Workshop “Infrastructures for energy transition”
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# Exploring Material-Energy Nexus for Resource and Climate Strategies


**Gang Liu**

Professor WSR in Industrial Ecology

SDU Life Cycle Engineering, University of Southern Denmark

Email: gli@kbm.sdu.dk


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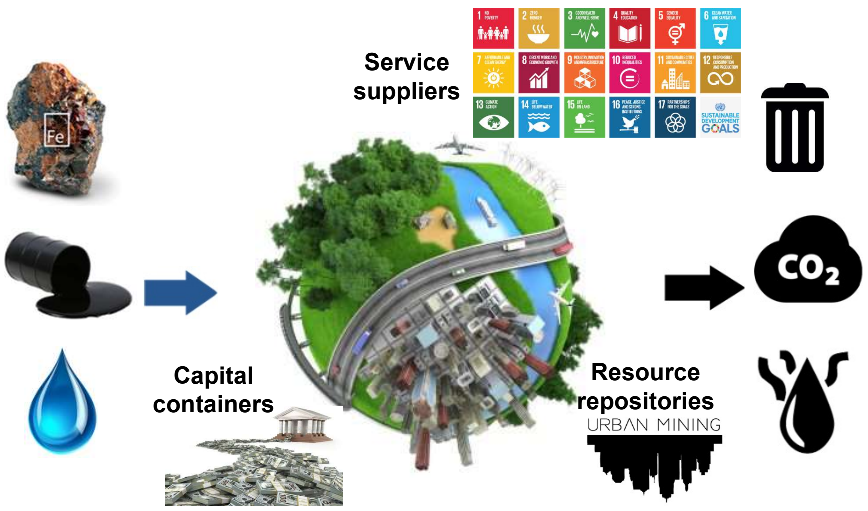
## Product and infrastructure stocks…




… define the boundary conditions for
socioeconomic metabolism and sustainability transition

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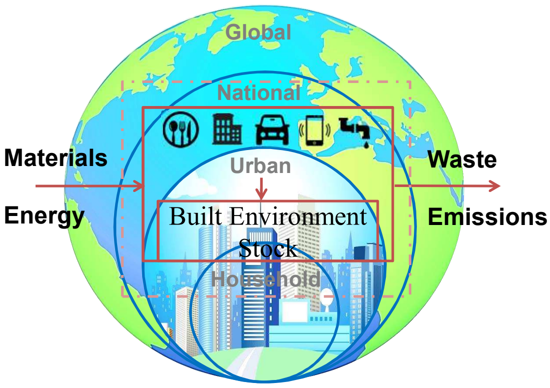
## We SMILE (societal metabolism and industrial ecology)

### - and strive to map and inform sustainable socio-metabolic transition for a circular, lean, and steady-state economy





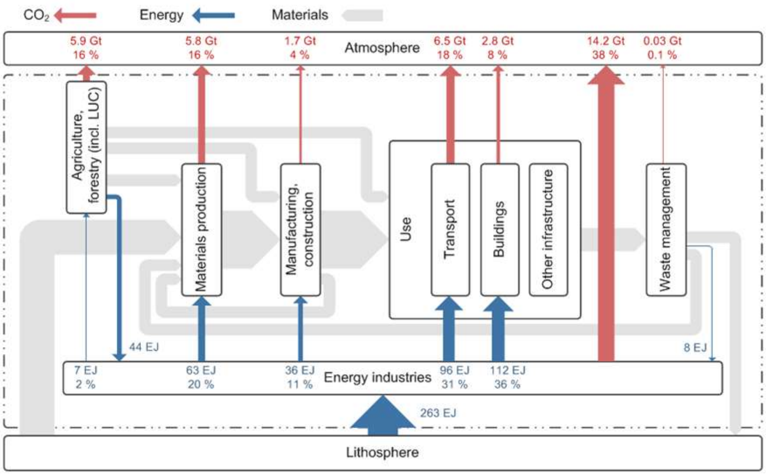
Case studies: metal cycles, agrifood chains, urban systems, low-carbon technologies…

Team: **Gang Liu (PI)**, 1 postdoc, 6 PhDs, 4-6 master students every year…



## Addressing sustainability in a socio-metabolic framework

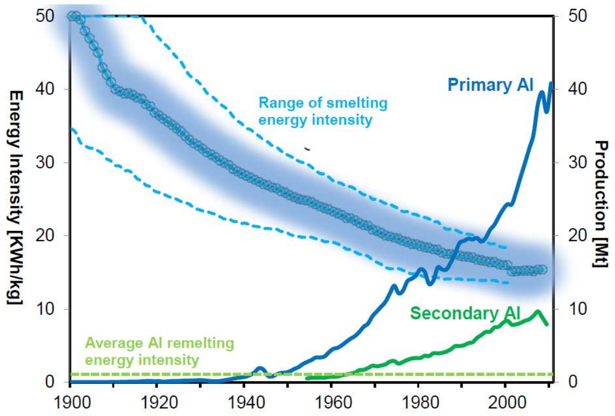
### - The material-energy-emission nexus




**1. Societies build on materials, which lead to energy use throughout the life cycle**
**2. The renewable energy transition relies on (critical) materials**

IPCC AR5, WG3 (2014), based on Müller and Liu et al. (2013)

## Case I: Materials → Energy Nexus: Aluminium

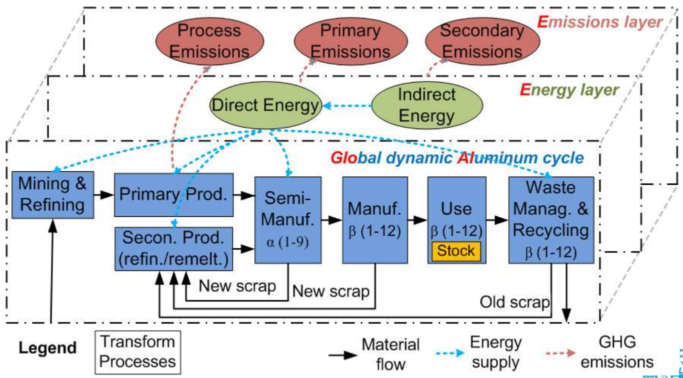



Opportunities and challenges of aluminium recycling

SDU LIFE CYCLE ENGINEERING Liu 2013, Env. Sci. Tech. 5/19

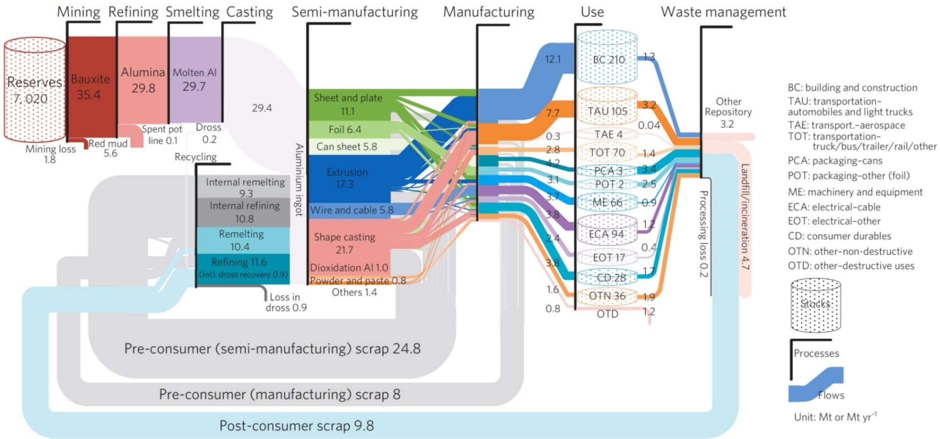
## Modelling energy use & GHG emissions associated with the material cycle

- Mass flow layer: mining, refining, production, use, recycling…
- Energy layer: direct energy use (nine types), indirect energy use
- Emissions layer: direct emissions, indirect emissions, process emissions




SDU LIFE CYCLE ENGINEERING Liu et al. 2013, Nature Climate Change 6/19

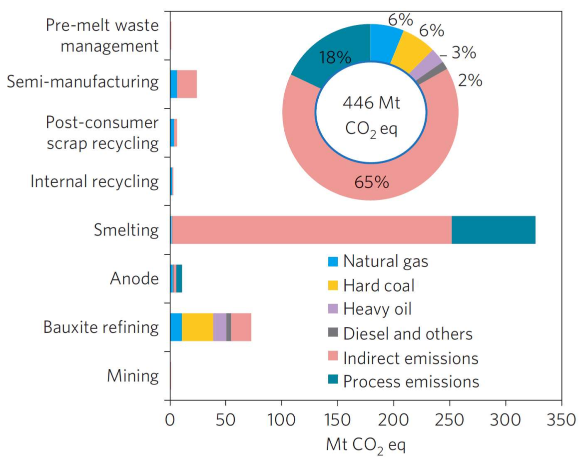
## The global Al cycle: The more circular, the better?




Global anthropogenic aluminium cycle in 2009

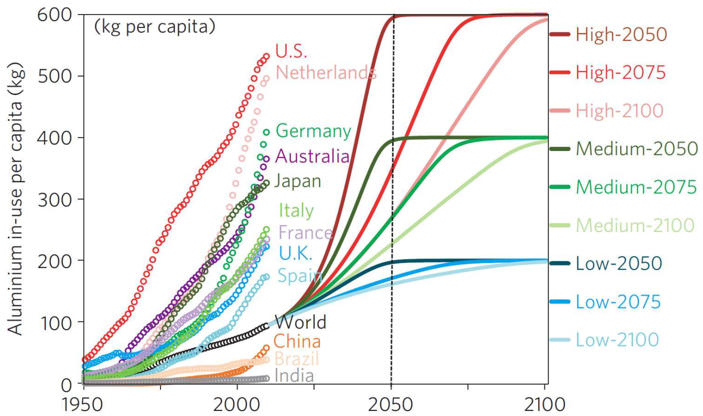


## GHG emissions of the global Al cycle in 2009




**Then how about the future?**
Future emissions ← Future Al cycle and flows ← Future stock patterns…

## A stock-driven model for future scenarios




**Hypothesis:** It is unlikely that per-capita Al stocks will grow indefinitely at the present speed. Most likely, growth will eventually slow down, level off or even decline over the long term as services provided by aluminum products may become saturated or as less aluminum is used to provide certain services.

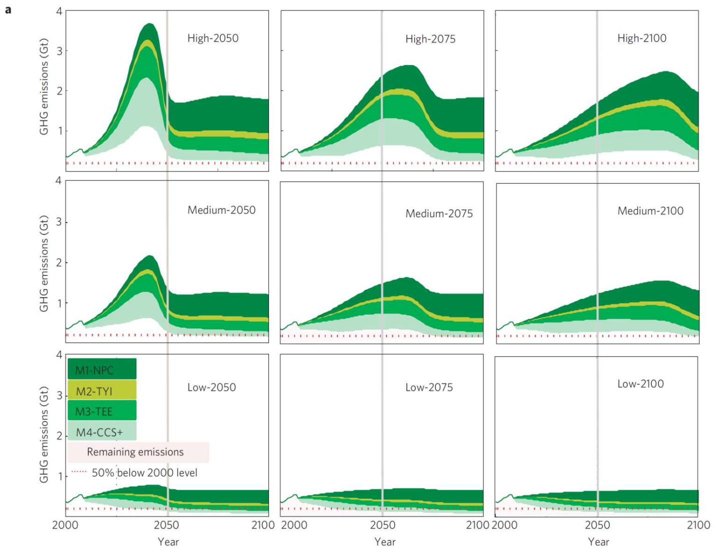


## Mitigation wedges and their implementation

**Table 1 | Mitigation wedges and their implementation in the model.**

| Wedge code | Description | Model implementation (details in the Supplementary information) |
|---|---|---|
| M1-NPC | Near-perfect collection | Collection rates of BC, TAU, TAE and TOT obsolete products will gradually reach 95% by 2050<br>Collection rates of all other obsolete products will gradually reach 90% by 2050 |
| M2-TYI | Technologies for yield improvement | Yield ratios (the efficiency of metal to downstream process relative to the sum of all process inputs) of all semi-manufacturing processes will gradually reach 90% by 2050<br>Yield ratios of all manufacturing processes will gradually reach 95% by 2050 |
| M3-TEE | Technologies for energy and emissions efficiency improvement | Inert anode and wetted cathode: electrolysis energy intensity is projected to reach 13.11 $kWh\ kg^{-1}$ by 2030, and starting then all process emissions from electrolysis are set to zero, whereas anode production emissions increase by a factor of 2.08 (ref. 8)<br>Global average energy intensity of bauxite refining is set to reach today's best-available-technology level (9.5 $GJ\ t^{-1}$) in 2020 (ref. 2) and keep an annual improvement of 0.25% afterwards[14]<br>Energy intensities of all semi-manufacturing processes are reduced by 25%, as demonstrated by continuous strip casting for rolling[8]<br>Oxy-fuel combustion: a 55% reduction is achieved on all natural gas energy use in the model[1] |
| M4-CCS+ | CCS and electricity decarbonization | CCS will be gradually implemented at 85% effectiveness until 2030 (ref. 1) on all coal power supplying electrolysis in the contract mix<br>Decarbonizing the electricity supply in the contract mix by 30% through greater use of renewables, clean coal and others |

# Stock dynamics and emission pathways of the global Al cycle

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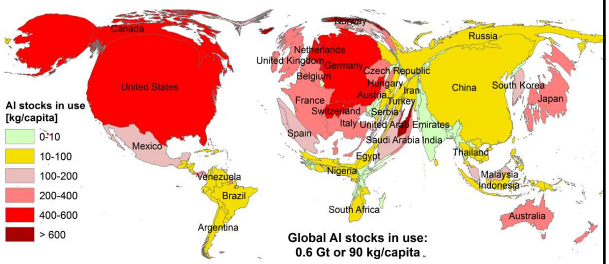
| | Emissions (2050/2000) | | | Acc. emissions (Gt, 2010–2050) | | | Max. reduction (%, 2000–2050) | | |
|---|---|---|---|---|---|---|---|---|---|
| | S-2050 | S-2075 | S-2100 | S-2050 | S-2075 | S-2100 | S-2050 | S-2075 | S-2100 |
| S-High | 5.7 | 6.5 | 4.7 | 86.0 | 52.5 | 41.9 | 27% | 77% | 22% |
| S-Medium | 3.8 | 4.1 | 3.4 | 56.6 | 39.9 | 35.1 | −21% | 2% | −17% |
| S-Low | 2.0 | 1.9 | 1.7 | 27.6 | 24.3 | 23.3 | −63% | −64% | −65% |


Liu et al. 2013, Nature Climate Change


# The 'scaling' effect:

## Growing complexity with spatial-temporal dynamics

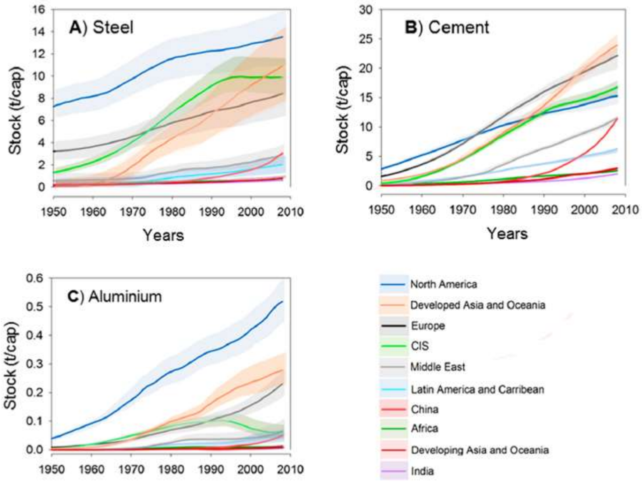




http://www.world-aluminium.org/statistics/massflow/


Liu et al. 2013, Env. Sci. Tech.; Bertram et al., 2017, Res. Cons. Recyl.; Liu 2018, in prep.

## Case II: Materials → Energy Nexus: Carbon footprint of infrastructure development

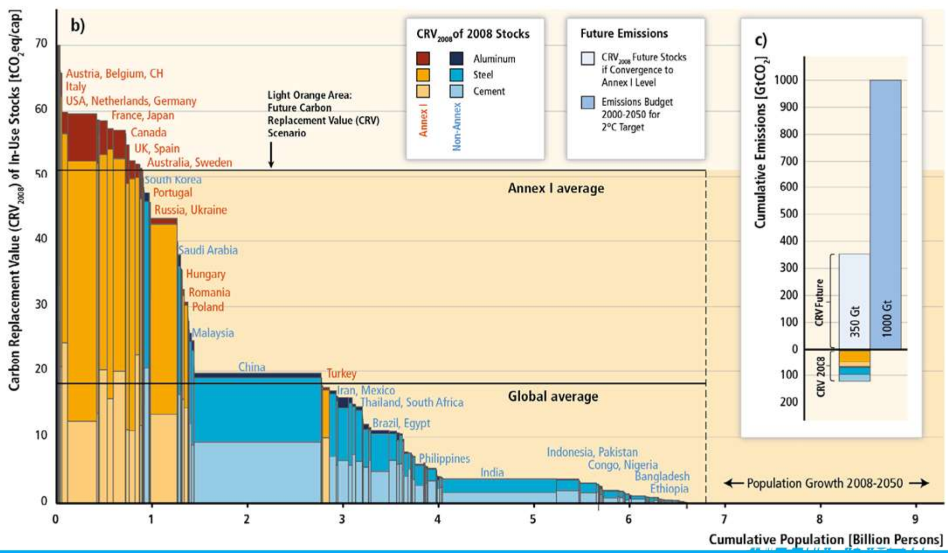



Historical per-capita material stocks in infrastructure - Fe, cement, and Al as a proxy

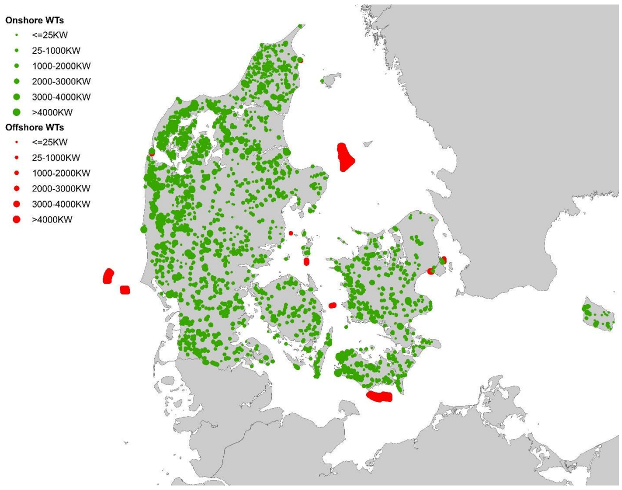


## Carbon footprint of built environment stocks

### (Carbon Replacement Value, CRV 2008)



# Case III: Energy → Materials Nexus: Danish wind energy




Will such a wind turbine map be seen across the world?

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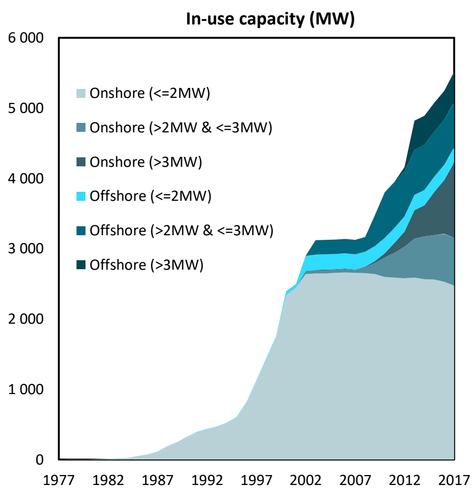
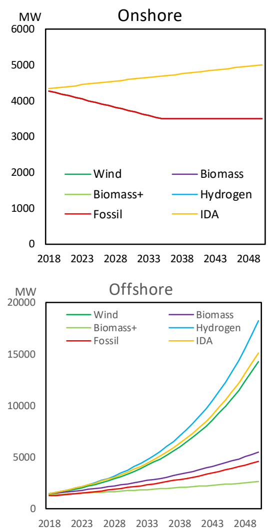
# Historical and future in-use capacity of Danish wind energy system

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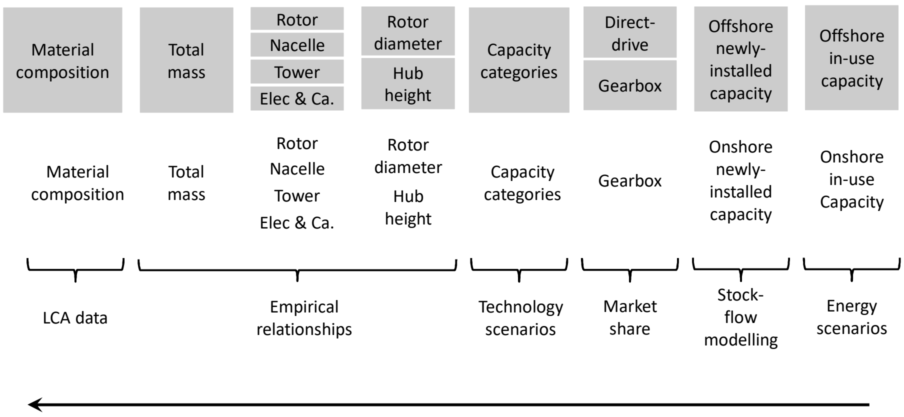
## A stock-driven & bottom-up demand forecasting

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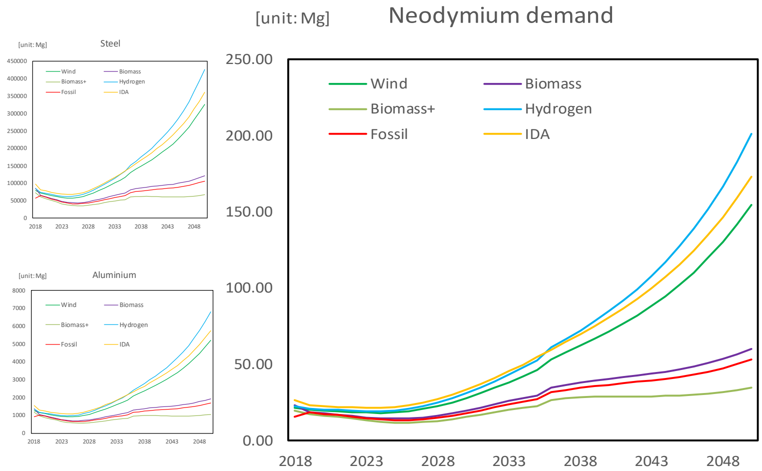
## Do we have enough materials and secure supply?




- Penetration rate of PM WTs: 15% (2015) to 50% (2050)
- Nd content: 196 kg/MW

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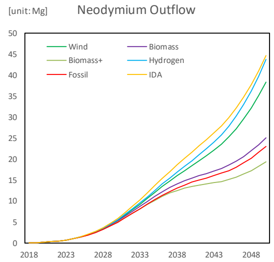
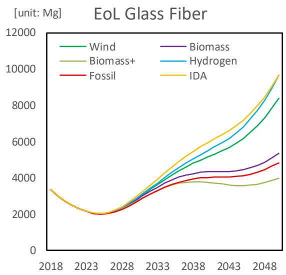
# Can we handle the (yet to come) waste issues?





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