RESOURCE EFFICIENCY

delivering more service with less energy, materials and impact

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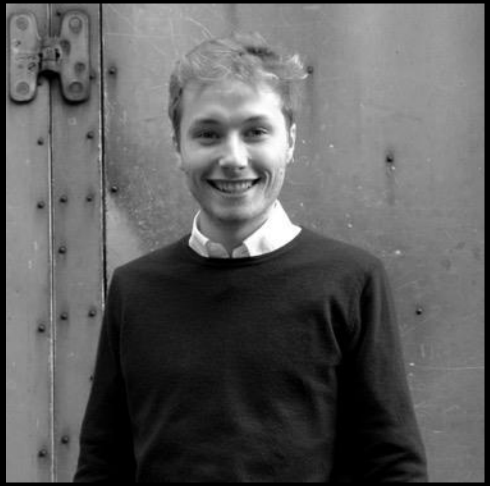
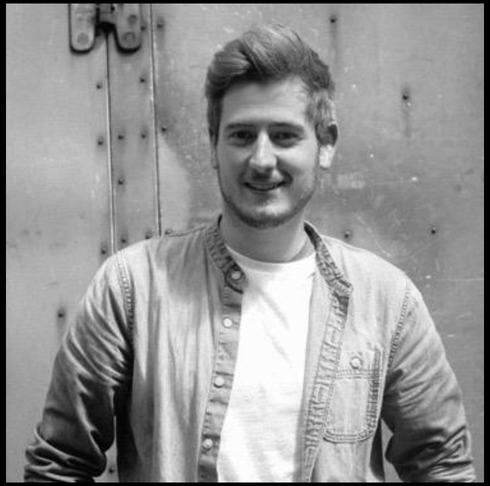




resource efficiency collective

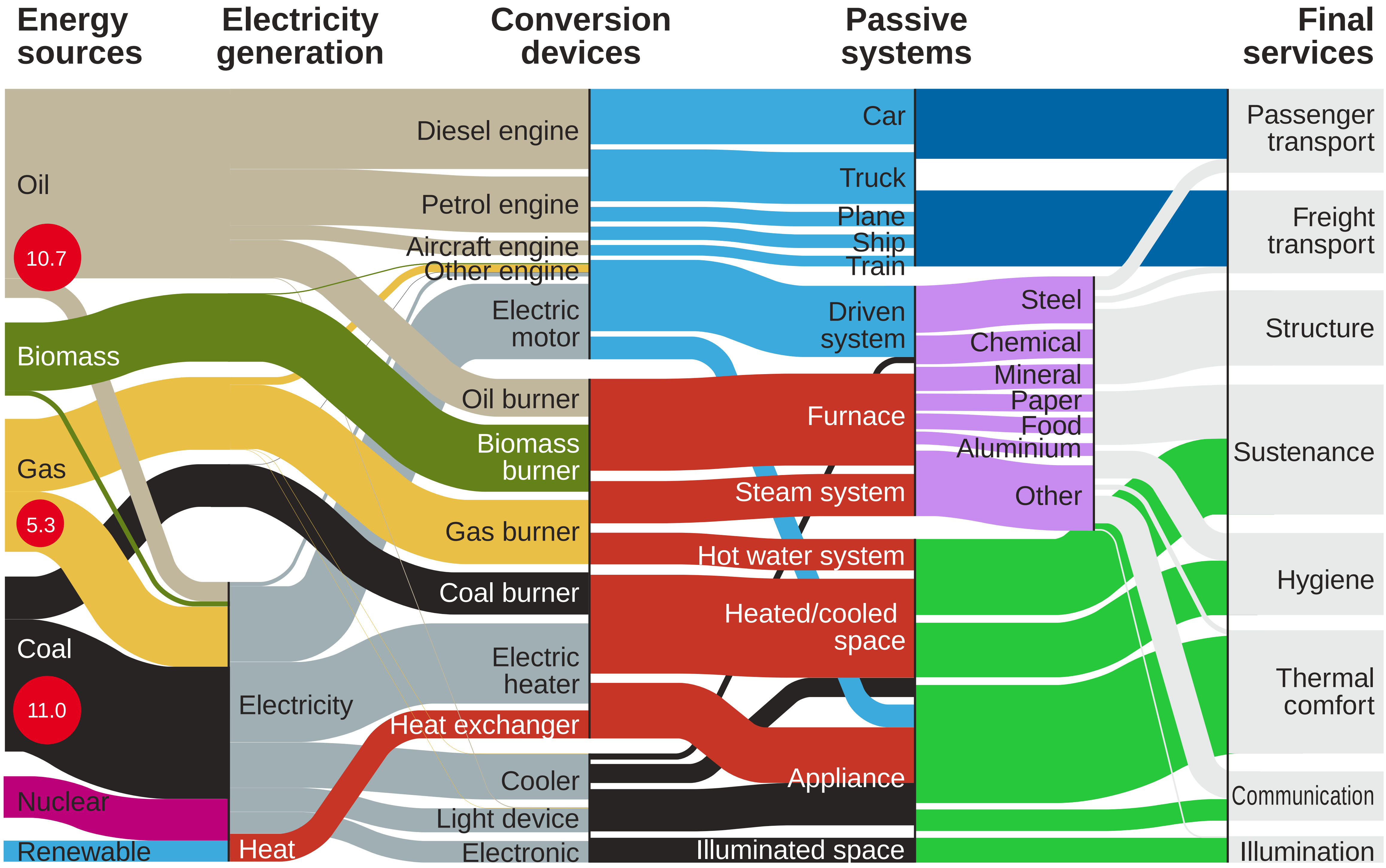
Resource Efficiency Collective is a research initiative at Cambridge University. Together, we seek answers to a challenging question: how can we deliver future energy and material services, while at the same time reducing resource use and environmental impact?

Resource flow analysis

The robustness of the higher level depends on the lower ones

MinFuture

Global energy flows



Global energy demand in 2005, total = 475 EJ

Global carbon emissions in 2005, total = 27 Gt CO_2

JM Cullen and JM Allwood
Energy Policy 38 (2010) 75–81

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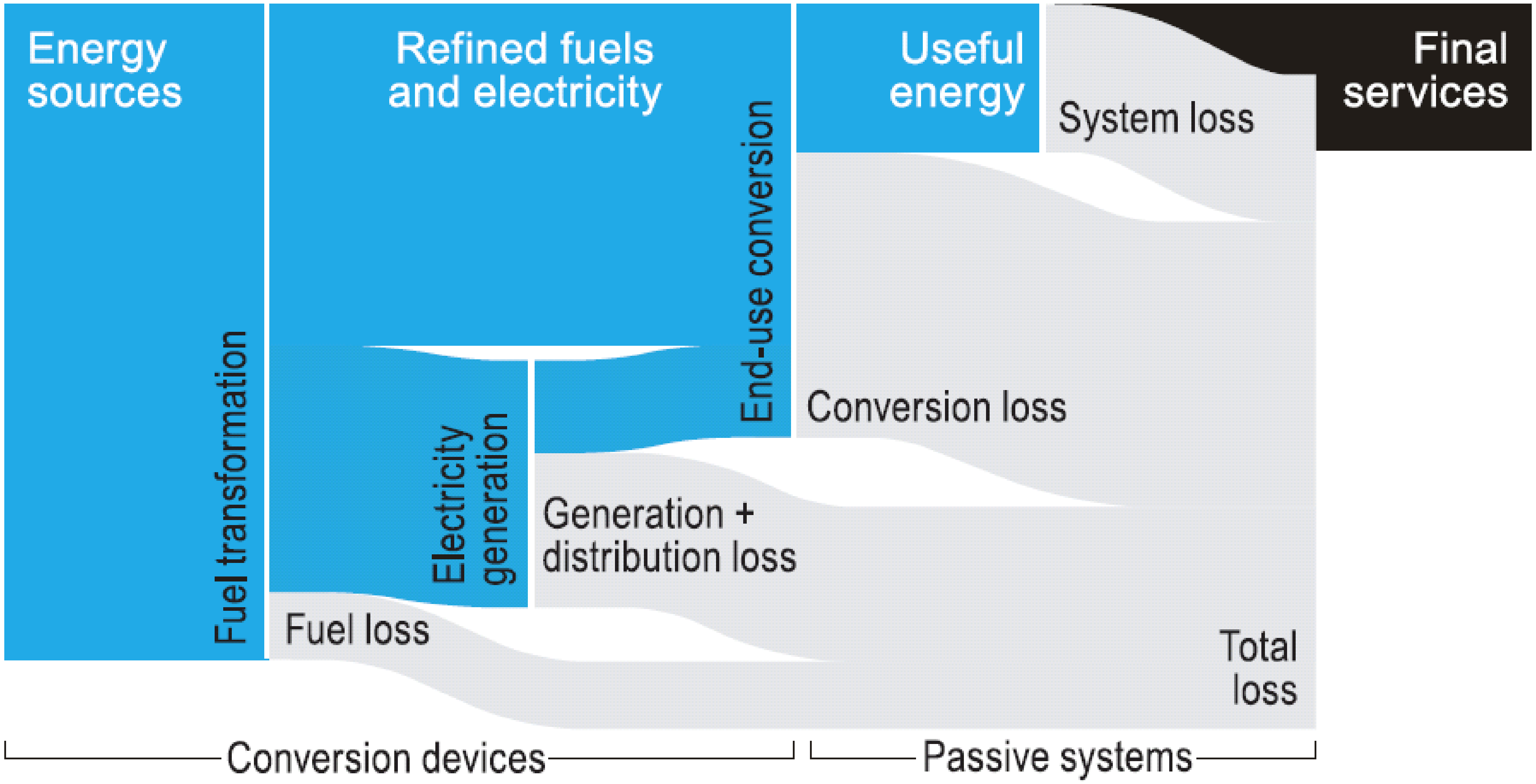
Energy supply chain



Services efficiency (energy)

How can we deliver future energy and material services, while reducing resource use and environmental impact?

Carbon emissions | **Service (energy)**

$$C = \frac{C}{E_p} \times \frac{E_p}{E_f} \times \frac{E_f}{E_u} \times \frac{E_u}{S} \times S$$

Carbon intensity | **Energy Conversion** | **Passive system**

Carbon emissions, **S**ervices delivered

Energy (**p**rimary, **f**inal, **u**seful)

Levers

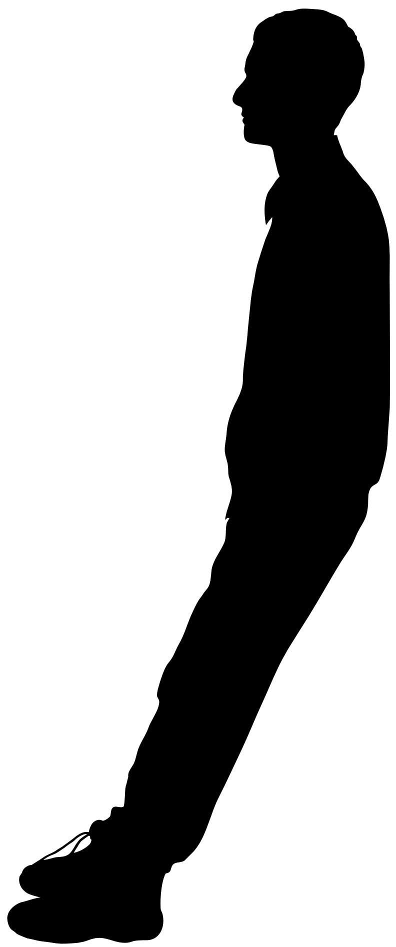
Energy decarbonisation

Energy efficiency

Service efficiency

Service reduction

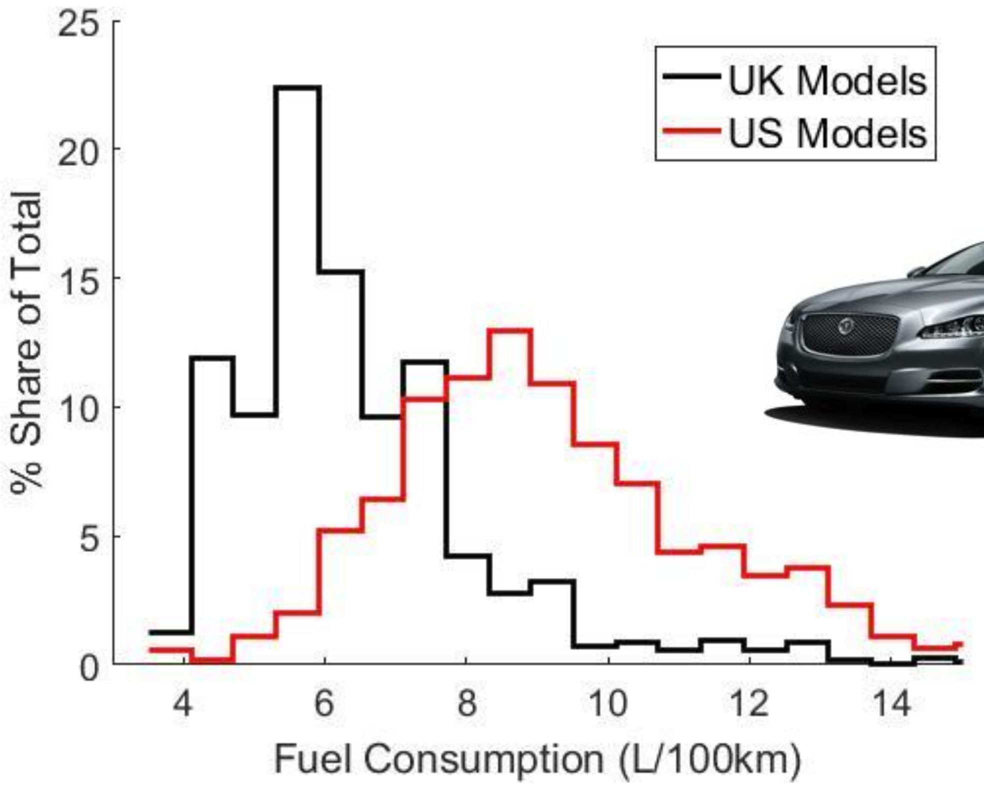
Watch out for rebound



Passenger transport distributions

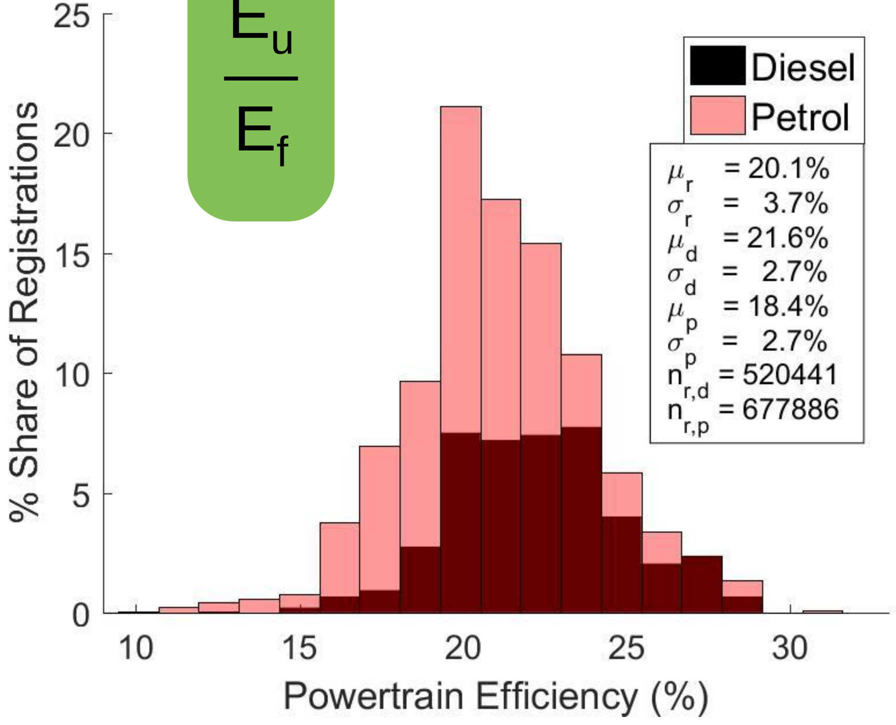
UK data, 2010

Distributions reveal differences in conversion efficiency and service delivery

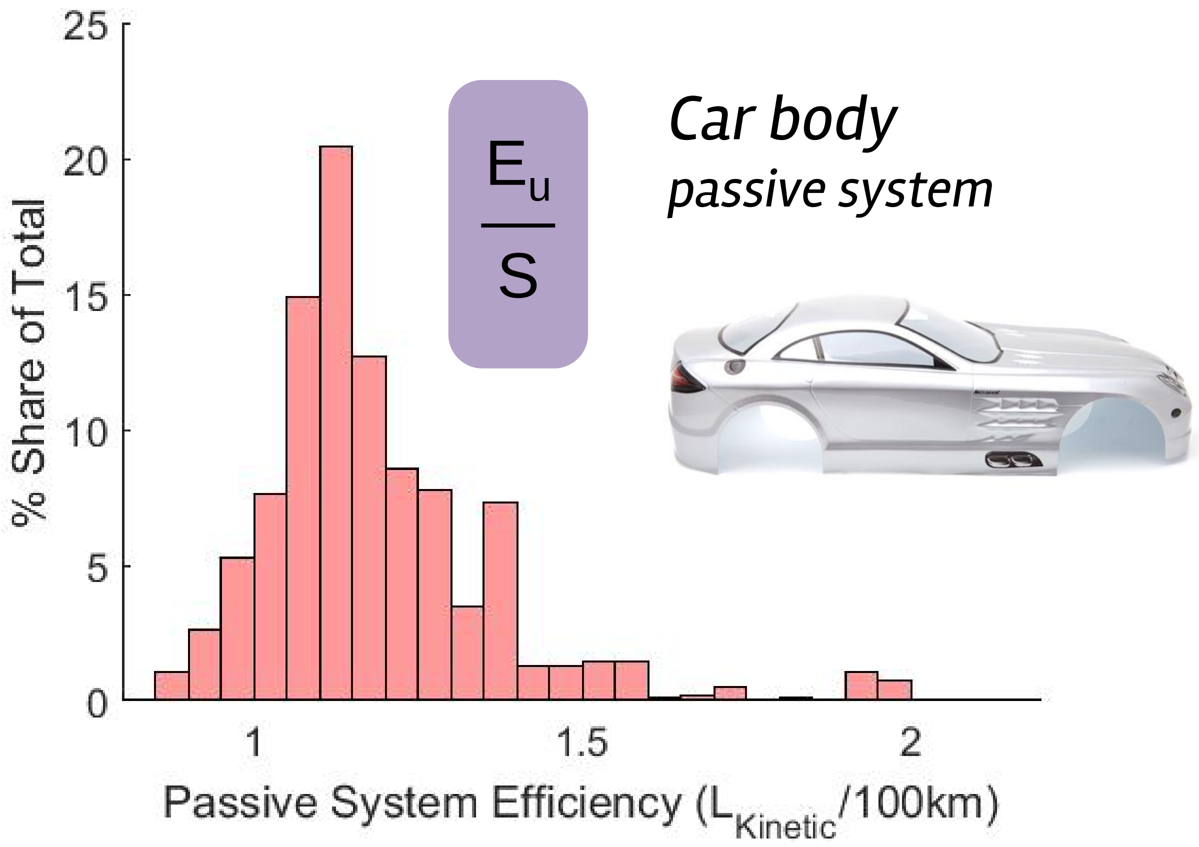


$\frac{S}{E_f}$

$\frac{E_u}{E_f}$



Engine
conversion device

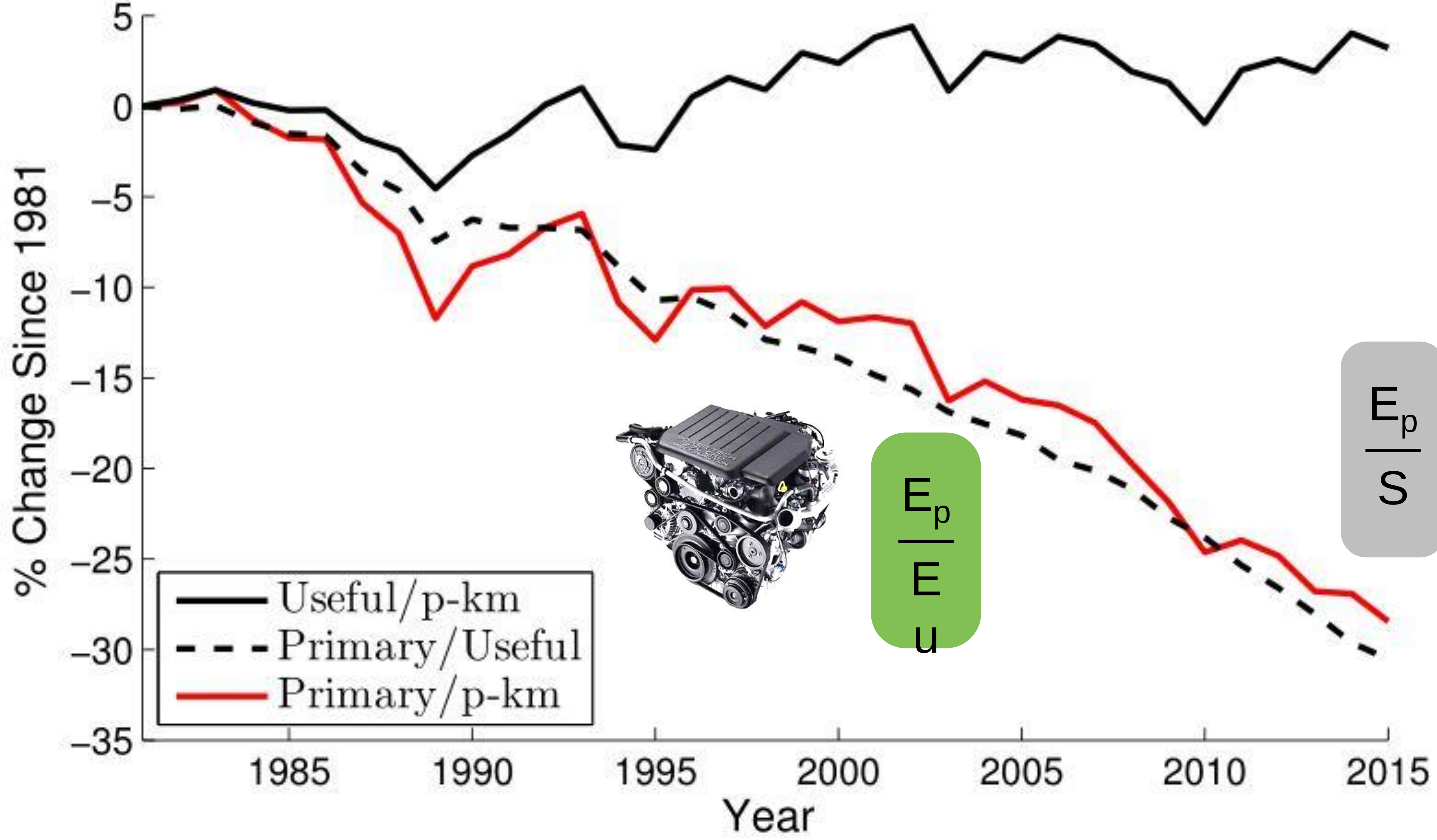


$\frac{E_u}{S}$

Car body
passive system

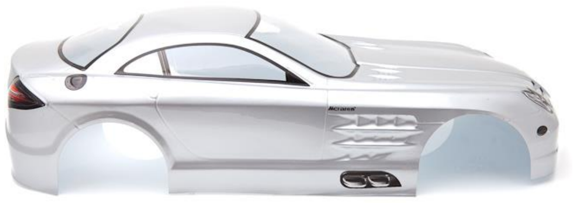
Passenger transport distributions

UK data, 2010



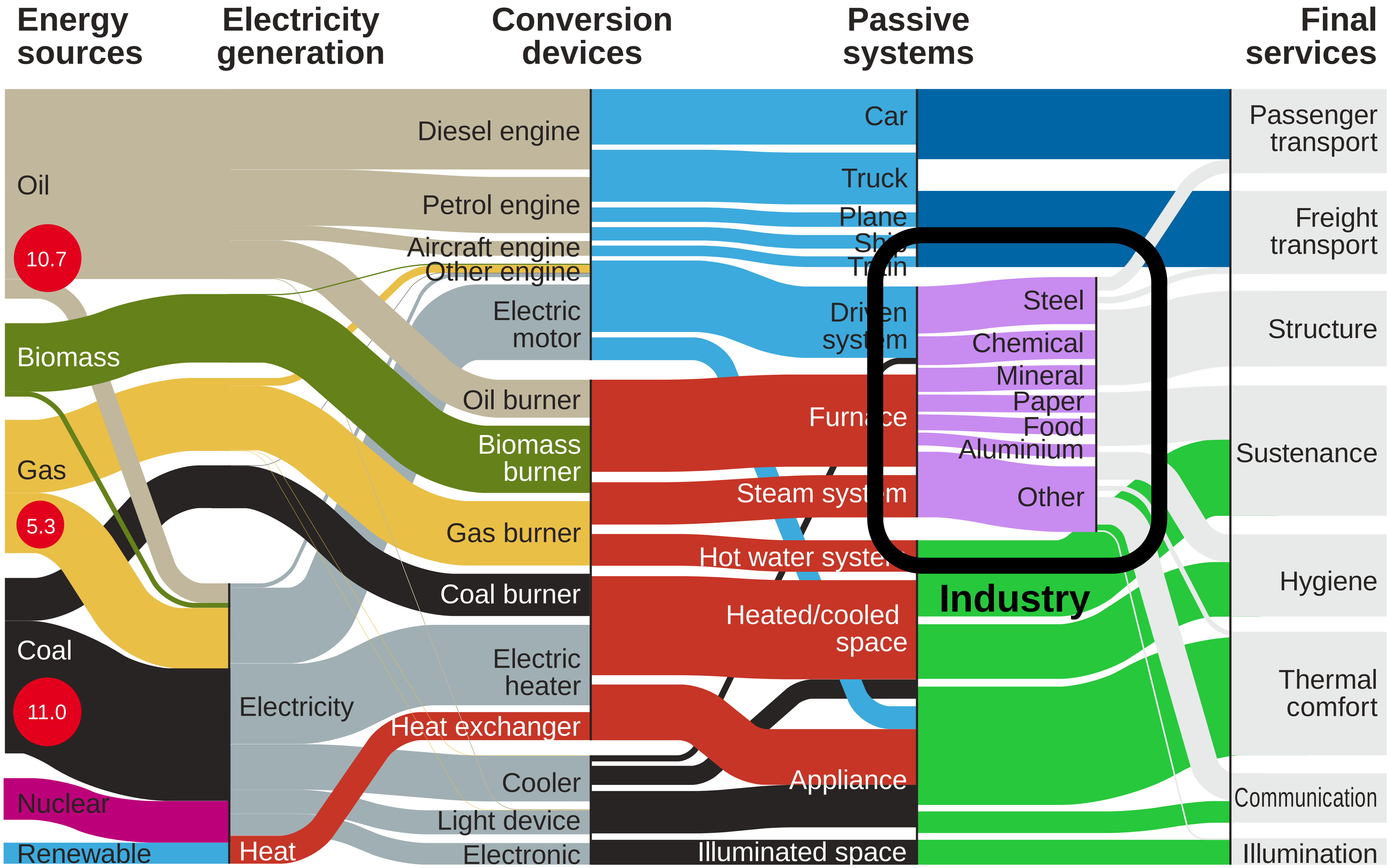
$\frac{E_p}{E_u}$

$\frac{E_u}{S}$



$\frac{E_p}{S}$

Global energy flows



Global energy demand in 2005, total = 475 EJ

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Service efficiency (materials)

How can we deliver future energy and material services,
while reducing resource use and environmental impact?

Carbon emissions

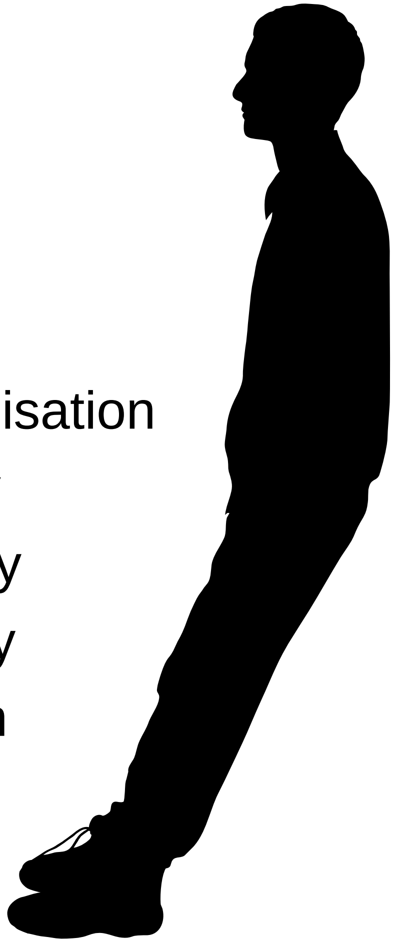
Service (materials)

$$C = \frac{C}{E_p} \times \frac{E_p}{E_f} \times \frac{E_f}{E_u} \times \frac{E_u}{M} \times \frac{M}{P} \times \frac{P}{S} \times S$$

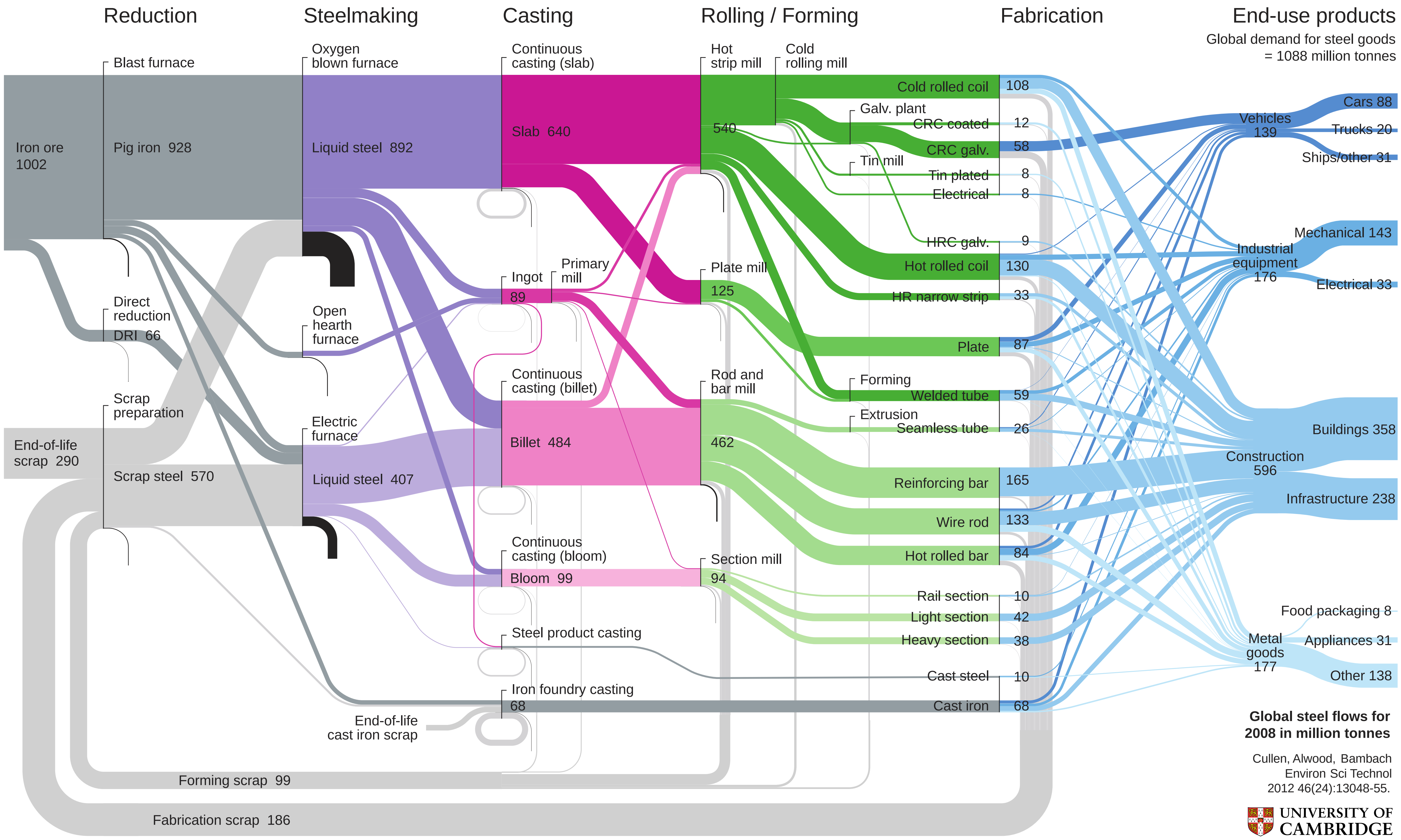
Carbon intensity | **Energy Conversion** | **Energy intensity** | **Material intensity** | **Product intensity**

Carbon emissions, **S**ervices delivered
Energy (**p**rimary, **f**inal, **u**seful), **M**aterials, **P**roducts

Levers
Energy decarbonisation
Energy efficiency
Material efficiency
Product efficiency
Service reduction



Global steel flows



Global steel flows for 2008 in million tonnes

Cullen, Alwood, Bambach
Environ Sci Technol
2012 46(24):13048-55.

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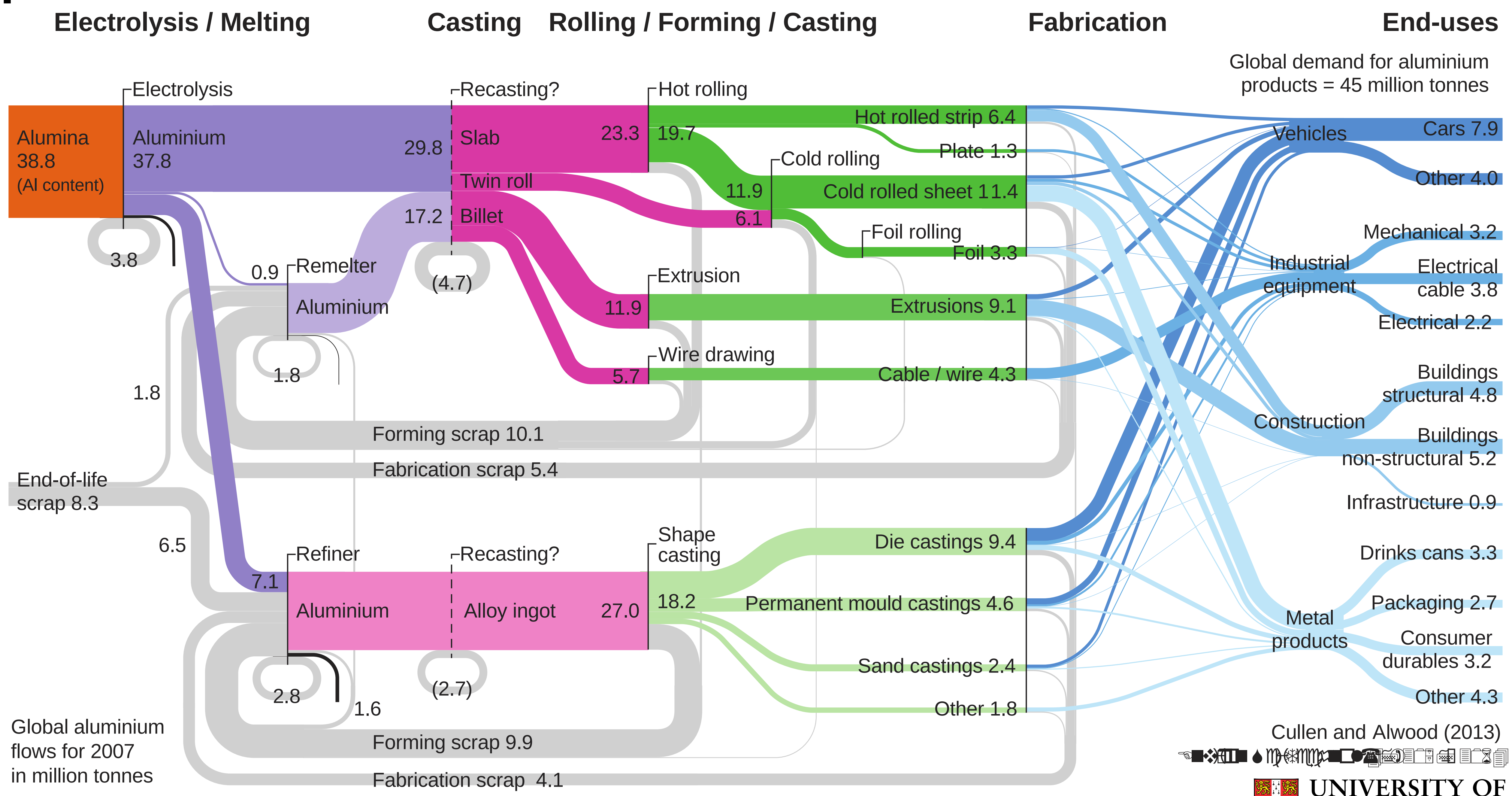
Global aluminum flows



Cullen and Allwood (2013)

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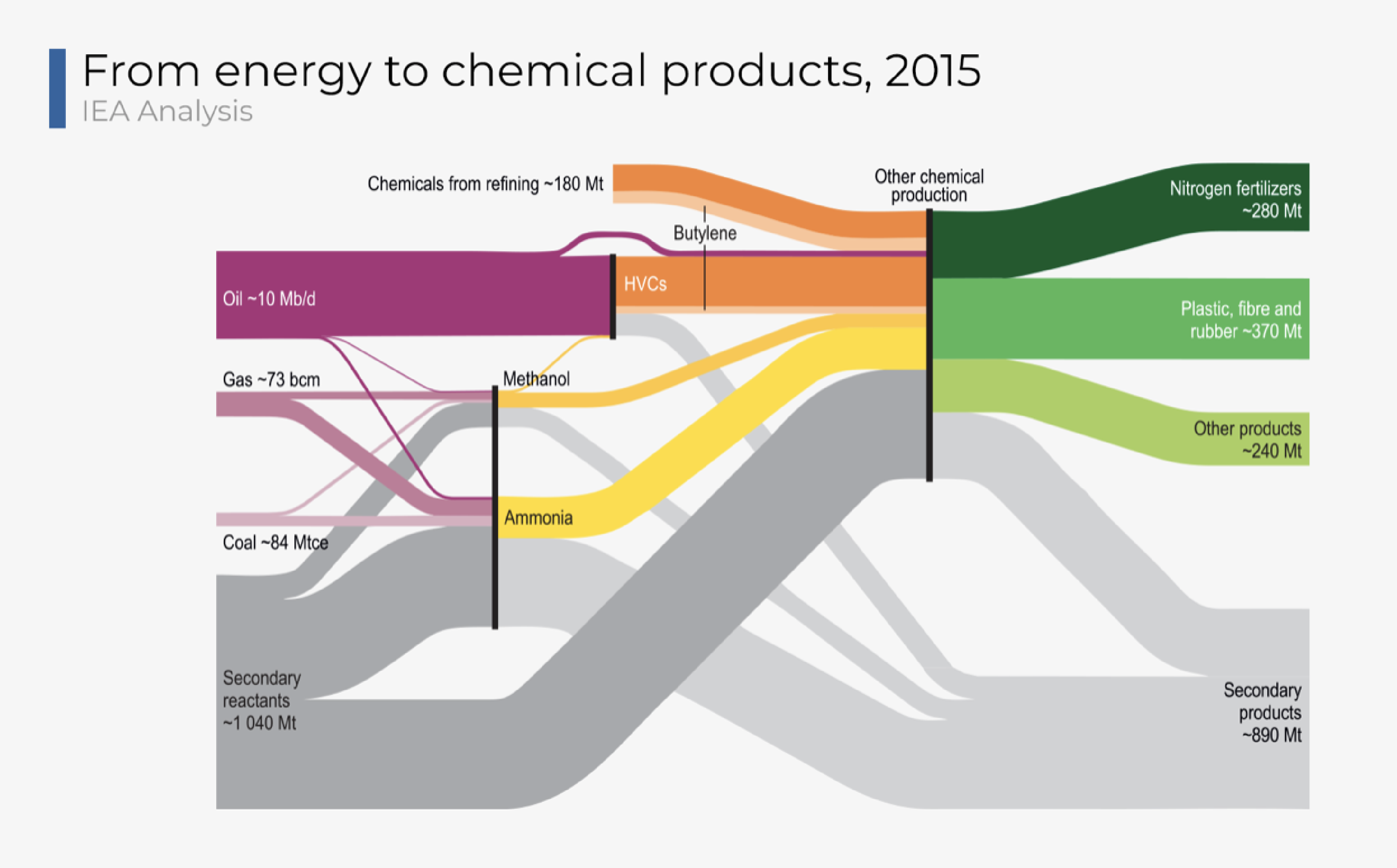
Global chemical flows

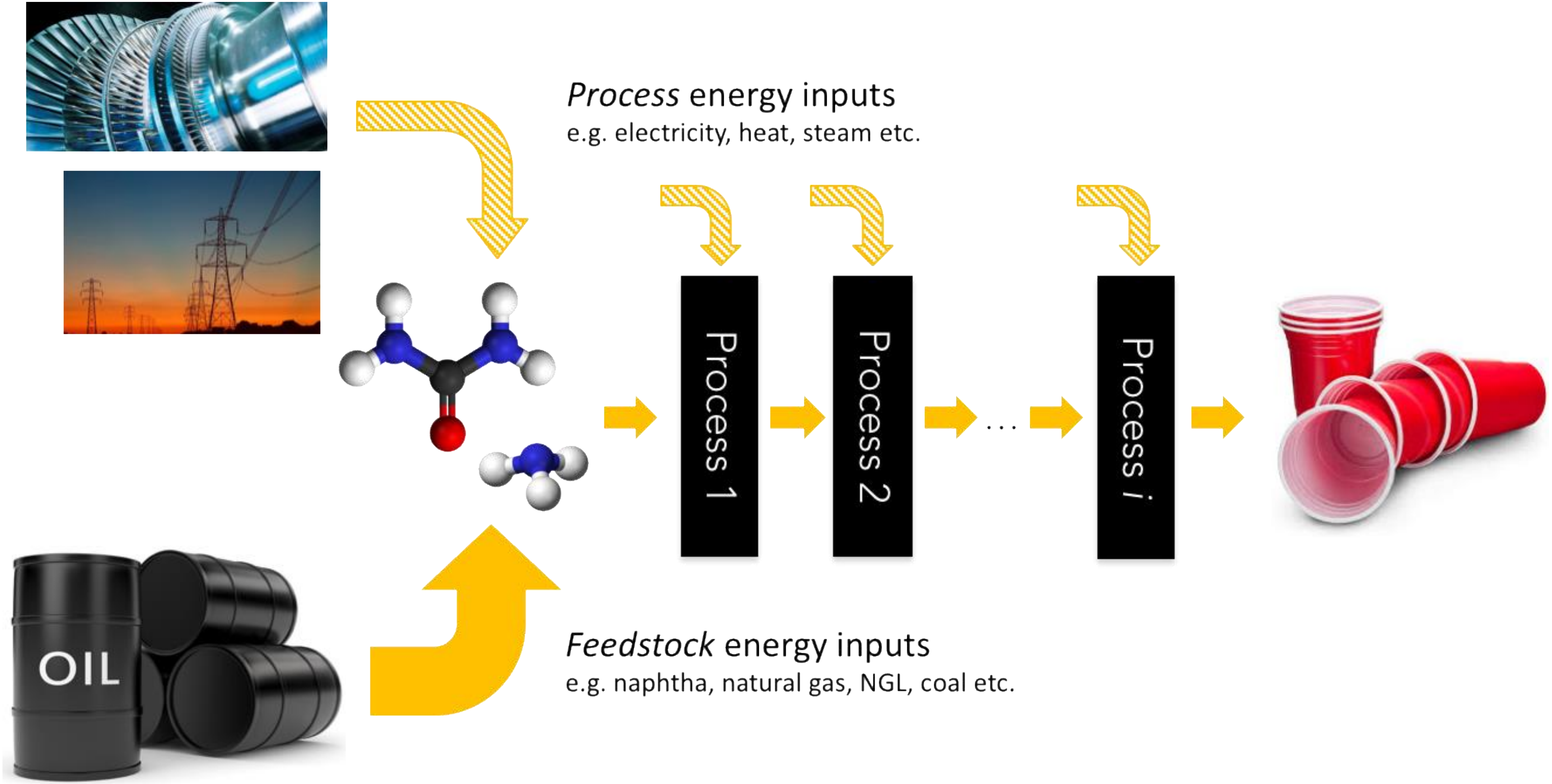
Report released
5 October

Peter Levi

PhD, IEA



Energy inputs: feedstock versus process



Energy inputs: feedstock versus process

World

2013

Million tonnes of oil equivalent

SUPPLY AND CONSUMPTION	Coal[1]	Crude oil	Oil products	Natural Gas	Nuclear	Hydro	Geotherm. solar etc.	Biofuels & Waste	Electricity	Heat	Total
Production	4006.39	4215.68	-	2908.63	646.48	325.93	161.36	1375.46	-	2.20	13642.14
Imports	830.71	2246.43	1174.72	872.91	-	-	-	15.89	59.94	0.00	5200.61
Exports	-861.05	-2181.49	-1238.37	-895.29	-	-	-	-13.84	-56.99	-0.01	-5247.03
Stock changes	-48.28	-6.84	-0.59	15.37	-	-	-	-0.50	-	-	-40.84
TPES	**3927.77**	**4273.78**	**-64.25**	**2901.63**	**646.48**	**325.93**	**161.36**	**1377.02**	**2.95**	**2.20**	**13554.88**
Transfers	-0.42	-181.46	224.28	-0.00	-	-	-	-	-	-	42.40
Statistical differences	-170.55	12.97	-9.27	10.27	-	-	-0.00	-0.36	1.80	-0.38	-155.51
Electricity plants	-2094.33	-39.86	-211.14	-748.65	-638.86	-325.93	-123.80	-86.98	1824.70	-0.63	-2445.47
CHP plants	-175.68	-0.01	-16.74	-322.41	-7.63	-	-2.55	-55.66	179.71	149.74	-251.23
Heat plants	-134.45	-0.79	-11.16	-97.92	-	-	-1.07	-11.27	-0.35	178.68	-78.33
Blast furnaces	-208.32	-	-0.43	-0.04	-	-	-	-0.03	-	-	-208.82
Gas works	-7.22	-	-3.13	3.44	-	-	-	-0.07	-	-	-6.99
Coke/pat.fuel/BKB/PB plants	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	-0.13	-	-	-71.43
Oil refineries	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	-	-	-	-73.66
Petrochemical plants	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	-	-	-	0.07
Liquefaction plants	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	-	-	-	-12.73
Other transformation	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	-78.20	-	-0.74	-82.30
Energy industry own use	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	-13.80	-168.63	-34.80	-819.83
Losses	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	-0.15	-163.67	-20.20	-218.25
TFC	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	**1130.35**	**1676.51**	**273.88**	**9172.80**
INDUSTRY	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	**193.55**	**710.29**	[illegible]	[illegible]
Iron and steel	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	3.70	99.65	[illegible]	[illegible]
Chemical and petrochemical	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	1.51	97.45	[illegible]	[illegible]
Non-ferrous metals	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0.13	77.78	[illegible]	[illegible]
Non-metallic minerals	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	8.81	49.91	[illegible]	[illegible]
Transport equipment	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0.02	21.42	[illegible]	[illegible]
Machinery	14.68	-	7.83	23.75	-	-	0.00	0.22	78.58	7.10	132.16
Mining and quarrying	7.46	-	24.13	7.26	-	-	0.00	0.18	28.88	2.65	70.56
Food and tobacco	23.67	0.01	10.50	42.07	-	-	0.00	32.24	39.32	11.61	159.43
Paper pulp and printing	18.96	-	4.38	22.55	-	-	0.17	55.39	36.66	11.36	149.47
Wood and wood products	2.43	-	1.72	2.54	-	-	0.00	10.47	8.53	2.01	27.70
Construction	4.40	0.00	27.94	7.16	-	-	0.00	0.39	13.96	1.78	55.63
Textile and leather	10.77	0.01	3.49	5.27	-	-	0.00	0.26	28.54	7.79	56.14
Non-specified	86.86	10.14	124.70	169.05	-	-	0.66	80.23	129.61	5.87	607.12
TRANSPORT	**3.54**	**0.02**	**2361.75**	**96.19**	-	-	**0.00**	**64.52**	**25.82**	-	**2551.85**
World aviation bunkers	-	-	163.55	-	-	-	-	-	-	-	163.55
Domestic aviation	-	-	100.13	-	-	-	-	-	-	-	100.13
Road	-	-	1823.17	35.47	-	-	-	63.71	0.25	-	1922.61
Rail	3.34	-	31.25	-	-	-	-	0.38	19.50	-	54.47
Pipeline transport	-	0.02	0.37	60.02	-	-	-	-	2.87	-	63.29
World marine bunkers	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0.03	-	-	190.37
Domestic navigation	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0.39	-	-	48.13
Non-specified	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0.01	3.20	-	9.32
OTHER	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	**872.28**	**940.40**	**150.50**	**3198.72**
Residential	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	837.71	451.00	105.99	2130.56
Comm. and publ. services	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	22.41	375.02	33.11	745.29
Agriculture/forestry	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	9.45	47.09	5.49	192.69
Fishing	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0.01	0.41	0.01	7.95
Non-specified	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	2.69	66.88	[illegible]	[illegible]
NON-ENERGY USE	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	-	-	-	[illegible]
in industry/transf./energy	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	-	-	-	[illegible]
of which: chem./petrochem.	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	-	-	-	[illegible]
in transport	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	-	-	-	[illegible]
in other	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	-	-	-	[illegible]

INDUSTRY	**2623.45**
Iron and steel	473.90
Chemical and petrochemical	366.99
Non-ferrous metals	118.87
Non-metallic minerals	361.67

NON-ENERGY USE	**798.77**
in industry/transf./energy	769.96
of which: chem./petrochem.	*577.14*
in transport	12.22
in other	16.60

Energy consumption

10% of total global final energy

27% of industrial final energy

Challenging sector to decarbonize

Source: IEA (2016) *World Energy Balances.*

Greenhouse gas emissions

7% of anthropogenic GHG emissions

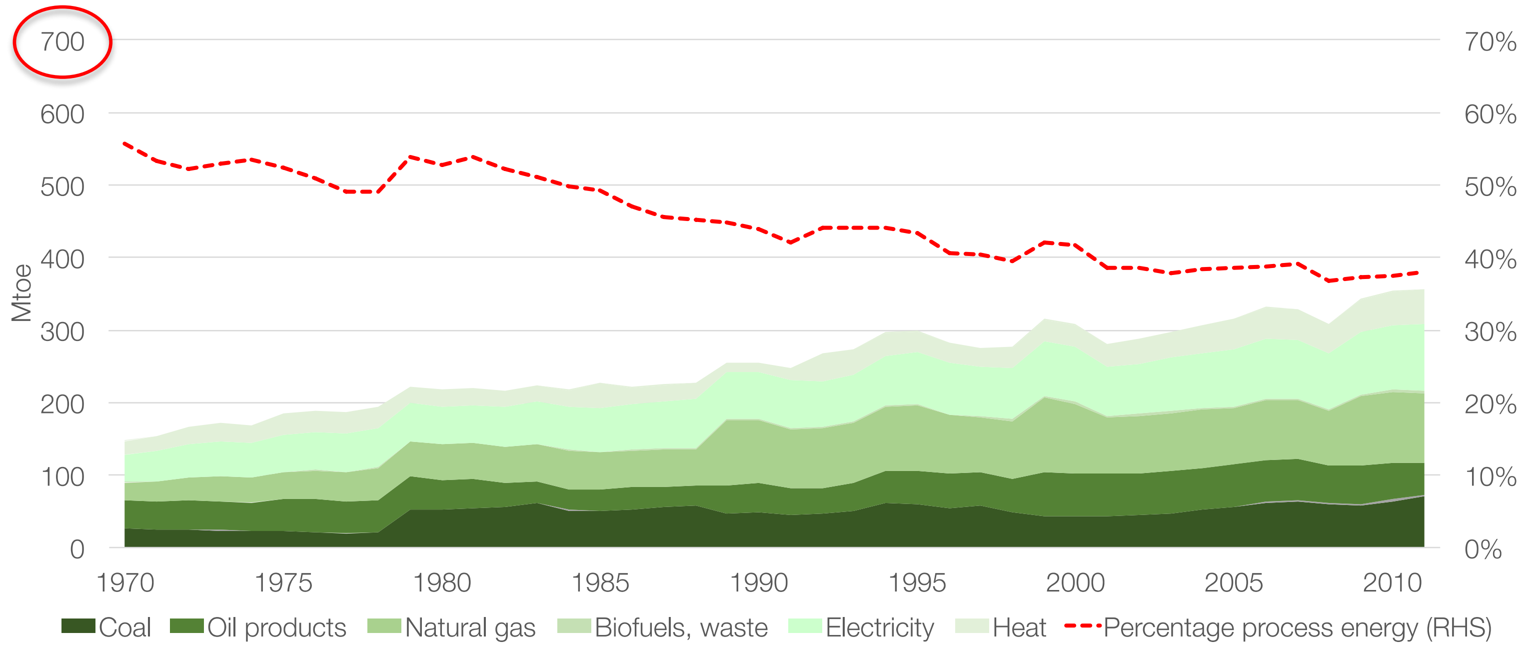
20% of industrial GHG emissions

Many more upon latent release

Source: IEA, DECHEMA & ICCA (2013) *Technology Roadmap: Energy and GHG Reductions in the Chemical Industry via Catalytic Processes*

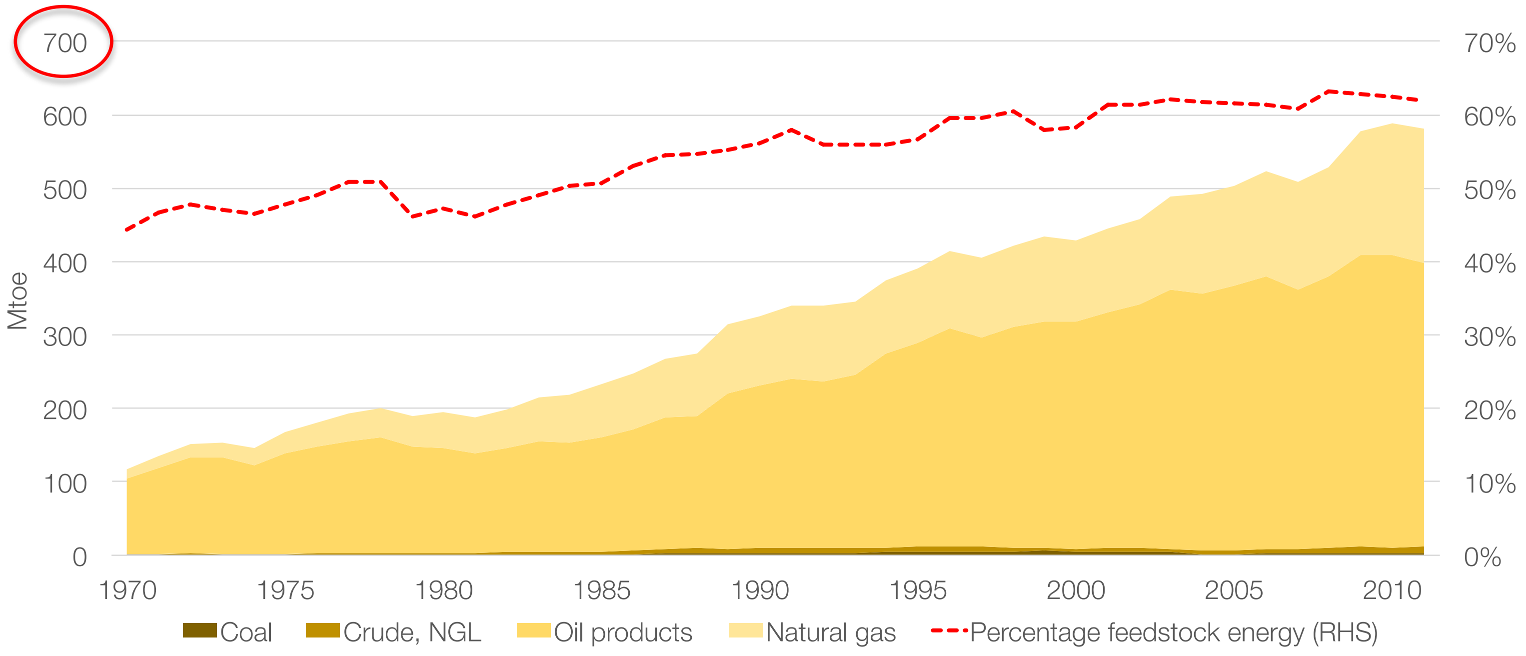
Feedstock energy is increasing as a share of inputs

Process energy inputs



Key point: Feedstock energy accounts for an increasing share of the sector's energy inputs and are ∽99% fossil fuels.

Feedstock energy inputs

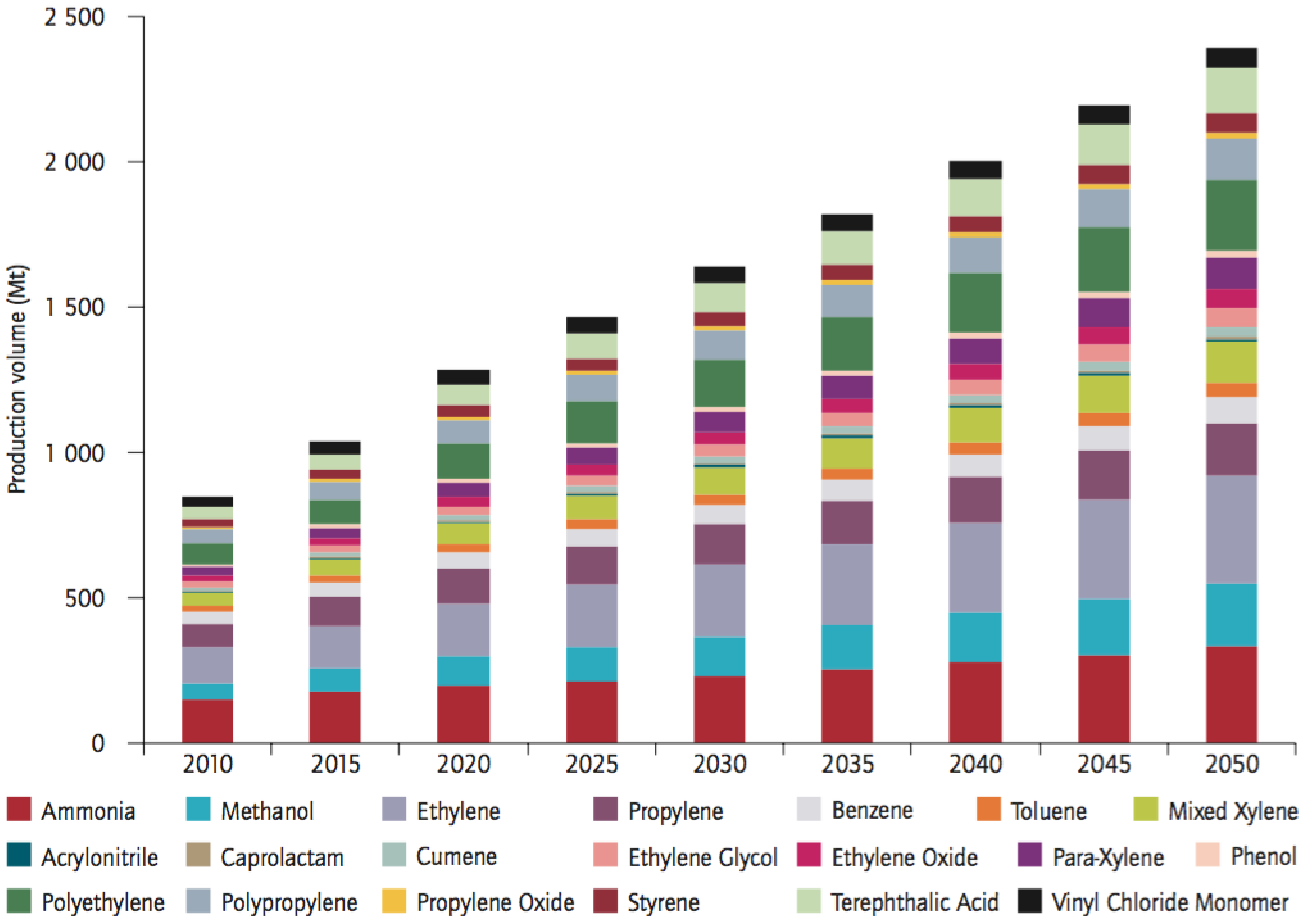


Source: IEA (2016) *World Energy Balances.*

The challenge for petrochemicals

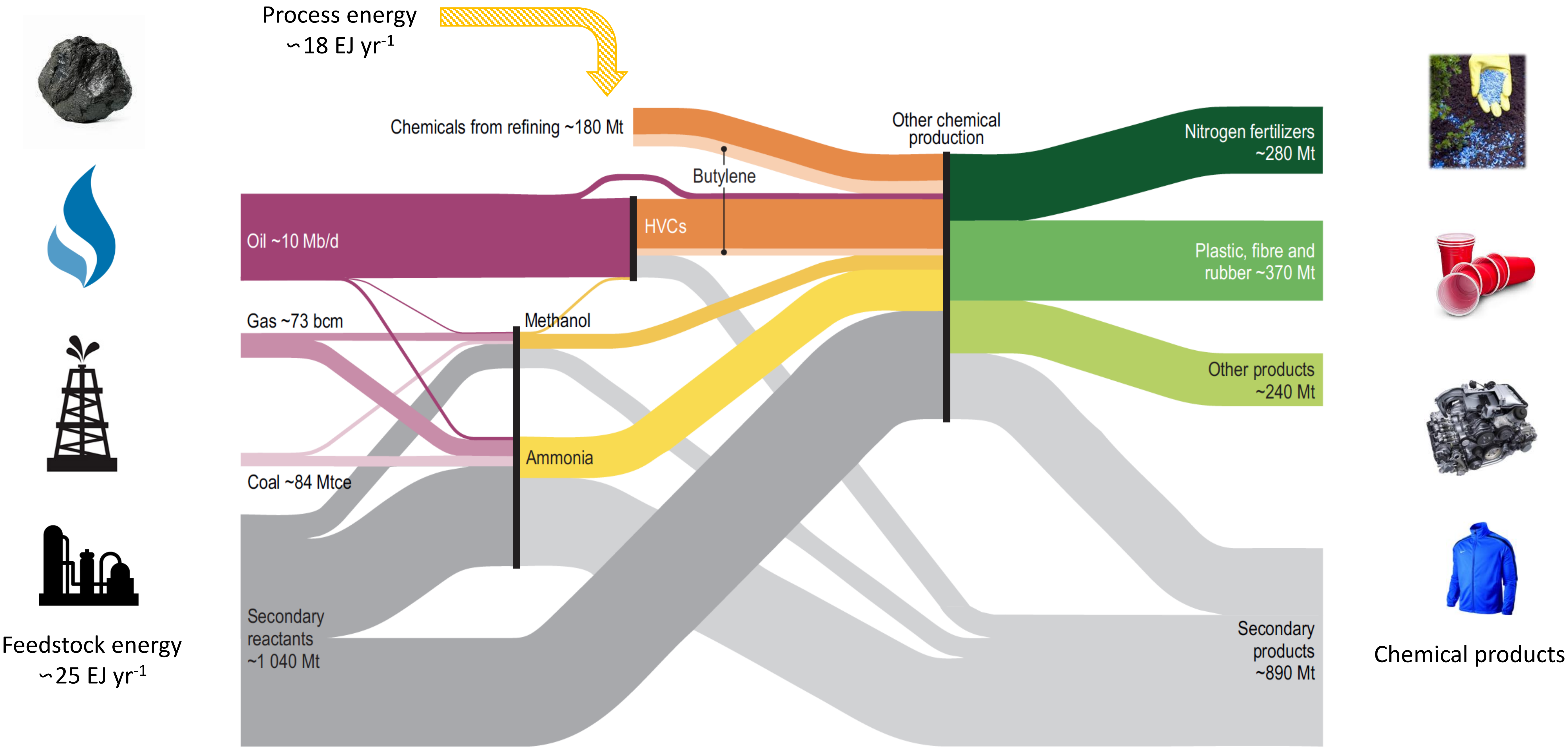
A 2.8-fold increase in demand is projected for the sector's 18 most energy-intensive large volume chemicals, over the period 2010-50.

A 30% reduction in direct CO_2 emissions with respect to current levels is required in industry by 2050, to maintain a 2DS trajectory



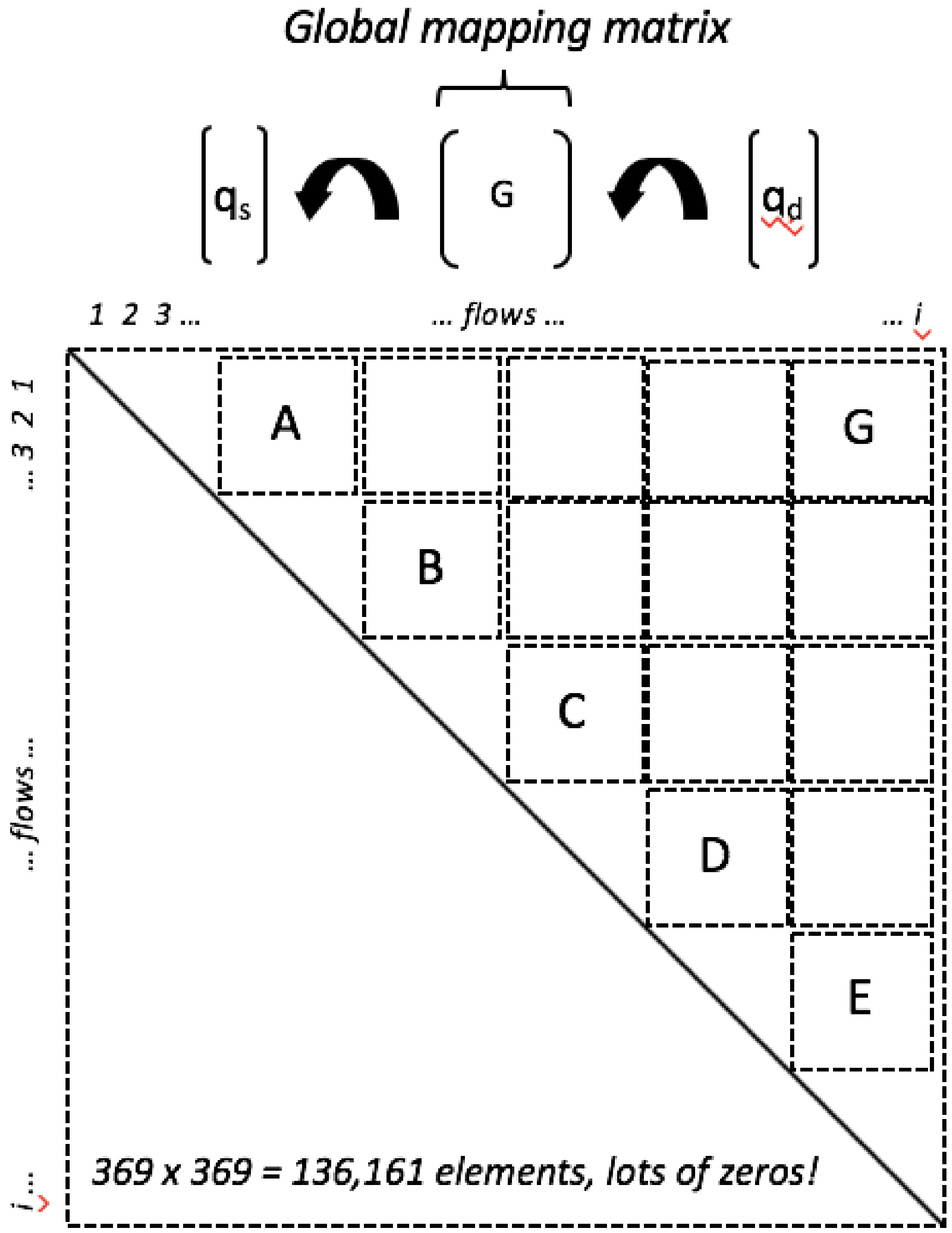
Source: IEA, DECHEMA & ICCA (2013) *Technology Roadmap: Energy and GHG Reductions in the Chemical Industry via Catalytic Processes*

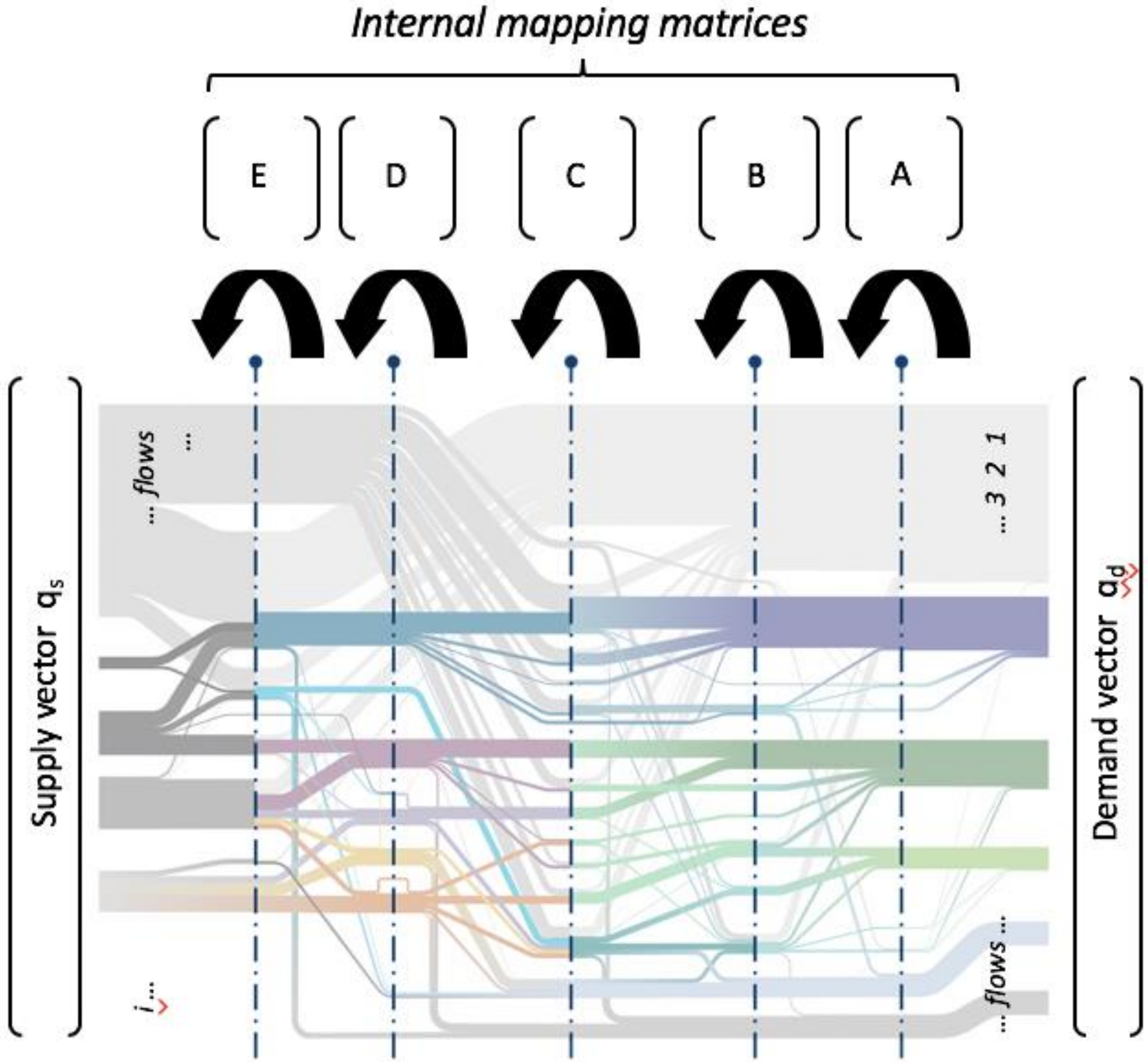
Global chemical flows



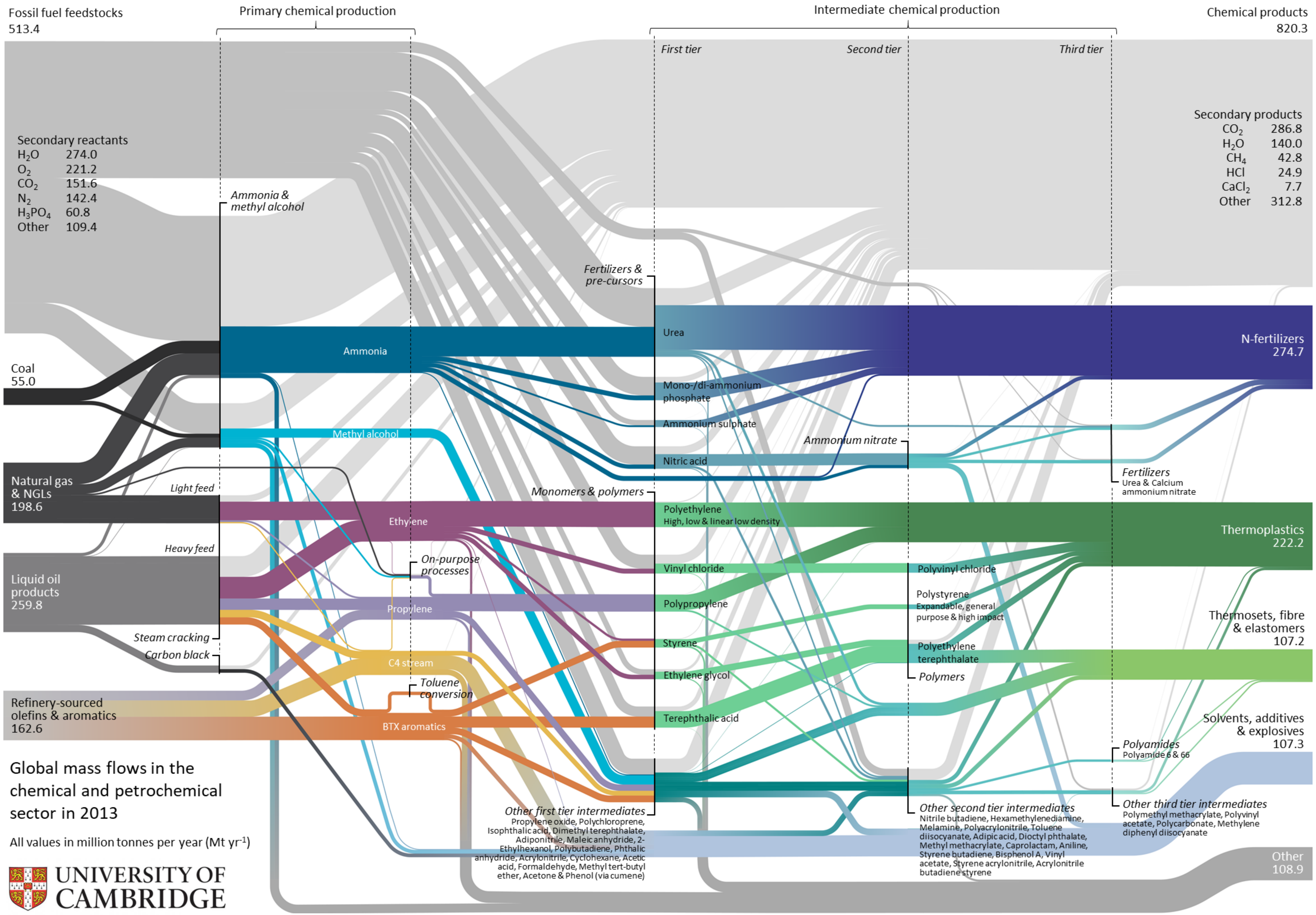
Source: Levi & Cullen (2017) *Mapping global flows of chemicals: From fossil fuel feedstocks to chemical products*

Feedstock mapping matrix





Global chemical flows



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Sustainable Materials : with both eyes open
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mindset
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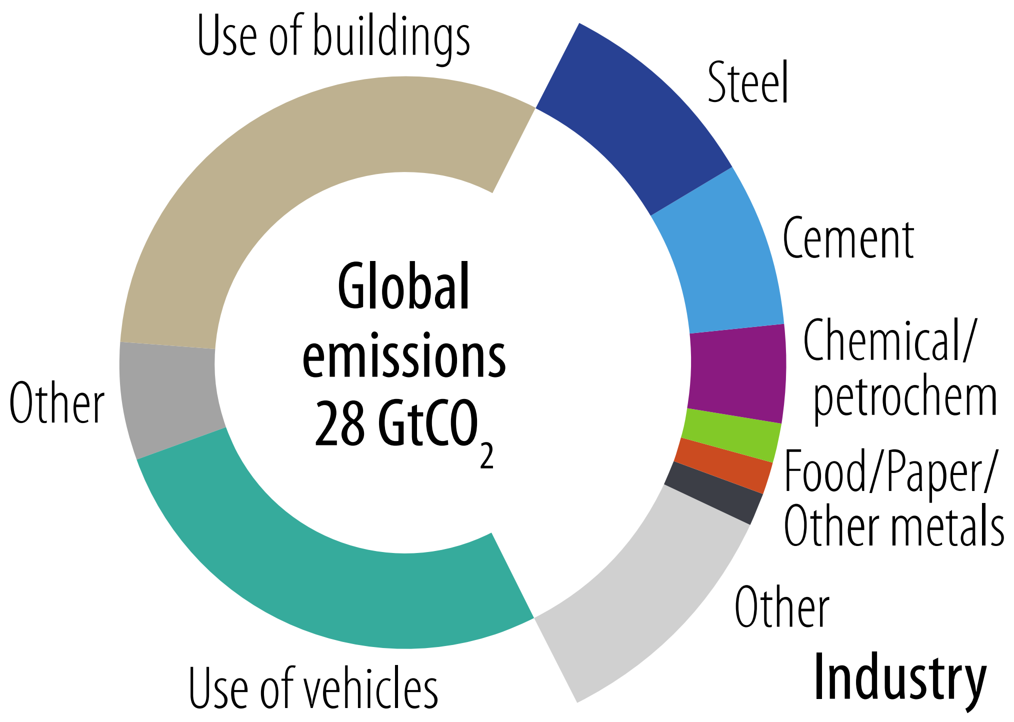
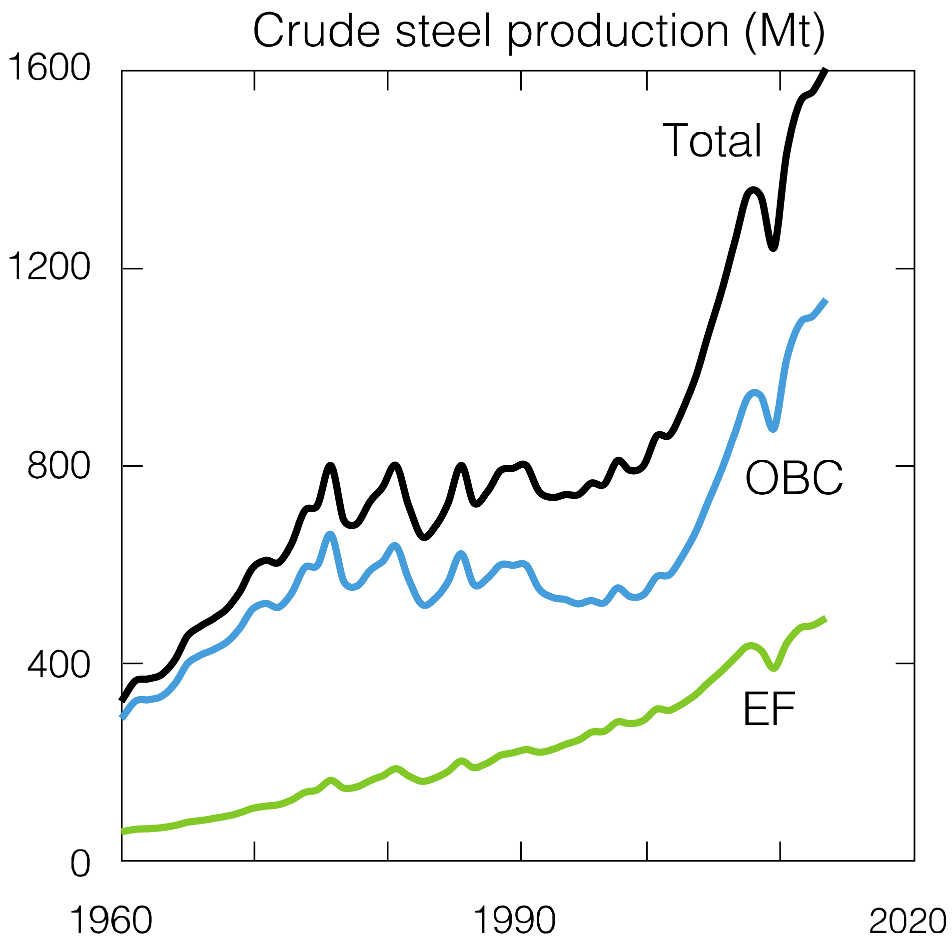
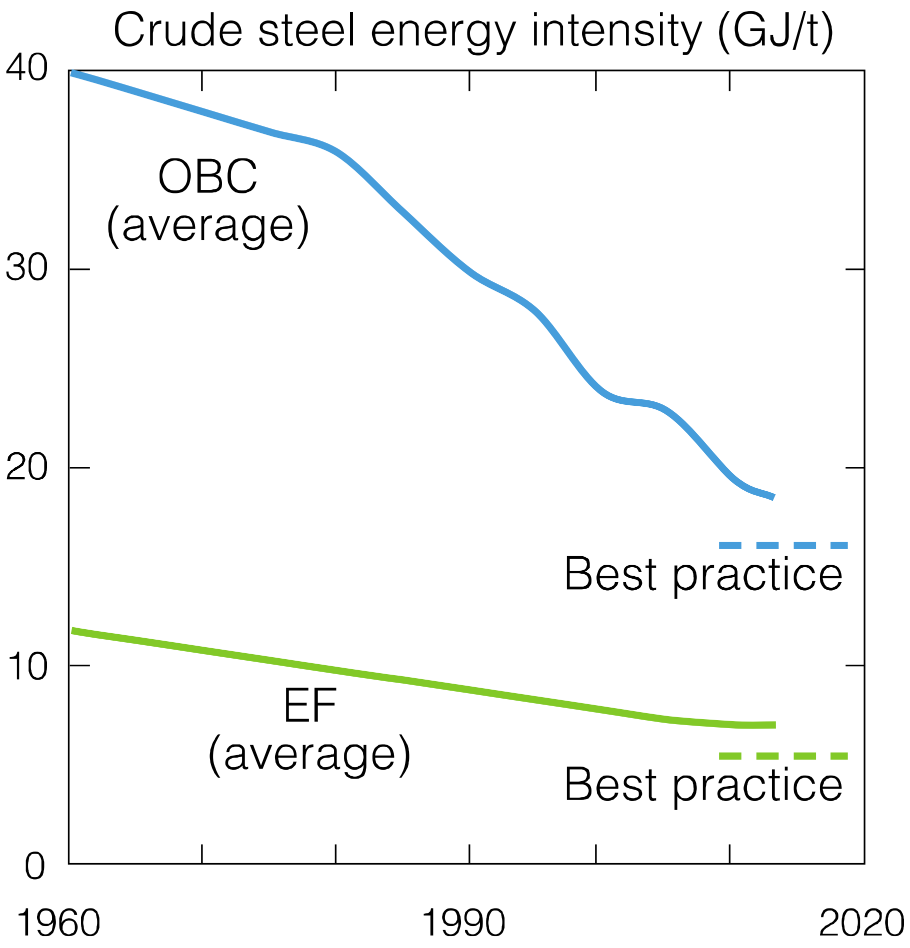
Global steel picture







Emissions

Steel is responsible for ~10% of global CO_2 emissions from energy and industrial processes

Demand

Global demand for steel has increased four-fold over 50 years, and is expected to more than double by 2050

Intensity

Steel production is already efficient. But halving emissions by 2050 will require a further 75% cut per tonne of steel

With one eye open

Energy efficiency
few efficiency gains
left, perhaps 10–20%

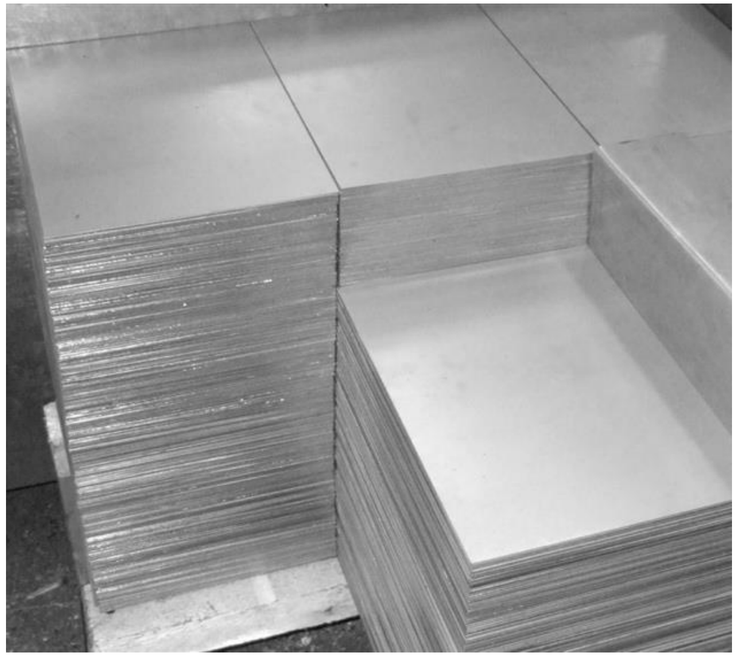
Novel processes
DRI, HIsarna, Smelt Reduction,
Electrolysis, Hydrogen

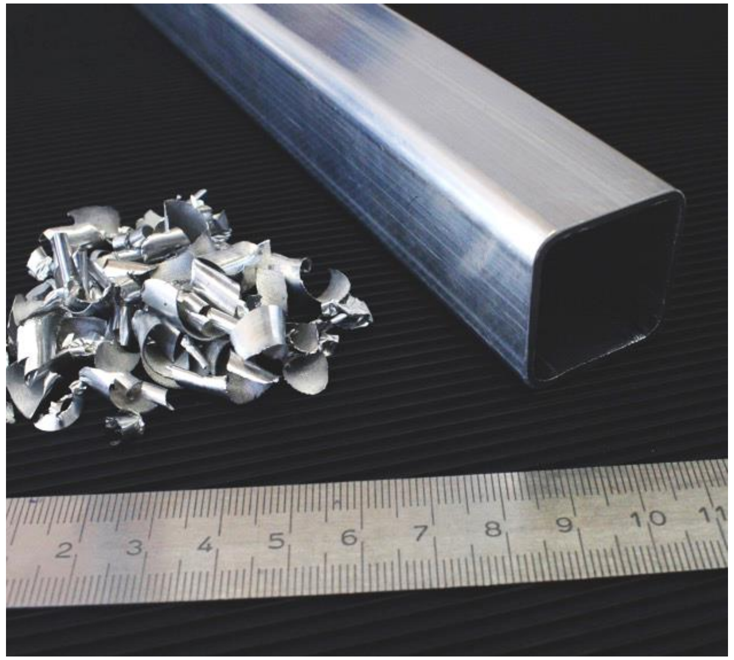
Recycling
increase recovery to 90%

Low carbon energy
renewables, nuclear, CCS

50% emission reduction per tonne
0% reduction in absolute emissions

With both eyes open





Use less by design
30% saving from putting metal in the right place

Reduce yield losses
¼ of all liquid metal is scrapped during production

Divert scrap
to other uses

Re-use with no melting
profitable in construction

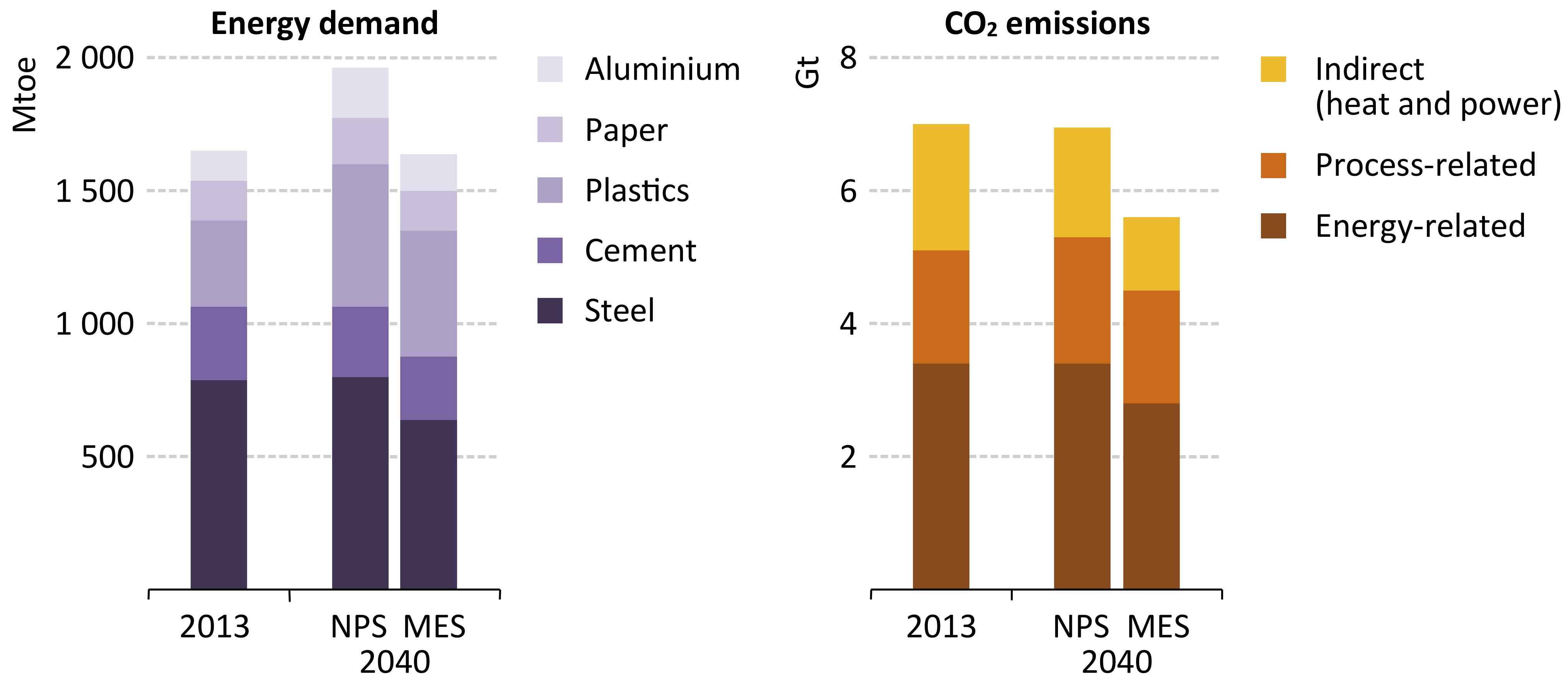
Longer life products
spread impacts over time

Reduce final demand
with more intense use

75% emission reduction per tonne
50% reduction in absolute emissions

Material efficiency

> Material efficiency **could deliver larger energy savings** in energy-intensive industries than energy efficiency.



Note: NPS = New Policies Scenario; MES = Material Efficiency Scenario.

Long-term potential for emissions reduction

50% reduction potential

With one eye open

Challenges

Key technologies are still under development

Novel technological are expensive

Replacement cycles for steel plants are slow

Scrap availability is constrained in a growing market

Renewable energy will likely be prioritised for other sectors

50% reduction potential

With both eyes open

Challenges

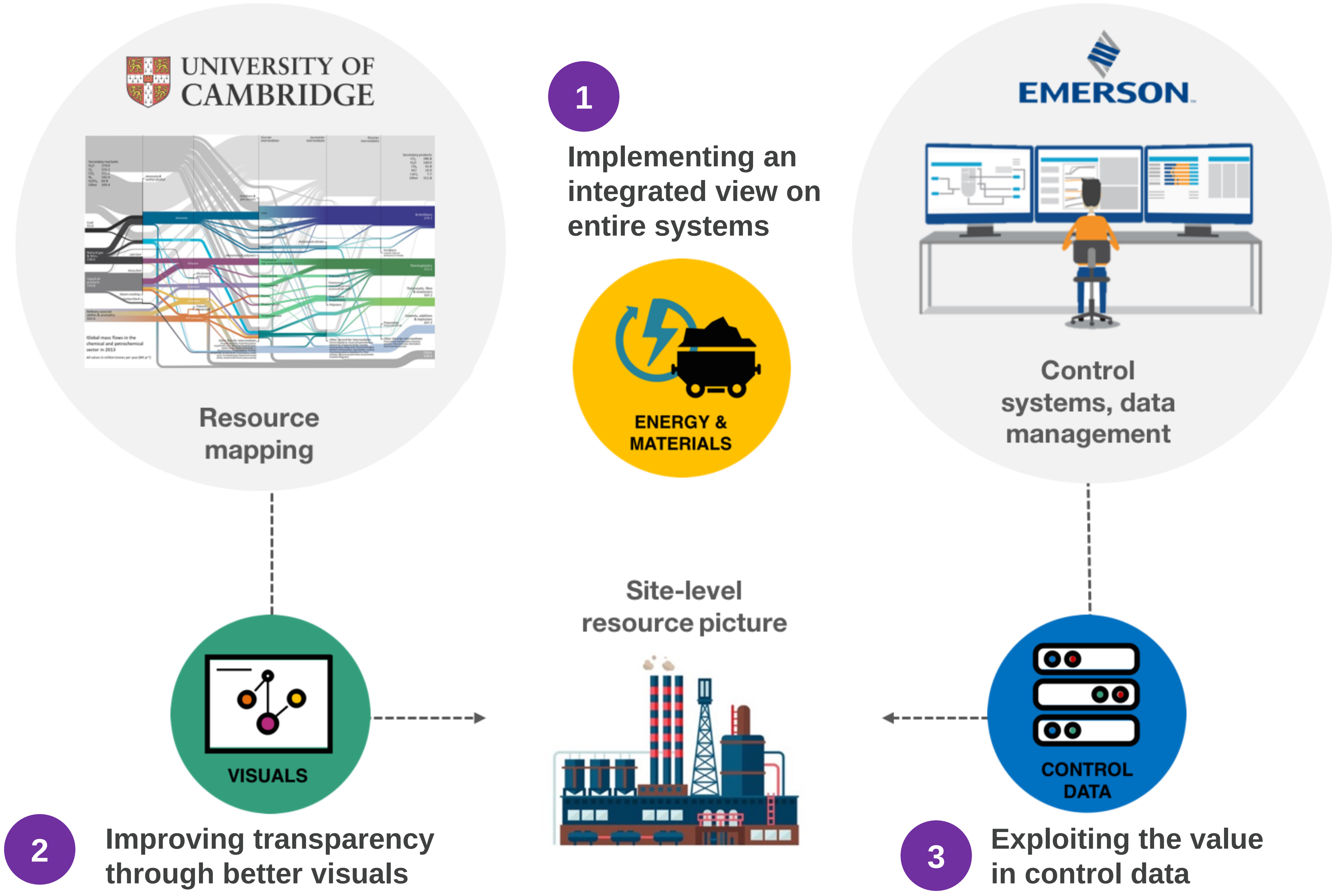
Changing behaviour of consumers is difficult

Circular economy business models are not necessarily profitable

Reconfiguring supply chains for reuse is challenging, requiring new rules to allocate value

Efforts to map how materials flow through society are still in their infancy

Integrated resource efficiency analysis



Ana Gonzalez Hernandez

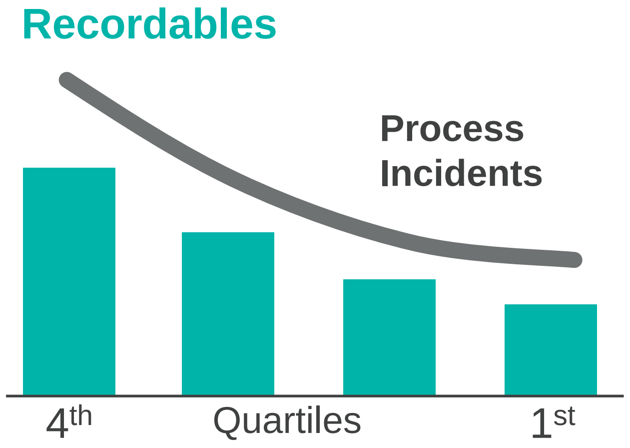
PhD, Emerson

Cambridge University is collaborating with Emerson to develop novel tools that can prepare industry for the future low-carbon and resource-efficient production era

Opportunities from average to top quartile

Safety

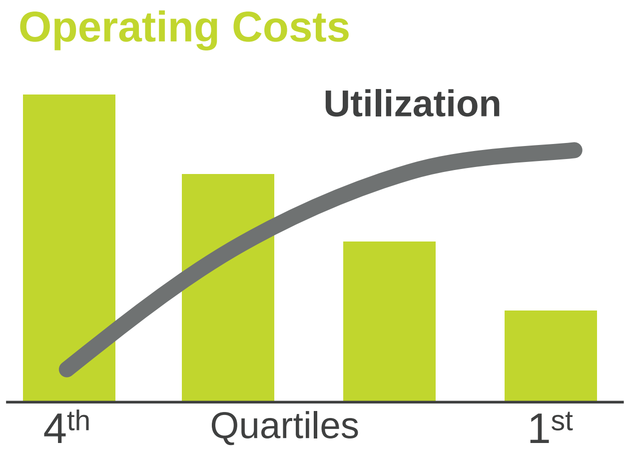
3X fewer recordables
and process incidents



Production

20% lower
operating costs

10% higher
Utilization Rate



Approximately

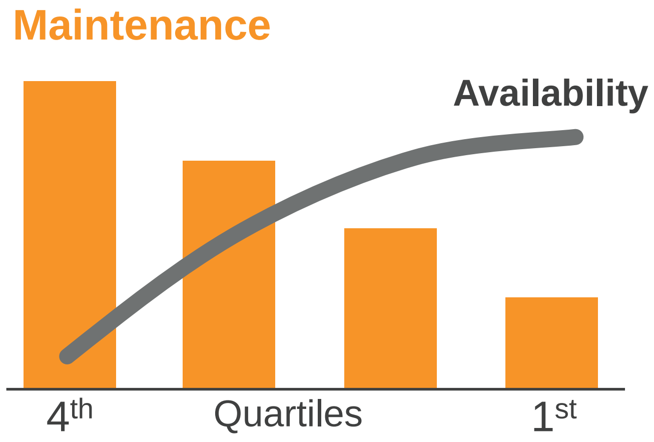
ONE TRILLION
DOLLARS

in company value is lost every year to
suboptimal operating performance

Reliability

4% higher
availability

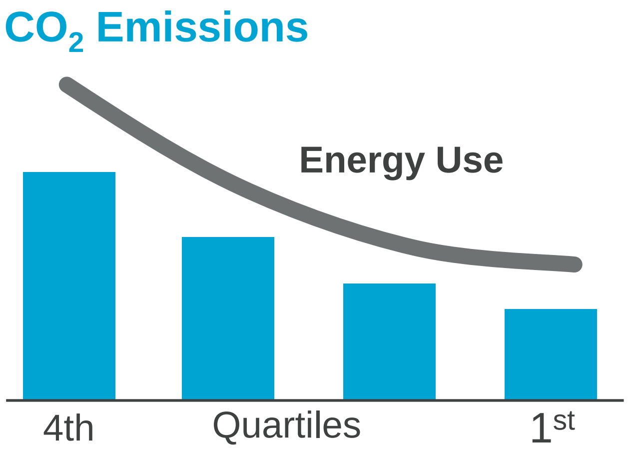
Half the maintenance costs



Emissions

30% lower
emissions

30% less
energy use



Sources: Refining and Petrochemical Benchmarks,
API, Solomon, OSHA, IHS Markit and Company Reports

EMERSON

Service efficiency (materials)

How can we deliver future energy and material services, while reducing resource use and environmental impact?

$$\frac{E_u + M_{in}}{M}$$

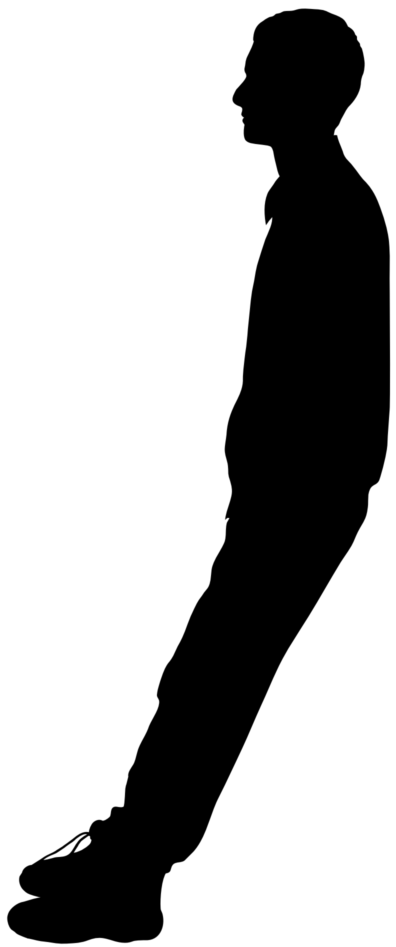
How do we measure this efficiency?

Carbon emissions | **Service (materials)**

$$C = \frac{C}{E_p} \times \frac{E_p}{E_f} \times \frac{E_f}{E_u} \times \frac{E_u}{M} \times \frac{M}{P} \times \frac{P}{S} \times S$$

Carbon intensity | **Energy Conversion** | **Material/product system**

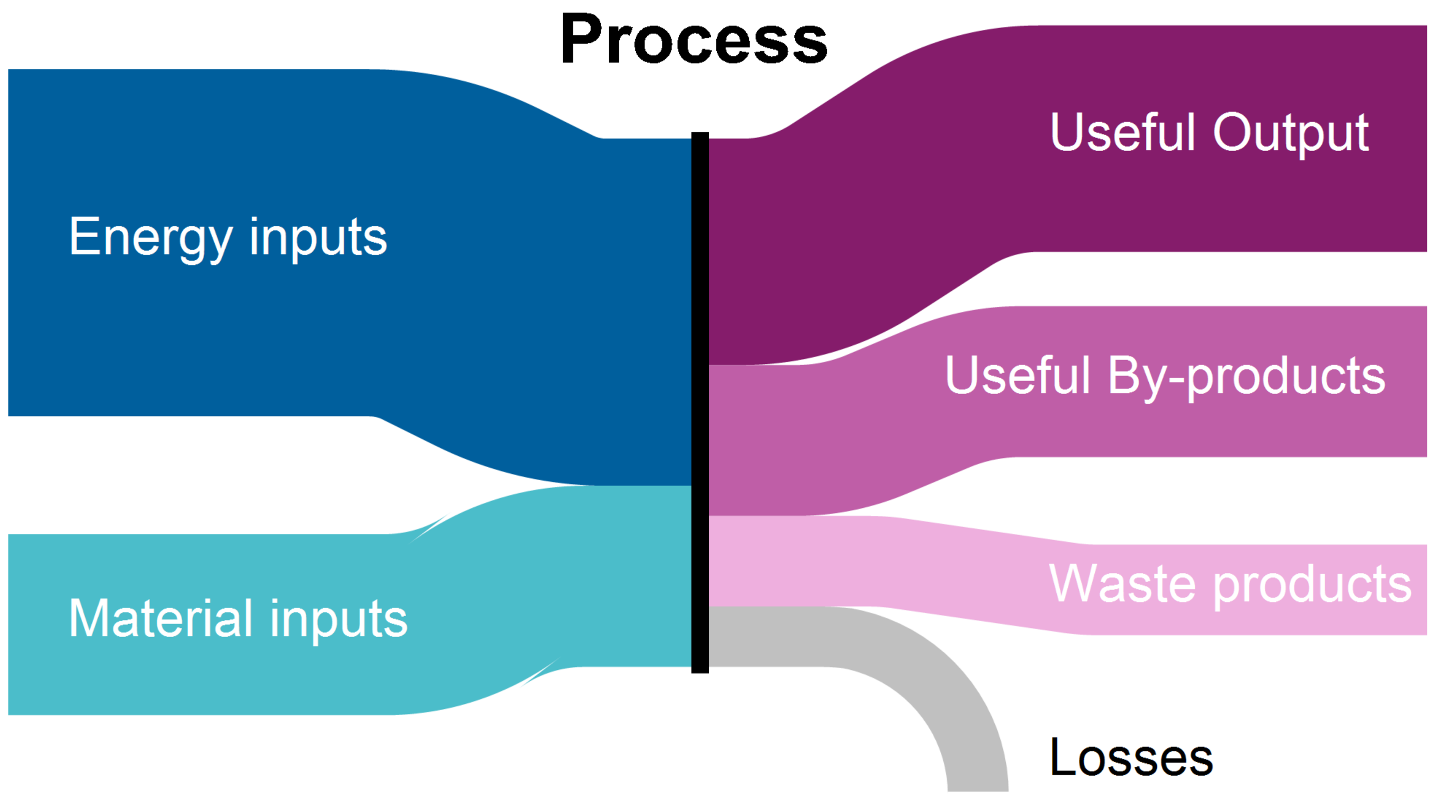
Carbon emissions, **S**ervices delivered
Energy (**p**rimary, **f**inal, **u**seful), **M**aterials, **P**roducts



Combining energy and materials

Resource input

Resources consumed over the life-cycle of a material



Useful output

Theoretical minimum work required to make a material

Resource efficiency = $\dfrac{\textbf{Useful output}}{\textbf{Resource input}}$

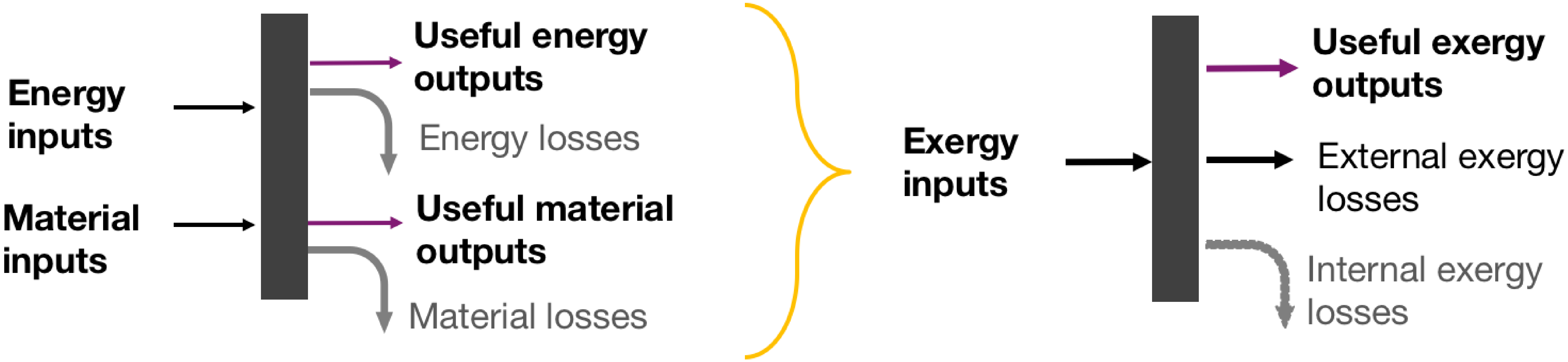
Captures:

1 Upgrade in material quality

2 Downgrade in energy quality

3 Materials Energy

Combining energy and materials : using exergy



ENERGY (joules) / **MATERIALS (kilograms)** X **Conversion factors (J/J, J/kg)** = **EXERGY (joules)**

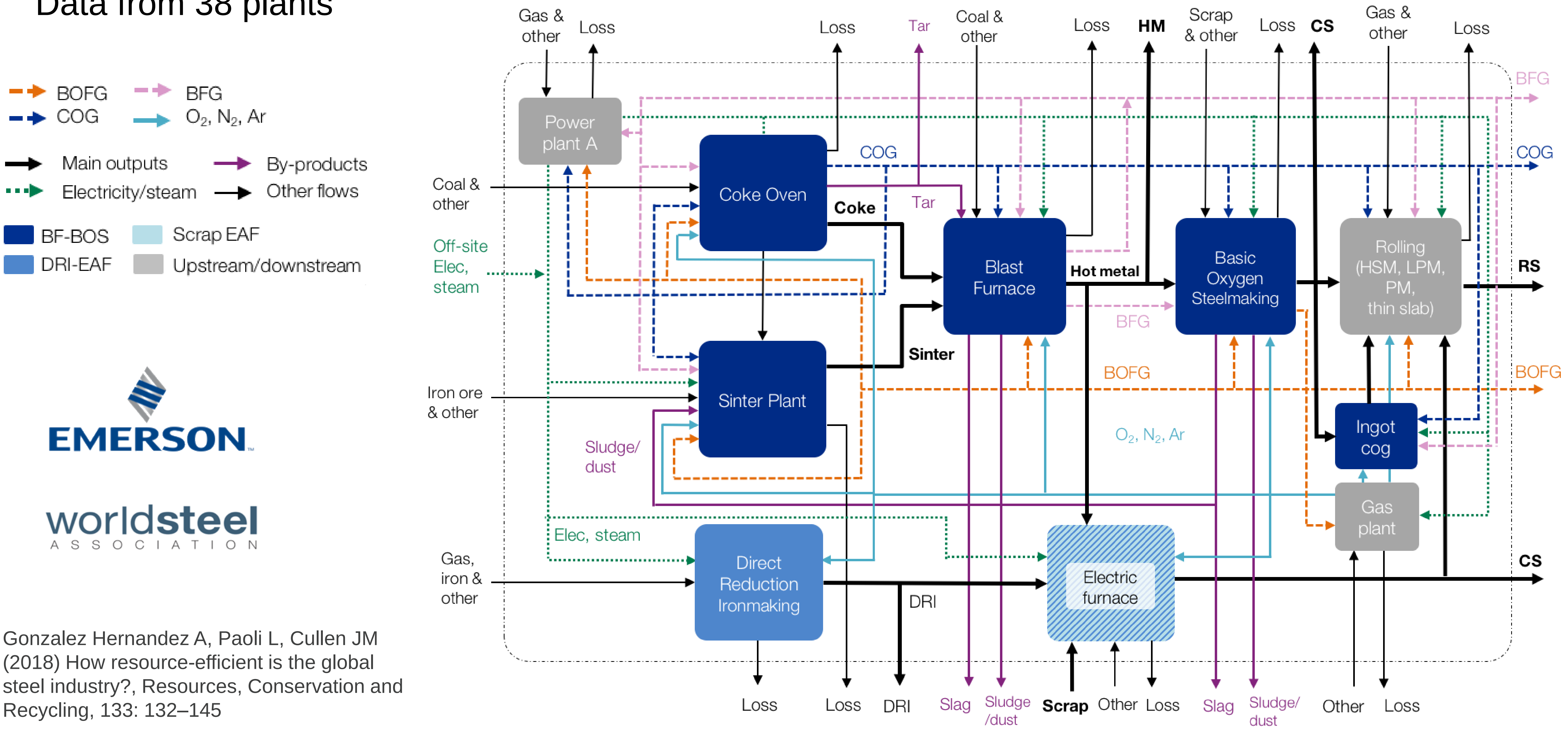
EXERGY CALCULATOR

We are developing a searchable database of exergy values and calculation formulas for materials and energy.

Global steelmaking

Case study 1

Data from 38 plants

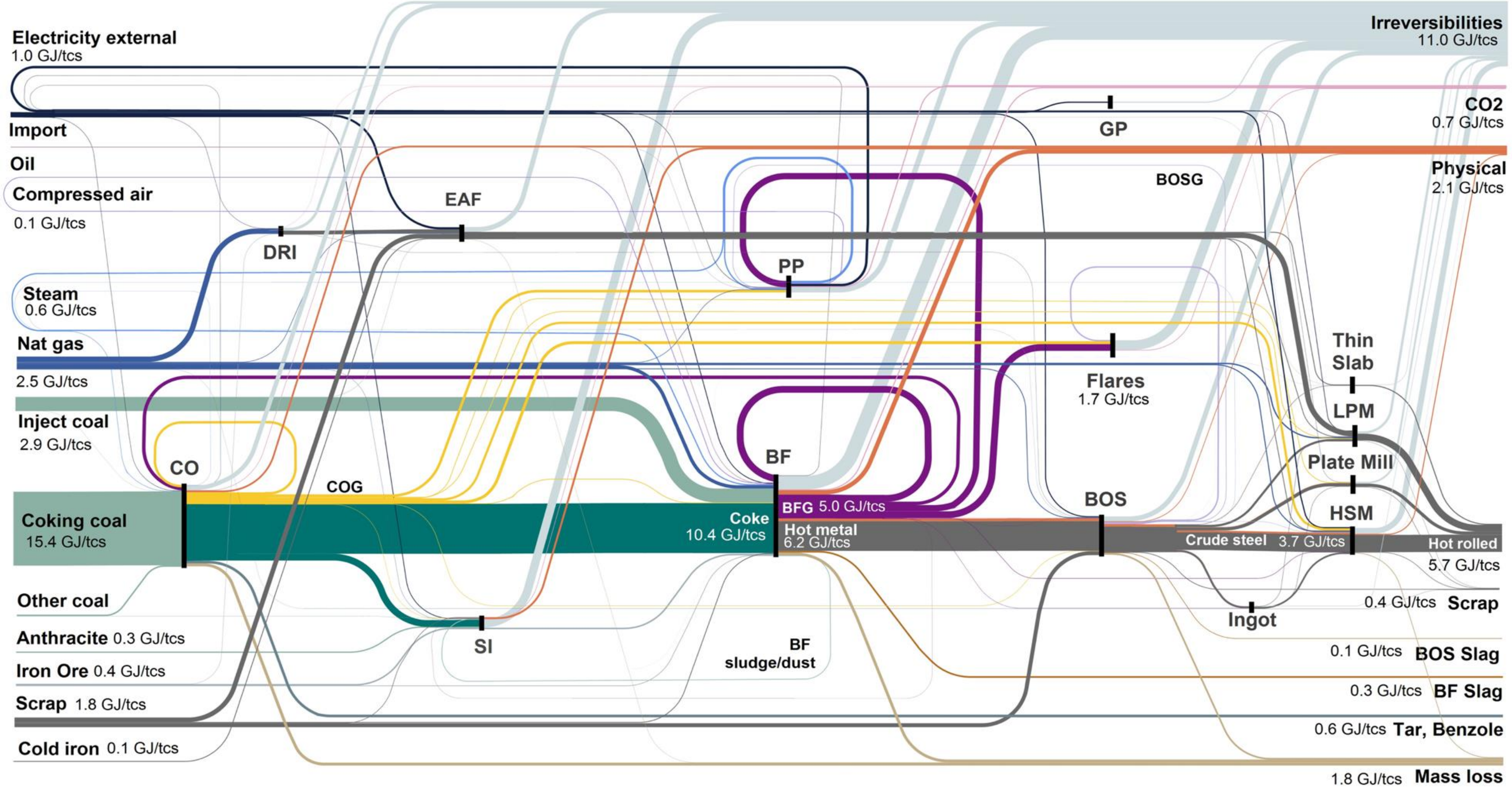


Gonzalez Hernandez A, Paoli L, Cullen JM (2018) How resource-efficient is the global steel industry?, Resources, Conservation and Recycling, 133: 132–145

Global steelmaking

Case study 1

Data from 38 plants



CO: coke oven; BF: blast furnace; BOS: basic oxygen steelmaking; HSM: hot-strip mill; EAF: electric arc furnace;
DRI: directly reduced ironmaking; SI: sintering; PP: power plant; GP: gas plant

EMERSON

worldsteel ASSOCIATION

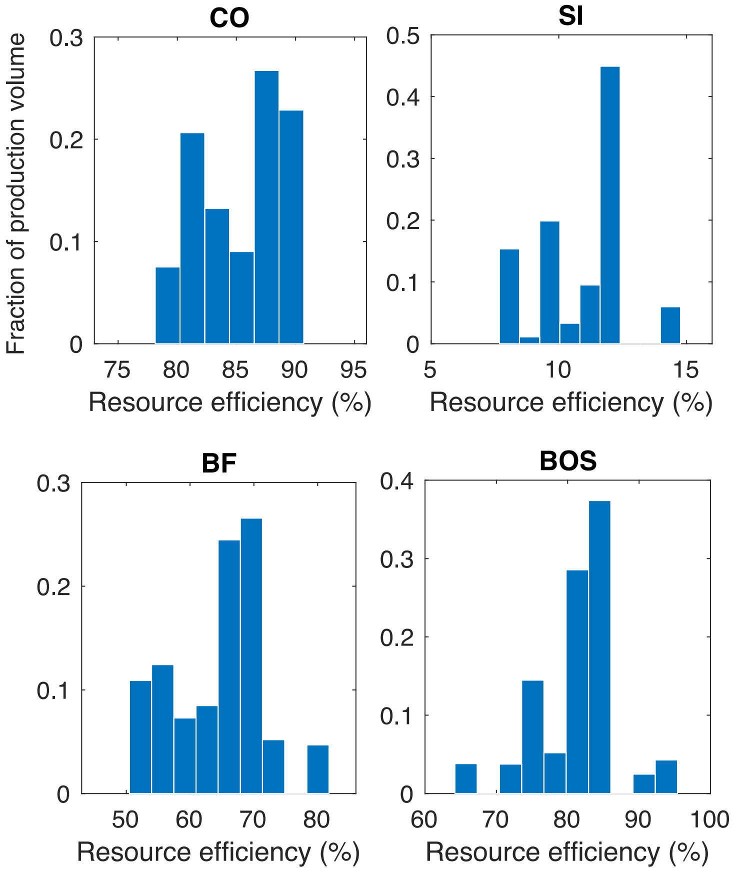
Global steelmaking

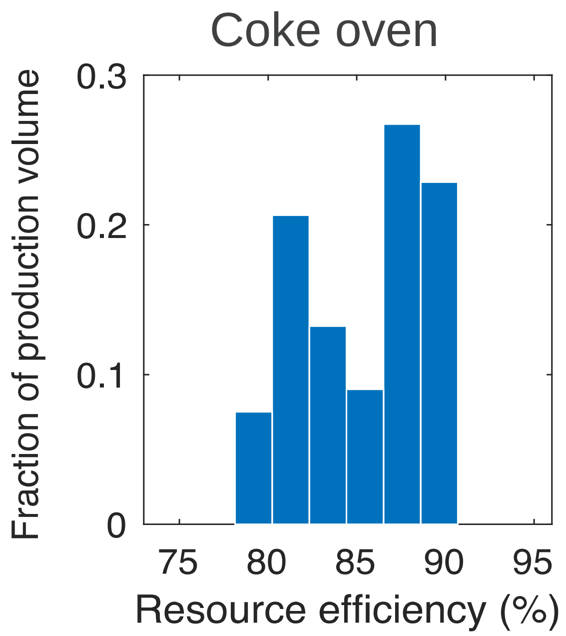
Case study 1

Data from 38 plants

What insights can we gain?

Comparing resource efficiency across production sites to reveal real insights

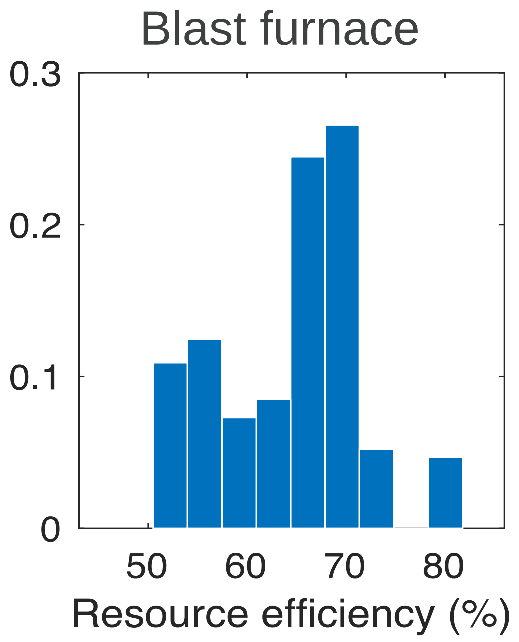




Resource efficiency ranges from 78 to 91%

Less scope for improvement

- **Narrow range:** similar inputs, consistent material by-product recovery (tar, benzole)
- **Bi-modal distribution, cause:** Coke Dry Quenching
- **Options**: improving recovery of COG; steam; recovering syngas/ammonia generated



Resource efficiency ranges from 50 to 81%

Substantial improvement potential

- **Wide range:** inherent flexibility in process, range of fuels and technologies available for improvement.
- **Bi-modal distribution, cause:** recovery of BFG.
- **Options**: top-gas recovery; injection pulverised coal, combustion monitoring and control.

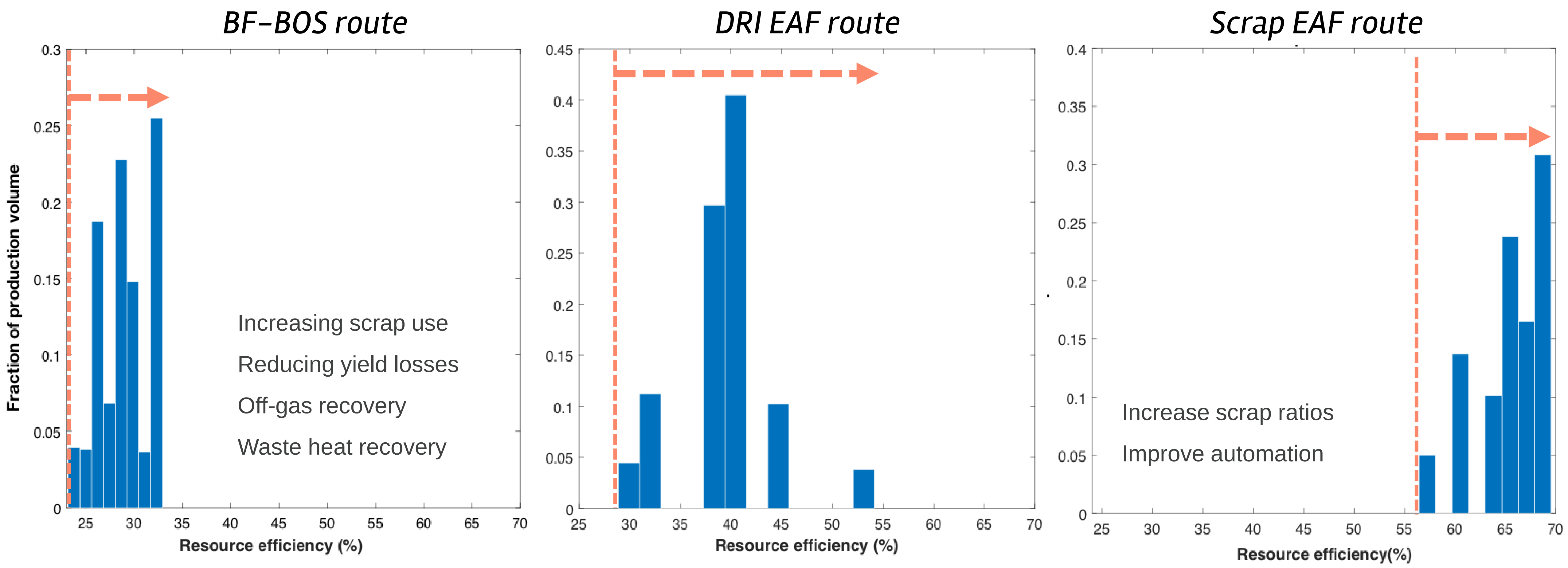
Global steelmaking

Case study 1

Data from 38 plants

Entire steel sector	33%	Primary production	29%	Secondary production	65%

Delivers a wider range of material and energy efficiency options, using a pragmatic approach

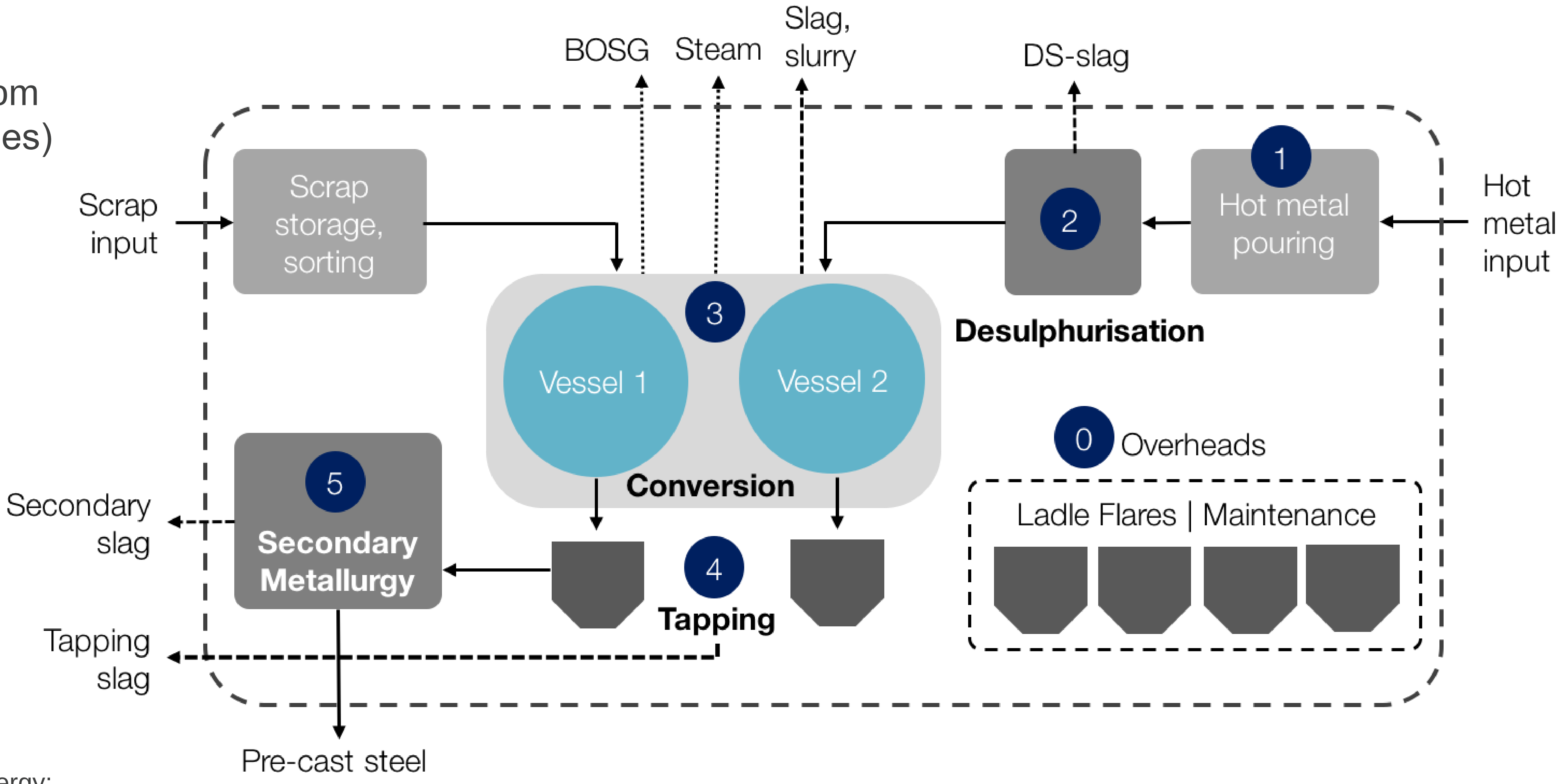


Basic oxygen steelmaking

Case study 2

Real-time control data

Control data extracted from across 900 ‘heats’ (batches)

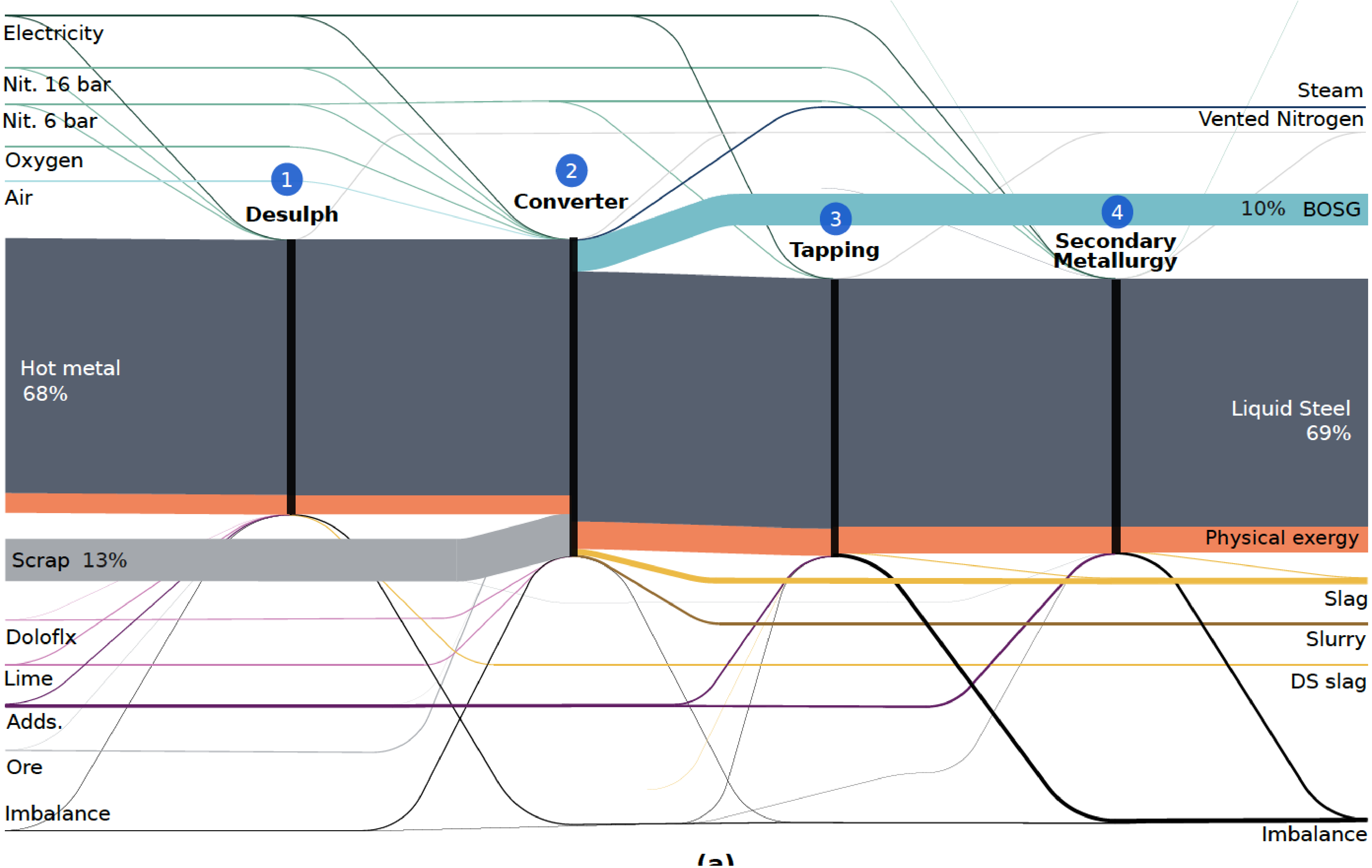


Gonzalez Hernandez A, Lupton RC, Williams C, Cullen JM (2018) Control data, Sankey diagrams, and exergy: Assessing the resource efficiency of industrial plants, Applied Energy, 218: 232–245

Basic oxygen steelmaking

Case study 2

Real-time control data



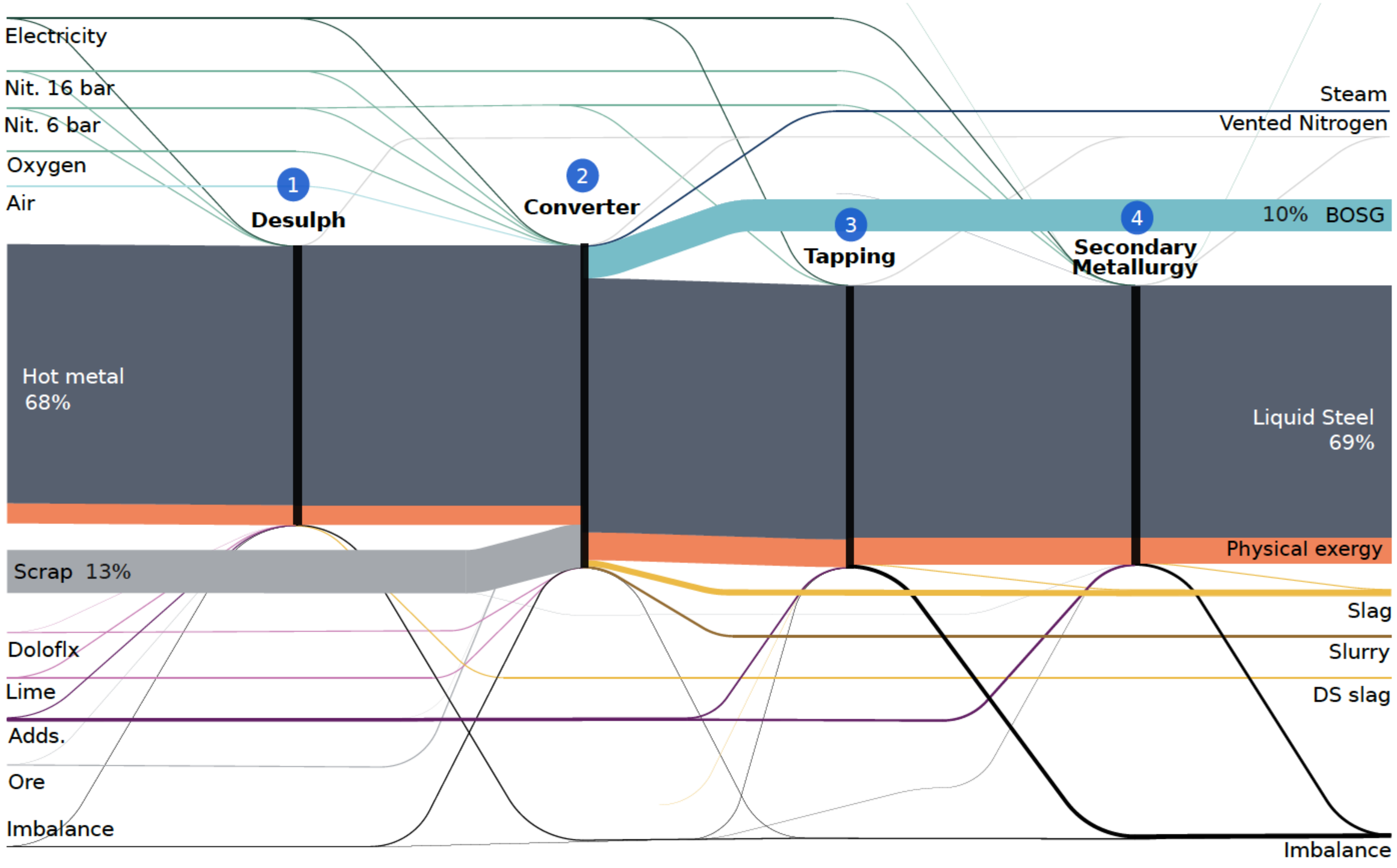
Resource efficiency across 900 batches

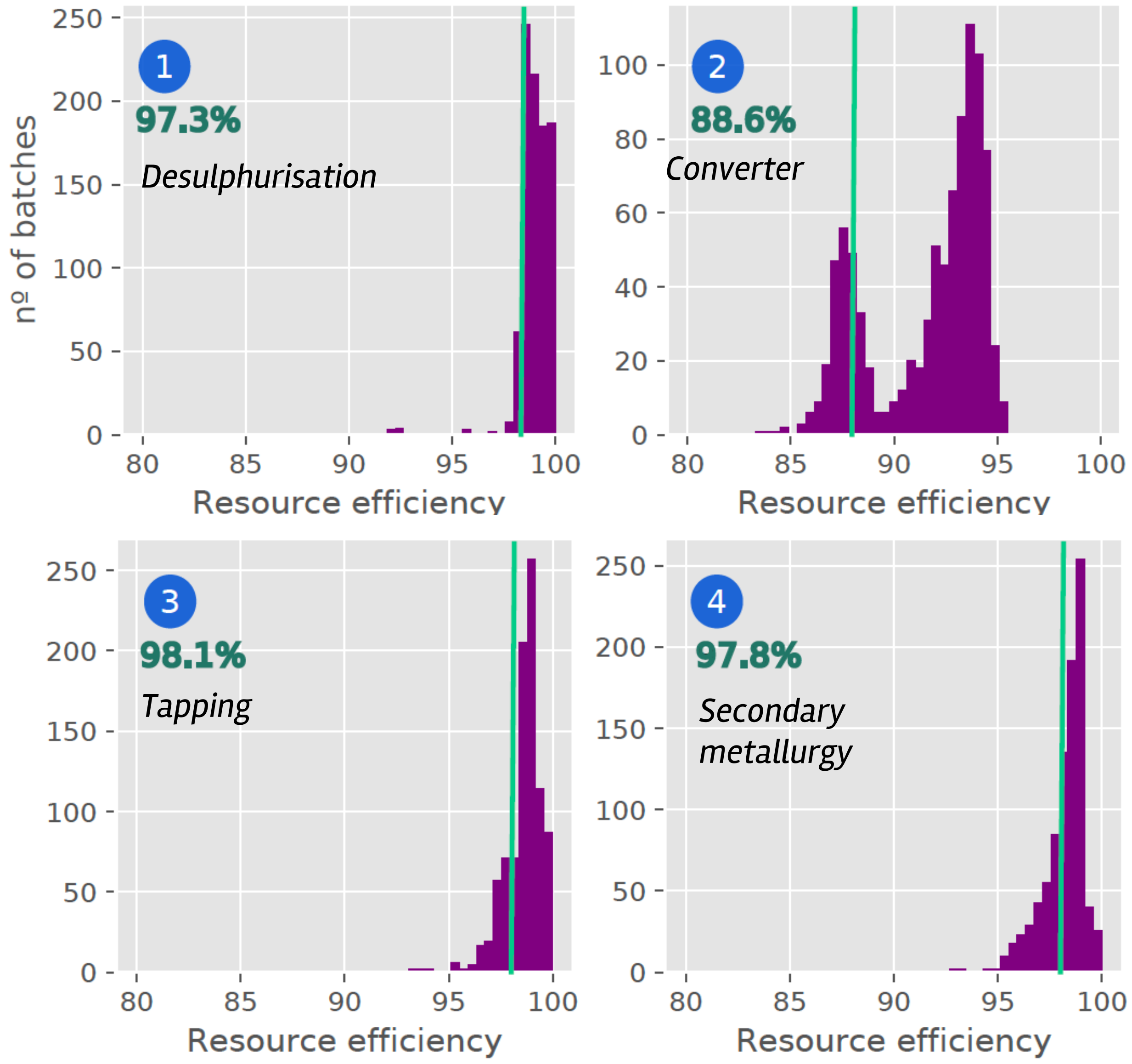
Gonzalez Hernandez et al. (2018) Applied Energy

Basic oxygen steelmaking

Case study 2

Real-time control data

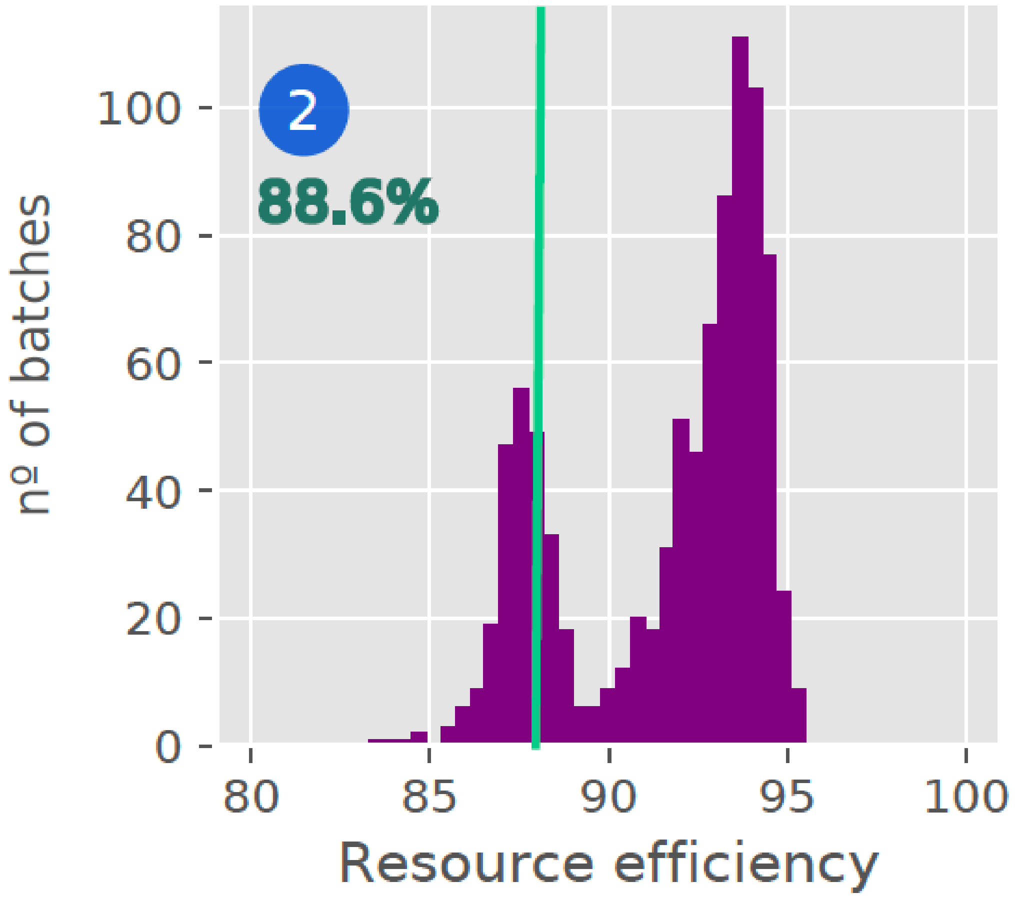


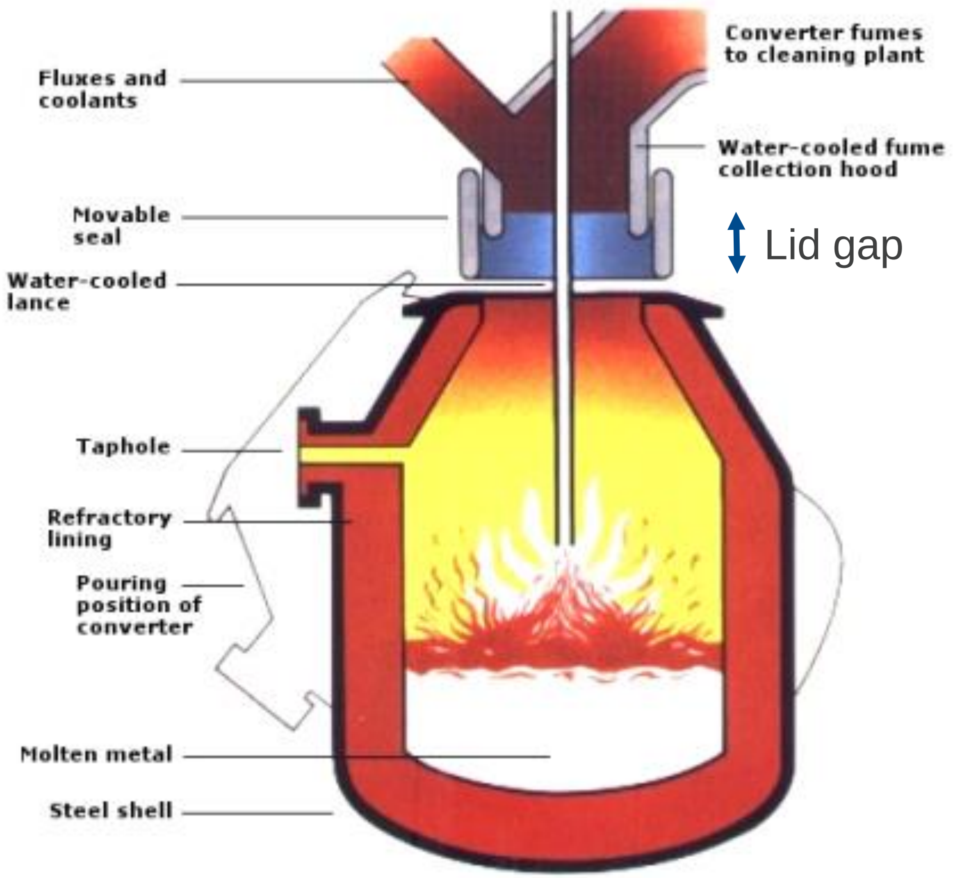


Basic oxygen steelmaking

Case study 2

Real-time control data





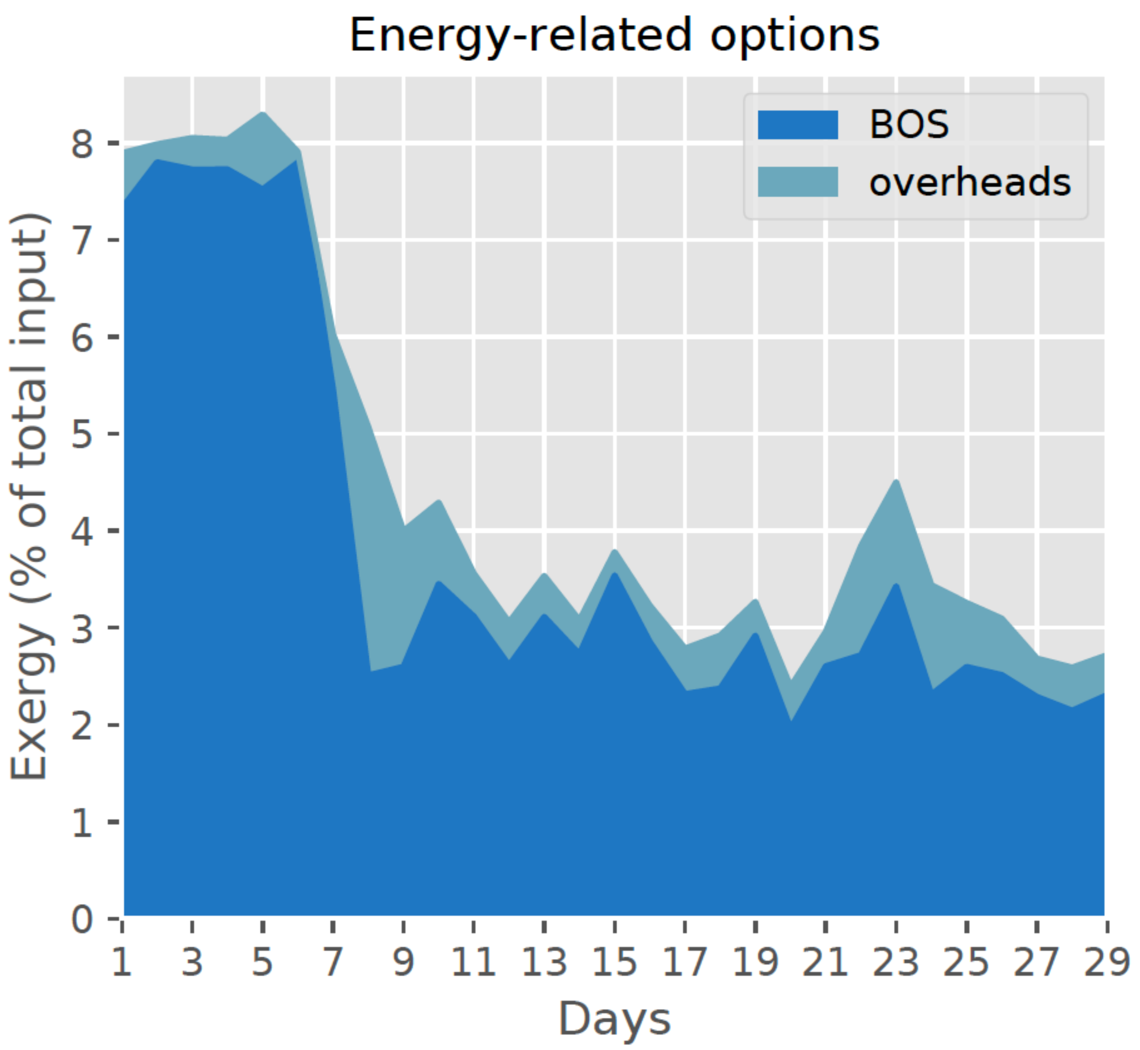
Two performance modes: arise because BOS gas is not recovered for every batch; in some batches it is still flared (lack of holding volume)

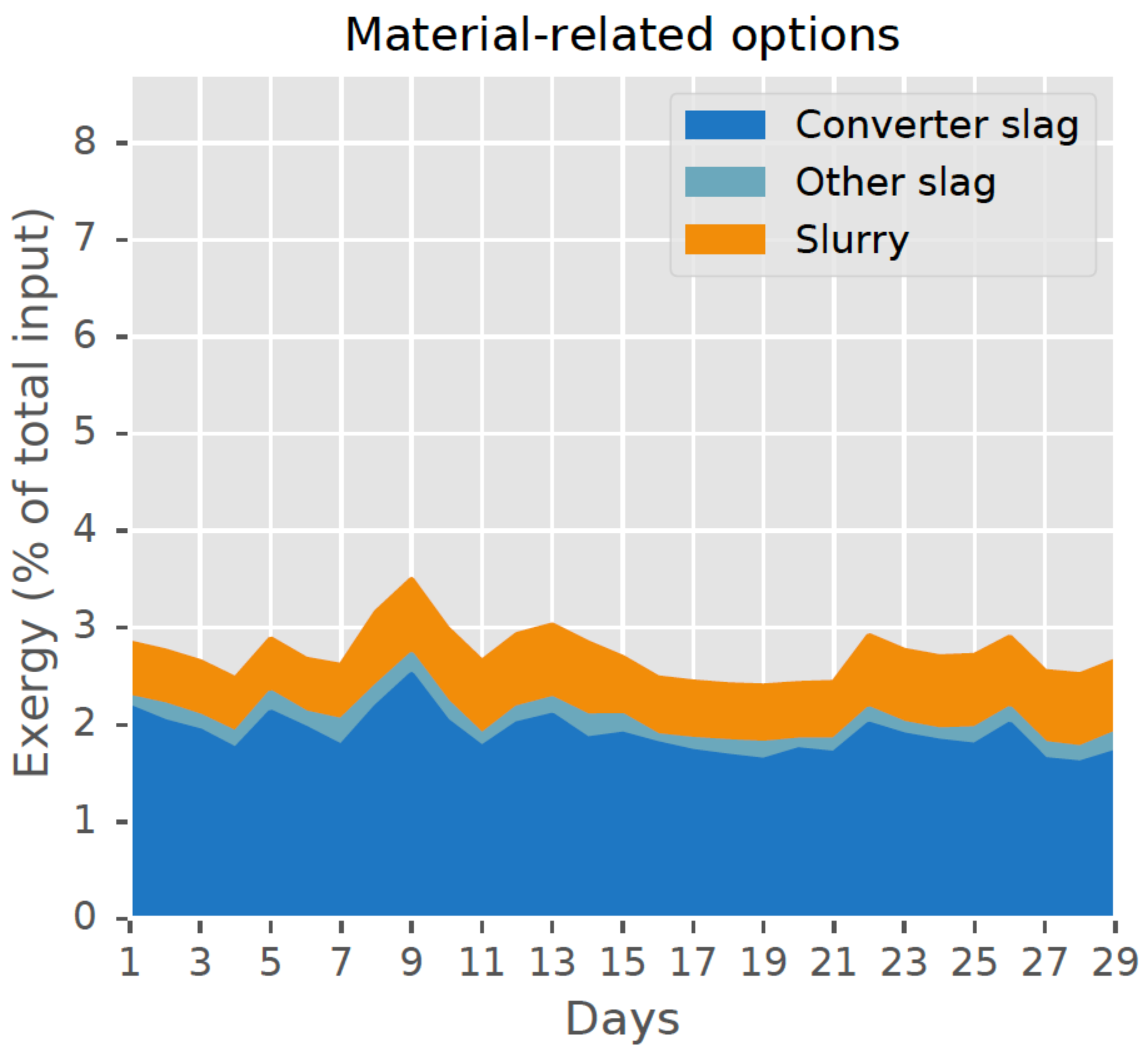
Variation within higher mode: partly a result of the differences in the calorific value of the BOS gas, caused by variations in the gap for the converter lid

Basic oxygen steelmaking

Case study 2

Real-time control data





Material efficiency savings are potentially as large as process energy efficiency savings

Resource efficiency

Going forward

★ Need to track supply chains from service delivery back to impact

★ Need to consider the whole system, i.e. both energy and materials

★ Exergy is a useful for measuring energy and materials on the same scale, reducing the complexity of efficiency metrics

★ Watch out for rebound when pulling one lever, in another lever

MinFuture