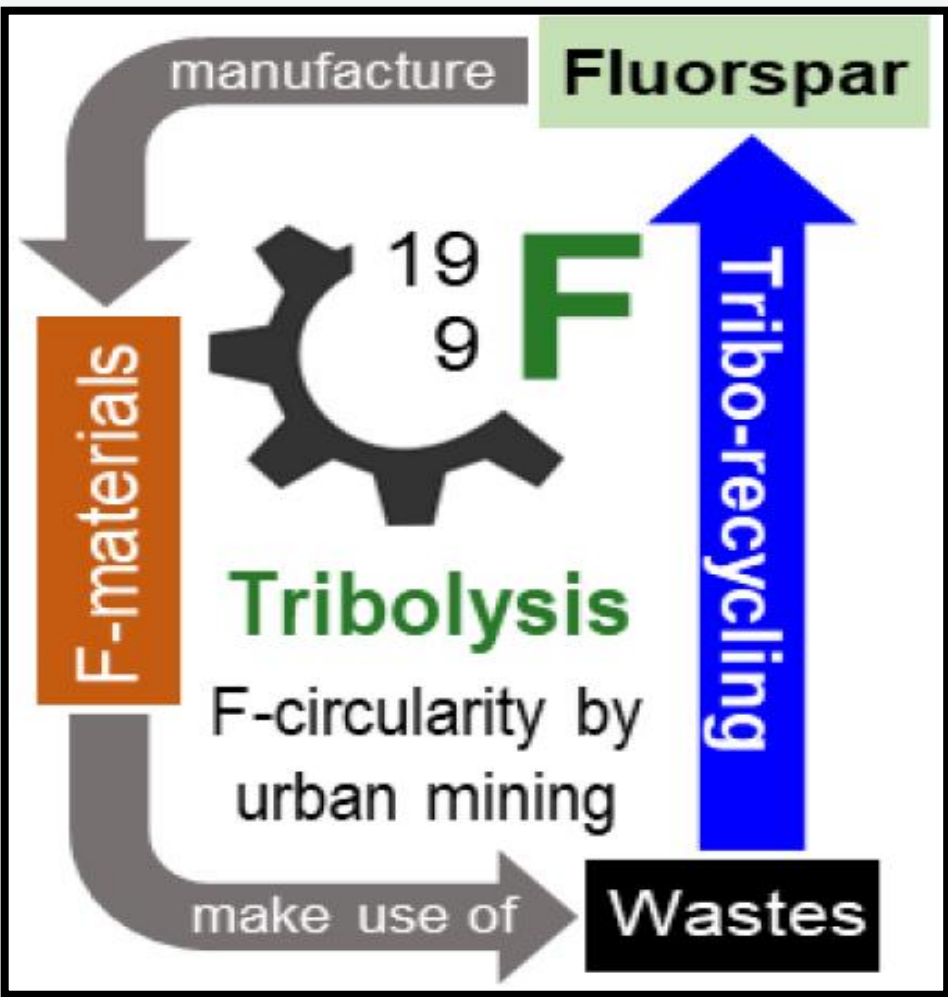


## Introduction



Fluoropolymers (FPs) are indispensable industries due to their chemical resistance, thermal stability, and durability but this same persistence turns into a major liability once these materials reach their end of life:

- Only 0.81 kt of the 23.5 kt of FP waste collected was actually recycled; majority is lost
- Landfilling and incineration fail to fully control fluorinated degradation products, may actively promote PFAS formation, and permanently waste material (OECD report)
- Because fluorine chemistry depends on  $\text{CaF}_2$ , this is not simply a waste-management challenge; it is a feedstock security issue for a critical raw material (CRM) as fluoropolymers are produced from the CRM  $\text{CaF}_2$
- Hence, in TriFluorium we close this gap using tribochemical recycling technologies



But how to quantify that those technologies are sustainable?

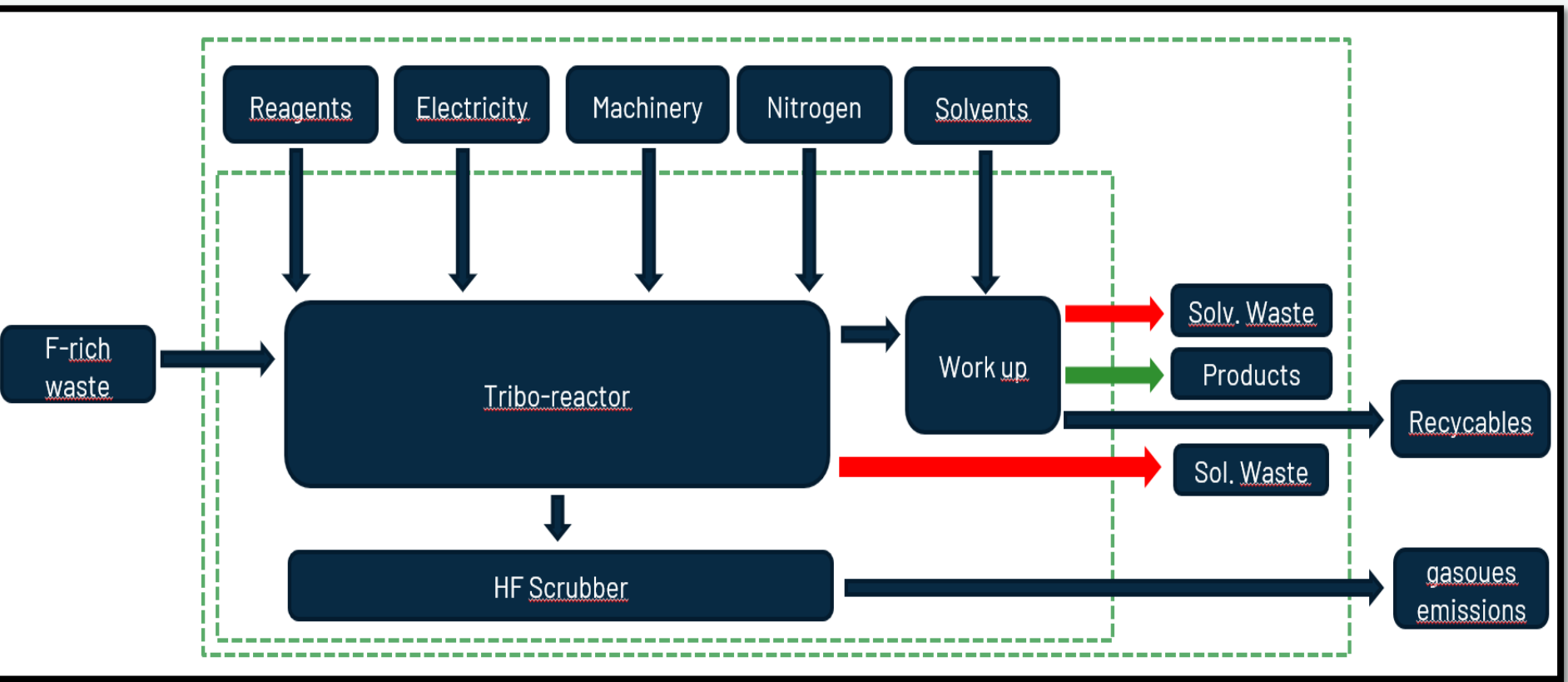
## Methodology

### Green Metrics

Process performance evaluation using mass- and energy-based indicators, using foreground experimental and stoichiometric data.

### Life Cycle Assessment (LCA)

- LCA framework: ISO 14040/44;
- Functional unit: 1 kg of waste treated; Boundary: Gate-to-gate
- Included: Material & energy inputs, reactor operation, emissions, waste treatment, and product recovery
- Background data/LCIA: ecoinvent 3.11/ EF 3.1



### Process Inputs

- Fluoropolymer waste, fluoride scavenger, electricity for triboreactor,  $\text{N}_2$ ,  $\text{H}_2\text{O}$  (solvent & cleaning)
- 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  $\text{CO}_2$  and evaporated water; potentially HFC gases

### Scenarios Considered



### Criticality

- In the assessment two methods were used to assess criticality
- CRM and SRM flows absolute masses tracked in across the life cycle of the process
  - Criticality weighting (developed in EU funded SH2E) was applied according to supply risk ( $SR_i$ ), European consumption ( $c_i$ ), import reliance ( $IR_i$ ) and end-of-life recycling rates ( $EoLR_{RIR}$ ).

$$\text{weighting value 'A' for a resource } i = \frac{SR_i}{c_i \times (1 - IR_i) \times (1 - EoLR_{RIR})}$$

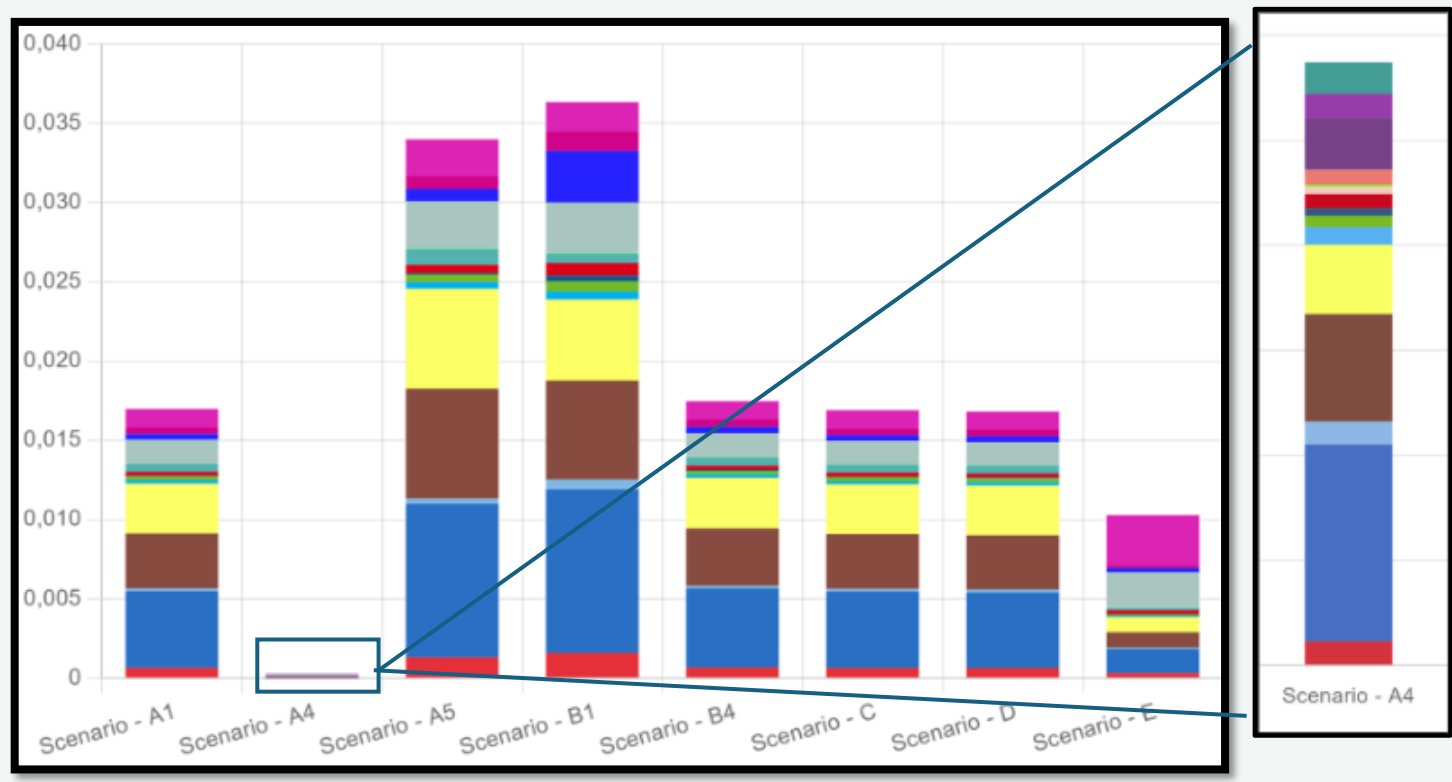
## Green Metrics Results

| Case                         | A1                              | A2                    | A3                 | A4                                             | A5                                          | Opt.      |       |
|------------------------------|---------------------------------|-----------------------|--------------------|------------------------------------------------|---------------------------------------------|-----------|-------|
| Description                  | Full conversion, Real Condition | As before, no solvent | As before, no Wash | as before, CO2 captured, 1 kWh/kg, no nitrogen | As initial, 50% Conversion, Excess to Waste | Best Case | Unit  |
| Yield                        | 100%                            | 100%                  | 100%               | 100%                                           | 50%                                         | 100%      | %     |
| Fluoride recovery            | 100%                            | 100%                  | 100%               | 100%                                           | 50%                                         | 100%      | %     |
| Carbon Efficiency            | 0%                              | 0%                    | 0%                 | 100%                                           | 0.00                                        | 100%      | %     |
| Atom Economy AE              | 67%                             | 67%                   | 67%                | 100%                                           | 33%                                         | 100%      | %     |
| Mole efficiency (M E)        | 1%                              | 67%                   | 67%                | 100%                                           | 0%                                          | 100%      | %     |
| E-Factor EF                  | 21.41                           | 0.00                  | 0.00               | 0.00                                           | 43.37                                       | 0.00      | g/g   |
| Reaction Mass Intensity RMI  | 26.70                           | 1.00                  | 1.00               | 1.00                                           | 53.40                                       | 1.00      | g/g   |
| Reaction Mass Efficiency RME | 100%                            | 100%                  | 100%               | 100%                                           | 50%                                         | 100%      | %     |
| Process Mass Intensity PMI   | 26.70                           | 1.00                  | 1.00               | 1.00                                           | 53.40                                       | 1.00      | g/g   |
| Process Mass Efficiency PME  | 4%                              | 100%                  | 100%               | 100%                                           | 2%                                          | 100%      | %     |
| Mass Intensity MI            | 1.00                            | 1.00                  | 1.00               | 0.00                                           | 2.00                                        | 1.00      | g/g   |
| Solvent Intensity            | 25.70                           | 0.00                  | 0.00               | 0.00                                           | 51.39                                       | 0.00      | g/g   |
| Water Intensity WI           | 25.70                           | 0.00                  | 0.00               | 0.00                                           | 51.39                                       | 0.00      | g/g   |
| Waste Water Intensity WWI    | 128.48                          | 107.07                | 0.00               | 0.00                                           | 256.96                                      | 0.00      | g/g   |
| Waste Intensity AI           | 0.80                            | 0.00                  | 0.00               | 0.00                                           | 0.81                                        | 0.00      | g/g   |
| Process Energy Intensity PEI | 63.15                           | 63.15                 | 63.15              | 3.60                                           | 126.30                                      | 0.00      | MJ/kg |

- Green metrics enable rapid process assessment, while LCA provides the full environmental picture and identifies the true impact drivers before scale-up
- GM is very sensitive to solvent and water intensity
- Usage of tribopair and auxiliaries is not assessed (see LCA)
- Takeaway for process design: mass and energy metrics alone tell you a process is efficient, not whether it's actually sustainable

## LCA Results

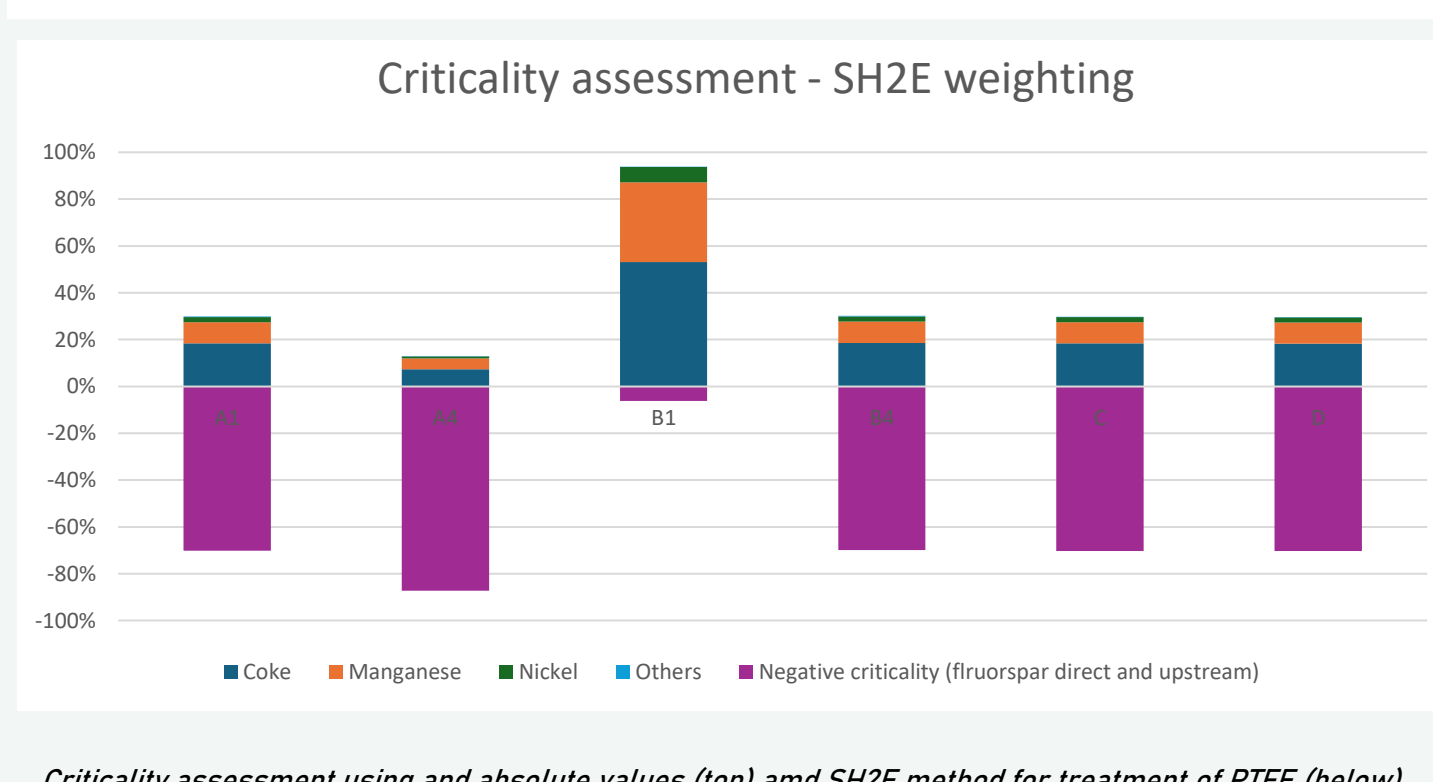
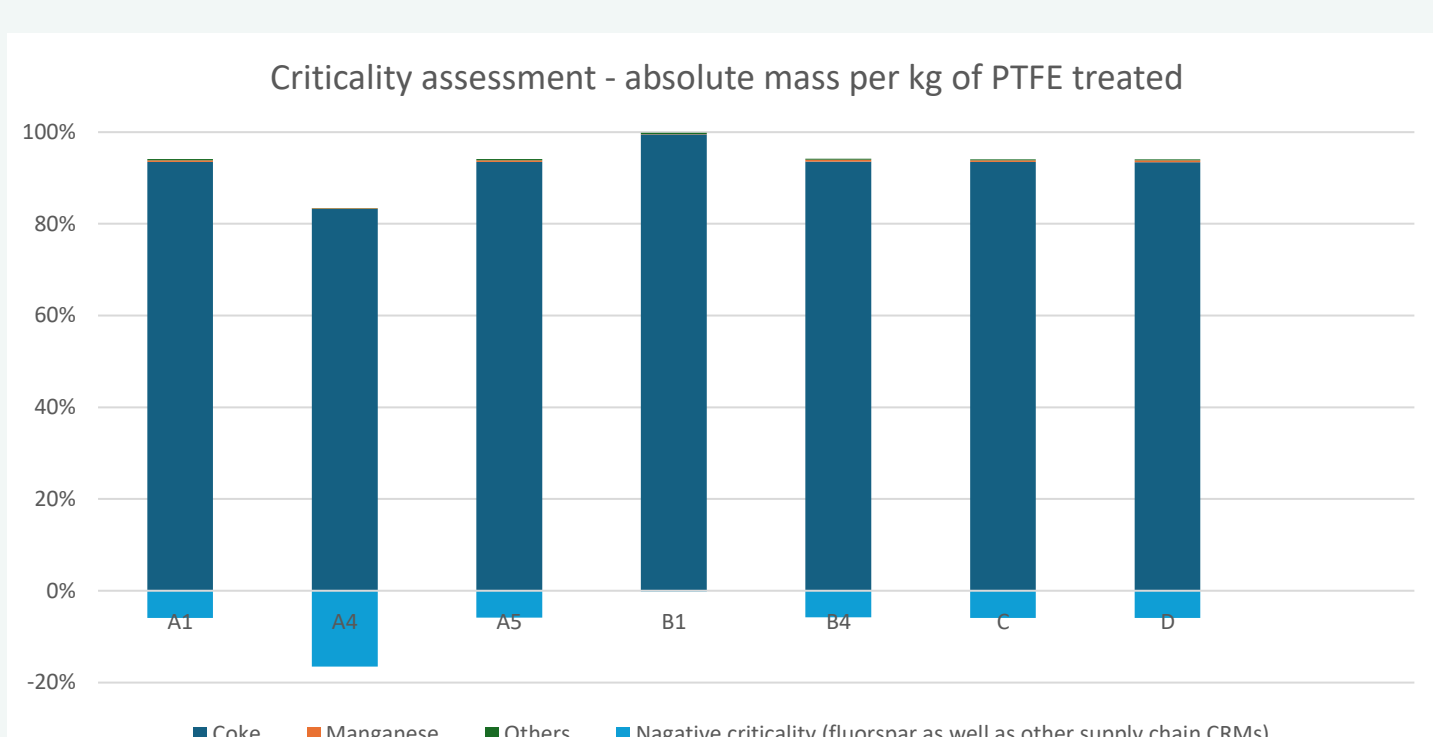
| Scenarios        | A1    | A2    | A3    | A4    | A5    | B1    | B2    | B3    | B4    | C     | D     | E     |
|------------------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| Reagents         | 0.4%  | 0.4%  | 0.4%  | 20.6% | 0.4%  | 0.2%  | 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 Climate Change (RCC) and Single scores (bar chart) using normalization and weighting from the EF 3.1 LCIA method and ecoinvent 3.11

- LCA provides an overall picture, especially when comparing synthesis with emerging technologies such as tribolysis (by-products, wear of materials)
- Reagents contribute to 21% in most beneficial scenario
- Main reduction potentials for tribolysis: lowering energy demand and extending equipment lifetime, not reagents or solvents
- Electricity dominates impacts across most scenarios

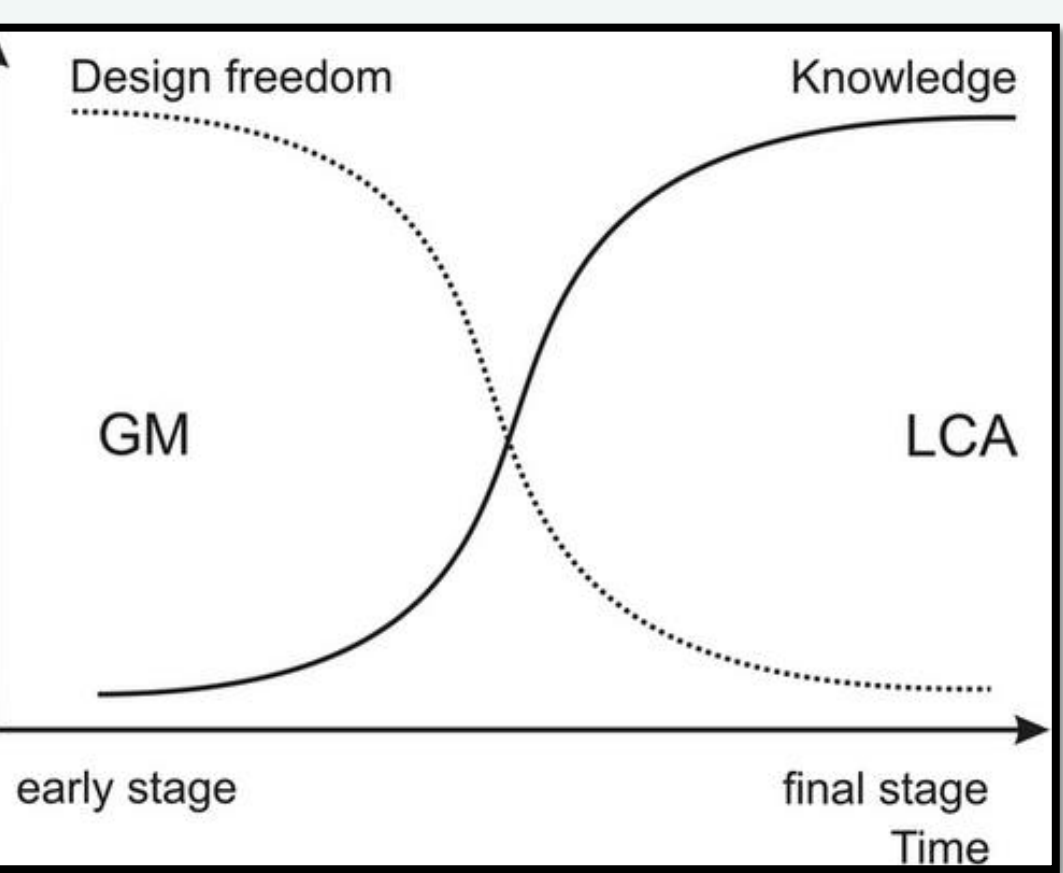
## Criticality Assessment



Criticality assessment using absolute values (top) and SH2E method for treatment of PTFE (below)

- Coking coal showed highest criticality through steel, electricity and compressed-air supply chains
- CRM use exceeded recovery, giving a net mass result of 23.1 kg per kg fluoropolymer treated
- Weighting contributions were 61% coking coal, 30.2% manganese and 7% nickel
- Longer component lifetimes, lower electricity demand and lower-criticality steel sourcing offer the greatest improvement potential

## Conclusions



### Green Metrics vs. LCA Method

- Green Metrics are a fast screening tool: they provide rapid, intuitive feedback on process efficiency and help identify optimization opportunities without the complexity of a full LCA
- LCA adds the system perspective: it revealed that electricity demand, largely overlooked as a single process metric, dominates the environmental impact of tribolysis followed by the equipment itself

### Sustainability of Tribolysis Process

- Electricity is the main impact driver  
→ Reducing energy demand is most relevant
- Equipment lifetime matters  
→ Short tribometer lifetimes increase impacts
- Renewable energy alone is not enough  
→ Switching to renewables shifts impacts
- Criticality comes from the tribometer setup  
→ Metals contribute to criticality burden

Conversion for Pro Kunststoff (2020); OECD (2024); Yang et al., *Nature* (2025), 640, 100–106; Hattori et al., *Nature Communications* (2026), 669; Cunningham et al., *Green Chemistry* (2002), 4, 521–527; Cristobal-Garcia et al. (2016), JRC; Sala et al. (2018), JRC; Bloomer et al. (2024); Arvidsson et al. (2024); Lucas et al., *Green Chemistry* (2024), 26, 9300–9309; Gehrmann et al., *Chemosphere* (2024), 365, 143403; SH2E project (2021), D3.1 Material Criticality Indicator.

| Process-level metrics | Climate change | Acidification | PM10 formation | PM2.5 formation | PM10 formation | PM2.5 formation | PM10 formation | PM2.5 formation | PM10 formation | PM2.5 formation | PM10 formation | PM2.5 formation |
|-----------------------|----------------|---------------|----------------|-----------------|----------------|-----------------|----------------|-----------------|----------------|-----------------|----------------|-----------------|
| Climate change        | 1.25           | 0.28          | 0.24           | 0.21            | 0.20           | 0.19            | 0.18           | 0.17            | 0.16           | 0.15            | 0.14           | 0.13            |
| Acidification         | 0.15           | 0.20          | 0.13           | 0.22            | 0.19           | 0.18            | 0.17           | 0.16            | 0.15           | 0.14            | 0.13           | 0.12            |
| PM10 formation        | 0.11           | 0.32          | 0.25           | 0.28            | 0.24           | 0.23            | 0.22           | 0.21            | 0.20           | 0.19            | 0.18           | 0.17            |
| PM2.5 formation       | 0.15           | 0.28          | 0.22           | 0.24            | 0.23           | 0.22            | 0.21           | 0.20            | 0.19           | 0.18            | 0.17           | 0.16            |
| PM10 formation        | 0.12           | 0.24          | 0.16           | 0.24            | 0.21           | 0.20            | 0.19           | 0.18            | 0.17           | 0.16            | 0.15           | 0.14            |
| PM2.5 formation       | 0.22           | 0.33          | 0.19           | 0.29            | 0.22           | 0.21            | 0.20           | 0.19            | 0.18           | 0.17            | 0.16           | 0.15            |
| PM10 formation        | 0.20           | 0.34          | 0.24           | 0.28            | 0.26           | 0.25            | 0.24           | 0.23            | 0.22           | 0.21            | 0.20           | 0.19            |
| PM2.5 formation       | 0.10           | 0.23          | 0.13           | 0.17            | 0.23           | 0.22            | 0.21           | 0.20            | 0.19           | 0.18            | 0.17           | 0.16            |
| PM10 formation        | 0.11           | 0.17          | 0.11           | 0.15            | 0.20           | 0.19            | 0.18           | 0.17            | 0.16           | 0.15            | 0.14           | 0.13            |
| PM2.5 formation       | 0.21           | 0.34          | 0.21           | 0.22            | 0.27           | 0.26            | 0.25           | 0.24            | 0.23           | 0.22            | 0.21           | 0.20            |
| PM10 formation        | 0.10           | 0.23          | 0.13           | 0.17            | 0.23           | 0.22            | 0.21           | 0.20            | 0.19           | 0.18            | 0.17           | 0.16            |
| PM2.5 formation       | 0.11           | 0.17          | 0.11           | 0.15            | 0.20           | 0.19            | 0.18           | 0.17            | 0.16           | 0.15            | 0.14           | 0.13            |
| PM10 formation        | 0.17           | 0.40          | 0.15           | 0.26            | 0.18           | 0.17            | 0.16           | 0.15            | 0.14           | 0.13            | 0.12           | 0.11            |
| PM2.5 formation       | 0.17           | 0.17          | 0.14           | 0.24            | 0.31           | 0.30            | 0.29           | 0.28            | 0.27           | 0.26            | 0.25           | 0.24            |
| PM10 formation        | 0.37           | 0.57          | 0.14           | 0.17            | 0.25           | 0.24            | 0.23           | 0.22            | 0.21           | 0.20            | 0.19           | 0.18            |
| PM2.5 formation       | 0.35           | 0.56          | 0.21           | 0.20            | 0.29           | 0.28            | 0.27           | 0.26            | 0.25           | 0.24            | 0.23           | 0.22            |
| PM10 formation        | 0.24           | 0.13          | 0.28           | 0.16            | 0.25           | 0.24            | 0.23           | 0.22            | 0.21           | 0.20            | 0.19           | 0.18            |
| PM2.5 formation       | 0.24           | 0.13          | 0.28           | 0.16            | 0.25           | 0.24            | 0.23           | 0.22            | 0.21           | 0.20            | 0.19           | 0.18            |