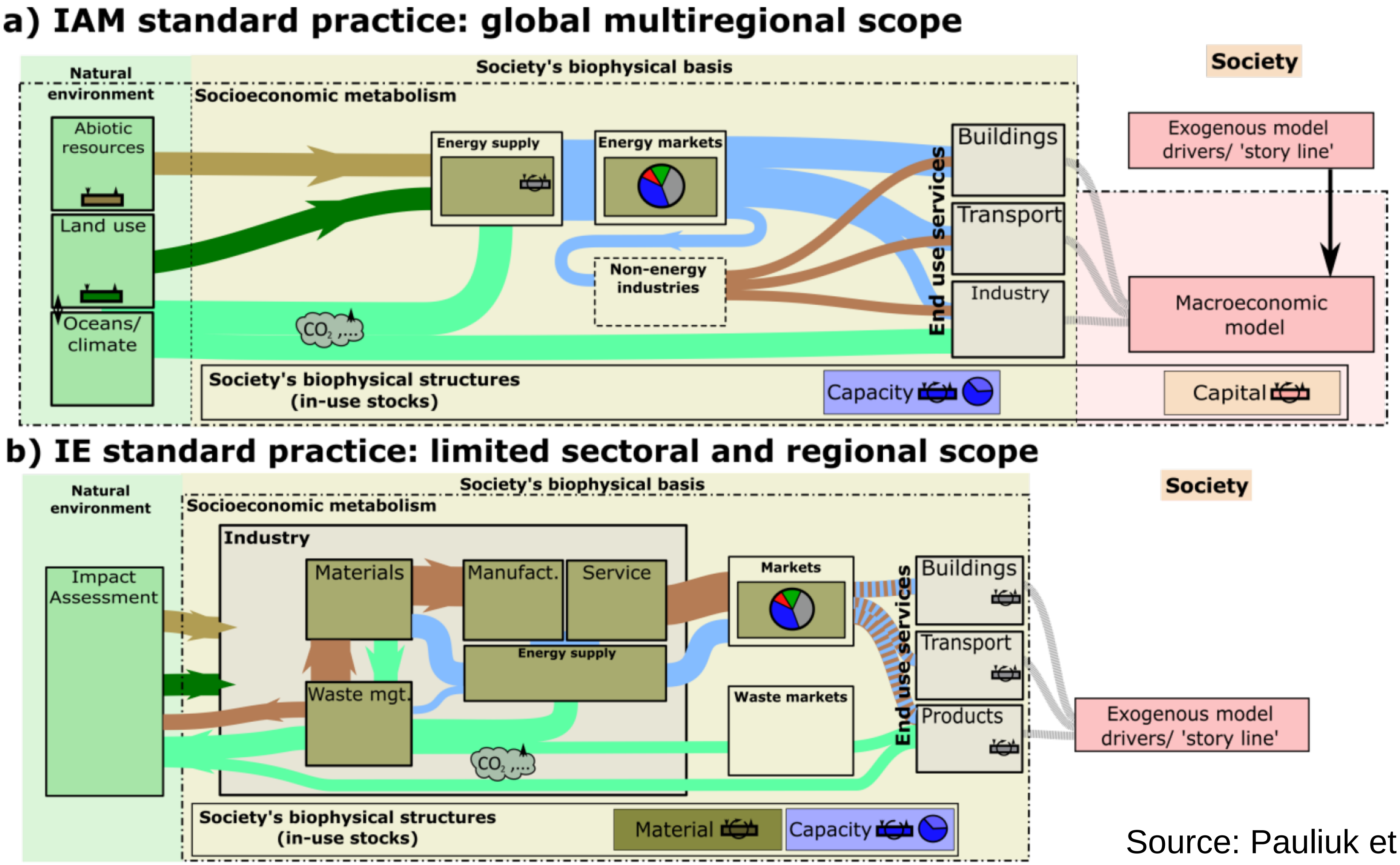
Integrating industrial ecology methods and IAMs

Volker Krey

17 October 2024

NTNU course: Integrated Assessment Modelling (EP8900)

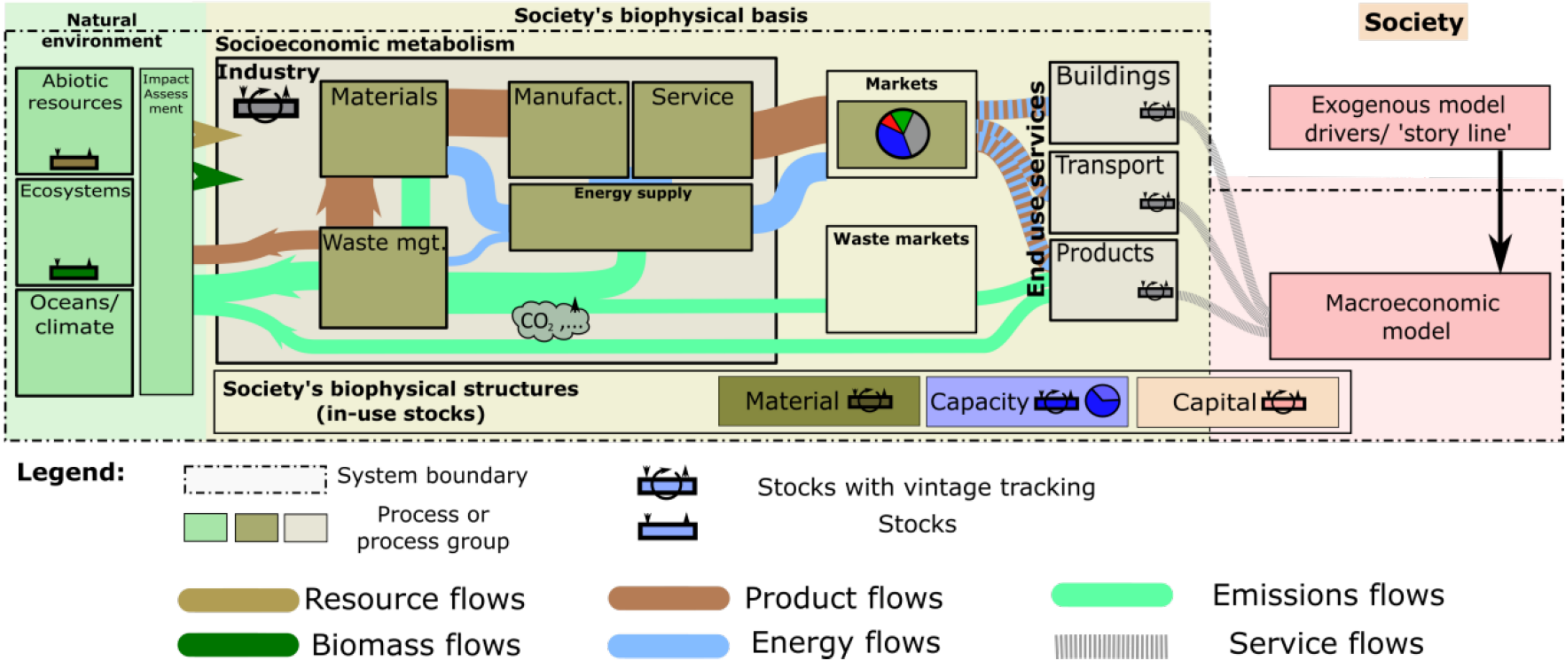
IAM vs. IE perspectives on social metabolism



Source: Pauliuk et al. (2017)

Integrated IAM-IE vision on social metabolism

c) Vision for integration of both perspectives : global multiregional scope



Source: Pauliuk et al. (2017)

Combining IAMs with LCA and MFA

Combining IE methods with IAMs

Two common approaches

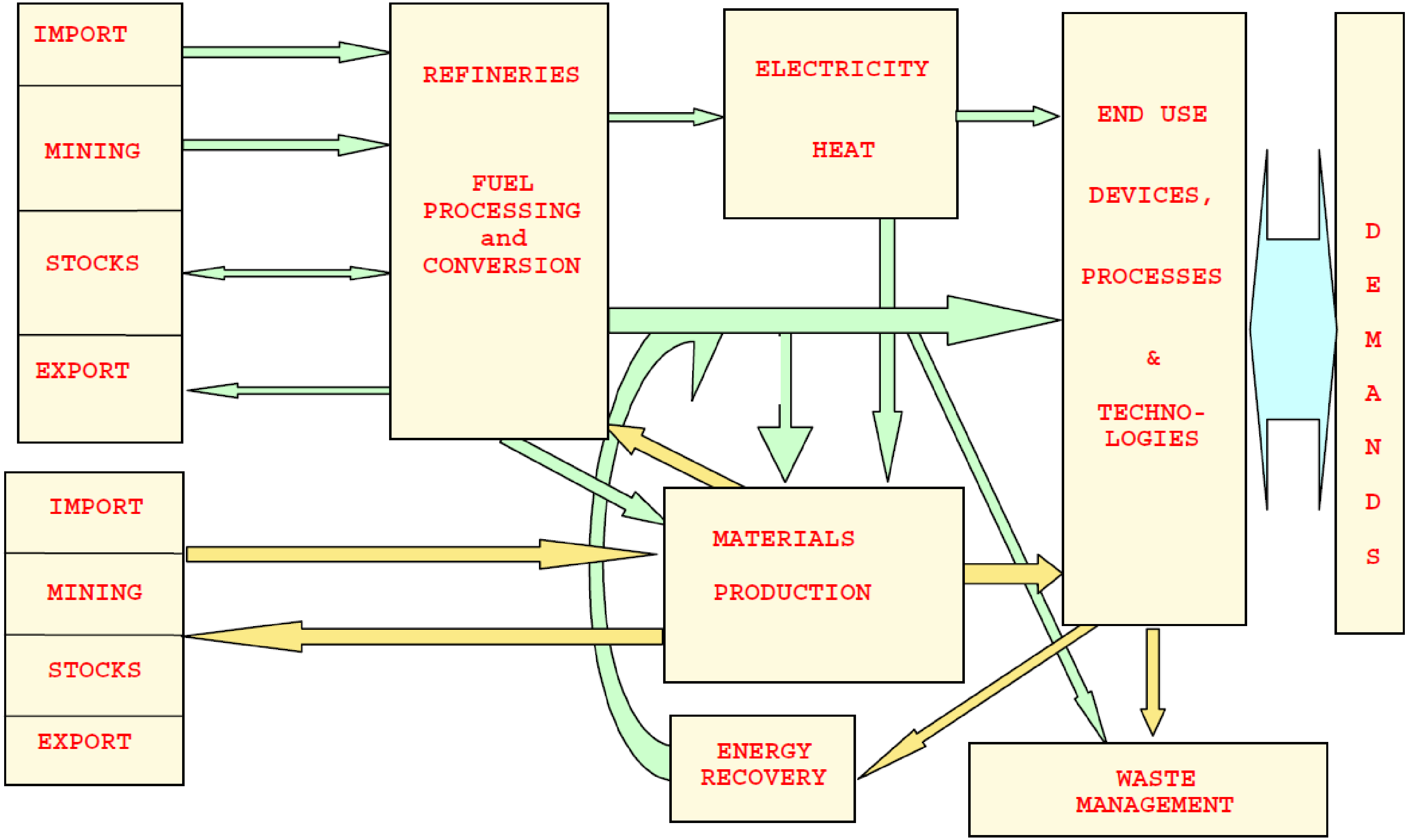
Endogenous representation

- e.g. integrating material supply chains directly into IAMs

Ex-post assessment

- e.g., applying prospective LCA to IAM scenarios

An early example: MARKAL-MATTER



Source: Sijm et al. 2002

MARKAL-MATTER

Coverage of materials in Western European MARKAL-MATTER model

SEPTEMBER 1998 ECN-C--98-065

MATTER 1.0

A MARKAL Energy and Materials System Model Characterisation

D.J. Gielen
T. Gerlagh
A.J.M. Bos

Table 2.2 *Materials in the Western European MARKAL model*

Code	Material	Code	Material
MCA	CONCRETE BUILDING BLOCKS [T]	MPA	CELLOPHANE [T]
MCB	BRICKS [T]	MPB	PHB/PHV (BIOPOL) [T]
MCC	CEMENT [T]	MPC	BUTADIENE RUBBER (BR) [T]
MCD	READY MIX CONCRETE [T CONCR. EQUIV.]	MPE	POLYETHYLENE [T]
MCE	PREFAB CONCRETE [T CONCR. EQUIV.]	MPF	ACRYLONITRILE BUTADIENE STYRENE [T]
MCH	HIGH STRENGTH CEMENT [T CONV. CEM. EQUI]	MPG	STYRENE BUTADIENE RUBBER [T]
MCK	PORTLAND CEMENT CLINKER [T]	MPM	NYLON 6.6 [T]
MCL	SAND-LIME BRICKS [T]	MPN	NYLON 6 [T]
MCM	MARBLE AND GRANITE STONES [T]	MPP	POLYPROPYLENE [T]
MCQ	QUICKLIME (CaO) [T]	MPR	UF RESINS [T]
MCS	FLOOR TILES + STONEWARE [T]	MPS	POLYSTYRENE [T]
MCT	GLASS [T]	MPT	POLYETHYLENE TEREPHTHALATE [T]
MCY	GYPSUM [T]	MPU	PVC [T EXCL. ADDITIVES]
MCZ	KAOLIN [T]	MPV	PVC [T INCL. ADDITIVES]
MIA	NITRIC ACID [T]	MPW	PUR [T]
MIC	CHLORINE [T]	MSA	ASPHALT [T]
MIF	AMMONIA [T NH3 EQUIV.]	MSB	BENZENE [T]
MIK	POTASH [T K2O EQUIV.]	MSC	CAPROLACTAM [T]
MIN	NAOH [T]	MSD	DETERGENTS [T]
MIP	PHOSPHORIC ACID [T P2O5 EQUIV.]	MSE	ETHYLENE [T]
MIS	SODA [T]	MSF	PROPYLENE [T]
MIZ	SODIUM CHLORIDE [T]	MSG	C4-FRACTION [T]
MMA	ALUMINIUM [T]	MSH	BUTADIENE [T]
MMB	COPPER CATHODE [T]	MSI	BUTYLENE [T]
MMC	CAST IRON [T]	MSJ	BTX [T]
MMD	DRI QUALITY STEEL [T]	MSK	TOLUENE [T]
MMF	DIRECT REDUCED IRON [T]	MSL	LUBRICANTS [T]
MMH	HIGH QUALITY CRUDE STEEL [T]	MSM	CYCLOHEXANE [T]
MMI	IRON [T]	MSN	CUMENE [T]
MML	LOW QUALITY CRUDE STEEL [T]	MSO	DIETHYLENE GLYCOL [T]
MMM	MEDIUM QUALITY CRUDE STEEL [T]	MSP	PAINT [T PAINT EQUIVALENTS]
MMN	REINFORCEMENT STEEL [T]	MSQ	XYLENES (MIXED) [T]
MMO	HOT ROLLED SECTION STEEL [T]	MSR	NATURAL ELASTOMERES (RUBBER) [T]
MMP	HOT ROLLED COIL STEEL [T]	MST	ETHYLENE OXIDE [T]
MMQ	COLD ROLLED COIL STEEL [T]	MSU	ETHYLENE GLYCOL [T]
MMR	COLD ROLLED COIL AT&F STEEL [T]	MSV	PROPYLENE OXIDE [T]
MMS	COLD ROLLED COIL F&P STEEL [T]	MSW	ACRYLONITRILE [T]
MMT	HEAVY PLATE STEEL [T]	MSX	P-XYLENE [T]
MMU	WIRE ROD STEEL [T]	MSY	O-XYLENE [T]
MMV	ALLOY STEEL [T]	MSZ	XYLENE RESIDUE [T]
MMW	GALVANIZED/TINPLATE STEEL [T]	MTA	TEREPHTHALIC ACID [T]
MMX	COPPER CONCENTRATE [T]	MTB	BUTANOL [T]
MMY	SEMI-FINISHED COPPER [T]	MTC	ACETONE [T]
MNA	COMPOST (15% H2O) [T]	MTD	PHENOL [T]
MNB	ROUNDWOOD (15% H2O) [T]	MTE	PHTHALIC ANHYDRIDE [T]
MNC	CHIPBOARD [T]	MTF	STYRENE [T]
MNF	FIBER BOARD [T]	MTG	VINYL CHLORIDE MONOMER (VCM) [T]
MNG	GRAVEL AND SAND [T]	MTH	FORMALDEHYDE [T]
MNK	PALM KERNEL OIL [T]	MTI	UREA [T]
MNL	MARIGOLD FLOWER OIL [T]	MTJ	ANILINE [T]
MNM	HIGH QUALITY WASTE PAPER PULP [T]	MTK	ACETIC ACID [T]
MNN	LOW QUALITY WASTE PAPER PULP [T]	MTL	HEXAMETHYLENEDIAMINE [T]
MNO	MECHANICAL PULP [T]	MTM	NITRO-BENZENE [T]
MNP	PACKAGING PAPER AND SANITARY PAPER [T]	MTN	METHYL ETHYL KETON (MEK) [T]
MNQ	GRAPHIC PAPER [T]	MTO	ADIPIC ACID [T]
MNR	NEWSPRINT [T]	MTP	I-PROPANOL [T]
MNS	WOOL [T]	MTQ	TOLUENEDIISOCYANATE [T]
MNT	SAWN TROPICAL HARDWOOD (15 % H2O) [T]	MTR	2-ETHYLHEXANOL [T]
MNU	CHEMICAL PULP [T]	MTS	CARBON BLACK [T]
MNV	VISCOSE/RAYON [T]	MTU	SURFACTANT (AES) [T]
MNW	OTHER SAWN WOOD/PLYWOOD (15 % H2O) [T]	MTV	ACETIC ANHYDRIDE [T]
		ORE	IRON ORE [T]
		OXY	OXYGEN [T]
		PEL	PELLETS [T IRON EQUIV.]
		SIN	SINTER [T IRON EQUIV.]

Source: Gielen et al. 1998

Endogenous representation: The example of MESSAGEix-Materials

Based on material by Florian Maczek, Gamze Unlu

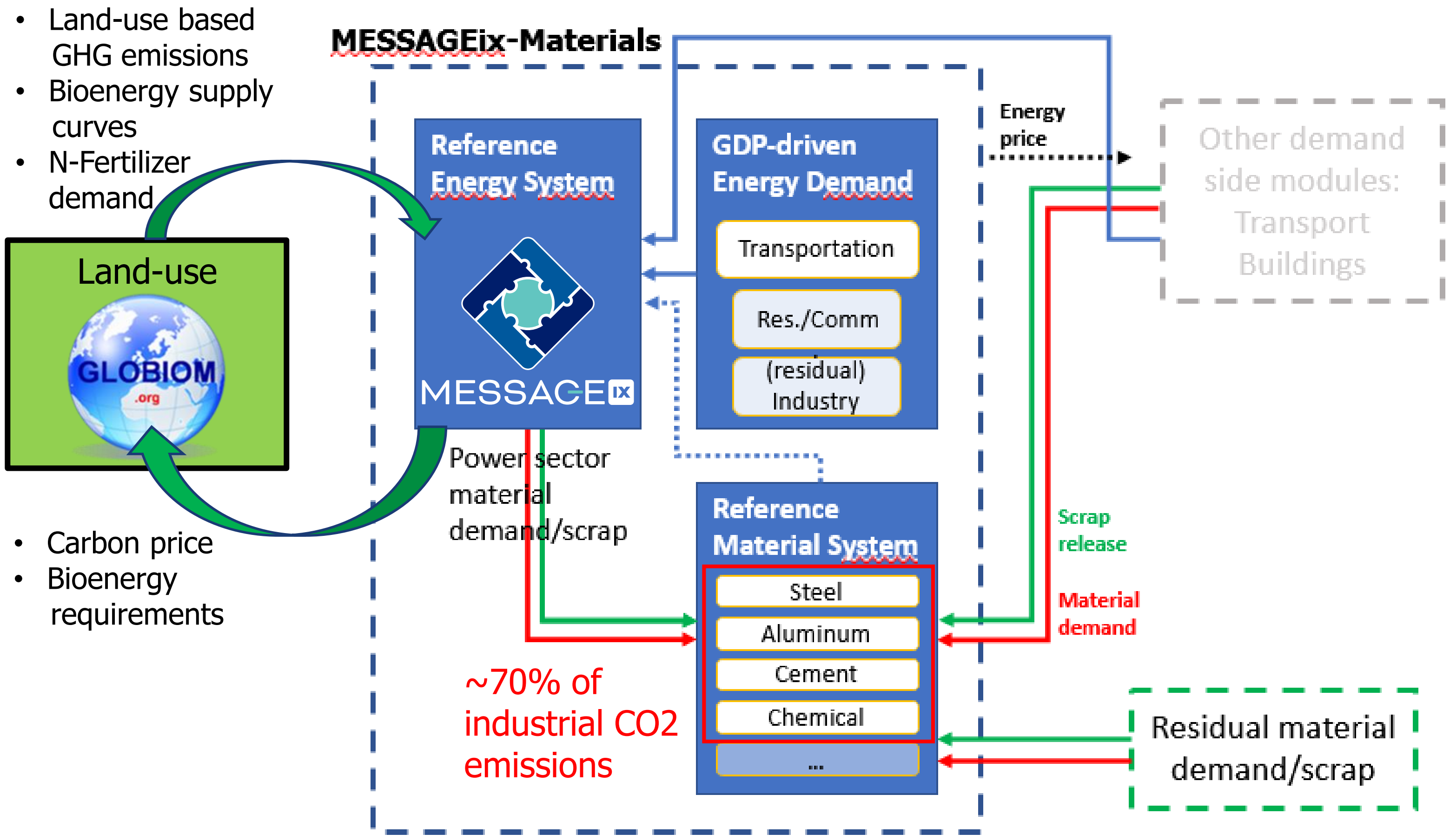
The MESSAGEix-Materials model

A **fully integrated extension** of MESSAGEix-GLOBIOM that adds:

- Explicit process-based supply chain models
- A generalized framework for biophysical material flows in the anthroposphere
- Explicit material demands (exogenous and/or endogenous)

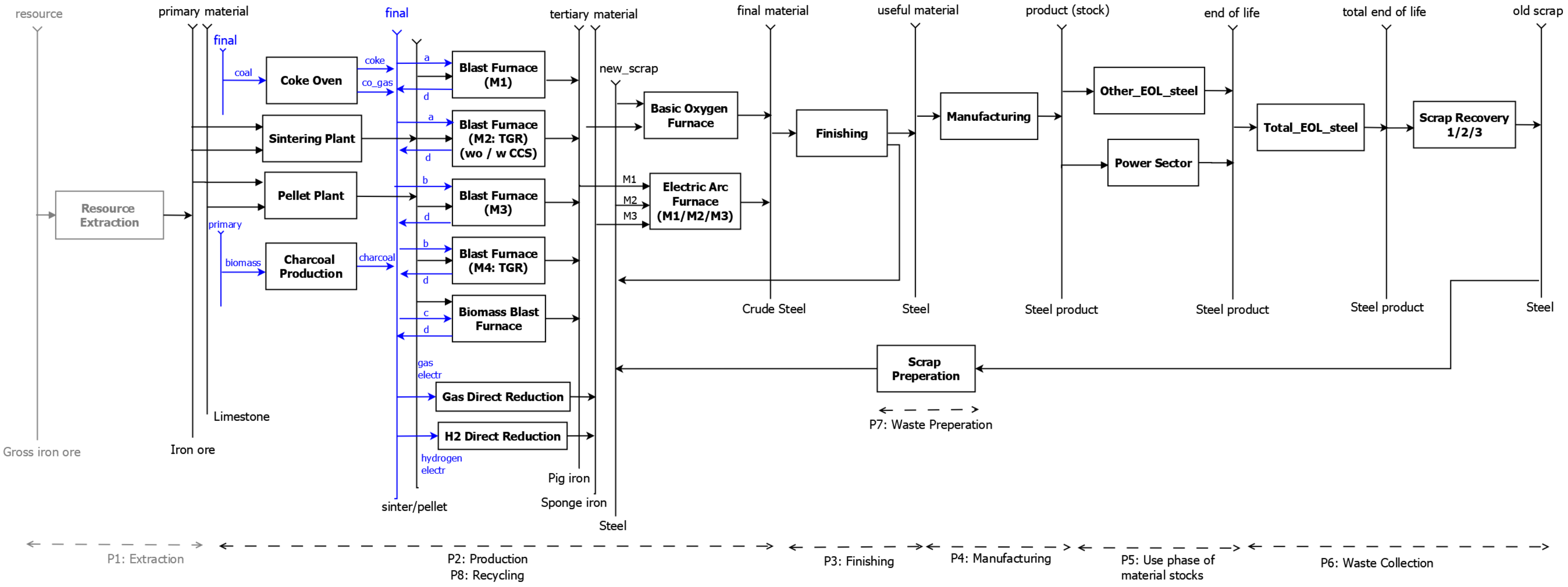
This allows:

- Assessment of new low-emission technologies in industry supply chains
- Stock and flow accounting of materials
- Assessment of demand transformations like **circular economy**

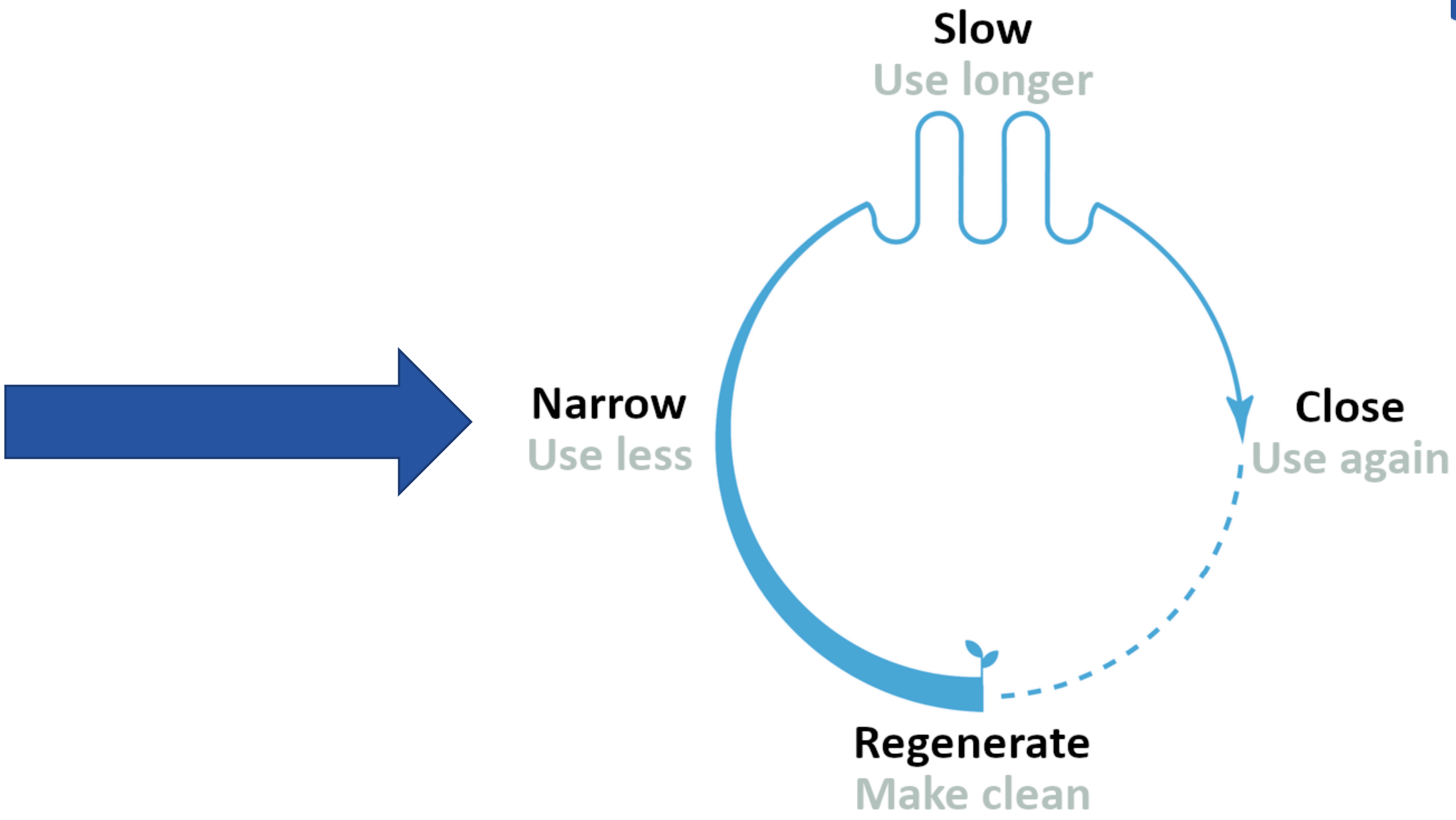


Ünlü G., Maczek F., Min J., Frank S, Glatter F., Kishimoto P., Streeck J., Eisenmenger N, Krey V, Wiedenhofer D.
MESSAGEix-Materials v1.0.0: Representation of Material Flows and Stocks in an Integrated Assessment Model (accepted). Geoscientific Model Development.

Material flows in MESSAGEix-Materials

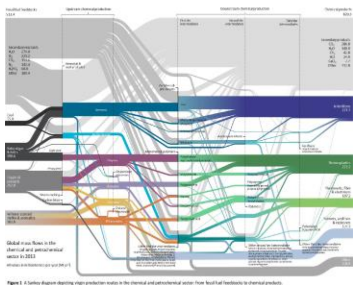


Principles of a circular economy

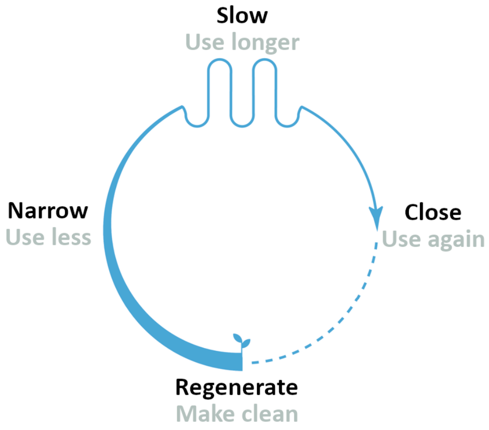


Konietzko, J., Bocken, N.M.P., Hultink, E.J. 2020. Circular ecosystem innovation: An initial set of principles. Journal of Cleaner Production. https://doi.org/10.1016/j.jclepro.2019.119942

Mapping circular economy to industry



MFAs, LCAs, international industry data providers



Circular economy principles

MESSAGEix Buildings

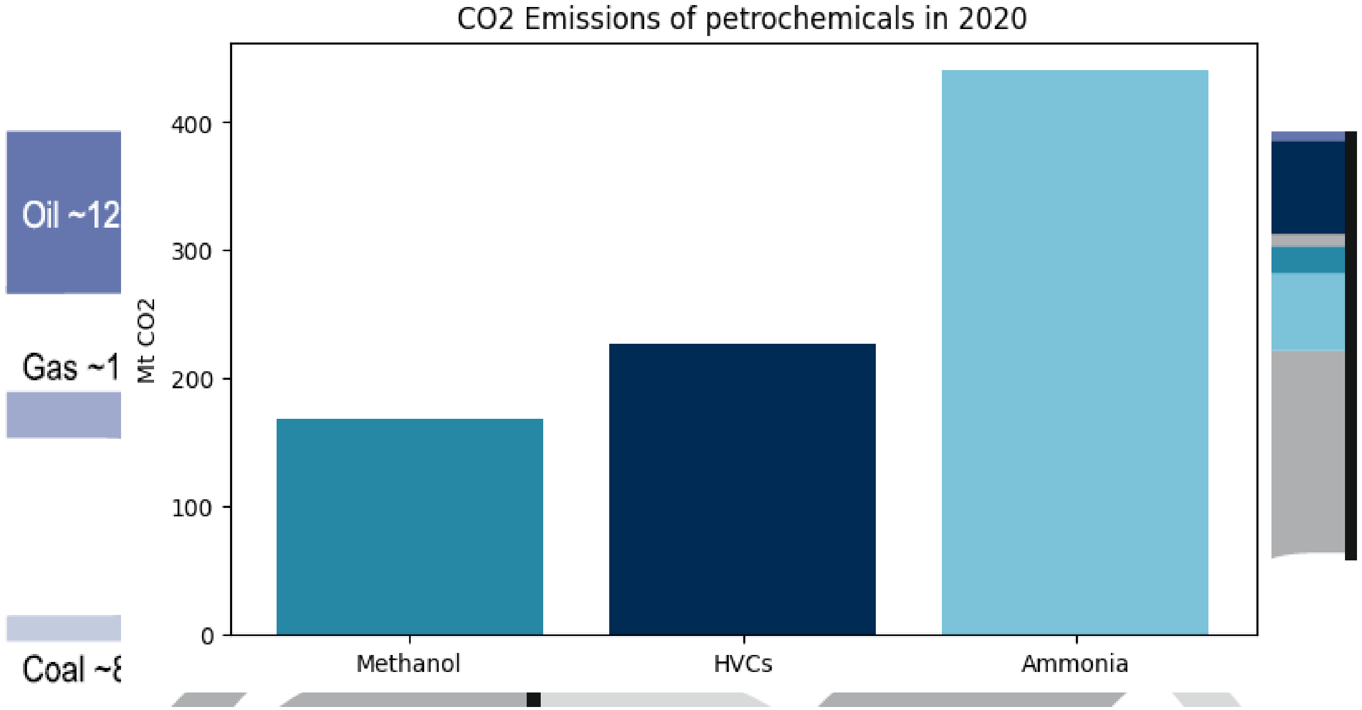
GLOBIOM.org

Demand sector models

MESSAGEix Materials

The petrochemical sector

- 3 main primary chemical groups:
  - **High Value Chemicals (Ethylene, Propylene, Aromatics)**
  - **Ammonia**
  - **Methanol**
- building blocks for almost every organic chemical
- responsible for ~60% of overall sector emissions



Isella A, Manca D. GHG Emissions by (Petro)Chemical Processes and Decarbonization Priorities—A Review. *Energies*. 2022;15(20):7560. https://doi.org/10.3390/en15207560

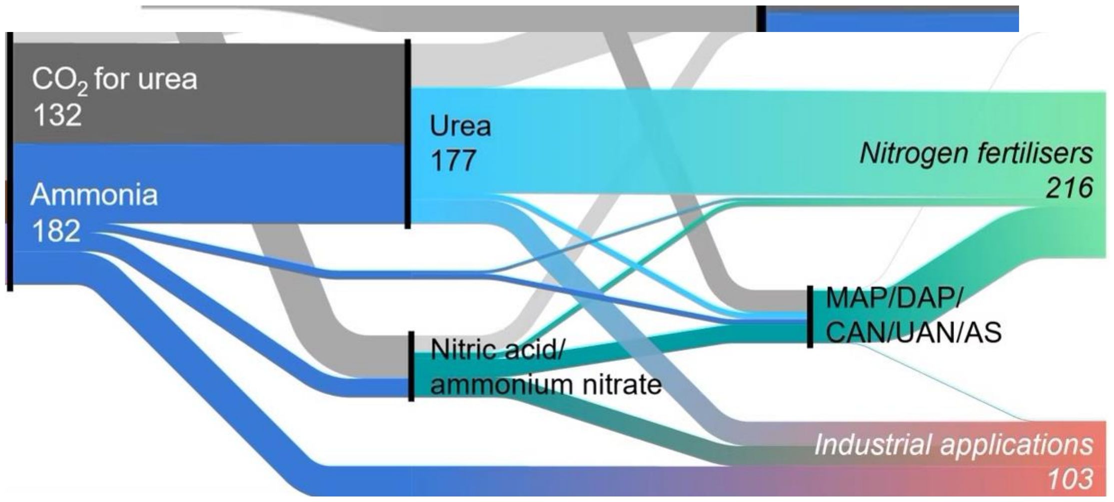
IEA. The Future of Petrochemicals - Towards more sustainable plastics and fertilisers. (2018).

Scenario Design: Circular Economy and Climate policy

		Circularity Measures	
Climate Policy		**Baseline**	**Circular Economy**
	No Policy	No Policy	No Policy + CE
	2 Degrees	2°C	2°C + CE

Circular economy in the ammonia industry

- 70-80% of ammonia is used to produce nitrogen fertilizers
- Ammonia is still produced from fossil fuels
- Fertilizer use can be used more efficiently
- Fertilizers are a „single-use“ product
- Fertilizers cannot be recycled
- Production from biomass or green hydrogen possible



IEA (2021), Ammonia Technology Roadmap, IEA, Paris
https://www.iea.org/reports/ammonia-technology-roadmap, License: CC BY 4.0

Narrow Slow Close Regenerate

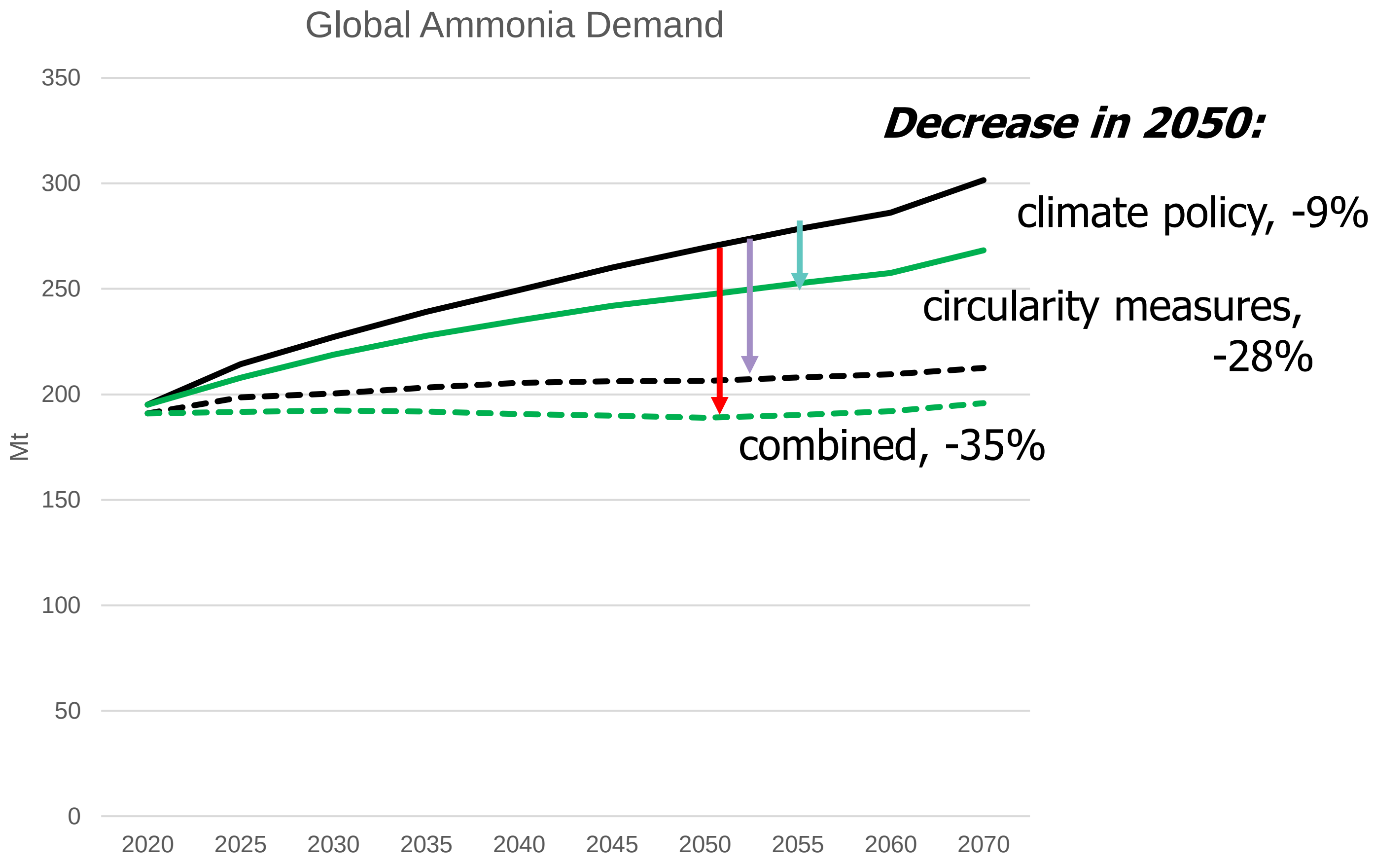
Modelling CE and climate change policy in the ammonia industry

Circularity Measure		
Chemicals	**Baseline**	**Circular Economy**
Ammonia (NH_3)		
No climate policy	No Policy	No Policy + CE
2°C climate policy	2°C	2°C + CE

Climate Policy

Narrow:

SDG12: reducing livestock calorie intake in overconsuming countries to 430 kcal/capita/day and halving food waste



Ammonia production from MESSAGEix-Materials under different scenarios

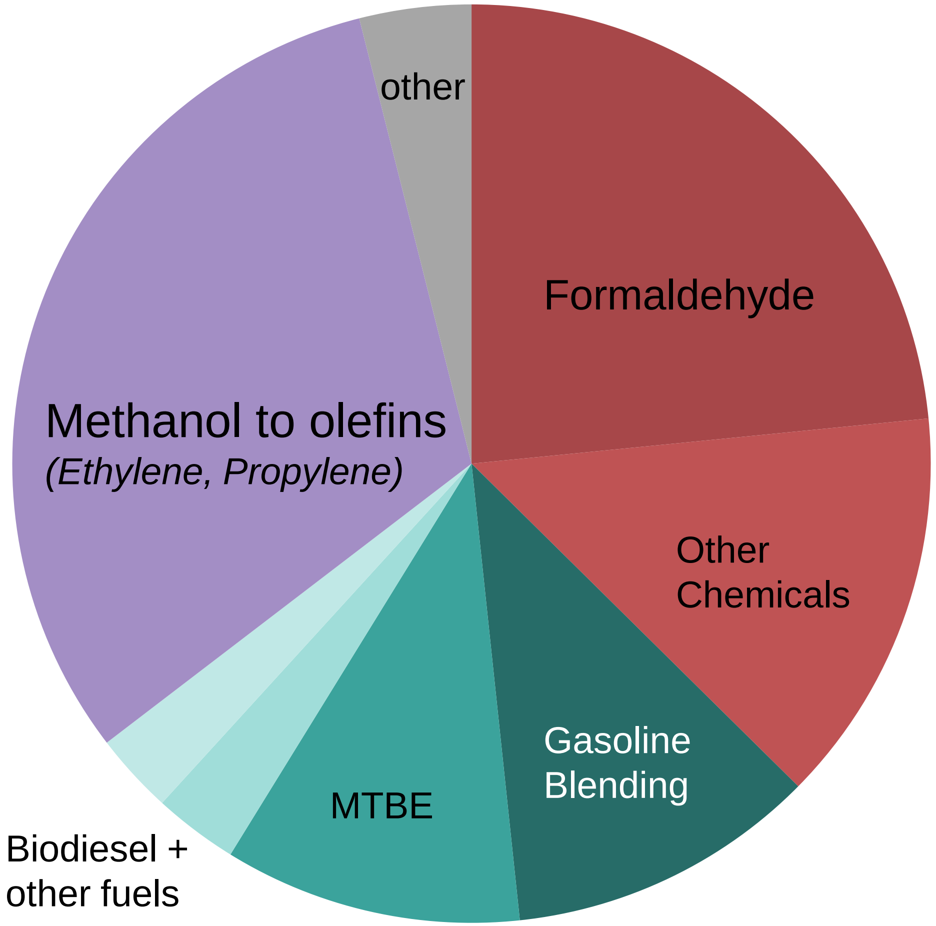
Circular economy and the methanol industry

Narrow and Regenerate:

1. **Methanol to olefins**

2. **Formaldehyde**

Global methanol demand



Dolan (2020), Emerging Global Energy Markets, Methanol Institute

adapted from: *MMSA World Supply and Demand Summary for Methanol Institute*

Circular economy in the methanol industry

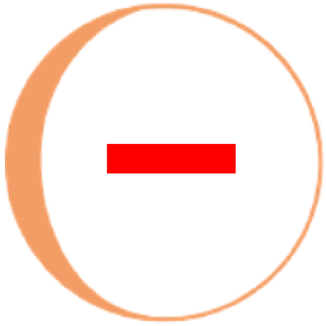
Narrow and Regenerate:

1. Methanol to olefins

- Most mature alternative to conventional olefin production that can utilize biogenic feedstocks

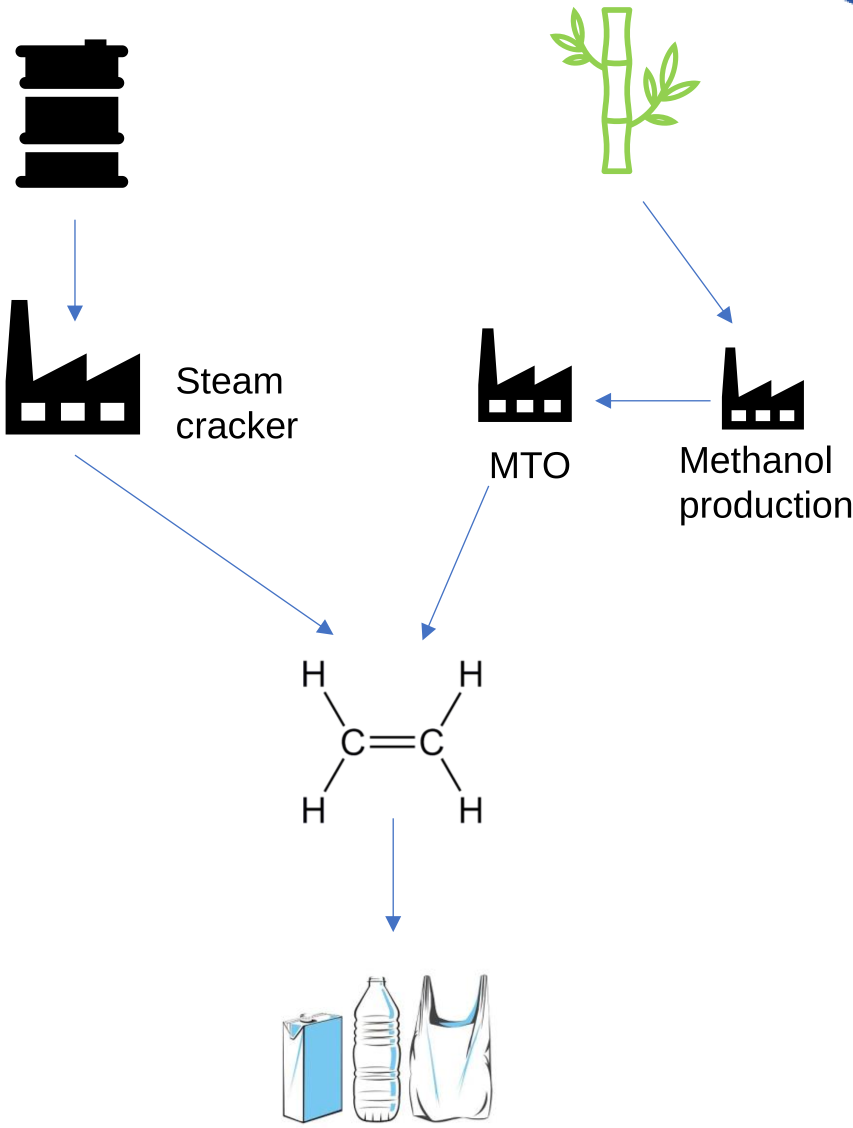
  Already deployed at industrial scale in China (using coal)

- Less effficient than conventional petrochemistry



Narrow

Regenerate



Circular economy in the methanol industry

Narrow and Regenerate:

2. Formaldehyde

- Mainly used to produce formaldehyde resins
- resins mainly used in engineered wood products (EWPs)
- EWPs historically „upcycling" of saw mill residues
- modern EWPs made of bigger solid wood pieces
- EWPs can replace concrete in buildings construction

Oriented strand board *(Source: dataholz.eu)*

Cross laminated timber *(Source: dataholz.eu)*

HoHo Vienna *(Source: dataholz.eu)*

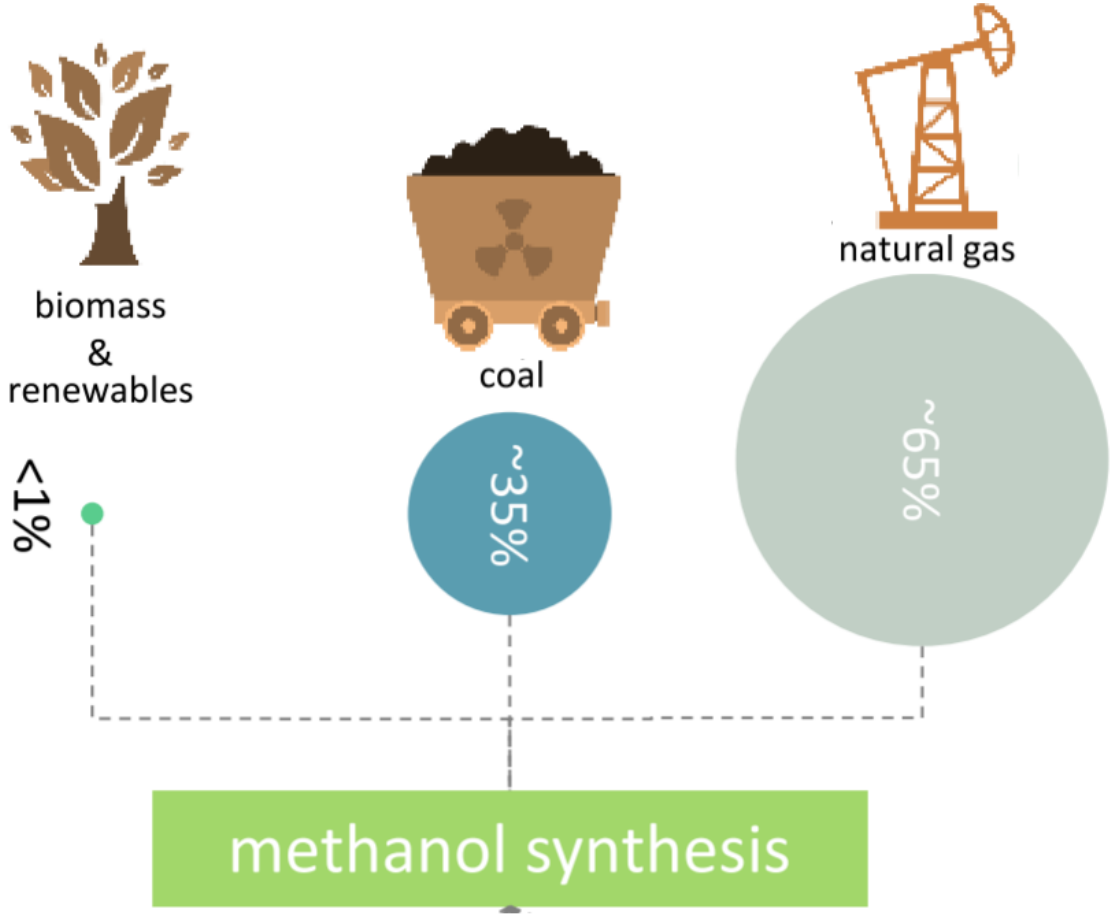
Circular economy and the methanol industry

Narrow and Regenerate:

1. **Methanol to olefins**

2. **Formaldehyde**

3. **Methanol is currently produced from fossil fuels**



Dolan (2020), Emerging: Global Energy Markets, Methanol Institute

adapted from: *MMSA World Supply and Demand Summary for Methanol Institute*

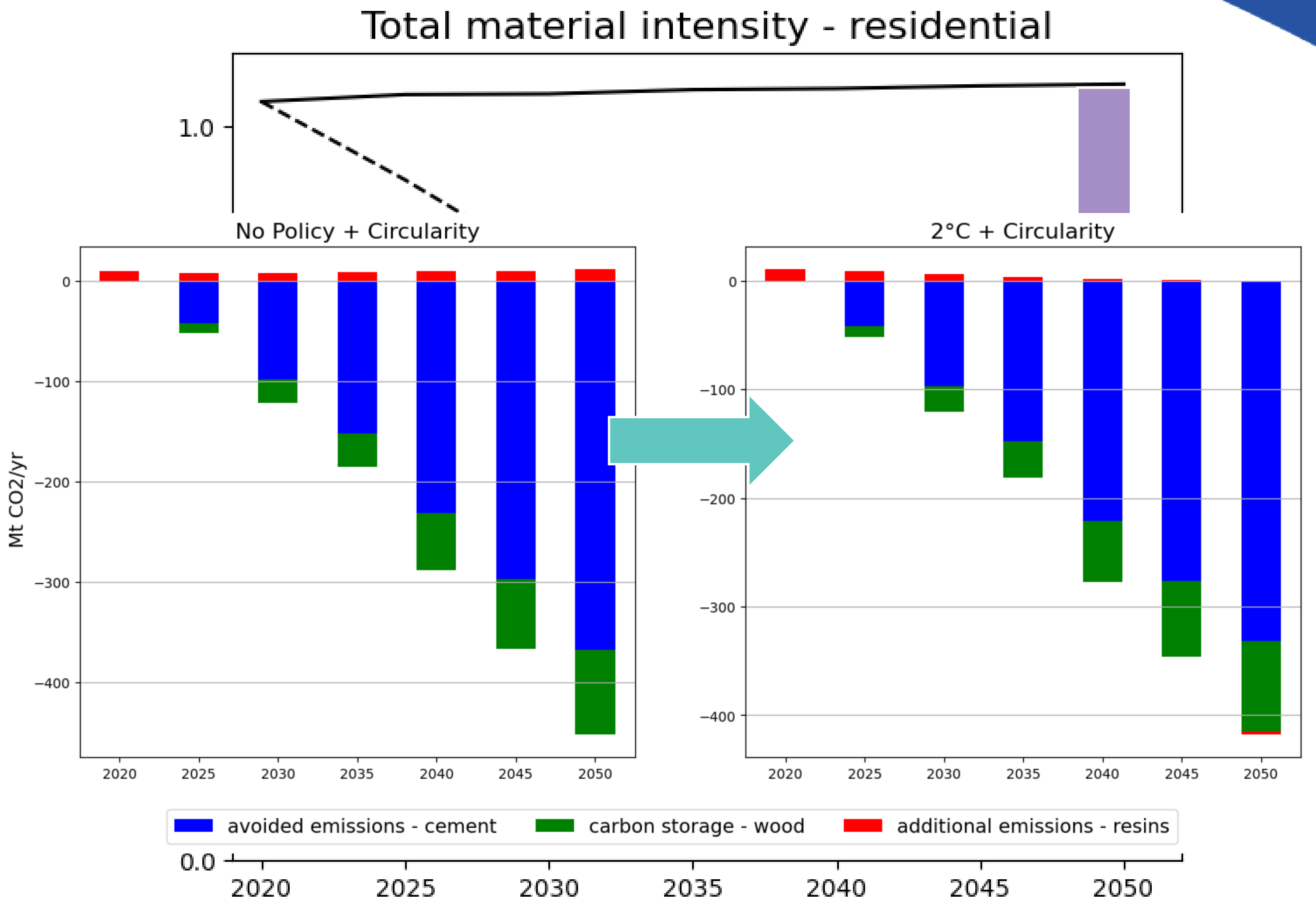
Methanol

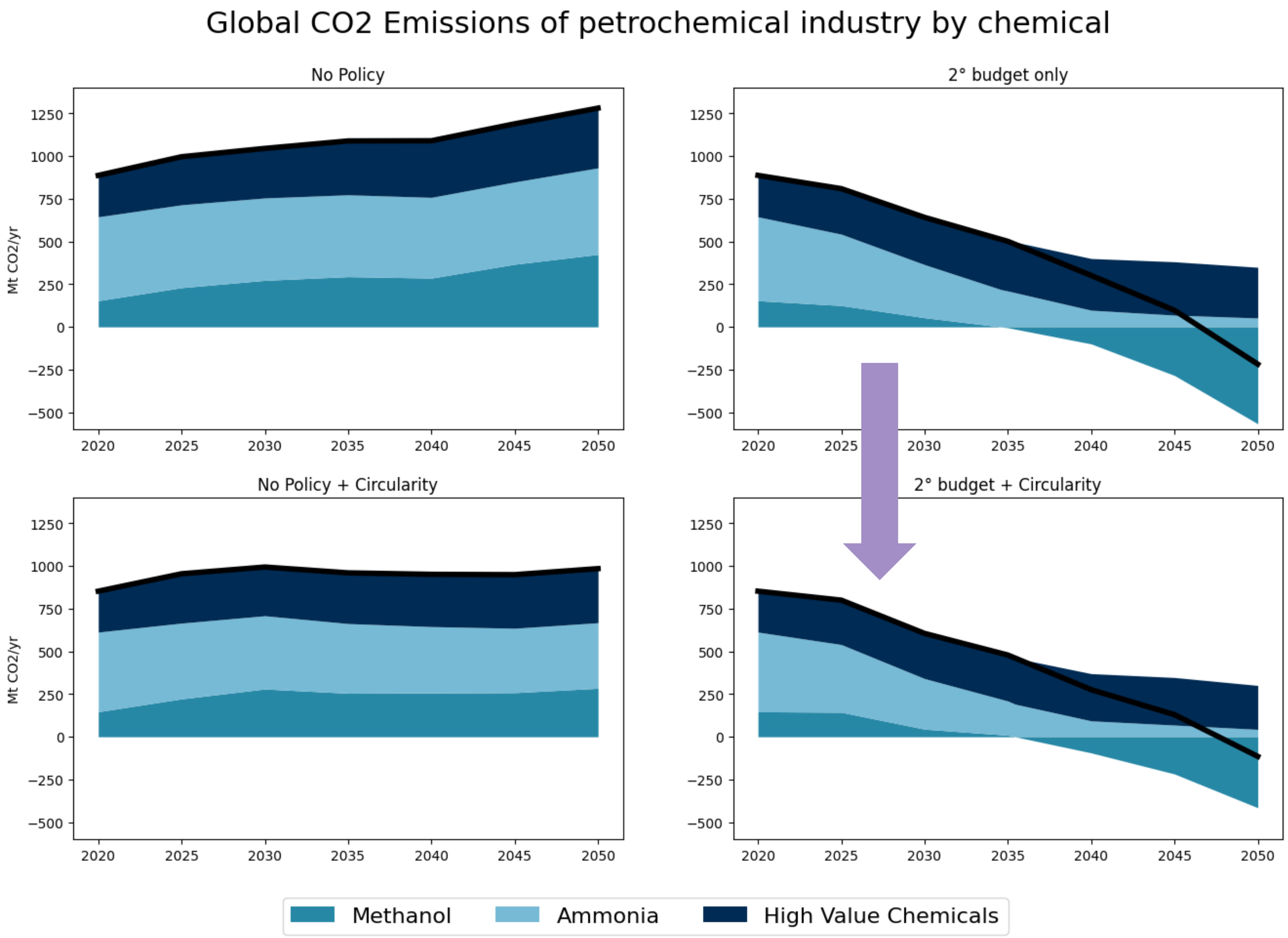
Circularity Measure		
Chemicals	**Baseline**	**Circular Economy**
Methanol		
No climate policy	No Policy	No Policy + CE
2°C climate policy	2°C	2°C + CE

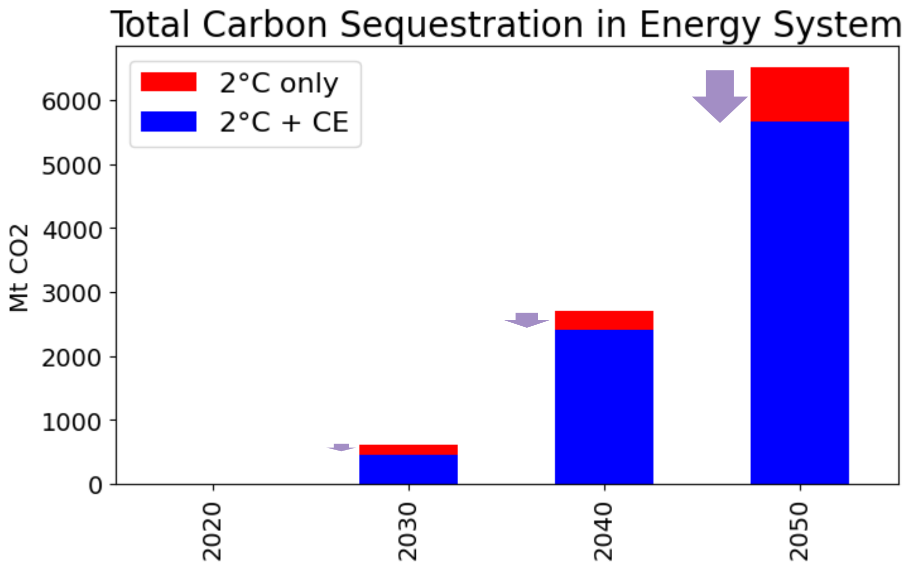
Climate Policy

Narrow & Regenerate:

Substitute conventional concrete-steel construction with modern timber construction using EWPs







-15% CCS **system-wide** in 2050 if CE policies are applied to petrochemical sector

Conclusion

- The petrochemical industry will remain to be an energy-intensive sector:
    - Conventional processes are close to thermodynamic optima
    - Renewable production is more energy intensive
- Thus, circular economy is highly relevant by increasing the feasibility of net-zero targets
- Integrated assessment models allow to assess cross-sectoral effects of circular economy strategies

Circular strategies for a low-carbon building sector

Based on material by Alessio Mastrucci, Xiaoyang Zhong, Florian Maczek, Fei Guo, Bas van Ruijven

CIRCULARITY SCENARIOS
FOR THE EU RESIDENTIAL SECTOR

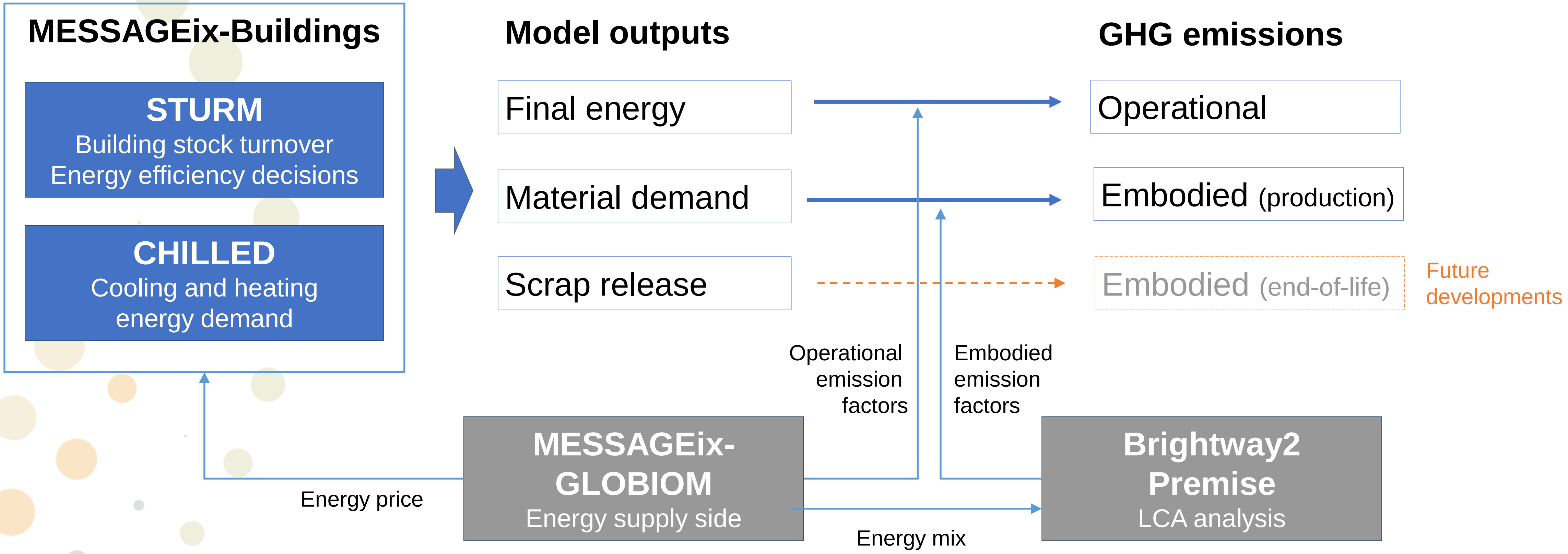
Motivation

- The built environment and construction sector are responsible for about 50% of all extracted material in the EU.
- **Circularity strategies** have great potential to reduce material demands and GHG emissions of buildings along their life-cycle.

Goals

- Explore the **effects of circularity interventions in future climate change mitigation scenarios** for the EU residential building stock.
- Develop illustrative circularity scenarios using a detailed **building sector model** (MESSAGEix-Buildings) linked to integrated assessment modelling (IAM).

MODELLING FRAMEWORK



Ref: Mastrucci et al. (2024) Circular strategies for building sector decarbonization in China: A scenario analysis. Journal of Industrial Ecology

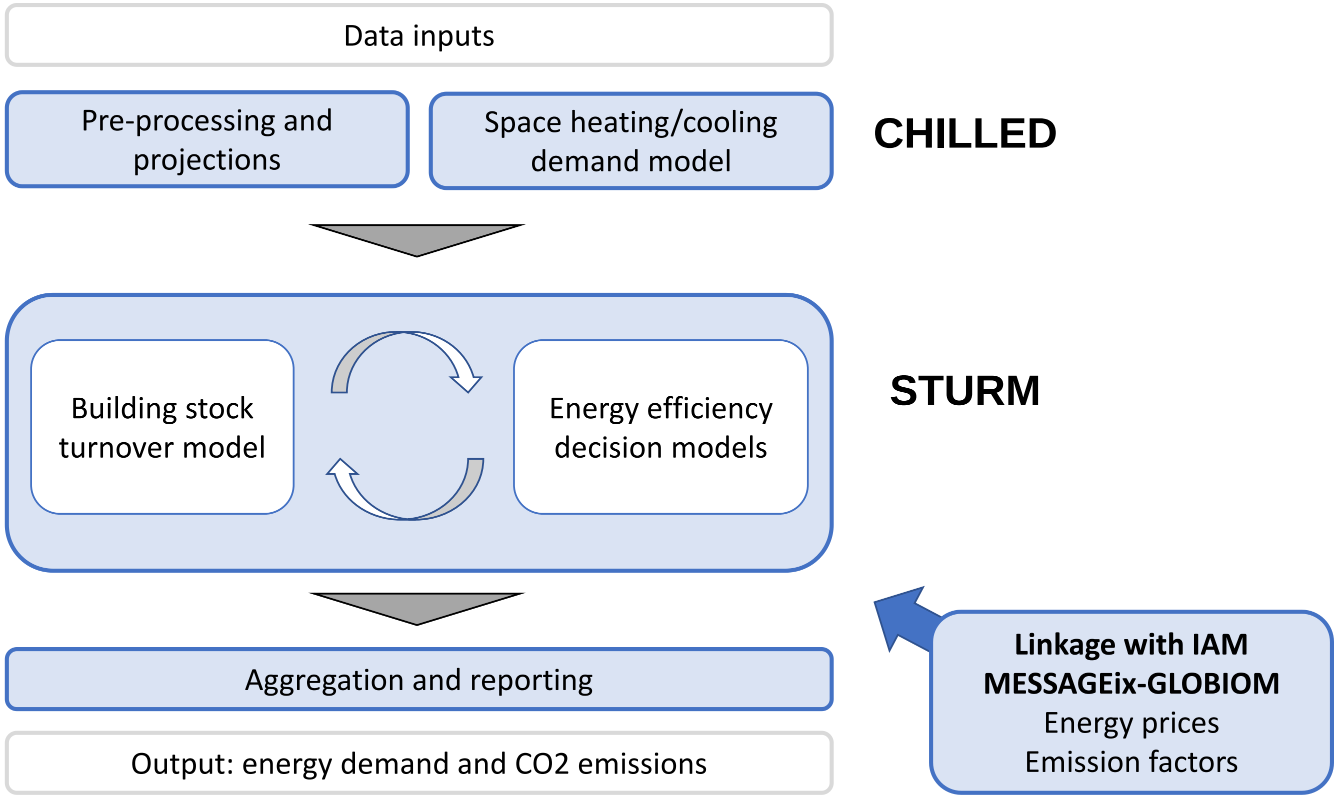
MESSAGEix-BUILDINGS: CHILLED – STURM MODELS

Energy demand model (CHILLED)

- Variable Degree Days
calculated over a spatial grid

Stock turnover model (STURM)

- Material Flow Analysis
New constructions and demolitions
- Discrete choice models
Household decisions on renovation and new construction based on life-cycle costs (investment, operation, intangible)



Ref: Mastrucci et al. (2021) Global scenarios of residential heating and cooling energy demand and CO_2 emissions. Climatic Change.

RESIDENTIAL IMPLEMENTATION FOR THE EU

- **Temporal resolution:** 5-10 years
  base year 2020
- **Spatial resolution:** country
- **End-uses:** Heating, Hot water, Cooling
- **Dimensions**: Climatic zones, Location (urban, rural), Housing types, Household types, Energy carriers, Construction materials
- **Input data:** statistics, building libraries, household surveys data, literature

Residential

Single-Family

Multi-Family

Energy efficiency cohorts	Energy carriers Space heating	Construction Materials
Existing Non-renovated <1945 1946-1990 1991-2015	Solid biomass Coal District heat. Gas Electricity Oil	Aluminum Concrete (Cement) Copper Glass Steel Wood
Existing Renovated Standard Advanced		
New Standard Advanced		

CIRCULAR ECONOMY STRATEGIES

Narrow-Slow-Close Framework

- **Narrow:** focus on reducing material stock buildup
- **Slow:** focus on keeping stocks in use for longer
- **Close:** focus on recycling and reuse

Circular: Combined Narrow-Slow-Close

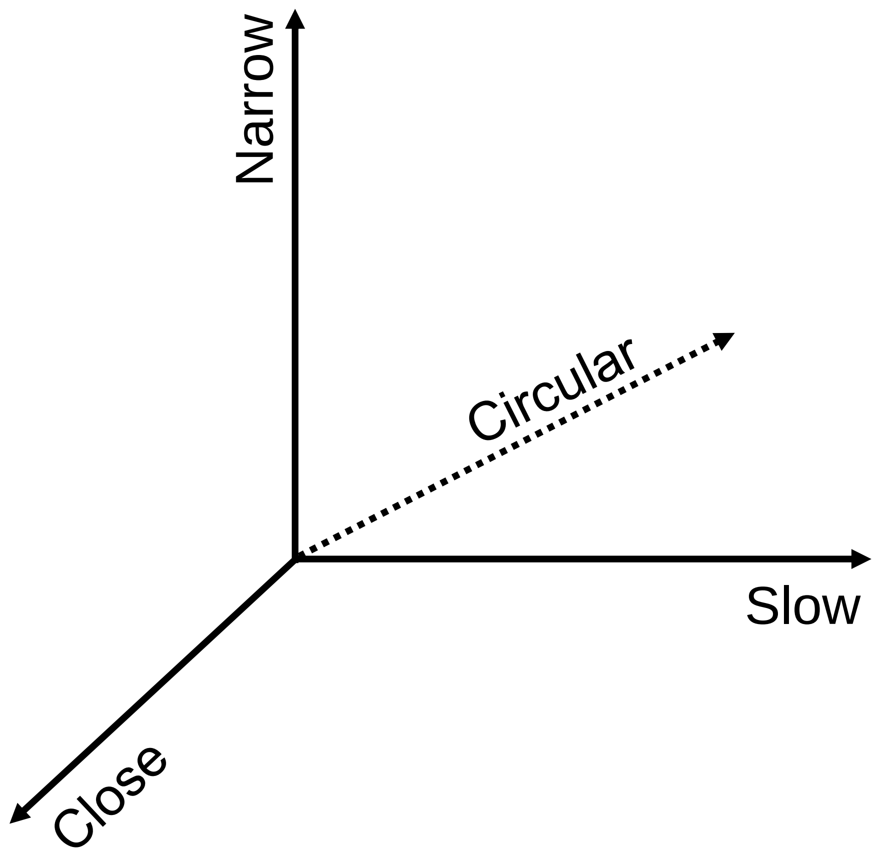


Figure courtesy: Volker Krey

CIRCULARITY SCENARIOS
FOR THE EU RESIDENTIAL SECTOR

Scenarios

Reference — Shared Socioeconomic Pathway SSP2
Continuation of current trends

Narrow:

Floor — **Floorspace reduction**
Reduction in new and existing buildings via co-housing and compact urban forms (-10% per-cap by 2050)

Wood — **Switch to wood-based construction**
Gradual switch in new constructions (up to 50% by 2030)

Slow:

Lifetime — **Lifetime extension**
New buildings (+25%): improved design
Existing buildings (+10%): higher renovation (2%/yr)

Circular — All strategies above combined

Climate policies

Current Policies (NPi)

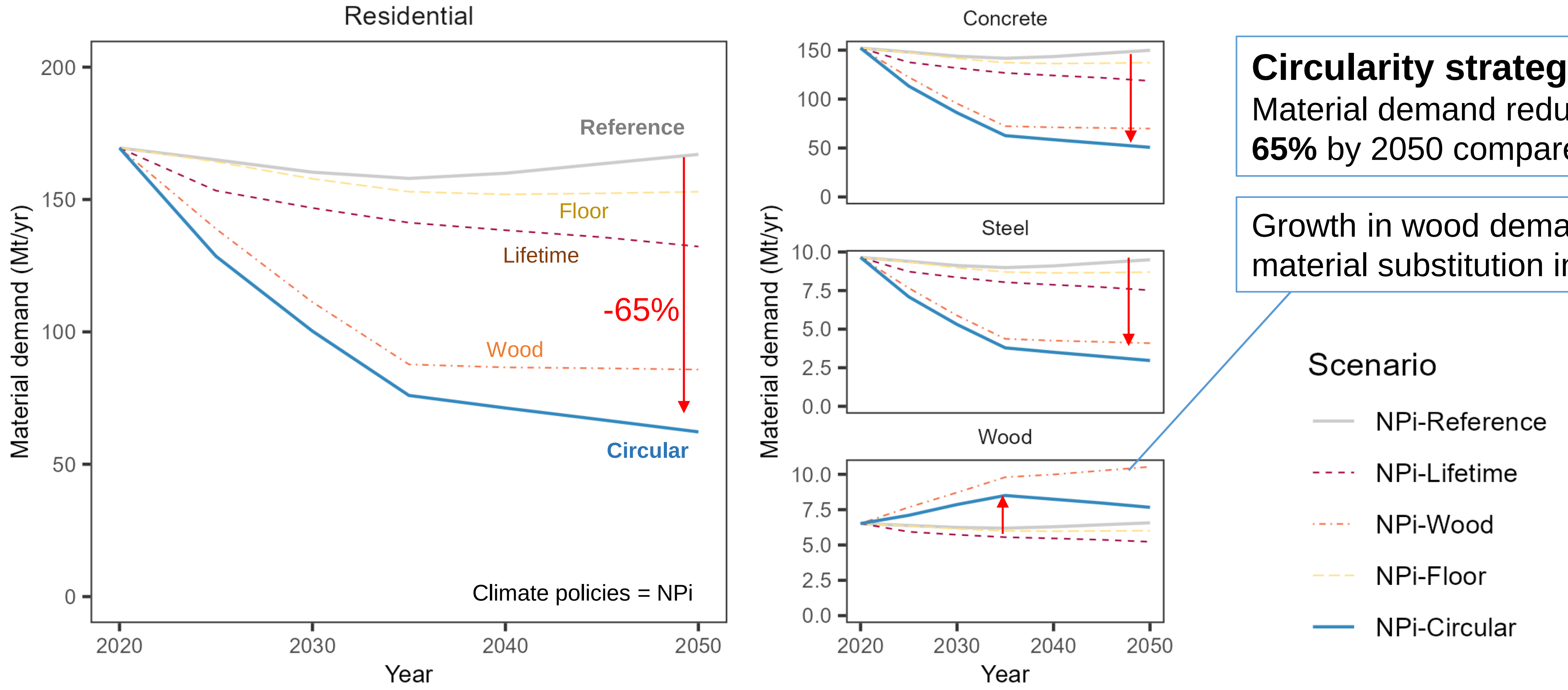
No stringent climate policies

Stringent climate policies (1.5°C)

Climate policies consistent with 1.5C targets

Model: MESSAGEix-Buildings (IIASA)
Life-cycle stages: material production, building operation (heating and cooling)
Materials: concrete, steel, wood, aluminum, copper, glass

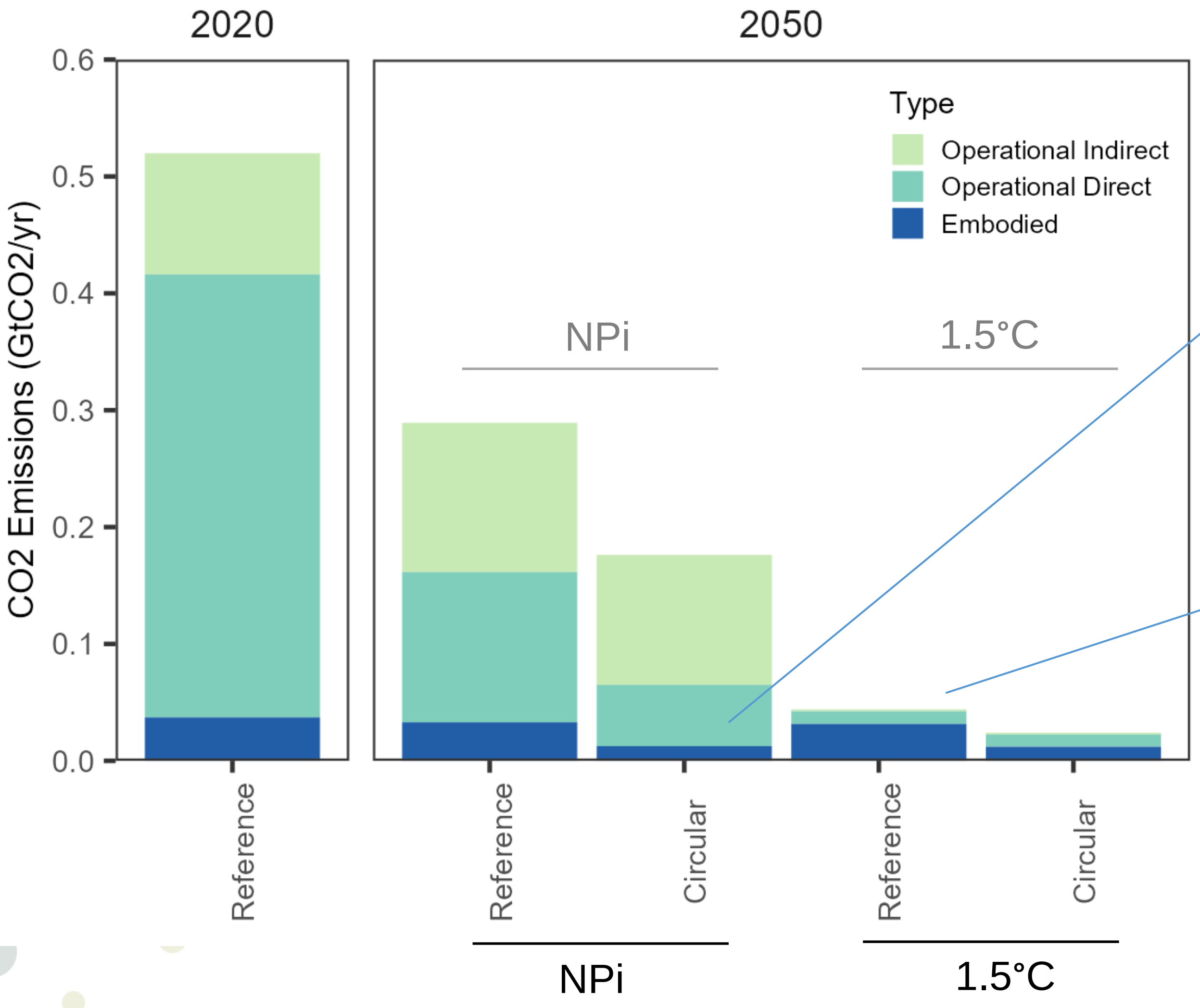
MATERIAL DEMAND - PRELIMINARY RESULTS



Circularity strategies (Narrow-Slow)
Material demand reduction potential:
65% by 2050 compared to Reference

Growth in wood demand driven by material substitution in new buildings

CO_2 EMISSIONS - PRELIMINARY RESULTS



Circularity strategies (Narrow-Slow)
CO_2 emission reduction potential by 2050 with no stringent climate policies (NPi):
-60% of embodied emissions
-40% of total emissions
(embodied+operational)

Climate mitigation scenarios (1.5°C):
Embodied emissions dominate:
Circularity strategies can deliver additional emission reductions

CONCLUSIONS: CIRCULARITY IN BUILDINGS

- The three investigated circularity strategies can reduce **up to 65% material demand** and **60% of CO_2 emissions embodied in residential buildings** compared to a reference scenario in 2050.
- These circular strategies deliver additional embodied emission reductions **critical to achieve ambitious climate targets**.

- Study published on the assessment of circularity strategies for building sector decarbonization in China.

JOURNAL OF INDUSTRIAL ECOLOGY
International Society for Industrial Ecology

RESEARCH ARTICLE | Open Access

Circular strategies for building sector decarbonization in China: A scenario analysis

Alessio Mastrucci, Fei Guo, Xiaoyang Zhong, Florian Maczek, Bas van Ruijven

First published: 11 July 2024 | https://doi.org/10.1111/jiec.13523

Ex-post assessment: Combining LCA methods and IAMs

Based on material by Gunnar Luderer (PIK), Romain Sacci, Alvaro Hahn (PSI)

Environmental assessment of alternative power sector decarbonization strategies

Key research questions:

- What are environmental co-benefits and adverse side-effects of the low-carbon transformation?
- How do alternative decarbonization pathways perform in terms of their environmental impacts?

Key publications:

- Pehl et al. (2017) “Understanding Future Emissions from Low-Carbon Power Systems by Integration of Life-Cycle Assessment and Integrated Energy Modelling.” *Nature Energy* 2 (11). https://doi.org/10.1038/s41560-017-0032-9.
- Arvesen et al. (2018). Deriving life cycle assessment coefficients for application in integrated assessment modelling. *Environmental Modelling and Software*, *99*, 111–125. https://doi.org/10.1016/j.envsoft.2017.09.010
- Luderer et al. (2019): Environmental co-benefits and adverse side-effects of alternative power sector decarbonization strategies, *Nature Communications* 10:5229. https://doi.org/10.1038/s41467-019-13067-8

Integrating IAM and LCA approaches

- **Integrated Assessment Modeling (IAM)** community considers the dynamics of the long-term transformation, but so far focused on climate change mitigation. Policy interventions can be considered explicitly using scenario approaches.
- **Life cycle assessment (LCA)** considers broad set of impacts, but mostly focuses on individual technologies and apply static assumptions, thus not considering the long-term system evolution

Prospective LCA methodology

- Aspects of future **technological change** addressed within the LCA
  - Changing performance of individual electricity generation technologies
  - Projected improvements in selected industrial processes
- **Coherent life cycle descriptions** for power generation options based on multiple case studies to allow for uncertainty estimates, choice of impacts based on ReCiPe methodology
- Separate **construction, operation, end-of-life** phases to be combined with tracking of capacity vintages in IAM
- **Embodied (upstream) energy requirements** of power technologies to account for indirect effects

References

- **Gibon, T.**, Wood, R., Arvesen, A., Bergesen, J.D., Suh, S., Hertwich, E.G., 2015. A methodology for integrated, multiregional life cycle assessment scenarios under large-scale technological change. Environmental Science & Technology.
- **Hertwich, E.G.,** Gibon, T., Bouman, E.A., Arvesen, A., Suh, S., Heath, G.A., Bergesen, J.D., Ramirez, A., Vega, M.I., Shi, L., 2015. Integrated life-cycle assessment of electricity-supply scenarios confirms global environmental benefit of low-carbon technologies. PNAS 112(20)

P I K

Workflow

Integrated Assessment Model

Capacities and production
- New Construction [MW/yr]
- Electricity Production [kWh_{el}/yr]
- Decomissions [MW/yr]

Impacts represented directly
- Air pollution
- Water use
- Fossil resources, CO2 storage

MAgPIE bioenergy scearios

Prospective Life-Cycle Assessment (THEMIS)

Mid-point coefficients (technology-specific) per kWh_{el}, MW, e.g.,
- Toxicity
- Land occupation
- Eutrophication
- Metal depletion
- Ionizing radiation

Embodied energy coefficients

Related **midpoint impacts**, *including indirect effects* due to embodied energy
- Air pollution (PM, O3, TAC)
- Water
- Fossil depletion, CCS

Joint assessment of midpoint and endpoint impacts

Innovations

- **Integration of Integrated Assessment Modeling and Life-Cycle-Assessment**
- **Air pollution** and **water use** represented by source in IAMs
- **Biomass** land and fertilizer requirements, as well as land-use change emissions from the MAgPIE land-use model
- **Comprehensive coverage** of all major power technologies
- Other impact categories (**toxicity, material resource requirements, land occupation, ionizing radiation,…**) from prospective LCA model THEMIS, accounting for future changes in technology performance
- **Grid and storage requirements** estimated based on DLR's REMix model (Berrill et al., 2016; Scholz et al., 2016; Pietzcker et al., 2016)
- **Systematic uncertainty analysis** based on multiple case studies (LCA) and multi-model IAM ensemble

P I K

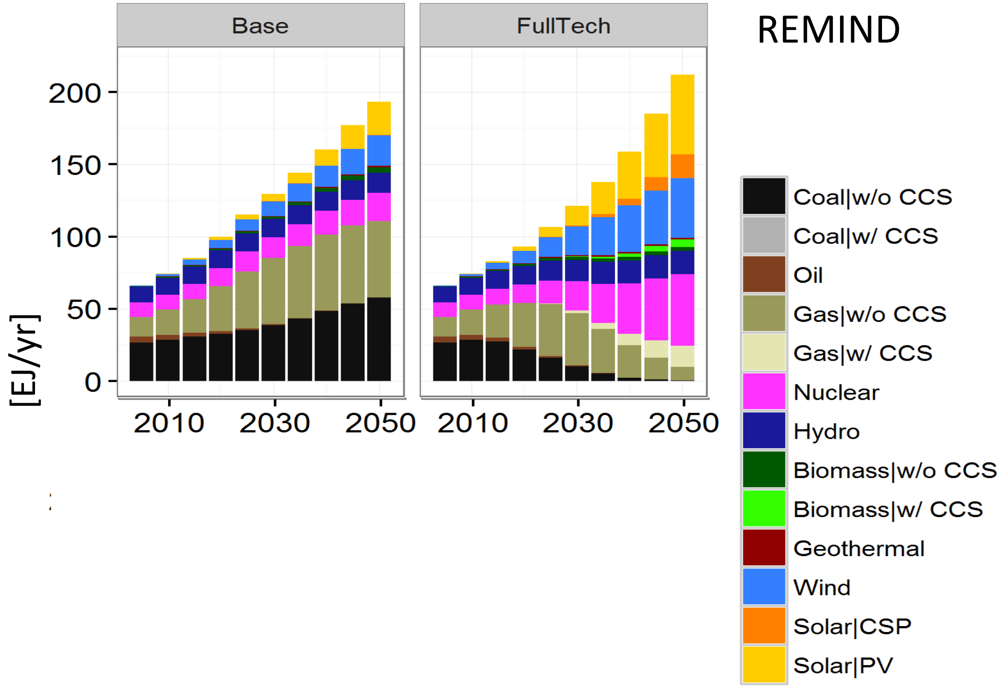
IAM scenarios considered

Climate policy implementation

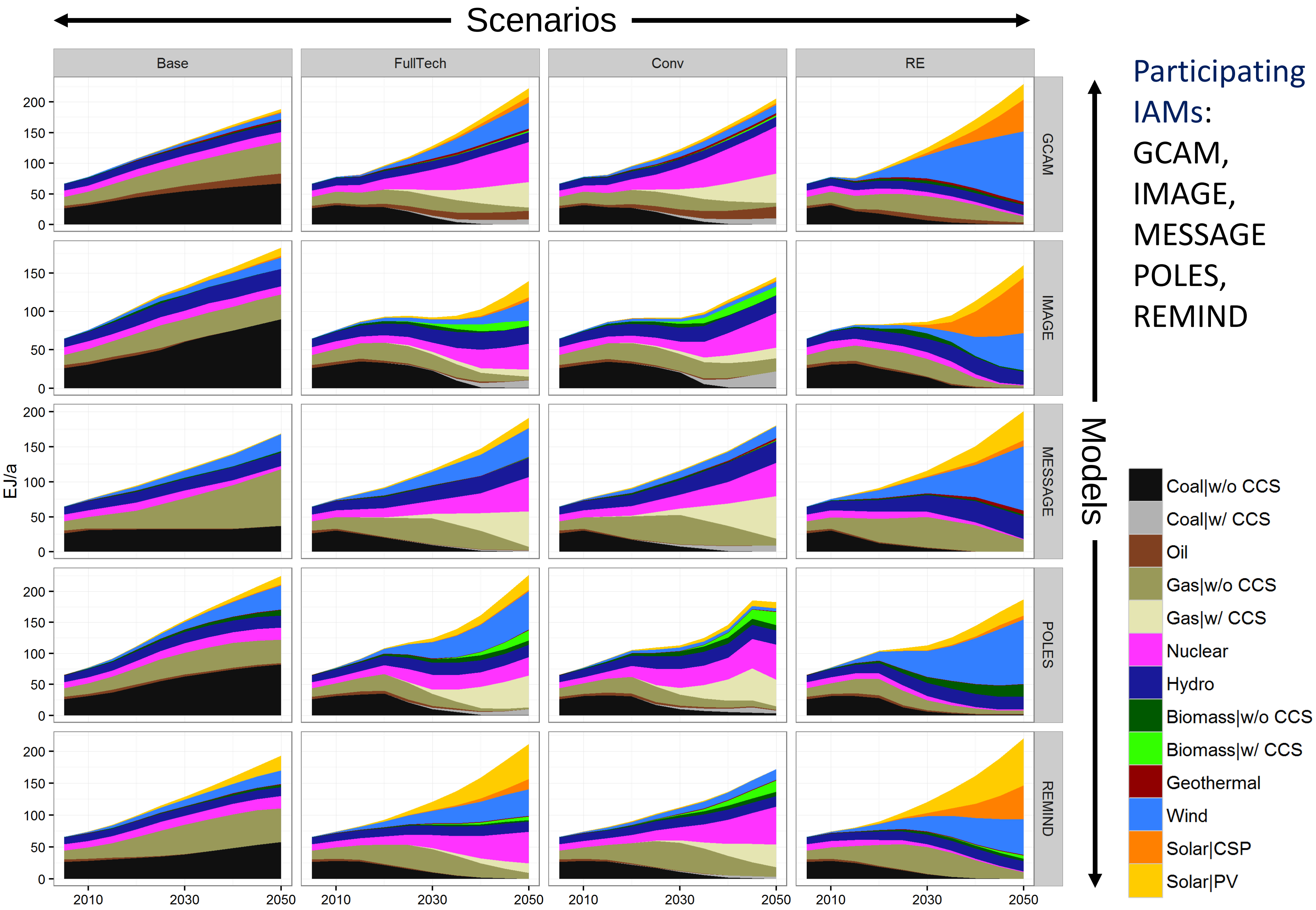
- Policy scenarios with constraint on cumulative 2011-2050 power sector emissions of 240 $GtCO_2$
- Comparable policy ambition in other sectors

Three different technology scenarios:

- **FullTech**
- **Conventional** (Wind and solar limited to 10%)
- **Renewable** (nuclear phase-out, no CCS for power stations)

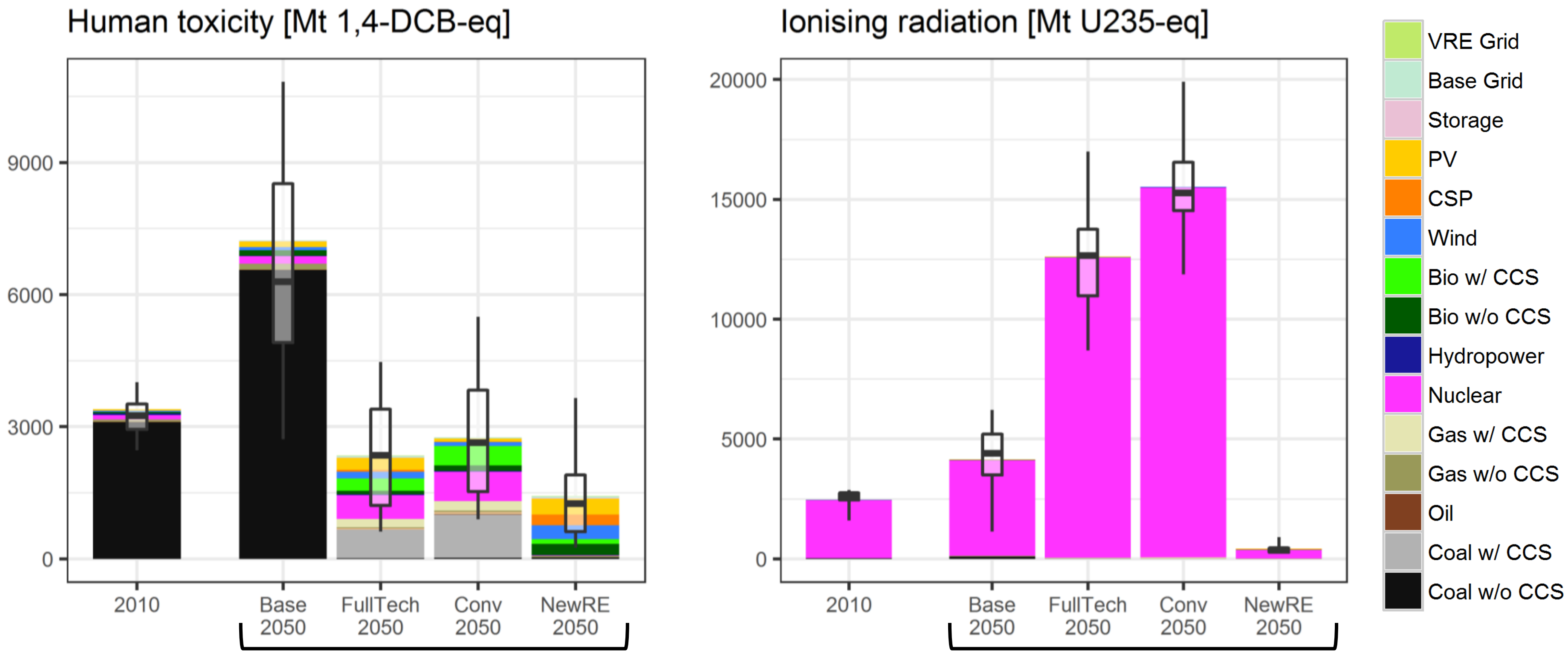


IAM scenarios considered

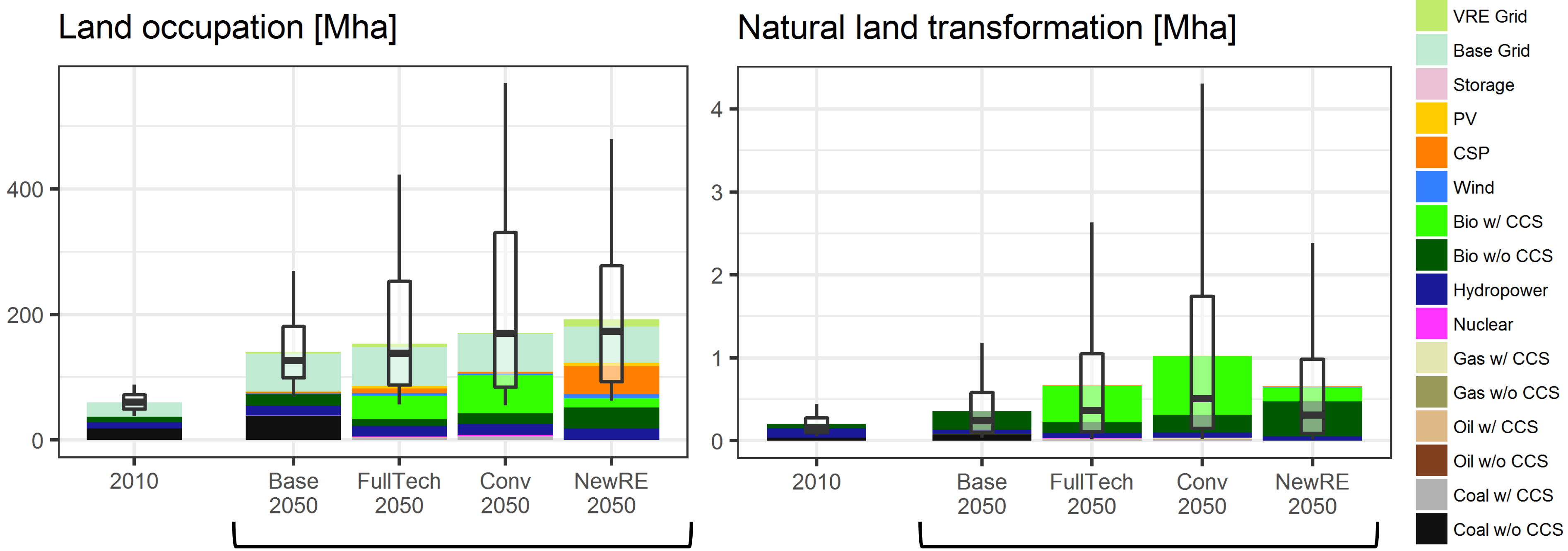


Participating IAMs:
GCAM,
IMAGE,
MESSAGE
POLES,
REMIND

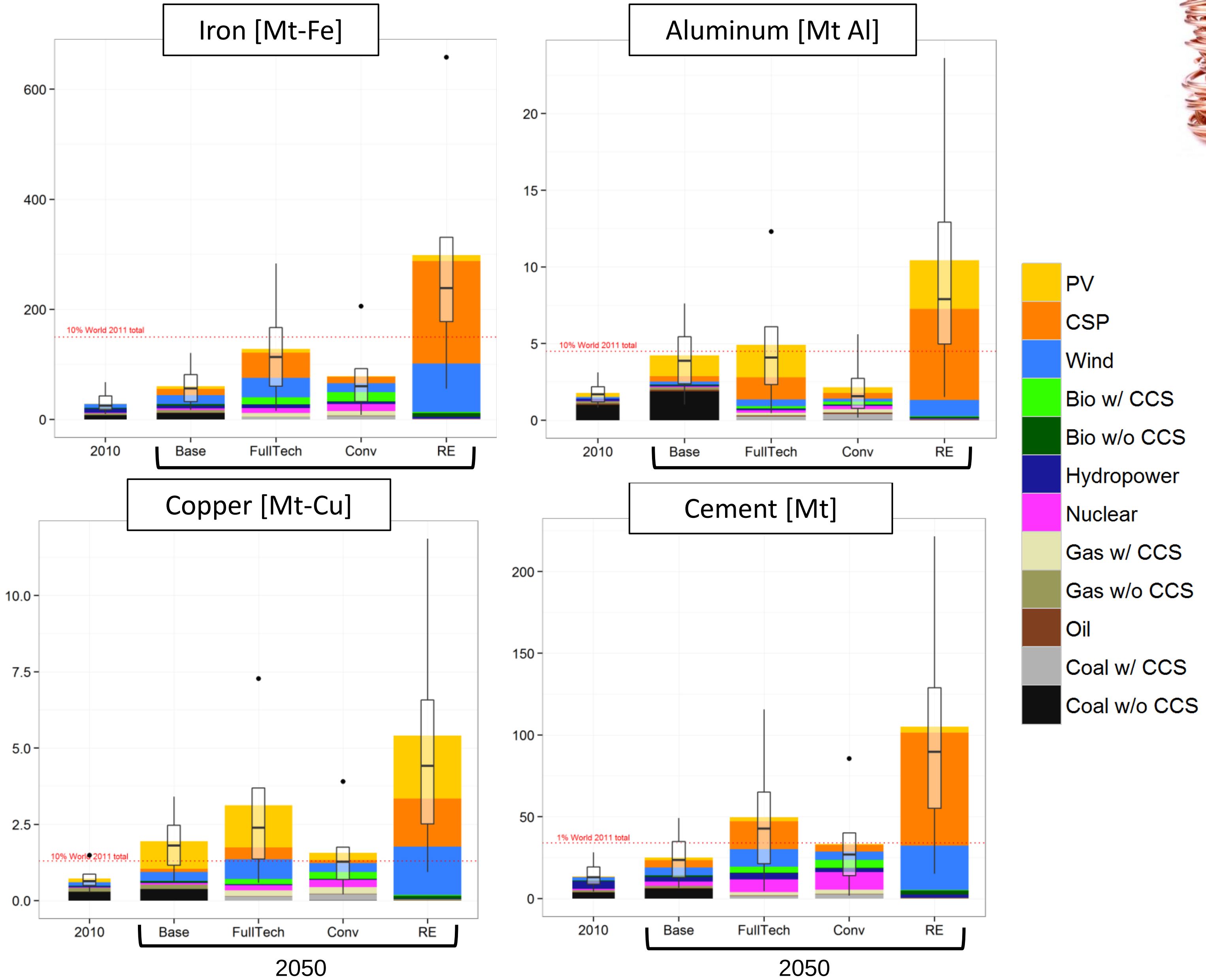
Health impacts (excl. air pollution)

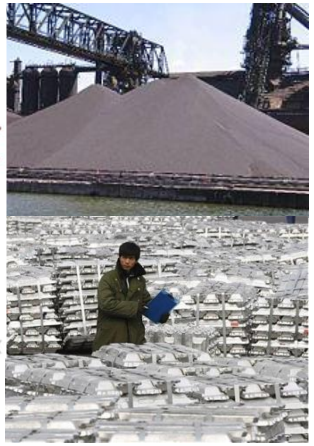


Land occupation and transformation



Bulk resource requirements





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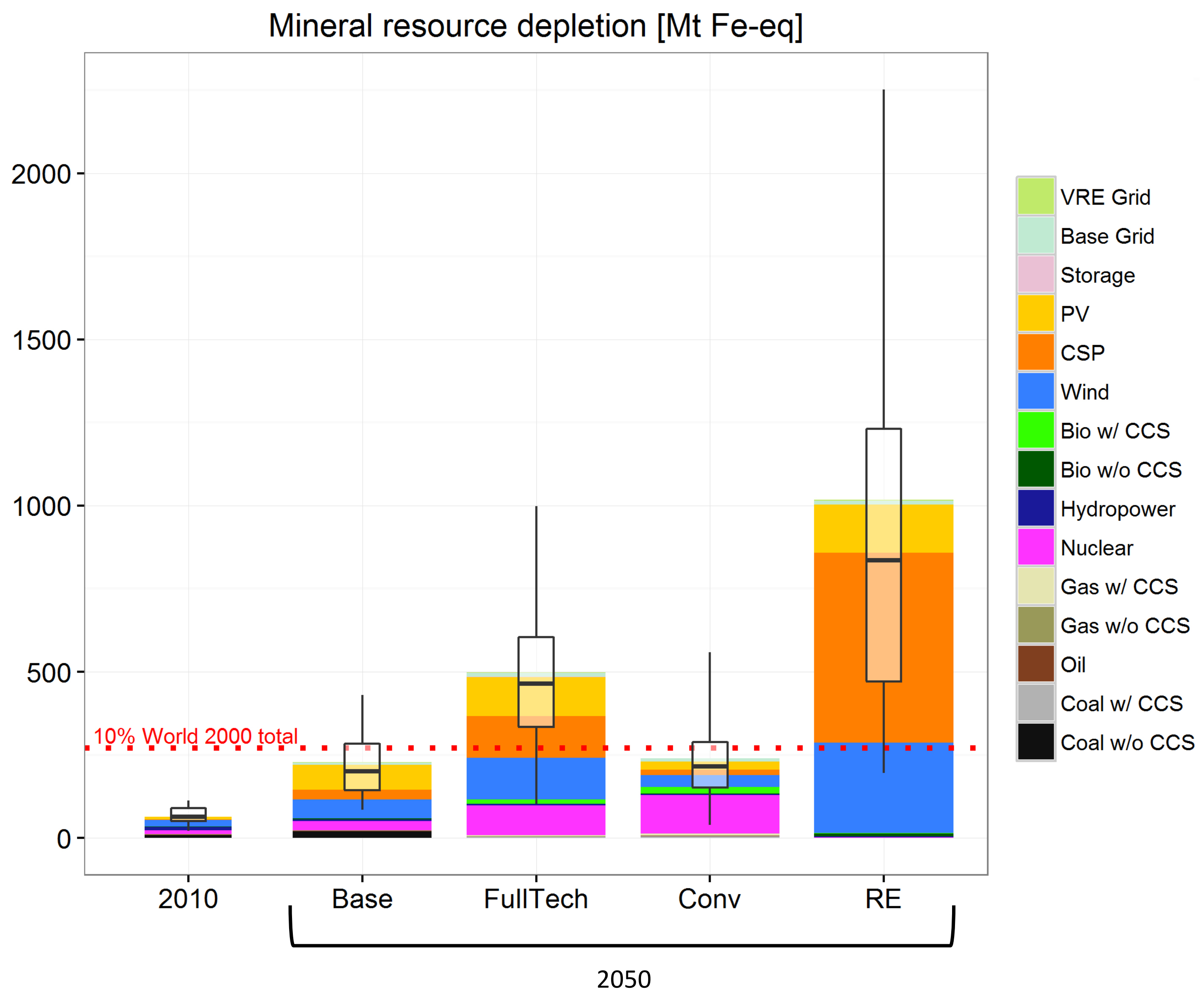
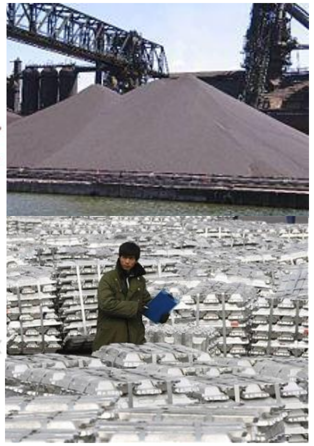
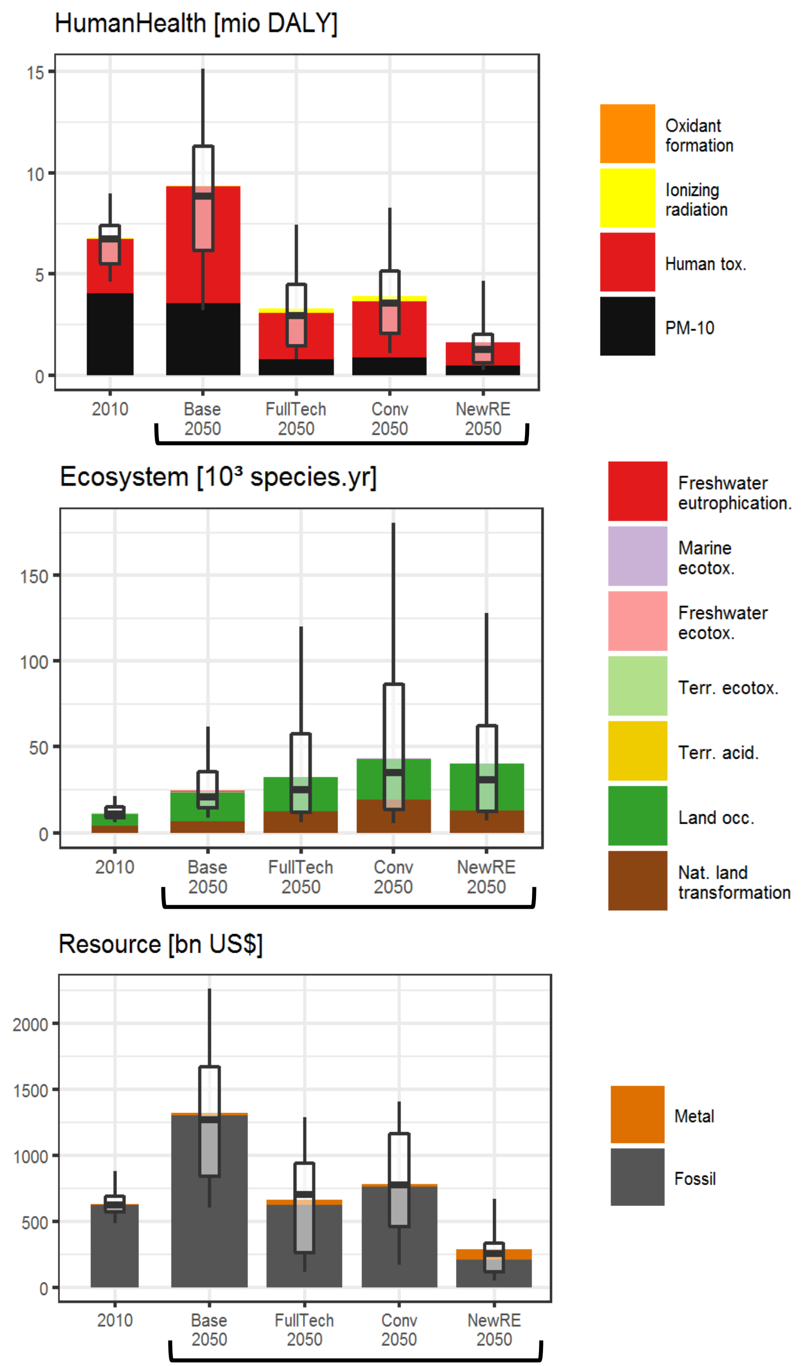
Mineral resource depletion





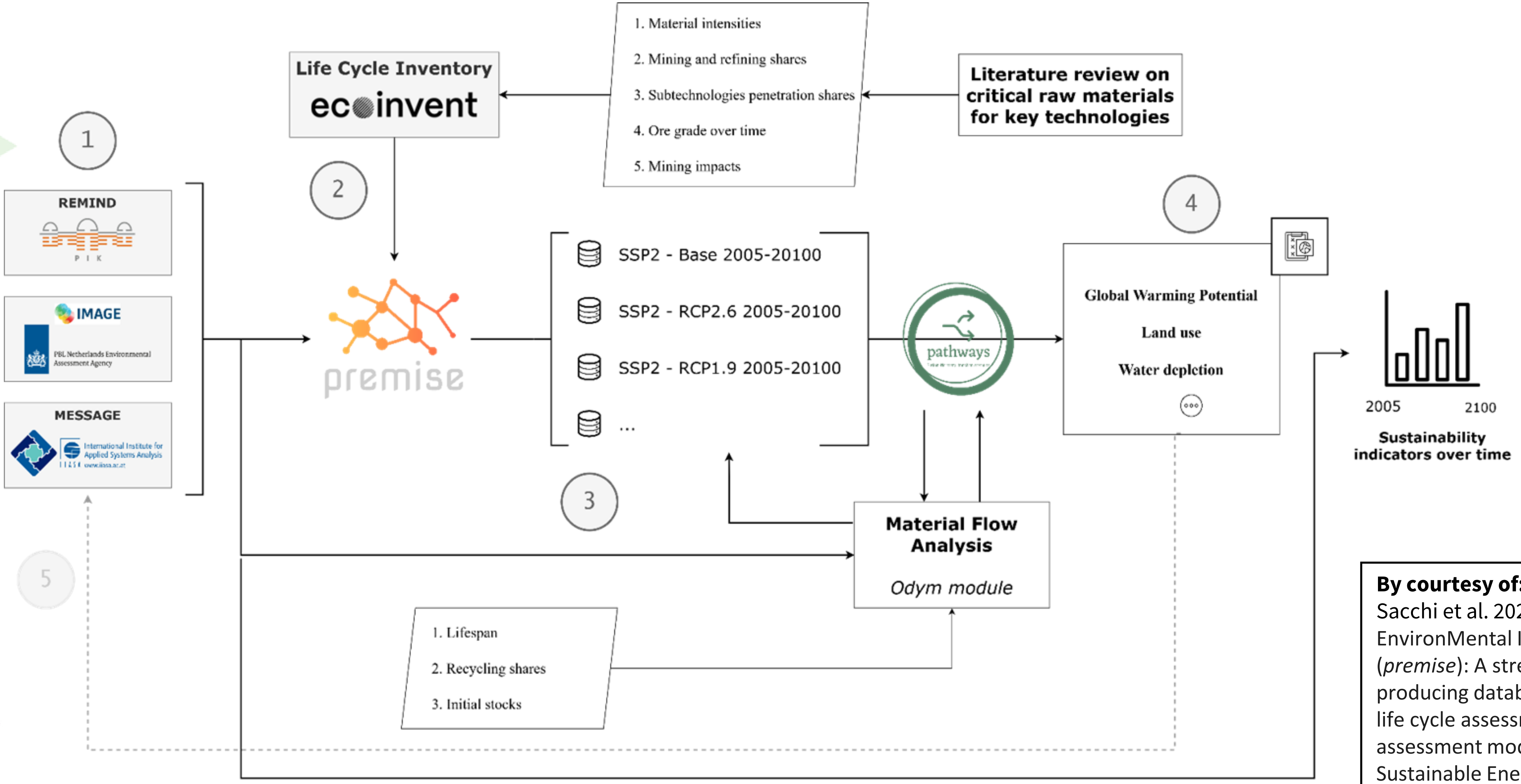
Combined assessment



Key insights

- Decarbonizing power supply has substantial co-benefits, especially for air and water pollution
- However, low-carbon transformation pathways have higher raw material requirements, higher risks related to radioactive substances, and increased land requirements
- Bioenergy has much greater adverse side-effects than the other renewables
- Conventional vs renewable power sector decarbonization strategies have distinctly different environmental risk profiles
    - Nuclear and CCS-based strategies are more water-intensive, higher radiation, and have fewer environmental co-benefits
    - Decarbonization based on wind and solar increases the requirements for raw materials

premise-pathways



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Coverage of minerals by technology

56 metals

Application	Zr	Zn	Y	Yb	V	W	Ti	Sn	Tb	Te	Ta	Sr	S	Ag	Si	Se	Sc	Sm	Rb	Ru	Rh	Re	Pr	K	Pt	P	Pd	Nb	Ni	Nd	Mo	Mn	Mg	Li	Pb	La	Ir	In	Hf	Graphite	Au	Ge	Ga	Gd	Eu	Er	Dy	Cu	Co	Cr	Ce	Cd	B	Be	Sb	Al	Sector
ICEV	✖		✖	✖		✖		✖	✖	✖	✖	✖		✖			✖	✖	✖	✖	✖	✖	✖		✖		✖	✖		✖	✖	✖		✖		✖		✖			✖	✖	✖	✖	✖	✖	✖		✖		✖			✖	✖	✖	Transport
EV			✖	✖						✖	✖						✖	✖			✖		✖		✖		✖	✖		✖	✖			✖		✖		✖			✖			✖	✖	✖	✖		✖		✖		✖	✖	✖	✖	
DDPM					✖				✖														✖					✖	✖	✖	✖	✖			✖												✖	✖		✖			✖			✖	Wind turbines
DDEE		✖							✖																			✖	✖	✖	✖	✖															✖	✖		✖			✖			✖	
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HTSP			✖																																																						
c-Si		✖						✖						✖	✖														✖						✖								✖					✖								✖	Photovoltaics
CdTe								✖		✖				✖															✖		✖				✖			✖										✖		✖		✖				✖	
CIGS		✖						✖						✖		✖															✖							✖					✖					✖				✖				✖	
a-Si								✖		✖					✖														✖		✖							✖				✖						✖		✖		✖	✖			✖	
PT-SF														✖																																											Concentrated solar
PT-PB		✖			✖		✖							✖	✖													✖	✖		✖	✖	✖															✖		✖						✖	
ST-SF														✖																																											
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LTO							✖																						✖					✖														✖								✖	
Lead-Acid																																			✖																						
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PAFC	✖	✖	✖																						✖		✖		✖		✖	✖				✖												✖		✖						✖	
PEMEL							✖													✖				✖	✖												✖											✖									Electrolyzers
AEL	✖													✖										✖	✖				✖											✖								✖	✖							✖	
HTEL-Y	✖		✖									✖											✖						✖			✖				✖													✖		✖						
HTEL-Sc																	✖																																								

~30 applications

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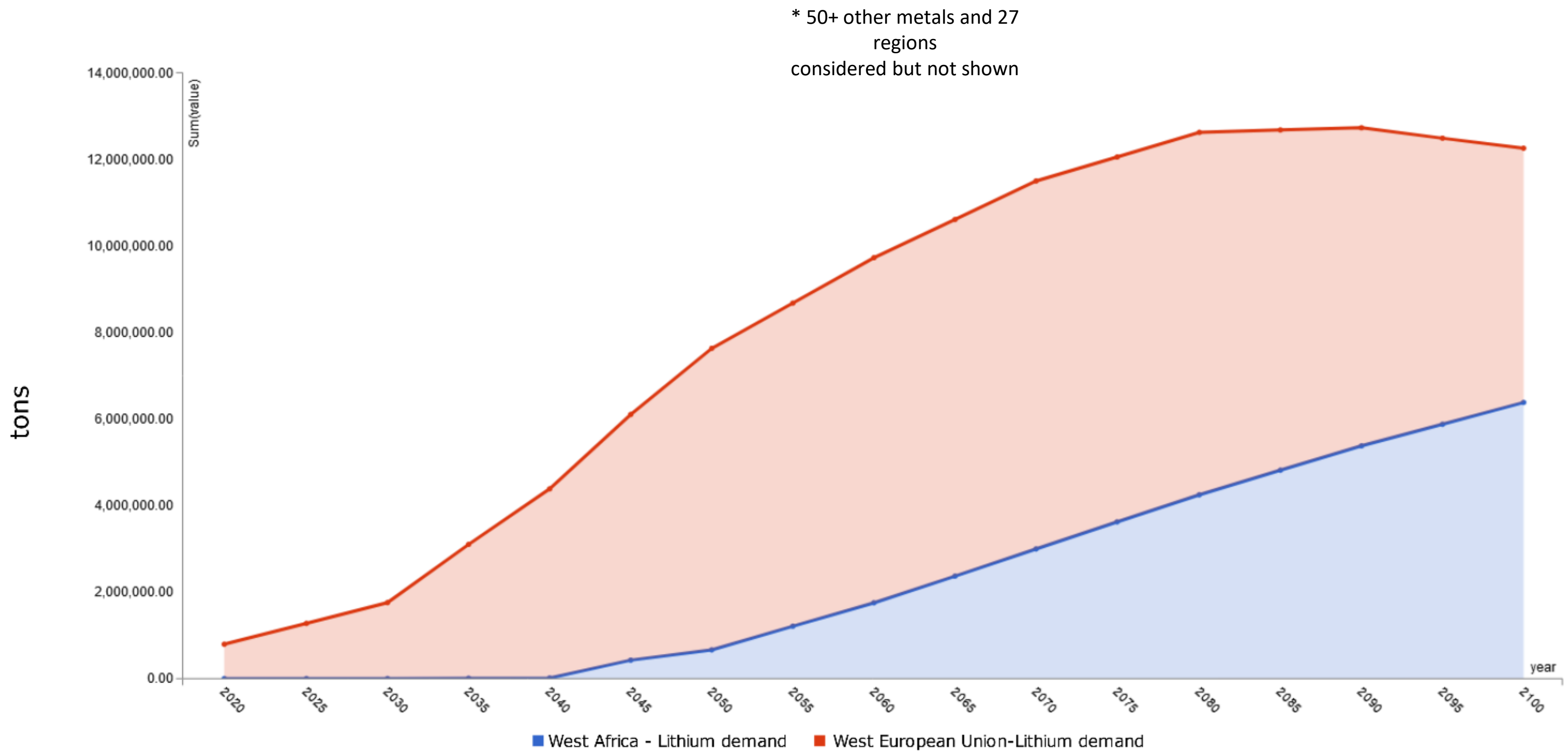
Illustrative results: LCA and material demand



Lithium demand over time for WEA and WEU (all consumers)

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Thank you very much for your attention!