Measuring economy-wide circularity of the United States: An input-output model in mass units

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Photo by Dennis Schroeder, NREL 46840

Integrated Energy Pathways

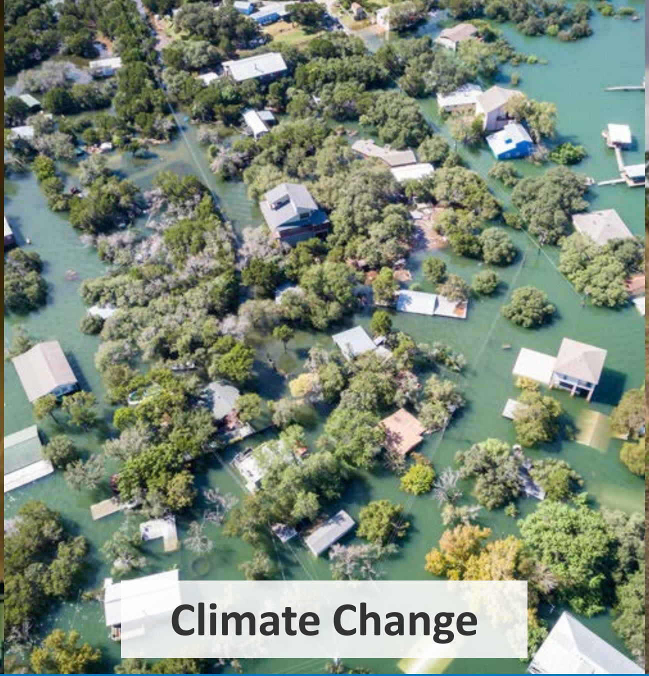
Electrons to Molecules

Circular Economy for Energy Materials

NREL's Vision:

A Clean Energy Future for the World

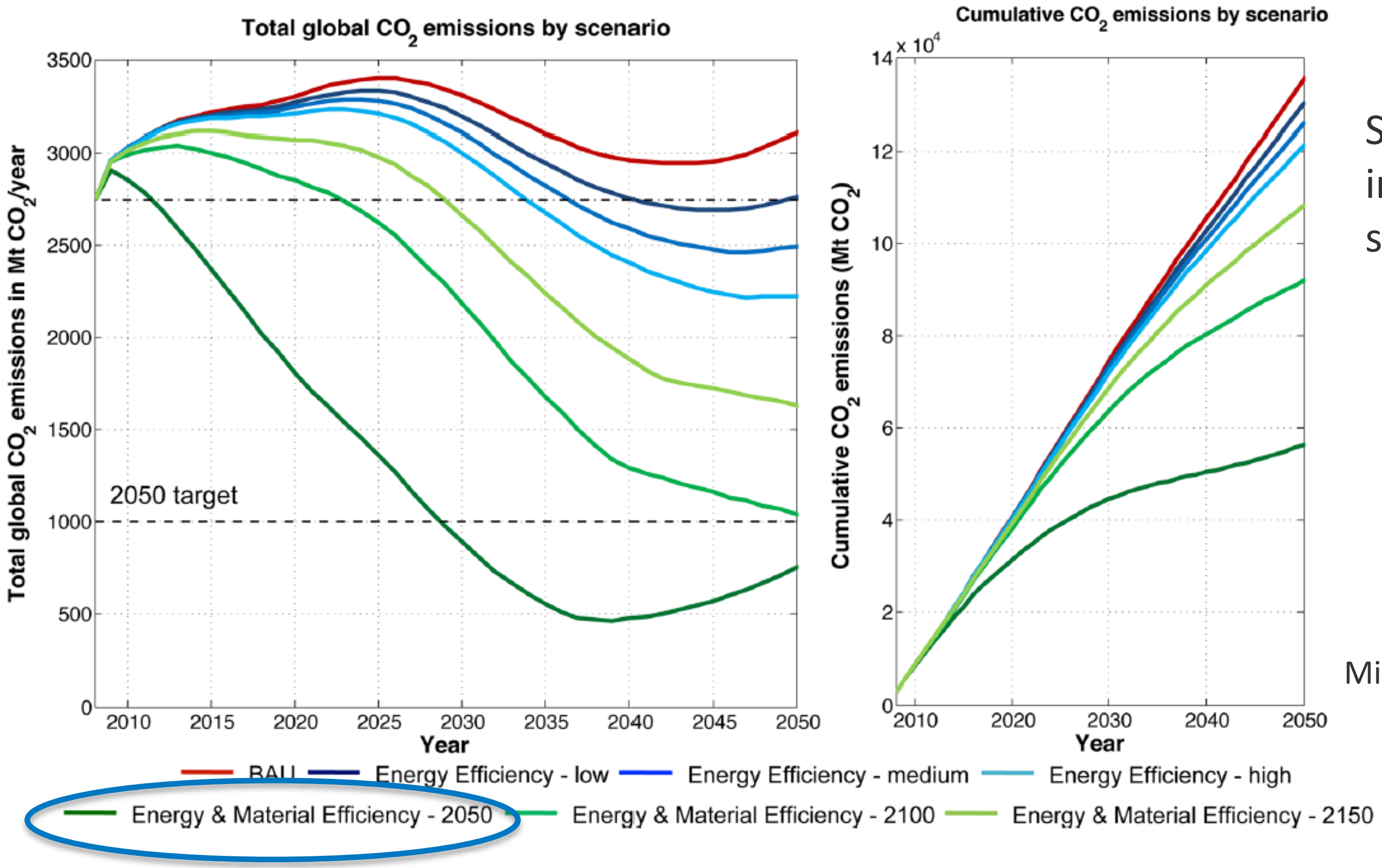
Three critical research areas respond to today's energy challenges and provide tomorrow's solutions



The Triple Planetary Crisis

The **triple planetary crisis** refers to the three main issues that humanity currently faces, reinforcing one another and driving further damage. Each must be resolved for us to have a viable future on this planet.

CE and Decarbonization



Steel industry scenarios

Milford et al. 2013

Circular Economy and Industry

- Manufacturers have renewed interest in Circular Economy

https://www.eastman.com/content/dam/eastman/corporate/en/media-center/resources/eastman-sustainability-report-2022.pdf

Circular Economy and Industry

- Only 5 of the 15 common sustainability reporting approaches incorporate CE; none incorporate it fully (Opferkuch et al. 2021 https://doi.org/10.1002/bse.2854)

Approach	Indicators used; treatment
EMAS	EMF indicators, voluntary
GRI	Undefined, mandatory
WEF	EMF indicators, WBCSD indicators, voluntary
BSI	EMF indicators, LCA, MFA, voluntary
UL	UL indicators, voluntary

CE Reporting only mandatory in one framework

Measuring the circular economy

- Circular economy pertains to physical, material goods
- Circular Economy Policies – directed towards **mass and composition** (Towa et al. 2021)
    - **Not decreasing monetary flows**

Image from https://www.energy.gov/eere/articles/timeline-path-lightweight-materials-cars-and-trucks

Quantification of mass flows at the economy level necessary to measure success

Background: Input-Output Modeling

- How can we model the flow of goods through supply chains when they are interdependent?

Nobel prize photo of Wassily Leontief, Wikipedia

Flow from sector i to sector j: z_{ij}

Final demand for sector i: f_i

Total output for sector i: x_i

$$x_i = \sum_{j=1}^{n} z_{ij} + f_i$$

Let technical coefficient $a_{ij} = \frac{z_{ij}}{x_j}$

$$\therefore\ x_i = f_i + \sum_{j=1}^{m} a_{ij} x_j$$

Matrix Form:

$$\begin{bmatrix} a_{11} & \cdots & a_{1n} \\ \vdots & \ddots & \vdots \\ a_{n1} & \cdots & a_{nn} \end{bmatrix} \begin{bmatrix} x_1 \\ \vdots \\ x_n \end{bmatrix} + \begin{bmatrix} f_1 \\ \vdots \\ f_n \end{bmatrix} = \begin{bmatrix} x_1 \\ \vdots \\ x_n \end{bmatrix}$$

Simplifies to

Leontief Model:

$$X = [I - A]^{-1} F$$

Direct coefficients (A) matrix allows us to recalculate all outputs based on changing final demand

Input-Output Modeling

A matrix

For every ton of final product, industry uses n tonnes of inputs from other sectors

Leontief inverse - multipliers

If production in sector increases by 1 tonne, overall production increases in all sectors

A	Agriculture	Manufacturing
Agriculture	0.15	0.25
Manufacturing	0.2	0.05

1 tonne of agricultural product sales need 0.15 tonnes of agricultural inputs and 0.2 tonnes of manufacturing inputs

L	Ag	Mfg
Ag	1.25	0.33
Mfg	0.26	1.12

+1 tonne agricultural products sold → 1.25 tonnes of agricultural inputs (including 1 tonne) and 0.26 tonnes of manufacturing inputs used

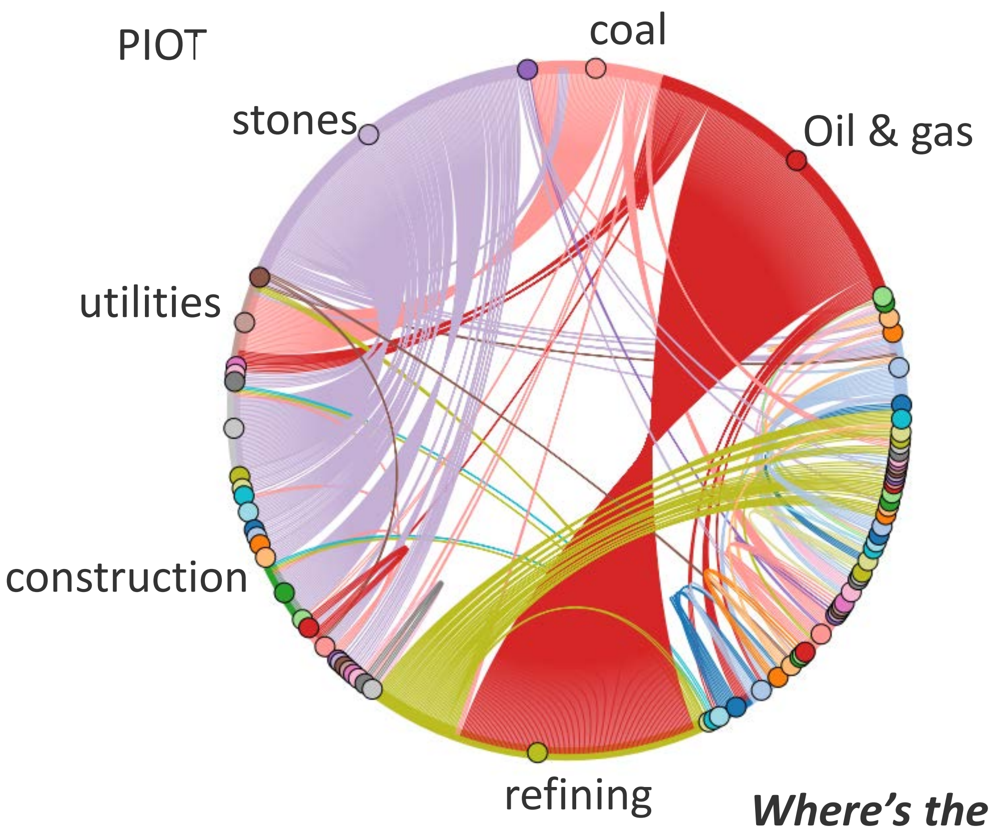
Methods – Table construction

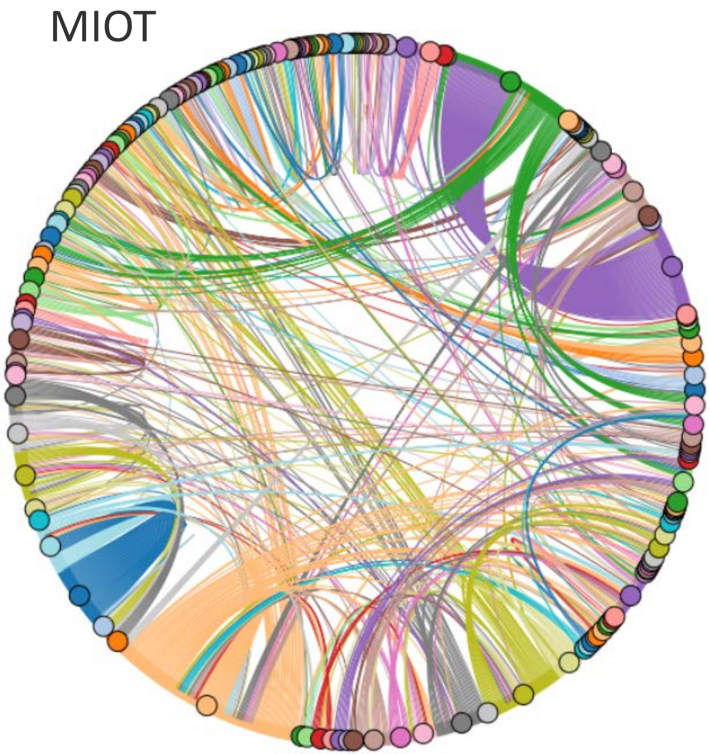
1. **Estimate physical flows**
    1. Collect data on flows from USGS & other statistical agencies
    2. Find price data to convert $ → kg
        1. Comtrade
        2. Heuristic approximation method
        3. Import prices → use; export prices → make
2. **Build tables**
3. **Make mass balances**
4. **Analysis/visualization**

EEIO Disaggregation

- **Estimate direct coefficients**
  - Gate-to-gate
- **Compute total coefficients**

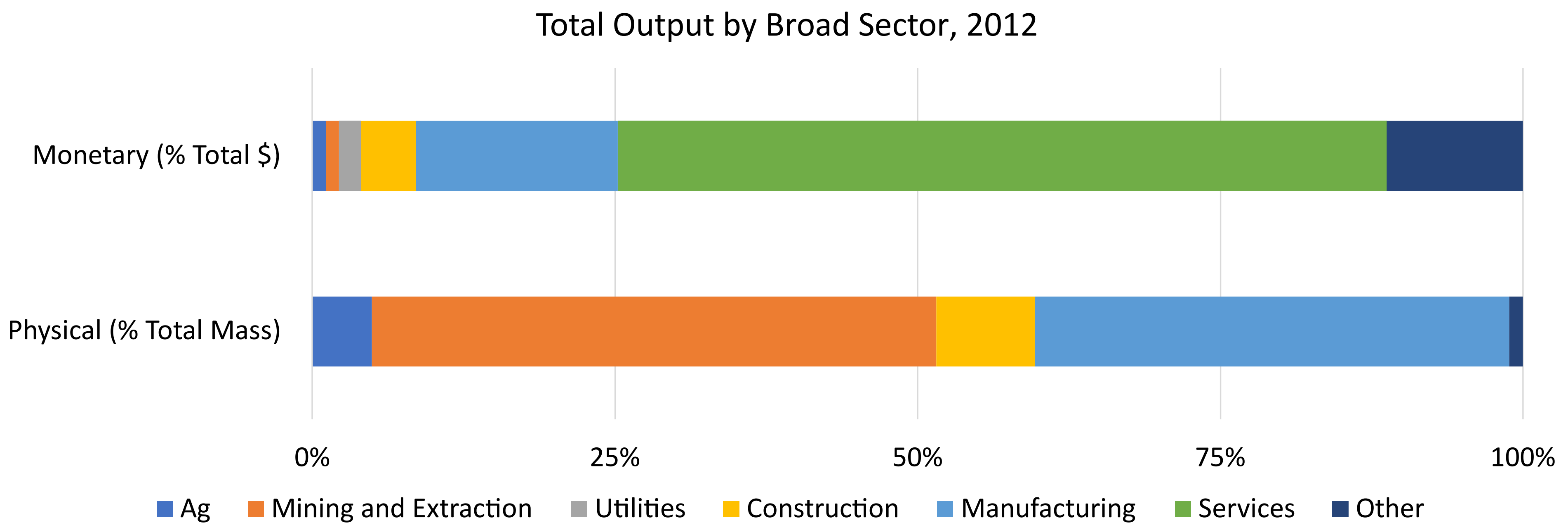
2012 Detailed IO Transactions Matrix





Wachs E., McMillan C., Podkaminer K., Kaarsberg T.; 2021.

Where's the stuff? Is the economy circular?
See at a glance with this PIOT visualization



Total Commodity Output from Physical and Monetary Use Tables

- Agriculture and Mining represent > 50% of physical output
- Note large differences between relative importance of sectors

Preliminary Results – Time Series of Physical IO Transactions Matrices

2010

2011

2012

2013

2014

2015

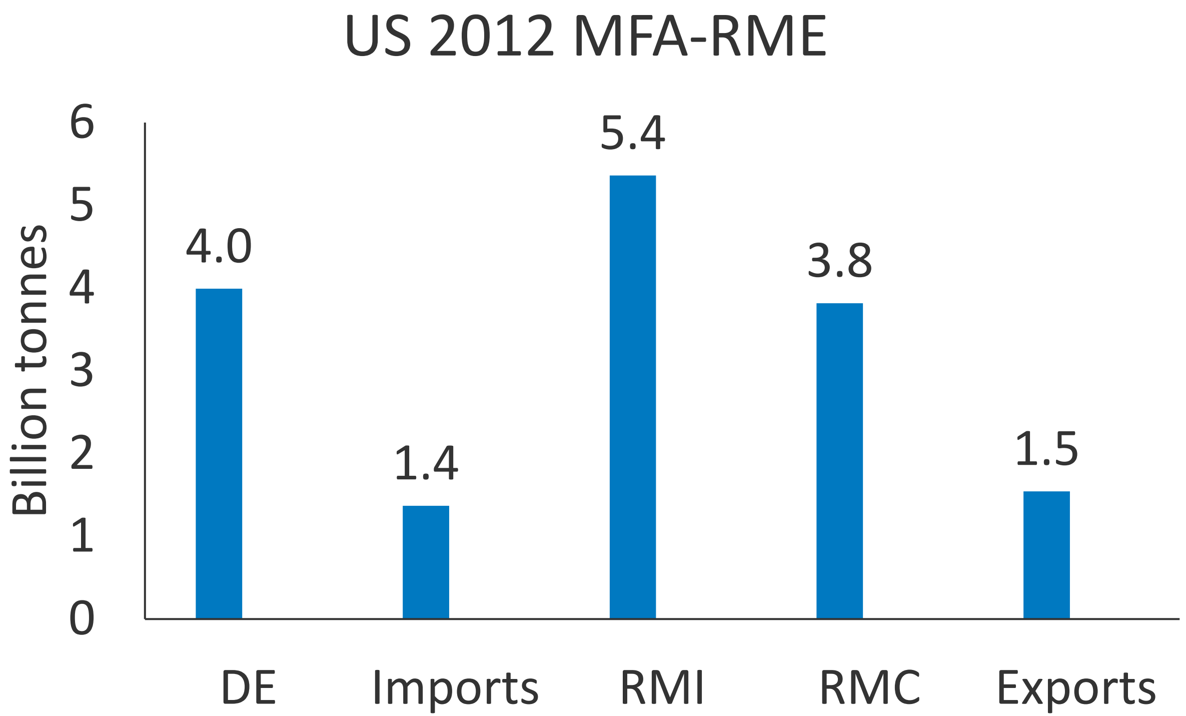
2016

2017

2018

2019

US: Raw Material Extraction via Physical IO 2012



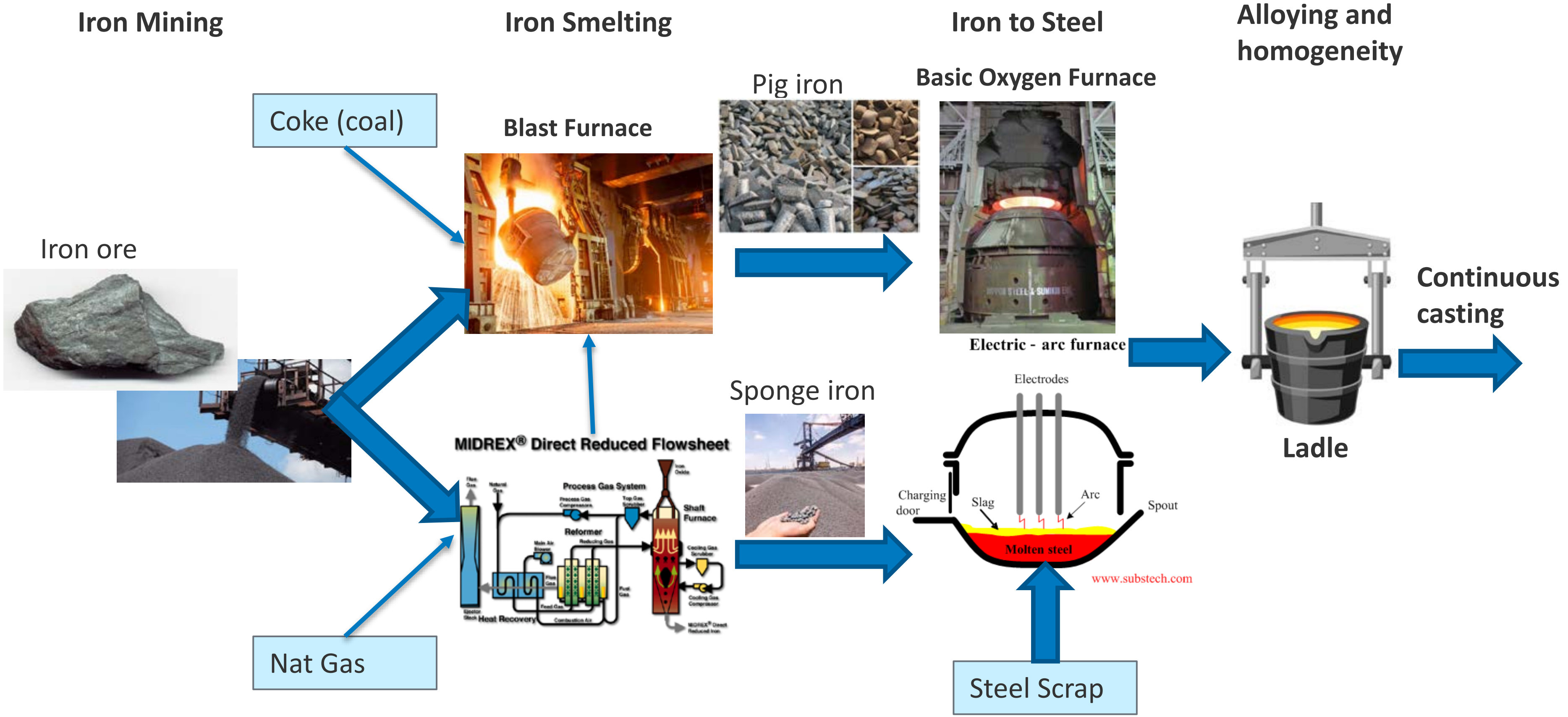
Material footprint (RMC) = Domestic Extraction + Imports - Exports

Excludes Biomass

Case Study: Iron and Steel Sector

- **Hard to decarbonize sector**
- **High portion of coal use – process emissions (coke)**
- **High greenhouse gas emissions**
- **Energy-intensive**

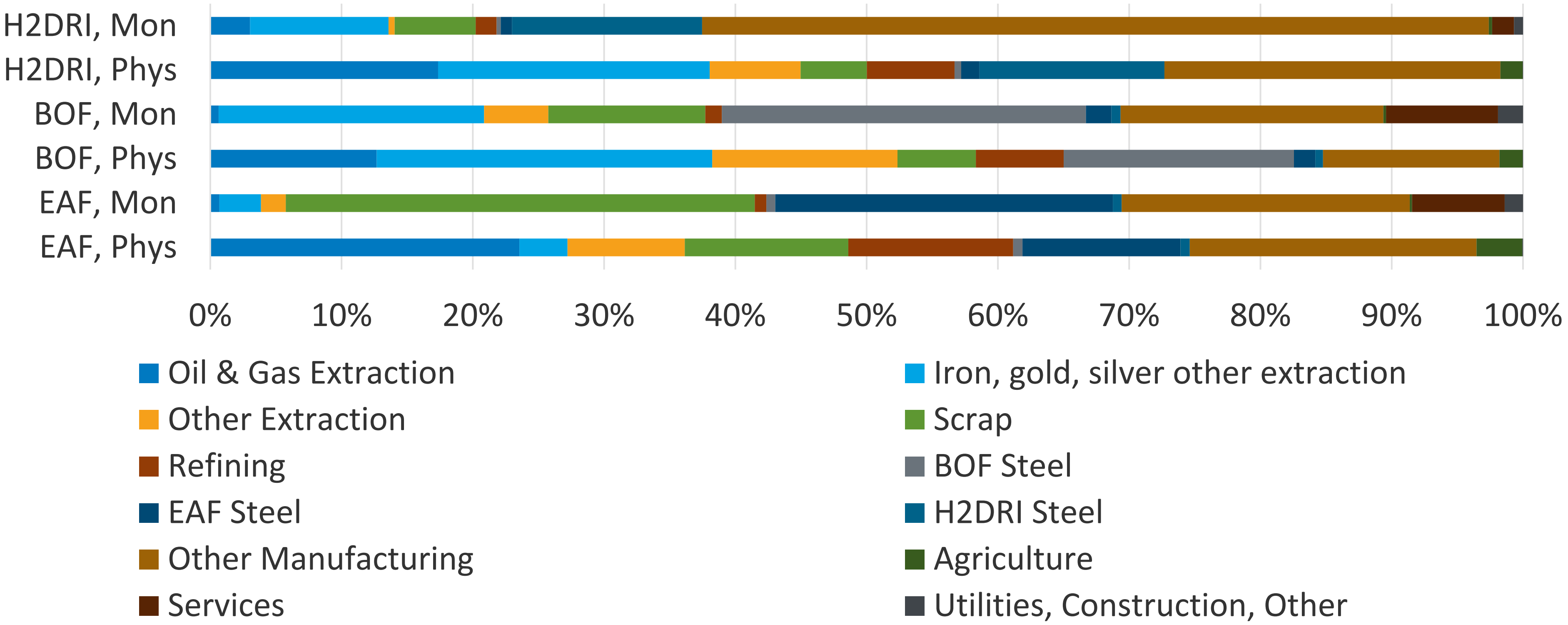
Iron and Steel Extraction, Refining and Primary Production



Methods

1. **Disaggregation of PIOT, Supply and Use Tables**
    1. Steel production
        1. BF-BOF, EAF, DRI – EAF
    2. Coal mining
        1. Metallic, thermal
2. **Disaggregation of EEIO Impact Vector**
3. **Simulate H2DRI in Steel – replace 50% BF-BOF steel**
4. **Analysis & Visualization**

Total Economy Requirements per kg or $ of Steel Demand by Production Process

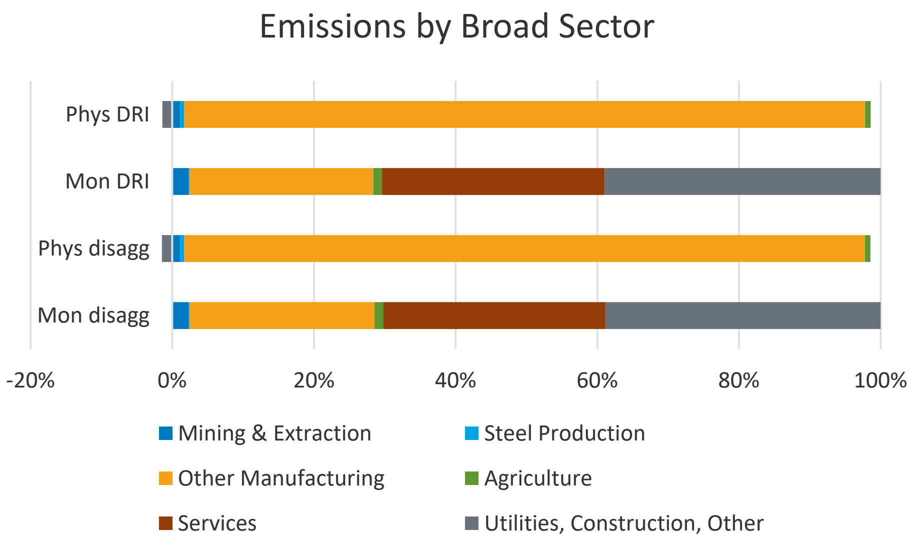


Extraction line: much lower in monetary tables

Dependence on Chemical Mfg for H2DRI (counterfactual)

Greenhouse Gas Emissions

Physical table assigns almost all emissions to manufacturing



Decreased Emissions	Mon	Phys	Mon diff	Phys diff
Total	0.41%	2.54%	12,964	45,377
Steel	7.56%	7.43%	327	805

Most reductions occur outside steel manufacturing

Conclusions

- Input-output in physical (mass) units promising method to track circular economy
  - Quickly see proportion of extraction in total flows
  - Interconnections of mass flows clearly shown
  - More work needed to further standardize approach

Conclusions (cont.)

- Case study shows that iron/steel sector looks very different in terms of physical versus monetary flows
- Supply chain emissions decrease more than steel sector emissions with switch from BF-BOF to H2DRI
- More work needed to understand multiple pathways for steel sector

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Thank You

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