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Integrating material cycles and circular economy strategies into the MESSAGEix model and its application to mobility infrastructure

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22 July 2025

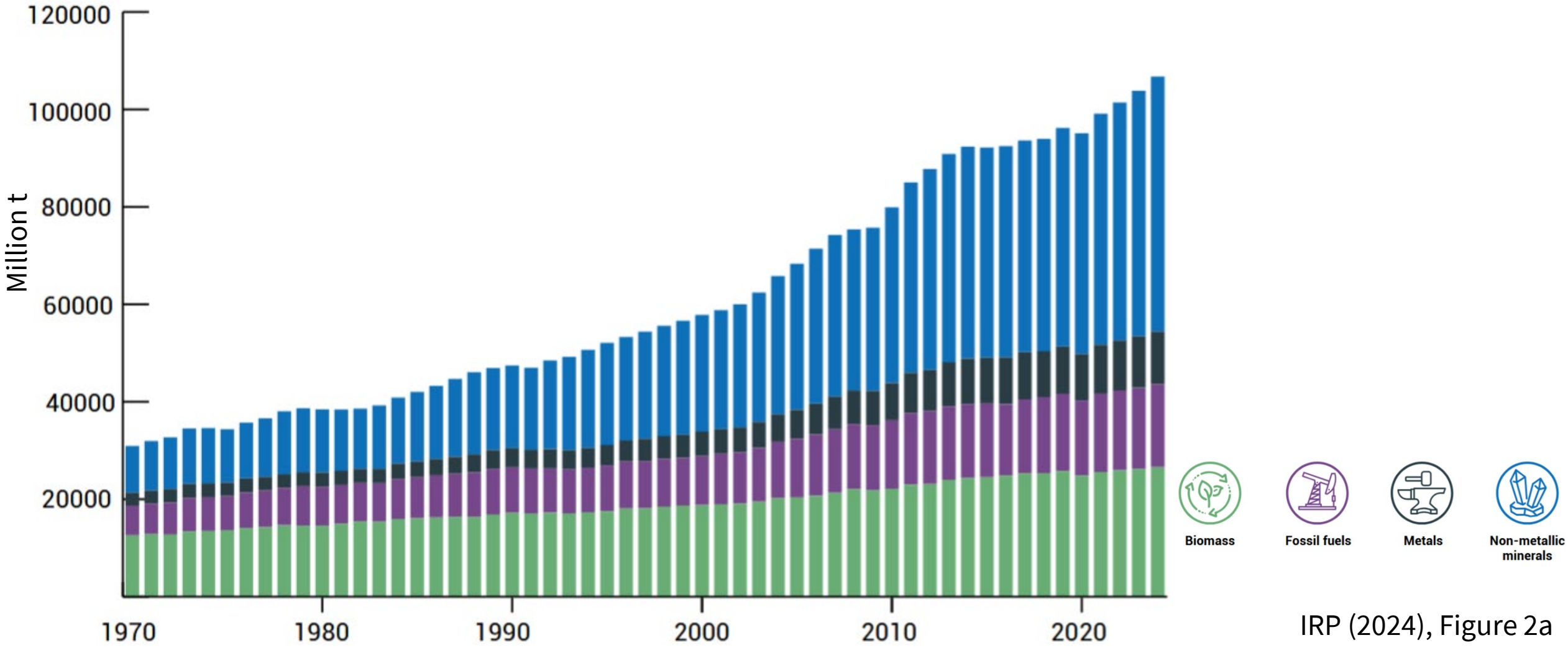
Overview

- Background
- MESSAGEix-Materials
- Circular Economy strategies for decarbonizing global mobility infrastructure
- Conclusions

Background

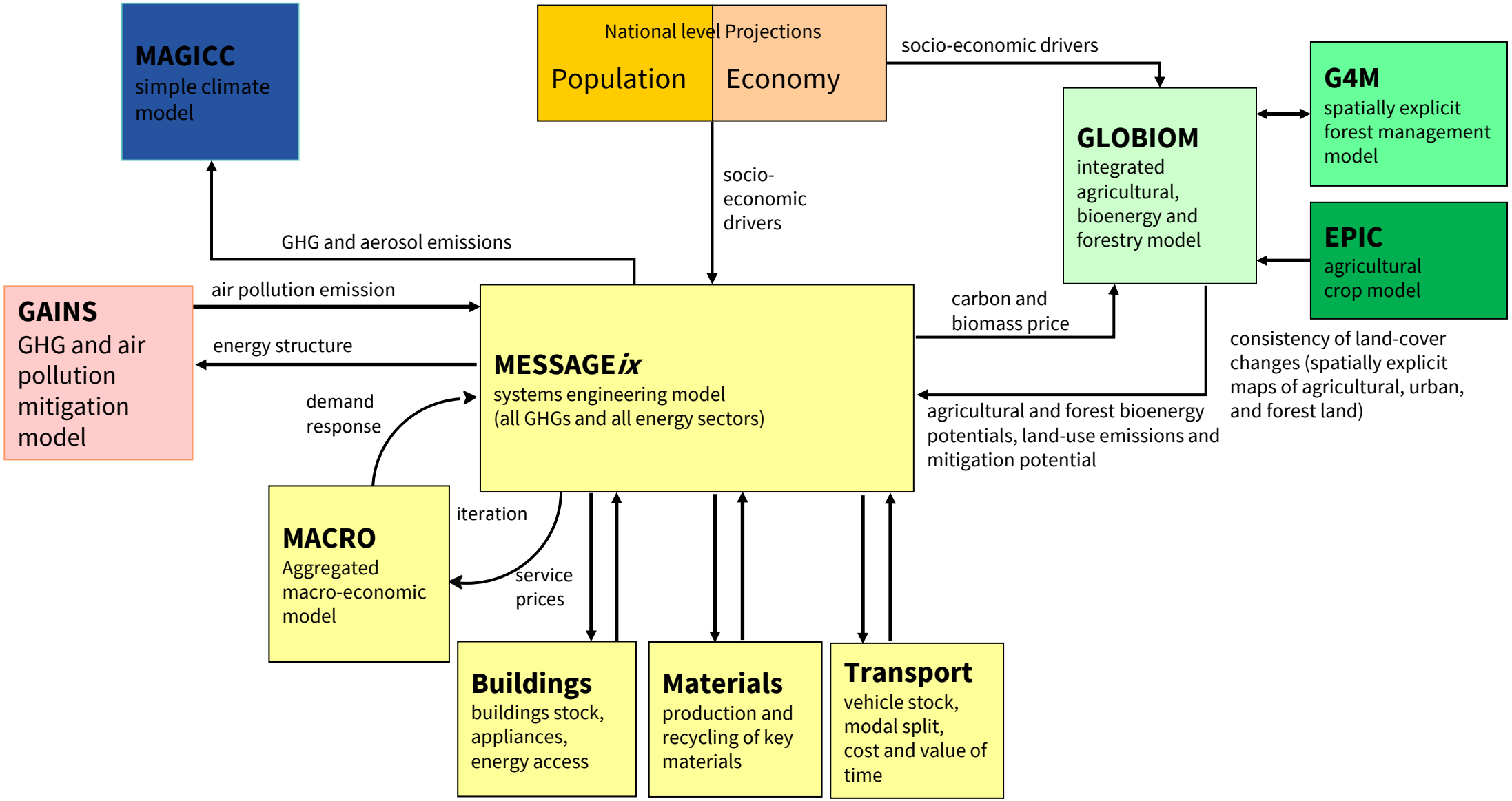
- Total **global material extraction** has more than **tripled** over the last 50 years
- Extraction of **metals and non-metallic minerals** has increased more than **five-fold**
- Use and production of materials responsible for more than **25% of global GHG emissions**
- Circular economy strategies can play a critical role in climate change mitigation
- Currently mitigation pathways **do not represent CE strategies adequately**

Global material extraction



IRP (2024), Figure 2a

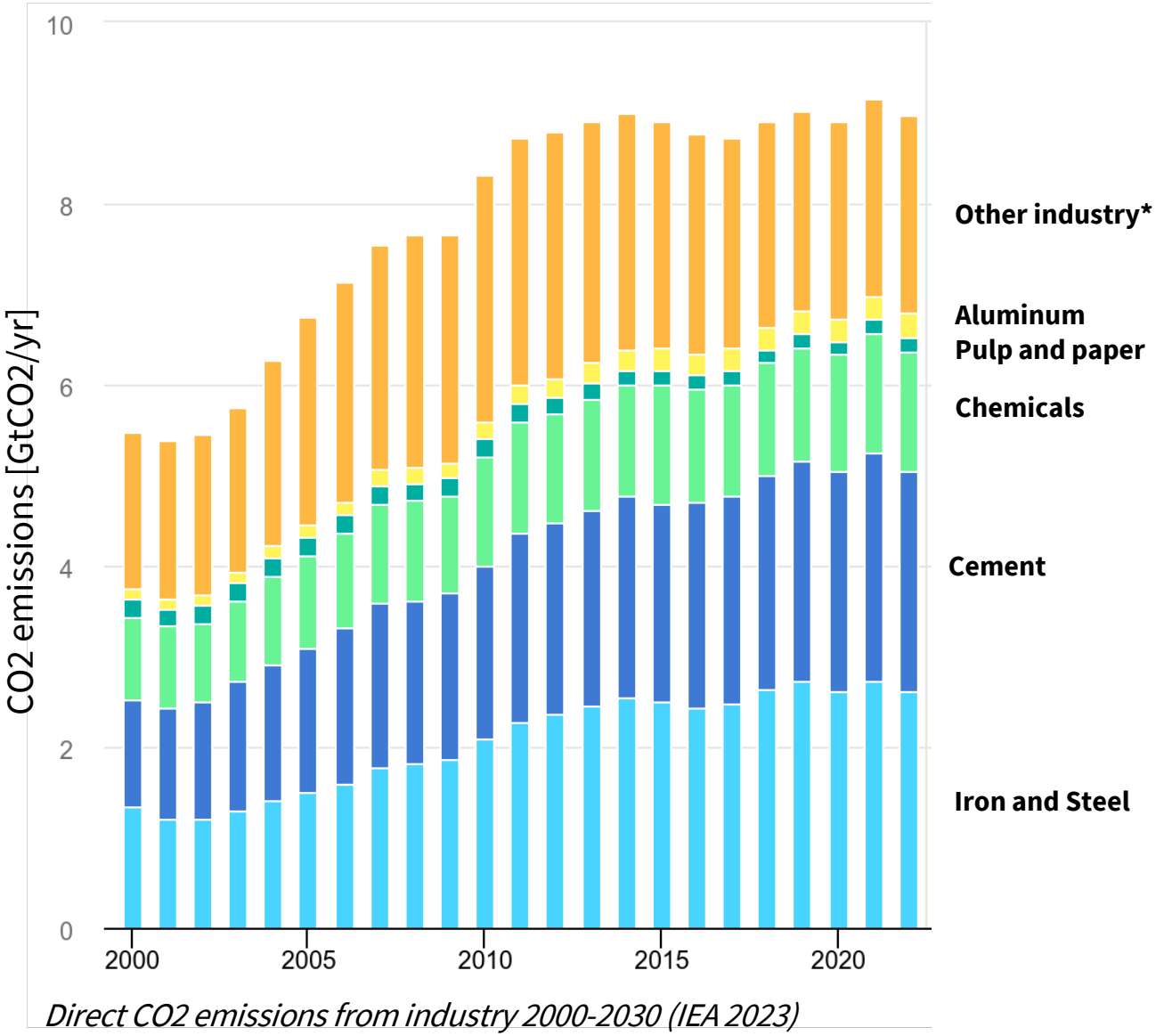
MESSAGEix-GLOBIOM-GAINS IAM framework



MESSAGEix-Materials

Energy-intensive industry sectors implemented (~70% of industrial CO2 emissions):

- Iron and Steel
- Aluminum
- Cement
- Chemicals
  - High-value chemicals (ethylene, propylene, BTX)
  - Ammonia
  - Methanol



Direct CO2 emissions from industry 2000-2030 (IEA 2023)

* Other industry: equipment & machinery, food and tobacco, wood, construction, textile and leather, infrastructure (road) etc.

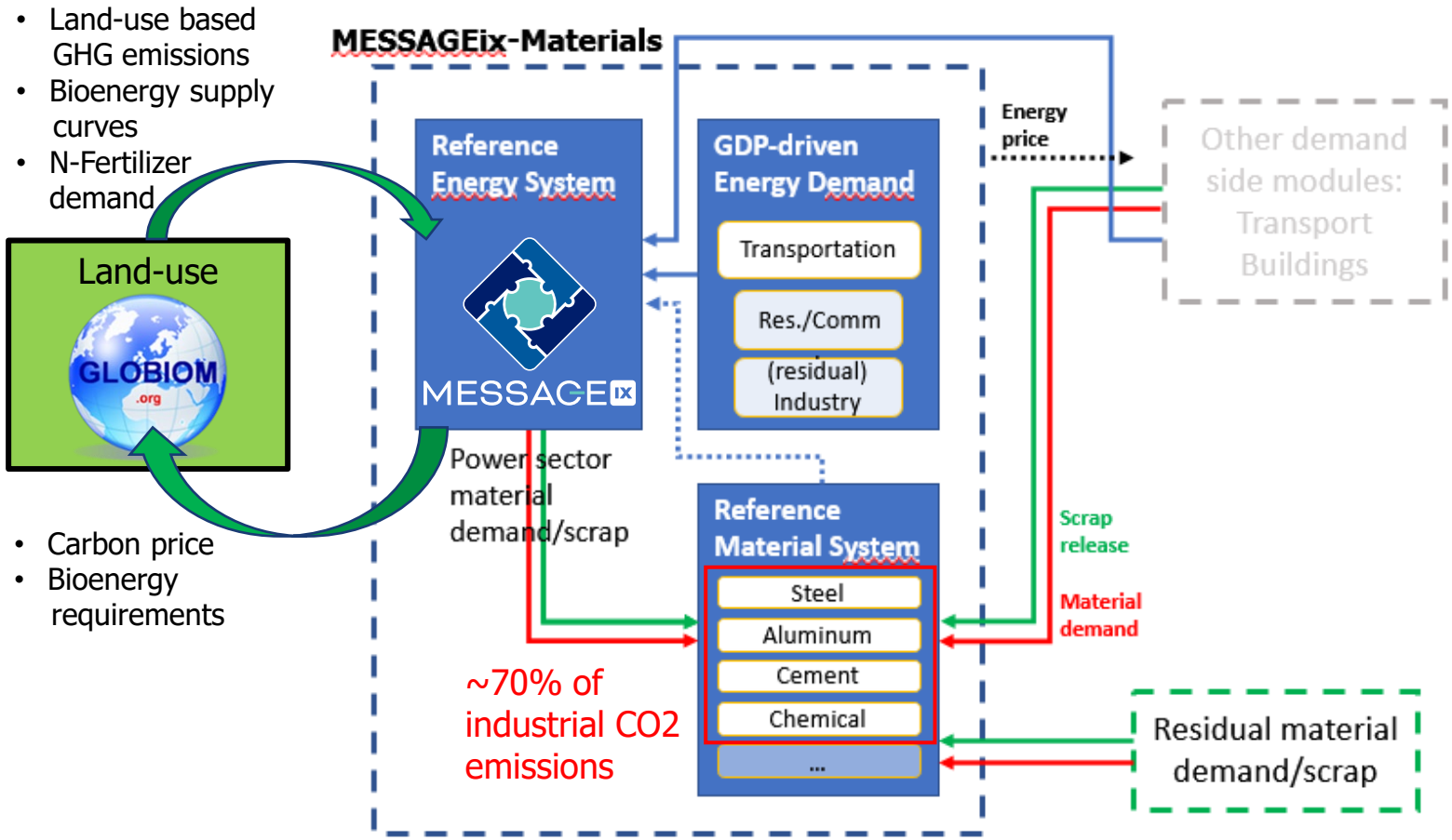
MESSAGEix-Materials

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 (2024). Geoscientific Model Development.

CIRCULAR ECONOMY STRATEGIES FOR DECARBONIZING GLOBAL MOBILITY INFRASTRUCTURE

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The CircEUlar project has received funding from the Horizon Europe Research and Innovative Action Programme under Grant Agreement No. 101056810, the Swiss State Secretariat for Education, Research and Innovation (SERI), and by UKRI.

Motivation

- With more than 300 Gt, mobility infrastructure accounts for one third of total material stocks in 2024.
- Material inputs are required for
    - build-up of new stocks
    - their maintenance
    - replacement of end-of-life
- Mobility infrastructure facilitates well-being by providing the key service of moving people and goods.
- The materials have embodied emissions and create path dependencies.

Research gap and questions

Currently, no scenarios for future mobility infrastructure expansion and associated material flows and emissions at the global scale

Evaluate biophysical implications of expansion and the mitigation potential of Circular Economy and decarbonization measures:

- How will future global mobility infratructure developments shape material stocks and flows?
- How much of the remaining global carbon budget will be required for mobility infrastructure development?
- What is the potential of both supply- and demand-side measures to mitigate increasing resource use and embodied emissions arising from future infrastructure development?

Methodology

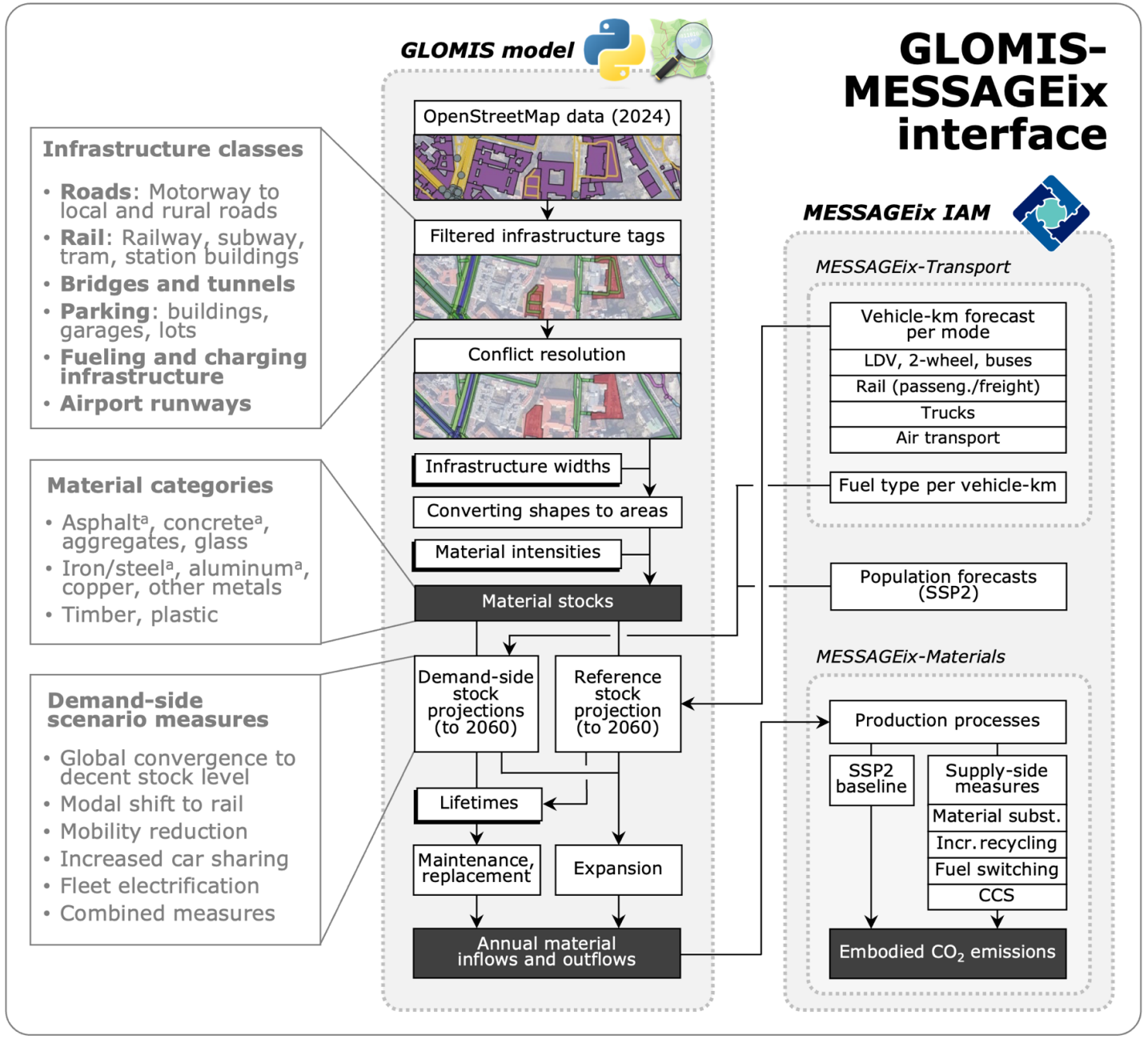
Soft-linked Material Flow Analysis (MFA) and Integrated Assessment Model (IAM)

GLObal **M**obility **I**nfrastructure **S**tocks (GLOMIS)**:** Stock-driven Material Flow Analysis (MFA) model based on crowd sourced data (OpenStreetMap)

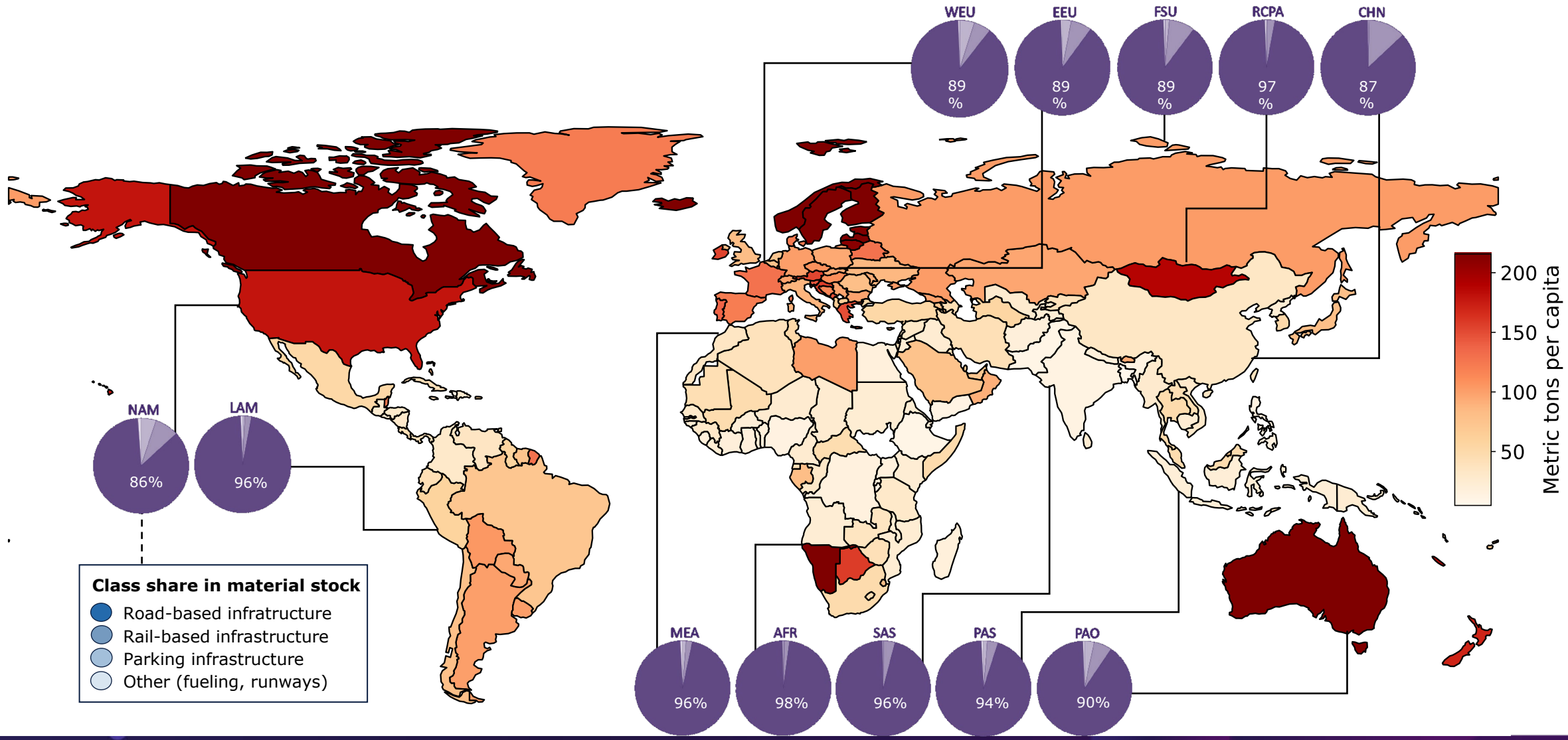
MESSAGEix-Materials:
IAM module with representation of detailed production processes in industry

Infrastructure Types: roads, bridges, tunnels, railways, subways, trams, stations, parking, refueling, airports

Materials: iron/steel, concrete, asphalt, aluminum (+ aggregates, copper, glass, plastic, timber, 'other metals')



Results: Material stocks in 2024



Circular Economy in Mobility Infrastructure

Demand Side

Modal shift to rail

- Development of low-carbon transport infrastructure (e.g., railways) to make operations more reliable and encourage mode shifting

Mobility Reduction

- Substitution of physical travel
- Reduce travel activity via better urban planning

Car Sharing

- Car sharing to reduce parking lots

Fleet Electrification

- Electrification of vehicle fleet

Supply Side

Extending Lifestime

- Improved maintenance

CCS

- Iron and Steel, Cement during production
- Accelerated Carbonation during recycling of concrete

Recycling

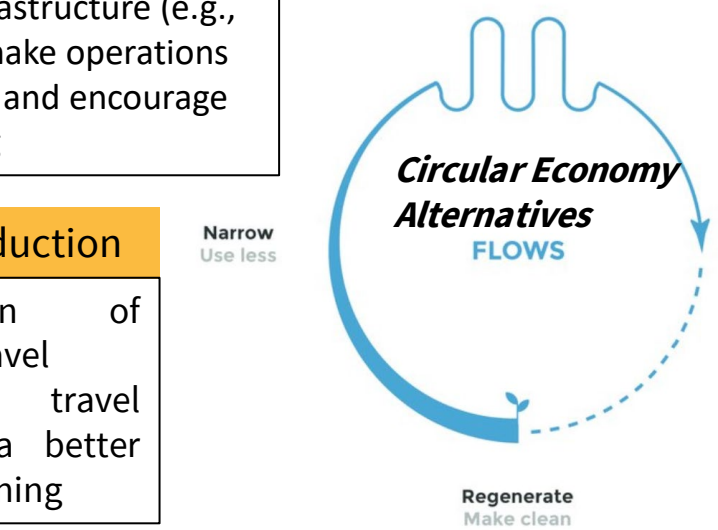
- Technological improvements in recycling (e.g. aluminum, steel)
- Higher secondary aggregate use in concrete and asphalt with decreased bitumen.

Fuel switch

- Switching to renewable fuels

Material Substitution

- Clinker replacement via fly ash, slag, clay
- Use of bio-bitumen produced from lignin



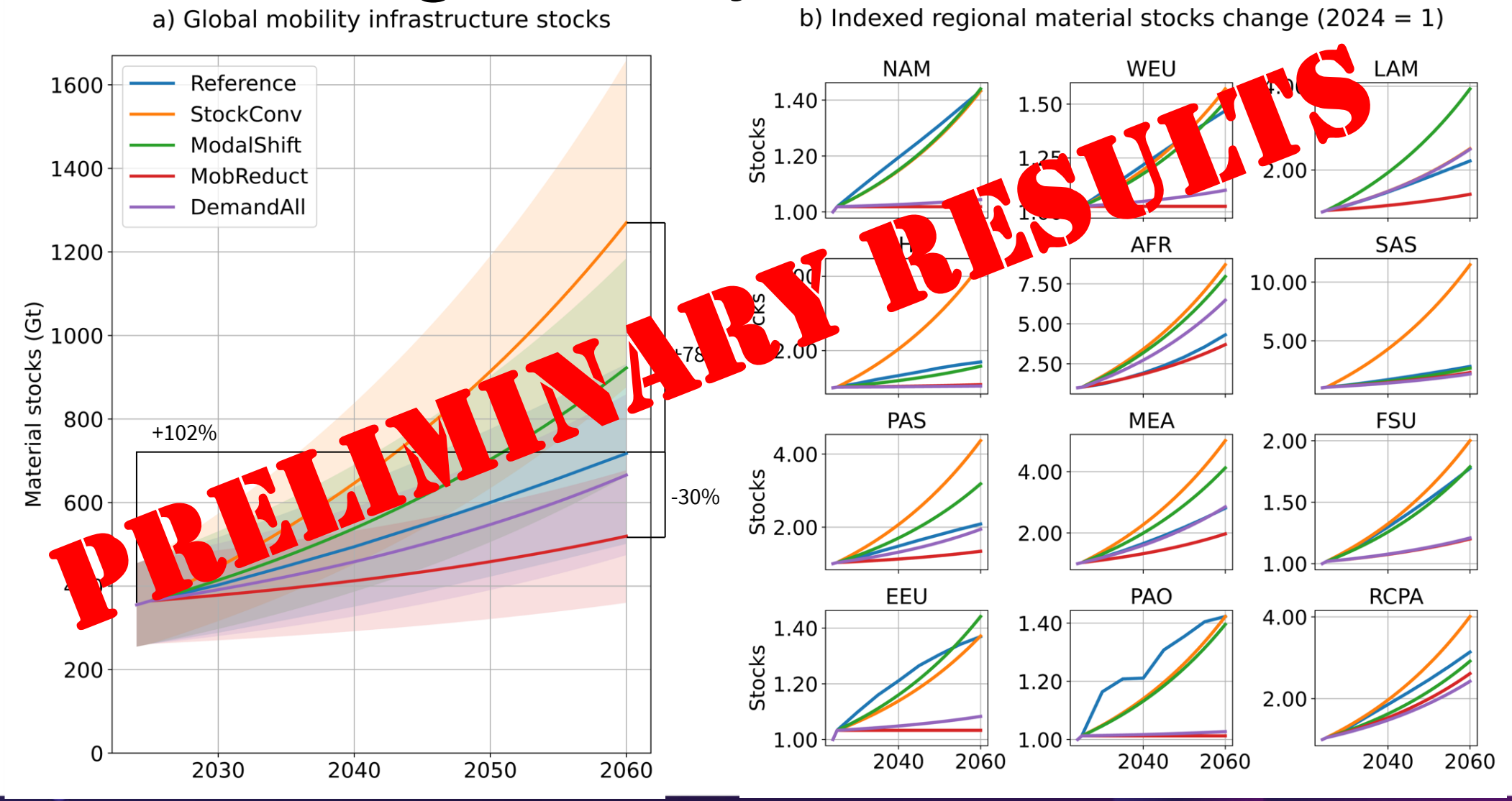
Scenarios

		Demand Side						
		Reference	Mobility Reduction	Modal shift	Car Sharing	Fleet Electrifi-cation	Demand All	Decent Stock Convergence
Supply Side	Default	Current practice						
	Material Substitution							
	Fuel Switch							
	Recycling							
	CCS							
	Supply All							

+ **climate policy**: current policies and 2°C

- **Reference:** Change in vkm based on SSP2 projections from MESSAGEix-Transport drive infrastructure.
- **Mobility reduction**: Total vkm of the default scenario in the year 2060 is reduced **30%** for HI, **20%** for UMI, **10%** for LMI and no reduction for LI countries (World Bank 2024, Harvey 2013).
- **Modal shift**: Countries converge to the share of top six countries with the highest rail-based vkm in 2060.
- **Car Sharing**: Doubling of car-sharing, leading to a reduction in parking space
- **Fleet Electrification**: Private passenger fleet electrification, leading to replacement of refueling infrastructure
- **Demand All**: Combined scenarios ModalShift, MobReduct, CarSharing and FleetElect
- **Decent Stock Convergence**: Convergence to ~1,500 m^2/cap total infrastructure area by 2060 (where HDI stagnates).

Results: Stock growth by 2060



Results: Embodied emissions 2025-2060

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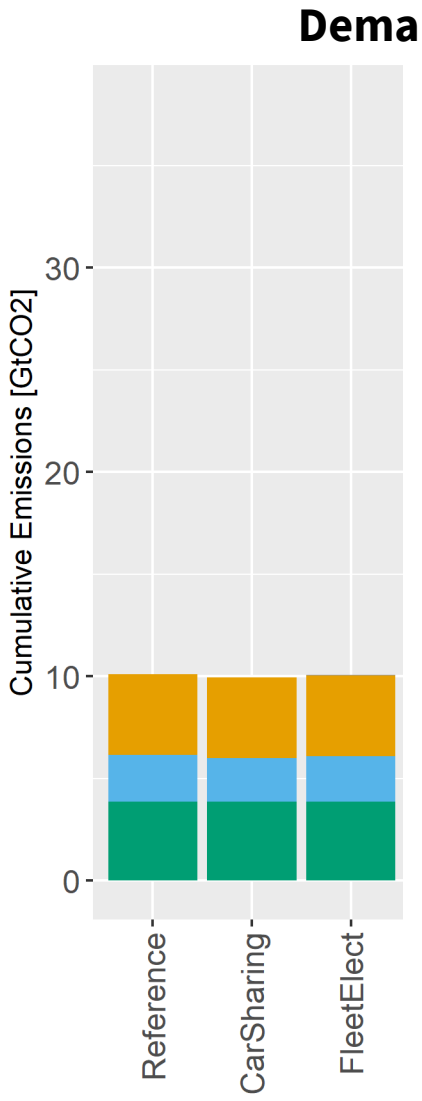

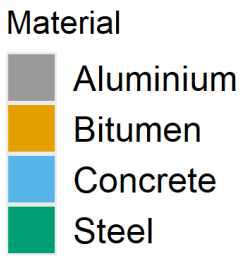

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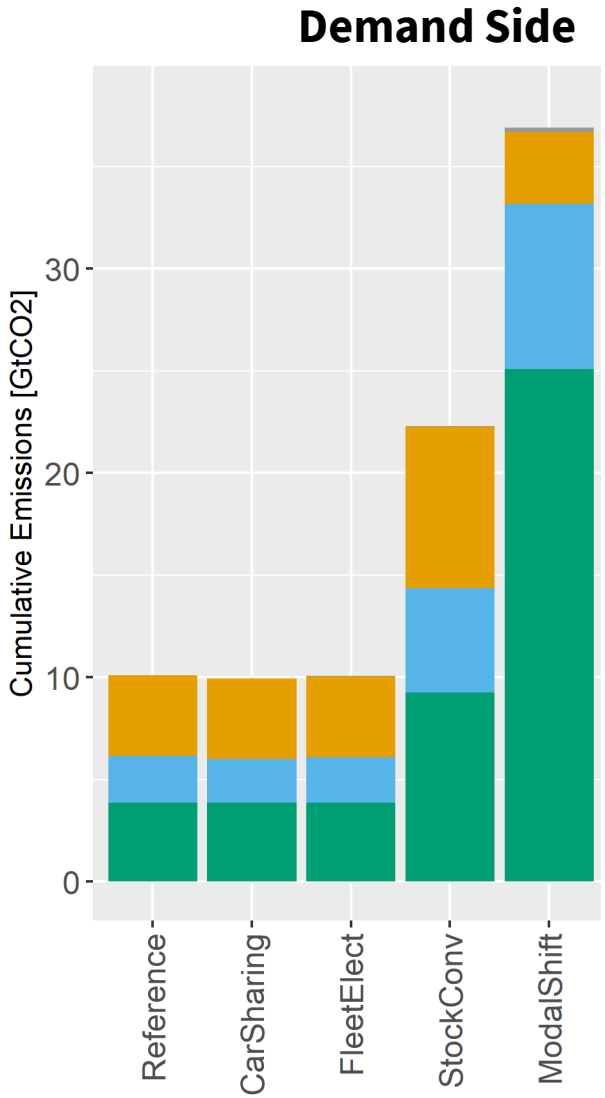

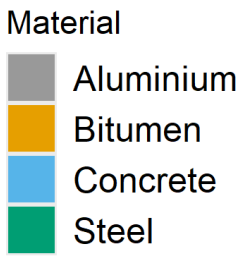

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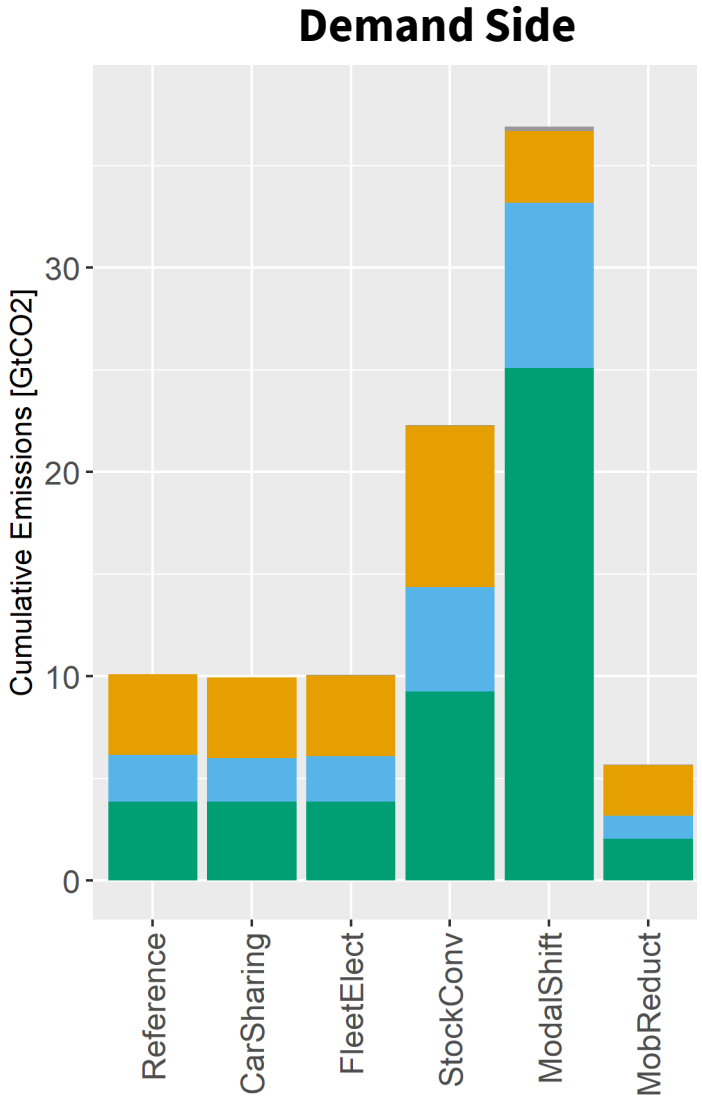

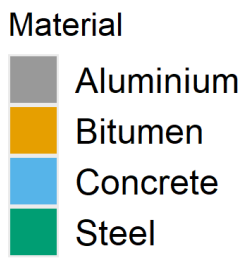

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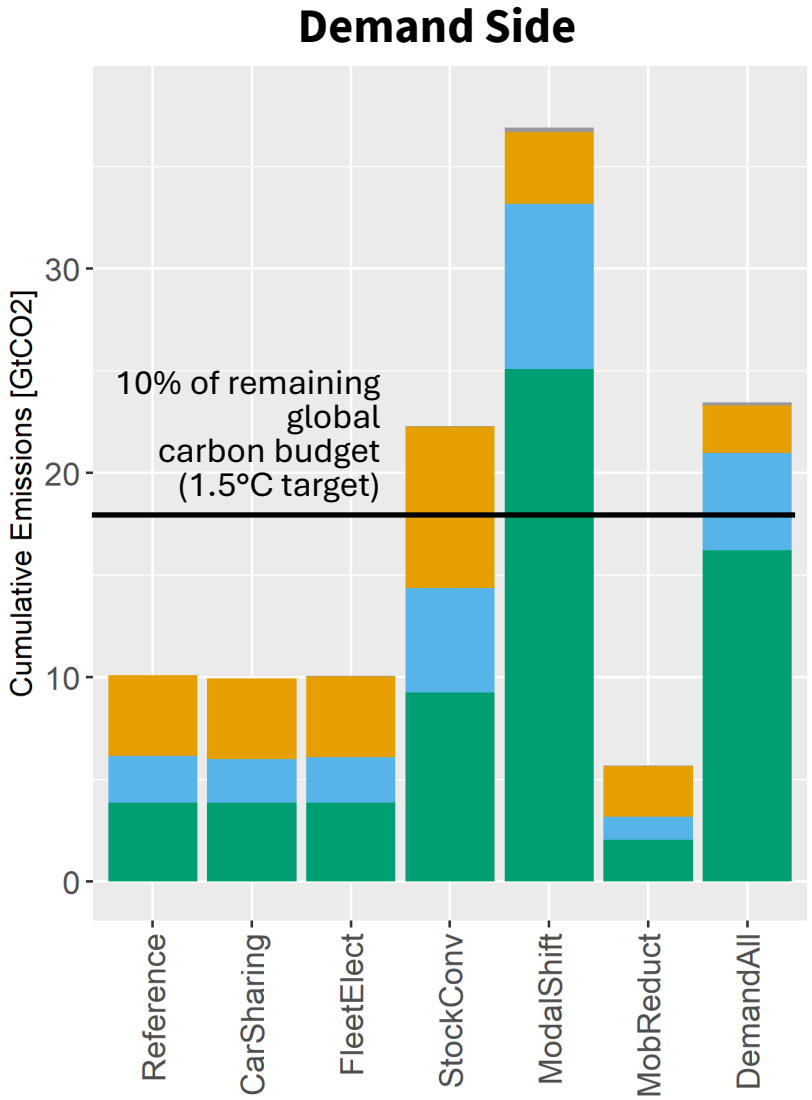

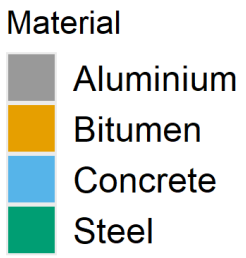

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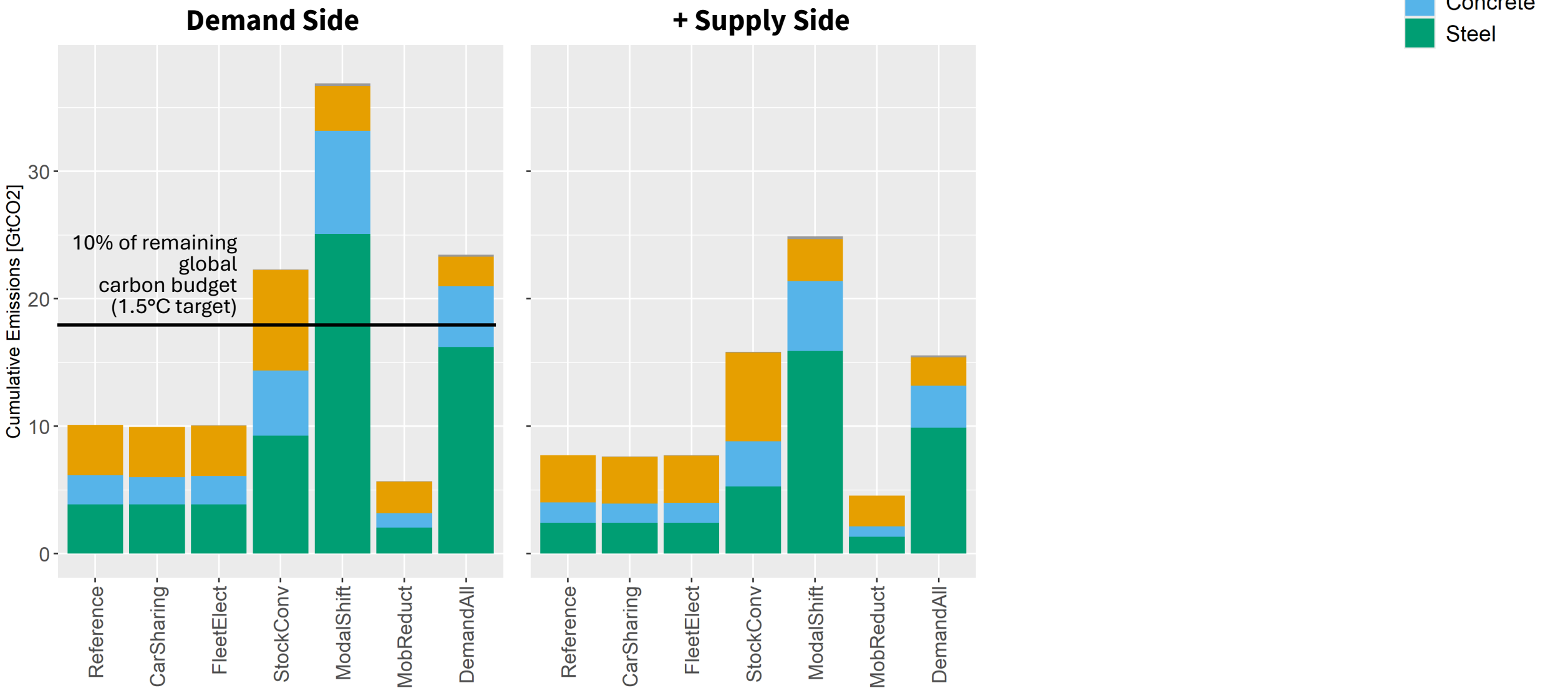

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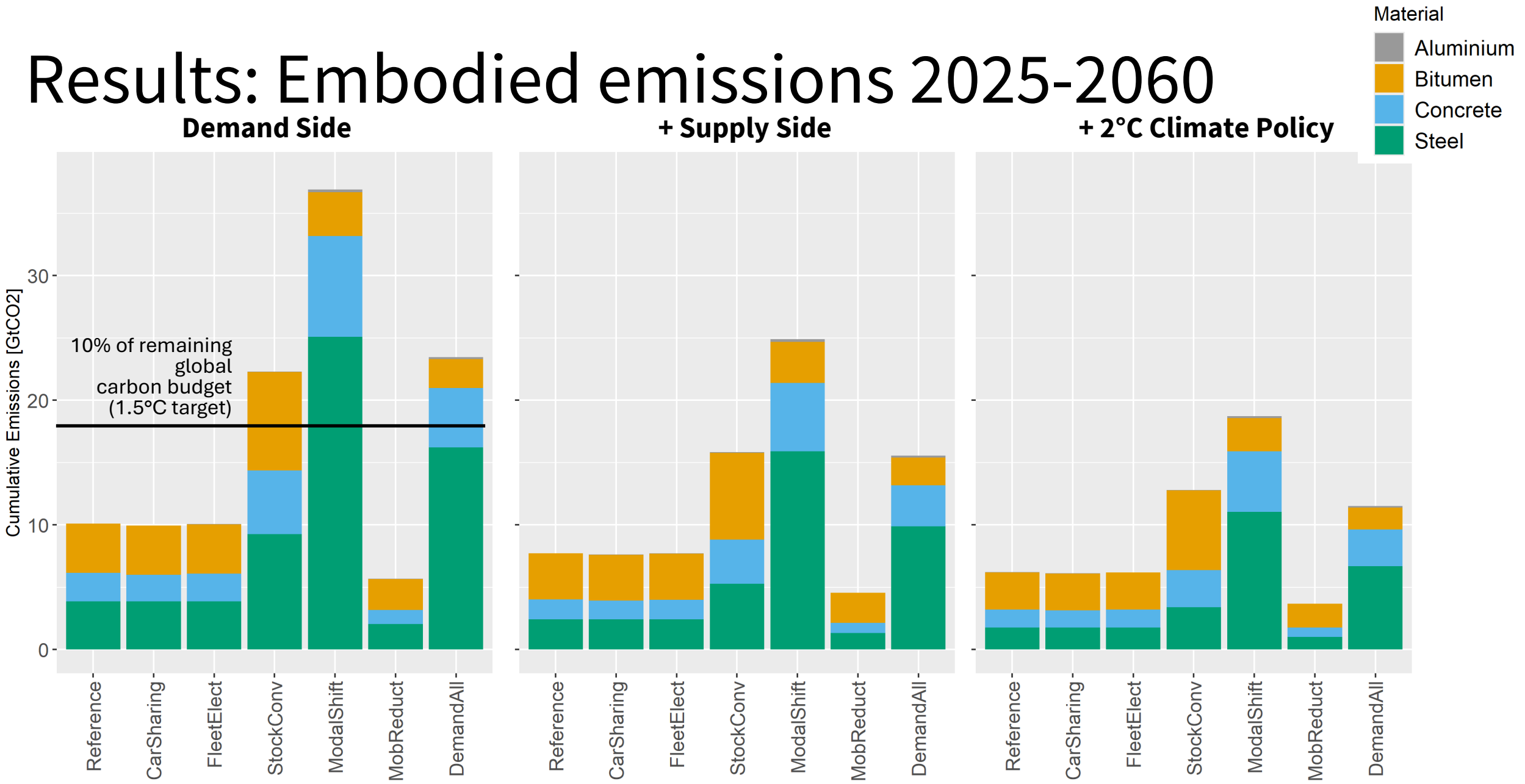

Conclusions: Mobility Infrastructure

- Mobility infrastructure requires 6-20% of remaining global carbon budget for keeping temperature increase below 1.5°C (175 GtCO2)
- If per capita stocks were to converge, most additional demand in stocks would be in Global South, doubling total stocks compared to reference scenario
- While stock convergence yields highest stocks, modal shift results in highest embodied emissions due emission-intensive metal production
- Combining mobility reduction with supply-side measures halves emissions
- Caveat: not all materials and lifecycle stages covered (e.g., material transport)
- Emissions embodied of rolling stock and operational emissions will be significant making modal shift essential for overall emission reduction
- Data situation challenging with poor knowledge of in-use material stocks, proprietary industry data and inconsistencies between different data sets

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Thank you.

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