
Environmental Science & Technology
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Article
Linking Life Cycle and Integrated Assessment Modeling to Evaluate Technologies in an Evolving System Context: A Power-to-Hydrogen Case Study for the United States
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Cite This: Environ. Sci. Technol. 2023, 57, 2464−2473
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Supported by: US Department of Energy

POP: FY21-23

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ACLCA 2023 Conference
SEPTEMBER 25-28
BURLINGTON, VT

Towards prospective LCA using Life-cycle Assessment Integration into Scalable Open-source Numerical models (LiAISON) framework for analyzing emerging low-carbon technologies


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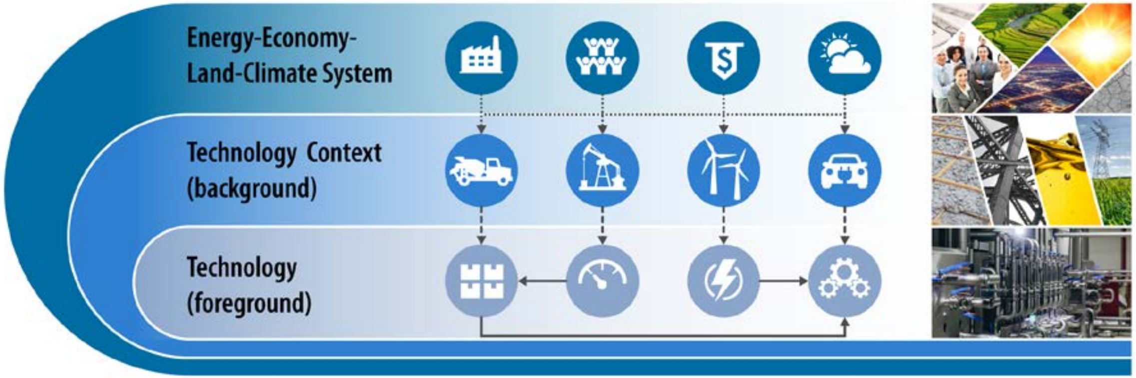
September 2023

https://pubs.acs.org/doi/10.1021/acs.est.2c04246

Lifecycle Analysis Integration into Scalable Open-source Numerical models



Funding: Department of Energy

POP: FY21-23

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Research Question: What are the future impacts and tradeoffs of present-day novel technologies accounting for transitions in the energy and manufacturing sectors as well as technology improvements?

Method: Coded, prospective life cycle assessment using long-term, coherent scenarios of the energy-economy-land-climate system to quantify the effects of background system changes and foreground technology improvements for various technologies.

Value-add: Inform R&D prioritization for novel technologies and preemptively address potential tradeoffs and unintended consequences of their large-scale deployment.

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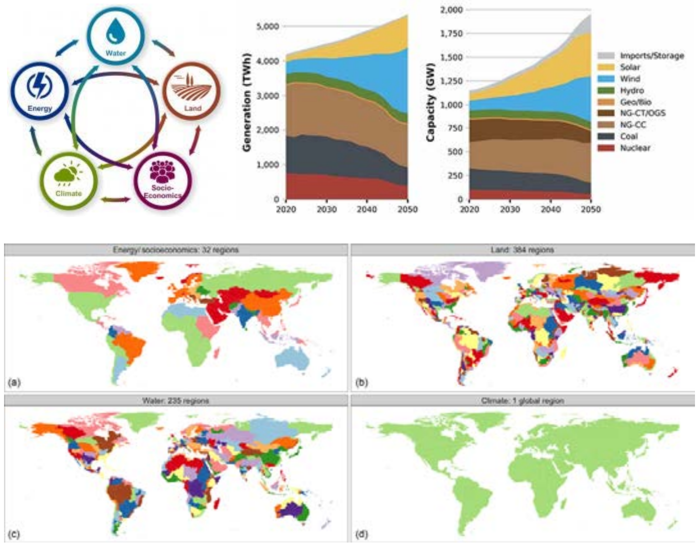
Linkages: FECM, BOTTLE, others

Vision / Motivation

Prospective system models



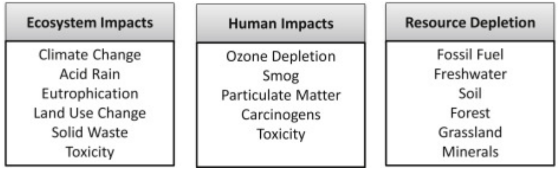
Comprehensive but scenarios often depend on limited metrics. Models are primarily cost-driven.

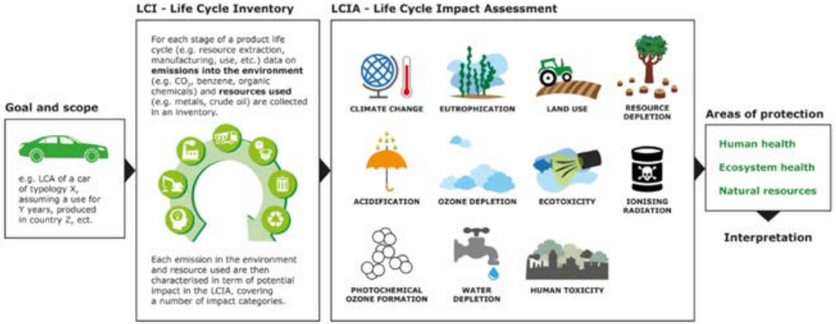
URL: nrel.gov; pnnl.gov

Phase 1

Future

Life Cycle Assessment

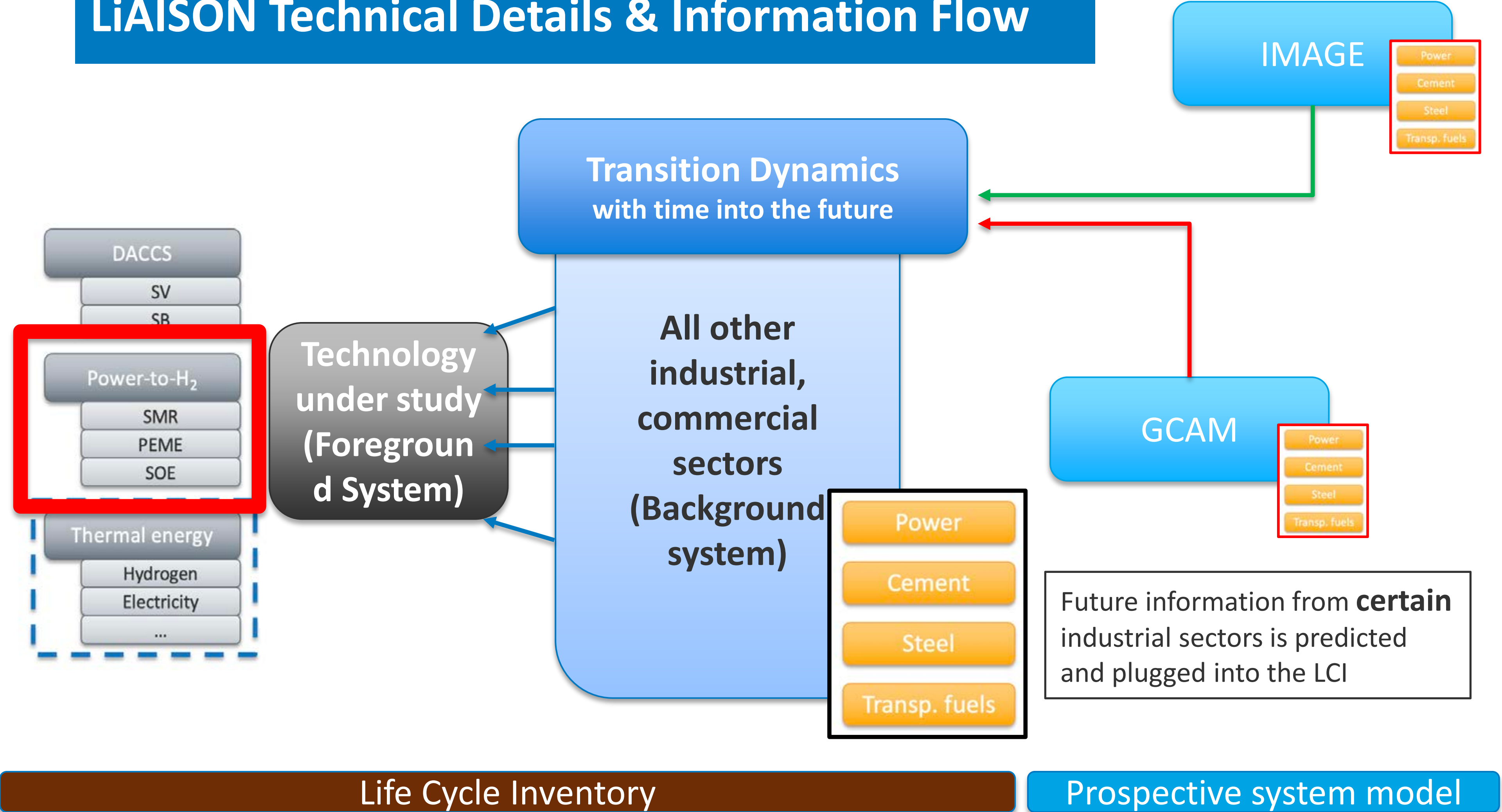




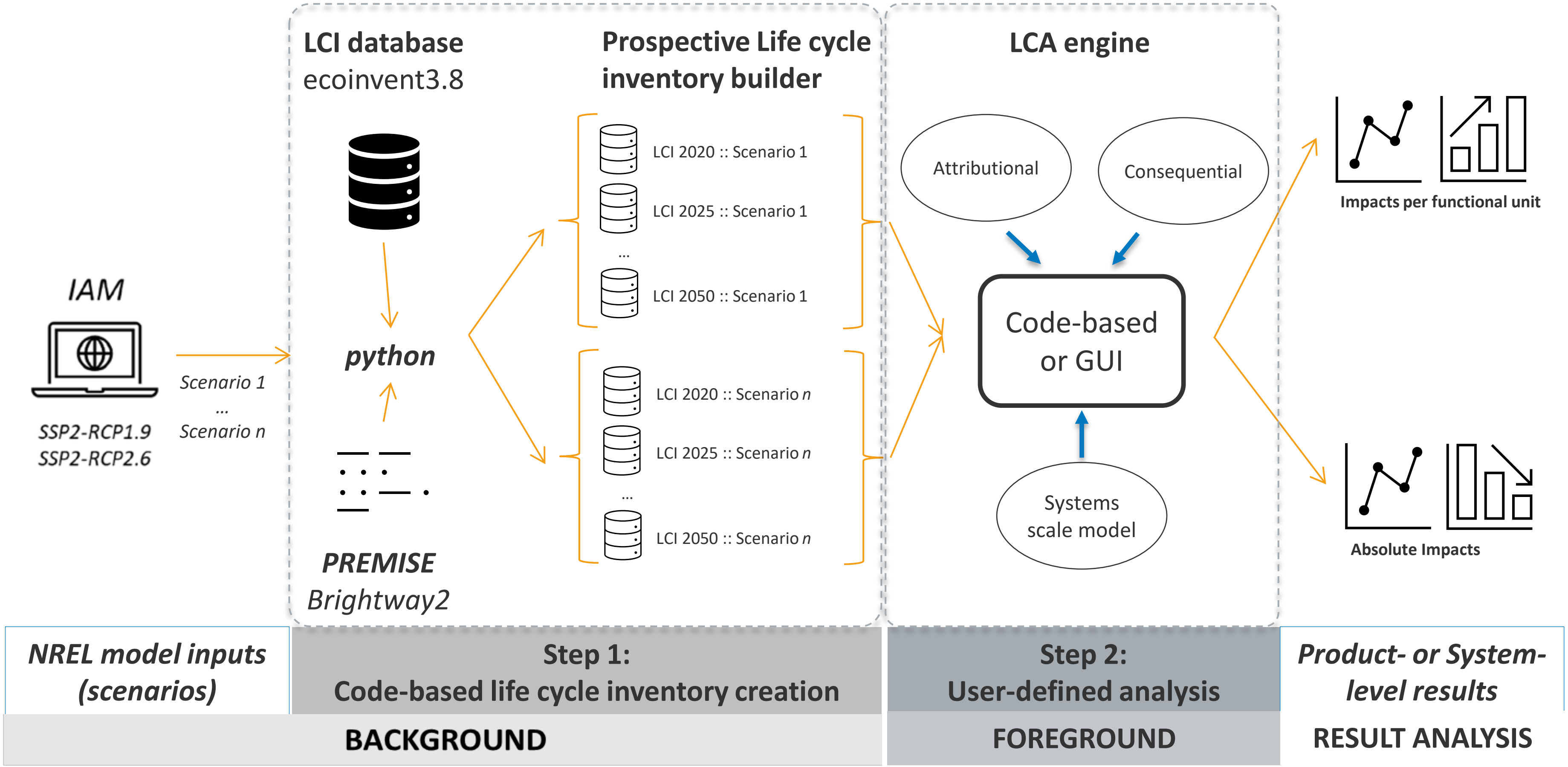
Multi-metric but results are context-specific. Analyses have varying system boundaries (hard to compare).

URL: https://eplca.jrc.ec.europa.eu/lifecycleassessment.html; https://www.sciencedirect.com/topics/engineering/life-cycle-impact-assessment

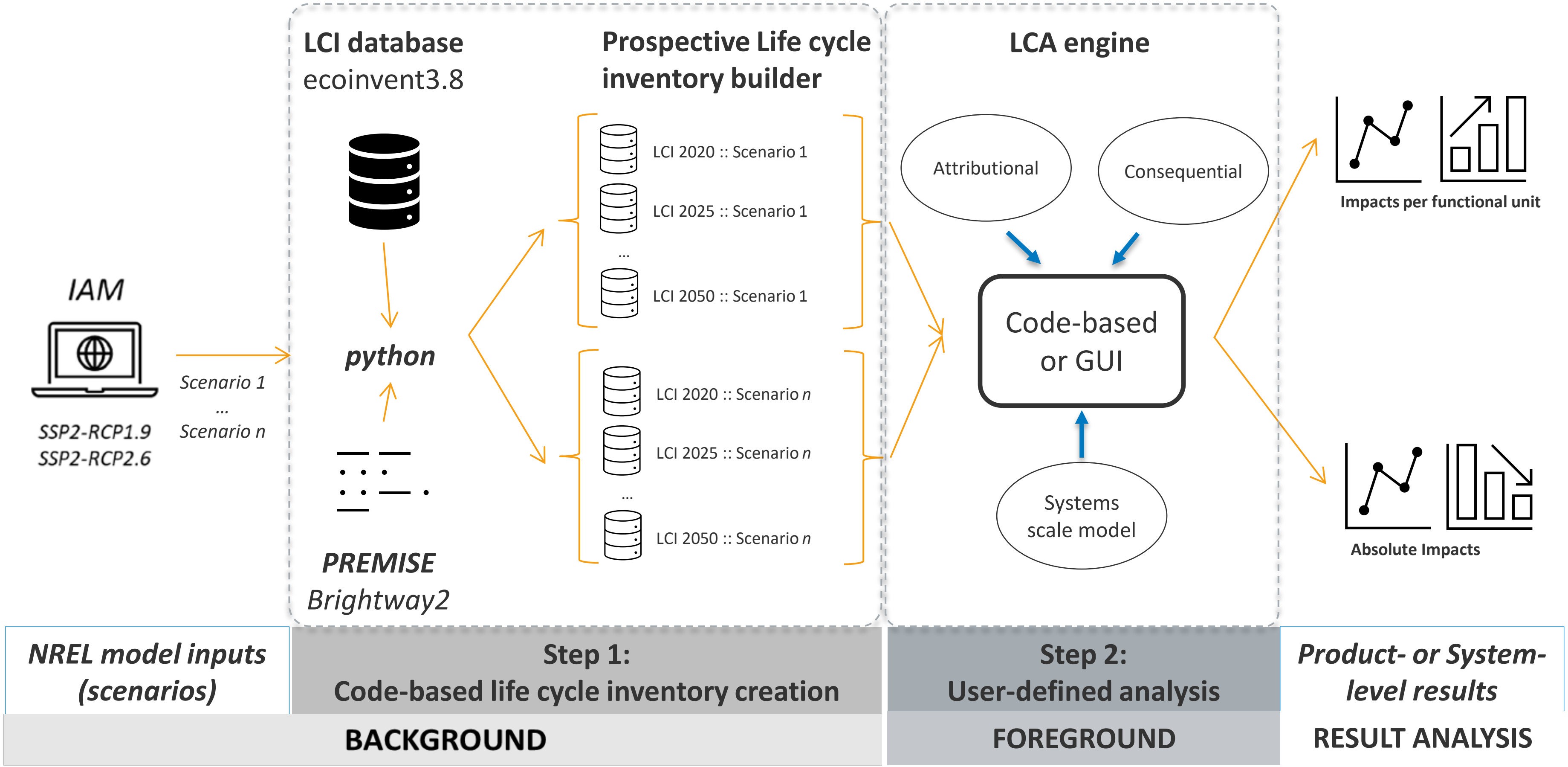
LiAISON Technical Details & Information Flow



Methodology - LiAISON Technical Details

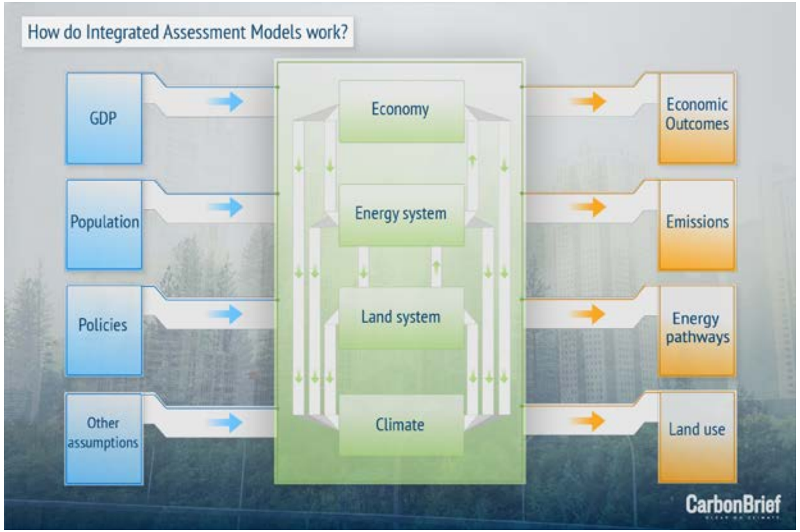


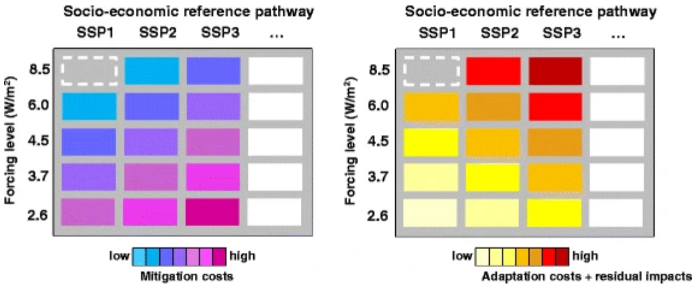
Methodology - LiAISON Technical Details



Integrated Background Scenarios

- Long-term, global projections of the coupled energy-economy-land-climate system.
- Derived from Integrated Assessment Models (IAM), e.g., GCAM (PNNL).
- Highly stylized but comprehensive.
- All scenarios are coherent, cross-sectoral and represent dynamics across physical and social systems.
- Comparability: Standardized outputs (SSP-RCP combinations).



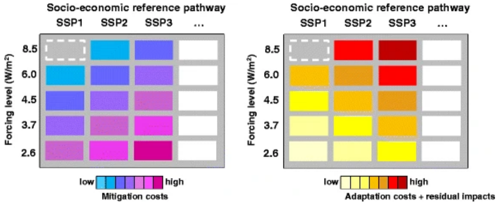


https://www.carbonbrief.org/qa-how-integrated-assessment-models-are-used-to-study-climate-change/

Sector Projections

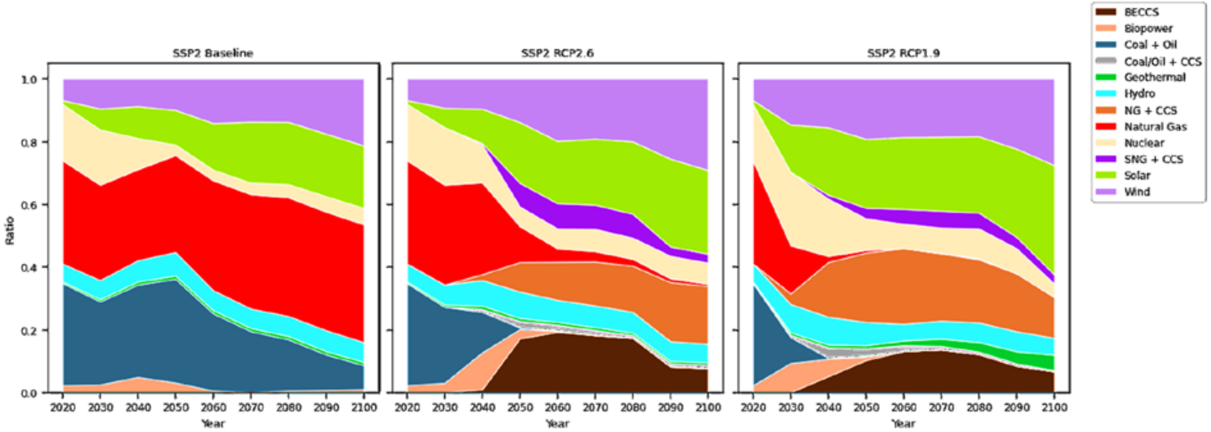
The background scenarios define technology compositions and efficiencies across four sectors:

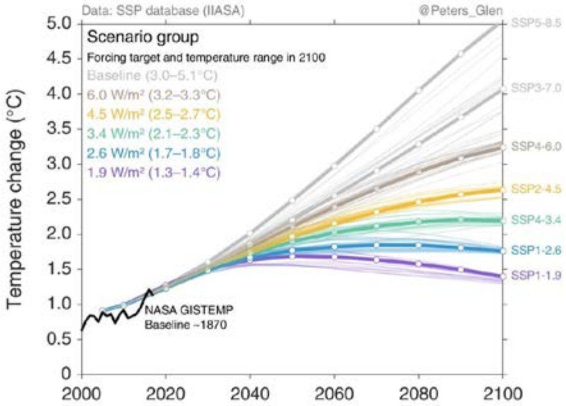
Power | Steel | Cement | Fuel



Example: power sector specifics – Shared Socio-Economic Pathways (IPCC)

- SSP2-RCP1.9: net zero GHG economy by 2035, net zero GHG economy by 2050
- SSP2-RCP2.6: delayed by ~ 20 years
- SSP2-reference: no targets





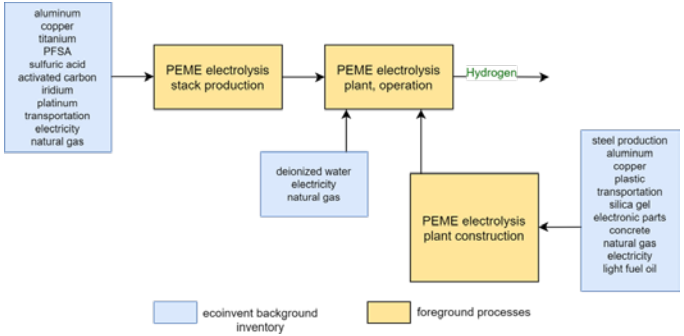
Case Study

Comparing hydrogen production technologies under a dynamically changing supply system of power, cement, steel and fuels – a prospective LCA case study.

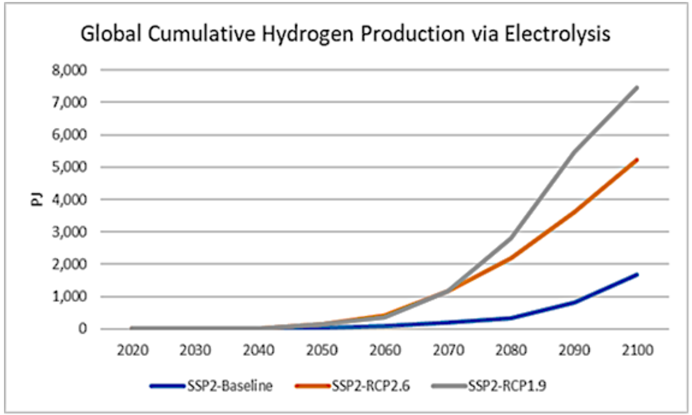
Power-to-Hydrogen (PtH$_2$)

Technologies:

- **Steam methane reforming (reference) :** H_2 generation via steam methane reforming of natural gas to produce syngas and then H_2. *(Baseline)*
- **Solid-oxide electrolysis (SOE):** H_2 generation via electrolysis in a fuel cell with a solid oxide/ ceramic electrolyte (adv: high efficiency).
- **Polymer-electrolyte-membrane electrolysis (PEME):** H_2 generation via electrolysis in a cell with a solid polymer electrolyte (adv: low weight and volume).



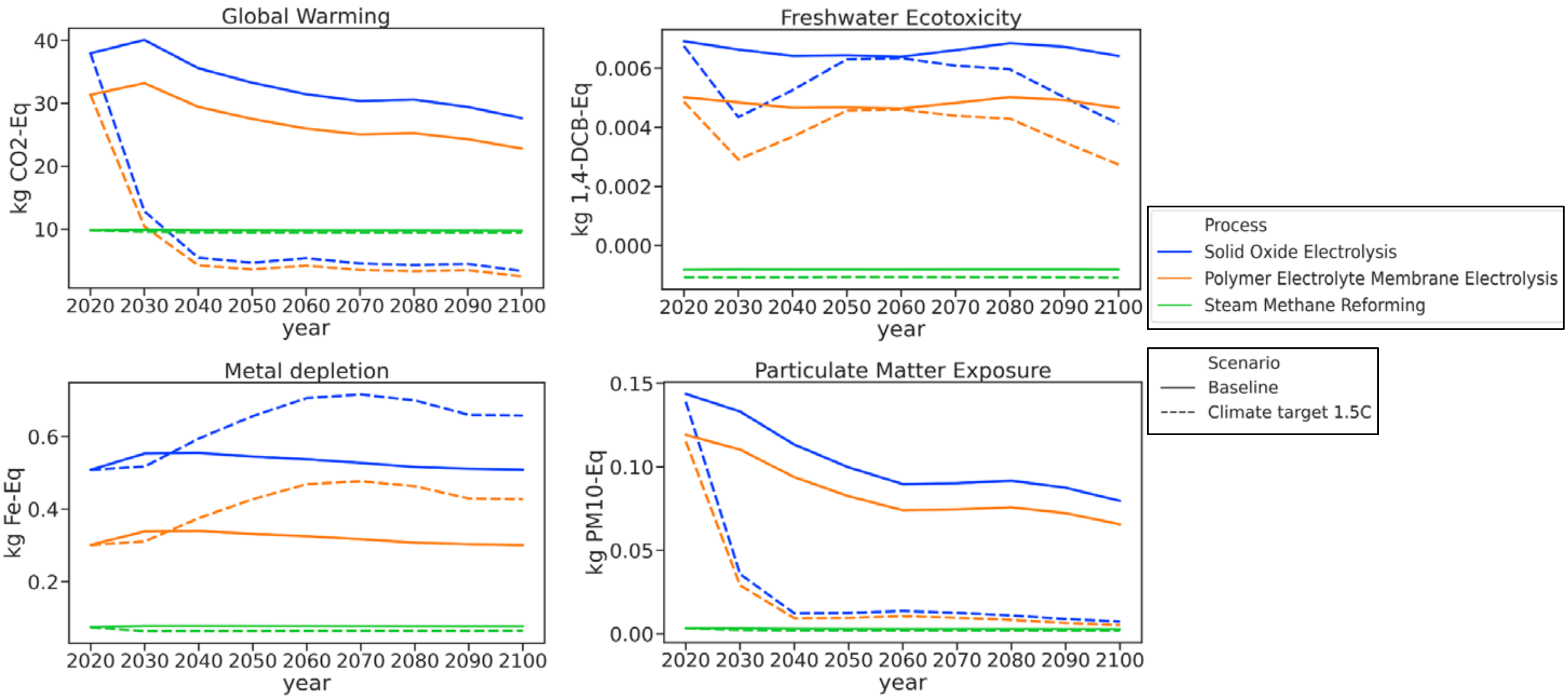
Adjusted to background deployment levels in the respective scenarios.
Foreground dynamics via learning-by-doing in the deployment stage.



CASE STUDY VISUALIZED

	Baseline Scenario (no policy)	Climate Target Scenario (1.5°C, 2050 net zero)
• Steam methane reforming (reference) • Polymer-electrolyte-membrane electrolysis (PEME) • Solid-oxide electrolysis (SOE)	**Research Question 1** Life Cycle metrics of Global Warming Footprint, Metal Depletion, Human Toxicity, Particulate Matter Exposure for production of 1 kg of H_2 **under dynamic supply chains for power, cement, steel and fuel production.**	
• Polymer-electrolyte-membrane electrolysis (PEME) with technology learning	**Research Question 2** Same study expanded with **improving cost and performance parameters of H_2 technologies** via learning by doing (deployment) over time.	

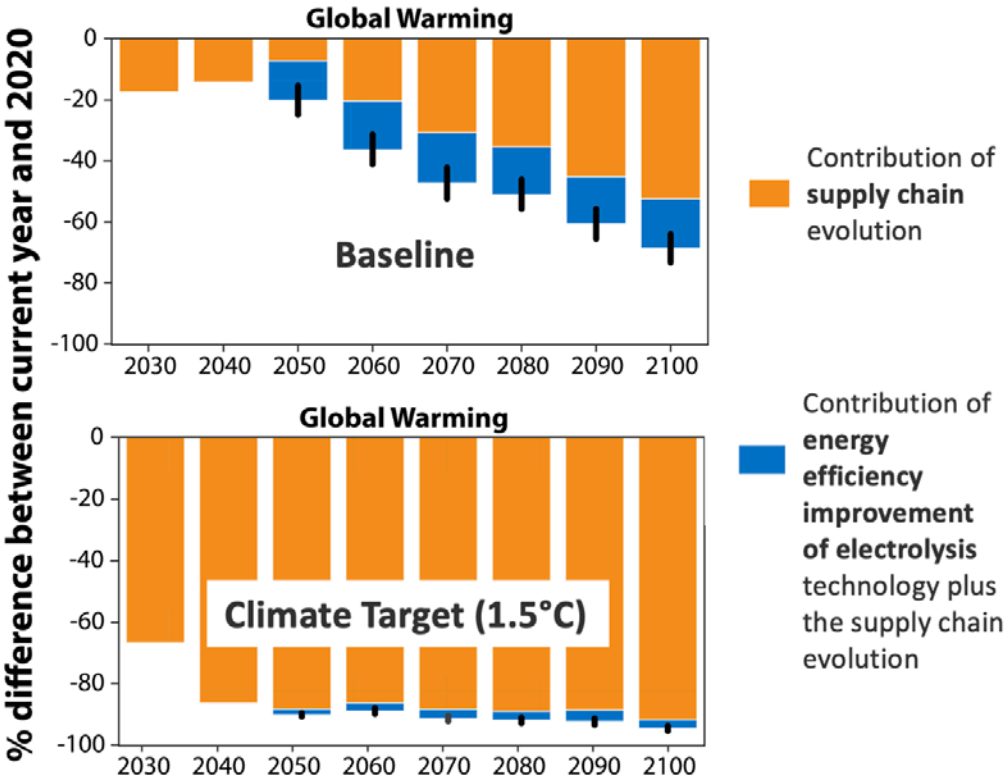
RQ1: Life cycle metrics production of 1 kg of H2 under dynamic supply chains for power, cement, steel and fuel production evolution.



Insights and Conclusions

- Electrolysis-based H_2 requires clean power to **reach CO_{2e}-parity** with SMR.
- Yet, in a Climate Scenario **Human and Ecotoxicity levels** are not reduced. Rather, the categories stagnate and even temporally increase. The largest reduction for these indicators happens in the Baseline Scenario because of increasing natural gas power production (and a respective reduction in coal-based power).
- **PM exposure** levels improve drastically in the Baseline (natural gas to coal shift) and improve further in a Climate Scenario (higher penetration of renewable energy).
- **Metal depletion** levels remain stable in the Baseline but increase sharply in the Climate Scenario with the high penetration of solar, wind, and bioenergy (with CCS) generation.
- **Major insight 1**: Temporal LCA results of the technologies are directly influenced by the projected technology context, power in particular.
- **Major insight 2**: Neither contextual scenario improves all LCA indicators (heterogenous result across metrics), indicating a strong need for improving the full life cycle of renewable energy technologies.

RQ2: Impact of energy efficiency of electrolysis process (PEME) improvement and evolving supply chain on global warming



Baseline

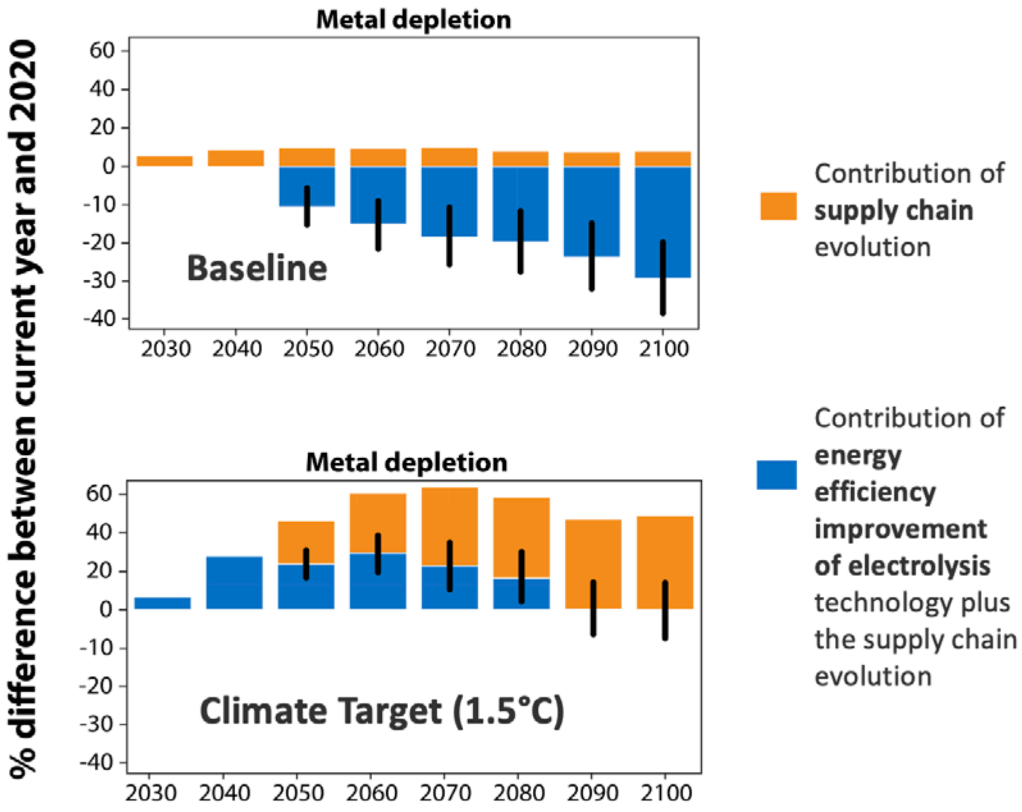
- Contribution of supply chain (background) evolution has the major contribution.
- However, even energy efficiency improvement of the electrolysis technology can contribute to a significant reduction.

Climate target (1.5°C)

- The efficiency improvement of electrolysis technology has very low contribution to emission reduction.

➢ **Reduction of carbon footprint of supply chain, including grid, is more important for decarbonization of hydrogen production process.**

RQ2: Impact of energy efficiency of electrolysis process (PEME) improvement and evolving supply chain on metal depletion



Baseline

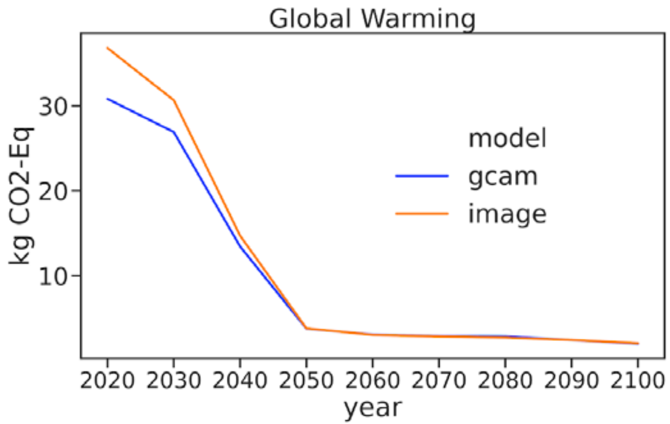
- The supply chain change increases metal depletion (positive values).
- Alternatively, the energy efficiency improvement of electrolysis technology results in significant metal depletion reduction.

Climate target (1.5°C)

- Metal depletion due to supply chain evolution is so large, it makes the net metal depletion value increase with time.

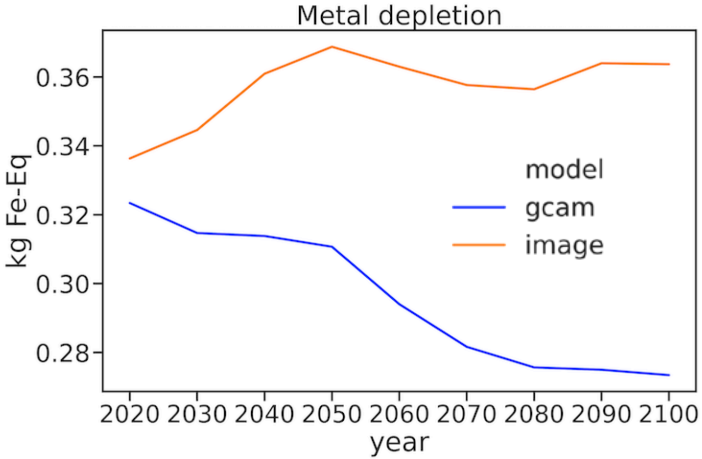
➢ Different environmental impact indicators are affected differently by supply chain evolution and process evolution separately.

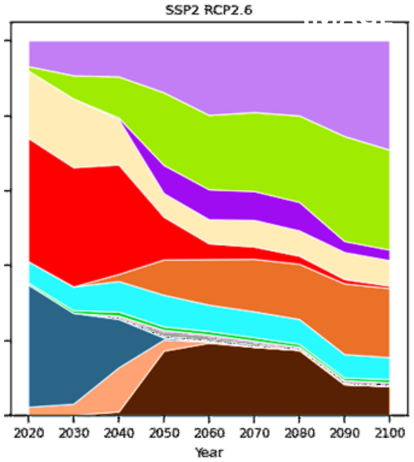
Prospective LCA of PEME process for the climate target (2°C) scenario using pathway information from IMAGE and GCAM.



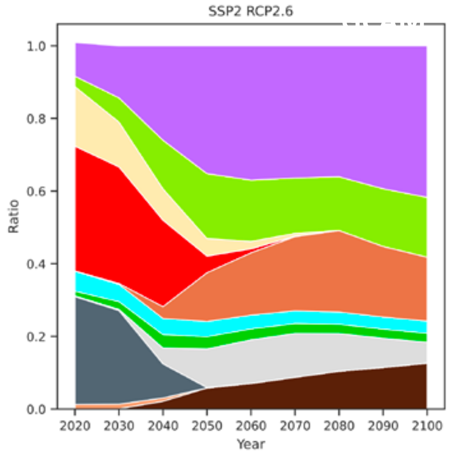
We integrate background changes as predicted by GCAM and integrate them into Ecoinvent 3.8 using LiAISON
We compare the LCA results from background changes as predicted by different IAM models.

Different background assumptions for the same scenarios SSP2-RCP2.6. Different IAMs have different ways to achieve emission reductions and global change.





Climate Target (2°C)



Thank you

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This work was authored by the National Renewable Energy Laboratory, operated by Alliance for Sustainable Energy, LLC, for the U.S. Department of Energy (DOE) under Contract No. DE-AC36-08GO28308. Funding provided by U.S. Department of Energy Office of Fossil Energy and Carbon Management. The views expressed in the article do not necessarily represent the views of the DOE or the U.S. Government.

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