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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

Patrick Lamers,* Tapajyoti Ghosh, Shubhankar Upasani, Romain Sacchi, and Vassilis Daioglou

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Life-Cycle Assessment Integration into Scalable Open-Source Numerical Models (LiAISON) for Prospective Impact Analysis of Novel Technologies

Supported by: US Department of Energy

POP: FY21-23

Partners

Pacific Northwest National Laboratory

Joint Global Change Research Institute

University of Maryland

PBL Netherlands Environmental Assessment Agency

Paul Scherrer Institut PSI

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Collaborators:

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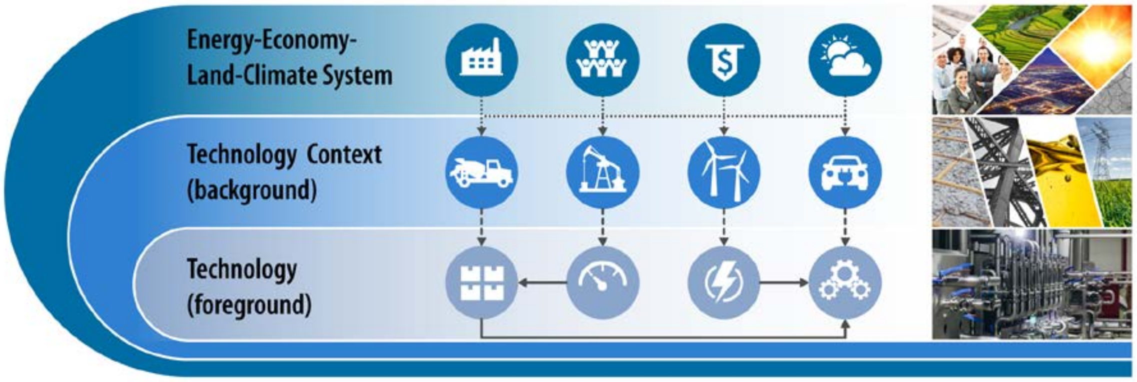
Lifecycle Analysis Integration into Scalable Open-source Numerical models



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.

Funding: Department of Energy

POP: FY21-23

Project staff

TJ Ghosh (PI)

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Partners

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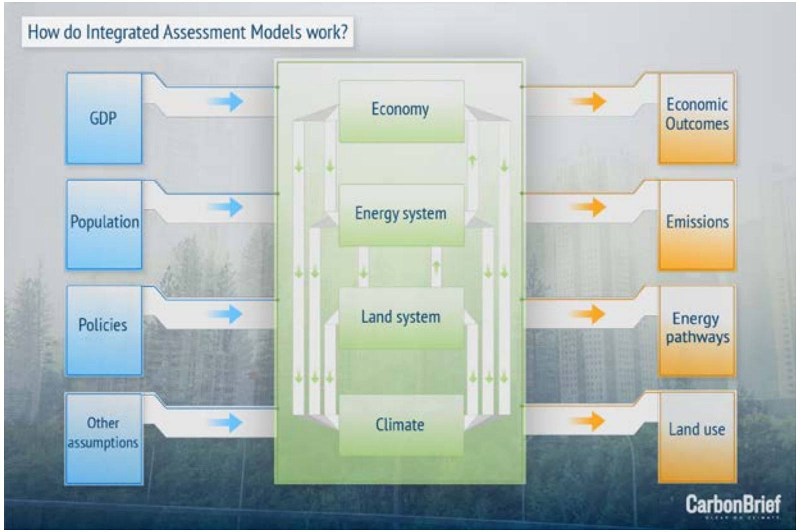
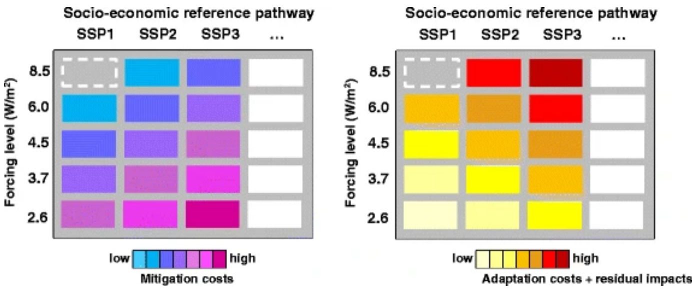
Linkages: FECM, BOTTLE, others

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/

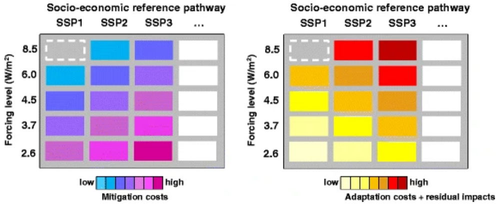
Sector projections

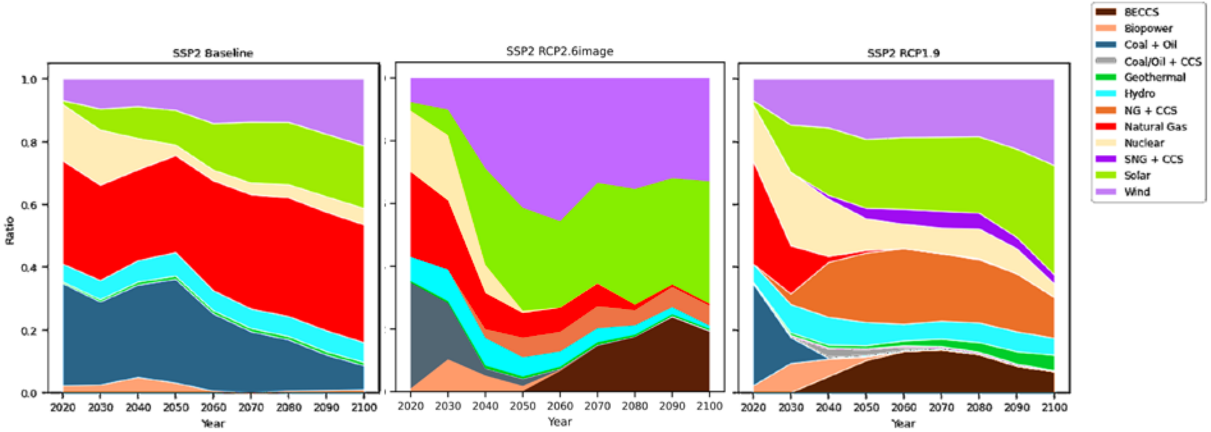
The background scenarios define technology compositions and efficiencies across four sectors:

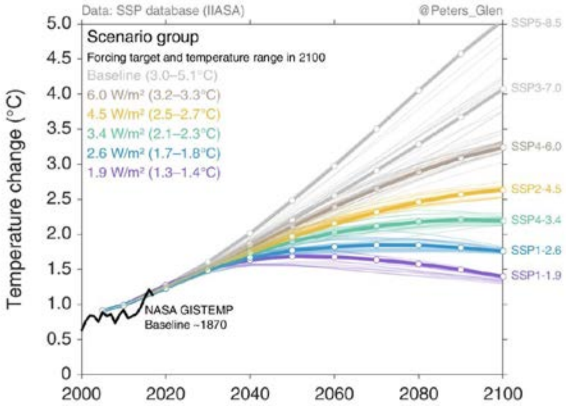
Power | **Steel** | **Cement** | **Fuel**

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

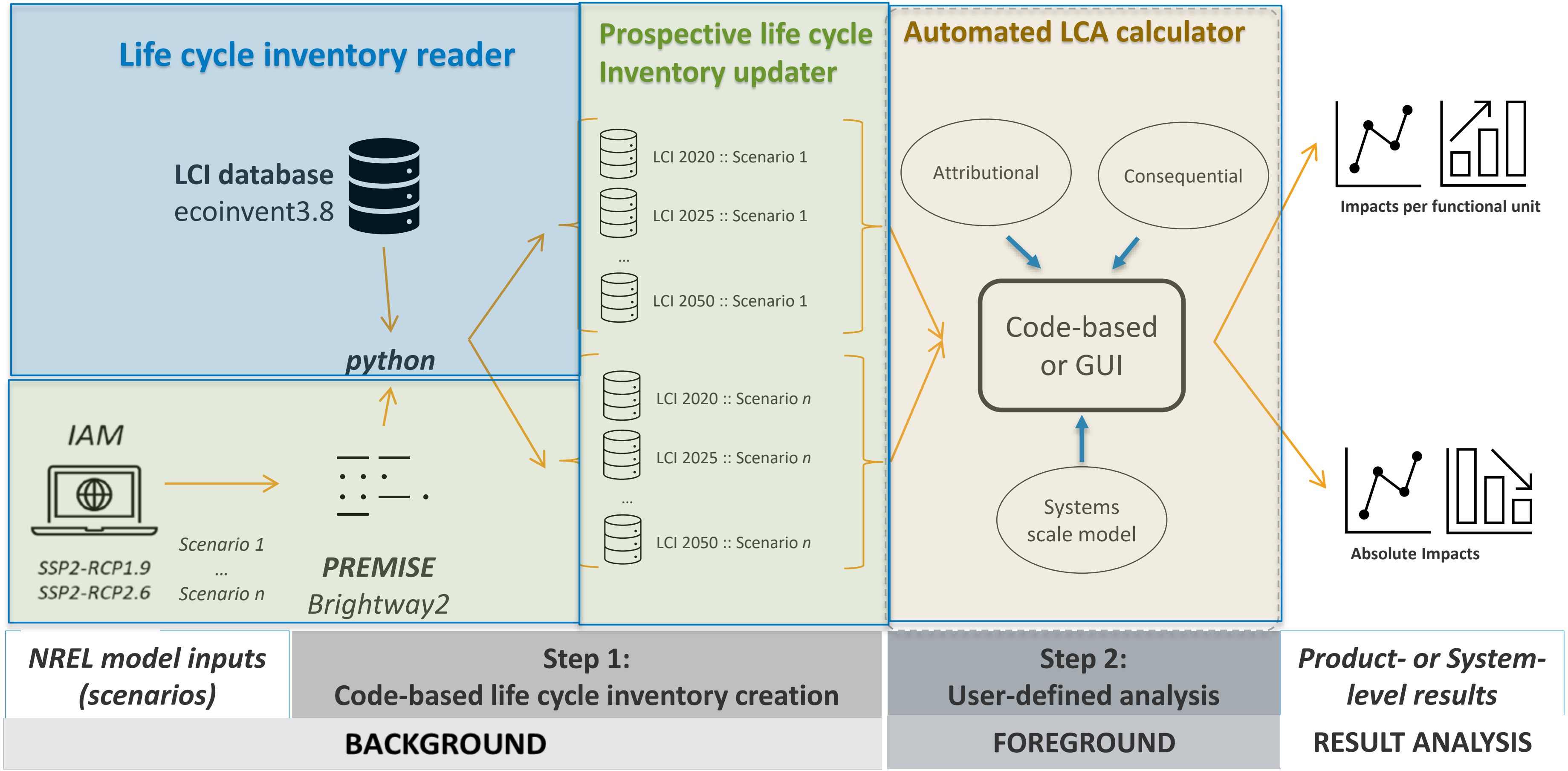
- SSP2-RCP1.9: net zero GHG economy by 2035, net zero GHG economy by 2050
- SSP2-RCP2.6: delayed by ~ 20 years
- SSP2-reference: no targets







Methodology



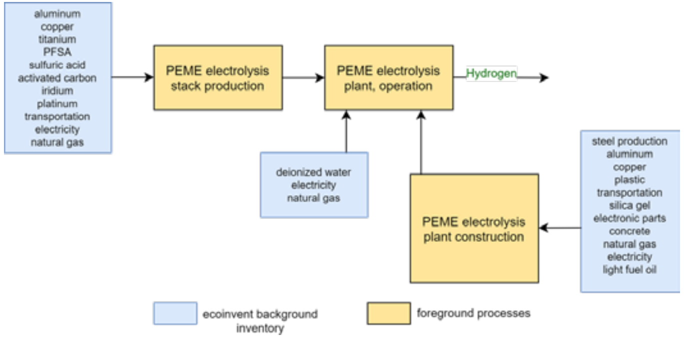
Case study

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

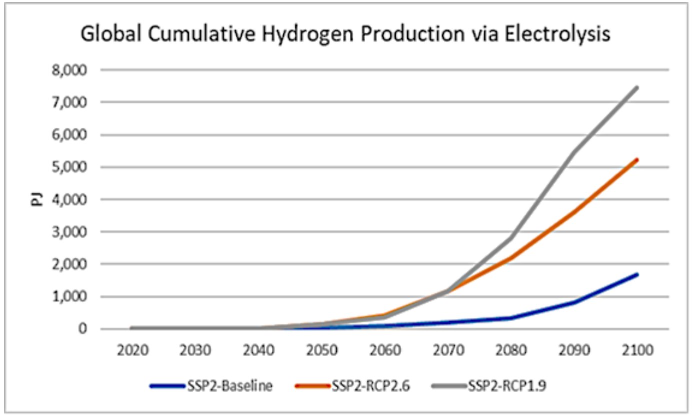
Power-to-Hydrogen (PtH_2)

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).



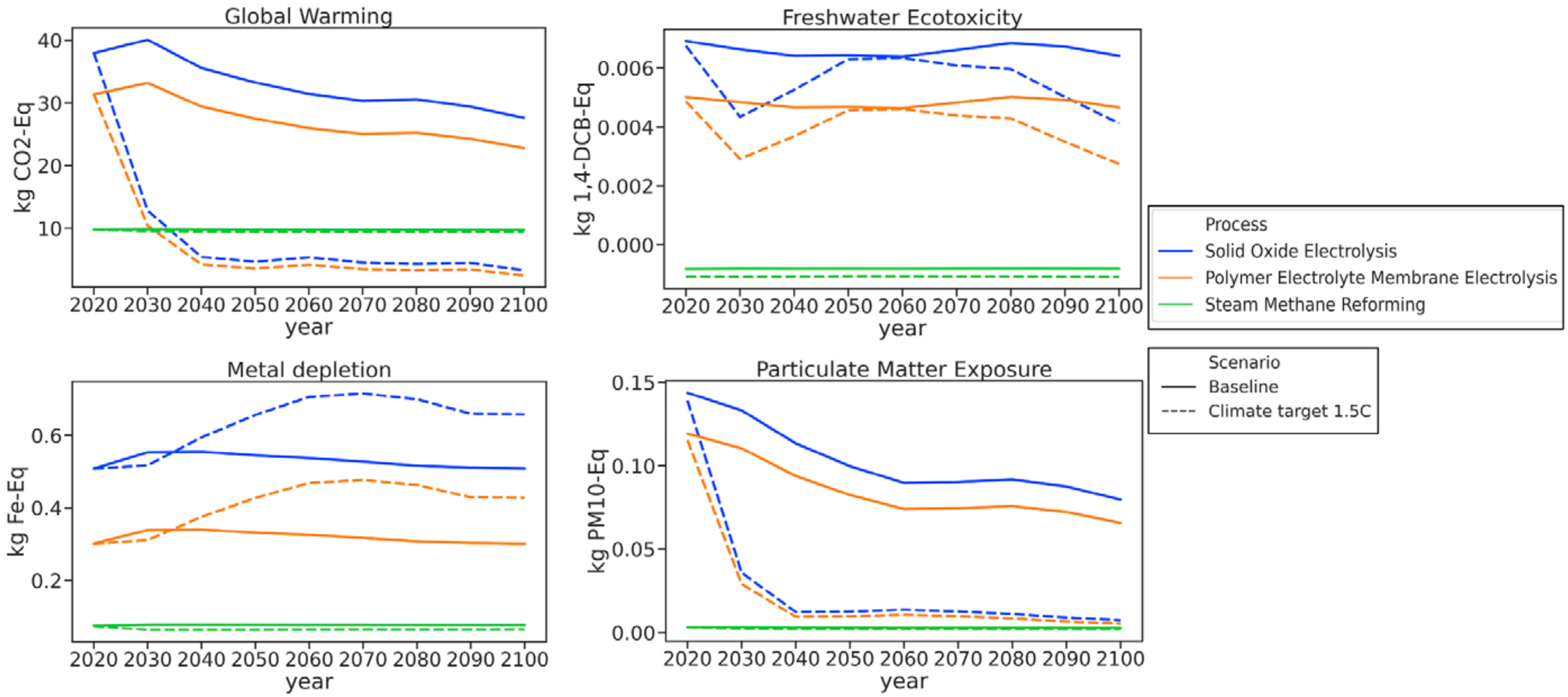
Adjusted to background deployment levels in the respective scenarios.
Foreground dynamics via learning-by-doing in the deployment stage.



Case study

	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 H_2 under dynamic supply chains for power, cement, steel and fuel production evolution.



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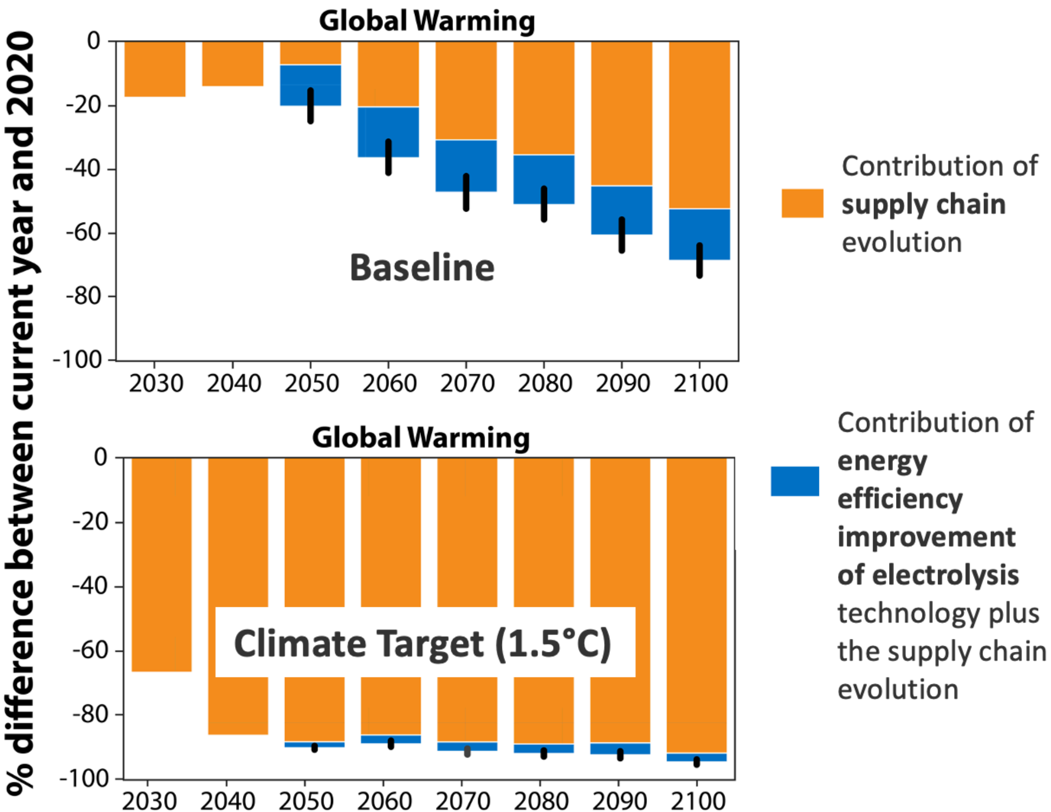
RQ2: Impact of energy efficiency of electrolysis process (PEME) improvement and evolving supply chain on global warming



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.**

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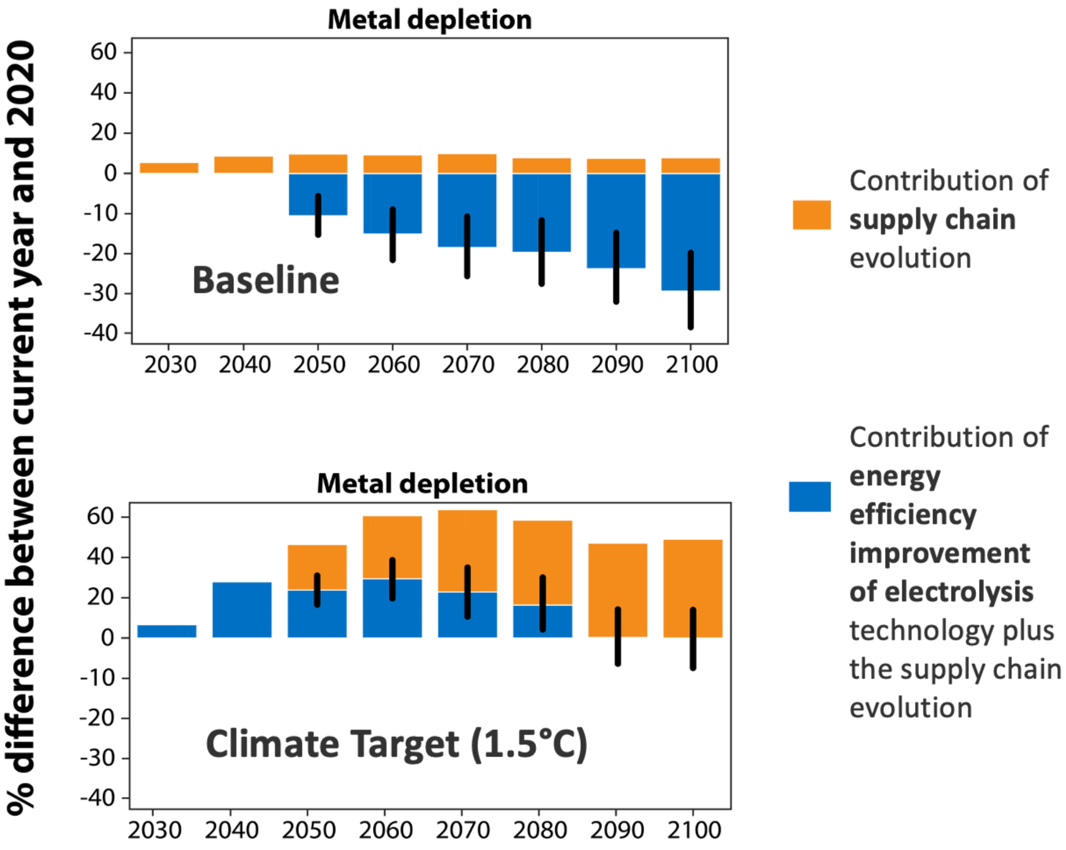
RQ2: Impact of energy efficiency of electrolysis process (PEME) improvement and evolving supply chain on metal depletion



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.

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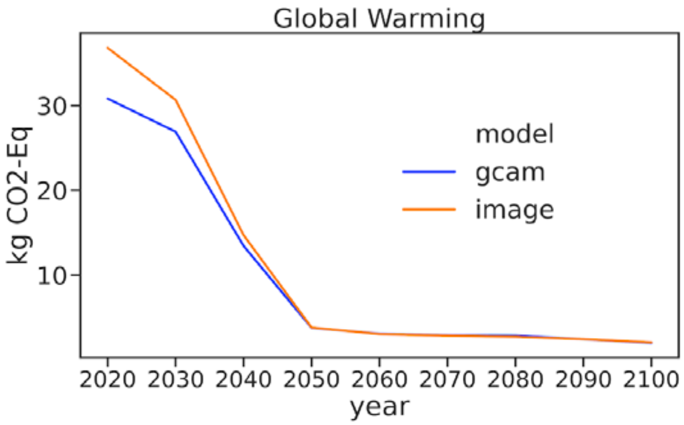
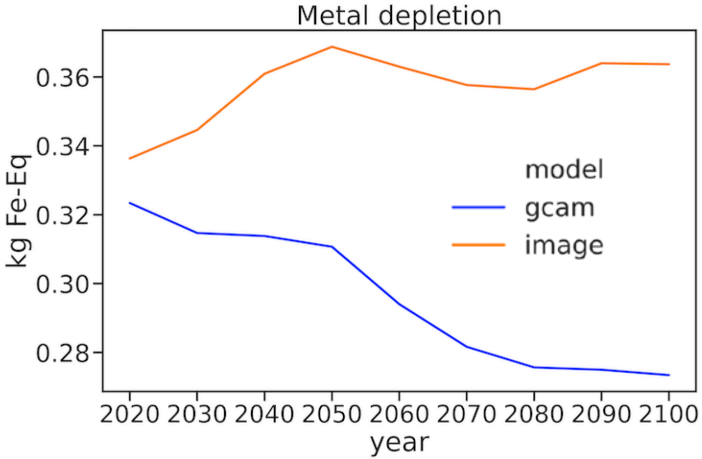
Prospective LCA of PEME process for the climate target (2°C) scenario using pathway information from IMAGE and GCAM.



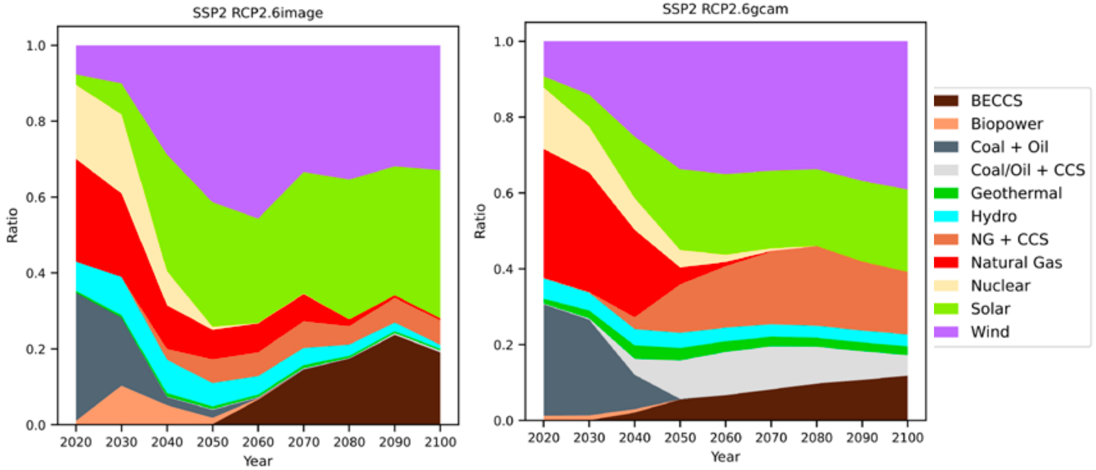
We integrate background changes as predicted by GCAM and integrate them into Ecoinvent 3.8 using LiAISON

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)



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Conclusions

- Electrolysis-based H_2 requires clean power to **reach CO_{2e}-parity** with SMR.
- Yet, in a Climate Mitigation scenario **Human and Ecotoxicity levels** are not reduced. Rather, the categories stagnate and even temporally increase. **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.
- Temporal LCA results of the technologies are directly influenced by the projected technology context, power in particular. 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.
- Environmental impact indicators are affected differently by supply chain evolution and process evolution separately.
- Different integrated assessment models achieve decarbonization with different sets of assumptions, rules and technological development. This affects the LCA results of some environmental indicators.

Thank you

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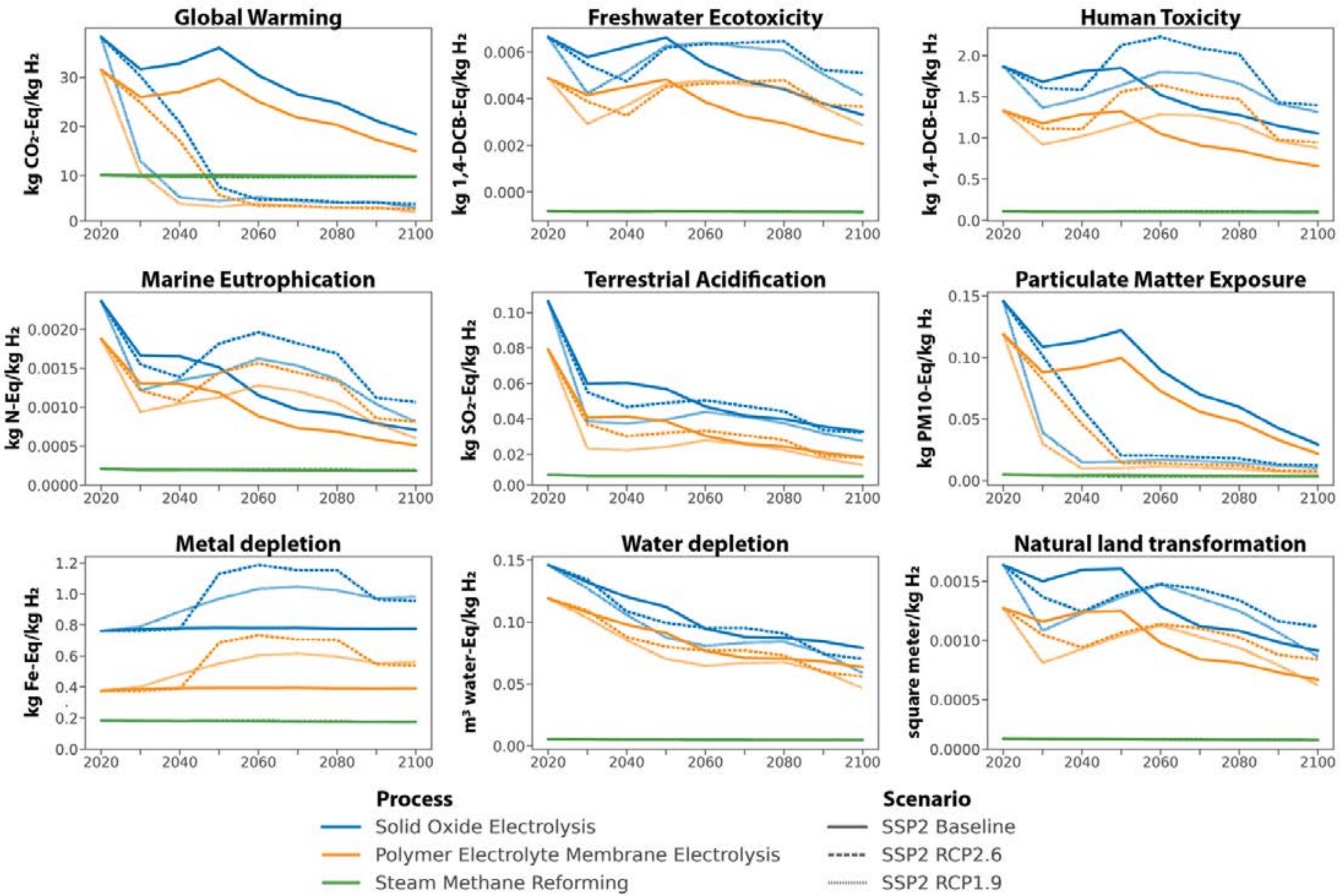
Future impacts (ReCiPe; 1 kg H_2) due to changes in the cement, steel, power, transport fuel sectors

GWP, PEME and SOE reach parity with SMR in 2050 and 2030 for SSP2-RCP2.6 and SSP2-RCP1.9 respectively.

Do not reach parity with SMR for the baseline case.

Impacts such as marine eutrophication, metal depletion and human toxicity increase due to deployment of BECCS and increased used of solar and wind for the decarbonization pathways.



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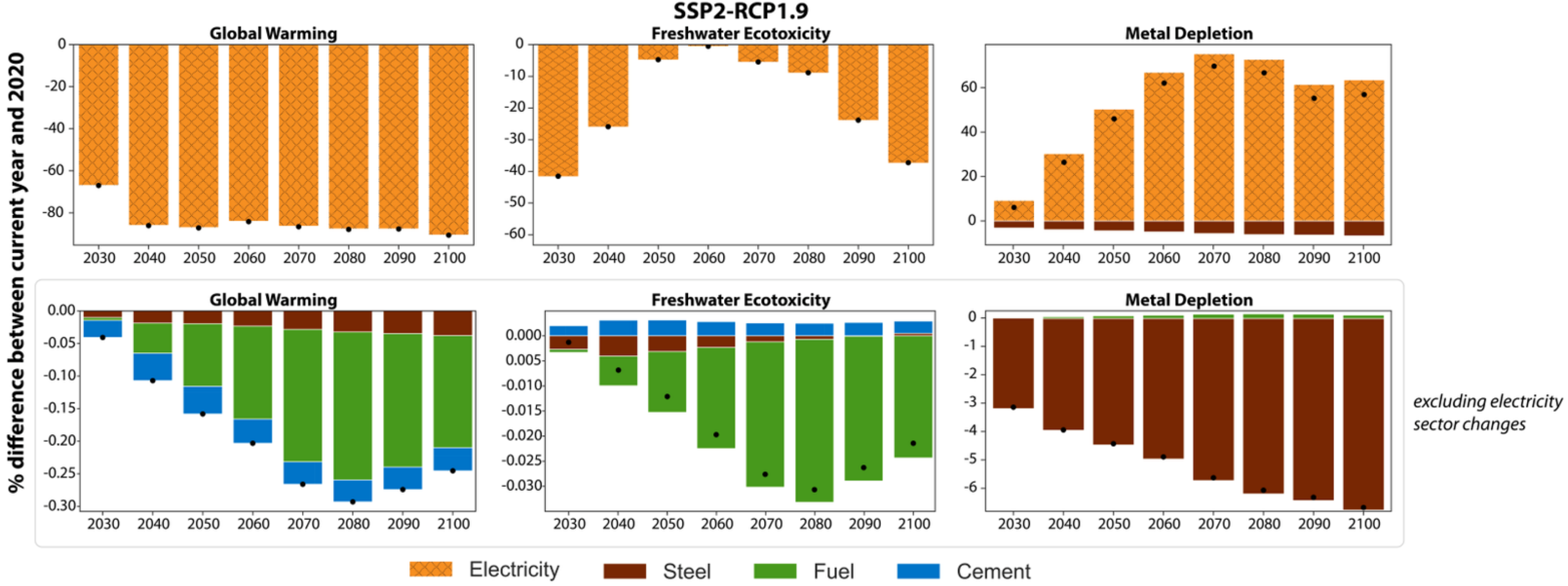
Specifying the dynamics per sector (background)



Example: PEME, SSP2-RCP1.9

- Power sector exhibits the largest influence (up to -80%; top left).
- Metal depletion is linked to steel sector dynamics (recycling rates and efficiencies).
- Dynamics for other sectors are still observed, but they do not contribute significantly (<1%; bottom right).
- Land and water impacts link back to transport fuel sector dynamics.

LiAISON computes these results for each technology-scenario combination allowing us to identify:

1) The influences of the individual sector dynamics;
2) Potential tradeoffs and underlying dependencies (e.g., hot spot analysis for power technologies)

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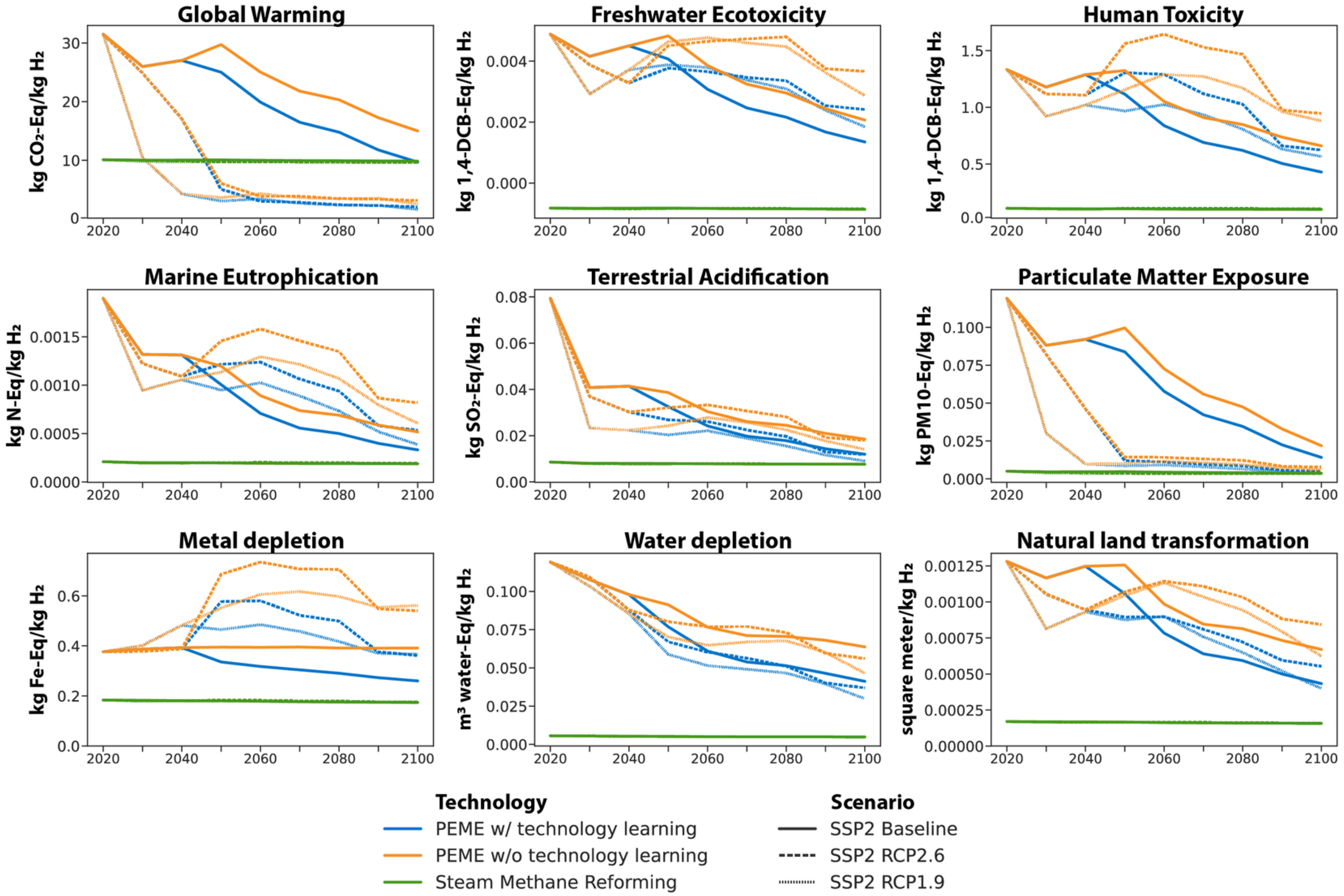
Beyond 2040 electrolysis is deployed globally on a large-scale, driving learning-by-doing improvements.

Learning-by-doing, further reduces impacts over time.

Benefits are largest for metrics that do not drop due to background changes, i.e., smaller benefits for GWP_{100} in mitigation scenarios, larger ones for impacts that rise, e.g., eutrophication.

Future impacts (ReCiPe; 1 kg H_2) due to changes in the background superimposed with technology learning at 5% energy efficiency improvement per year



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R&D influence *vs.* systems context

PEME

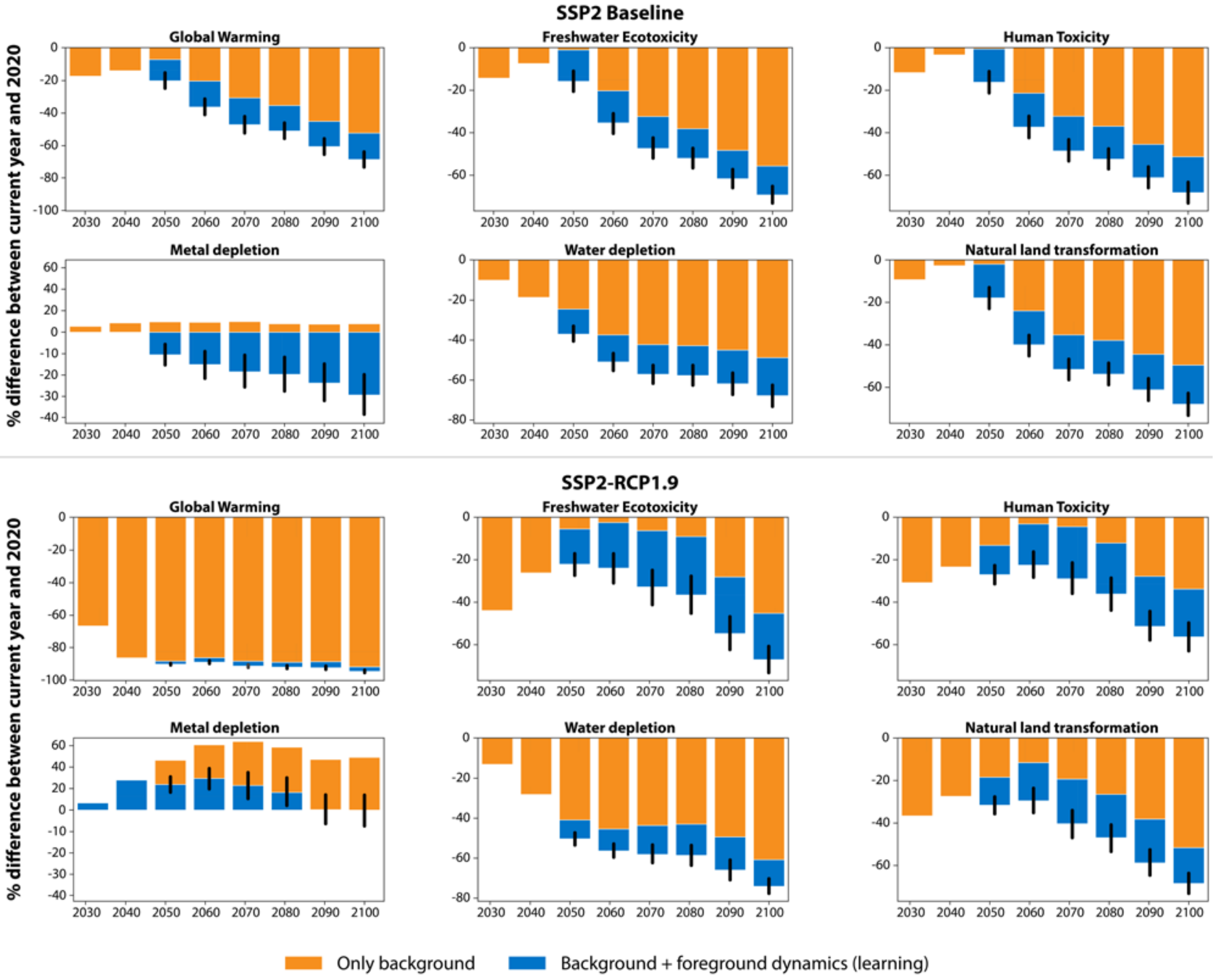
ReCiPe

SSP2-Baseline

PEME

ReCiPe

SSP2-RCP1.9



If the electricity grid evolves according to RCP1.9 pathway, PEME will have less contribution to decarbonization

Thus, evolving the background rather than improving PEME efficiency will have more impact on decarbonization.

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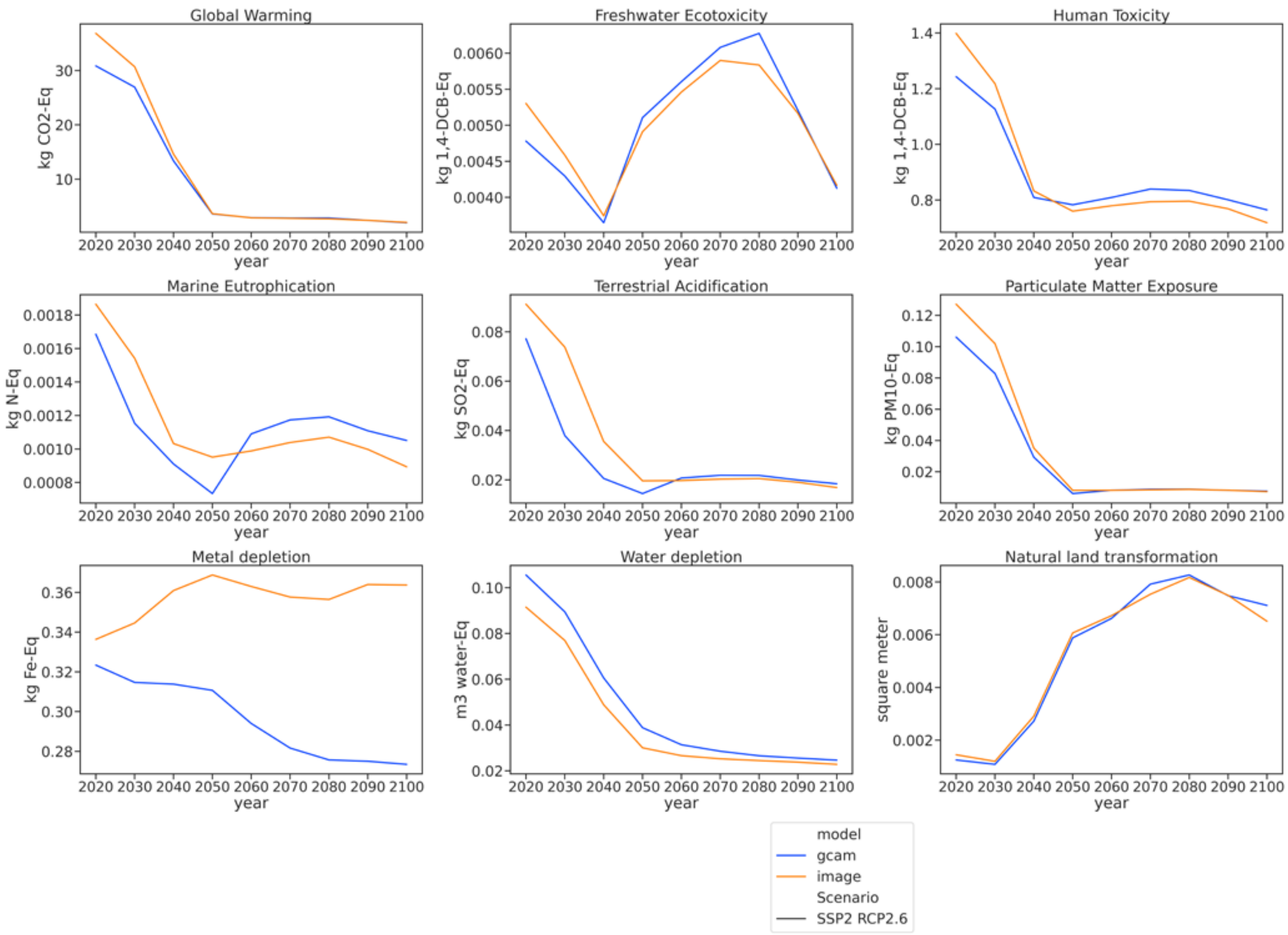

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