PSI Center for Nuclear Engineering and Sciences
Center for Energy and Environmental Sciences

Beyond elementary flows

Edge-based Impact Assessment for Context-sensitive LCA in Brightway

Sacchi, Romain
Menacho, Alvaro Hahn
Seitfudem, Georg
Agez, Maxime
Schlesinger, Joanna
Koyamparambath, Anish
Santillán Saldivar, Jair
Loubet, Philippe
Bauer, Christian

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Why a New Approach to LCIA?

Conventional LCIA applies CFs at the "elementary flow"

$$h = Q \cdot B \cdot A^{-1} \cdot f$$

with Q (q×1), a vector of CFs (one per elementary flow)

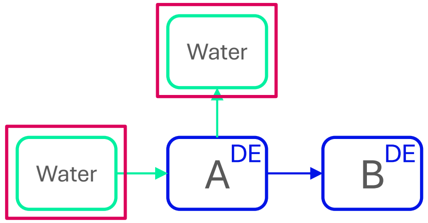
- Spatial and relational context is often lost during inventory aggregation

- Regionalized methods exist, but:

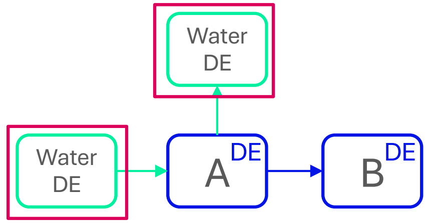
    - Deduplicating elementary flows (current practice): cannot scale, leads to complex, error-prone models
    - GIS[1,2]: scientifically robust, but requires expertise (little uptake so far)

- Need: a scalable, context-sensitive, intermediate alternative

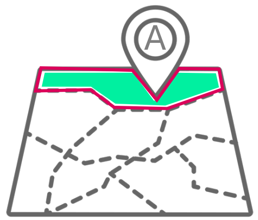
Conventionally



Flows deduplication



GIS-based



[1] Mutel, C. L., et al. (2012). GIS-based regionalized life cycle assessment: How Big is small enough? Methodology and case study of electricity generation. https://doi.org/10.1021/es203117z

[2] Li, J., et al. (2021). Spatializing environmental footprint by integrating geographic information system into life cycle assessment: A review and practice recommendations. https://doi.org/10.1016/j.jclepro.2021.129113

From Node to Edges

- Shifts CF application from nodes to edges (i.e., exchanges)

biosphere-to-technosphere edges

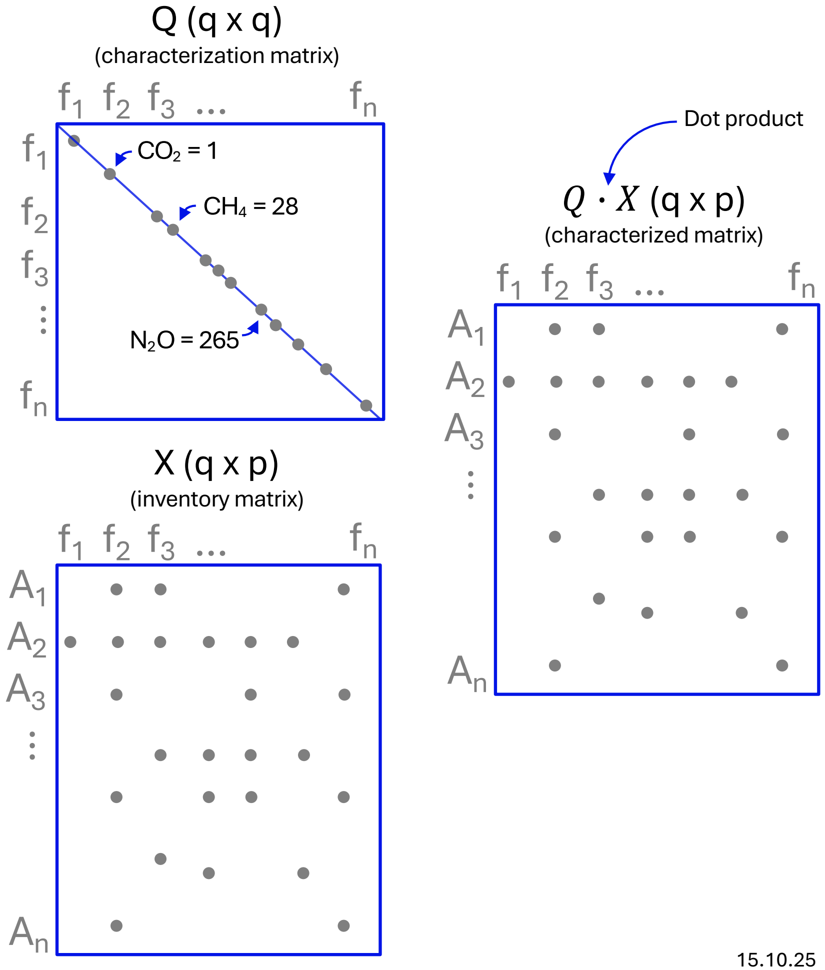
$$H = \sum_{i=1}^{q}\sum_{j=1}^{p} E_{ij} \cdot X_{ij} \cdot f = \sum (E \circ X) \cdot f$$

technosphere-to-technosphere edges

$$T = (-A \circ M) \cdot diag(s)$$

$$H = \sum_{i=1}^{q}\sum_{j=1}^{p} E_{ij} \cdot T_{ij} = \sum (E \circ T)$$

- Allows CFs to depend on any edge or node attributes:
    - Supplying & consuming nodes' location
    - Sector or activity type (e.g., CPC)
    - Scenario parameters (e.g., GHG concentrations)
- Implemented in open-source Python library *edges*[3]



[3] https://github.com/Laboratory-for-Energy-Systems-Analysis/edges

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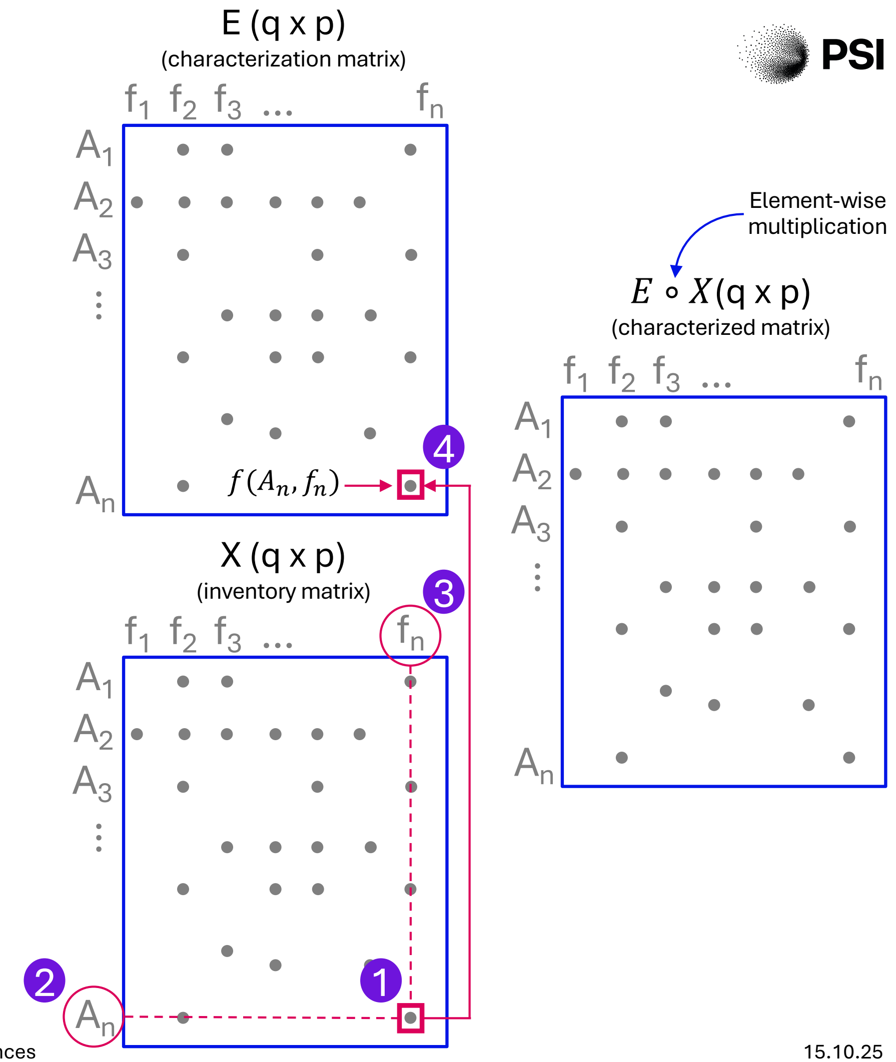

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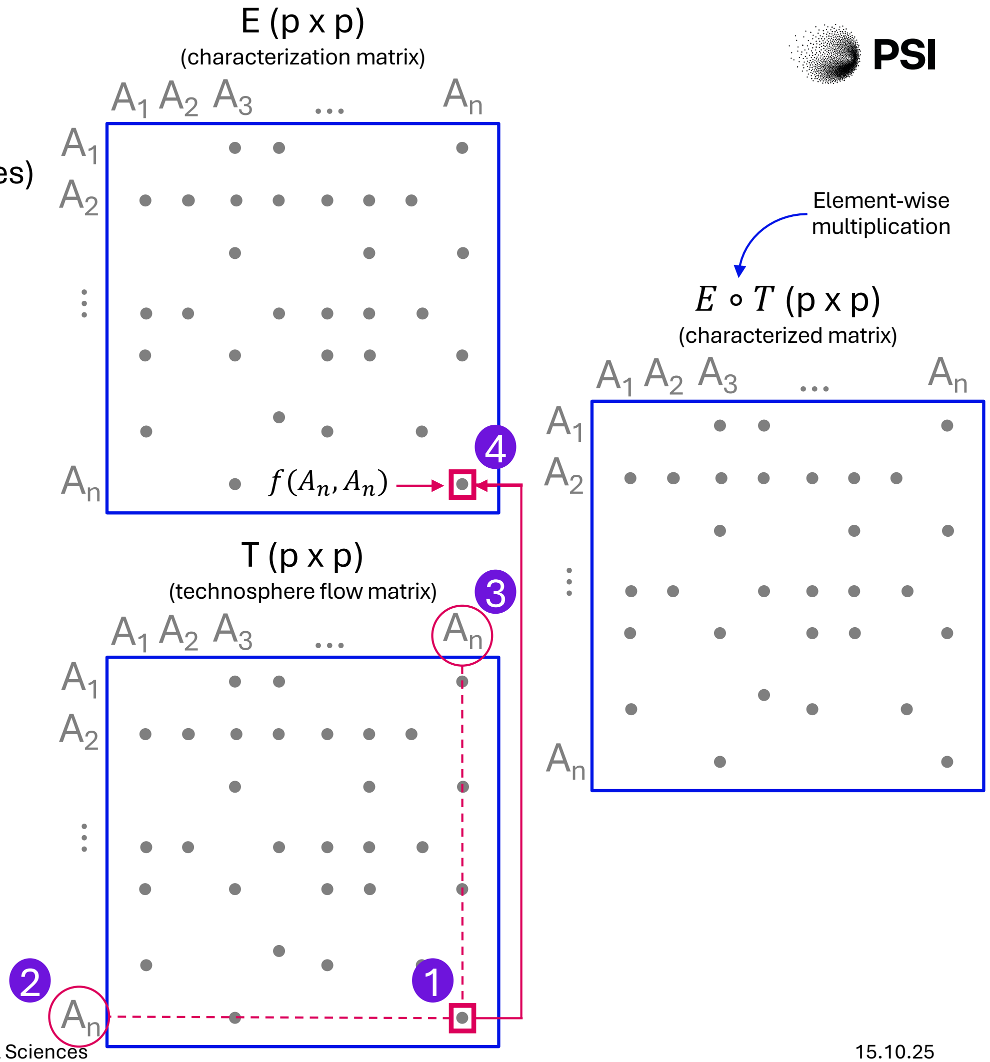


Let’s try it out!

Notebook: brightcon-edges.ipynb
Duration: 15 min

Use Case 1: regionalization

Scope

- 1 kg of hydrogen from PEM electrolyzer in France
- AWARE 2.0
- Country-level CF
  - CPC:
    - Agricultural
    - Non-agricultural
    - Unknown
- Variability/uncertainty:
  - Conventional distribution types (normal, lognormal, etc.)
  - Discrete empirical
  - Nested distribution
  - Symmetrical sampling to avoid decorrelation during Monte Carlo

Edges LCIA method (excerpt)

```
{
    "supplier": {
       "name": "Water, lake",
       "categories": [
          "natural resource",
          "in water"
       ],
       "matrix": "biosphere"
    },
    "consumer": {
       "location": "AM",
       "matrix": "technosphere",
       "classifications": {
          "CPC": [
             "01"
          ]
       }
    },
    "value": 88.6,
    "weight": 799882000,
    "uncertainty": {
       "distribution": "discrete_empirical",
       "parameters": {
          "values": [
             84.5,
             87.9
          ],
          "weights": [
             0.031,
             0.969
          ]
       },
       "negative": 0
    }
}
```

Location -specific

Targets farming activities

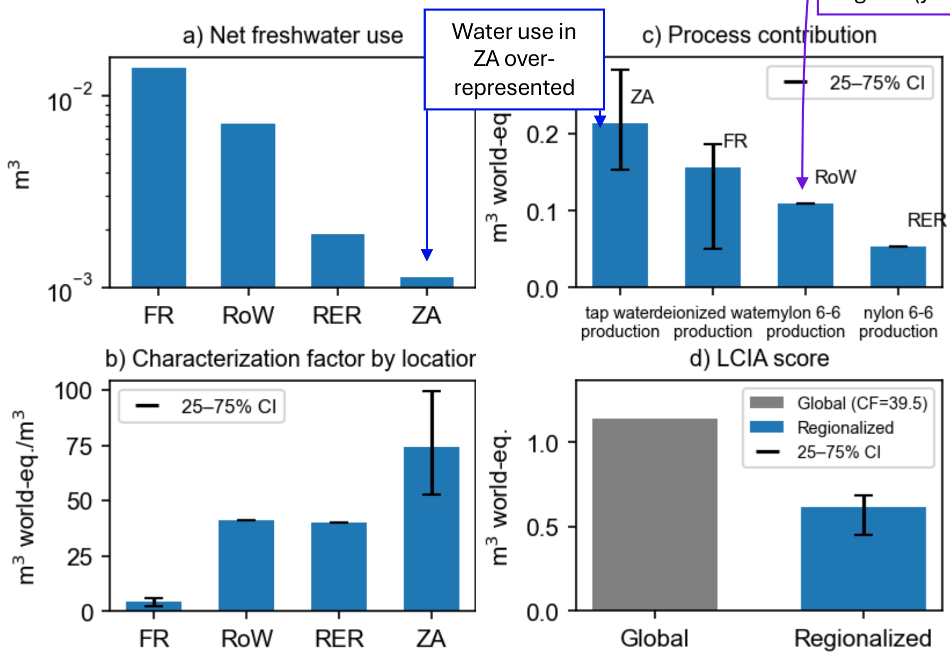
For weighted average CFs

Watershed-specific values

Weighted probabilities

Results

Cannot propagate error for composite regions (yet)



Use Case 2: technosphere characterization

Scope

- 1 kg of hydrogen from PEM electrolyzer in France
- GeoPolRisk 1.0[4]
- Estimates supply risk due to the use of abiotic resources (an indicator of criticality)
- Country-to-country CF
- Builds upon a previous approach: characterizes intermediate resources (instead of elementary flows «in ground» before losses and allocation)

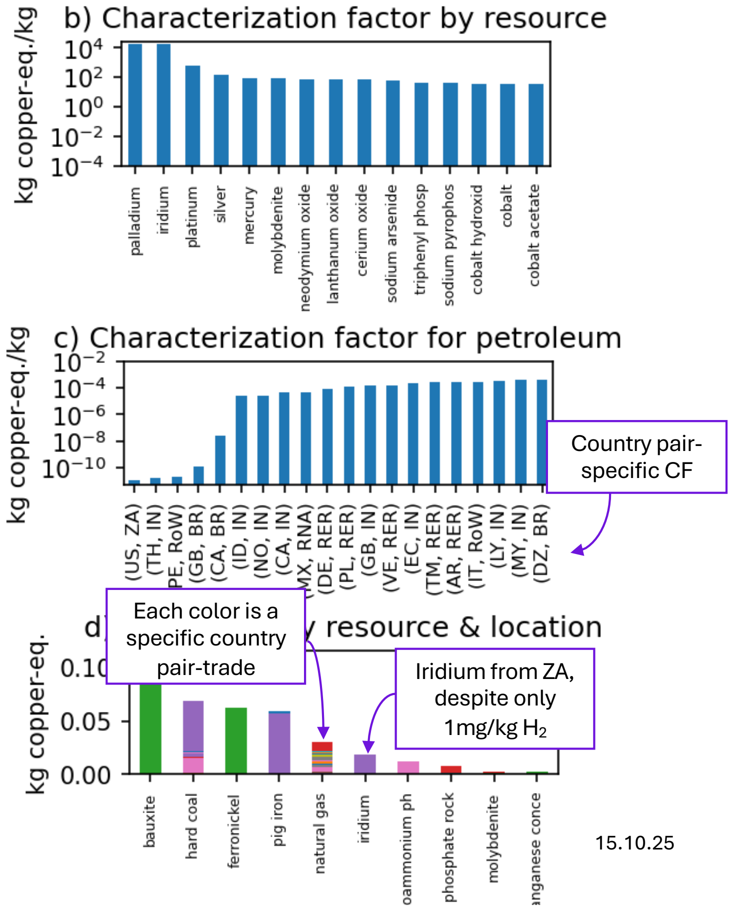
Edges LCIA method (excerpt)


```
{
  "supplier": {
    "name": "aluminium production",
    "reference product": "aluminium",
     "location": "AU",
     "operator": "startswith",
     "matrix": "technosphere",
     "excludes":[
           "alloy",
           "liquid",
           "market"
     ]
  },
  "consumer": {
     "location": "CA",
     "matrix": "technosphere"
  },
  "value": 2.420e-4
  "weighting": 250.4
}
```


Country pair-specific

Technosphere edges

Results



[4] Koyamparambath, A., Loubet, P., Young, S. B., & Sonnemann, G. (2024). Spatially and temporally differentiated characterization factors for supply risk of abiotic resources in life cycle assessment. Resources, Conservation and Recycling, 209(May), 107801.

Use Case 3.a: scenario-based characterization

PSI

Scope

- 1 kg of hydrogen from PEM electrolyzer in France
- Global Warming Potential[5]

CH_4 (ppb)				
RCP	1.9	2.6	4.5	8.5
2020	1866			
2050	1,428	1,519	2,020	2,446
2080	1,150	1,197	1,779	2,652
2100	1,036	1,056	1,683	2,415

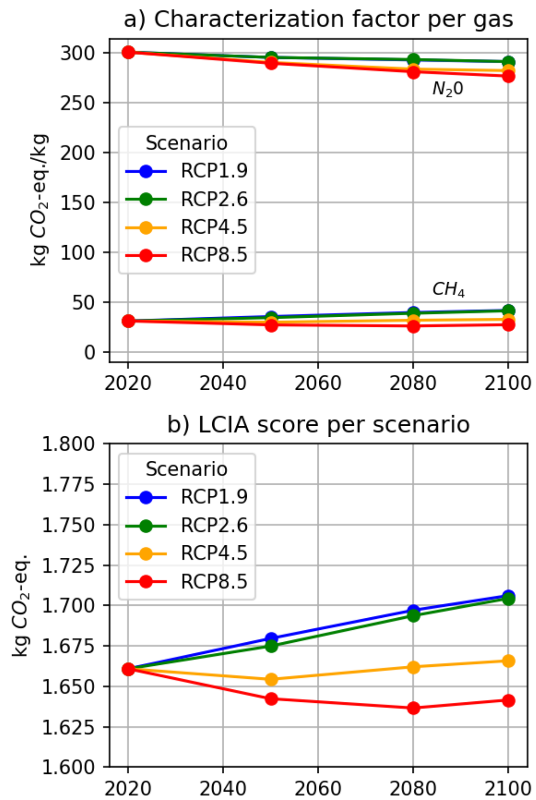
N_2O (ppb)				
RCP	1.9	2.6	4.5	8.5
2020	332			
2050	344	344	356	358
2080	350	349	373	380
2100	354	354	377	392

Edges LCIA method (excerpt)

```
{
  "supplier": {
    "name": "Methane, fossil",
    "operator": "contains",
    "matrix": "biosphere"
  },
  "consumer": {
    "matrix": "technosphere"
},
 "value": "GWP('CH4', H, C_CH4)"
}
```

Calls an external function that calculates the AGWP

Results



[5] Intergovernmental Panel on Climate Change (IPCC). (2023). Annex III: Tables of Historical and Projected Well-mixed Greenhouse Gas Mixing Ratios and Effective Radiative Forcing of All Climate Forcers. In Climate Change 2021 – The Physical Science Basis. https://doi.org/10.1017/9781009157896.017

Use Case 3.b: scenario-based characterization

Scope

- 1 kg of hydrogen from PEM electrolyzer in France
- ReCiPe 2016, Fossil fuels scarcity[6]
- Surplus extraction costs using static marginal cost increase (MCI) values per fossil fuel type
- Symbolic expression
- Recalculated using IAM scenario outputs

Edges LCIA method (excerpt)

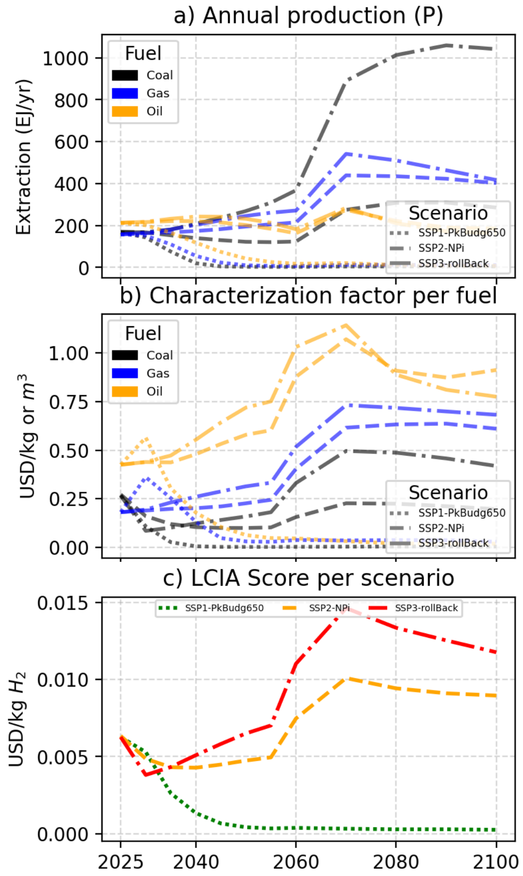
```
{
  "supplier": {
    "name": "Oil, crude",
    "categories": [
      "natural resource",
      "in ground"
    ],
    "matrix": "biosphere"
  },
  "consumer": {
    "matrix": "technosphere"
  },
  "value": "(MCI_OIL * P_OIL / 5) / (1 + d)"
}
```

Marginal extraction cost [USD/GJ²]

Annual extraction volume [EJ/year]

Discount rate

Results



[6] Vieira, M. D. M., Ponsioen, T., Goedkoop, M., & Huijbregts, M. A. J. (2016). Fossil resource scarcity. In ReCiPe 2016. A harmonized life cycle impact assessment method at midpoint and endpoint level. Report I: Characterization (pp. 95–118).

Limitations

- Does not replace site-specific impact assessment
  - Geo-referenced inventories coupled with tools to model fate, exposure, and effect based on real-world environmental data are preferable
- Relies on the availability and quality of relevant metadata (e.g., locations, classifications) in inventories and characterization factor definitions

Conclusions

- Represents a pragmatic and scalable advancement for context-sensitive environmental assessment
- Provides a robust yet accessible solution for regionalized, relational, and prospective life cycle assessments.

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R. Sacchi, A. H. Menacho, G. Seitfudem, M. Agez, J. Schlesinger, A. Koyamparambath, J. Santillán-Saldivar, P. Loubet and C. Bauer, Int. J. Life Cycle Assess.

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romain.sacchi@psi.ch