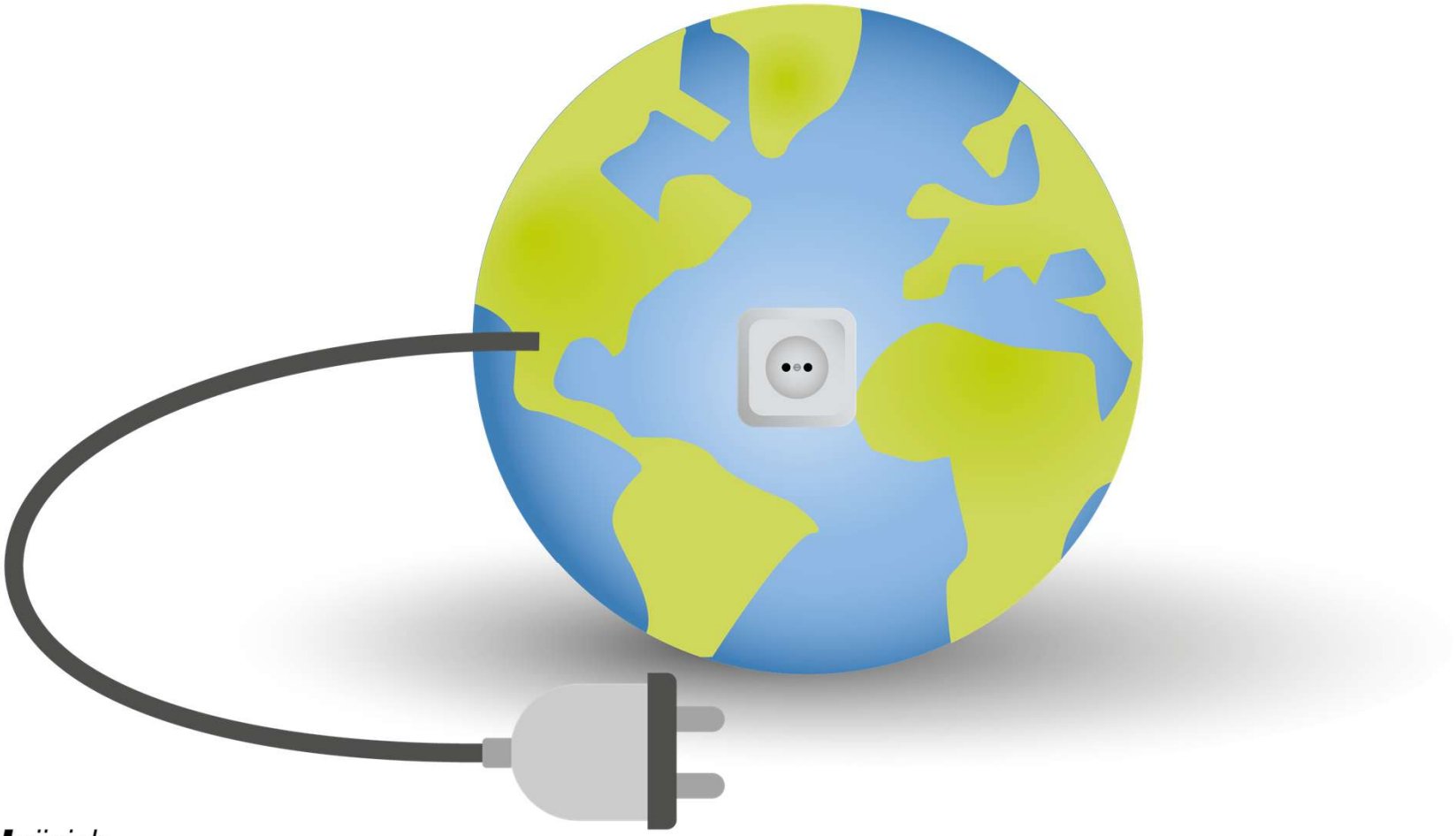
ETH zürich

epse
ENERGY & PROCESS SYSTEMS ENGINEERING

CO_2, Biomasse und Recycling: Wege zu einer Kreislaufwirtschaft innerhalb der planetaren Grenzen

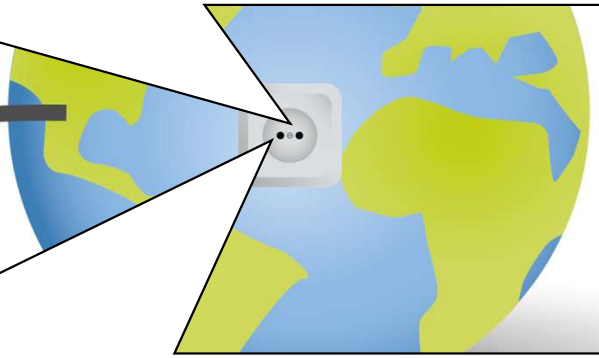
André Bardow
ETH Zürich

The vision: A sustainable world



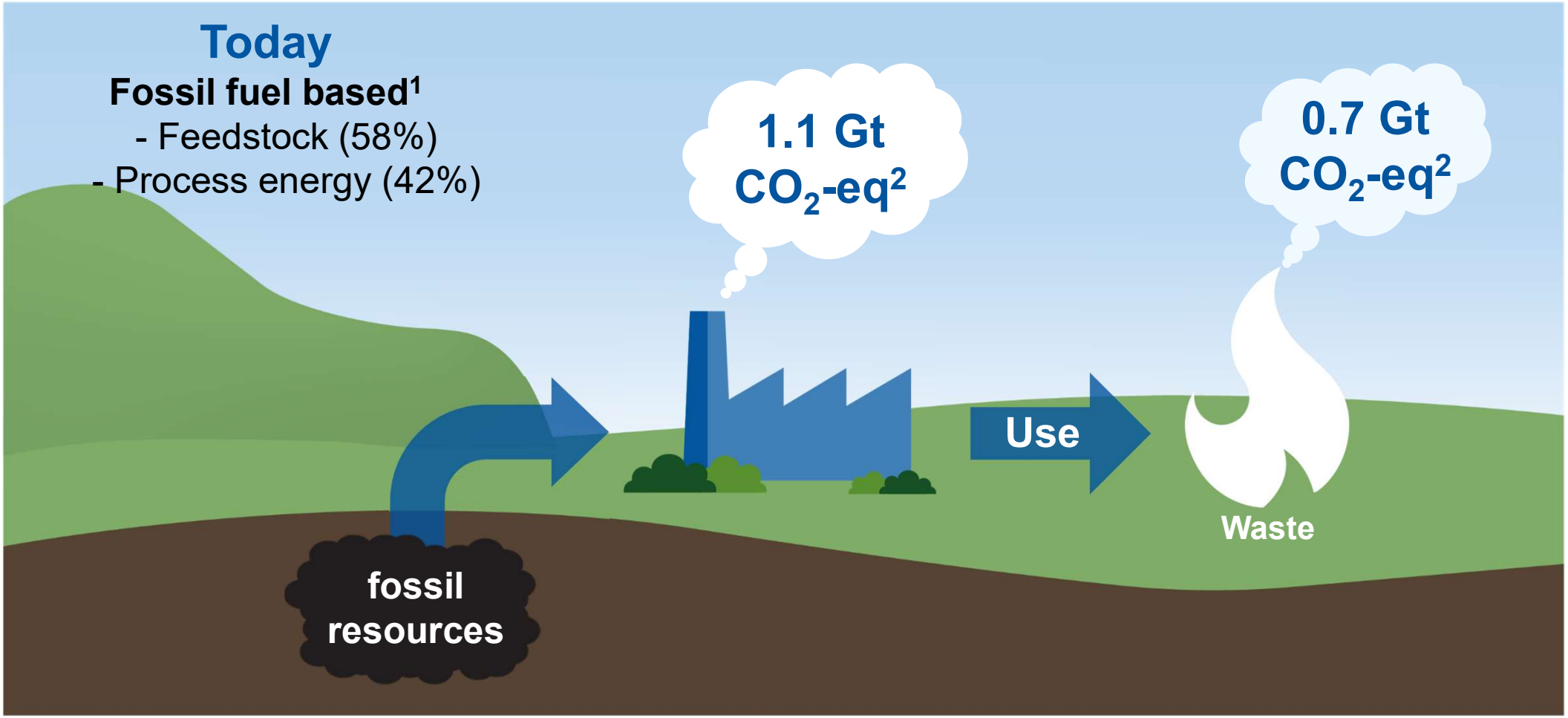
A sustainable world is more than clean electricity

The next challenge:
Defossilization of the material world



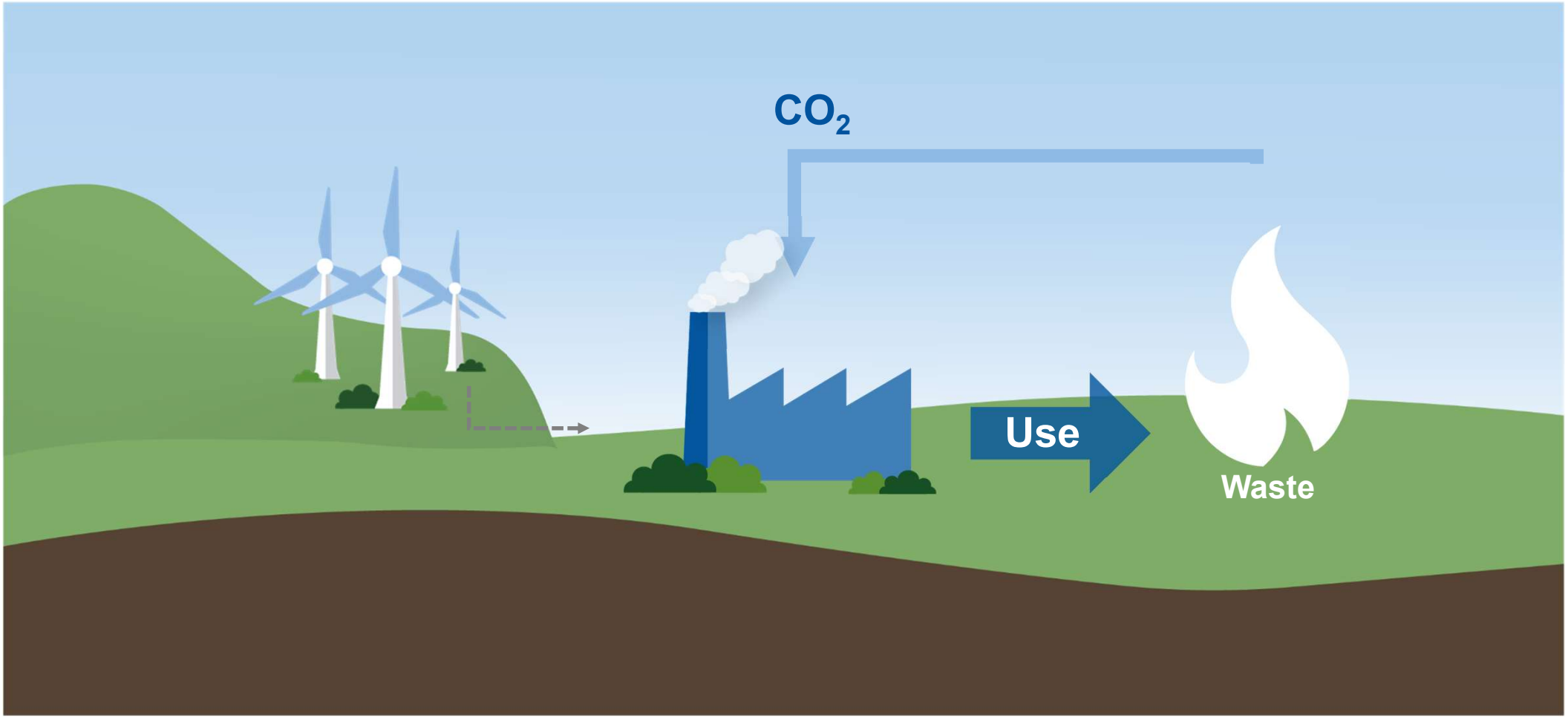
Carbon recycling can contribute to
defossilization of the material world

The Global Chemical and Plastics Industry

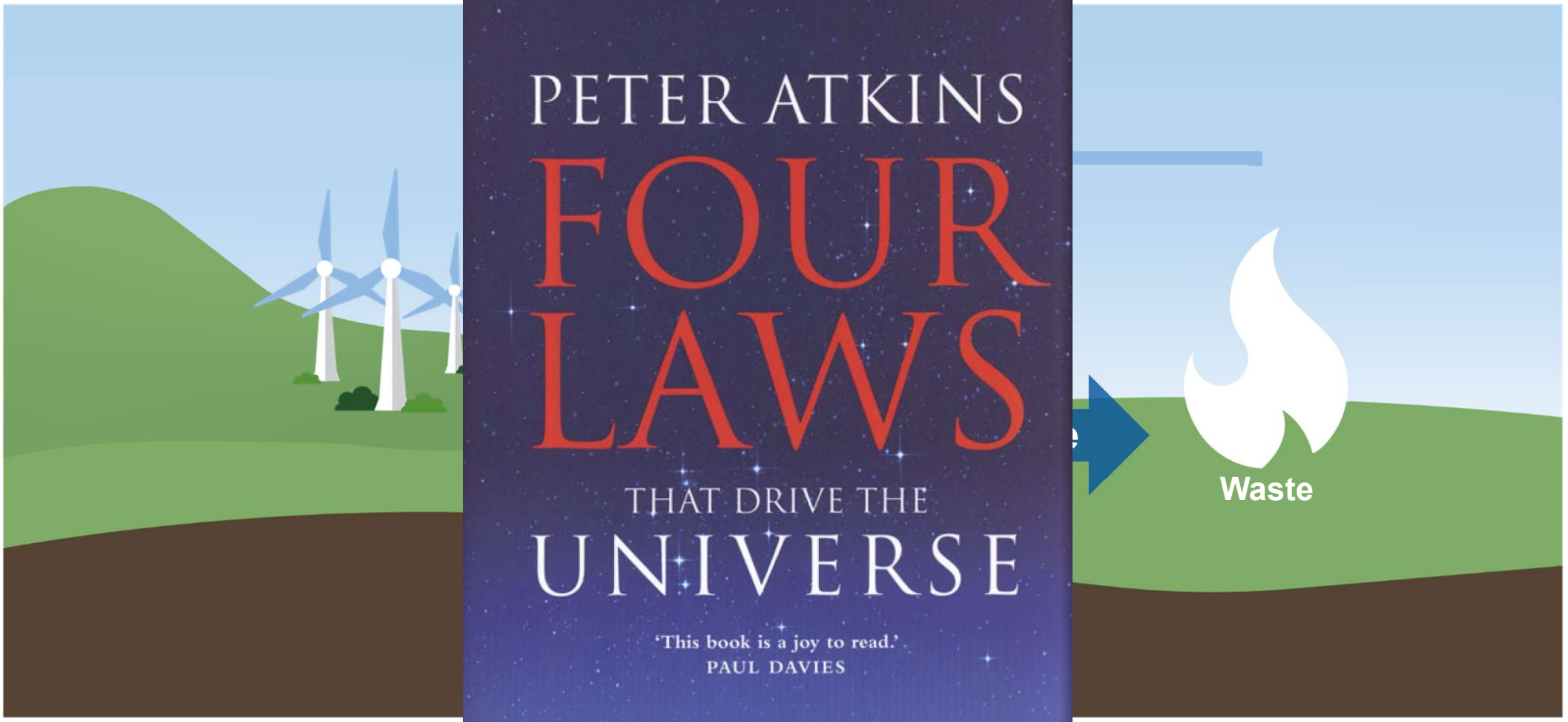


[1] IEA, DECHEMA, ICCA (2013), Technology Roadmap
[2] Zheng and Suh. *Nature Climate Change*. 2019. https://doi.org/10.1038/s41558-019-0459-z

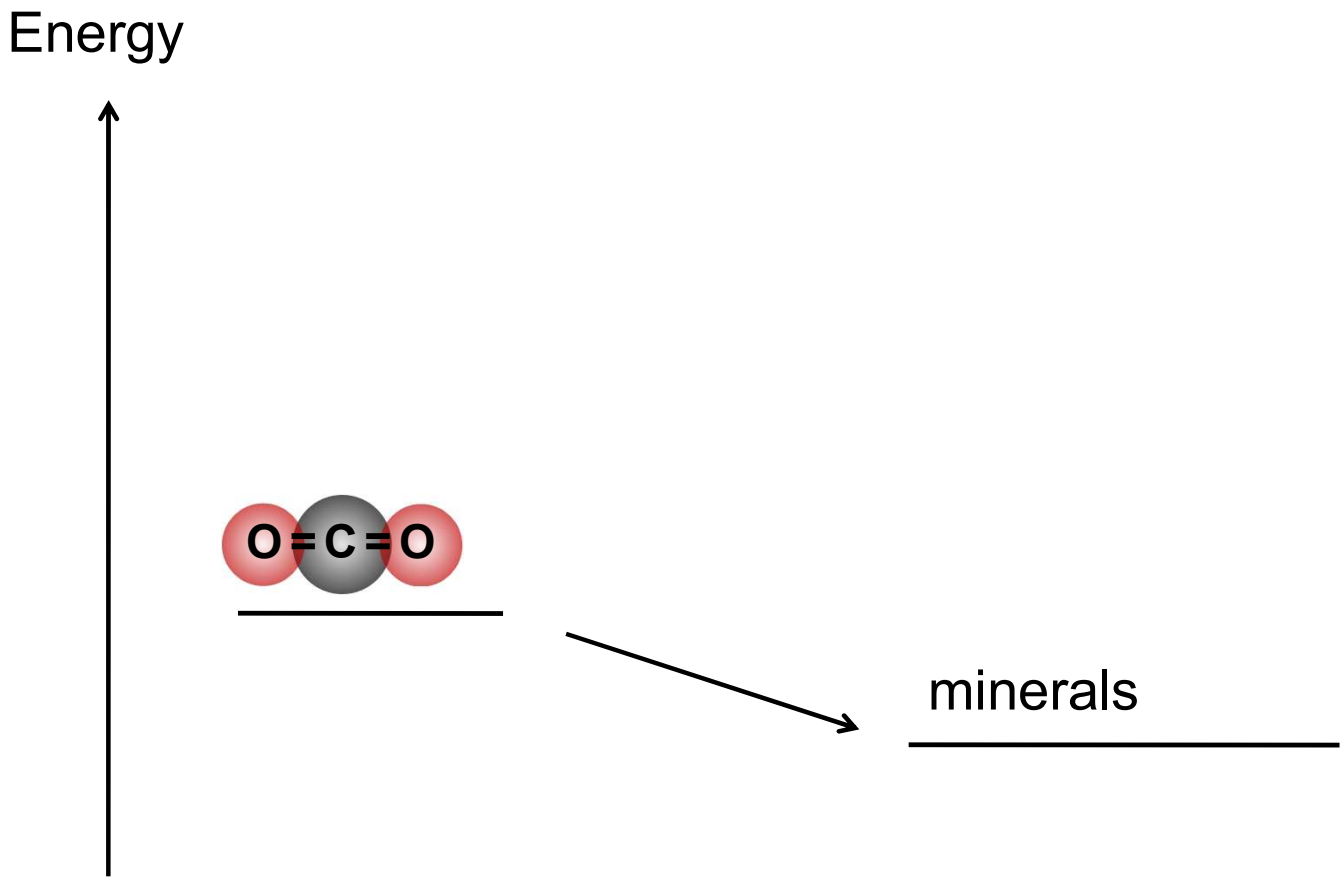
Idea: CIRCULAR industry by CO_2 recycling



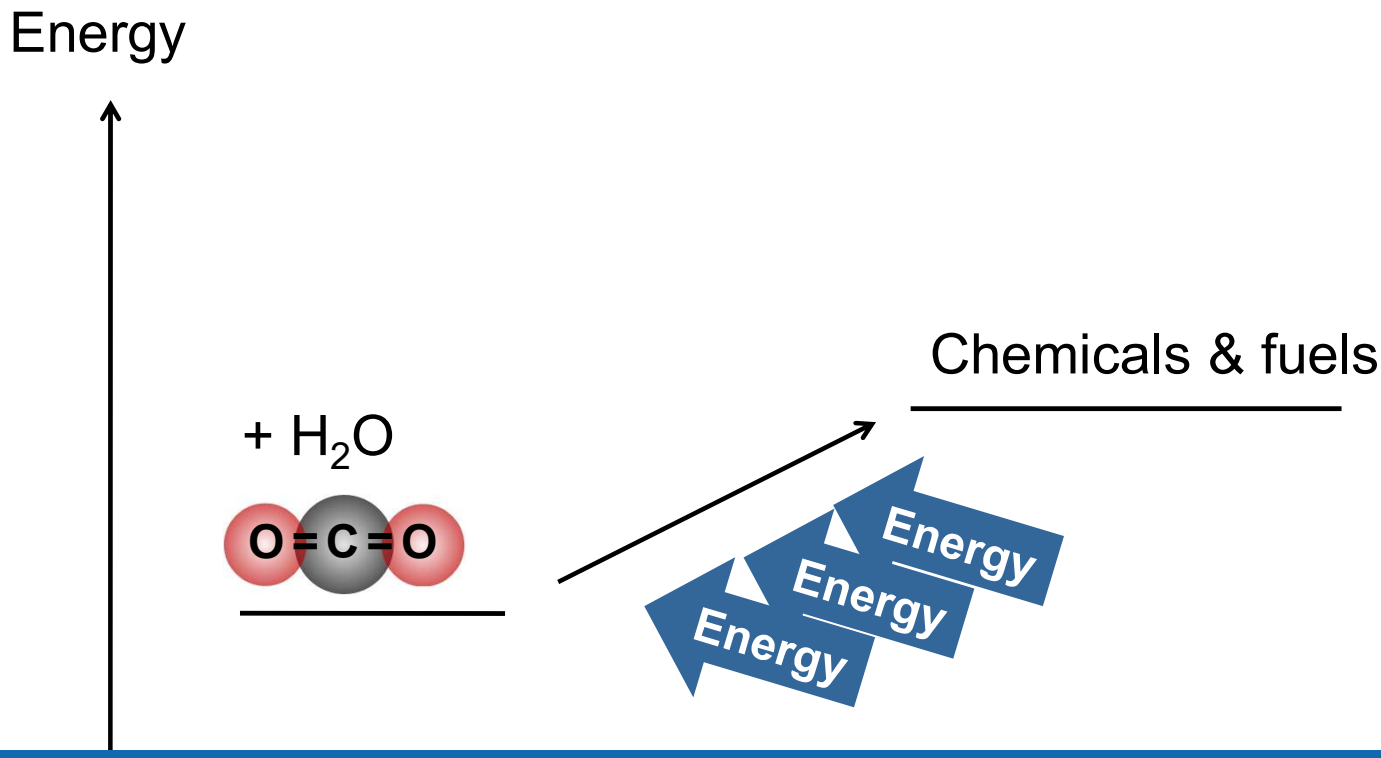
Idea: CIRCULAR ind



Thermodynamics of CO_2 conversion

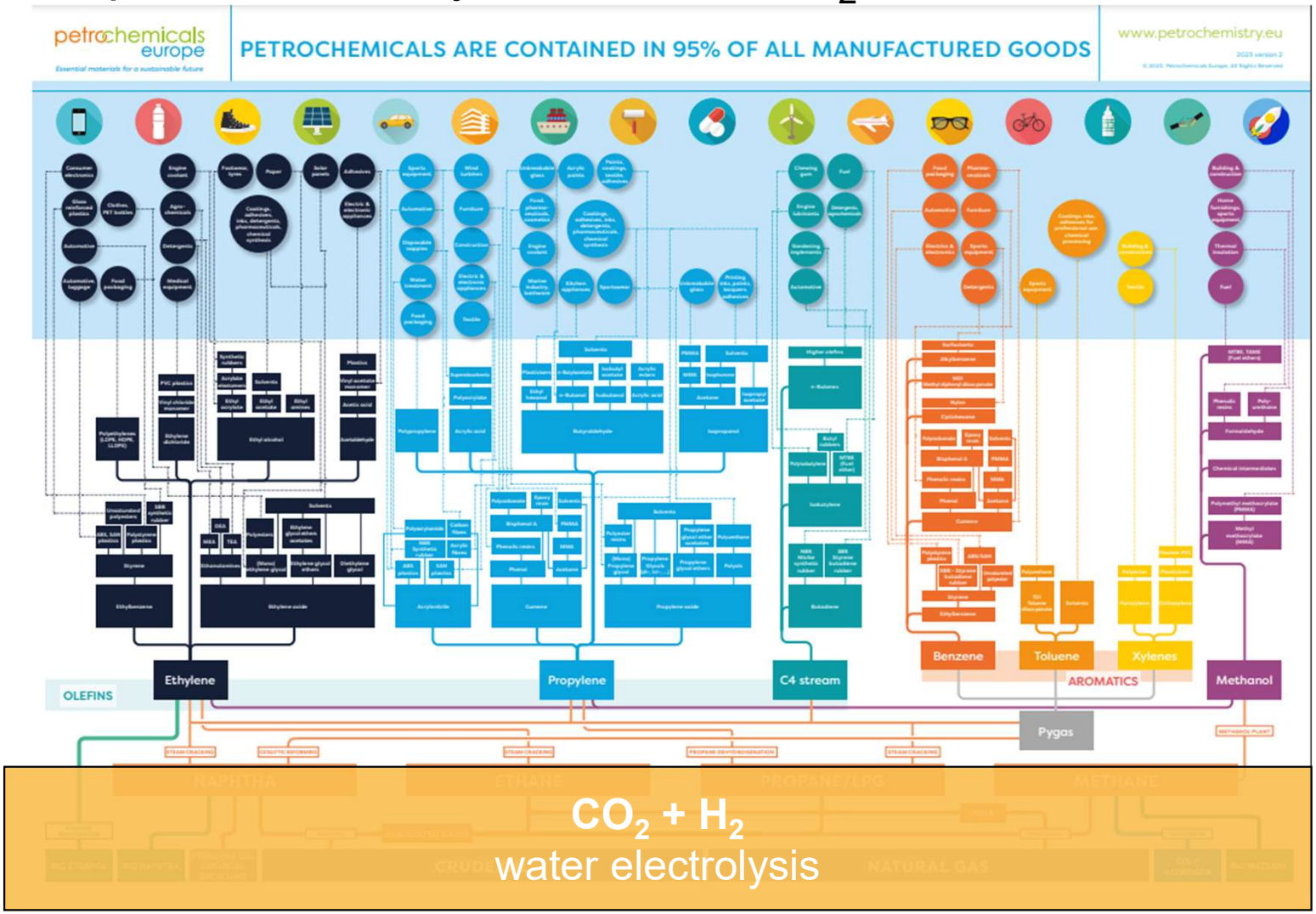


Thermodynamics of CO_2 conversion



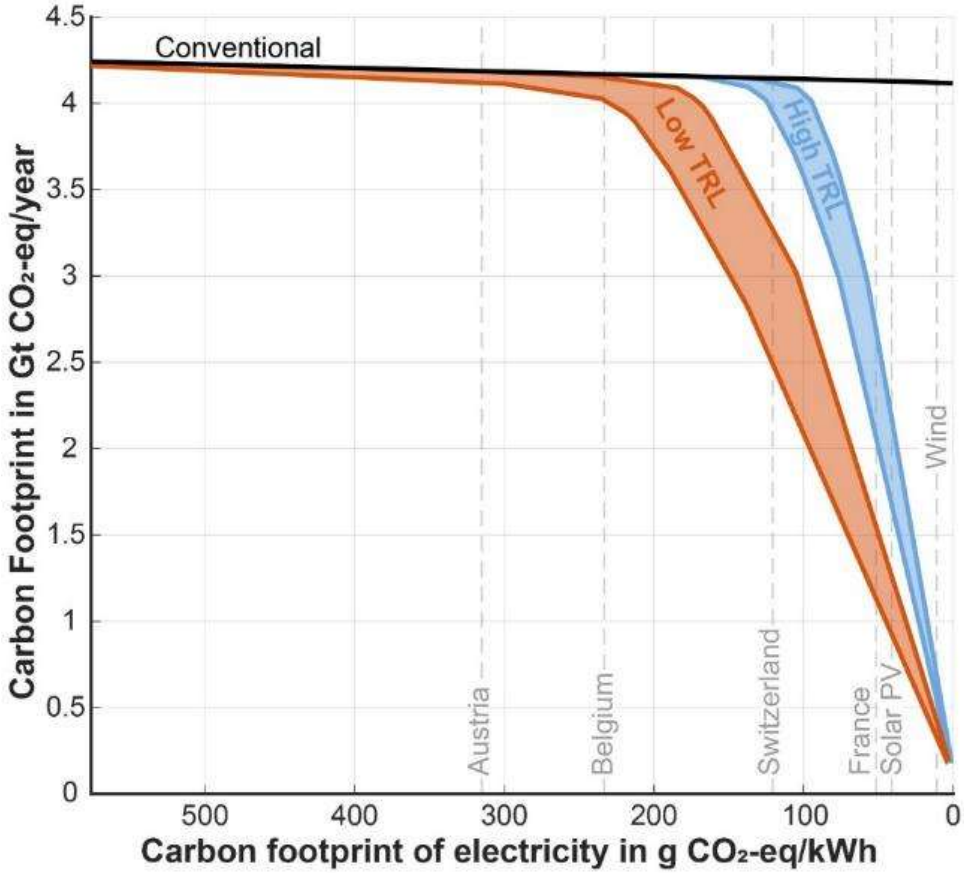
CO_2 conversion starting from CO_2 + water
= Inverting combustion

The plastics industry – based on CO_2 and water



- Polyamide 6
- Polyamide 66
- PET pellets (fiber-grade)
- PET pellets (bottle-grade)
- Polyacrylonitrile fiber
- Polyethylene, HD
- Polyethylene, LD
- Polyethylene, LLD
- Polypropylene
- Polystyrene, GP
- Polystyrene, HI
- Polyurethane, flexible
- Polyurethane, rigid
- Polyvinyl chloride

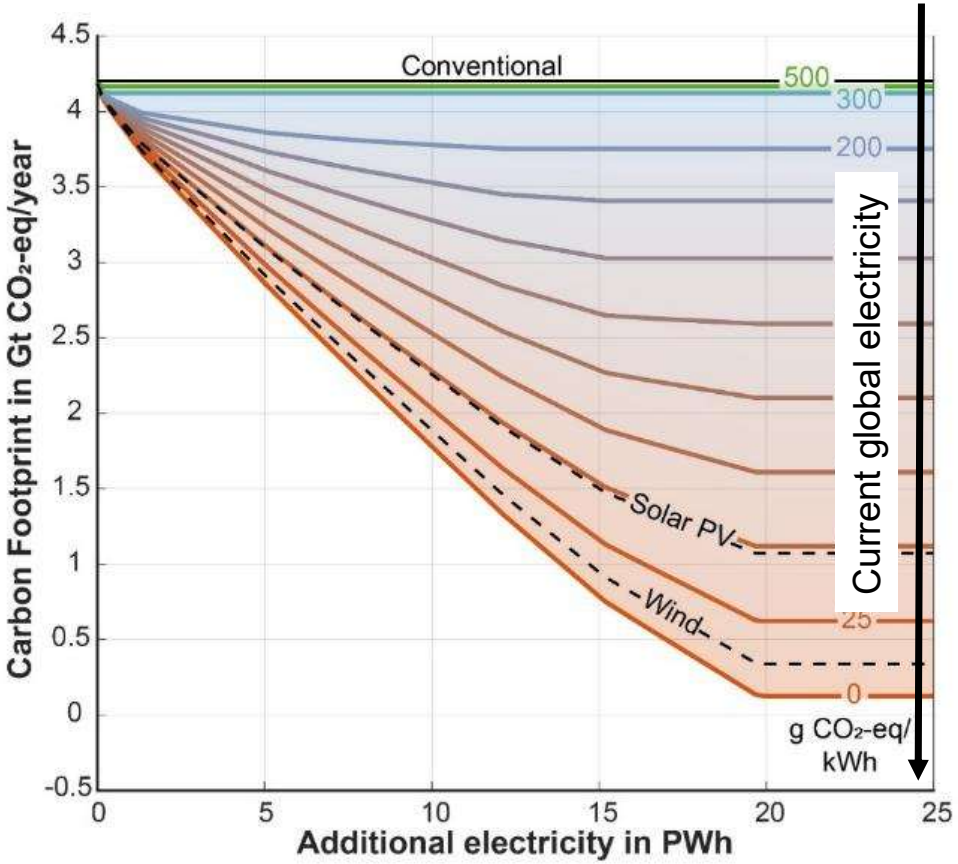
CO_2-Mitigation Potential of CCU in the Chemical Industry



- CCU can lead to practically carbon-neutral plastics
- GHG savings require low-carbon electricity
- Better technology can accelerate the transition

Kätelhön, Meys, Deutz, Suh, Bardow, *PNAS*, 2019

CO_2-Mitigation Potential of CO_2-based plastics



- CCU can lead to practically carbon-neutral plastics
- GHG savings require **a lot of** low-carbon electricity
- Declining efficiency

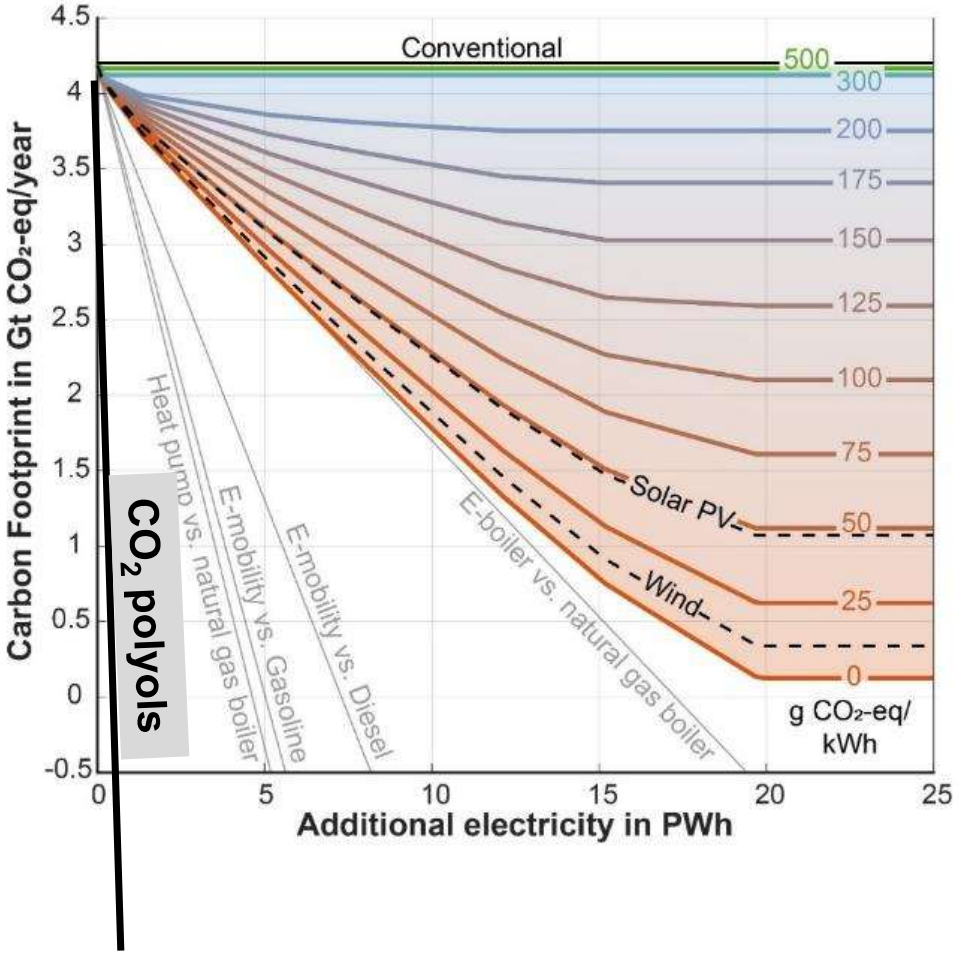

Arne Kätelhön


Raoul Meys


Sarah Deutz

Kätelhön, Meys, Deutz, Suh, Bardow, *PNAS*, 2019

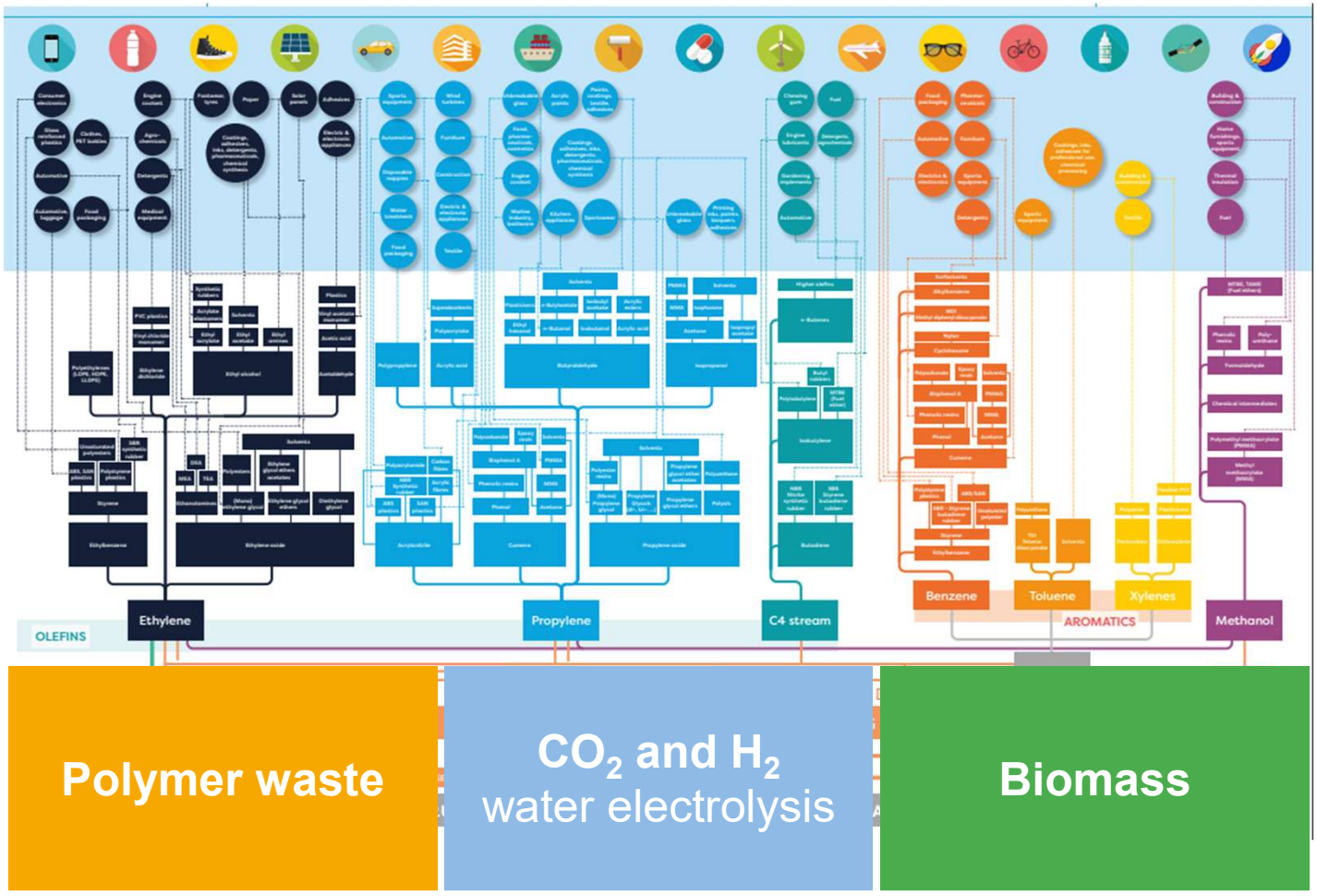
Power-to-Plastics vs Power-to-X



- CCU can lead to practically carbon-neutral plastics
- GHG savings require **a lot of** low-carbon electricity
- Declining efficiency
- Power-to-Plastics often less efficient than Power-to-Heat and Power-to-Mobility
- but there are CCU opportunities

Sternberg, Bardow, *Energy Environ. Sci.*, 2015, 8, 389
Kätelhön, Meys, Deutz, Suh, Bardow, *PNAS*, 2019

The plastics industry – based on circular carbon flows



Polymer waste

CO_2 and H_2 water electrolysis

Biomass

- Polyamide 6
- Polyamide 66
- PET pellets (fiber-grade)
- PET pellets (bottle-grade)
- Polyacrylonitrile fiber
- Polyethylene, HD
- Polyethylene, LD
- Polyethylene, LLD
- Polypropylene
- Polystyrene, GP
- Polystyrene, HI
- Polyurethane, flexible
- Polyurethane, rigid
- Polyvinyl chloride


Raoul Meys


Marvin Bachmann

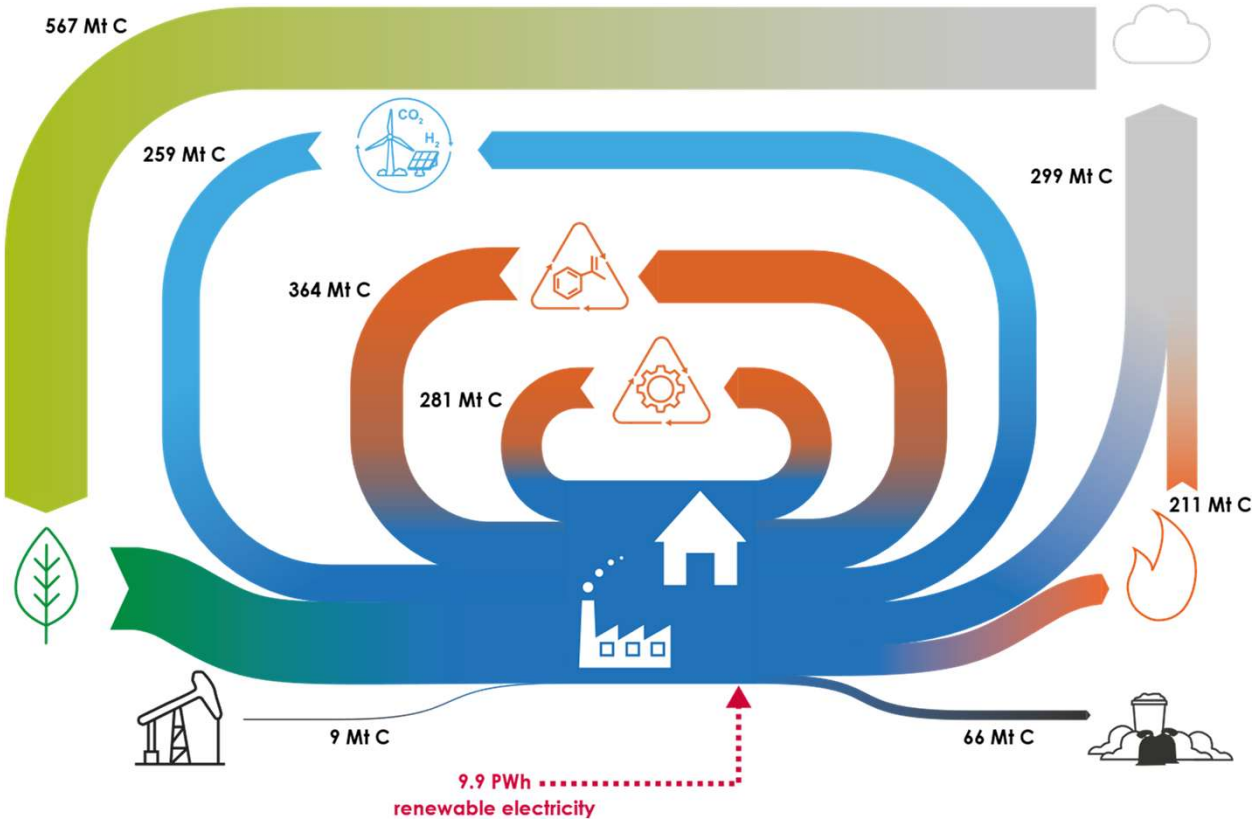

Christian Zibunas


Leonard Müller


Arne Kätelhön


Benedikt Winter

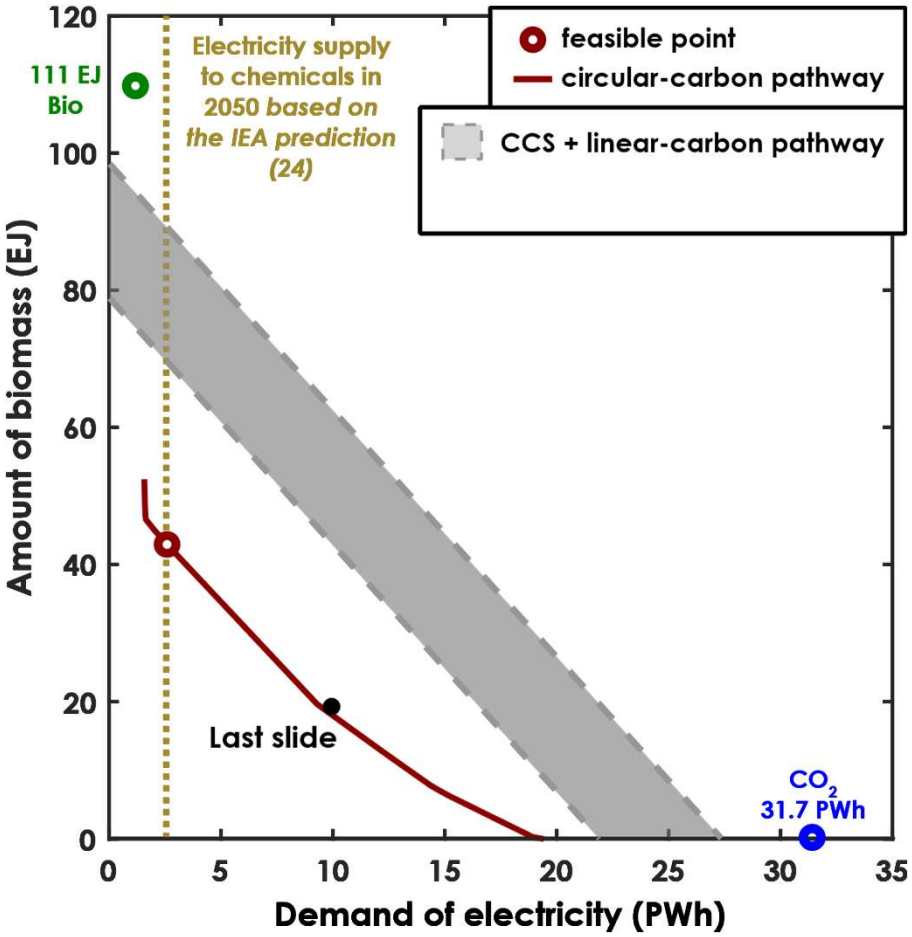
Net-zero plastics by optimal circular carbon cycles



✓Combining all circular technologies achieves carbon-neutral plastics*

Meys et al., *Science*, **2021**

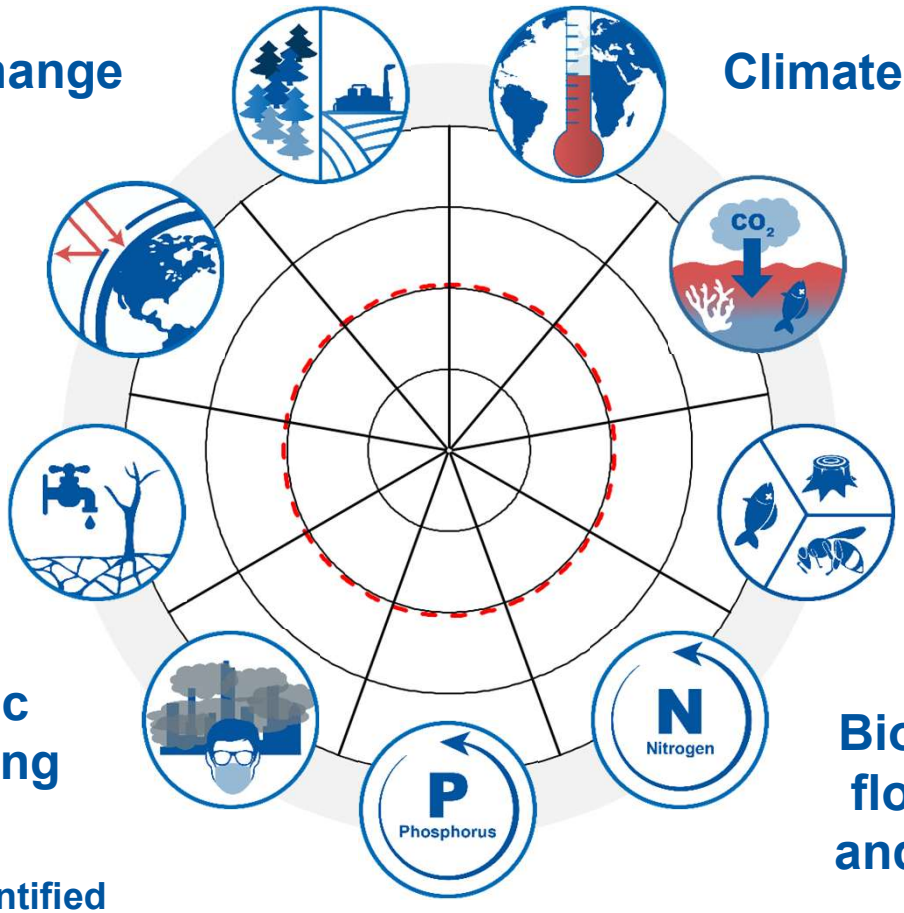
Resources for net-zero plastics



A circular-carbon economy
can achieve carbon-neutral plastics
using less energy
than linear fossil-based benchmark.

Meys et al., *Science*, **2021**

Beyond GHG emissions: Planetary Boundaries



Land-system change

Climate change

Stratospheric ozone depletion

Ocean acidification

Freshwater use

Biosphere integrity

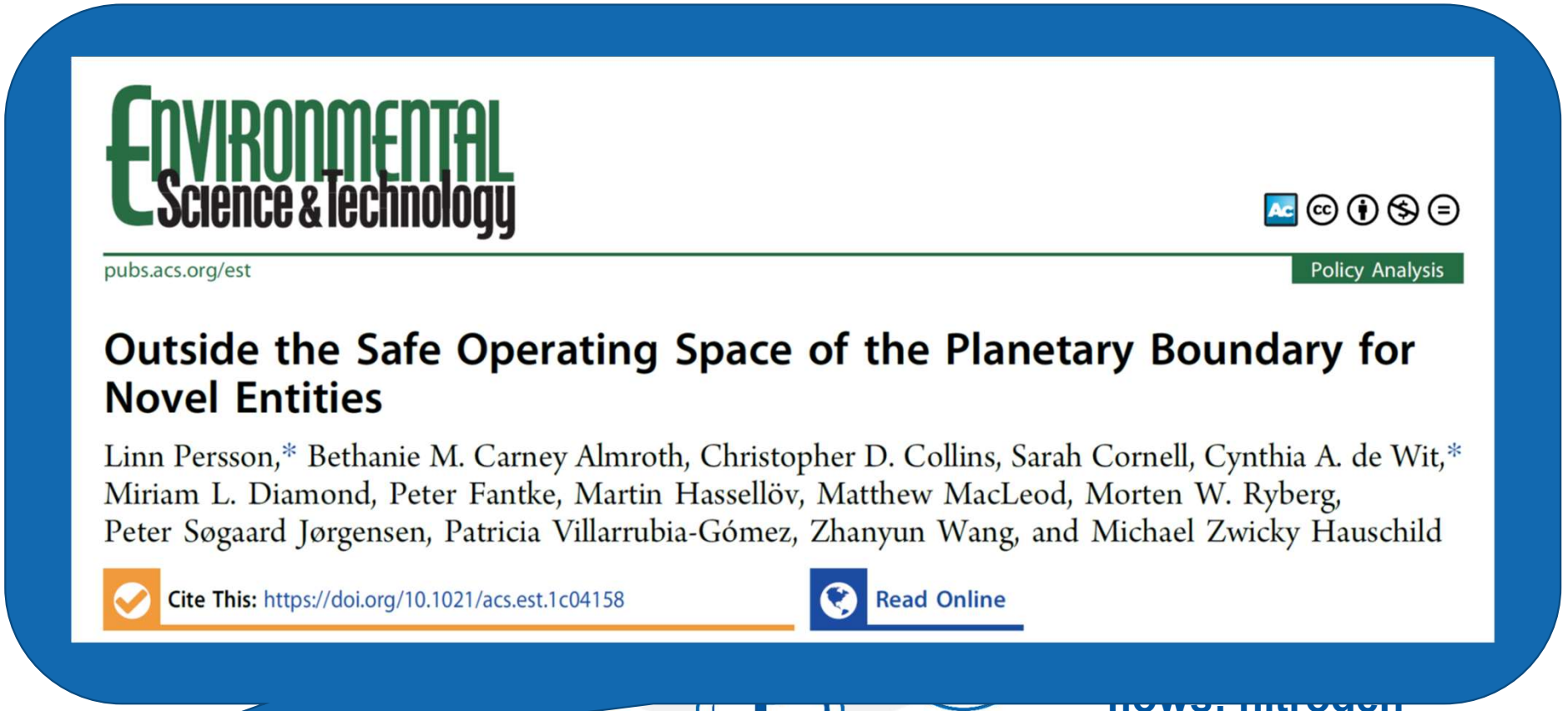
Atmospheric aerosol loading

Biogeochemical flows: nitrogen and phosphorus

Novel entities could not be quantified

Steffen et al., *Science*, 2015

Beyond GHG emissions: Planetary Boundaries



Environmental Science & Technology

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Policy Analysis

Outside the Safe Operating Space of the Planetary Boundary for Novel Entities

Linn Persson,* Bethanie M. Carney Almroth, Christopher D. Collins, Sarah Cornell, Cynthia A. de Wit,* Miriam L. Diamond, Peter Fantke, Martin Hassellöv, Matthew MacLeod, Morten W. Ryberg, Peter Søgaard Jørgensen, Patricia Villarrubia-Gómez, Zhanyun Wang, and Michael Zwicky Hauschild

Cite This: https://doi.org/10.1021/acs.est.1c04158

Read Online

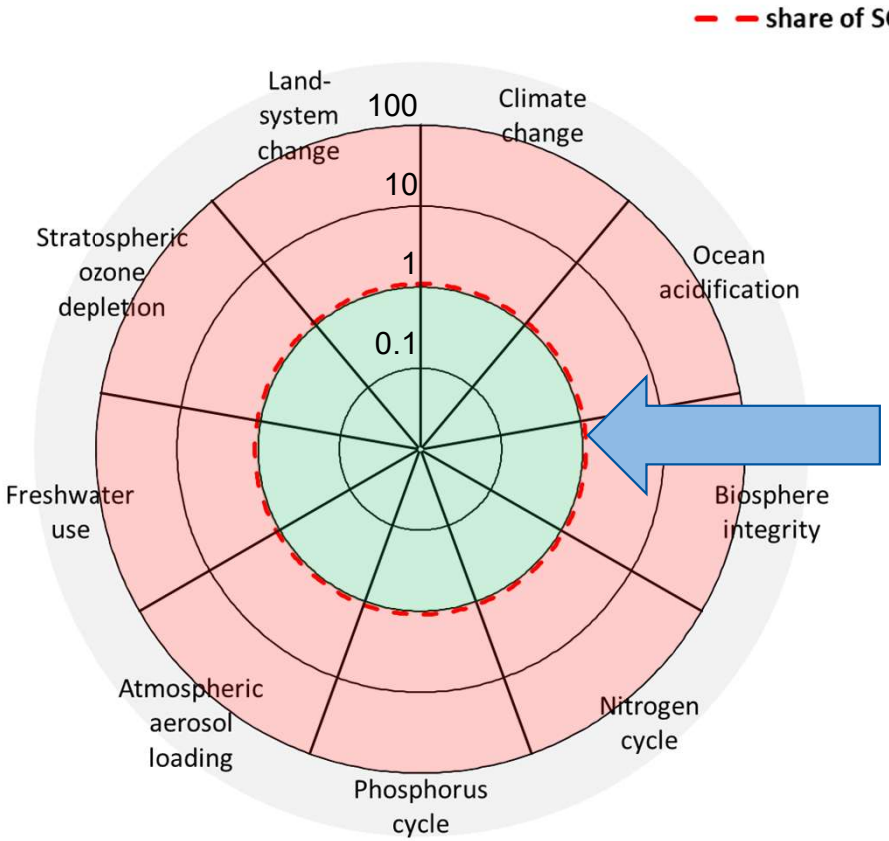
Phosphorus

Novel entities could not be quantified

and phosphorus

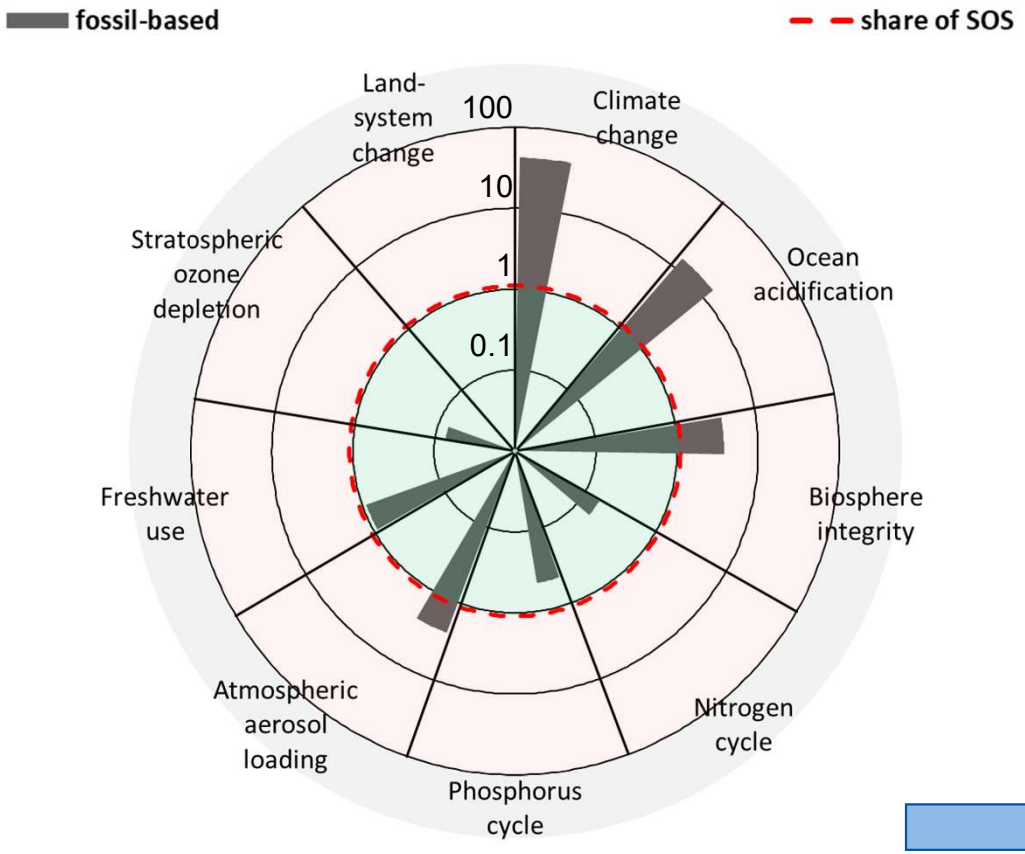
Steffen et al., *Science*, 2015

The planetary footprints of global plastic production



- Plastics industry ≠ global economy
- Downscaling required
- Share of safe operating space = 1.1%
- Assigned by consumption expenditure

The planetary footprints of global plastic production 2030



- Fossil-based plastics transgress
  - Climate change by **38 times**
  - Ocean acidification by **12 times**
  - Biosphere integrity by **3 times**
  - Aerosol loading by **1 time**

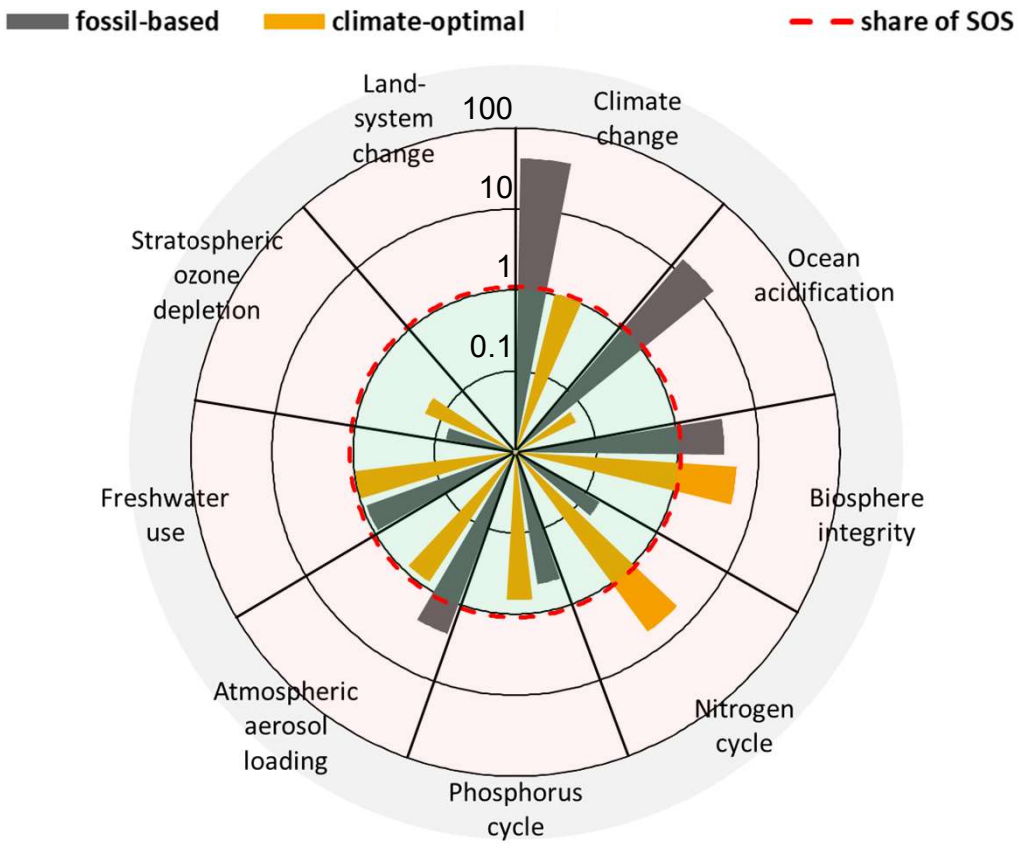
Fossil-based plastics are unsustainable


Marvin Bachmann


Christian Zibunas


Jan Hartmann

The planetary footprints of global plastic production 2030

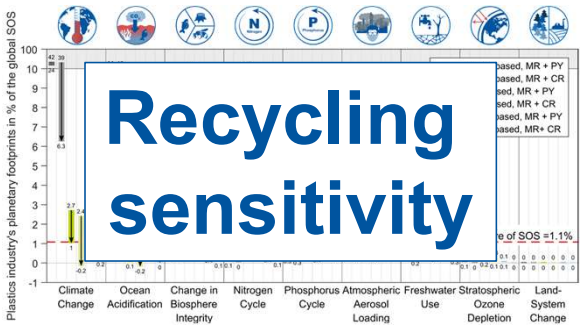


- Climate-optimal plastics transgress
  - Biosphere integrity by **5 times**
  - Nitrogen cycle by **5 times**
- Impacts from bio-based plastics
  - High land occupation
  - High fertilizer application

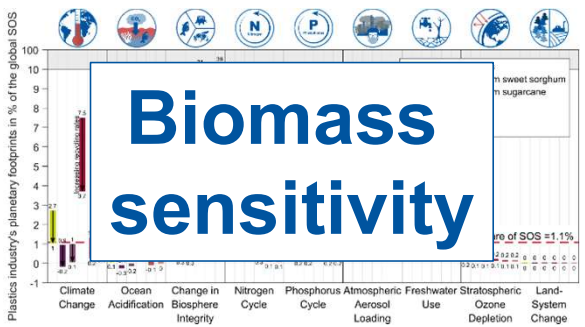
Climate-optimal plastics are still unsustainable

Bachmann, Zibunas et al., *Nature Sustainability,* 2023

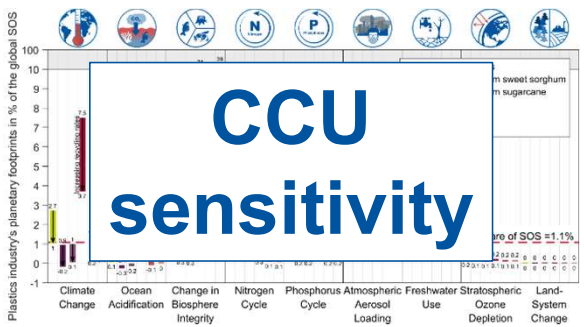
Improvements towards absolute sustainability



Recycling sensitivity



Biomass sensitivity



CCU sensitivity

Improve recycling efficiency

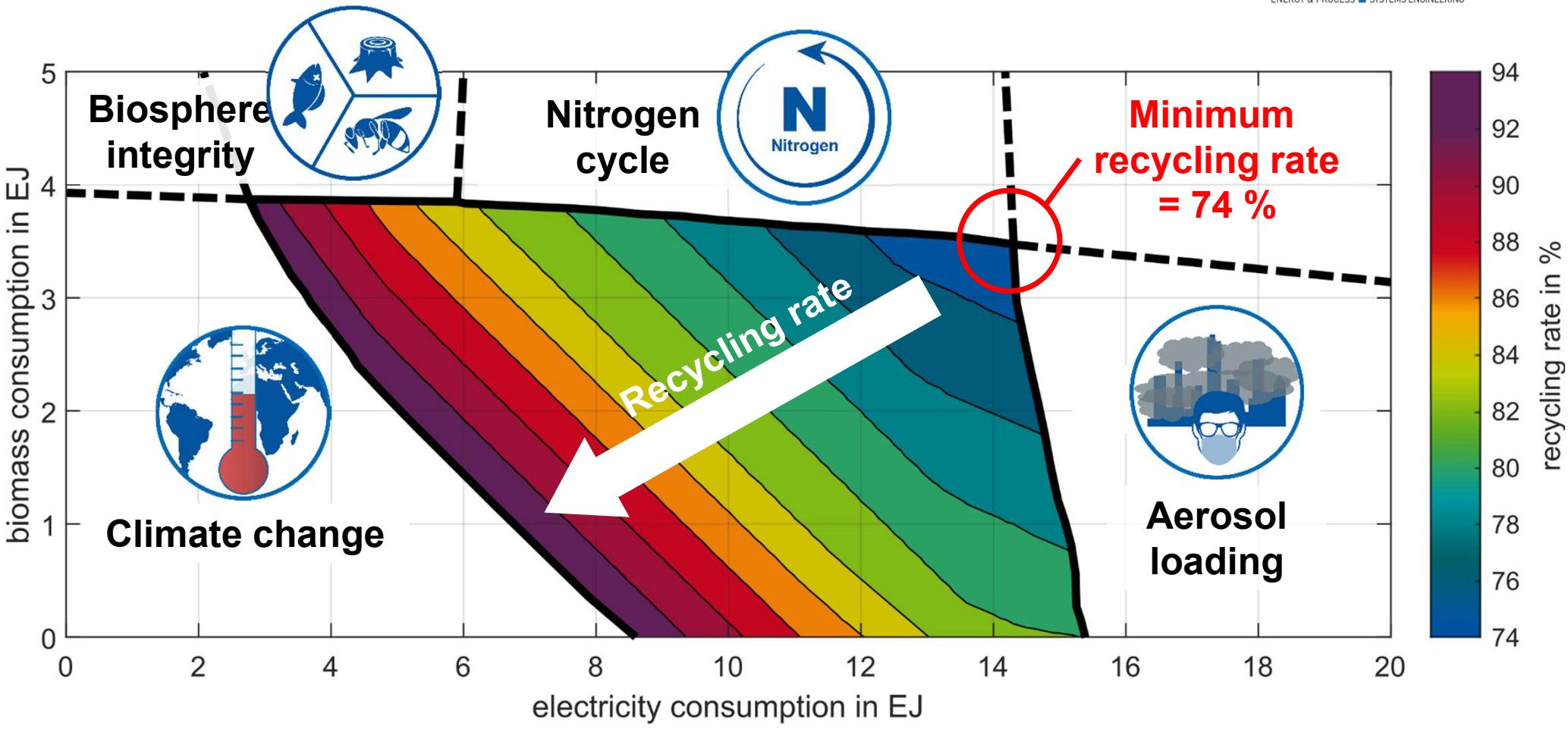
Reduce feedstock impact

Reduce electricity impact

Best case	High efficiency chemical monomer recycling	Energy crops	Wind power

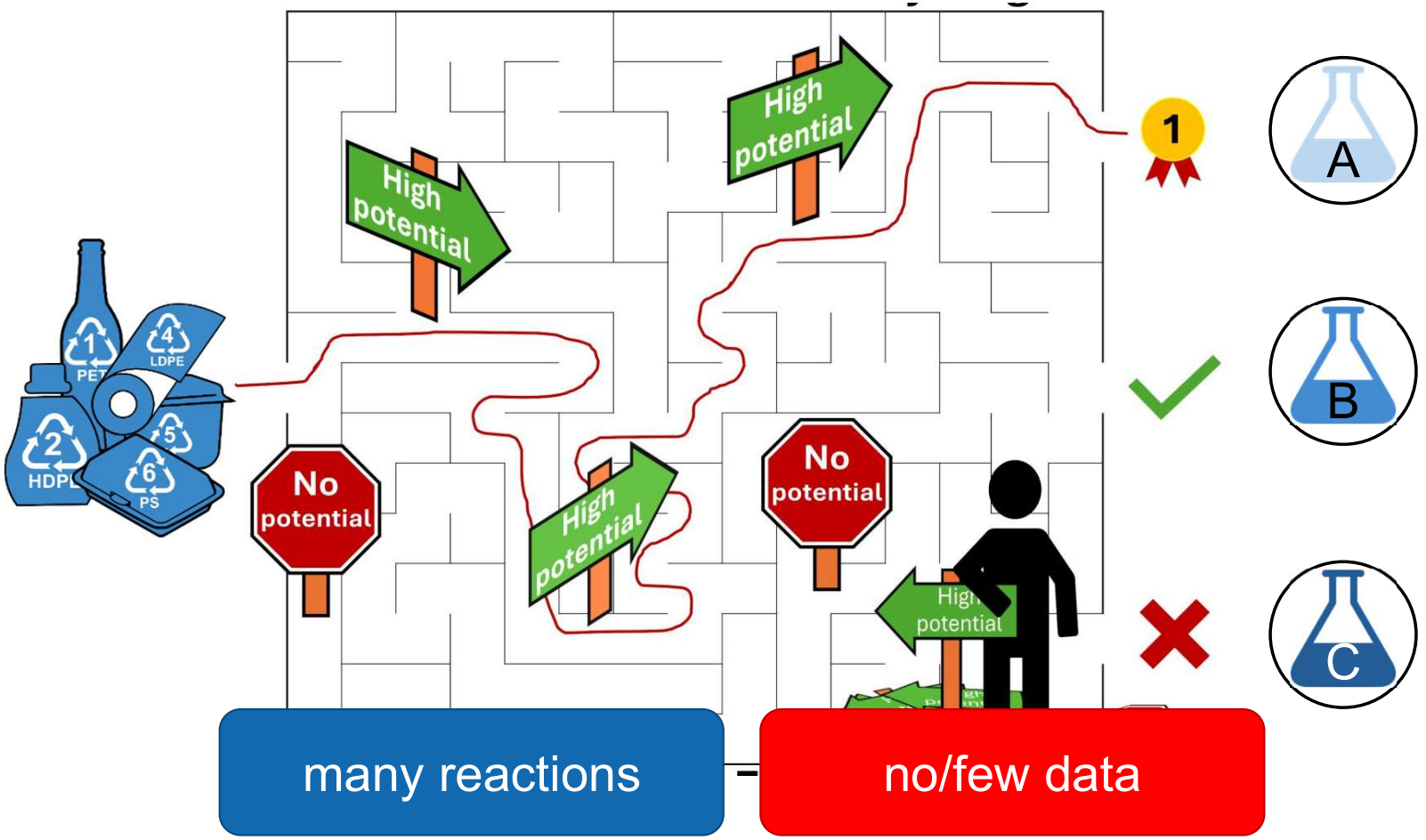
Bachmann, Zibunas et al., *Nature Sustainability,* 2023

Solution space for sustainable plastics in 2030



Bachmann, Zibunas et al., *Nature Sustainability,* 2023

The Maze of Chemical Recycling

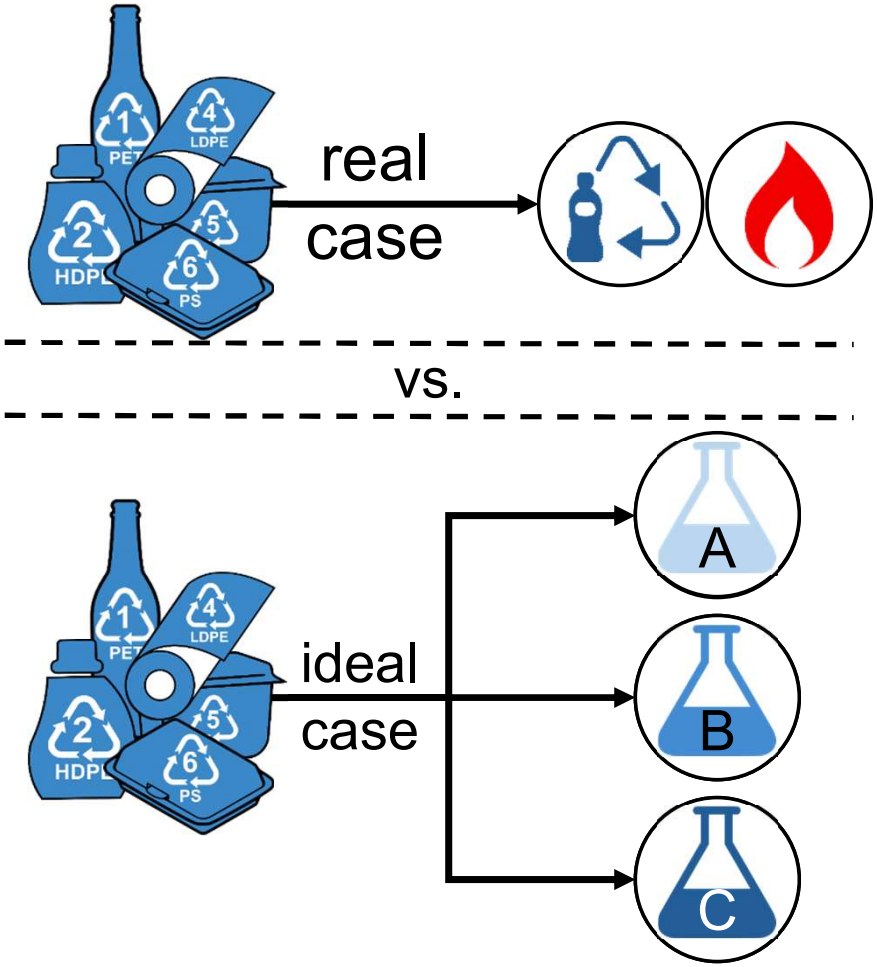



Martin Pillich

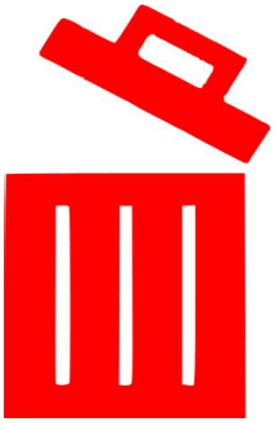

Raoul Meys

Pillich et al., *Green Chem.*, 2024; Meys et al. *Resour. Conserv. Recy*, 2020

The approach



The environmental potential

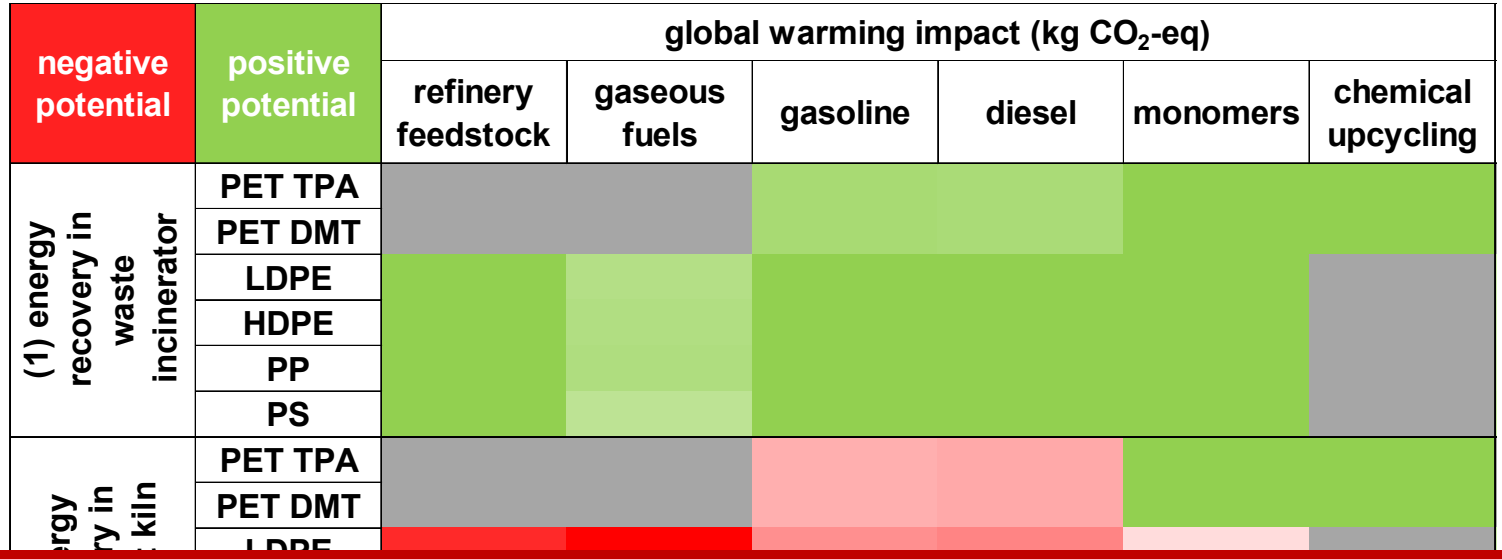


no potential benefits

potential benefits

Meys, Frick, Westhues, Sternberg, Klankermayer, Bardow, *Resour. Conserv. Recy*, 2020

Which chemical recycling? High substitution for high potential



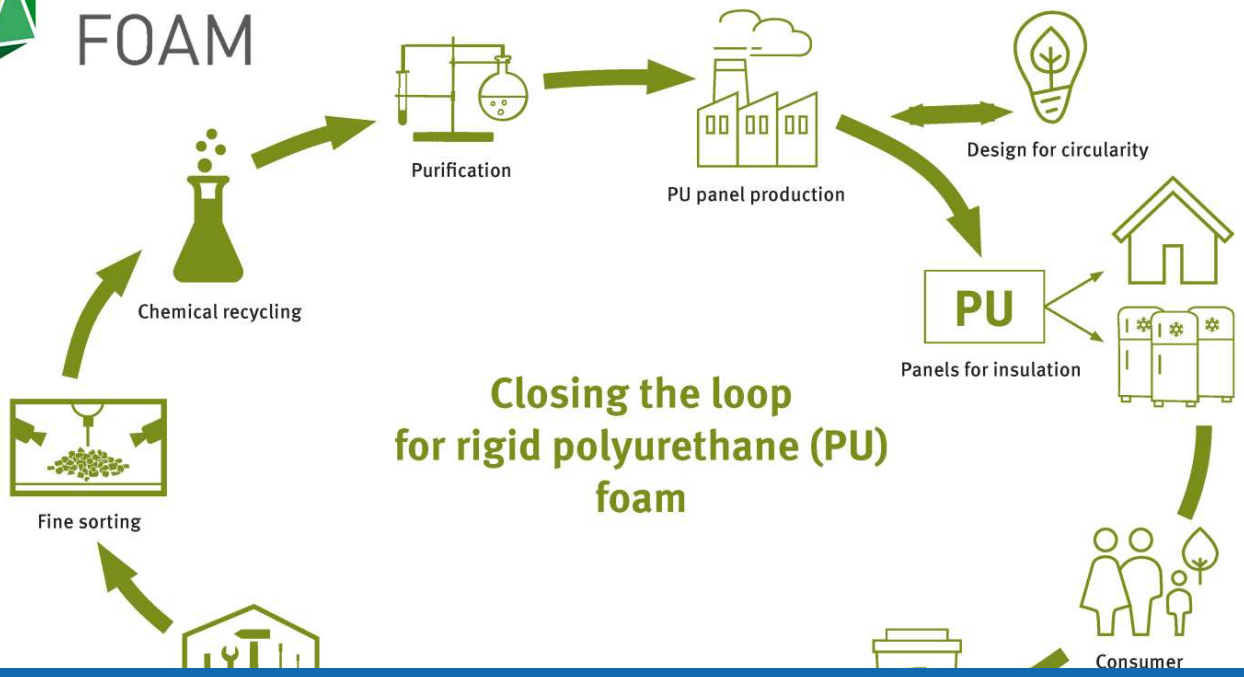
Key messages:

1) Recycle only waste that is poorly used today
2) Produce emission-intensive chemicals: Monomers & upcycling

Meys, Frick, Westhues, Sternberg, Klankermayer, Bardow, *Resour. Conserv. Recy*, 2020

Recycle only waste that is poorly used today: Polyurethane

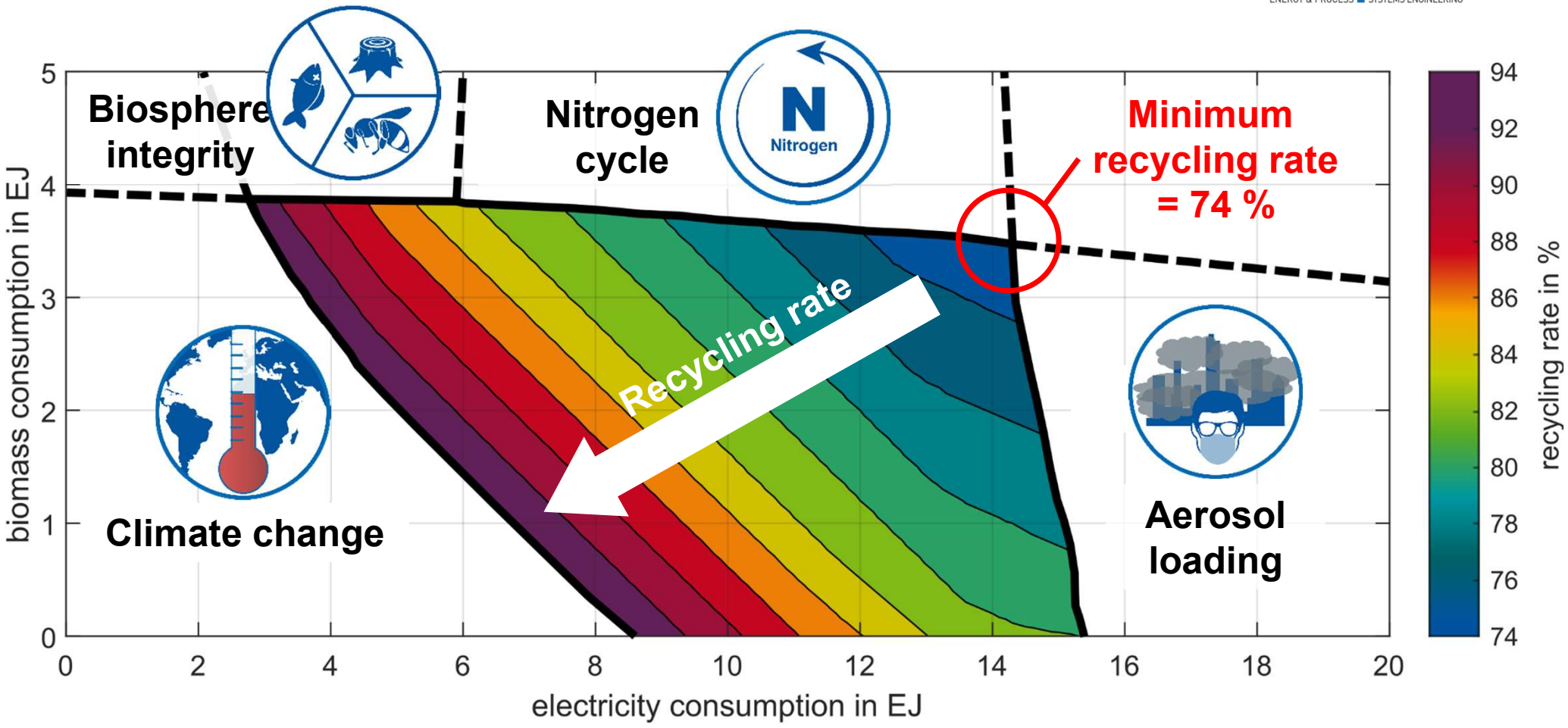
CIRCULAR FOAM



✓Successful development and demonstration of novel recycling pathways

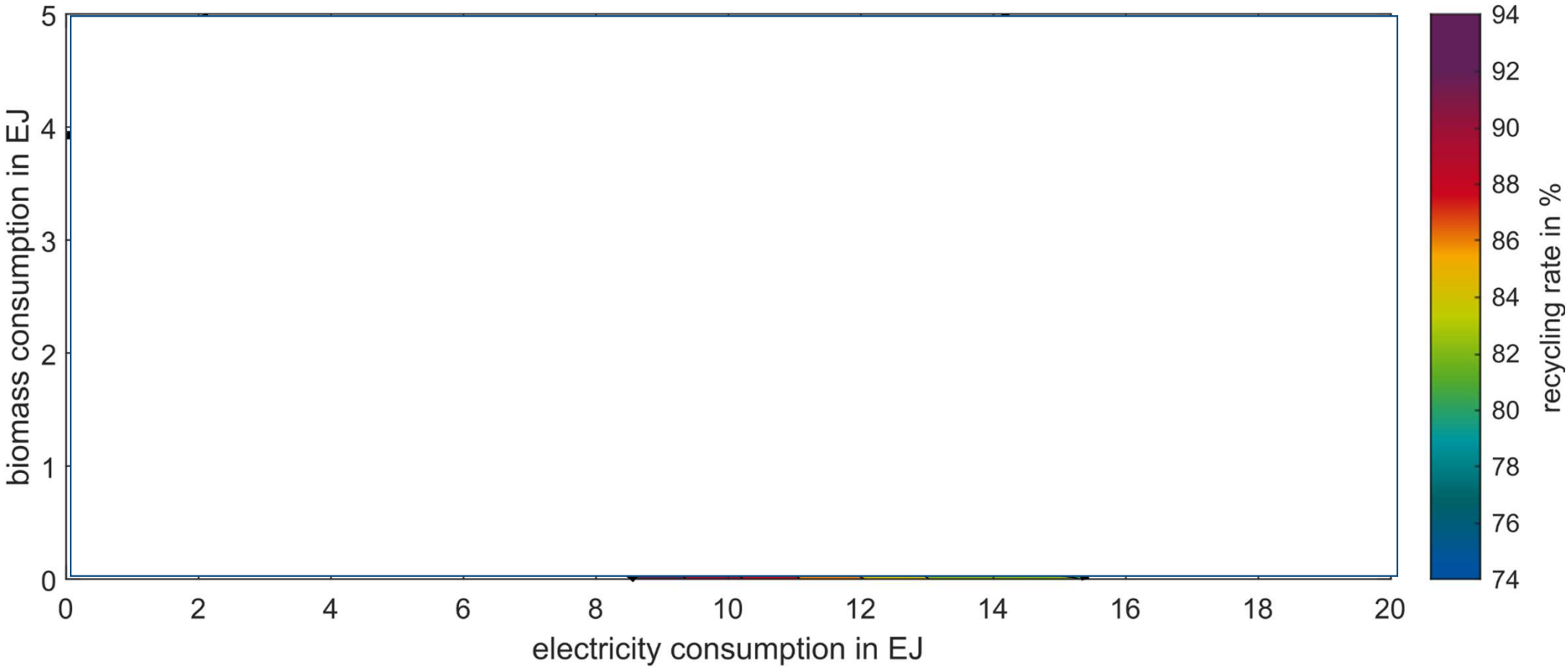
The project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101036854

Solution space for sustainable plastics in 2030



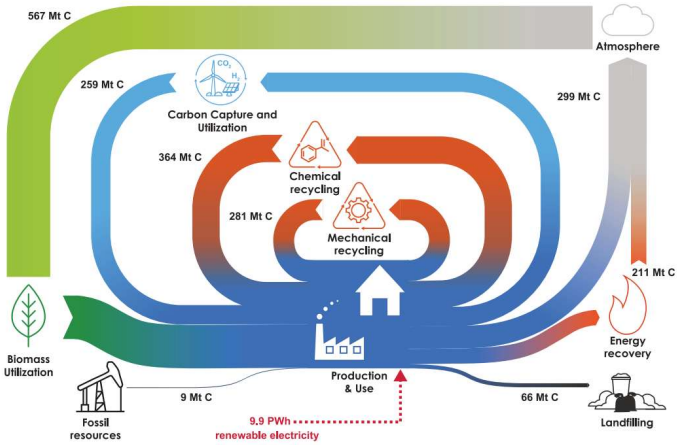
Bachmann, Zibunas et al., *Nature Sustainability,* 2023

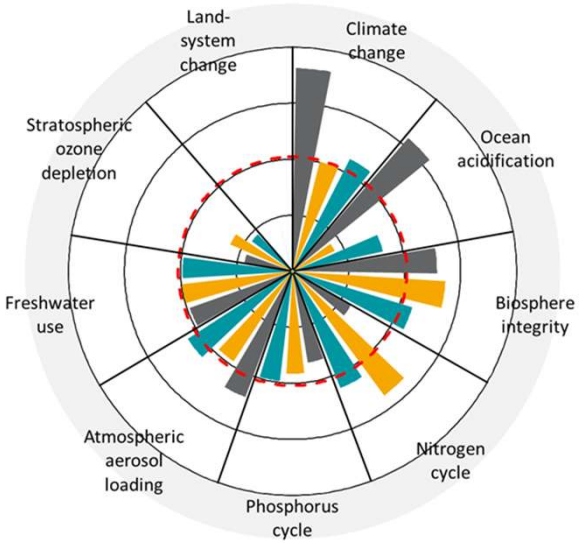
Solution space for sustainable plastics in 2050

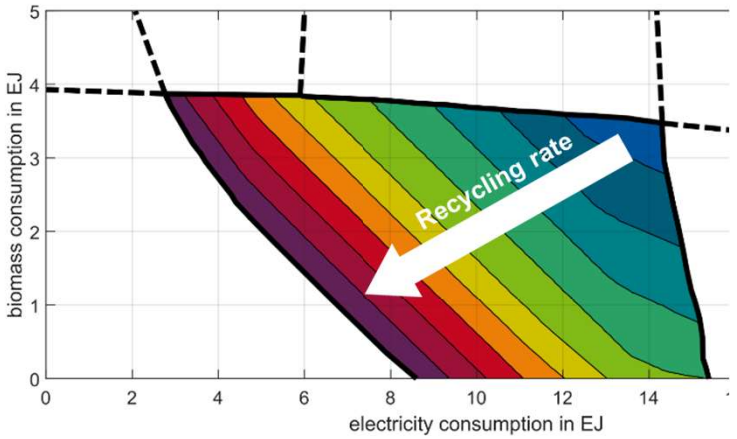


Bachmann, Zibunas et al., *Nature Sustainability,* 2023

Key insights







We need ALL circular technologies

Carbon-neutral plastics is feasible, saves energy and on par in OPEX

- but not enough

Enhancing recycling is KEY towards sustainability

- but not enough

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