BEST 402 Industrial Ecology @UBC

The Interplay Between Resource Use and Climate Action in Industrial Systems

How can material flow analysis contribute to decarbonization pathways?

Qian Zhang

The Robert M. Buchan Department of Mining

Queen’s University

October 19, 2023

6 CLEAN WATER AND SANITATION

7 AFFORDABLE AND CLEAN ENERGY

8 DECENT WORK AND ECONOMIC GROWTH

9 INDUSTRY, INNOVATION AND INFRASTRUCTURE

11 SUSTAINABLE CITIES AND COMMUNITIES

12 RESPONSIBLE CONSUMPTION AND PRODUCTION

13 CLIMATE ACTION

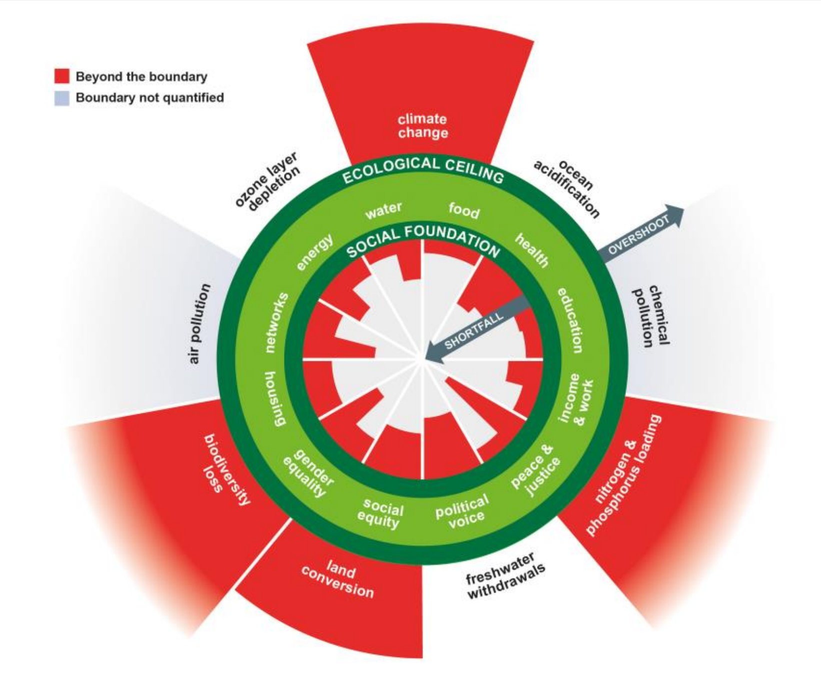
Queen’s UNIVERSITY

My Background: A Journey of Data Mining for Sustainability

- Environmental Science & Economics
- Environmental Science (Atmospheric Chemistry)
  - Ozone Pollution / Greenhouse Gas Emissions
- Urban Engineering (Environmental Engineering)
  - Carbon Footprint / Industrial Ecology
- Mining Engineering (Green Mining Value Chain)
  - Circular Economy / Climate-Smart Mining

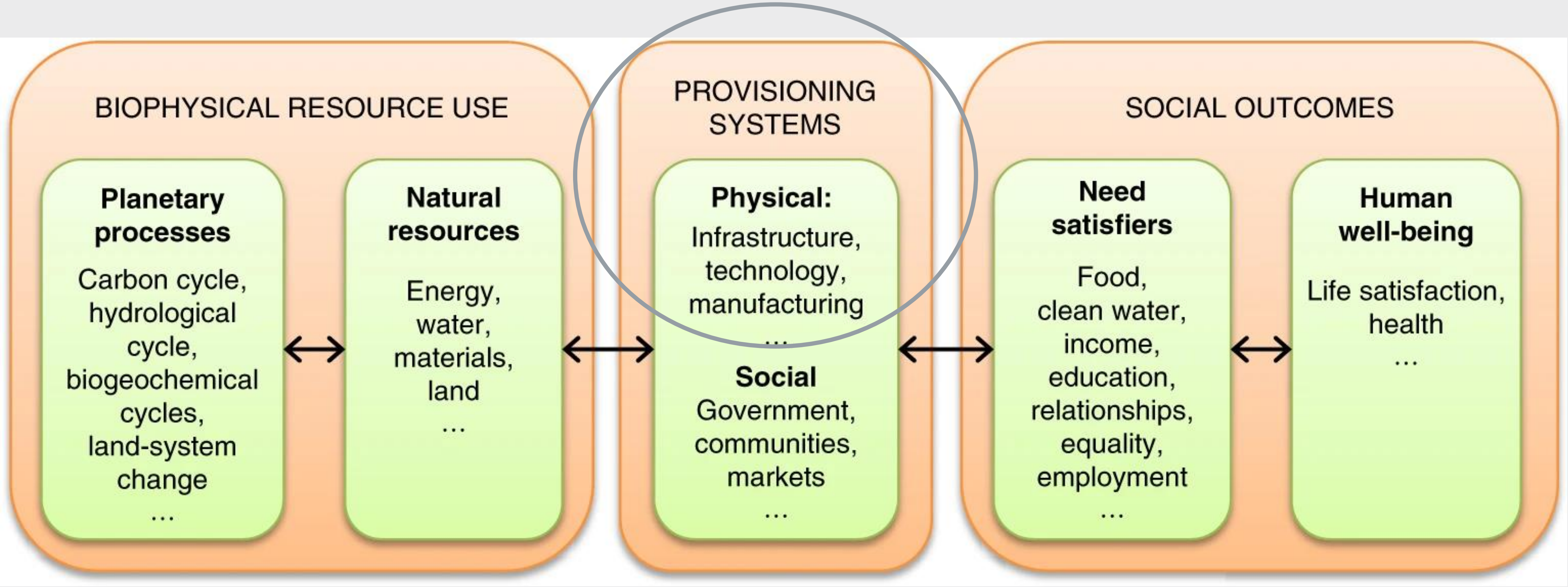
(EIT, 2019)

Towards Integrated Management of Technological and Ecological Systems



https://theanthropocene.org/film/

IE: Physical Provisioning Systems of Sustainable Well-Being


BIOPHYSICAL RESOURCE USE

Planetary processes
Carbon cycle, hydrological cycle, biogeochemical cycles, land-system change
…

↔

Natural resources
Energy, water, materials, land
…

↔

PROVISIONING SYSTEMS

Physical:
Infrastructure, technology, manufacturing
…

Social
Government, communities, markets
…

↔

SOCIAL OUTCOMES

Need satisfiers
Food, clean water, income, education, relationships, equality, employment
…

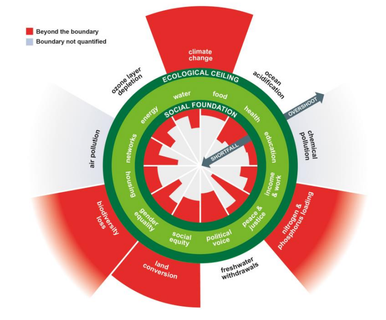
↔

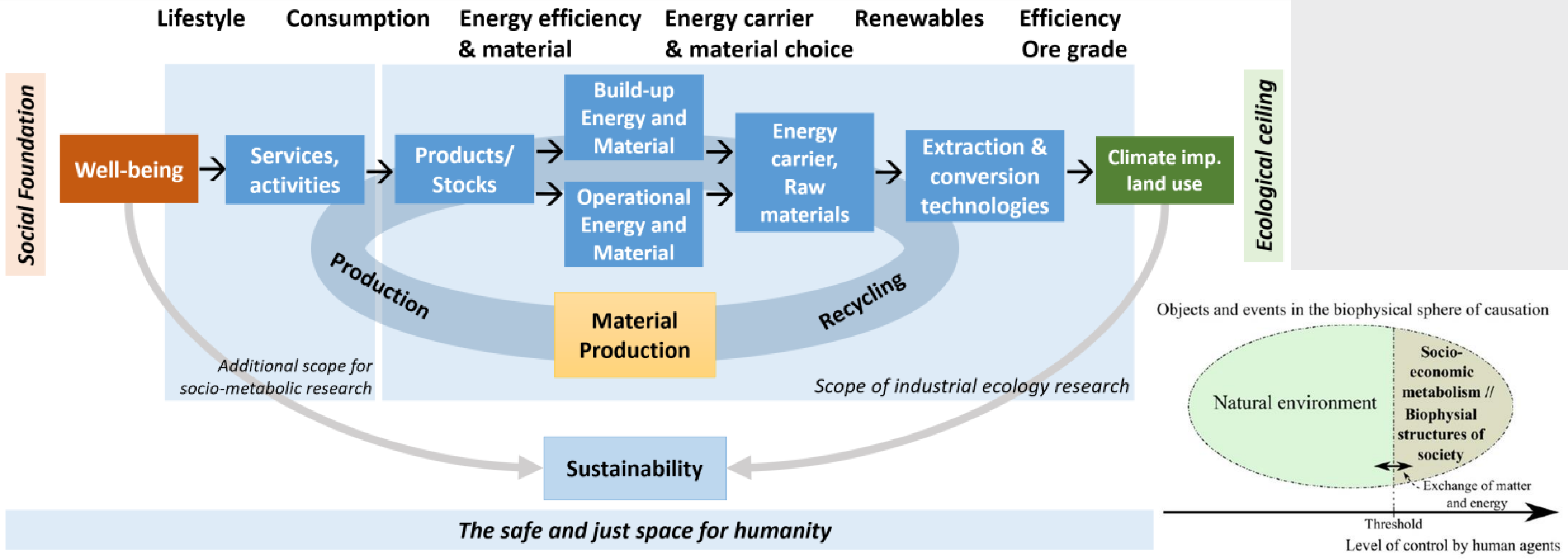
Human well-being
Life satisfaction, health
…

(O'Neill et al., 2018)

"Industrial ecology aims to reduce the environmental impact of industry by examining material and energy flows in products, processes, industrial sectors, and economies."

IE: Operationalizing the Doughnut Economics Framework





Lifestyle | Consumption | Energy efficiency & material | Energy carrier & material choice | Renewables | Efficiency Ore grade

Social Foundation

Well-being → Services, activities → Products/ Stocks → Build-up Energy and Material / Operational Energy and Material → Energy carrier, Raw materials → Extraction & conversion technologies → Climate imp. land use

Ecological ceiling

Production

Material Production

Recycling

Additional scope for socio-metabolic research

Scope of industrial ecology research

Sustainability

The safe and just space for humanity

Objects and events in the biophysical sphere of causation

Natural environment

Socio-economic metabolism // Biophysial structures of society

Exchange of matter and energy

Threshold

Level of control by human agents

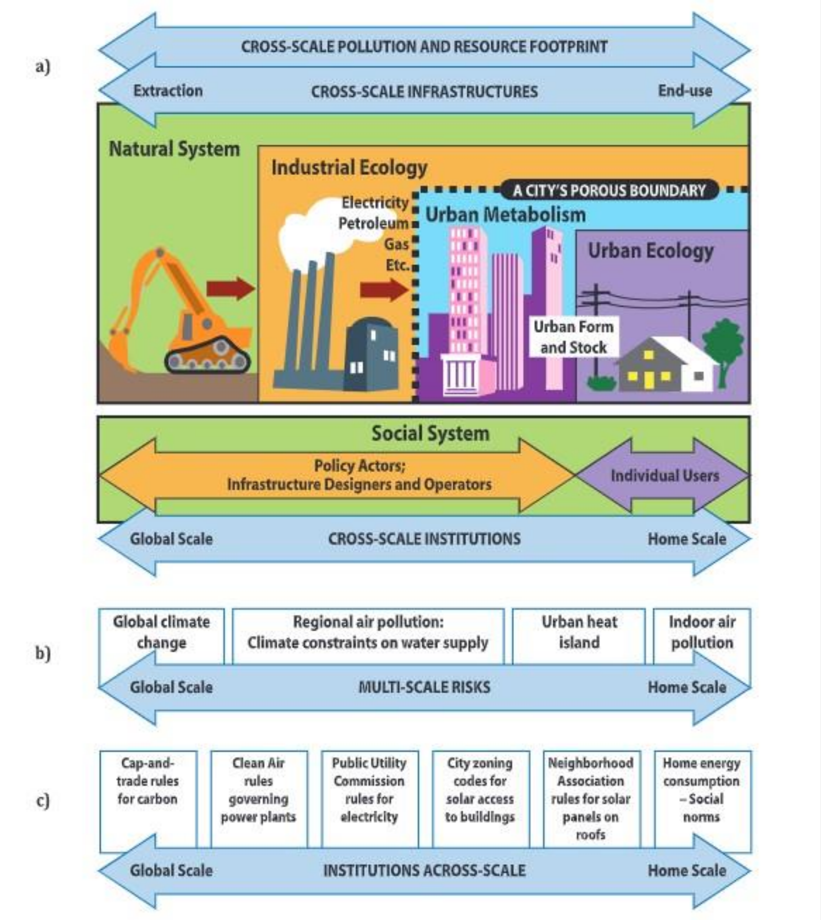
([Pauliuk, 2023](#))

Case Studies

- **Static MFA**
  - **Nexus Research: Interdependence and Interaction**

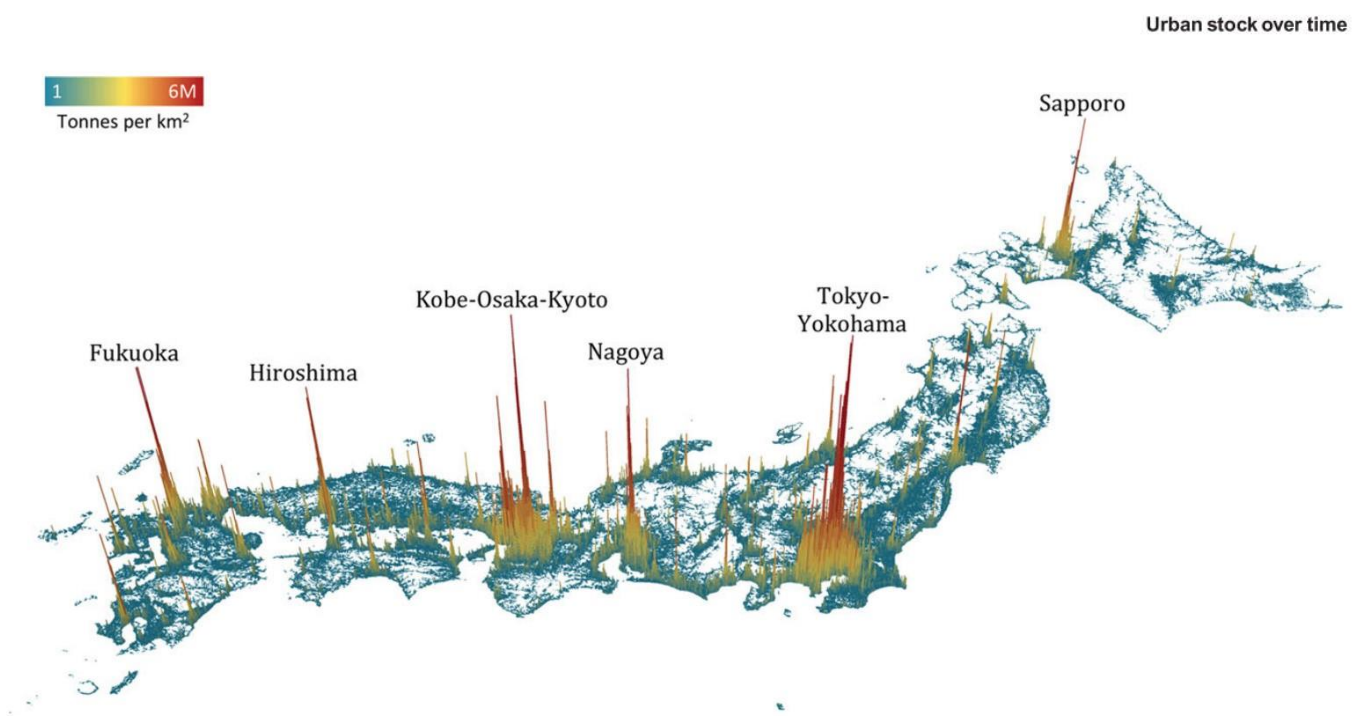
- **Dynamic MFA**
  - **Socio-Economic Metabolism: Gigaton Problems**

The Weight of Cities



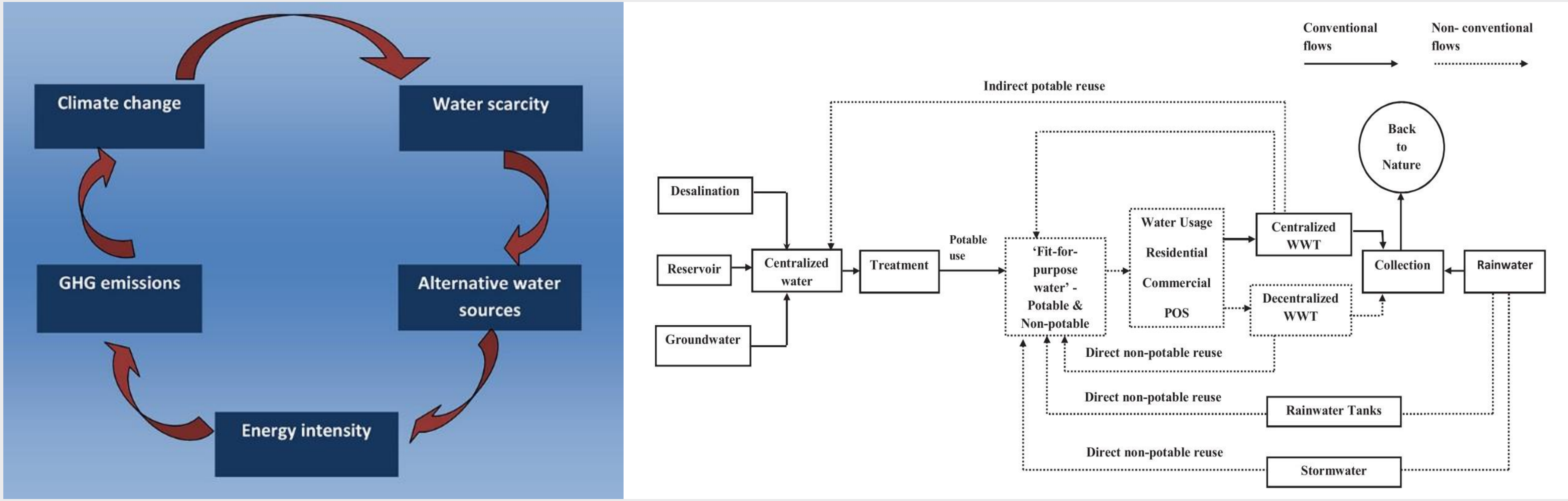
Socio-ecological-infrastructural systems framework (Ramaswami et al., 2012)

Urban stock by 4D-GIS (Tanikawa & Hashimoto, 2009; Tanikawa et al., 2015)



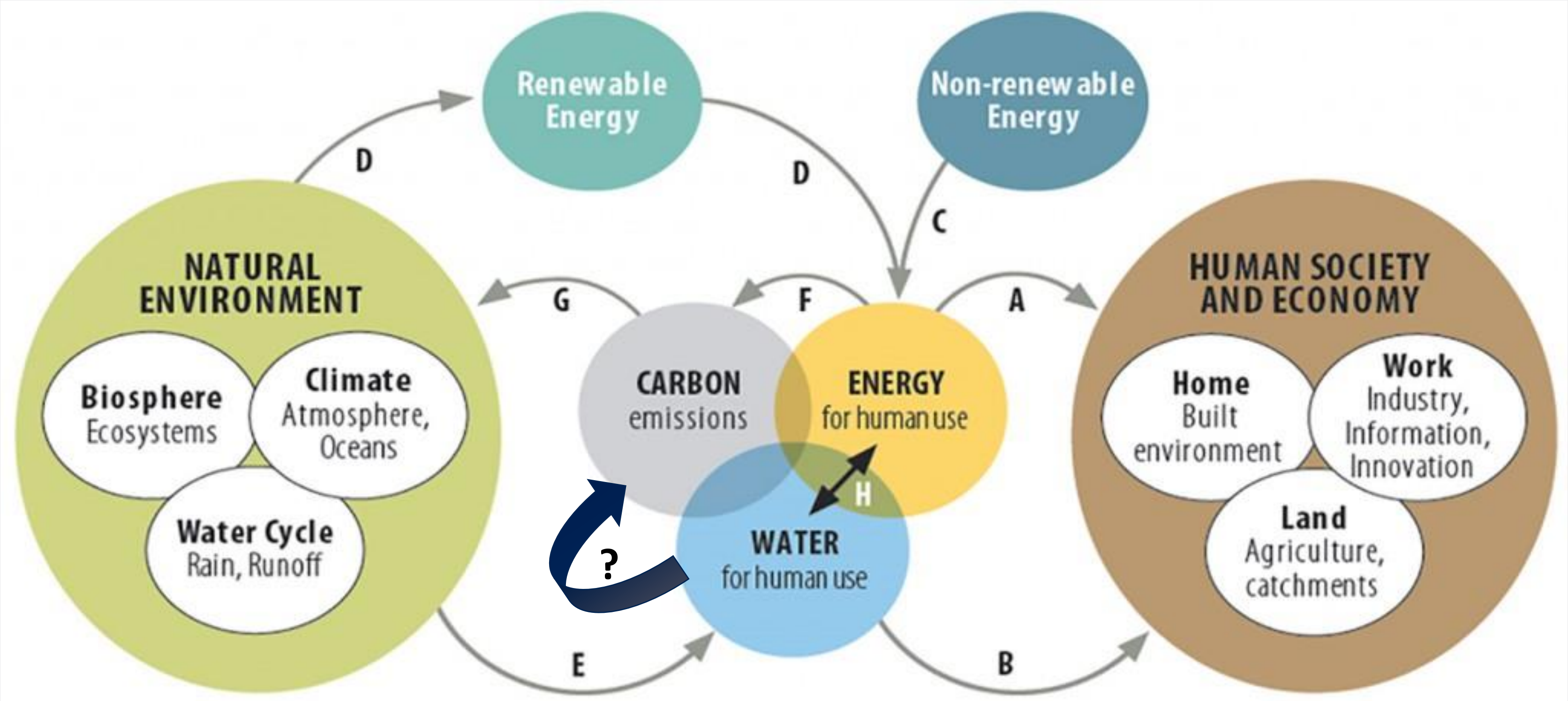
International Resource Panel: The Weight of Cities (2018)

Urban Water Systems



(Nair et al., 2014)

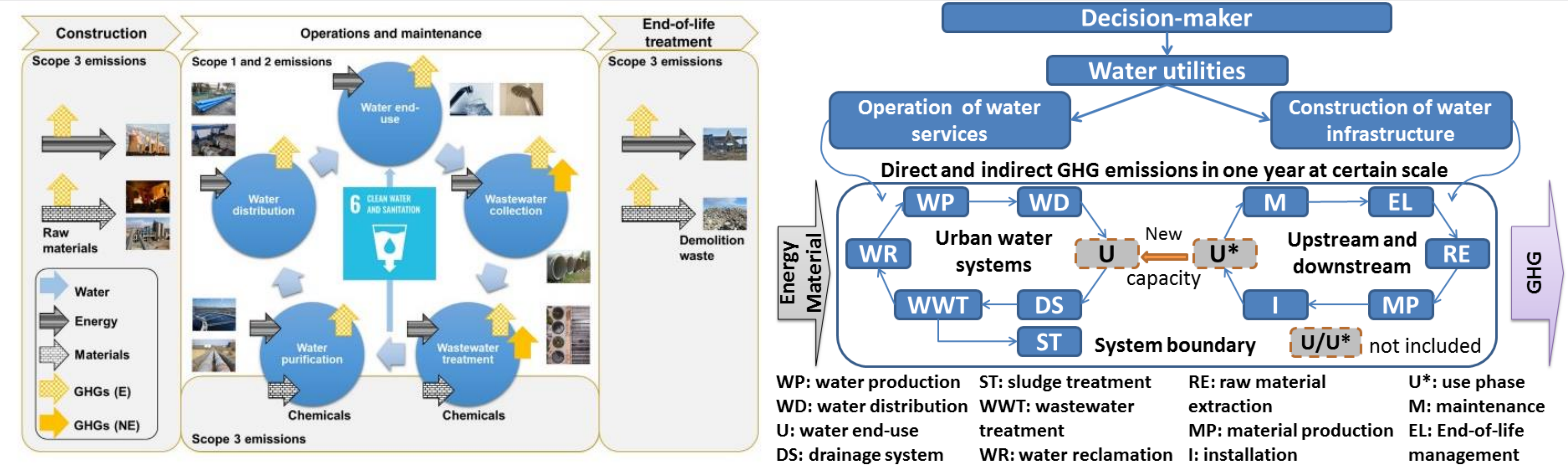
Water-Energy-Carbon Nexus



1. **GHGs from treatment processes**
2. **GHGs embodied in infrastructure**
3. **GHGs induced by water services**

PMSEIC (2010). Challenges at Energy-Water-Carbon Intersections. Prime Minister's Science, Engineering and Innovation Council, Canberra, Australia

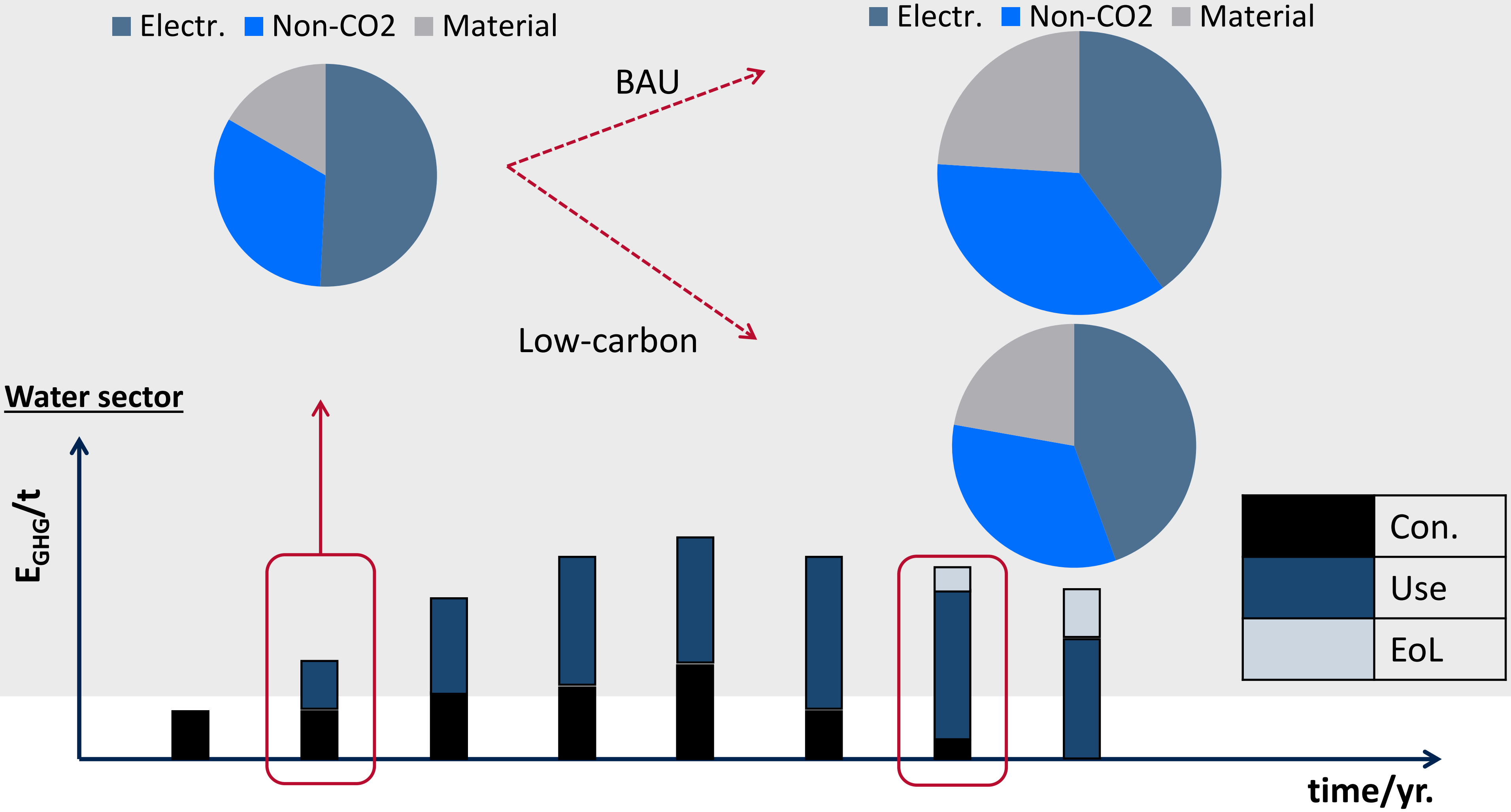
Our GHG Accounting Framework for Urban Water Systems



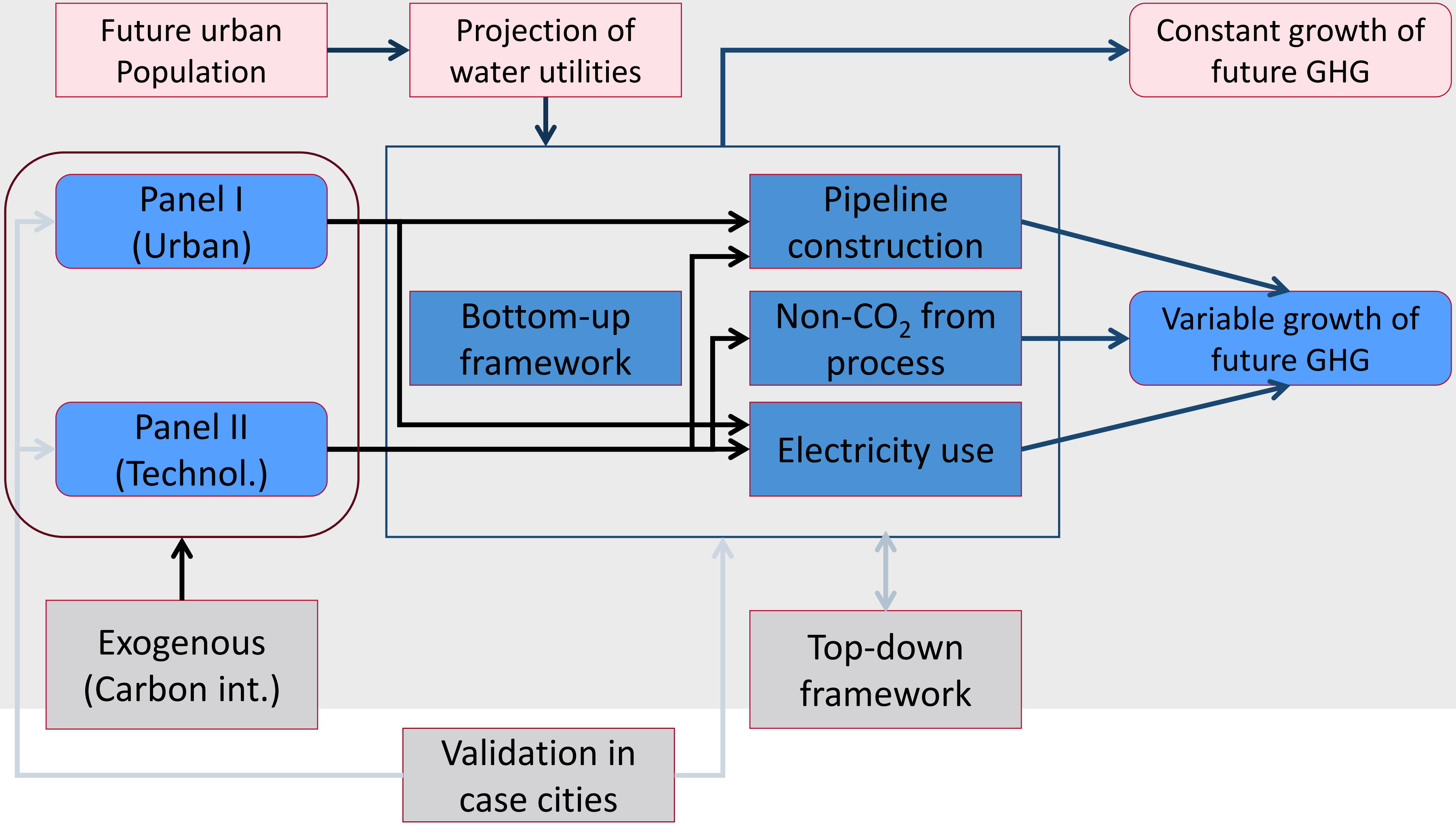
WP: water production
WD: water distribution
U: water end-use
DS: drainage system
ST: sludge treatment
WWT: wastewater treatment
WR: water reclamation
RE: raw material extraction
MP: material production
I: installation
U*: use phase
M: maintenance
EL: End-of-life management

Zhang, Q., Smith, K., Zhao, X., Jin, X., Wang, S., Shen, J., & Ren, Z. J. (2021). Greenhouse gas emissions associated with urban water infrastructure: What we have learnt from China's practice. *Wiley Interdisciplinary Reviews: Water*, *8*(4), e1529.

A Low-Carbon Future of Urban Water Systems



GHG Projections of Urban Water Systems



Future urban Population

Projection of water utilities

Constant growth of future GHG

Panel I (Urban)

Panel II (Technol.)

Bottom-up framework

Pipeline construction

Non-CO_2 from process

Electricity use

Variable growth of future GHG

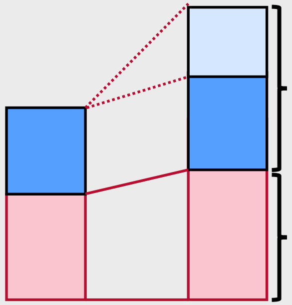
Exogenous (Carbon int.)

Top-down framework

Validation in case cities

What is the future?

GHG emissions

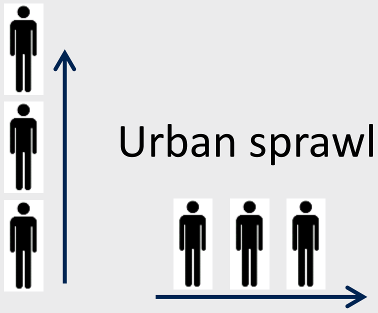


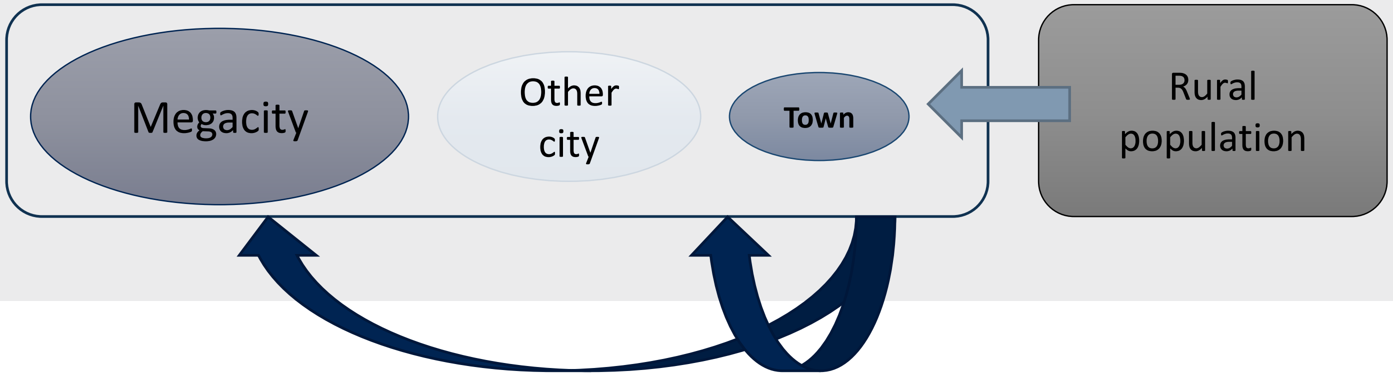
Variable growth: Affluence and Technology driven

Constant growth: Population driven

Urbanization Impact on Water System's GHGs

Panel I **(Urban)**	**Compact or not** **Population density for design, capita/km^2**				**In-migration to mega-cities or not** **Relative growth rate of residents**			
		Megacity	**Other city**	**Town**		**Megacity**	**Other city**	**Town**
S1A	**Yes**	50,000	30,000	10,000	**No**	150%	100%	50%
S1B	**No**	10,000	10,000	3,000	**No**	150%	100%	50%
S1C	**Yes**	50,000	30,000	10,000	**Yes**	50%	100%	150%
S1D	**No**	10,000	10,000	3,000	**Yes**	50%	100%	150%

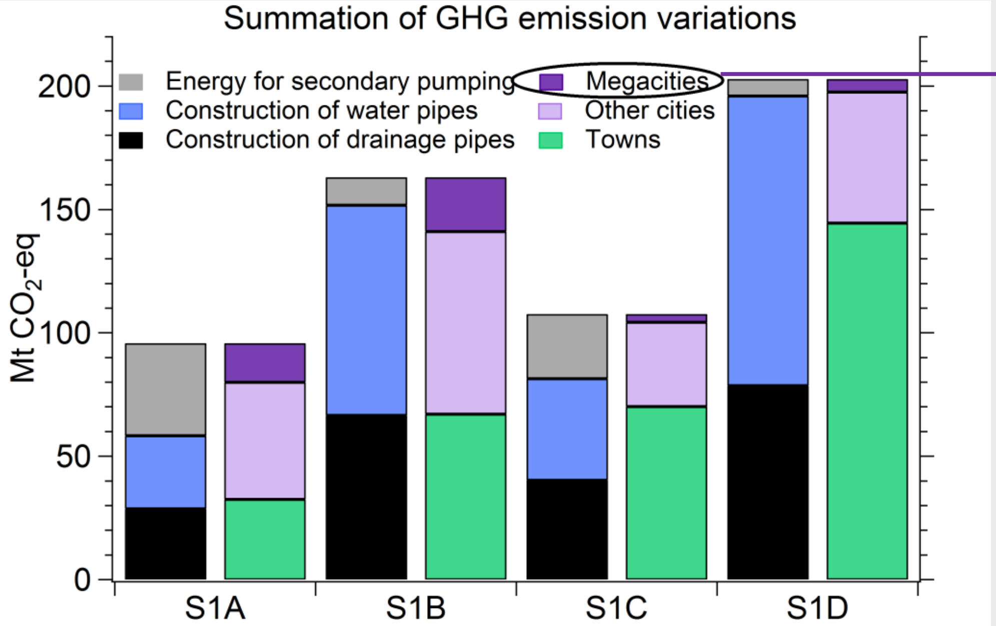




Zhang, Q., Liu, S., Wang, T., Dai, X., Baninla, Y., Nakatani, J., & Moriguchi, Y. (2019). Urbanization impacts on greenhouse gas (GHG) emissions of the water infrastructure in China: Trade-offs among sustainable development goals (SDGs). Journal of Cleaner Production, 232, 474-486.

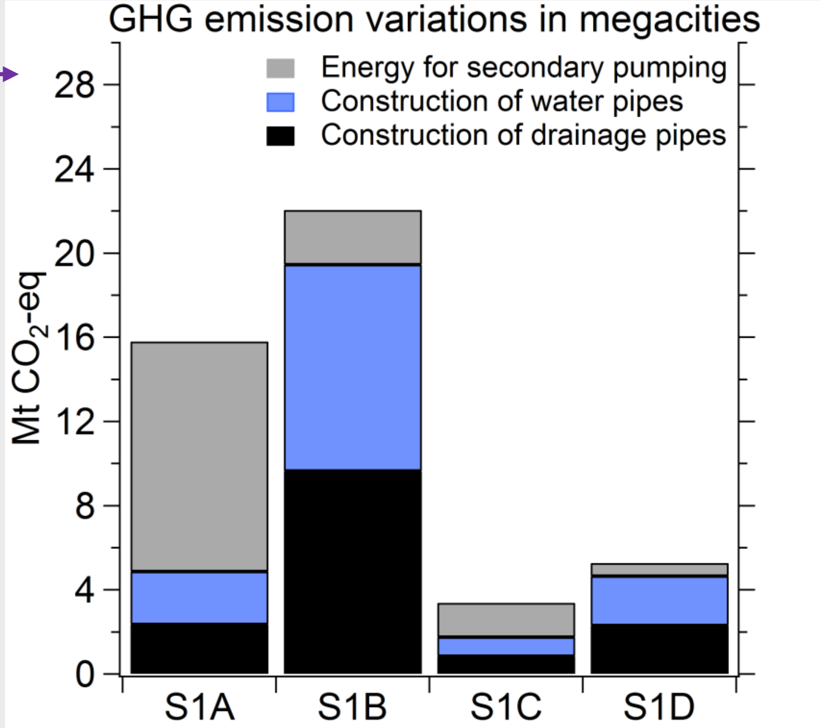
Panel I: Urban Policy vs. Material Efficiency

- Lowest case (S1A): compact design without restriction of in-migrants



Panel I	More people in megacity	Less people in megacity
More need of land	Ib	Id
Less need of land	Ia	Ic

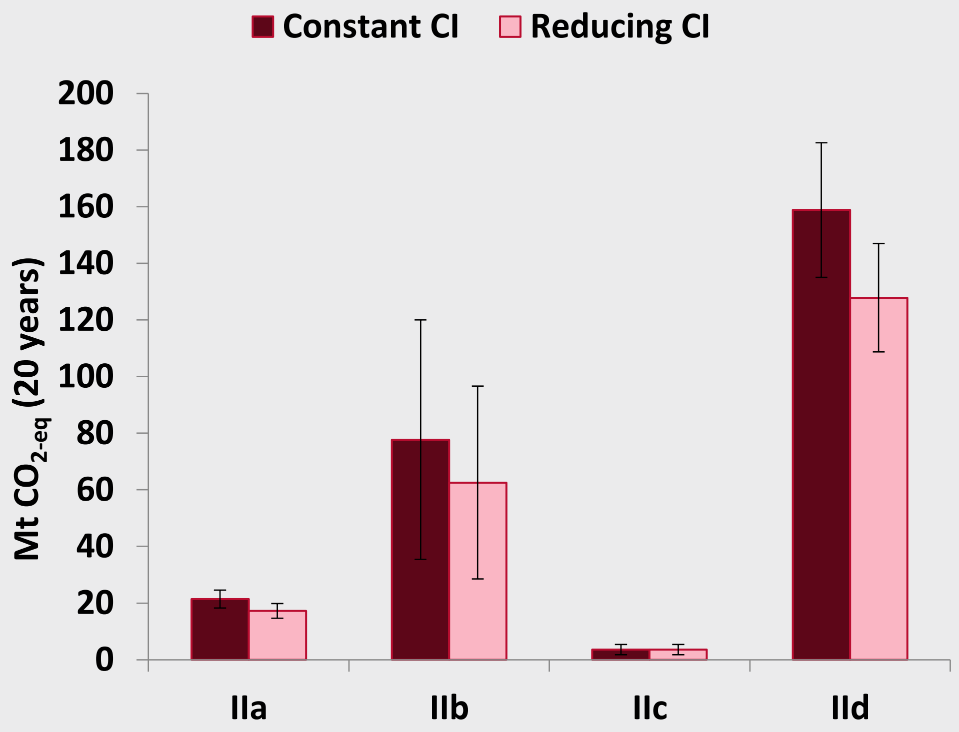
- S1A: Significant growth of energy for secondary pumping in compact design



(Zhang et al., 2019)

Panel II: System Upgrade vs. Additional GHGs

Subsystem	**Option IIa**	**Option IIb**	**Option IIc**	**Option IId**
Pipeline system	Water Pipe upgrade			
Water supply		Desalination		
Sludge disposal			Alternative sludge disposal	
Wastewater treatment				Stricter WW permits (Standard II→IA)



Cost: GHG emissions (this study)
Benefit:
a) Reduce water leakage;
b) Increase water supply;
c) Save land resource;
d) Better water quality.

Error bar: electricity use 15%, methane emissions 50%, pipeline construction 50%

(Zhang et al., 2019)

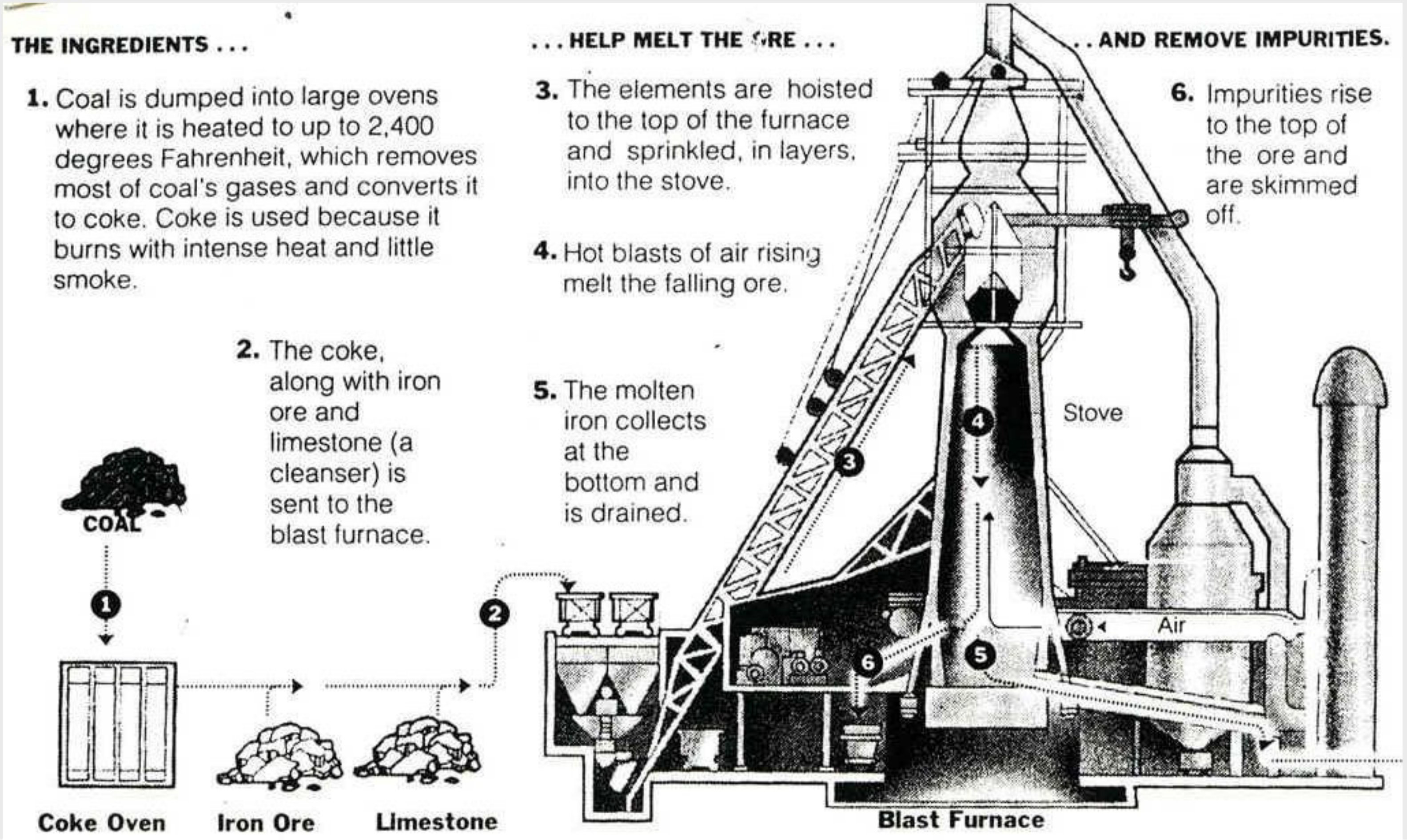
Case Studies

- Static MFA
  - Nexus Research: Interdependence and Interaction

- **Dynamic MFA**
  - **Socio-Economic Metabolism: Gigaton Problems**

Coal and Iron: Historical Symbols for Industrial Revolutions


(Völklingen Ironworks, World Heritage, 2022)


THE INGREDIENTS . . .

1. Coal is dumped into large ovens where it is heated to up to 2,400 degrees Fahrenheit, which removes most of coal's gases and converts it to coke. Coke is used because it burns with intense heat and little smoke.

2. The coke, along with iron ore and limestone (a cleanser) is sent to the blast furnace.

. . . HELP MELT THE ORE . . .

3. The elements are hoisted to the top of the furnace and sprinkled, in layers, into the stove.

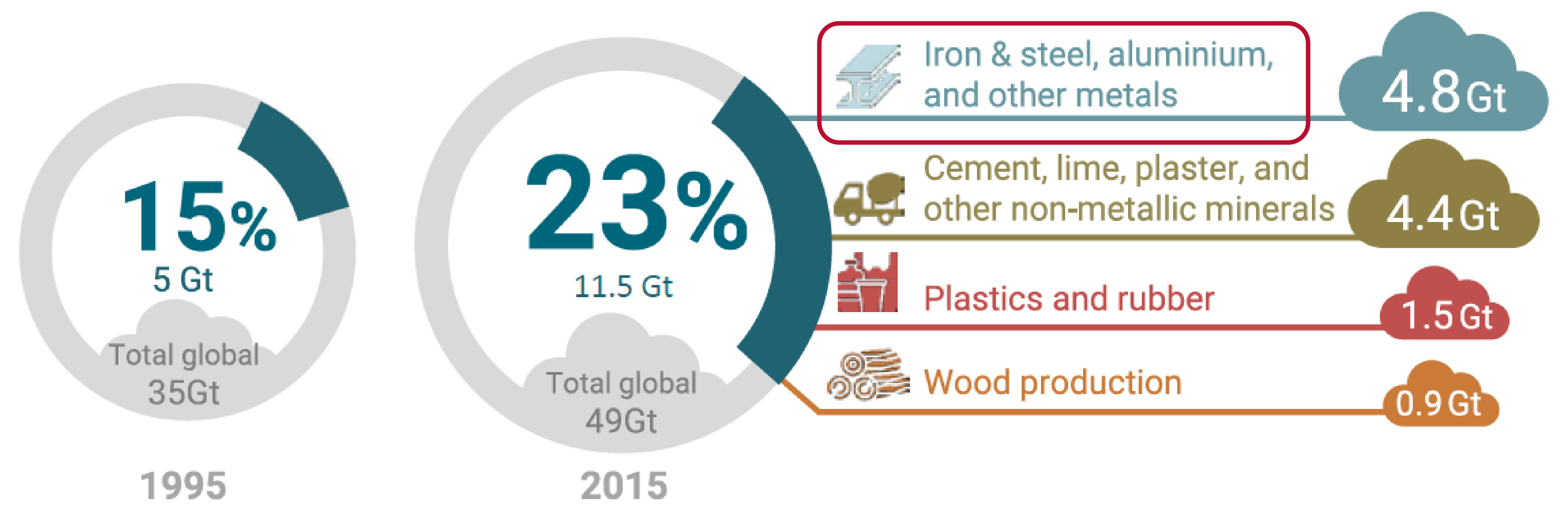
4. Hot blasts of air rising melt the falling ore.

5. The molten iron collects at the bottom and is drained.

. . AND REMOVE IMPURITIES.

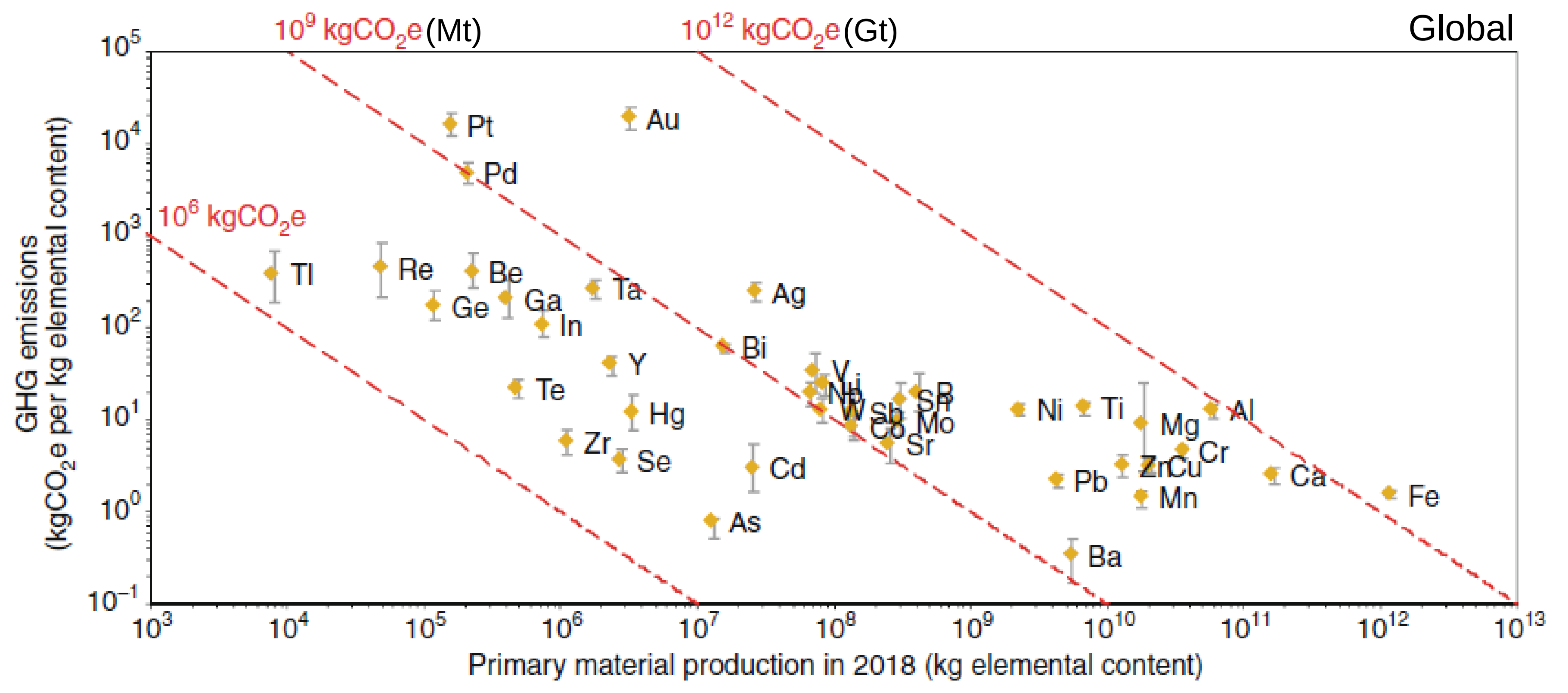
6. Impurities rise to the top of the ore and are skimmed off.

Carbon-Intensive Material Production



(Hertwich et al., 2019)

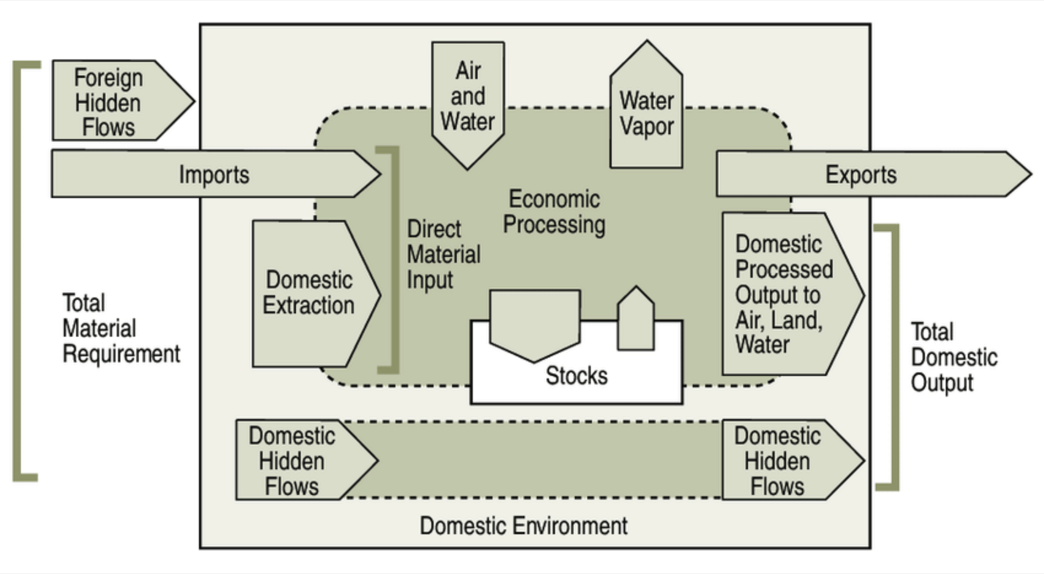
Triple Gigaton Problems (Raw Material – GHGs – Waste)



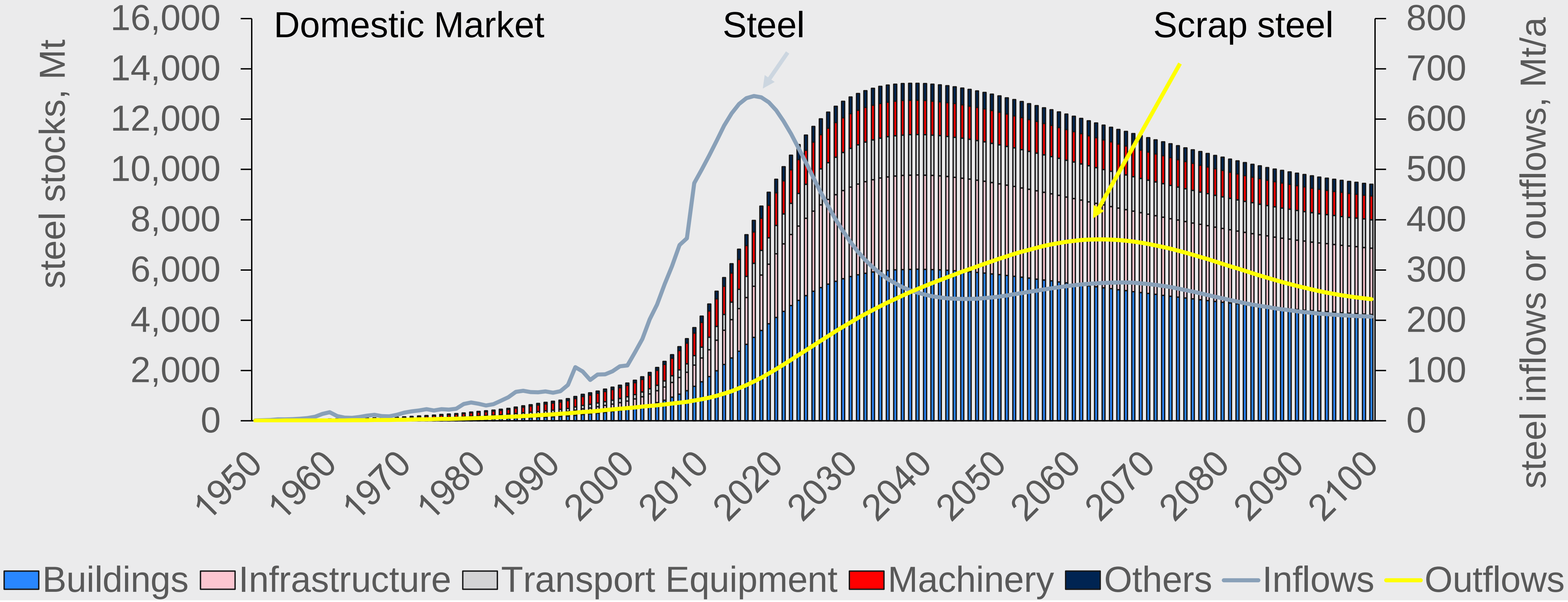
(Azadi et al., 2020)

Dynamic Material Flow Analysis

- Inflows (***I***) = Stock Changes (***S***) + Outflows (***O***)
- $\boldsymbol{I_i(t) = \frac{dS_i(t)}{dt} + O_i(t)} \qquad (1)$
- $\boldsymbol{O_i(t) = \sum_{t' \leq t} I_i(t')\, L_i(t - t', LT_i, \sigma_i)} \qquad (2)$
  - ***L***: likelihood of end-of-life
  - ***LT***: life time, ***σ***: standard variations

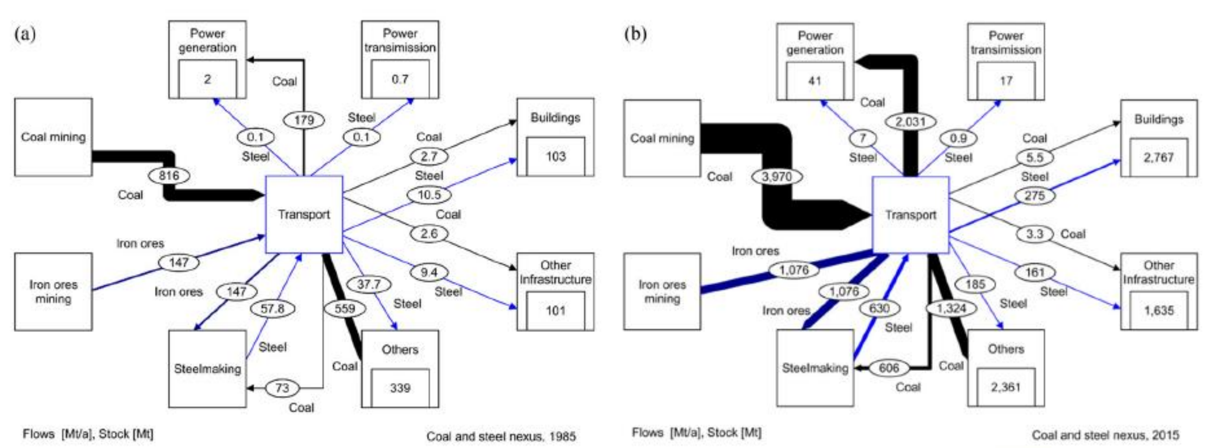


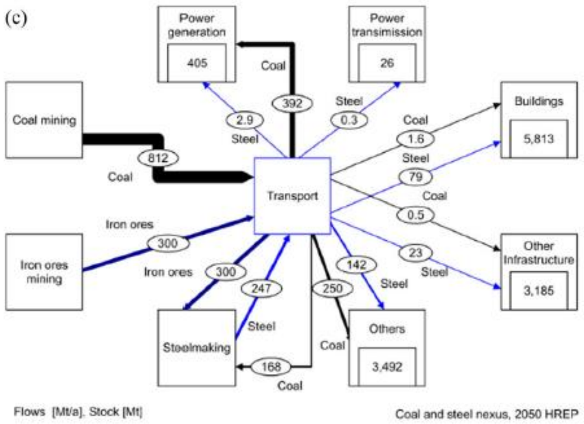
China’s Steel Flows and Stocks

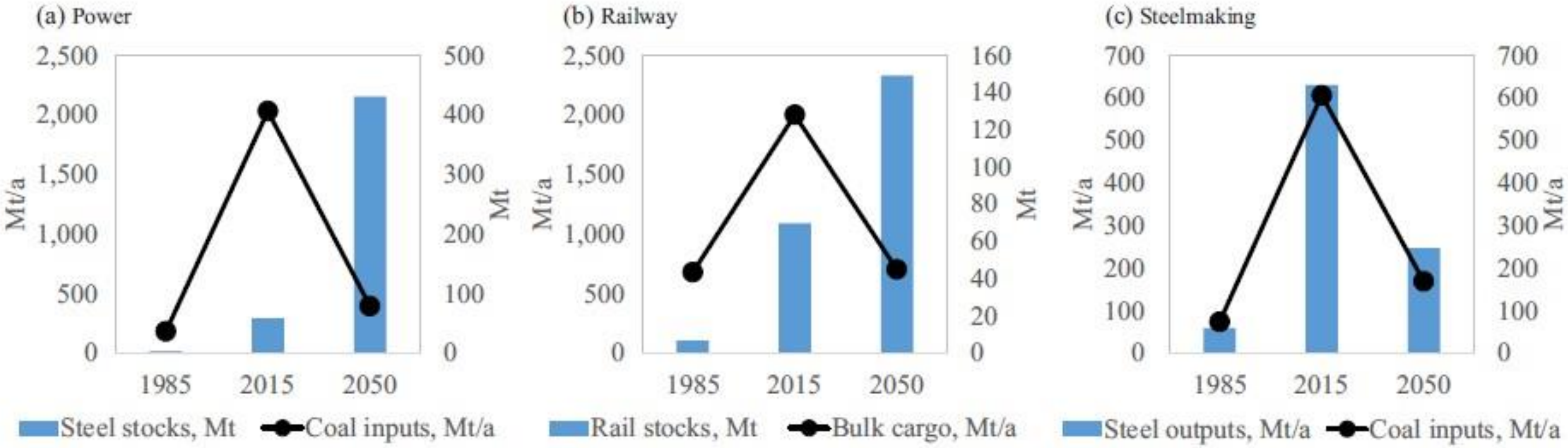


Zhang, Q., Kennedy, C., Wang, T., Wei, W., Li, J., & Shi, L. (2020). Transforming the coal and steel nexus for China's eco-civilization: Interplay between rail and energy infrastructure. *Journal of Industrial Ecology*, 24(6), 1352-1363.

China’s Coal and Steel Nexus towards a Low-Carbon Future

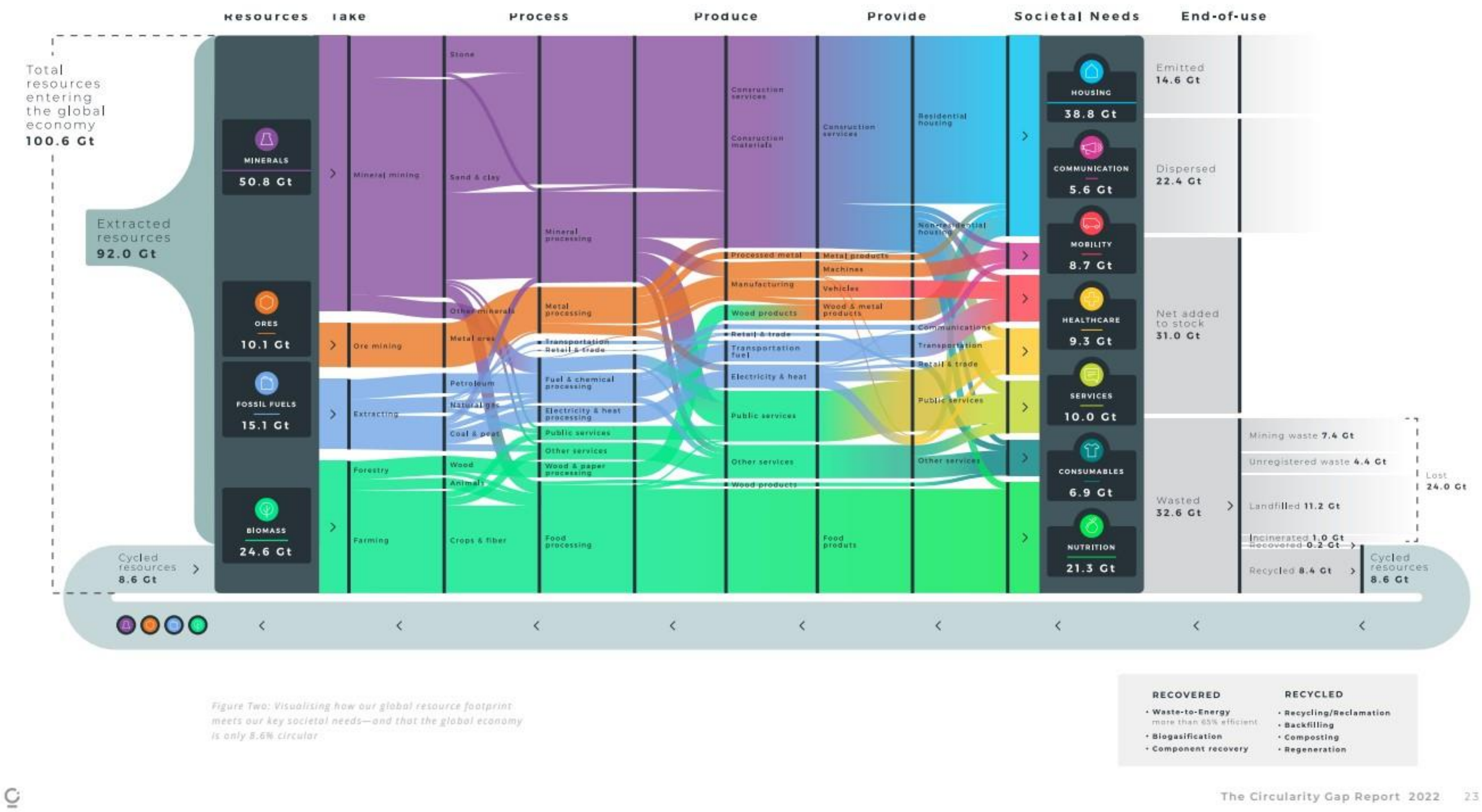






(Zhang et al., 2020)

Global Material Circularity : 8.6% (2022)



RECOVERED
- Waste-to-Energy more than 65% efficient
- Biogasification
- Component recovery

RECYCLED
- Recycling/Reclamation
- Backfilling
- Composting
- Regeneration

Figure Two: Visualising how our global resource footprint meets our key societal needs—and that the global economy is only 8.6% circular

The Circularity Gap Report 2022 23

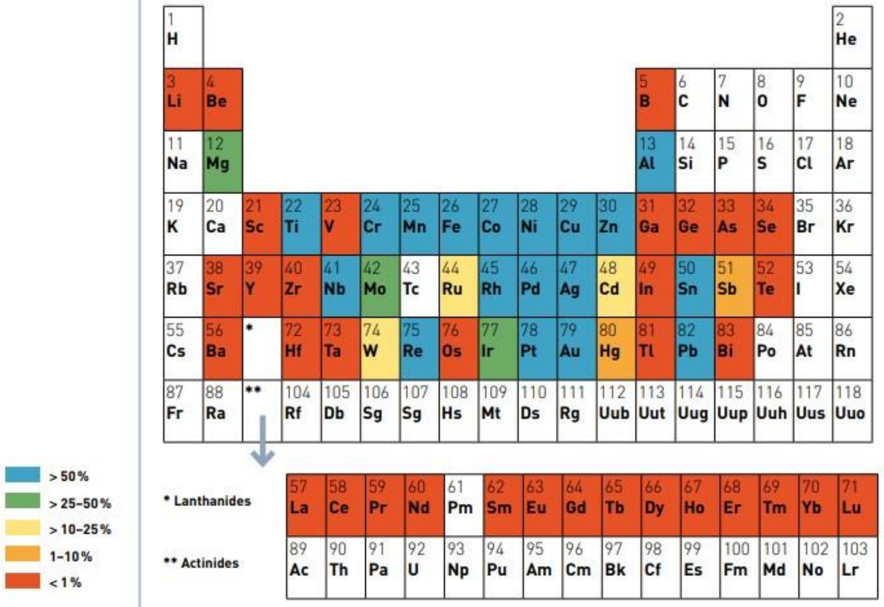


Figure 4. EOL-RR for sixty metals: The periodic table of global average end-of-life (post-consumer) functional recycling (EOL-RR) for sixty metals. Functional recycling is recycling in which the physical and chemical properties that made the material desirable in the first place are retained for subsequent use. Unfilled boxes indicate that no data or estimates are available,

Only <1% of some critical minerals (Li, In, REEs, *etc.*) are recycled after use

The Circularity Gap Reporting Initiative: 2022 CGR REPORT
International Resource Panel: Recycling Rates of Metals: A Status Report (2011)

Circular Economy ≠ Recycling

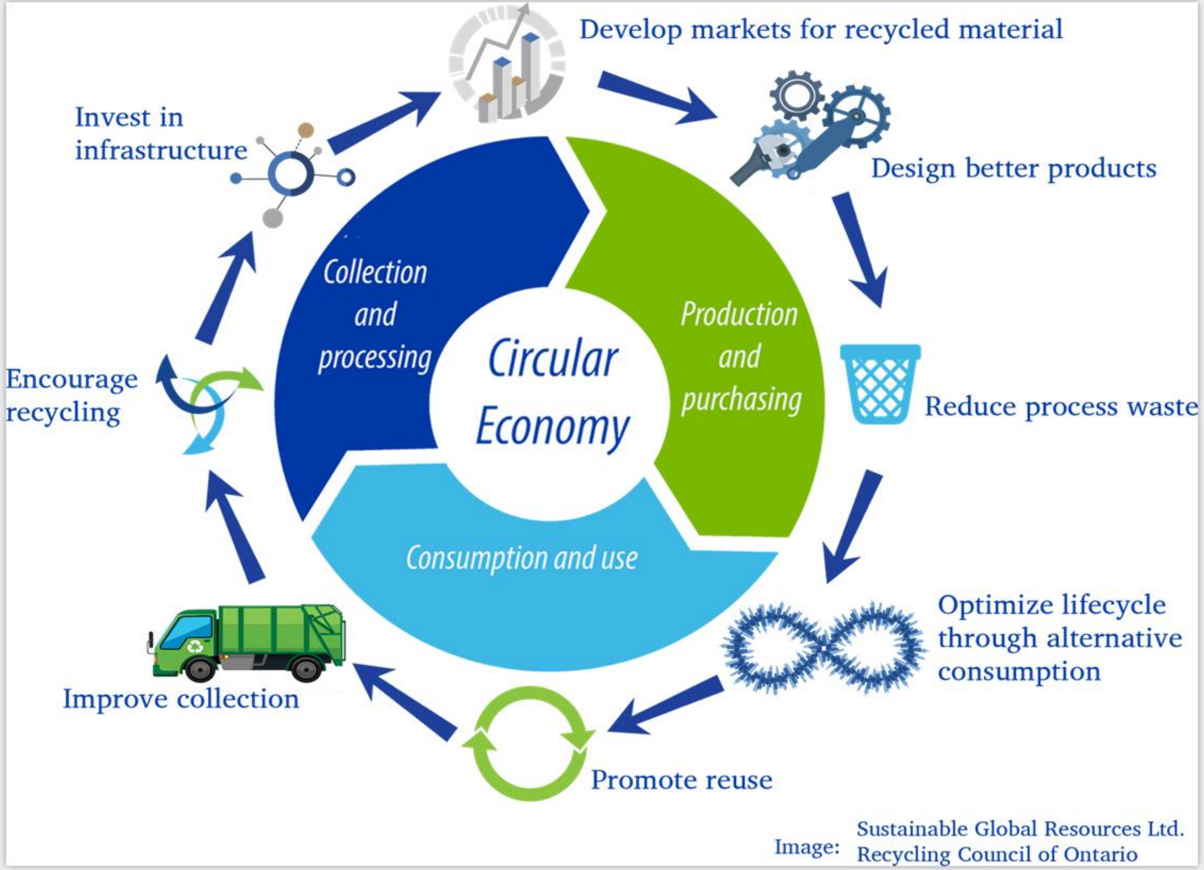
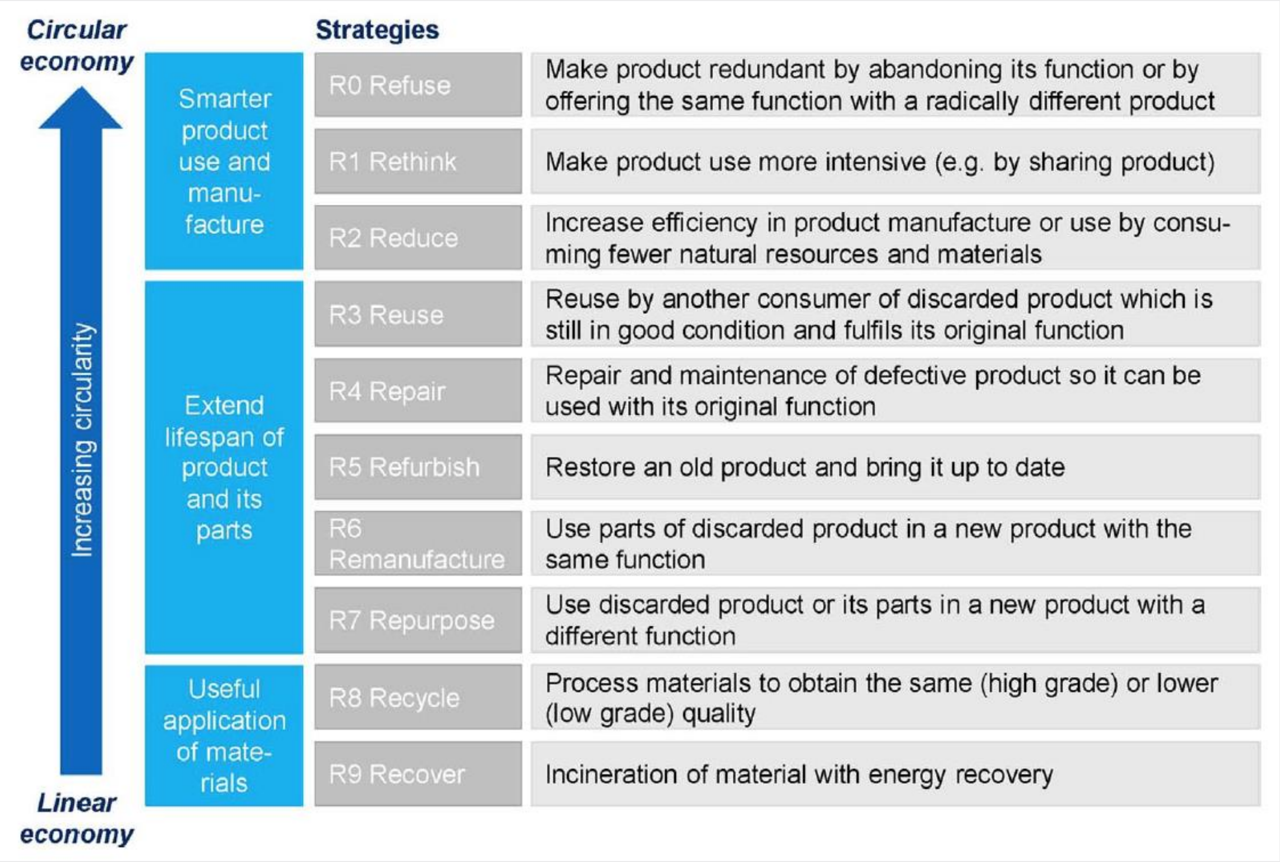


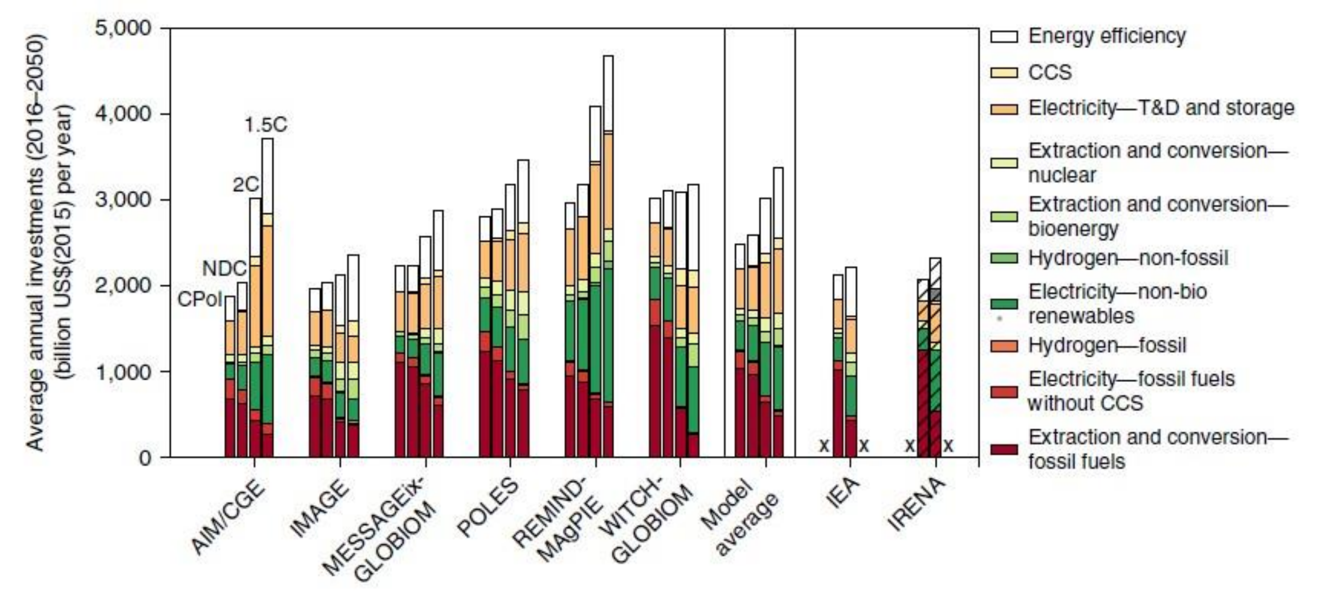
Image: Sustainable Global Resources Ltd.
Recycling Council of Ontario



Circular economy ↑ Increasing circularity ↑ Linear economy		Strategies	
Circular economy	Smarter product use and manufacture	R0 Refuse	Make product redundant by abandoning its function or by offering the same function with a radically different product
		R1 Rethink	Make product use more intensive (e.g. by sharing product)
		R2 Reduce	Increase efficiency in product manufacture or use by consuming fewer natural resources and materials
	Extend lifespan of product and its parts	R3 Reuse	Reuse by another consumer of discarded product which is still in good condition and fulfils its original function
		R4 Repair	Repair and maintenance of defective product so it can be used with its original function
		R5 Refurbish	Restore an old product and bring it up to date
		R6 Remanufacture	Use parts of discarded product in a new product with the same function
		R7 Repurpose	Use discarded product or its parts in a new product with a different function
	Useful application of materials	R8 Recycle	Process materials to obtain the same (high grade) or lower (low grade) quality
Linear economy		R9 Recover	Incineration of material with energy recovery

Takeaways

- **Do the *Right* Thing Efficiently.**
  - Take systems-based approaches to decipher trade-offs
- **Gigaton Problems Need *Gigaton* Solutions.**
  - Capacity building for scaling up solutions



(McCollum et al., 2022)

Thank you for your attention!