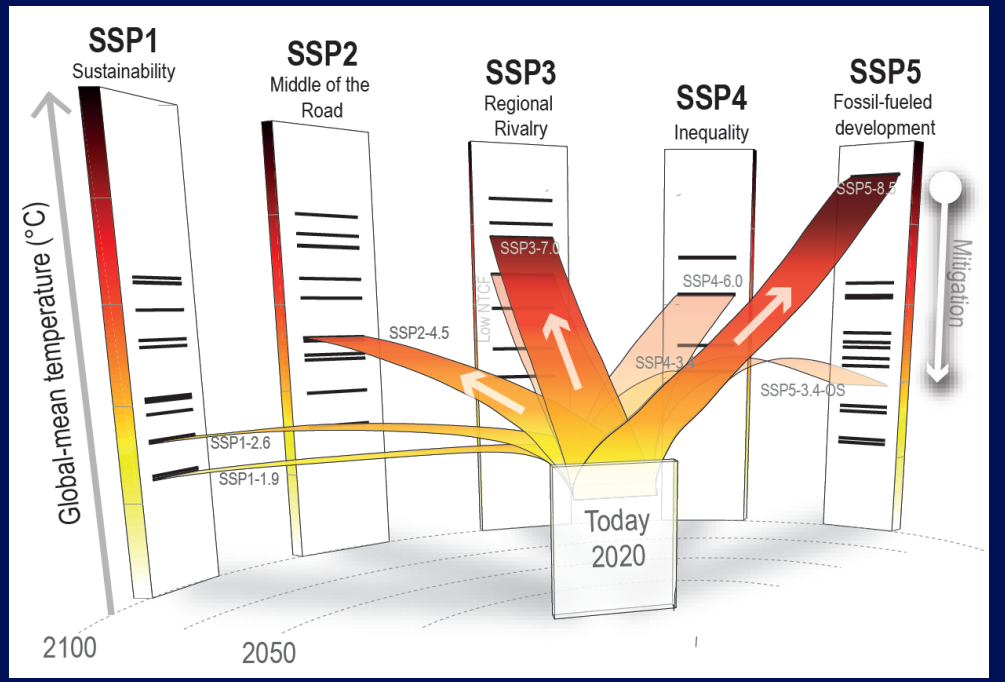
Including broad future scenarios in prospective LCA



Bernhard Steubing

Universiteit Leiden
The Netherlands

CML
Institute of Environmental Sciences
Department of Industrial Ecology

Discover the world at Leiden University

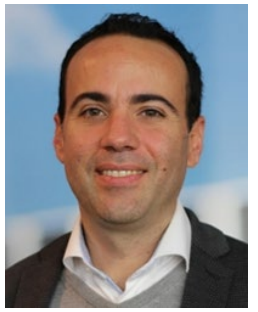
Prospective/ex-ante LCA team @CML

Arnold Tukker

Jeroen Guinée

Stefano Cucurachi

Bernhard Steubing



Carlos Blanco

Paul Behrens

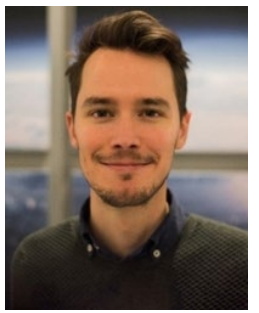
Brenda Miranda X.

Natalya Tsoy

Vrishali Subramanian

Martin Koese

Sander van Nielen



Nic Navarre

Marc van der Meide

Carina Harpprecht

+ others

Talk content

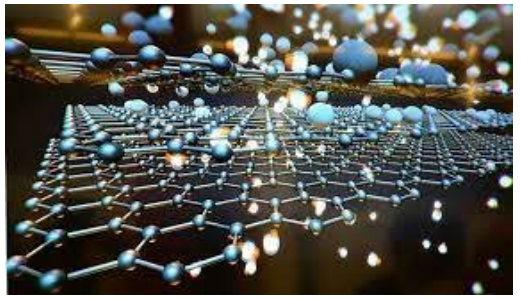
- Why broad future background scenarios for prospective LCA?
- Recent progress and tools for generating and using prospective LCI databases
- Does it matter? Results from studies using background scenarios
- Challenges and possible next steps

We live in an era of great technological change. Climate change. Environmental guidance is crucial.

Mobility transition

Energy transition

Bioeconomy



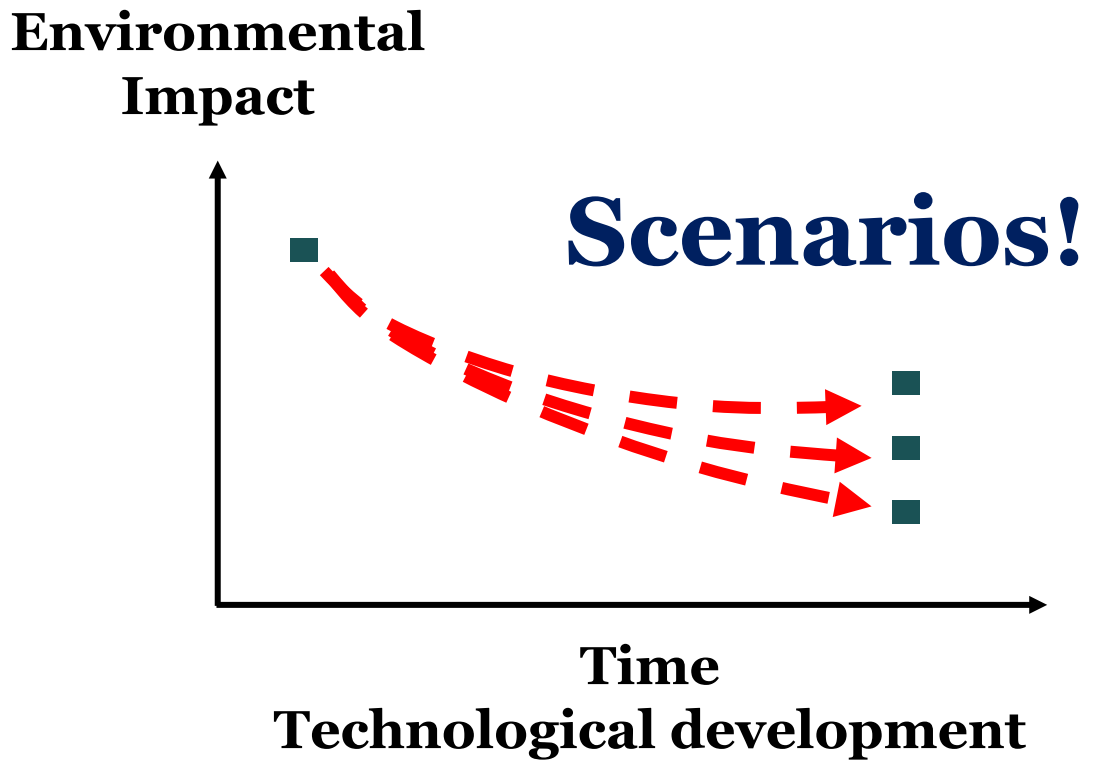
New materials and technology

Artificial intelligence

… and much more…

Prospective LCA

Prospective (or ex-ante) LCA tries to *anticipate environmental impacts* of products and services provided by *future technologies*.



What is a scenario?

A scenario is a description of how the future may develop, based on a coherent and internally consistent set of assumptions… (IPCC 2021)

What is a scenario?

A scenario is a description of how the future may develop, based on a coherent and internally consistent set of assumptions…

about key drivers including demography, economic processes, technological innovation, governance, lifestyles, and relationships among these driving forces (IPCC 2021)

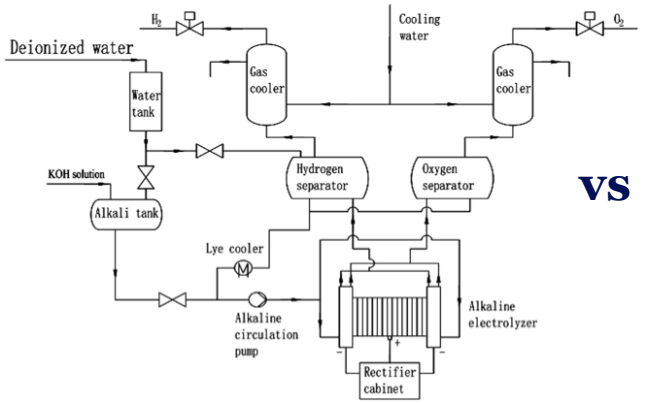
Different kinds of scenarios

Broad (global) scenarios

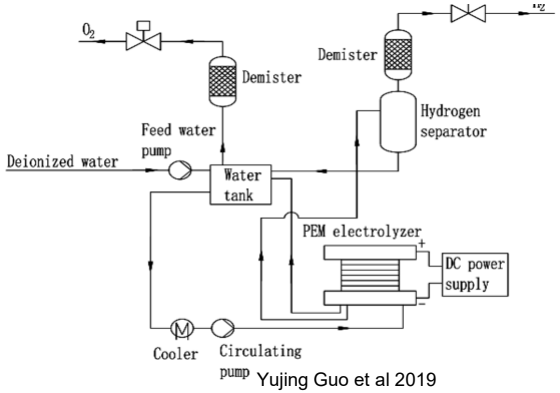
- For the global economy
- Relevance for prospective LCAs in general
- **Background scenarios**

Narrow (local) scenarios

- For specific technologies
- Limited to a specific prospective LCA
- **Foreground scenarios**



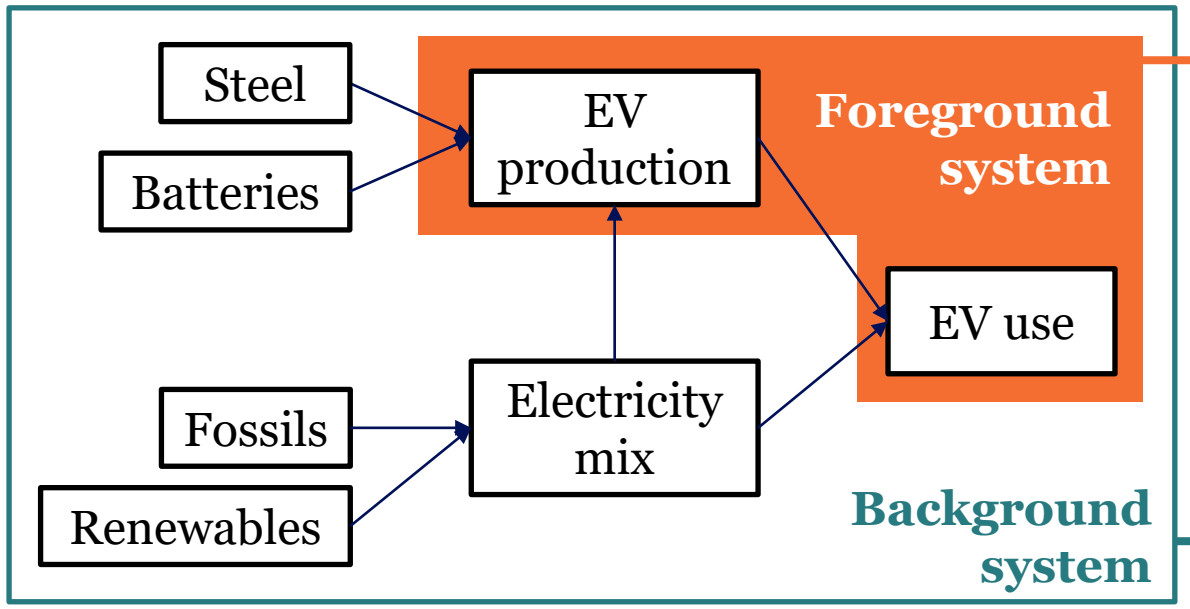
vs



Yujing Guo et al 2019

Foreground and background scenarios

A car manufacturer wants to make an LCA for an EV (electric vehicle) *in 2030*:



Foreground scenarios:

*How will the **EV** of 2030 look like?*
How will it be used?

Background scenarios:

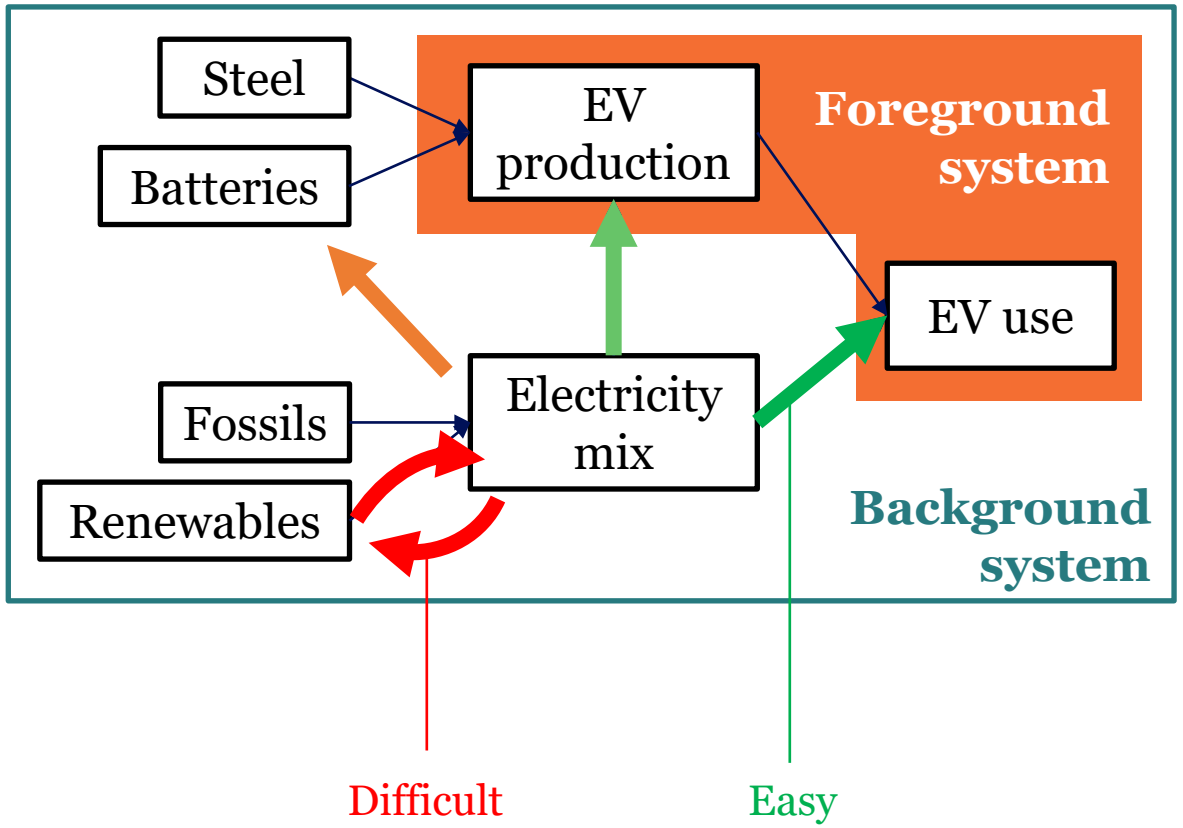
*How will supply chains in the wider **economic system** of 2030 look like?*

- Important, but difficult to consider
  (at least by individual stakeholders)

Our economy is deeply interlinked!

- E.g. Electricity mix affects:
  - EV use
  - EV production
  - Materials / components production
- But greener raw materials also improve electricity mix *and most other products*!
  - Feedback loops

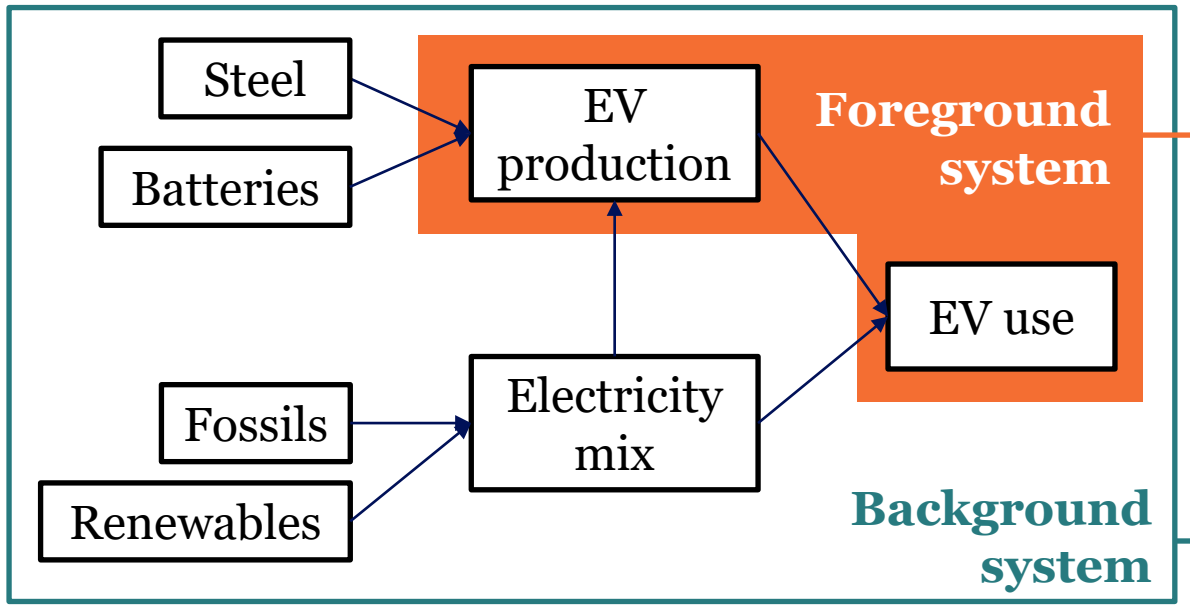
➔ Broad future (background) scenarios help LCA practitioners to consider the combined effect of future changes



to model for an LCA practitioner

Narrative consistency

A car manufacturer wants to make an LCA for an EV (electric vehicle) *in 2030*:



optimistic

optimistic

?

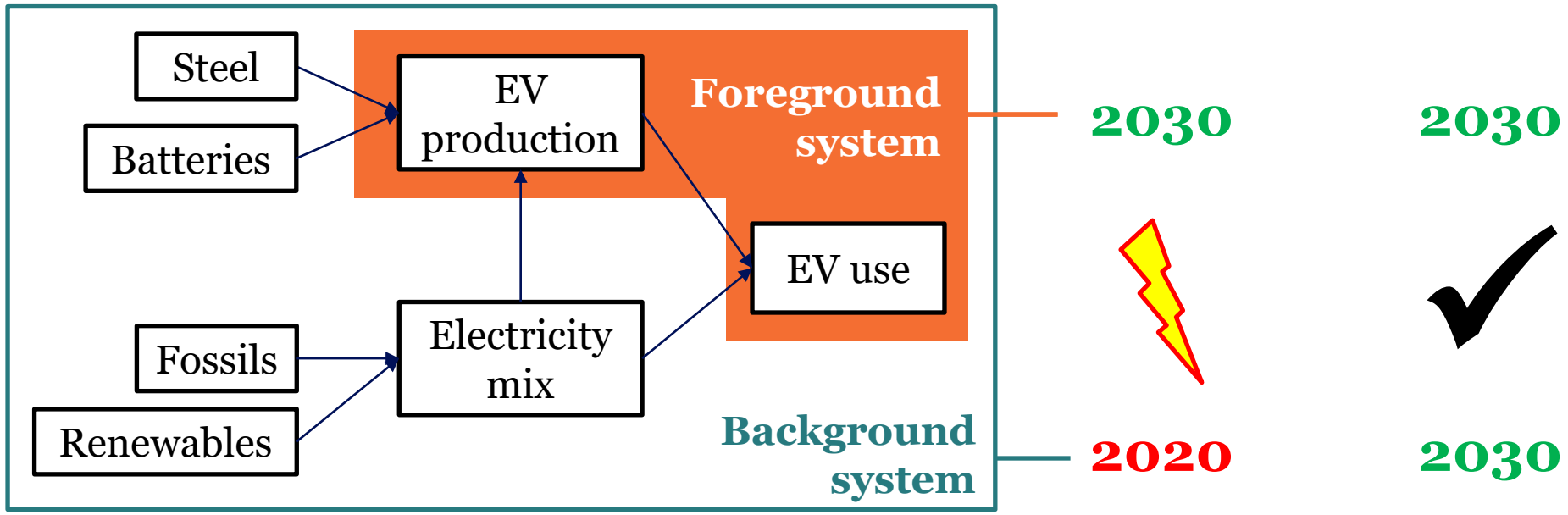
✓

pessimistic

optimistic

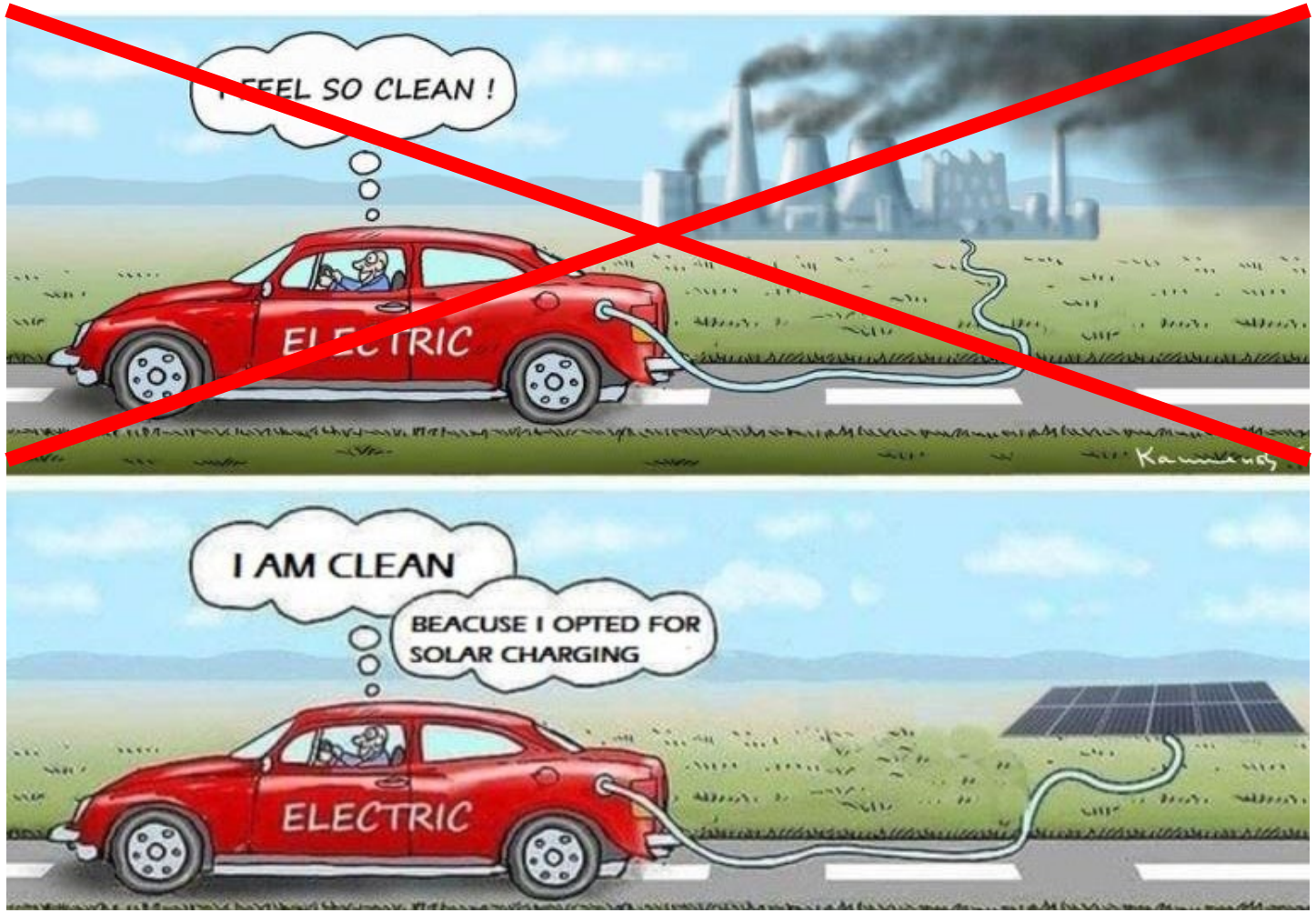
Temporal consistency

A car manufacturer wants to make an LCA for an EV (electric vehicle) *in 2030*:




McLAIN BUILDING
Peoples Feder
SAVINGS
& Loan Associati
WESTERN UNION

Is this important?
Yes, the “background” matters for LCA results!



https://www.researchgate.net/figure/Electric-Vehicle-Vs-Diesel-Vehicle_fig4_344458370

LCA can be very influential for decision making and public opinion

We need to look at the future, not the past, in order to get a better idea on the potential of future technologies!

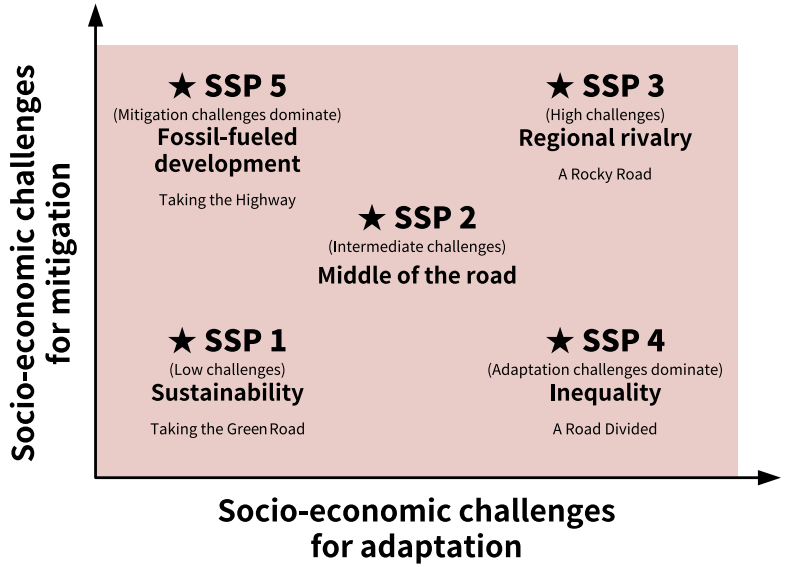
Terminology “pLCI database”

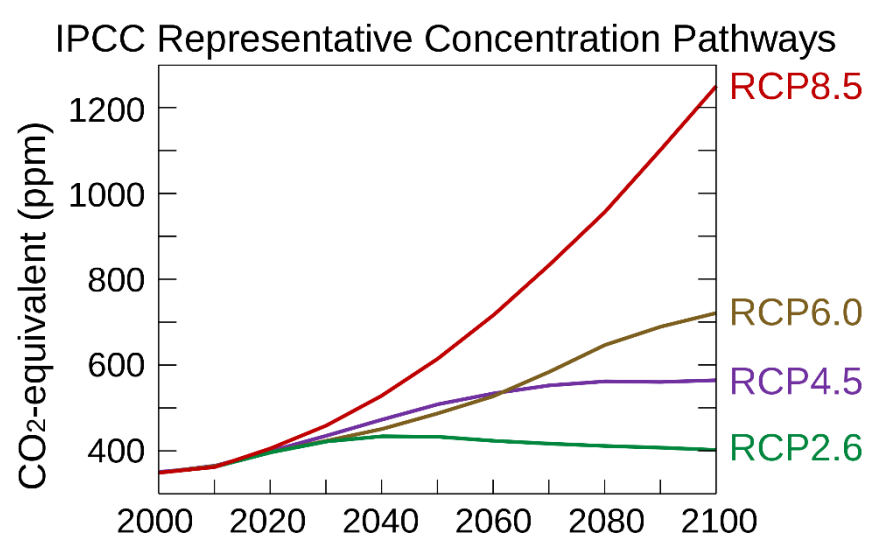
pLCI database = ***prospective life cycle inventory database***

The difference to a regular LCI database is that *it represents LCI data for a specific future point in time for a specific scenario*.

A short and incomplete history of pLCI databases

- NEEDS project (2004-2009)
  - First systematic approach to generate future scenarios of the ecoinvent database (electricity supply and other sectors)
- THEMIS model (Gibon 2015; Hertwich 2015)
  - Hybrid (MRIO-LCA) model including IEA energy and NEEDS scenarios
- "When background matters" (Mendoza 2018)
  - Combine data from the integrated assessment model IMAGE and ecoinvent (focus electricity supply)
  - IAMs model SSPs (Shared Socio-economic Pathways) and RCPs (representative concentration pathways)
  - python package for systematic modifications of LCI databases (wurst)
- Premise (Sacchi 2022)
  - python package for generating pLCI databases (premise)
  - Strongly based on IAM data (IMAGE, REMIND)
  - Electricity and additional sectors





Integrated Assessment Models (IAMs)

Global regionalized models that consider broad socio-economic and technological developments and their consequences over time.

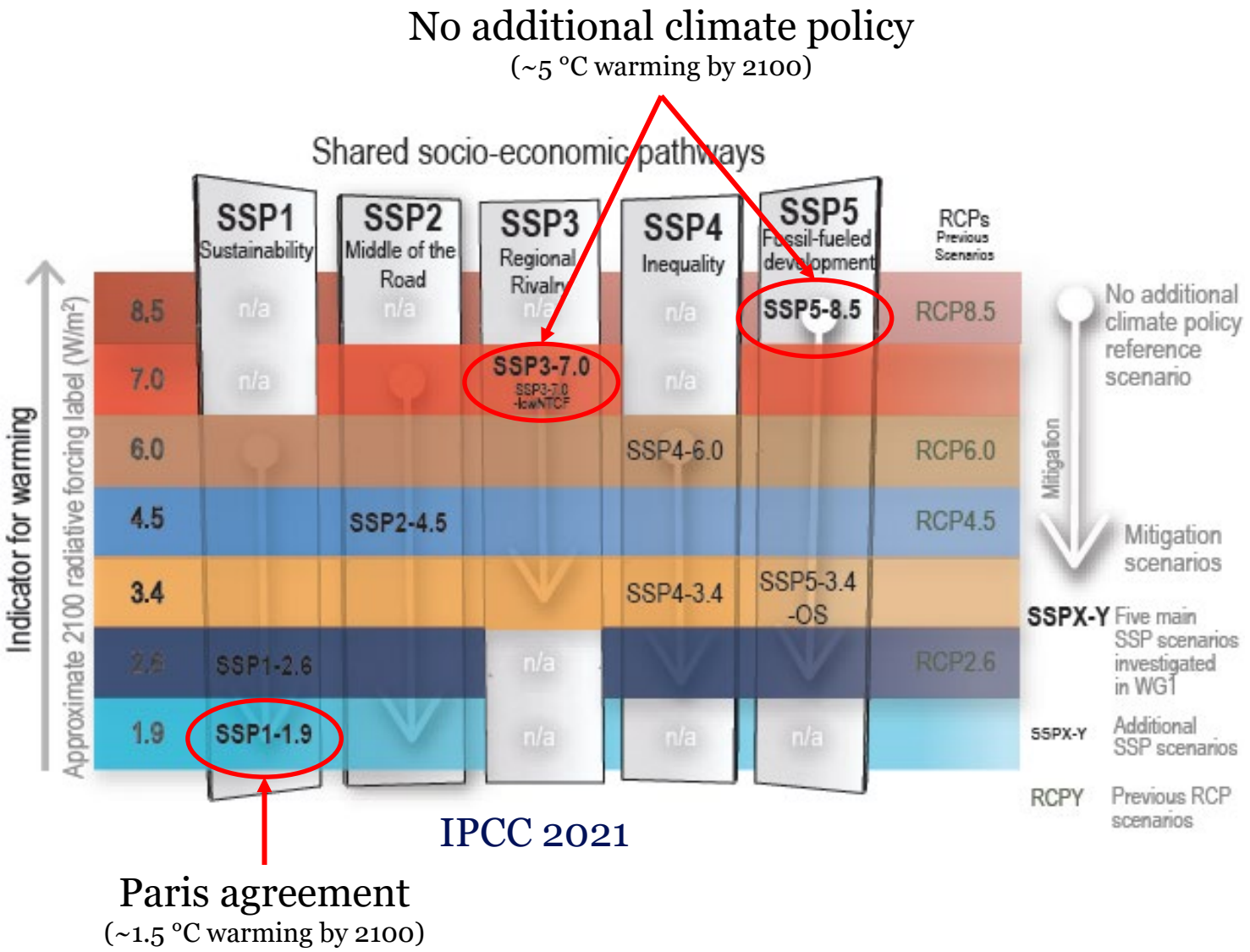
Used to inform policy makers on climate change and other environmental or socio-economic criteria.

Key drivers:

- Population
- GDP
- Food demand
- Technological development
- Etc.

Scenarios:

- Shared-Socioeconomic Pathways (SSPs)
- Representative Concentration Pathways (RCPs)



Premise (Sacchi 2022)

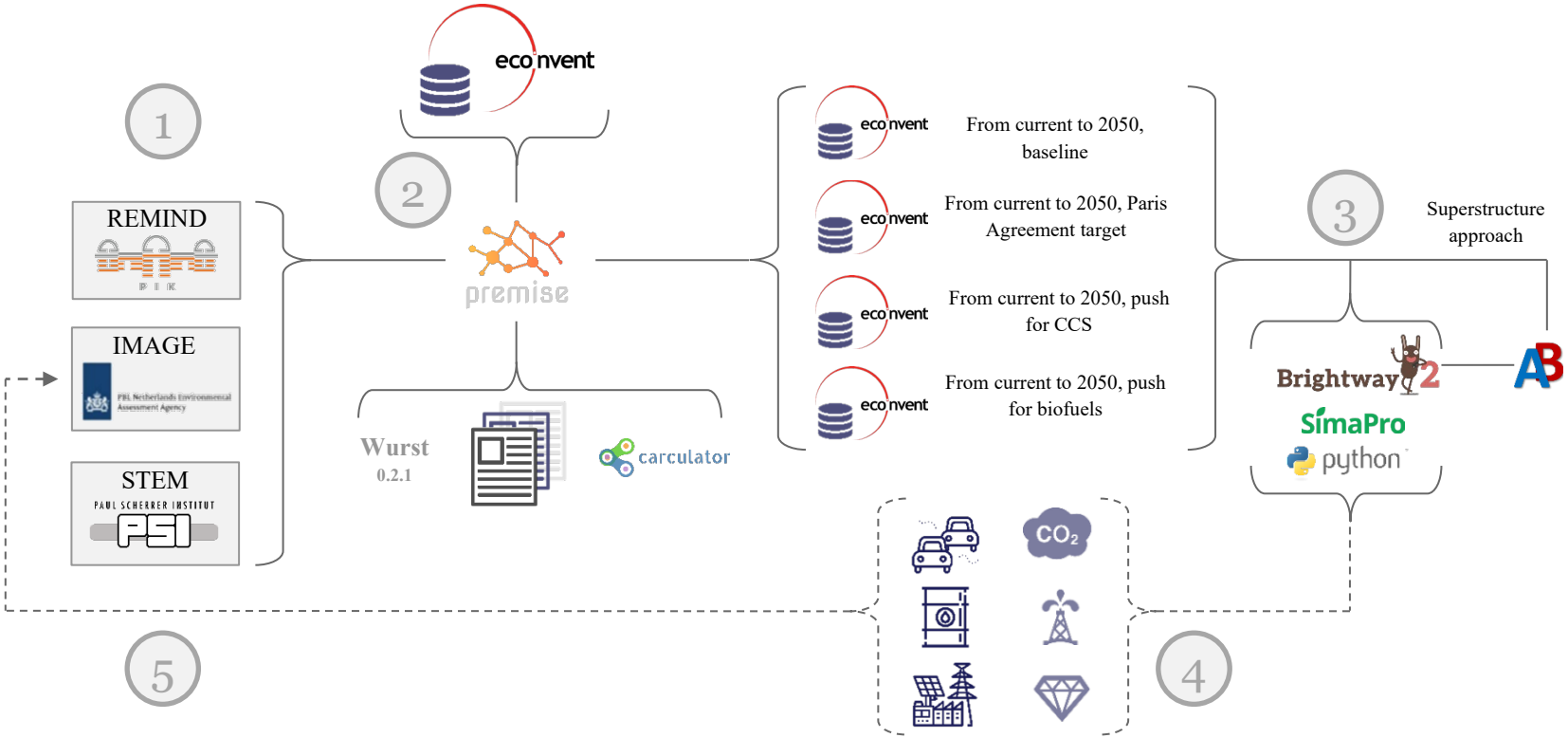
Steps

1) Input data: future scenarios from IAMs and the LCI database ecoinvent

2) Integration of future scenario data with the LCI database via premise

3) Export of pLCI databases in various formats

4 & 5) optional feedback of environmental indicators to IAMs



3 IMAGE and 5 REMIND scenarios are available (until 2100)

Figure based on *Sacchi 2022*

Open-source python packages

- **Brightway**: LCA framework
- **Wurst**: systematic transformations of LCI databases *[based on brightway]*
- **Premise**: integration software for IAM (and other) data with LCI databases *[based on wurst]*
- **Superstructure approach**: conversion of multiple LCI databases into a single LCI database (superstructure) and a scenario difference file *[based on brightway]*
- **Activity Browser**: graphical user interface to brightway; implements "scenario-LCA" based on superstructure approach *[based on brightway]*

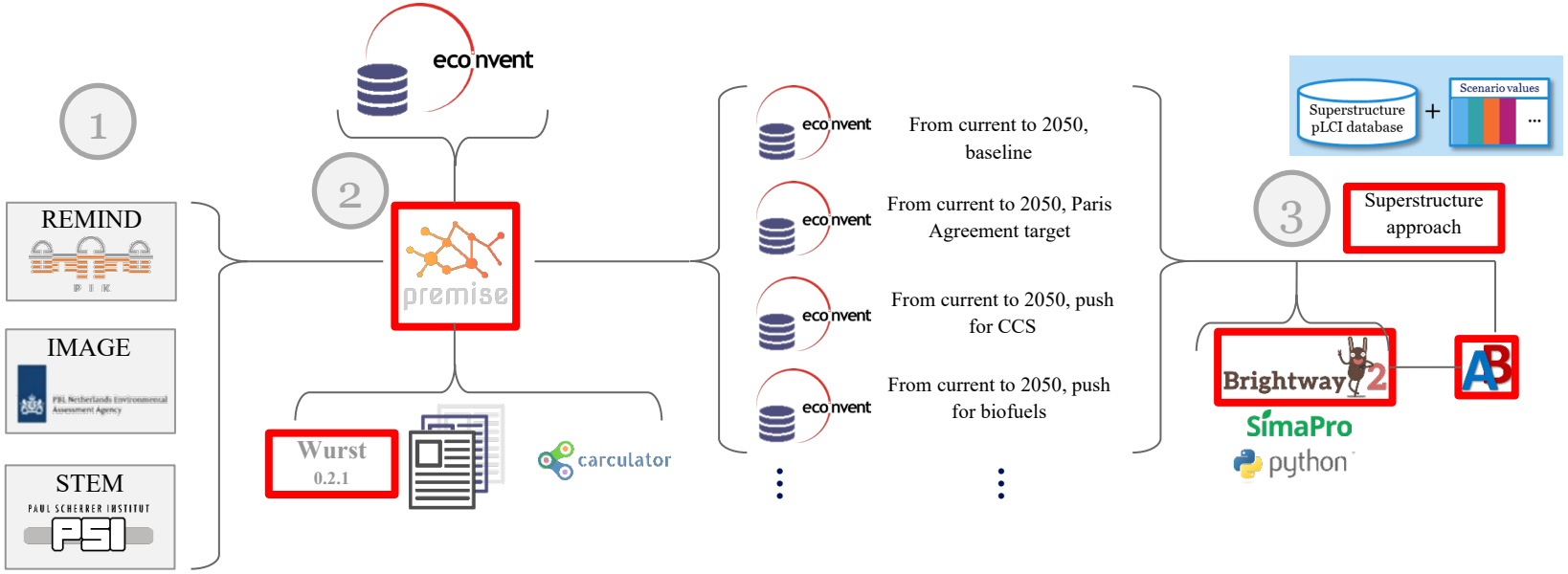


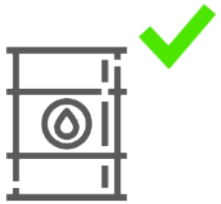
Figure based on *Sacchi 2022*

What does *premise* (try to) do?

Slide of Romain Sacchi

Power

Create regional electricity markets
Adjust power plant efficiency



Fuels

Create regional fuel markets
Add new production pathways (synthetic fuels)

Metals recycling

Adjust future recycled content

30%

Hot pollutant emissions

Adjust hot pollutant emission from GAINS

80%

Renewables

Adjust solar PV and wind turbines efficiency

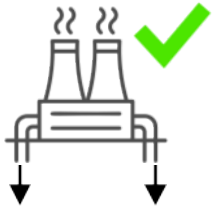
80%

Transport

Create market for passenger and freight road transport

Industry

Adjust efficiency for cement and steel production (fuel mix, process efficiency, material composition, etc.)

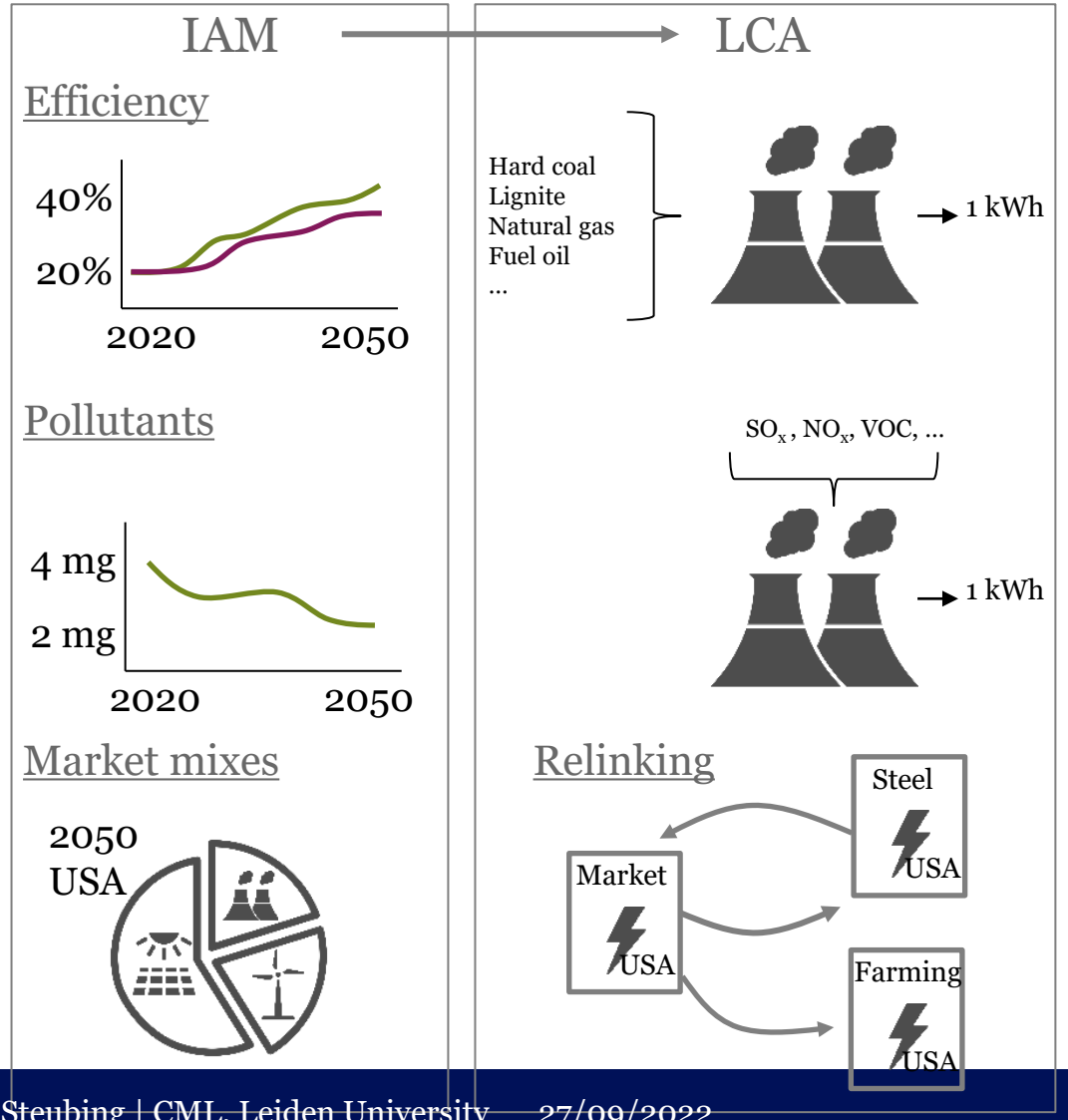


Carbon capture and storage

Add carbon capture and storage where needed

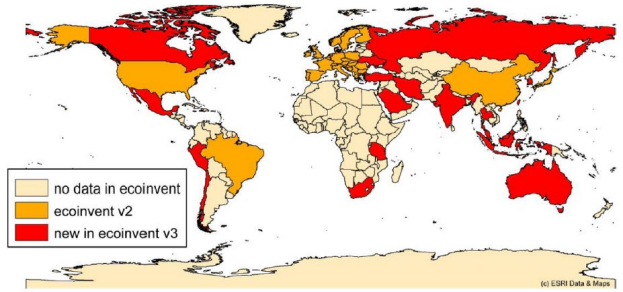
Example of transformation: power generation

Slide partly by Romain Sacchi



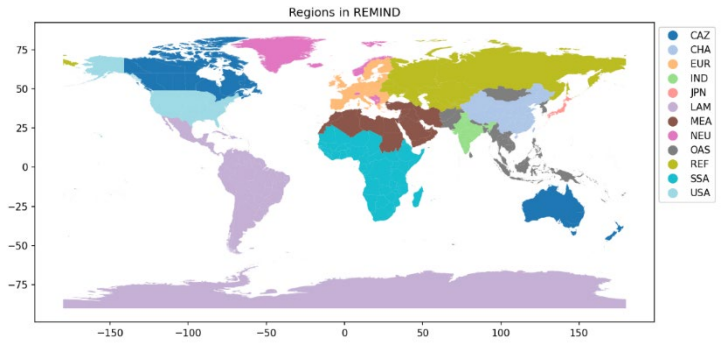
In a pLCI database, regions of transformed sectors are defined by the IAM

Regions in ecoinvent



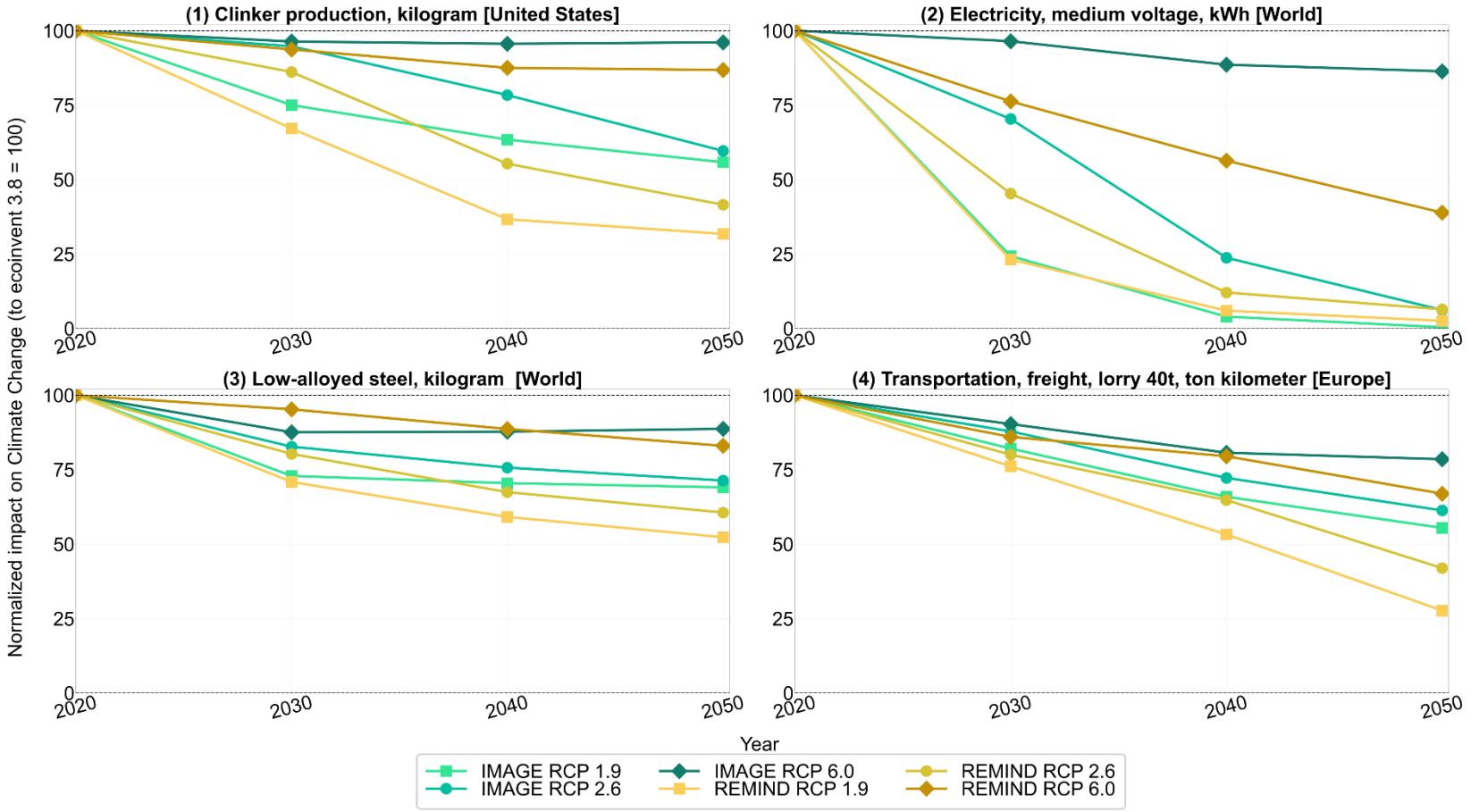
Treyer 2016

Regions in an IAM



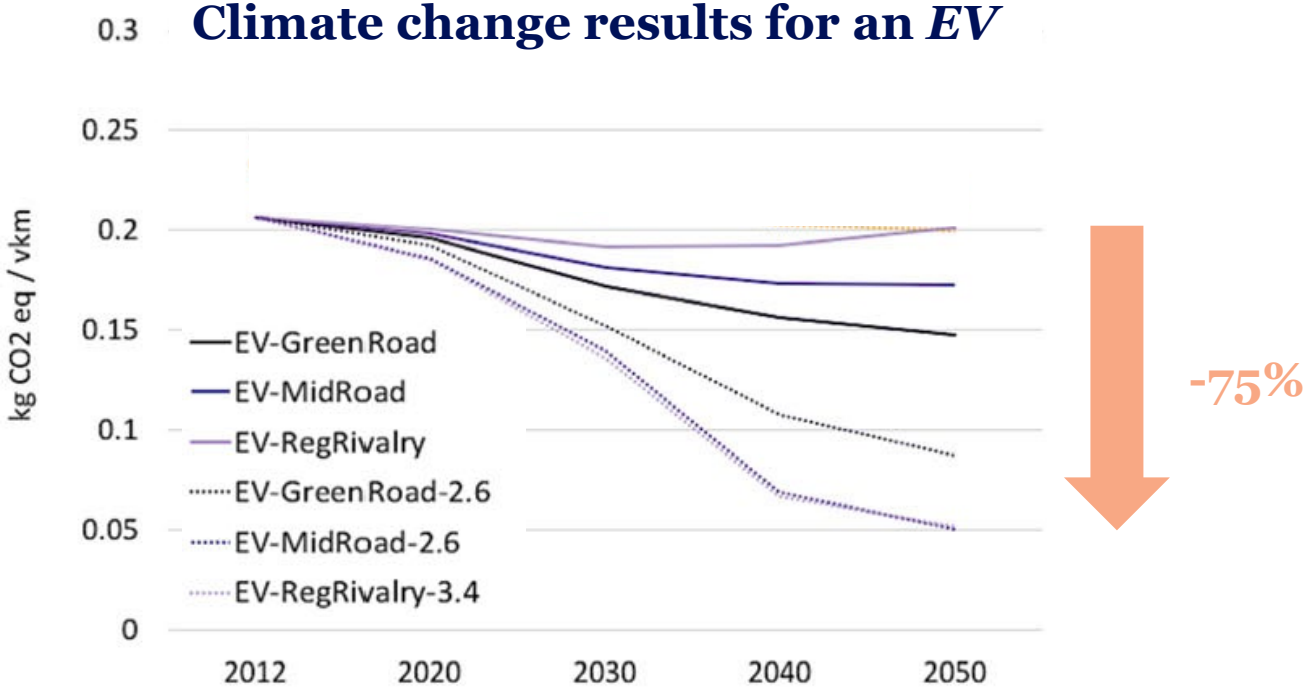
Is this important? Electricity (Sacchi 2022, based on premise)

- Substantial impact reductions across sectors
- Much is due to lower GHG per kWh of electricity and electrification
- Results strongly depend on the scenario and the IAM



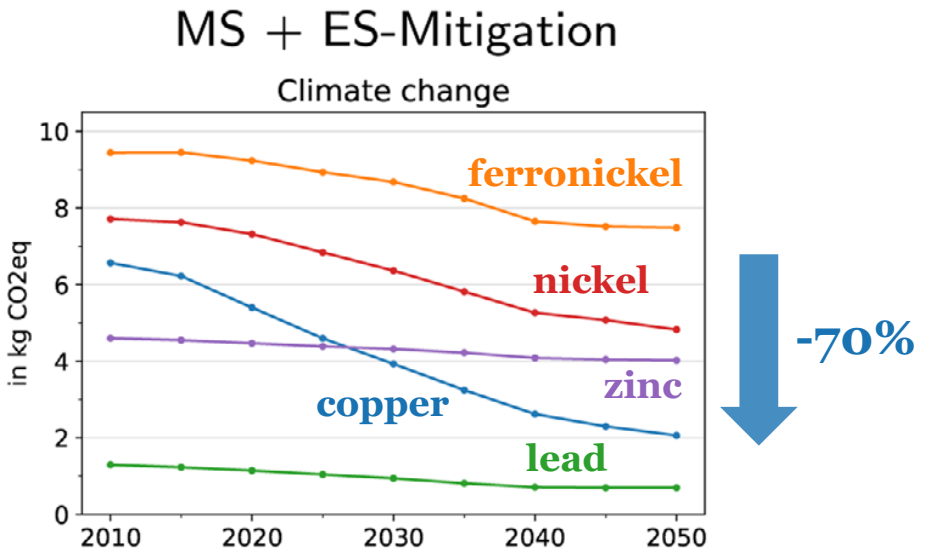
Electric vehicles and Metals
(based on Mendoza 2018)

Climate change results for an *EV*



Mendoza 2018

Climate change results for *metals*



Harpprecht 2021
Based on Mendoza 2018

Mobility: lithium-ion batteries

(from *Xu 2022*, based on premise, Harpprecht 2021, and Meide 2022)

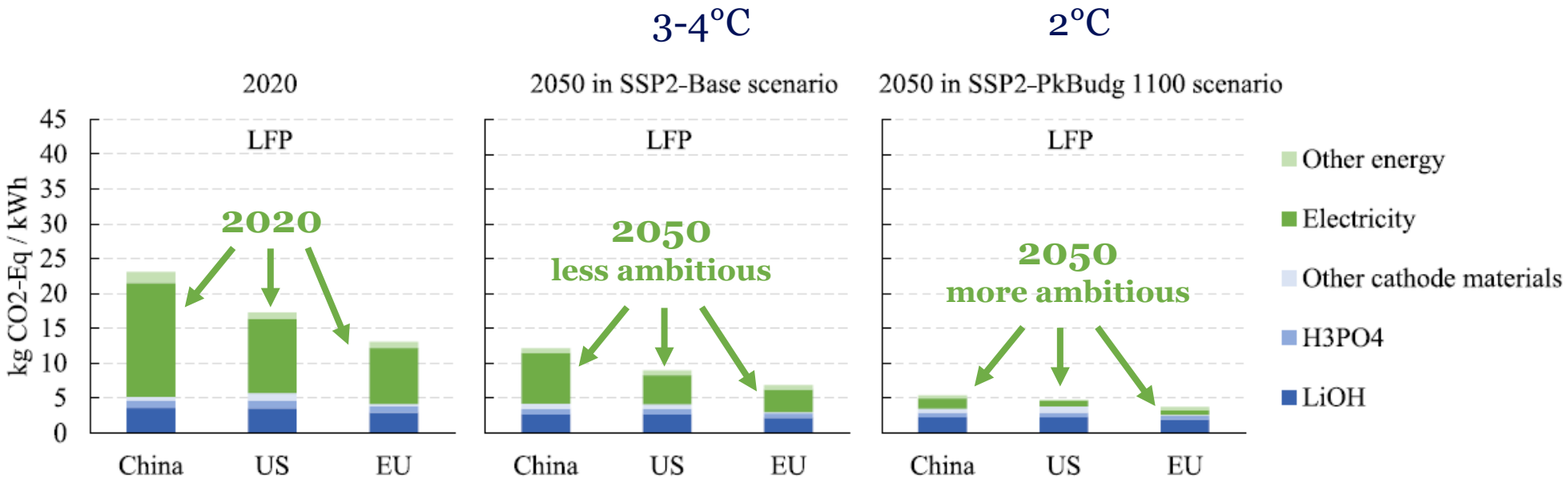


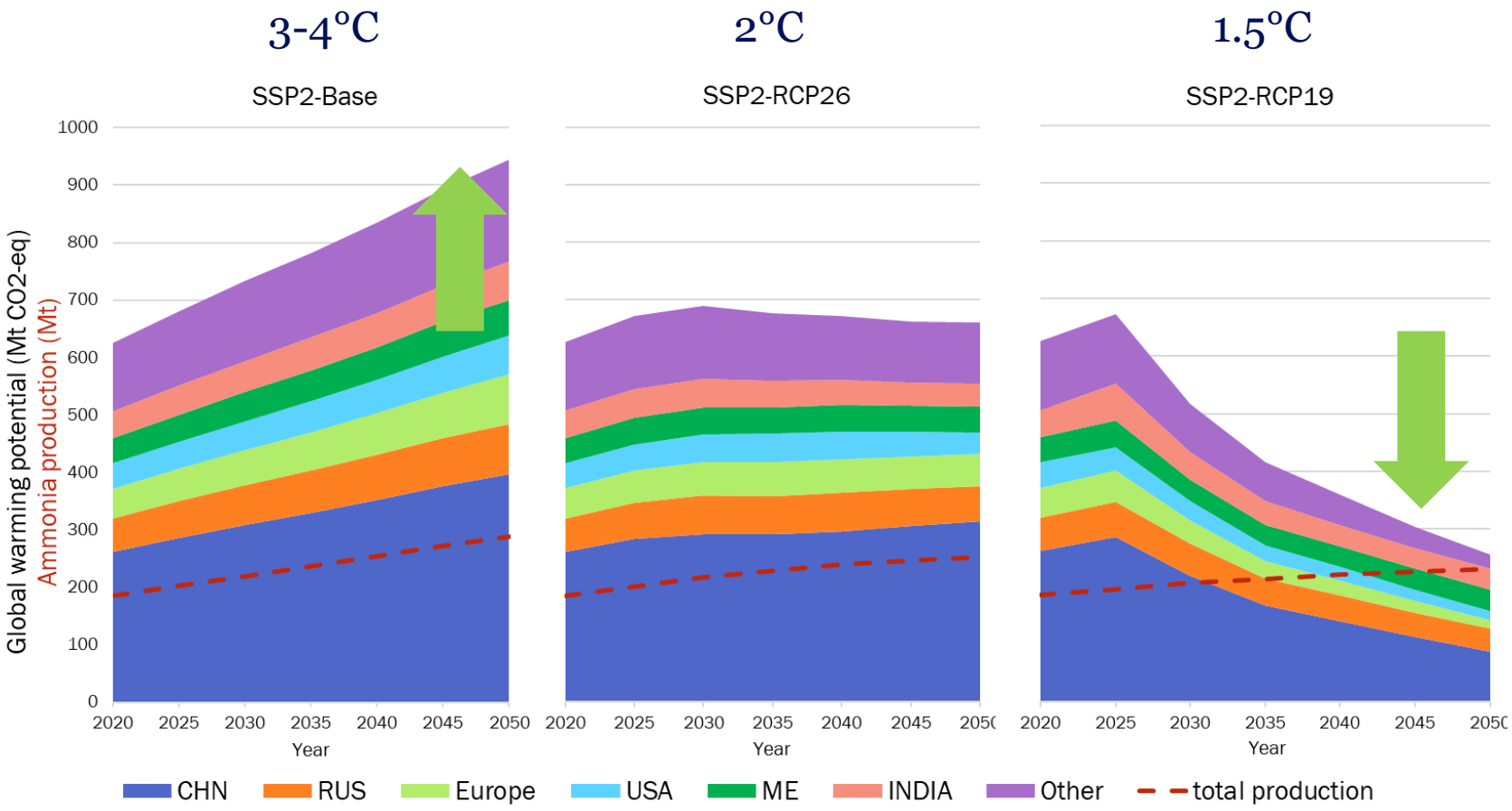
Fig. 6. Absolute contribution analysis of GHG emissions of the cathode production split by materials and energy, in terms of 1 kWh battery cell capacity.

- The decarbonization of the energy supply plays a crucial role
- (the change of future metal supply chains had a smaller effect in our study)

Chemicals: ammonia production
(Boyce in prep, based on premise)

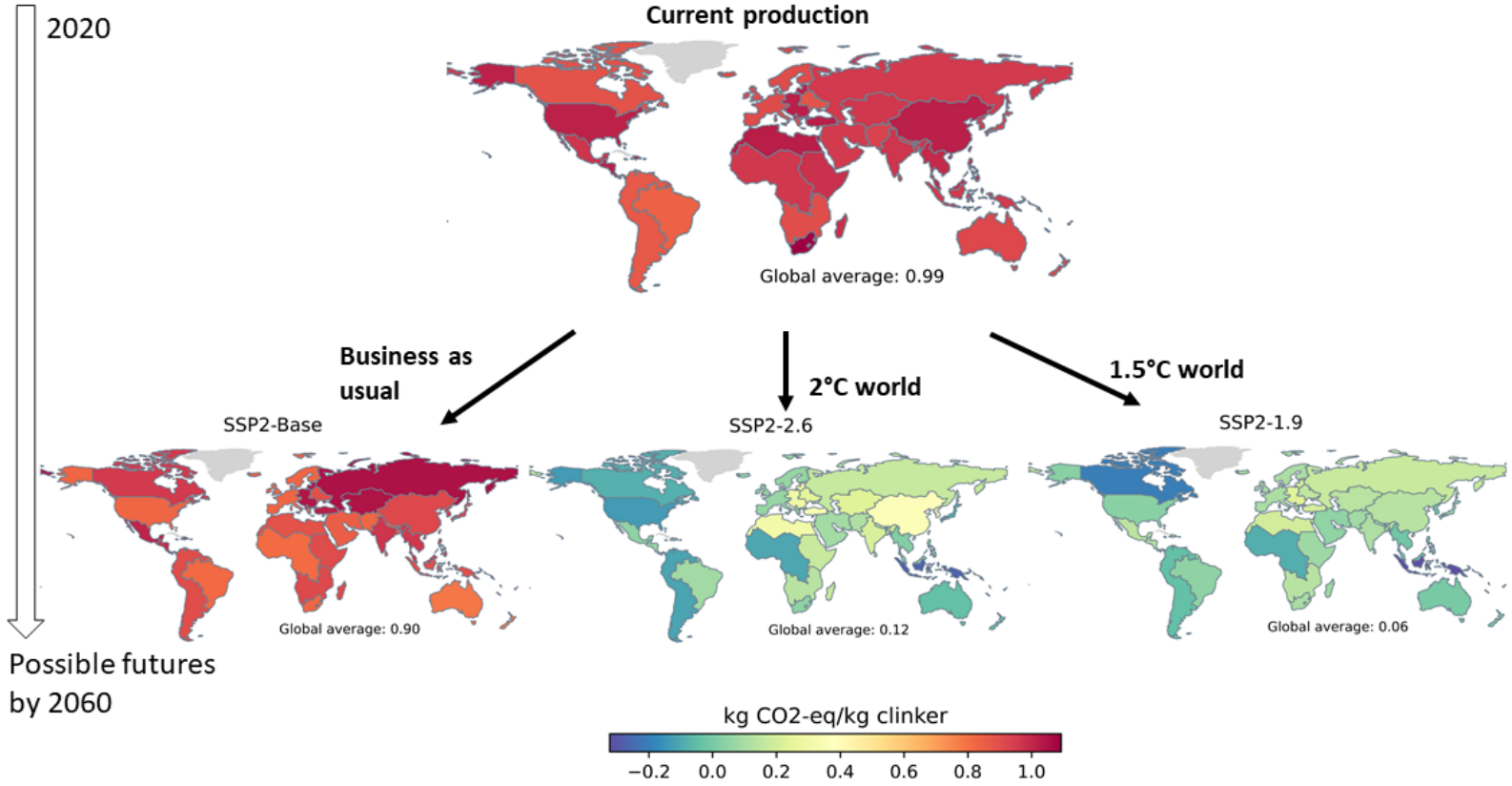
- GHG emissions from global ammonia production can be substantially lowered

- Key factors:
  - future demand
  - supply of clean electricity
  - shift to green hydrogen
  - CCS



Bulk materials: cement production
(Müller in prep, based on premise)

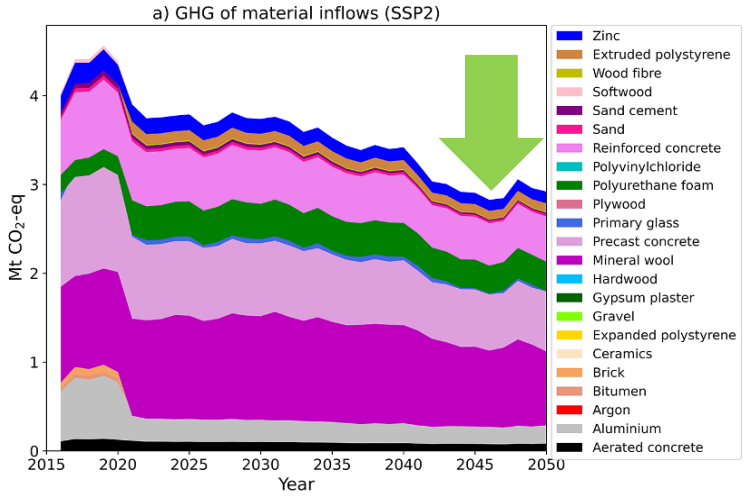
- GHG emissions from global cement production may be substantially lower in the future
- CCS is a major factor in this (next to electricity) and so there is considerable uncertainty to these results
- There may also be trade-offs with other environmental impact categories

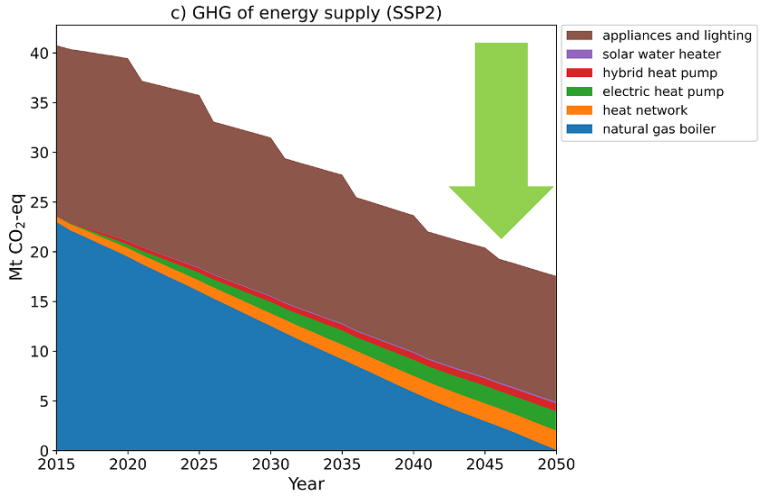


Building stock
(Yang 2022, based on premise)

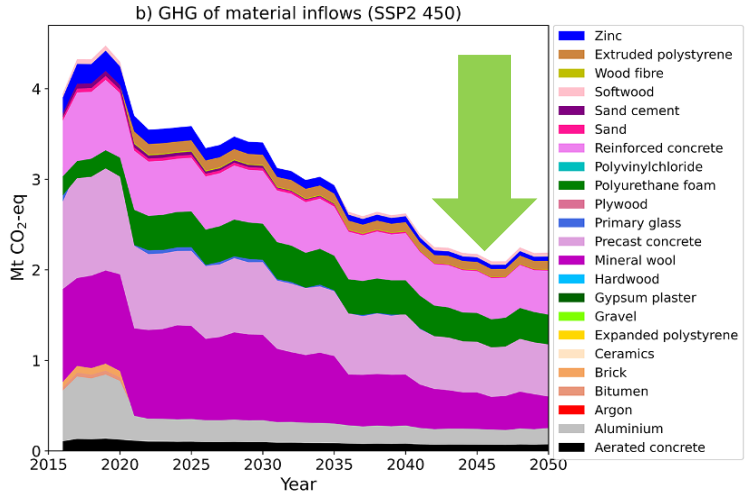
- Notable reduction of GHG of building materials by 2050 through cleaner electricity
- Substantial reduction of operational energy related GHG emissions

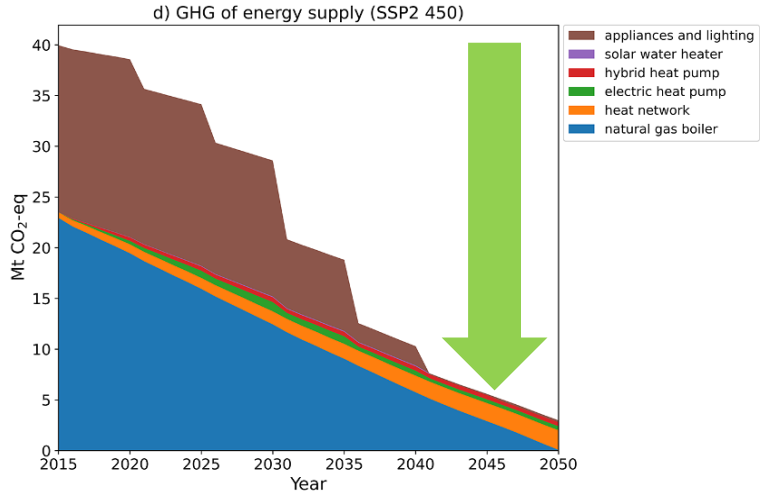
3-4°C





2°C





Growing list of work that makes use of and/or contributes to pLCI databases

Application sector	Studies	pLCI database	Contribution to premise?
Passenger cars, BEVs, heavy duty vehicles	Cox 2018, Cox 2020; Dirnaichner, 2022; Sacchi 2021; Sacchi 2022	Mendoza 2018 Premise	yes
Metal supply (Cu, Ni, Zn, Pb; Co)	Harpprecht 2021; Meide 2022	Mendoza 2018	
EV batteries	Xu 2022	Premise	Possibly
Offshore wind power	Li 2022	Premise	
Building stock	Zhong 2021 Yang 2022	Mendoza 2018 premise	
Ammonia	Boyce in prep	Premise	Yes
Cement	Müller in prep; Cavalet 2022 (more ongoing)	Premise	Planned
Heat supply	Myridinas in prep	Premise	Possibly
Hydrogen production	Wei in prep	Premise	Possibly
Electric aircrafts	Strathoff 2022	Premise	
Biofuels for ships	Watanabe 2022	Premise	
Electricity supply	Gibon 2022	Premise	

See also references slide

Challenges
for
pLCI databases

www.welt.de%2Fvermischtes%2Farticle132060329%2FSo-kann-jeder-die-Eiger-Nordwand-hochsteigen.html

Sectoral coverage

Challenge:

- Sectoral coverage
- Environmental coverage
- Consistency vs. quality
- Harmonization and acceptance
- Sharing
- Use in LCA software
- Interpretation

Current premise scenarios include:

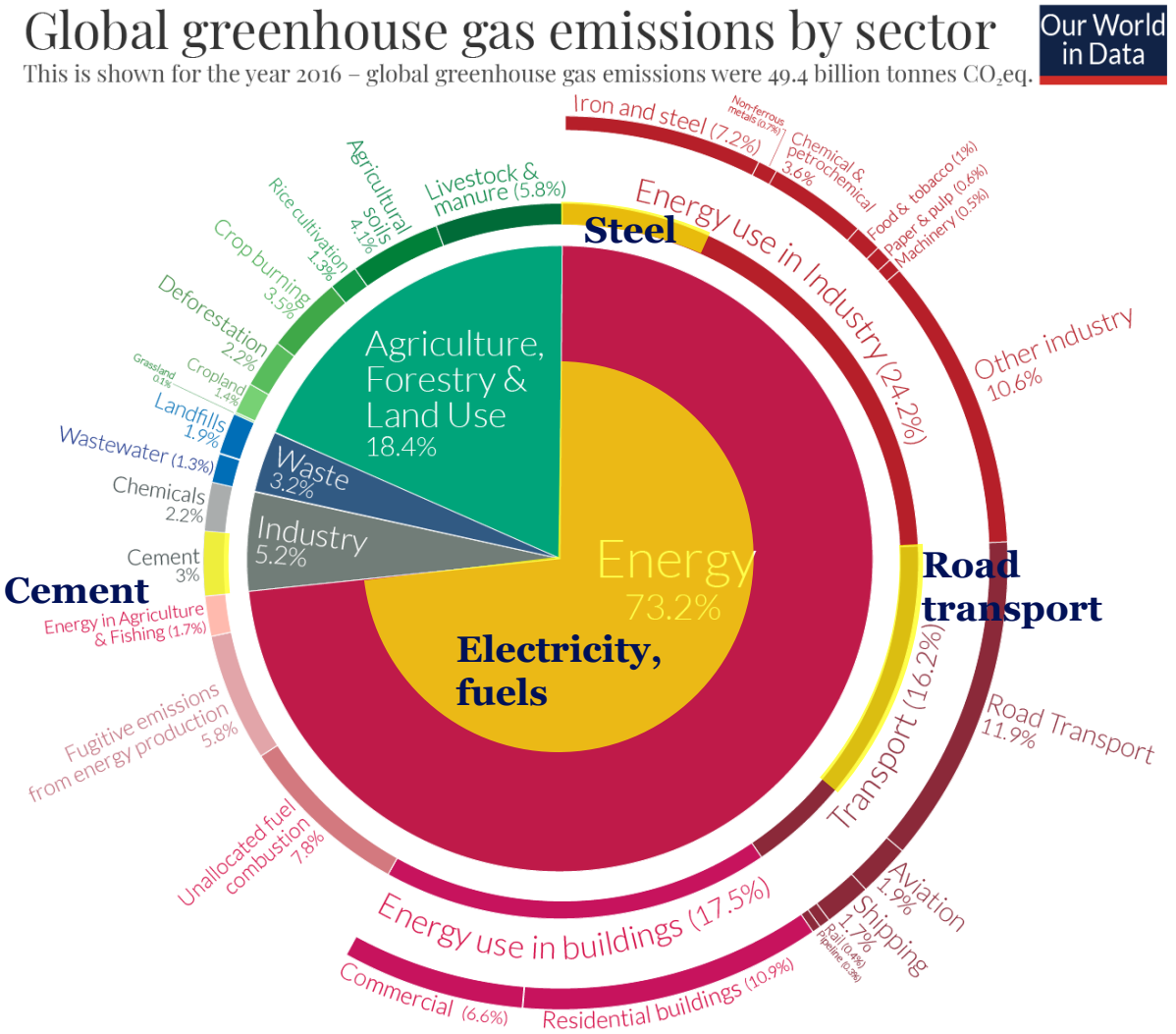
- Energy production: electricity, fuels
- Energy use in industry: cement, steel
- Transport: trucks, cars, buses, two-wheelers

Ongoing development:

- Ammonia, heat, cement, metals, hydrogen, …

Important sectors **missing**:

- Many raw materials, metals
- Chemicals
- Agriculture, food, forestry, bioeconomy
- Circularity: reuse, recycling, re…



https://ourworldindata.org/emissions-by-sector

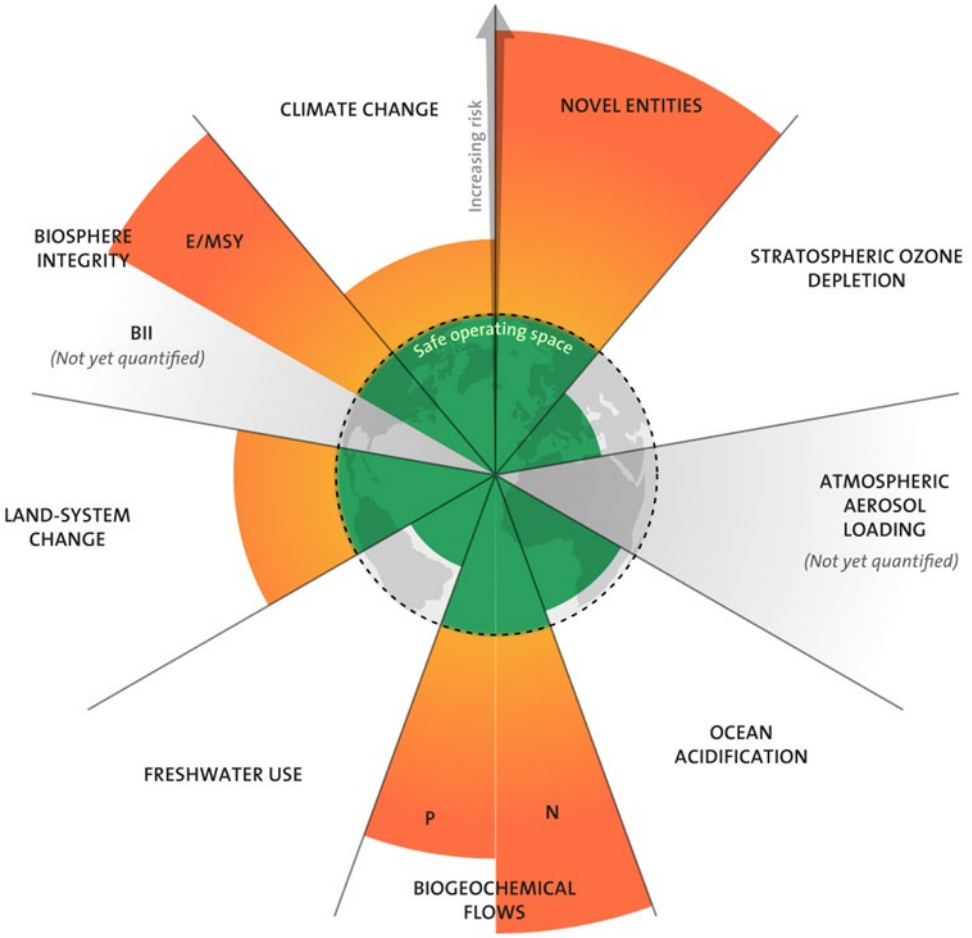
Environmental coverage

Challenge:

- Sectoral coverage
- Environmental coverage
- Consistency vs. quality
- Harmonization and acceptance
- Sharing
- Use in LCA software
- Interpretation

- While current pLCI databases can be used for full LCIA, they are generated with a focus on climate change
- More attention should in the future be given to other impact categories
- Prioritization based on planetary boundaries?

Planetary Boundaries



Designed by Azote for Stockholm Resilience Centre, based on analysis in Persson et al 2022 and Steffen et al 2015. https://www.stockholmresilience.org/research/research-news/2022-01-18-safe-planetary-boundary-for-pollutants-including-plastics-exceeded-say-researchers.html

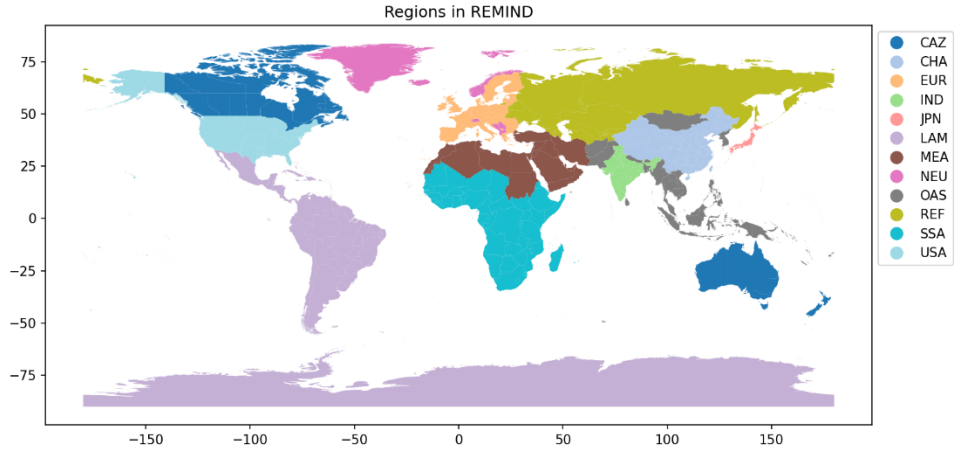
Consistency vs quality/detail

Challenge:

- Sectoral coverage
- Environmental coverage
- Consistency vs. quality
- Harmonization and acceptance
- Sharing
- Use in LCA software
- Interpretation

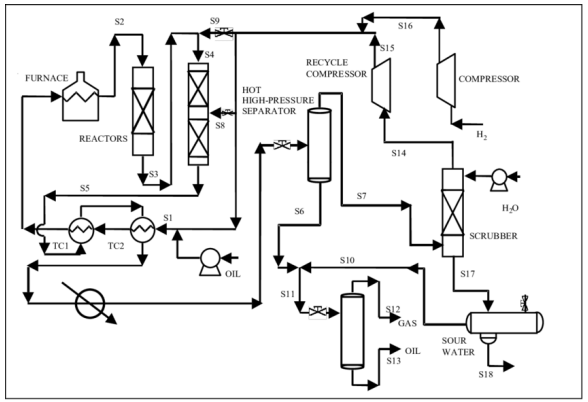
- Scenario data should be:
  - as **consistent** as possible
  - as **good** as possible
- But: there is no single consistent data source that covers everything at sufficient technical detail
- Solution: use additional data sources
- Better solution (?): improve IAMs with that data

Consistent (e.g. IAMs)



VS

Good (specific datasets)



Harmonization and acceptance

Challenge:

- Sectoral coverage
- Environmental coverage
- Consistency vs. quality
- Harmonization and acceptance
- Sharing
- Use in LCA software
- Interpretation

- Diversity of scenarios is scientifically interesting
- But harmonization is to be strived for to make cross-comparisons easier
- Perhaps the way forward is to have a smaller set of well-developed and accepted scenarios

https://www.c2ccertified.org/news/article/harmonization-of-material-health-tools-leaps-forward

Sharing

Challenge:

- Sectoral coverage
- Environmental coverage
- Consistency vs. quality
- Harmonization and acceptance
- Sharing
- Use in LCA software
- Interpretation

- Public sharing of pLCI databases currently hindered by licensing restrictions
- Best solutions currently:
  - "Local generation" via python code
  - Sharing on demand
- We need easier solutions to reach normal LCA practitioners

https://www.nbs.net/articles/making-the-sharing-economy-sustainable

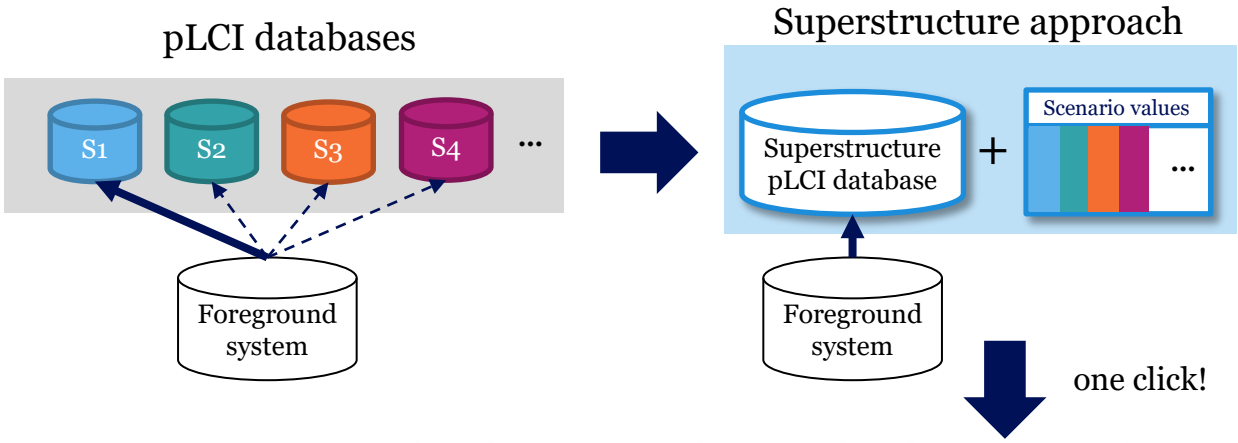
Use in of pLCI databases in LCA software

Challenge:

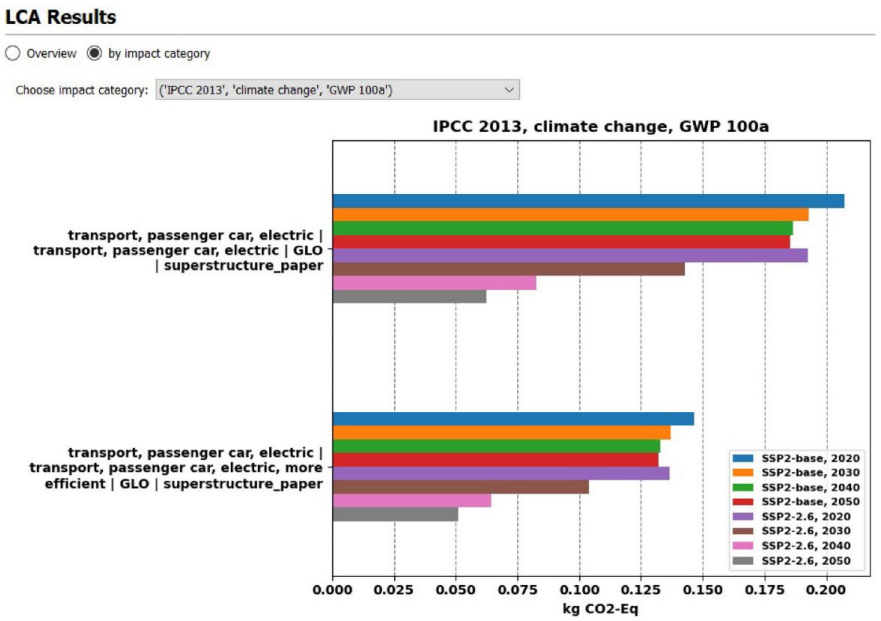
- Sectoral coverage
- Environmental coverage
- Consistency vs. quality
- Harmonization and acceptance
- Sharing
- Use in LCA software
- Interpretation

- Practical obstacle: dealing with *multiple* background systems (representing different scenarios and years)
- *LCA software should enable users to «switch» the background scenario and perform scenario LCAs in a simple way*
- Possible solution: Superstructure approach (Steubing and Koning 2021)

How to deal with multiple background systems?



Implemention in the Activity Browser



Interpretation

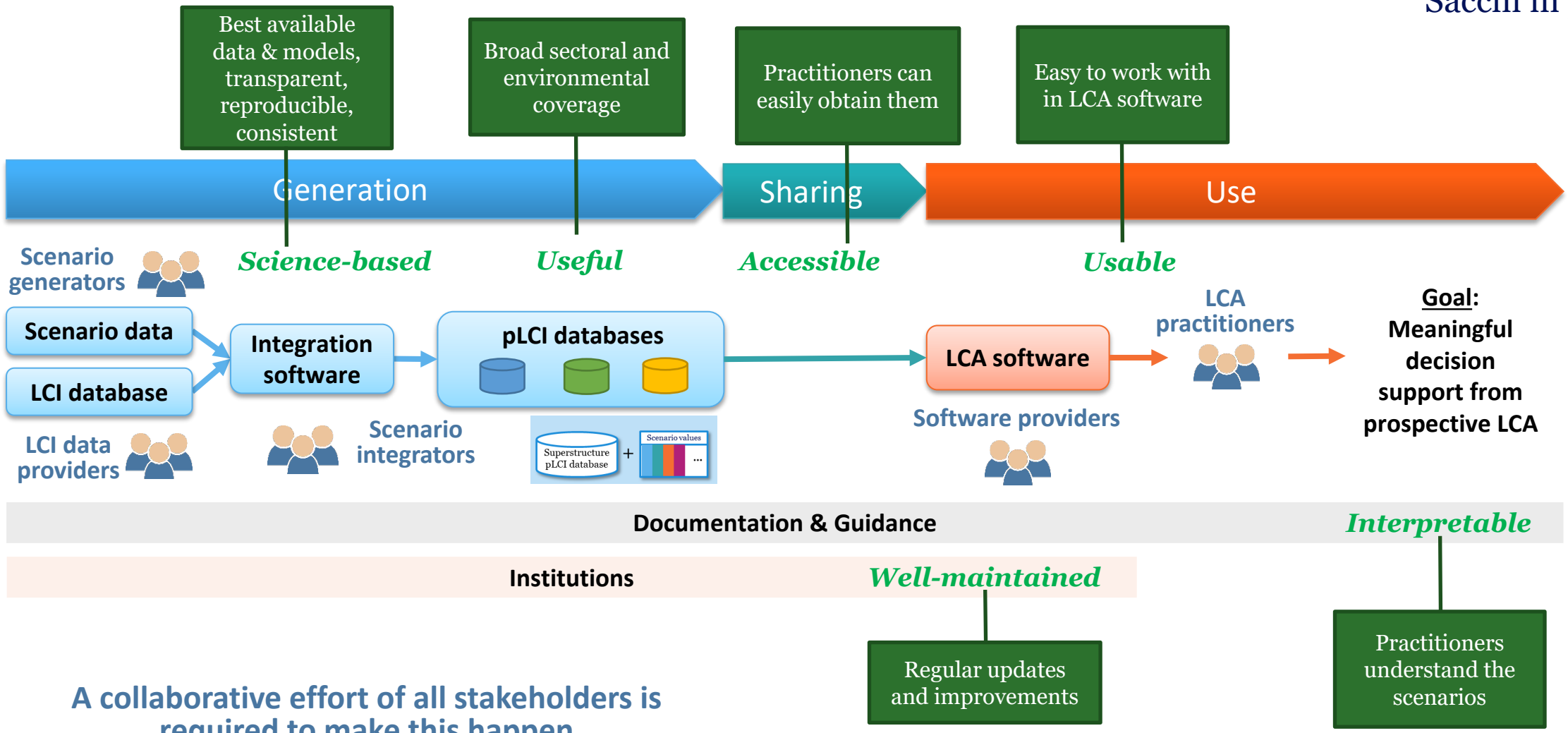
Challenge:

- Sectoral coverage
- Environmental coverage
- Consistency vs. quality
- Harmonization and acceptance
- Sharing
- Use in LCA software
- Interpretation

- LCA practitioners need to understand
  - What BG scenarios represent
  - What their limitations are
- In order to correctly interpret and communicate LCA results
- LCA practitioners need guidance for that

Vision: "Qualities" of pLCI databases

Steubing, Mendoza, Sacchi in prep



Conclusions

- Good scenarios really matter! For LCA results, for stakeholder opinions and for decision making. Important to get this right!
- The systematic generation of pLCI databases is an exciting and important development for prospective LCA
- pLCI databases are increasingly being used (at least in academia)
- Lots of work remains to improve these databases and make them ready for a wider use in LCA practice – collaborative effort needed

Links to open-source tools

- *Brightway2* (LCA framework): https://github.com/brightway-lca
- *Activity-Browser* (GUI for Brightway): https://github.com/LCA-ActivityBrowser/activity-browser
- *Brightway-superstructure* (superstructure approach): https://github.com/LCA-ActivityBrowser/brightway-superstructure
- *premise* (IAM-LCA coupling): https://github.com/polca/premise
- *wurst* (systematic transformation of LCA databases): https://github.com/polca/wurst

Selected references

Methodology

- Sacchi R, Terlouw T, Siala K, Dirnaichner A, Bauer C, Cox B, Mutel C, Daioglou V, Luderer G (2022) PRospective EnvironMental Impact asSEment (premise): A streamlined approach to producing databases for prospective life cycle assessment using integrated assessment models Renewable Sustainable Energy Rev 160:112311 doi:https://doi.org/10.1016/j.rser.2022.112311
- Mendoza Beltran A, Cox B, Mutel C, van Vuuren DP, Font Vivanco D, Deetman S, Edelenbosch OY, Guinée J, Tukker A (2018) When the Background Matters: Using Scenarios from Integrated Assessment Models in Prospective Life Cycle Assessment J Ind Ecol doi:10.1111/jiec.12825
- Steubing B, de Koning D (2021) Making the use of scenarios in LCA easier: the superstructure approach Int J Life Cycle Assess 26:2248-2262 doi:10.1007/s11367-021-01974-2

Use of broad future scenarios (list not comprehensive)

- Cox B, Mutel CL, Bauer C, Mendoza Beltran A, van Vuuren DP (2018) Uncertain Environmental Footprint of Current and Future Battery Electric Vehicles Environ Sci Technol 52:4989-4995 doi:10.1021/acs.est.8b00261
- Cox B, Bauer C, Mendoza Beltran A, van Vuuren DP, Mutel CL (2020) Life cycle environmental and cost comparison of current and future passenger cars under different energy scenarios Applied Energy 269:115021 doi:https://doi.org/10.1016/j.apenergy.2020.115021
- Harpprecht C, Oers L, Northey SA, Yang Y, Steubing B (2021) Environmental impacts of key metals' supply and low-carbon technologies are likely to decrease in the future J Ind Ecol 25:1543-1559 doi:10.1111/jiec.13181
- van der Meide M, Harpprecht C, Northey S, Yang Y, Steubing B (2022) Effects of the energy transition on environmental impacts of cobalt supply: A prospective life cycle assessment study on future supply of cobalt J Ind Ecol n/a doi:https://doi.org/10.1111/jiec.13258
- Li C, Mogollón JM, Tukker A, Dong J, von Terzi D, Zhang C, Steubing B (2022) Future material requirements for global sustainable offshore wind energy development Renewable Sustainable Energy Rev 164:112603 doi:https://doi.org/10.1016/j.rser.2022.112603
- Xu C, Steubing B, Hu M, Harpprecht C, van der Meide M, Tukker A (2022) Future greenhouse gas emissions of automotive lithium-ion battery cell production Resources, Conservation and Recycling 187:106606 doi:https://doi.org/10.1016/j.resconrec.2022.106606
- Zhong X, Hu M, Deetman S, Steubing B, Lin HX, Hernandez GA, Harpprecht C, Zhang C, Tukker A, Behrens P (2021) Global greenhouse gas emissions from residential and commercial building materials and mitigation strategies to 2060 Nature Communications 12:6126 doi:10.1038/s41467-021-26212-z
- Yang X, Hu M, Tukker A, Zhang C, Huo T, Steubing B (2022) A bottom-up dynamic building stock model for residential energy transition: A case study for the Netherlands Applied Energy 306:118060 doi:https://doi.org/10.1016/j.apenergy.2021.118060
- Dirnaichner, A. et al. Life-cycle impacts from different decarbonization pathways for the European car fleet. Environ. Res. Lett. 17, 044009 (2022).
- Sacchi, R., Bauer, C., Cox, B. & Mutel, C. When, where and how can the electrification of passenger cars reduce greenhouse gas emissions? Renew. Sustain. Energy Rev. 162, 112475 (2022).
- Sacchi, R., Bauer, C. & Cox, B. L. Does Size Matter? The Influence of Size, Load Factor, Range Autonomy, and Application Type on the Life Cycle Assessment of Current and Future Medium? The Heavy-Duty Vehicles. Environ. Sci. Technol. 55, 5224–5235 (2021).
- Ueckerdt, F. et al. Potential and risks of hydrogen-based e-fuels in climate change mitigation. Nat. Clim. Chang. 2021 115 11, 384–393 (2021).
- Watanabe, M. D. B., Cherubini, F. & Cavalett, O. Climate change mitigation of drop-in biofuels for deep-sea shipping under a prospective life-cycle assessment. J. Clean. Prod. 364, 132662 (2022).
- Gibon, T., Menacho, À. & Guiton, M. Carbon Neutrality in the UNECE Region: Integrated Life-cycle Assessment of Electricity Sources UNITED NATIONS ECONOMIC COMMISSION FOR EUROPE. https://unece.org/sites/default/files/2022-04/LCA_3_FINAL March 2022.pdf (2021).
- Cavalett, O., Watanabe, M. D. B., Fleiger, K., Hoenig, V. & Cherubini, F. LCA and negative emission potential of retrofitted cement plants under oxyfuel conditions at high biogenic fuel shares. Sci. Reports 2022 121 12, 1–14 (2022).
- Dávila, J., Sacchi, R. & Pizzol, M. Preconditions for CCUS to deliver climate neutrality in cement production. Appl. Energy.
- Lamers, P., Ghosh, T., Upasani, S., Sacchi, R. & Daioglou, V. 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. Environ. Sci. Technol.
- Strathoff, P. et al. On the Design and Sustainability of Commuter Aircraft with Electrified Propulsion Systems. AIAA Aviat. 2022 Forum (2022) doi:10.2514/6.2022-3738.

Thank you!
Questions?

b.steubing@cml.leidenuniv.nl

Universiteit Leiden
The Netherlands

This presentation is inspired by work of and exchange with great colleagues, e.g. **Romain Sacchi, Angelica Mendoza, Chris Mutel, Stefano Cucurachi, Jeroen Guinée, Carina Harpprecht, Marc van der Meide, Brenda Xicotencatl, Reinout Heijungs, Carlos Blanco Rocha, Paul Behrens, Sander van Nielen, and others…**