The role of metal forming in a world with zero emissions

ICTP 2023 Cannes,
Wednesday 27th September 2023, 09.30-10.15

Professor Julian Allwood FREng

Use Less Group, University of Cambridge

Allwood-office@eng.cam.ac.uk

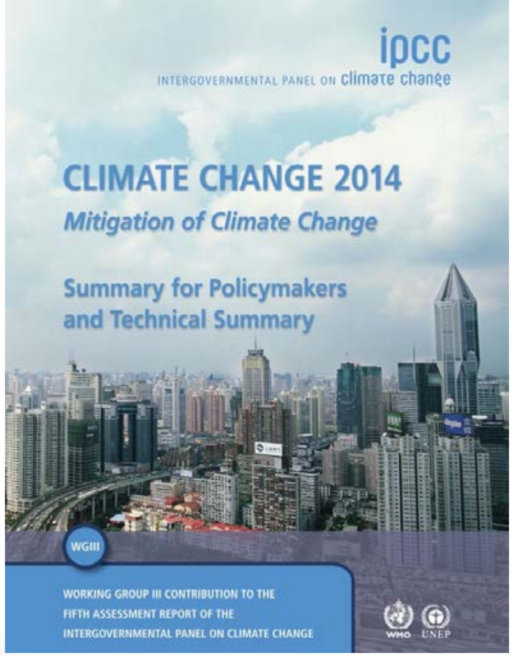
Access and references

- A pdf of the slides used in this talk can be downloaded from:

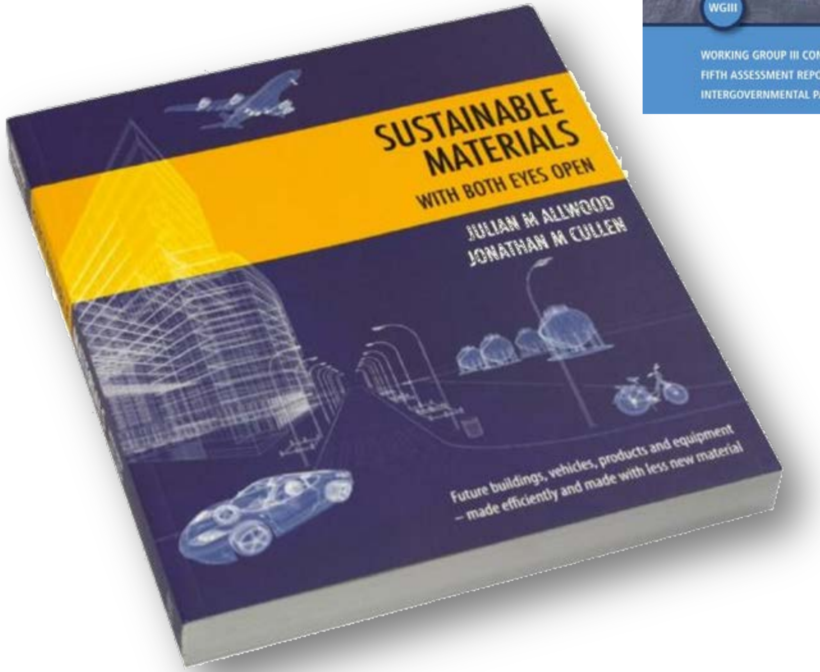
  www.uselessgroup.org/about-us/blog

- There is a full set of references at the end of the slide-pack

Background

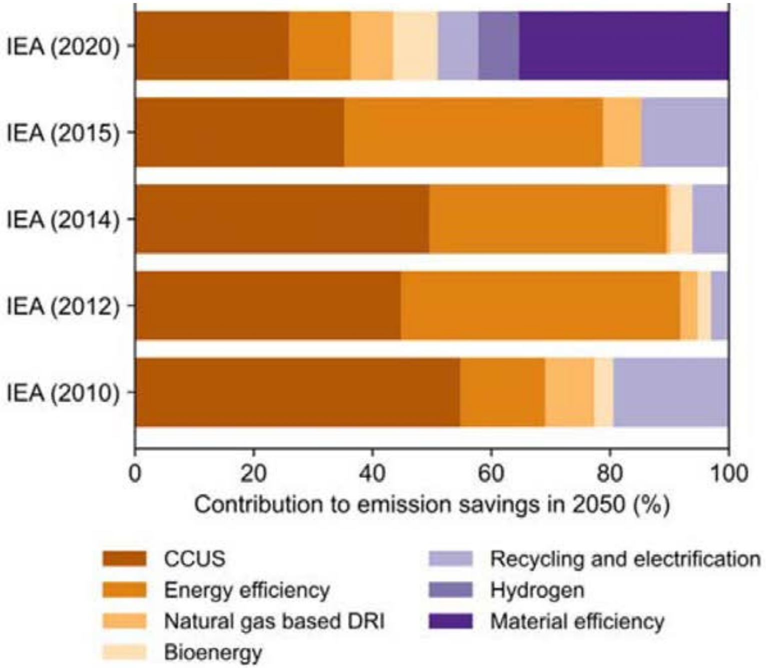


ICTP 2011: Aachen



www.withbotheyesopen.com

Steel de-carbonisation



Source: Watari et al. (2023)

18 FEBRUARY 2016 | VOL 530 | NATURE | 281

Correspondence

Technology alone won't save climate

A dragon was buried at the Paris climate meeting (COP21): 'climate sceptics' disappeared. Now we face a second, equally formidable dragon: unreasonable optimism about 'new' energy technologies. This optimism supports economic-growth models driven by innovation, but depends on an unimaginable scale and rate of deployment.

Defeating the second dragon requires that we reconsider our habits of energy usage. Thirty years of engine-efficiency gains have been eclipsed by our preferences for ever-larger cars that are often 20 times heavier than the passengers — but these are habits, not needs.

...

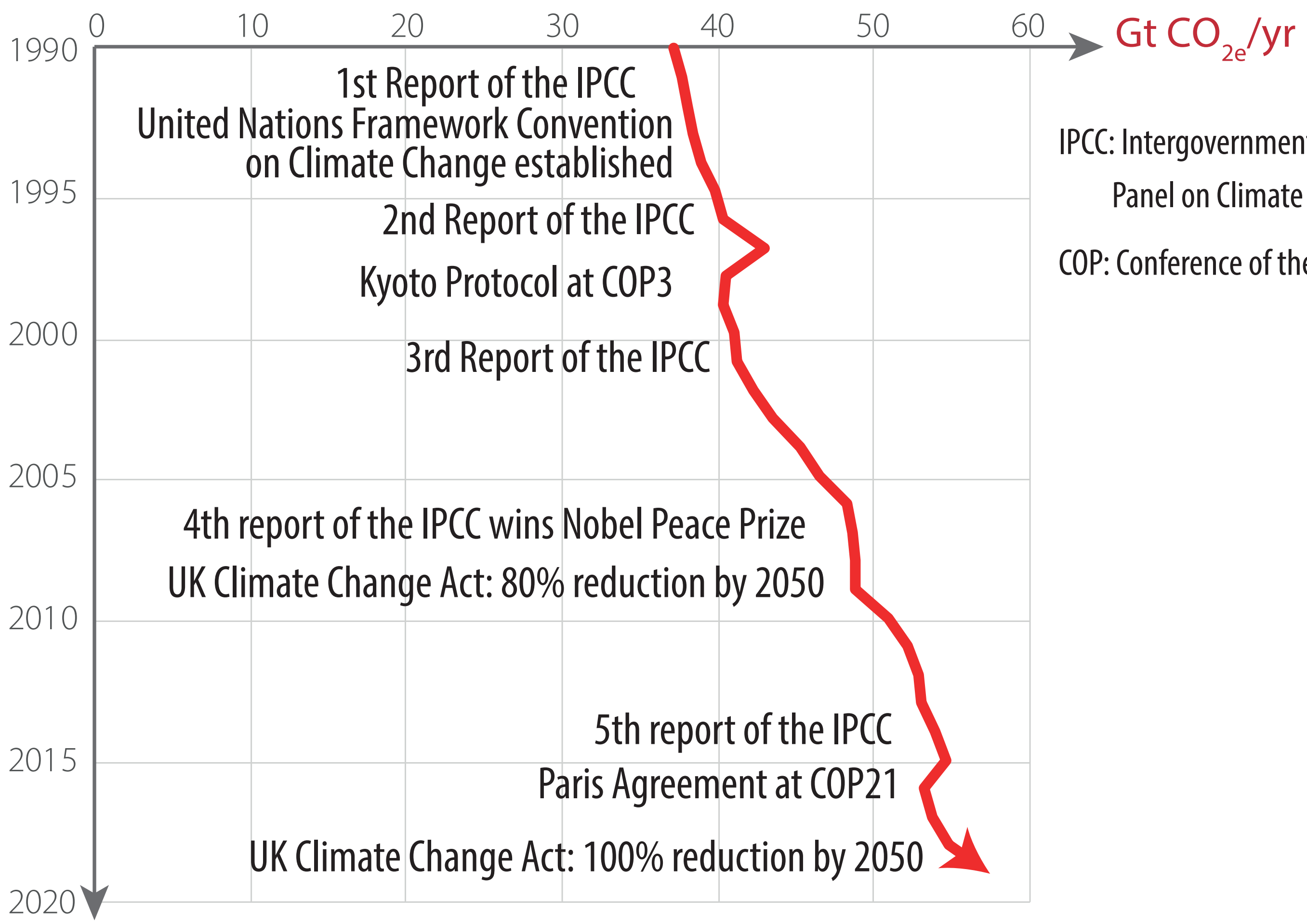
Challenging our habits of energy use should be the first priority of climate policy.

Julian Allwood *University of Cambridge, UK.*

Climate policy summary

Rising emissions and pledges

Global discussions and emissions



IPCC: Intergovernmental Panel on Climate Change

COP: Conference of the parties

Legally committed to zero emissions by 2035:

- **Finland**

Legally committed to zero emissions by 2040:

- **Austria, Iceland**

Legally committed to zero emissions by 2045:

- **Germany, Sweden**

Legally committed to zero emissions by 2050:

- **EU, USA, UK, S Korea, Australia, Canada**

Policy document for zero emissions by 2050:

- **Most South American countries**

Policy document for zero emissions by 2060:

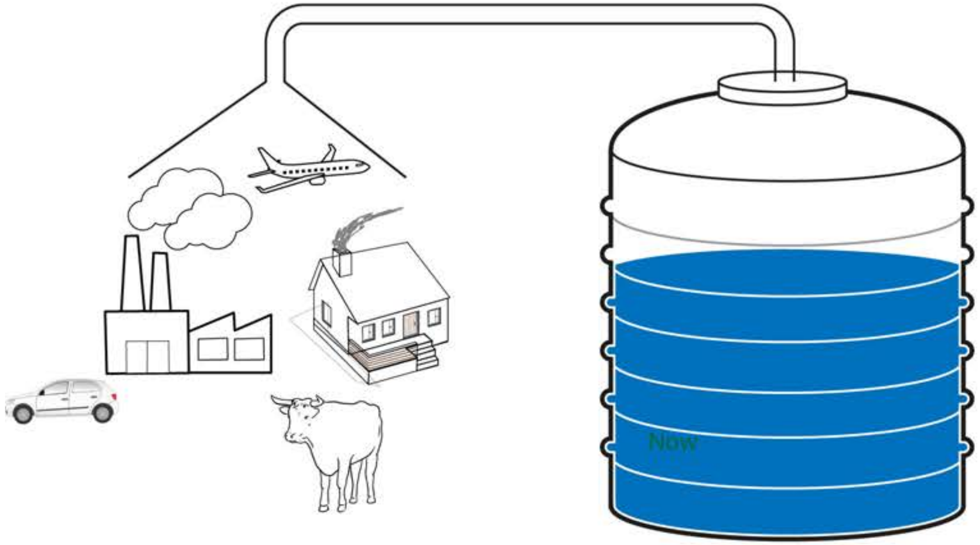
- **China**

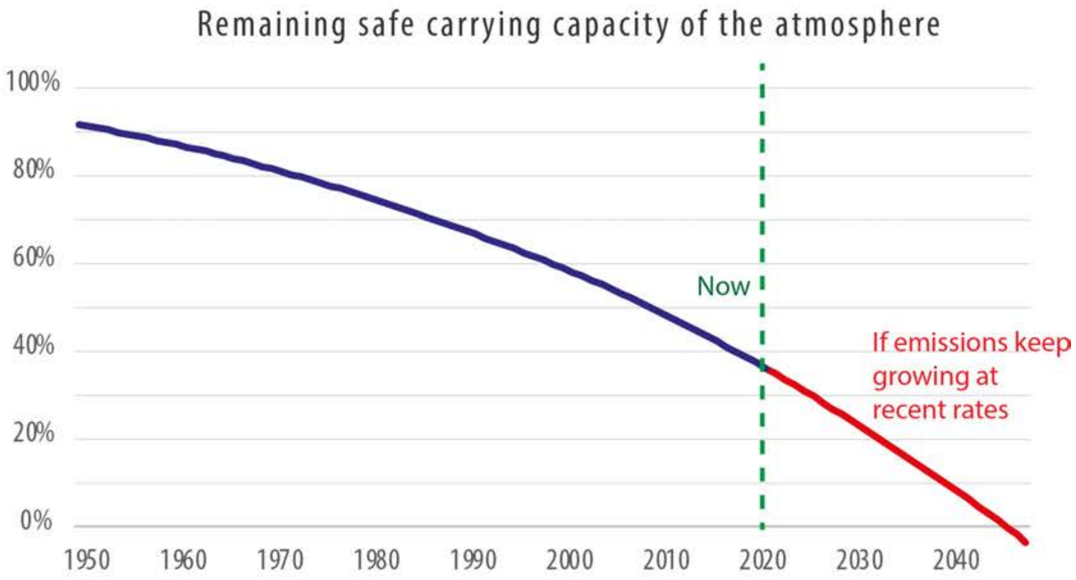
Policy document for zero emissions by 2070:

- **India**

Data from https://eciu.net/netzerotracker

Accumulated not annual emissions are the problem

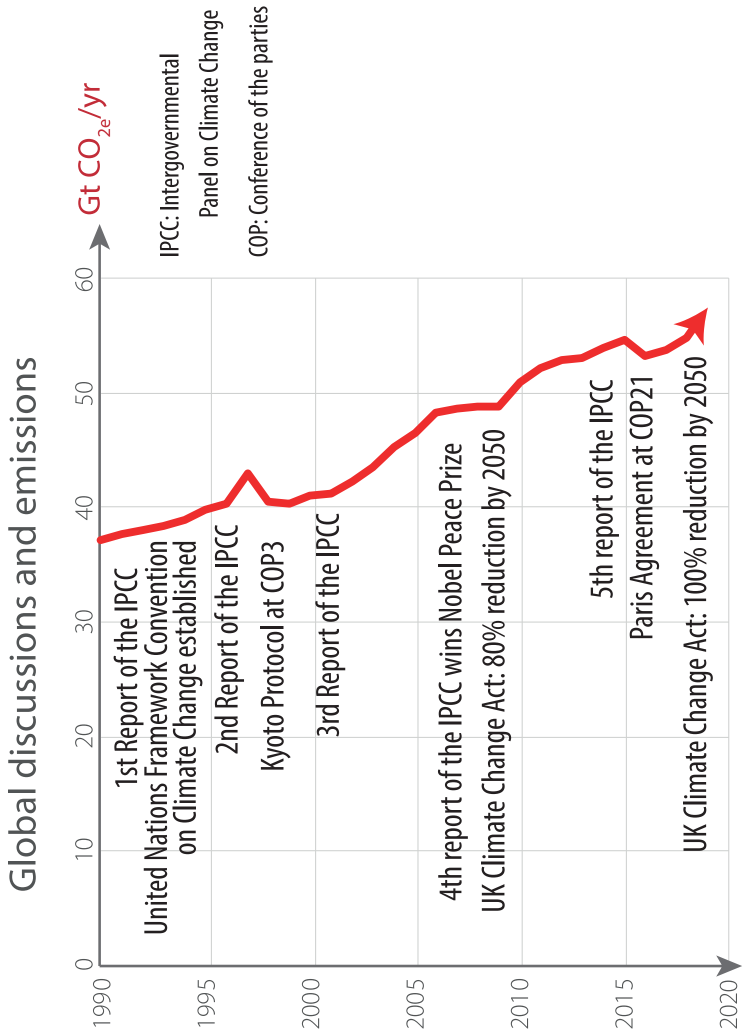


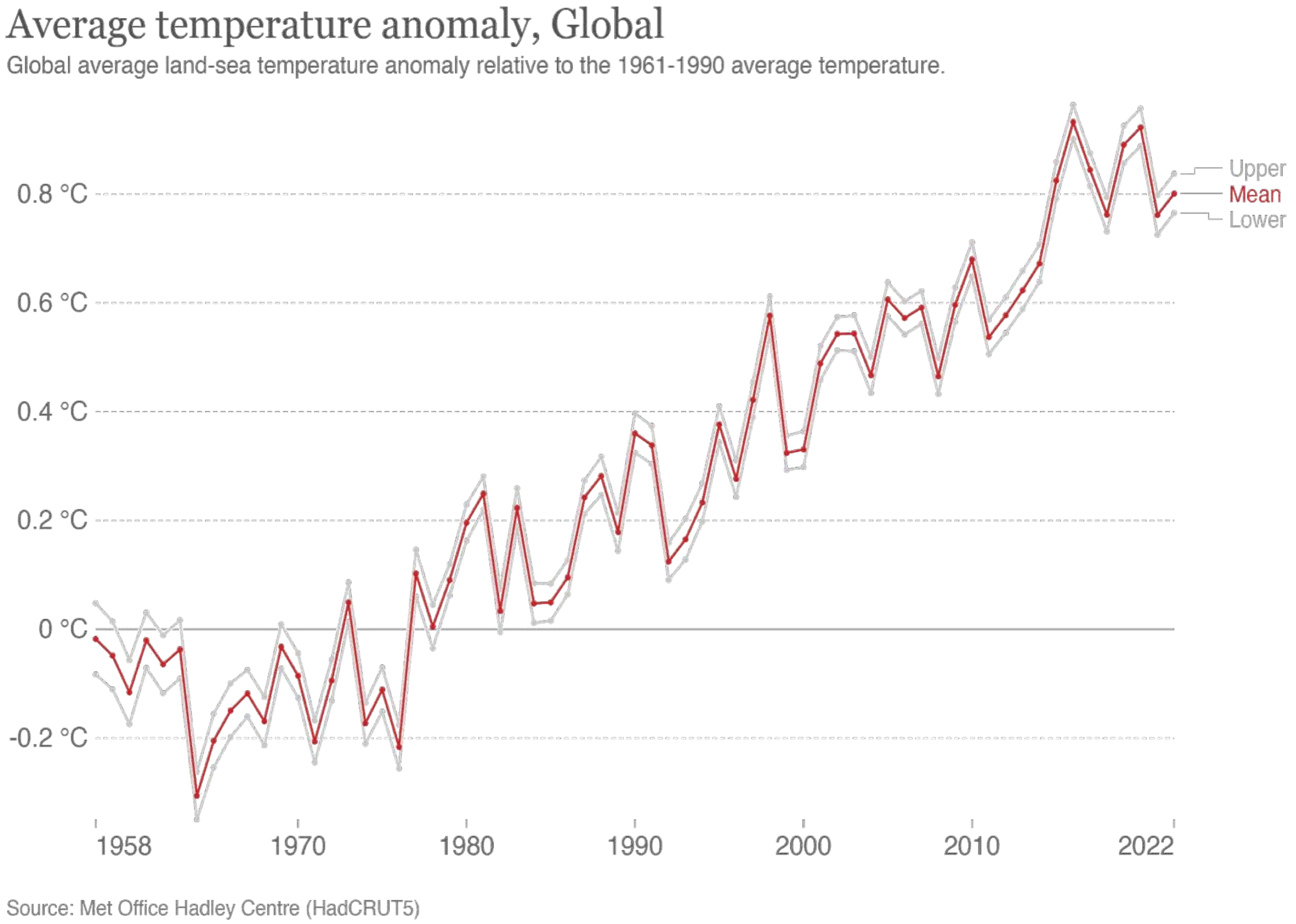


Timeline

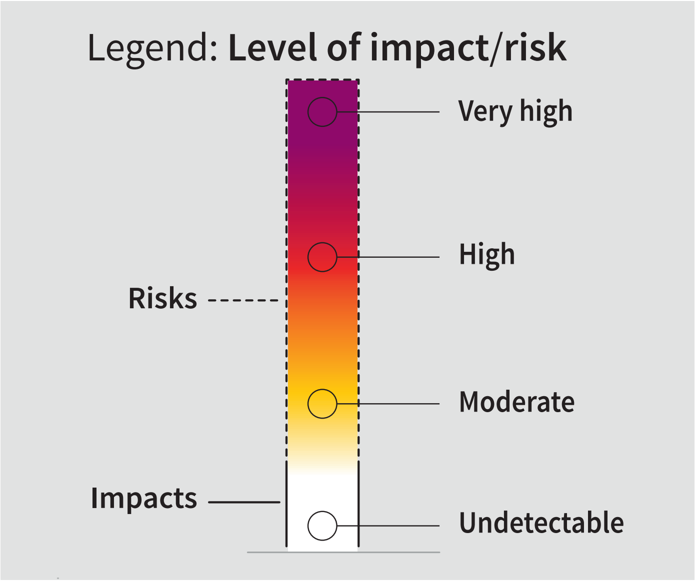
- The accumulation of emissions causes the problem, so the timeline to zero matters
- Everybody has different priorities and constraints
- But the upper-limit of safe capacity is widely agreed

Rising temperature and risk

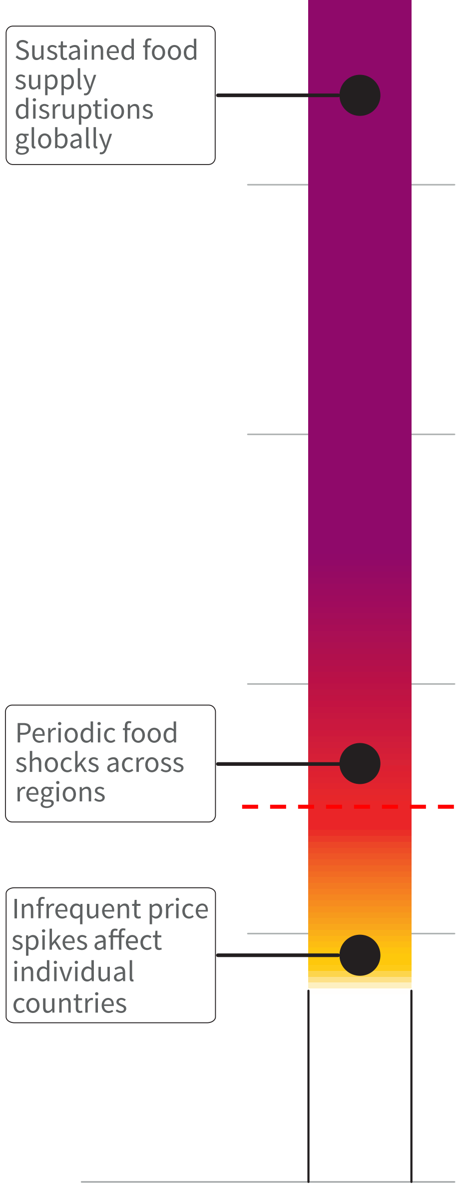




Rising temperature and risk



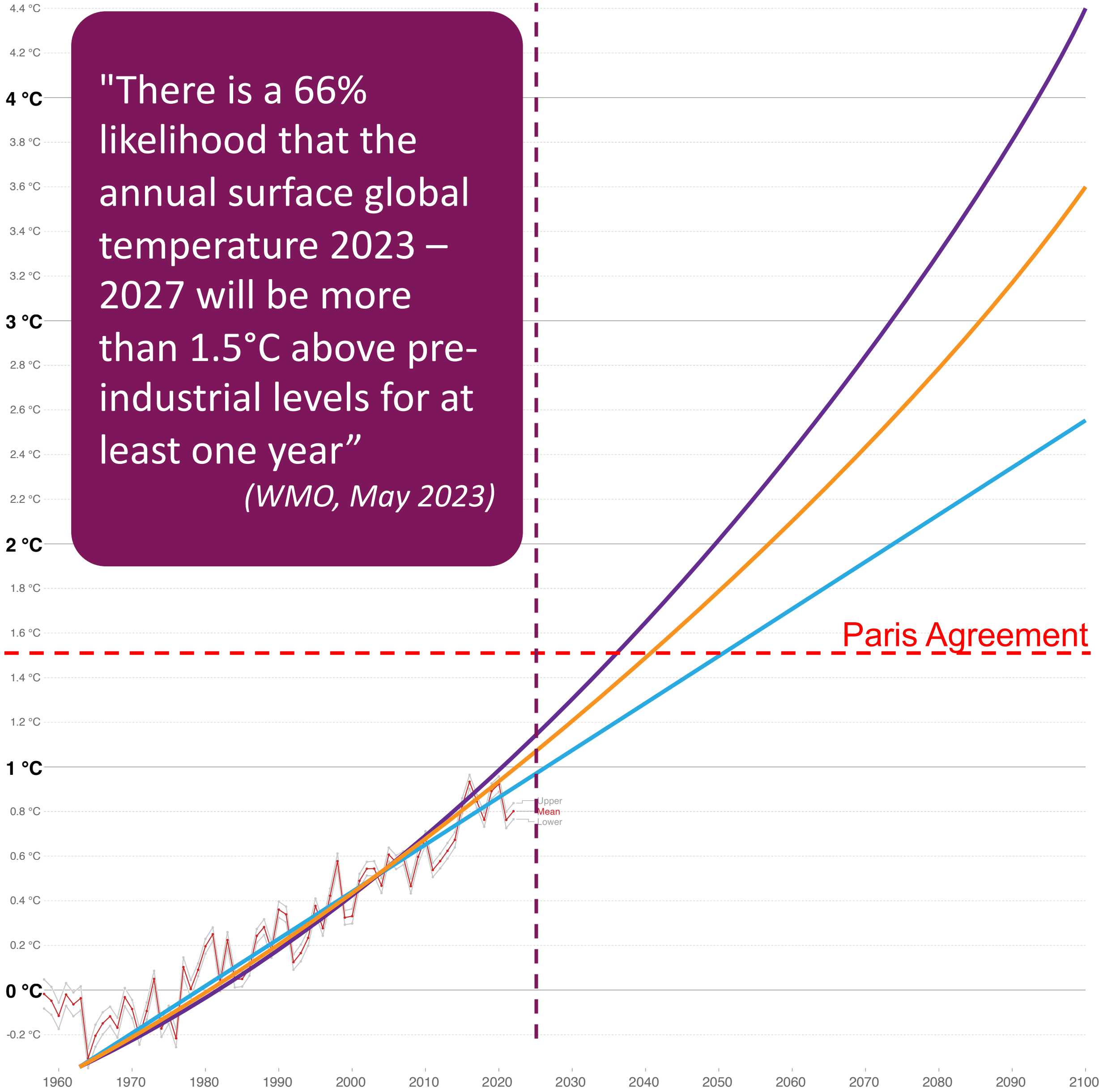
Source IPCC SRCCL (2019)



Food supply instabilities

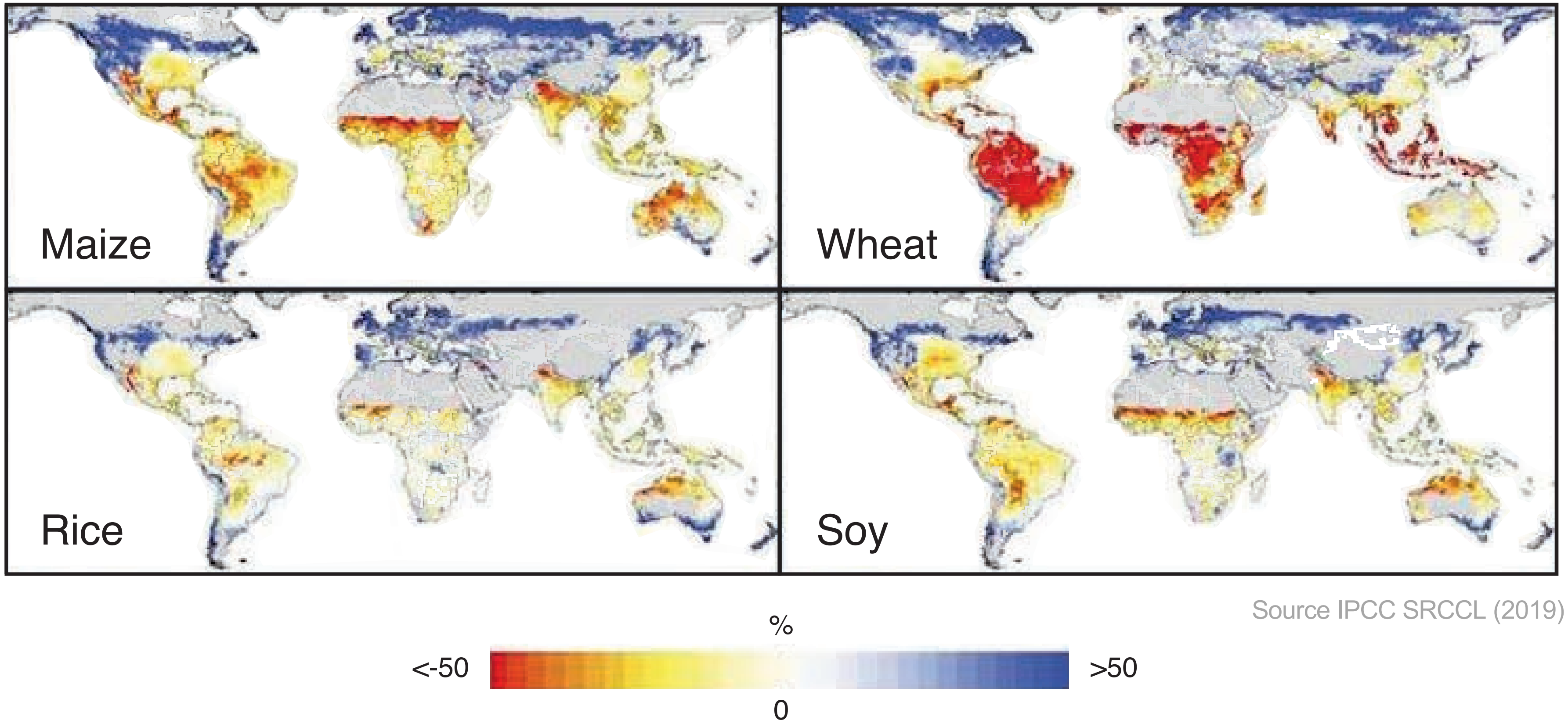
IPCC AR6 Projected temperature anomaly, Global

Global average land-sea temperature anomaly relative to the 1961-1990 average temperature.



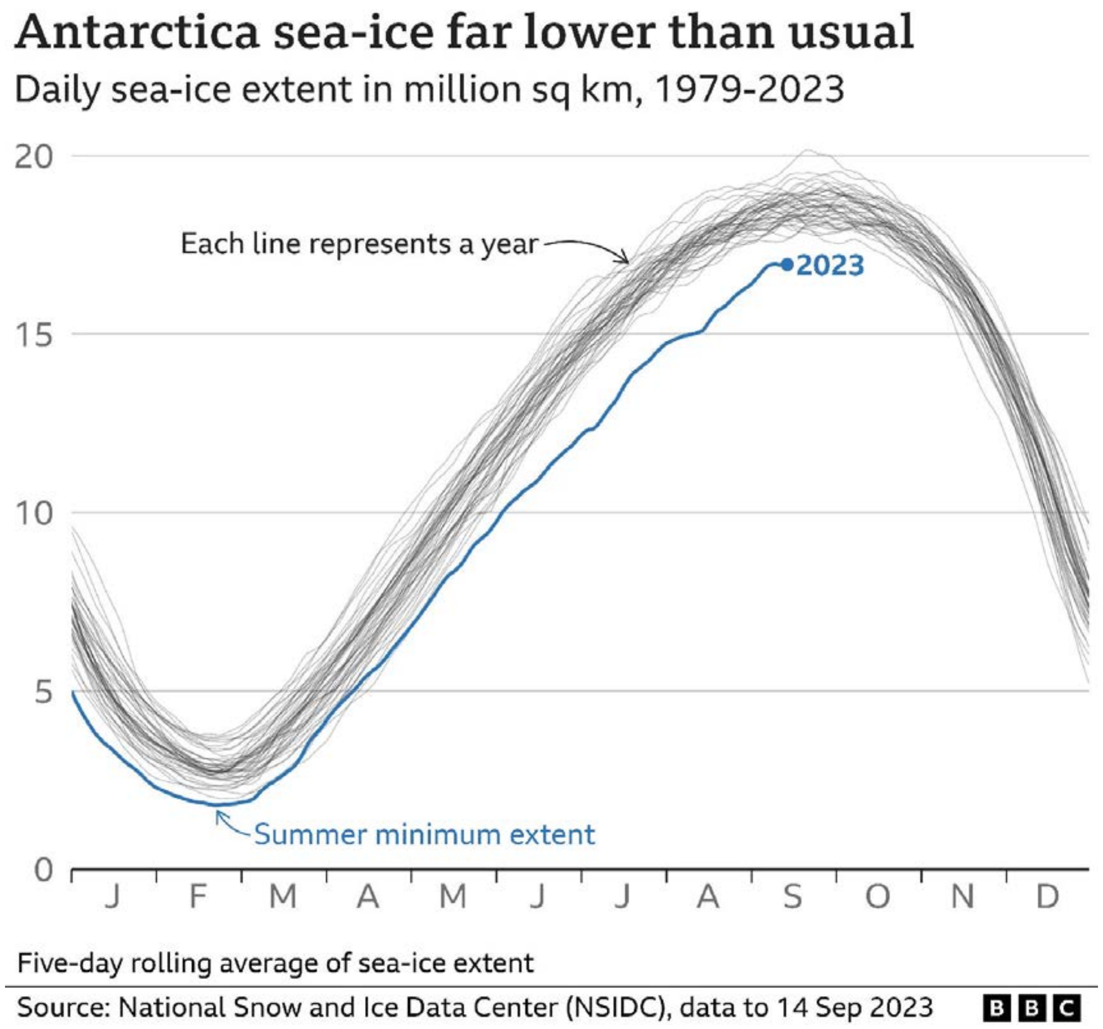
Rising temperature and risk

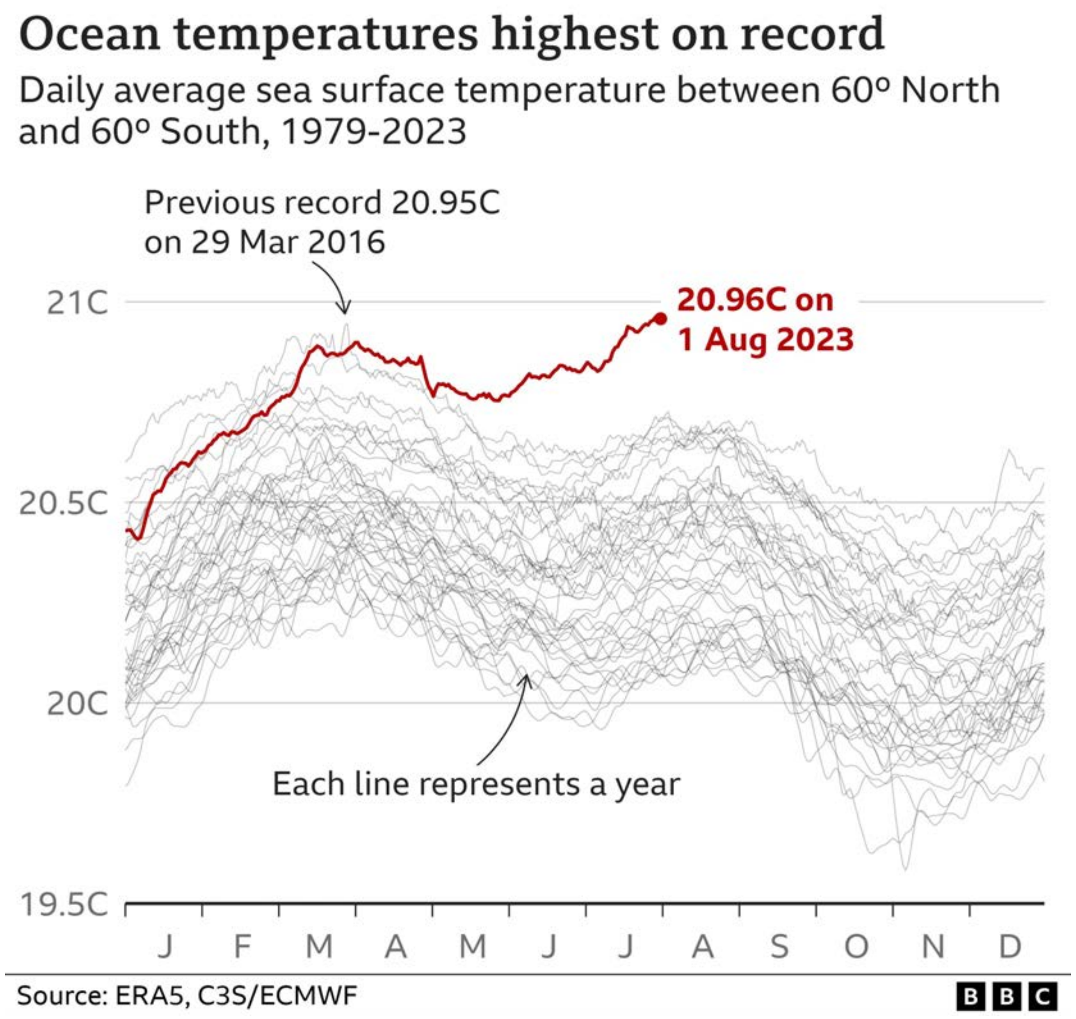
Crop yield changes 1990-2090 averaged over Global Gridded Crop Models



Source IPCC SRCCL (2019)

Rising temperature and risk: tipping points





Possible responses

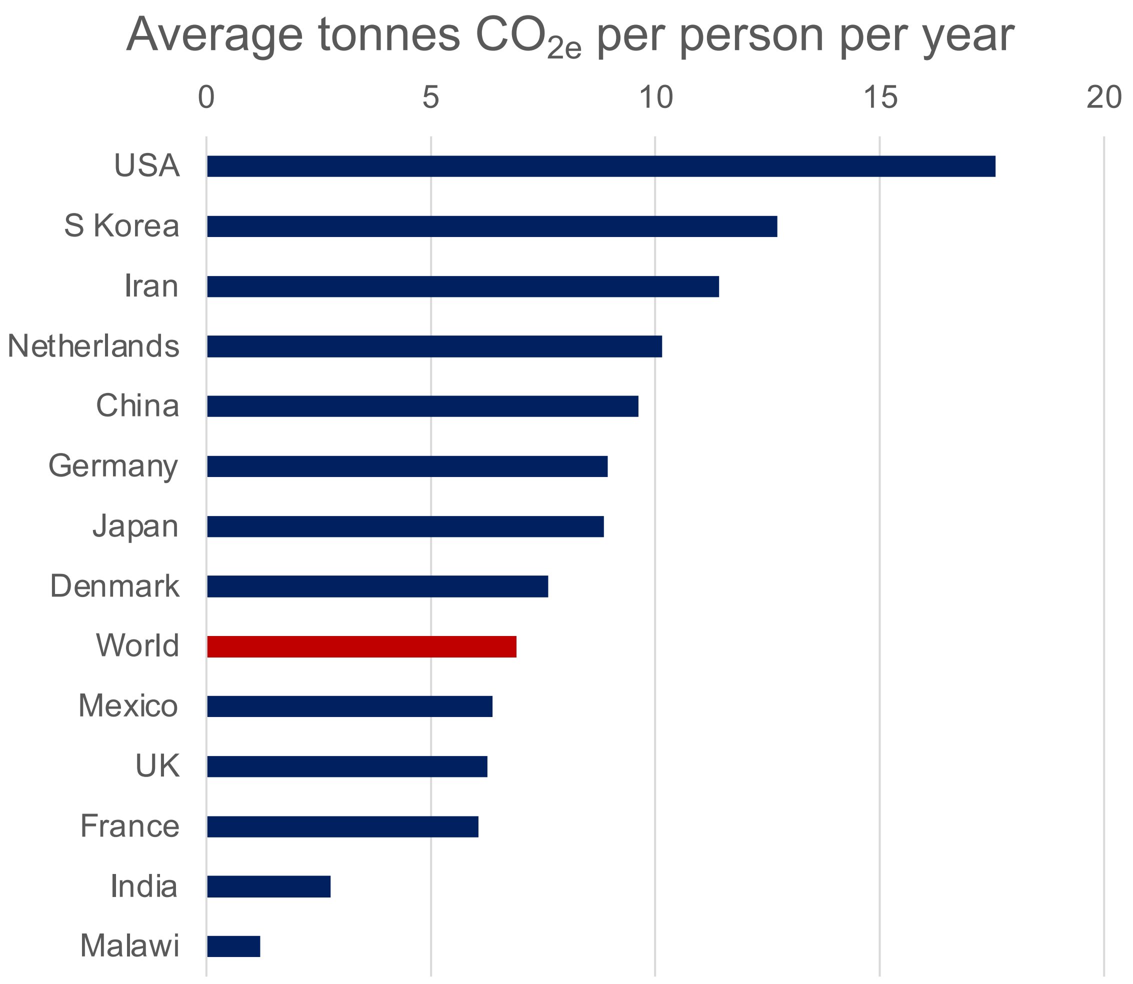
Four main options (none of which will be politically popular)

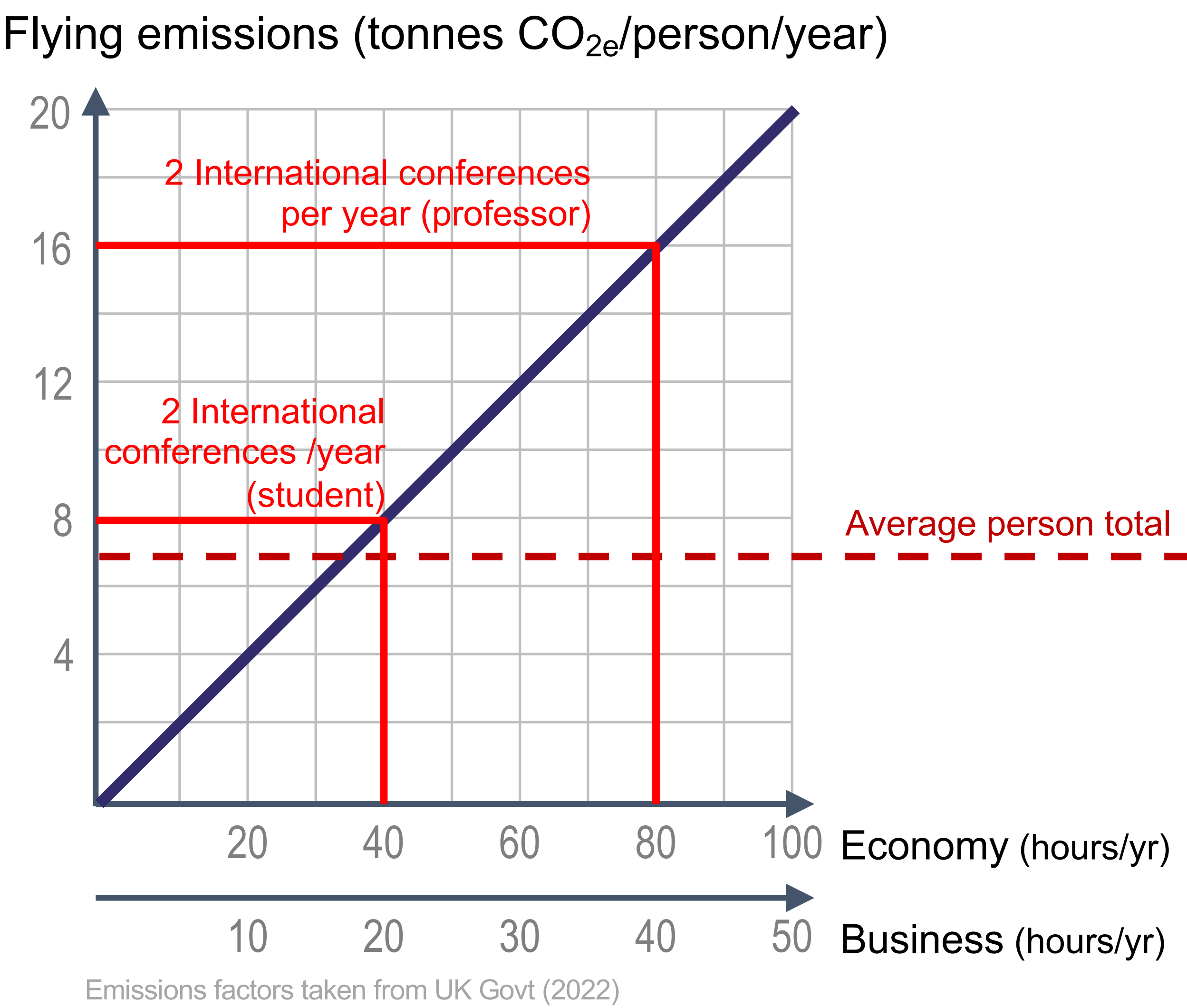
- New-technologies motivated by carbon pricing
- Regulation to ban emissions
- Voluntary restraint (by virtue or market preferences)
- Crisis response

Reality of constrains creates opportunities

- First mover advantages in business
- Research motivated by new questions

Academic responsibility

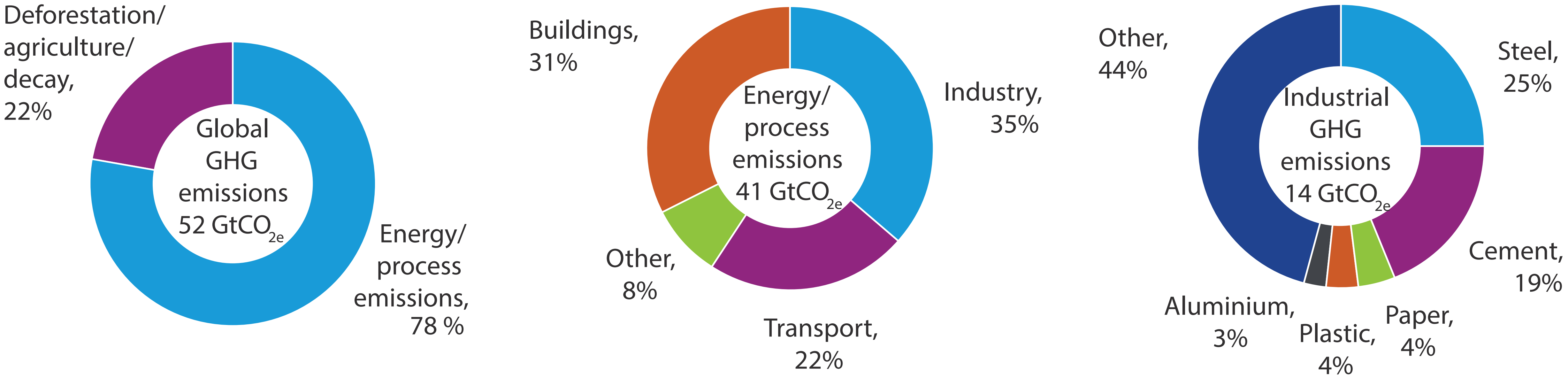




Source: https://ourworldindata.org/grapher/per-capita-ghg-emissions
(The page at this link then gives all the primary data sources)

Zero-emissions production of steel and aluminium

Materials and global emissions



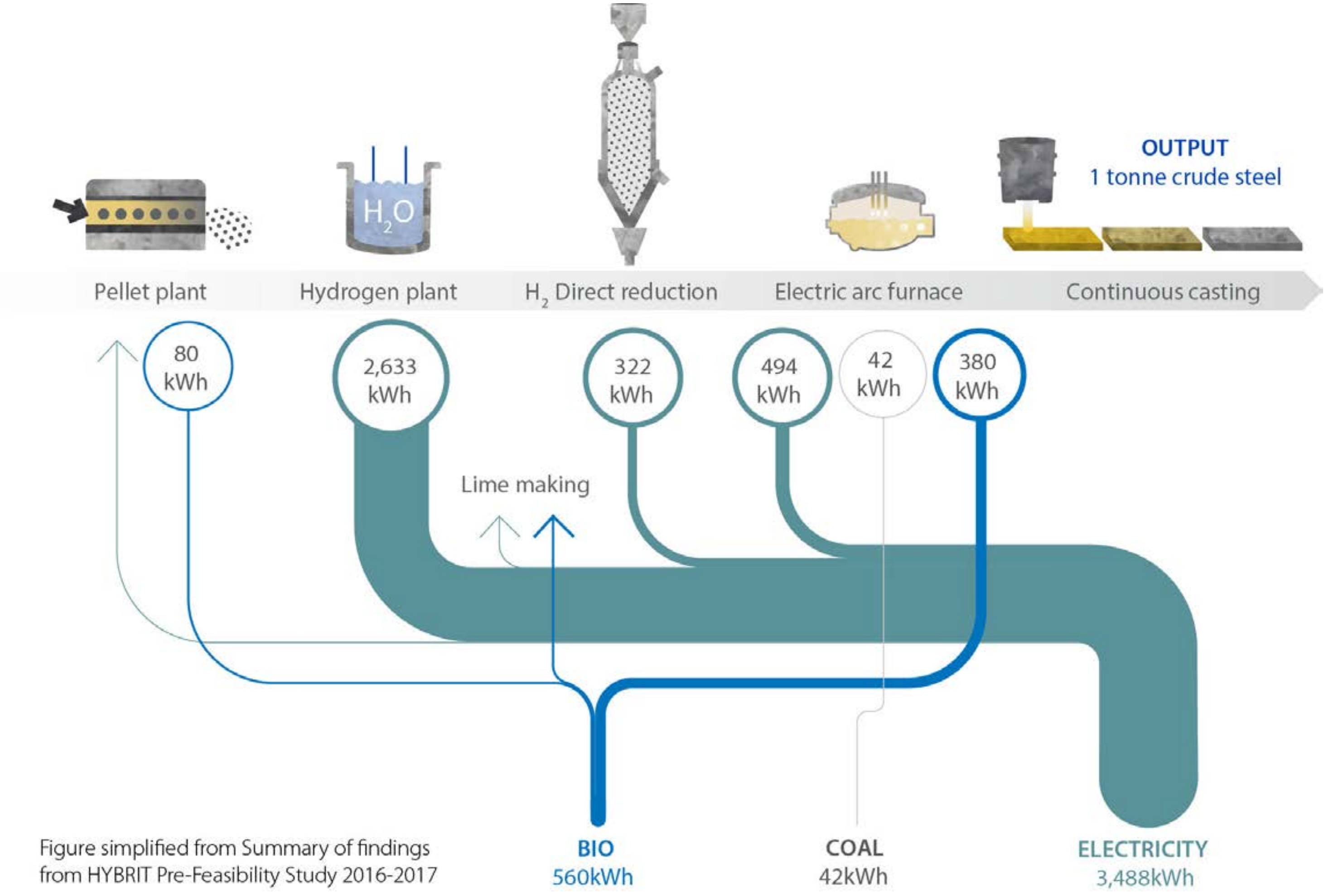
Source Allwood & Cullen (2012)

Options for making zero emissions steel from ore

- Carbon capture and storage
  - One pilot plant in Abu Dhabi (ADNOC Al Reyadah phase 1) opened in 2016 and is making ~400kt steel/year while capturing ~800kt CO_2/year
  - The captured gas is used to enhance the extraction of natural gas – more methane is extracted than CO_2 injected.
  - There is no independent verification of any of the reports from this site
  - No other steel+CCS plants are planned at present
  - Every article written about CCS is authored by a group who want it to happen
  - At best CCS captures 90% of the emissions.

Options for making zero emissions steel from ore

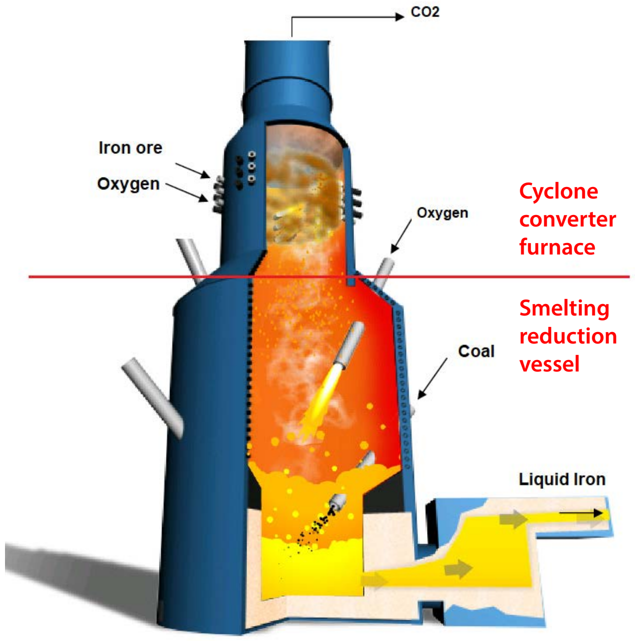
- Hydrogen
  - SSAB in Sweden has begun early trials HYBRIT process and may begin industr operation after 2040
  - “Fossil Free Electricity is the Key”: the process requires 3,500 kWh/tonne stee compared to ~500 kWh/tonne for makir steel from scrap with an electric arc furnace: **seven times** more

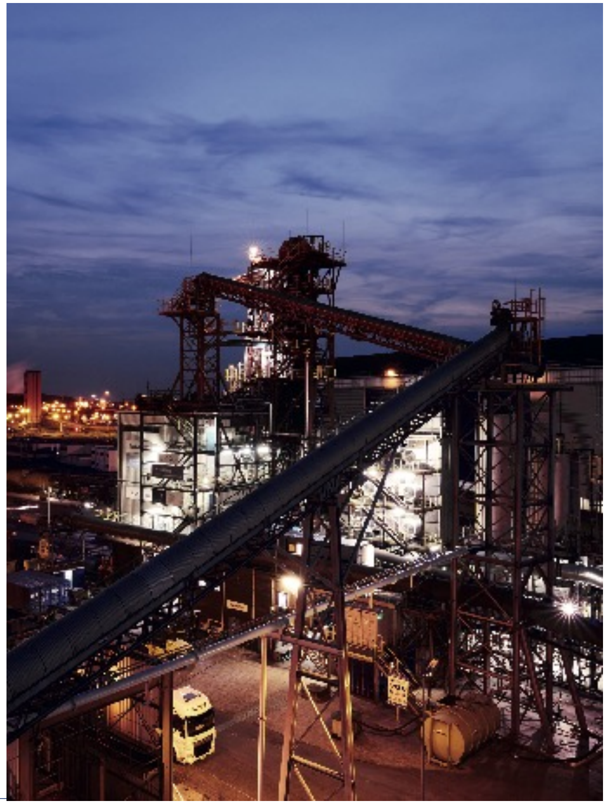


Source HYBRIT (2017)

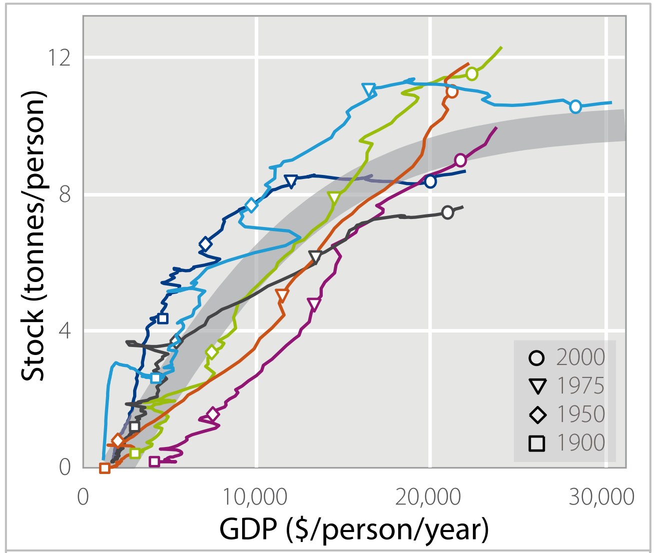
Options for making zero emissions steel from ore

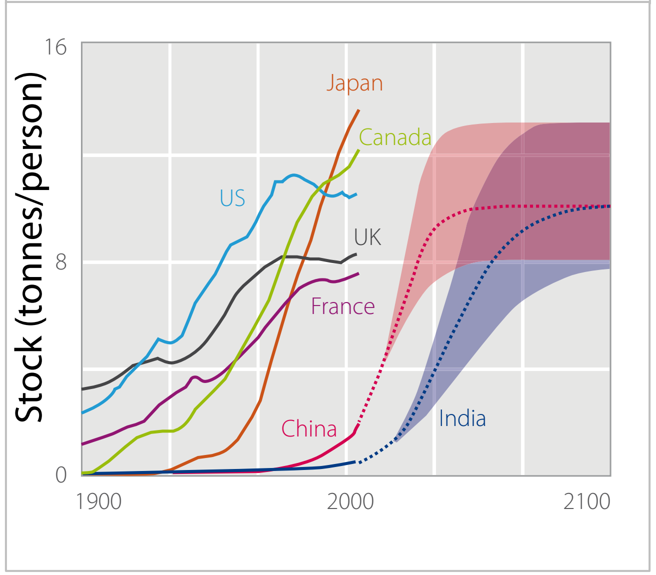
- Others
  - ULCOS in Europe explored a range of options to make steel with *less* CO_2 – i.e. not zero
  - HISARNA at Tata Steel Ijmuiden has been in development since 1986, has a theoretical capacity of 65,000 tonnes of steel per year, but has only been tried for a few weeks. It reduces emissions by ~20% and could potentially by connected to a CCS operation
  - Tata is considering an industrial scale plant in India - by 2030 at best

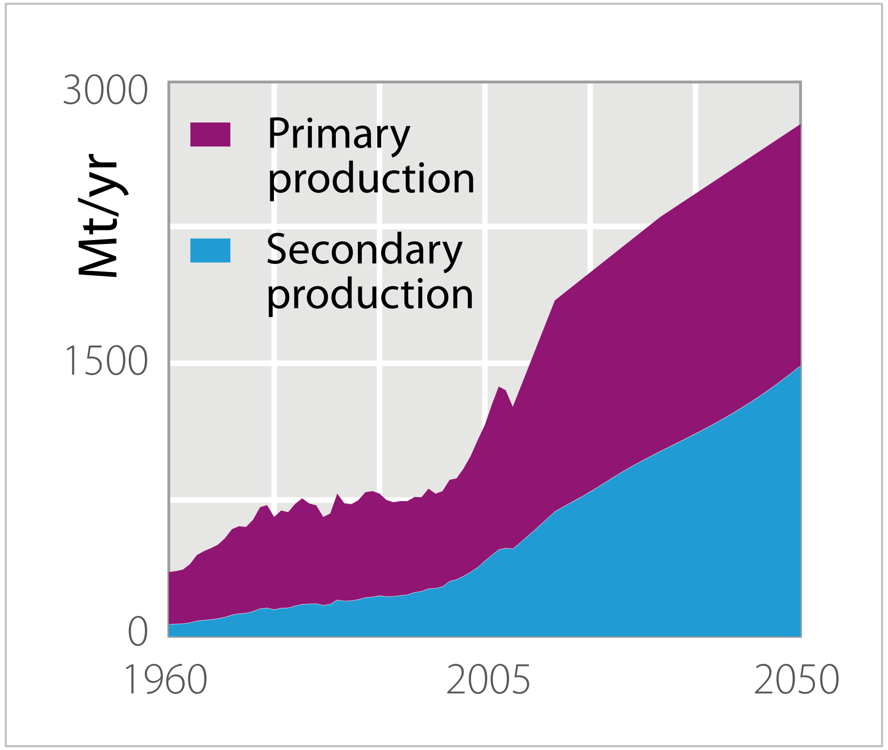




Recycling will grow with scrap-supply





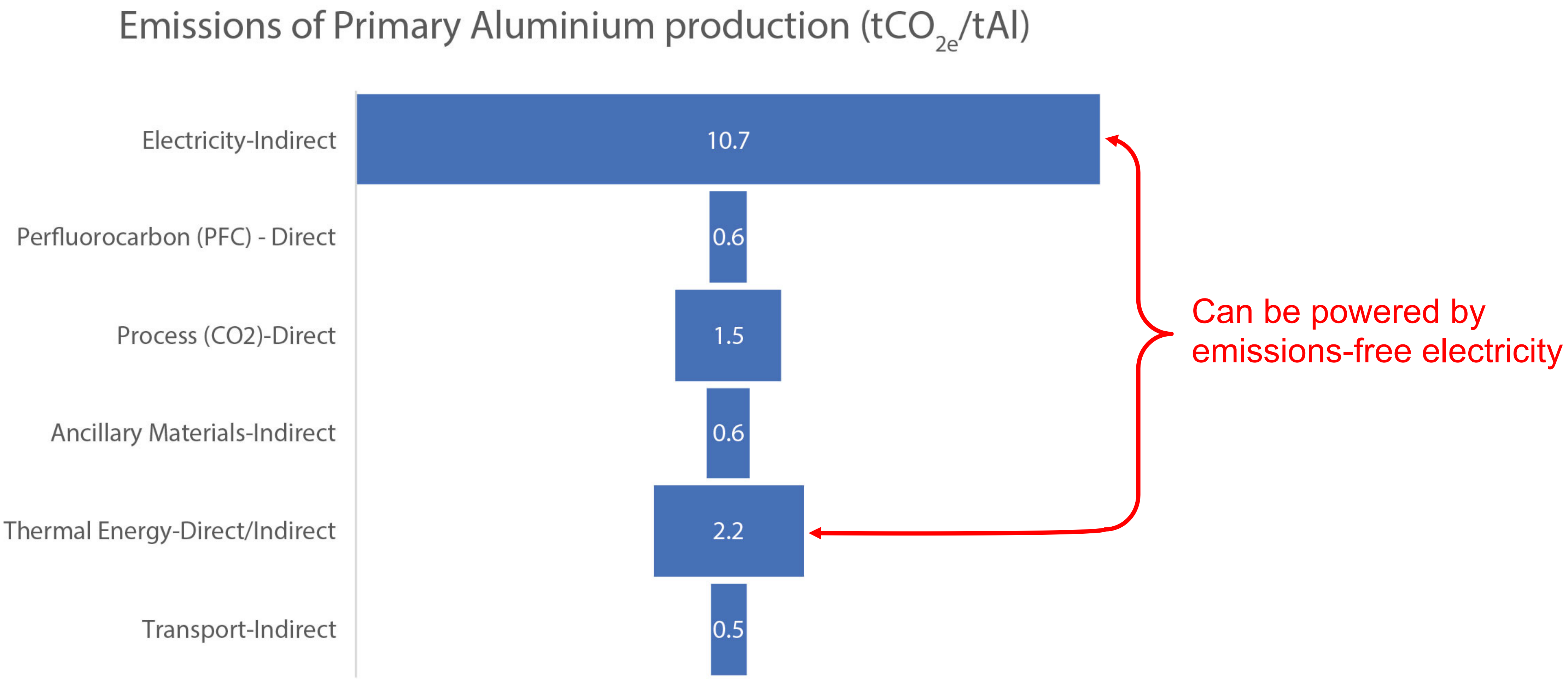


Source Allwood & Cullen (2012)

Steel-making options

Technology	Blast furnace	Gas + DRI	Electric Arc Furnace	Blast Furnace + CCS	Hydrogen reduction
Global capacity Mtonnes/yr	1,300	100	**700 and will double**	0.4	0
Emissions (tonnes CO_{2e}/tonne steel)	2.9	~0.9-2.0	**0.3**	0.3	2.1
Electricity (kWh/tonne)		500	**500**		3500
Zero emissions?	CCS only	CCS only	**Yes**	90% reduction, one small demonstrator	Yes – but huge electricity demand

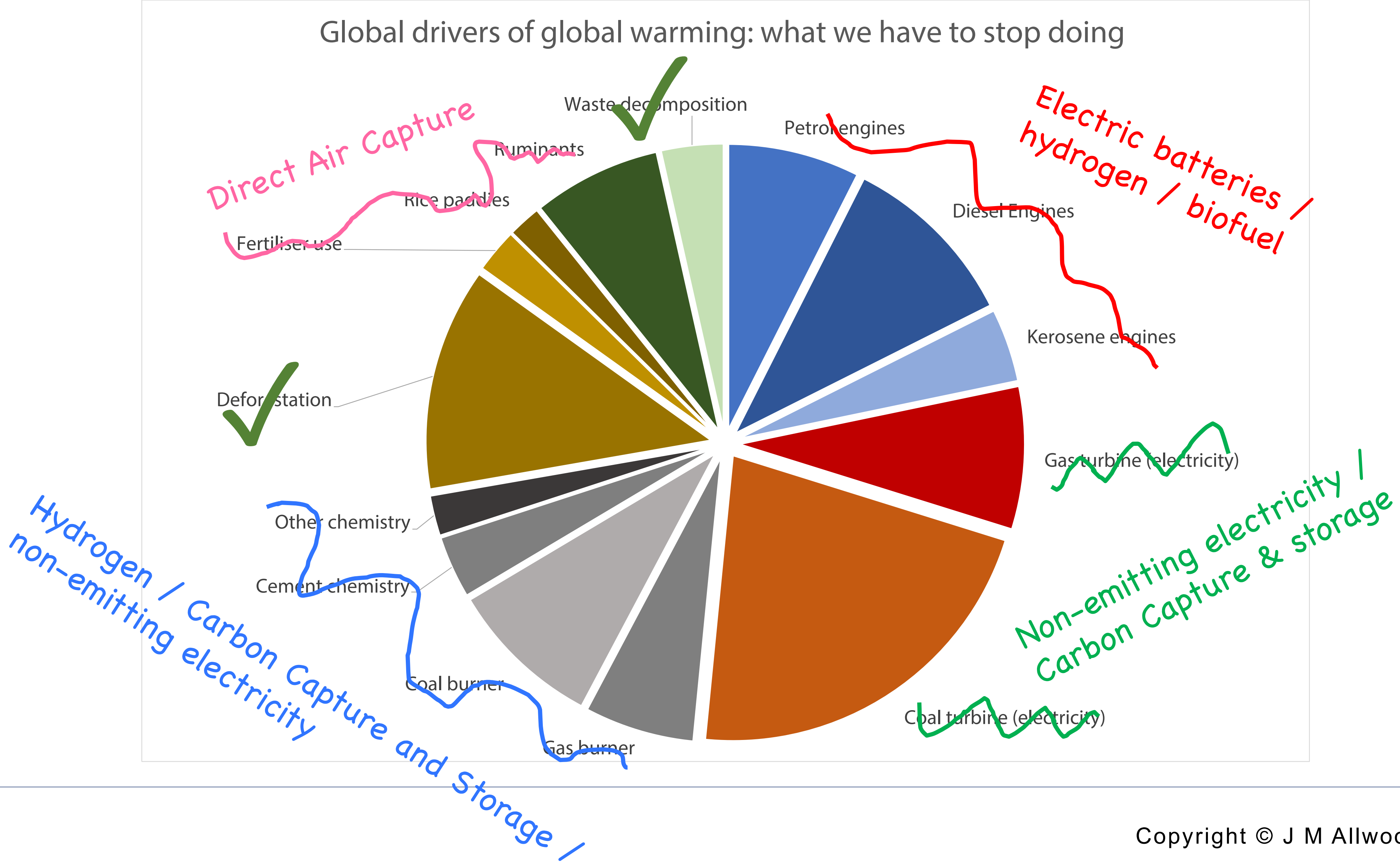
Primary aluminium production



2018 Global Data from International Aluminium Institute (IAI, 2018)

Aggregation & deployment rates

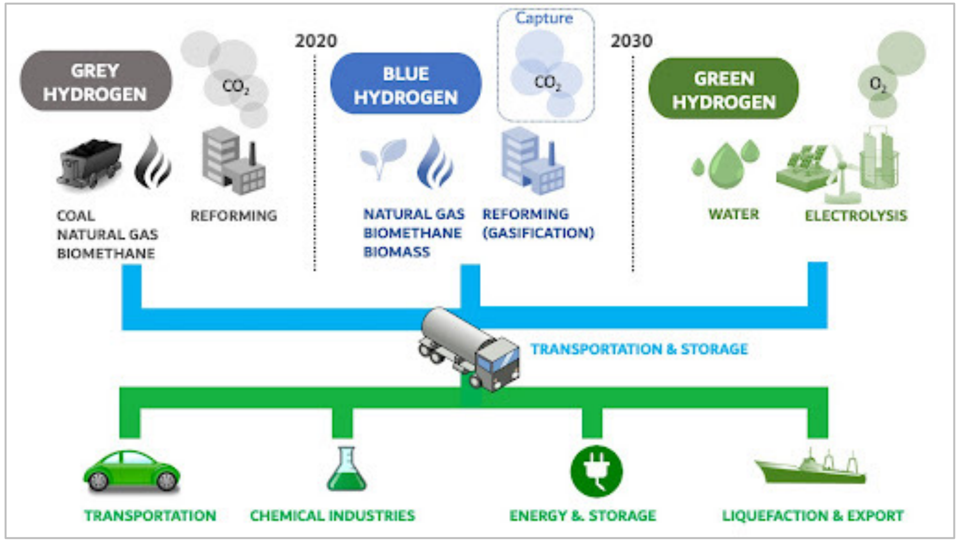
Incumbent thinking on how to reach zero emissions

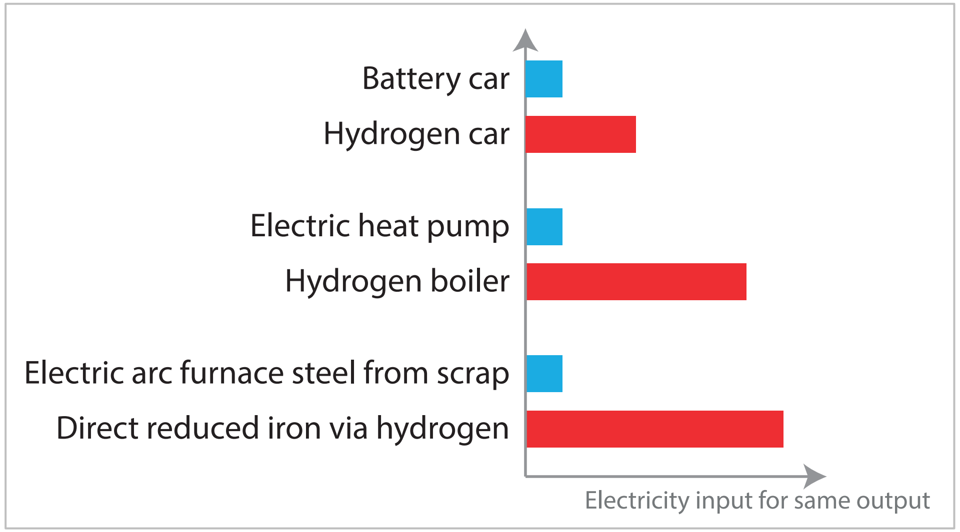


Burden-shifting with hydrogen

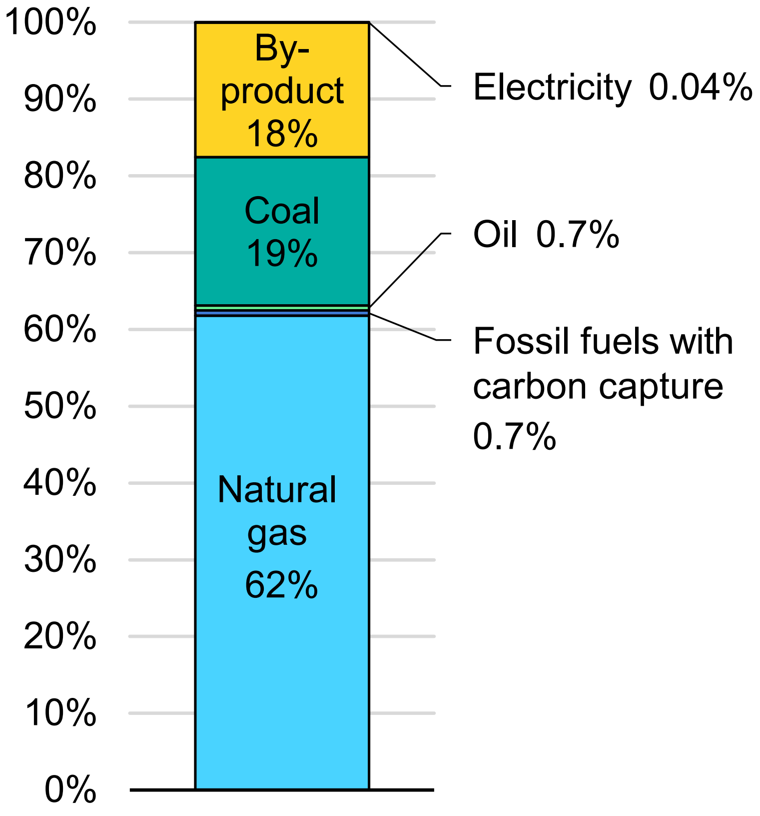
Hydrogen could be used for:

- Powering aeroplanes
- Powering cars
- Home heating
- Making steel
- Energy storage
- Producing ammonia
- Producing methanol
- …





Hydrogen production 2021

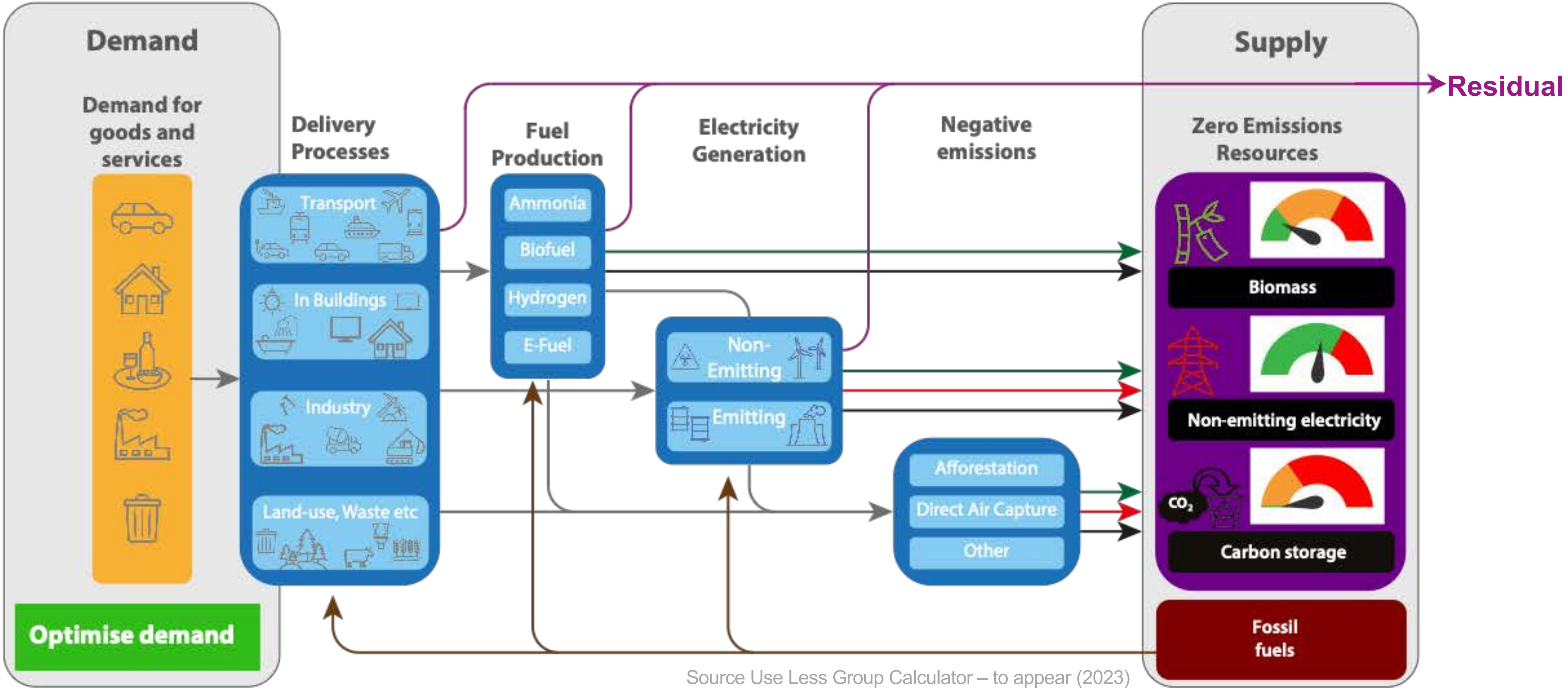


Source: International Energy Agency (2022)

Other forms of burden-shifting

- Trade
- Carbon offsets
- “Negative emissions technologies”
- Bio-fuels
- Synthetic fuels
- …

Aggregating demand for three "zero-emissions resources"



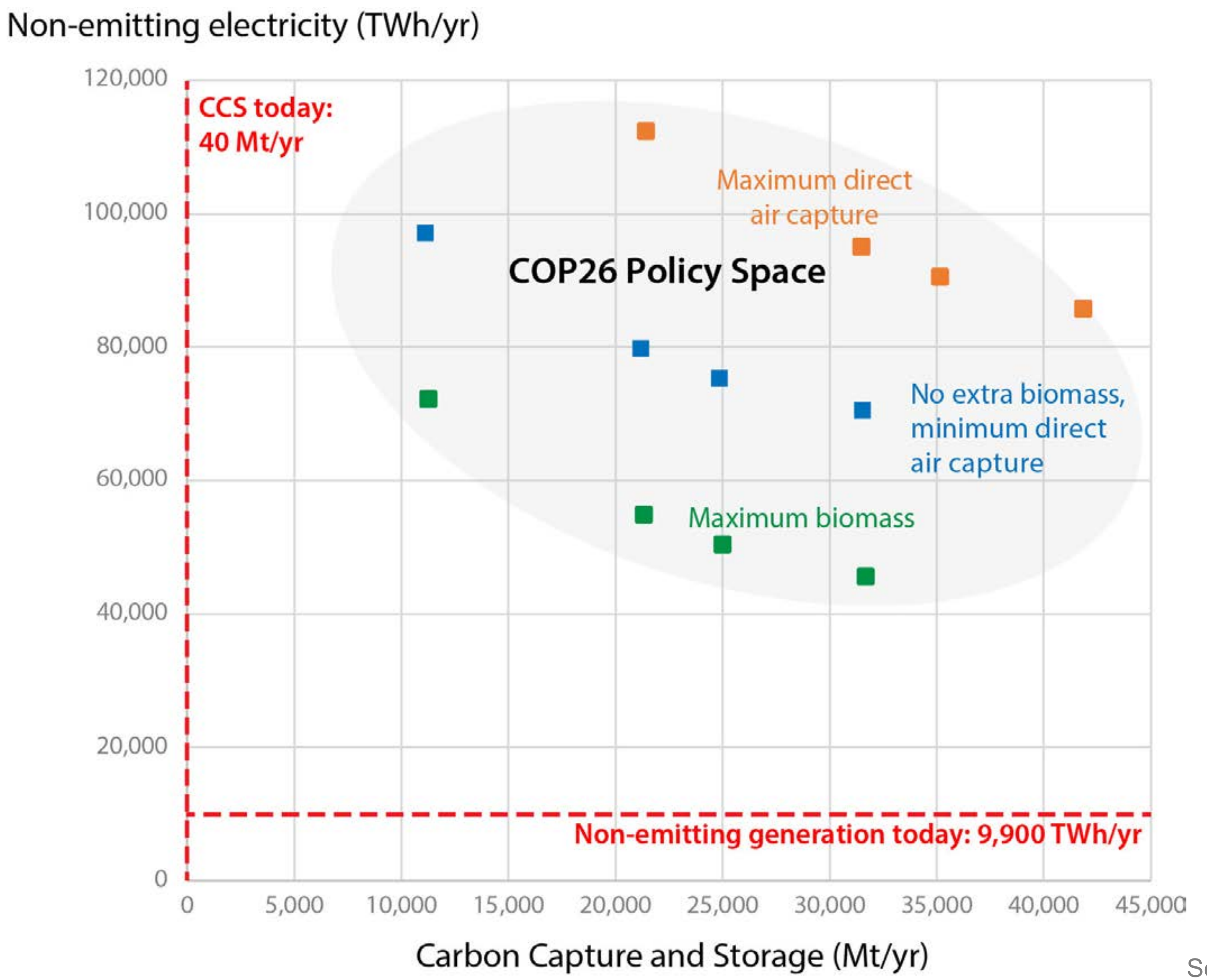
Source Use Less Group Calculator – to appear (2023)

Aggregation analysis

Sector	2020 GHGs (MtCO2/yr)	Physical units	Option 1	Option 2
Road vehicles	6,100	2,700 G litres petrol/diesel	140-320 litres biofuel per tonne biomass	6 litres petrol equivalent to 20kWh electric power
Train	200	40 G litres diesel	As above	As above
Shipping	900	370 G litres diesel	As above	19kWh per litre synthetic fuel
Aviation	2,900	470 G litres kerosene	As above	As above
Electricity (emitting)	10,000	17,000 TWh	10,000 Mt CCS	17,000 TWh non-emitting generation
Electricity (non-emitting)		9,900 TWh		
Space heating	6,700	8,800 TWh gas boiler output	6,700 Mt CCS	1kWh heat pump = 3.1kWh gas boiler
Blast furnace Steel	3,700	1,400 Mt Steel	3,700 Mt CCS	3.5MWh/tonne steel via green hydrogen
Cement	3,100	4,100 Mt Cement	3,100 Mt CCS	
Other industry	6,700		6,700 Mt CCS	Same total electricity as steel
Deforestation	1,100	Assumed to stop		
Fertiliser/rice/soil/crop	5,300	Un-changed	Direct Air Capture	
Ruminants	3,000	Un-changed	Direct Air Capture	
Waste	1,600	Assumed to stop		
Direct Air Capture		Applicable to all emissions	4MWh/t capture and store plus 1 t CCS per t DAC	

Data from multiple sources: https://ukfires.org/blog-cop26/

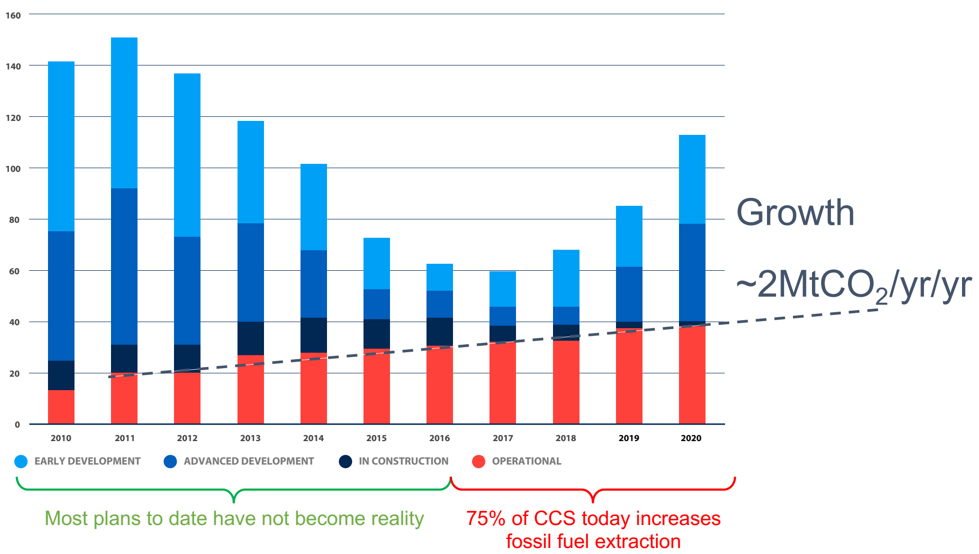
Aggregation of plans discussed at COP26

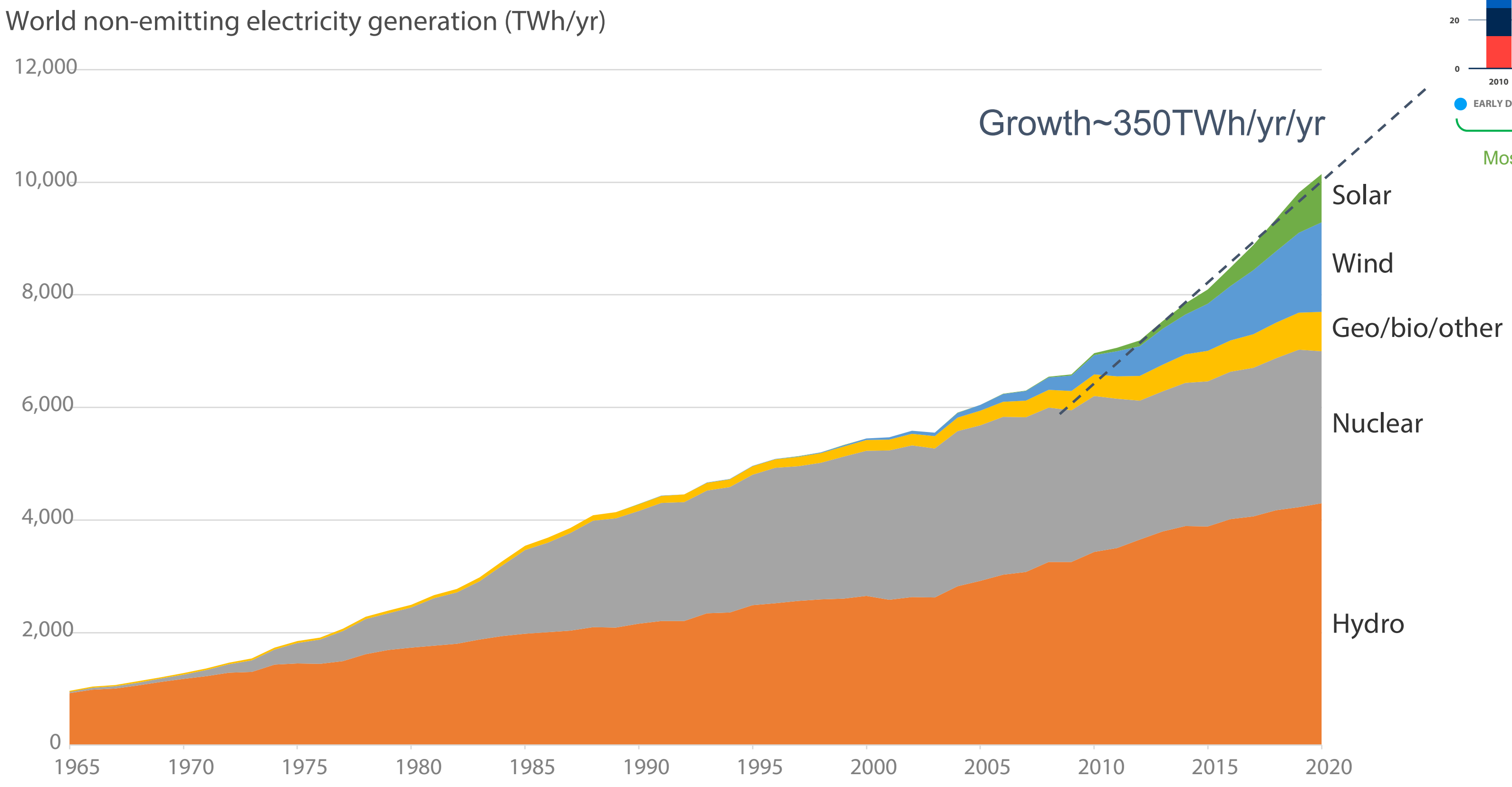


Source: https://ukfires.org/blog-cop26/

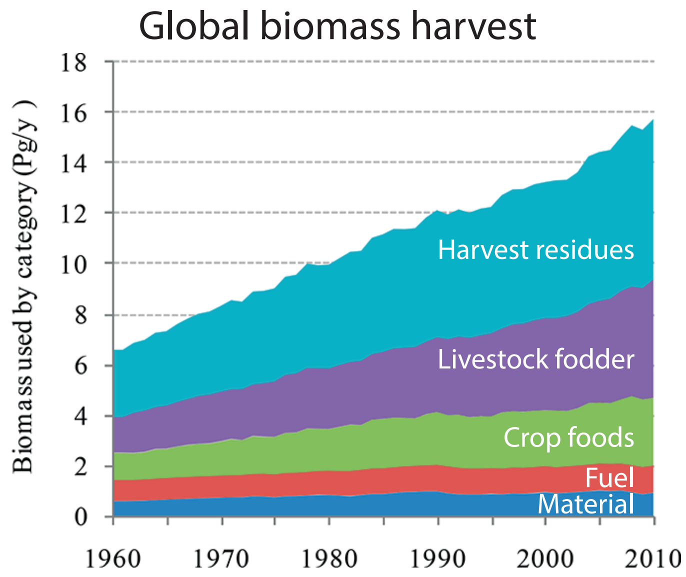
Deployment rates

Source Global CCS Institute (2021)



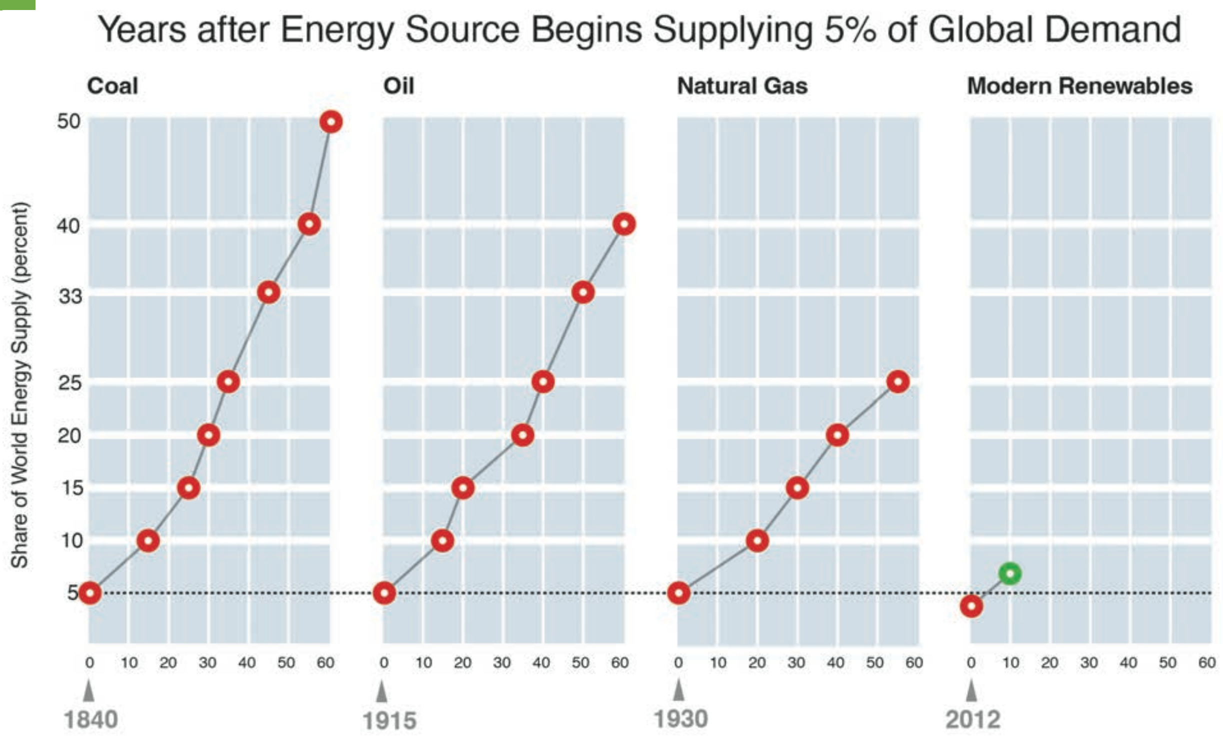


Source BP Statistical Review of World Energy (BP, 2021)

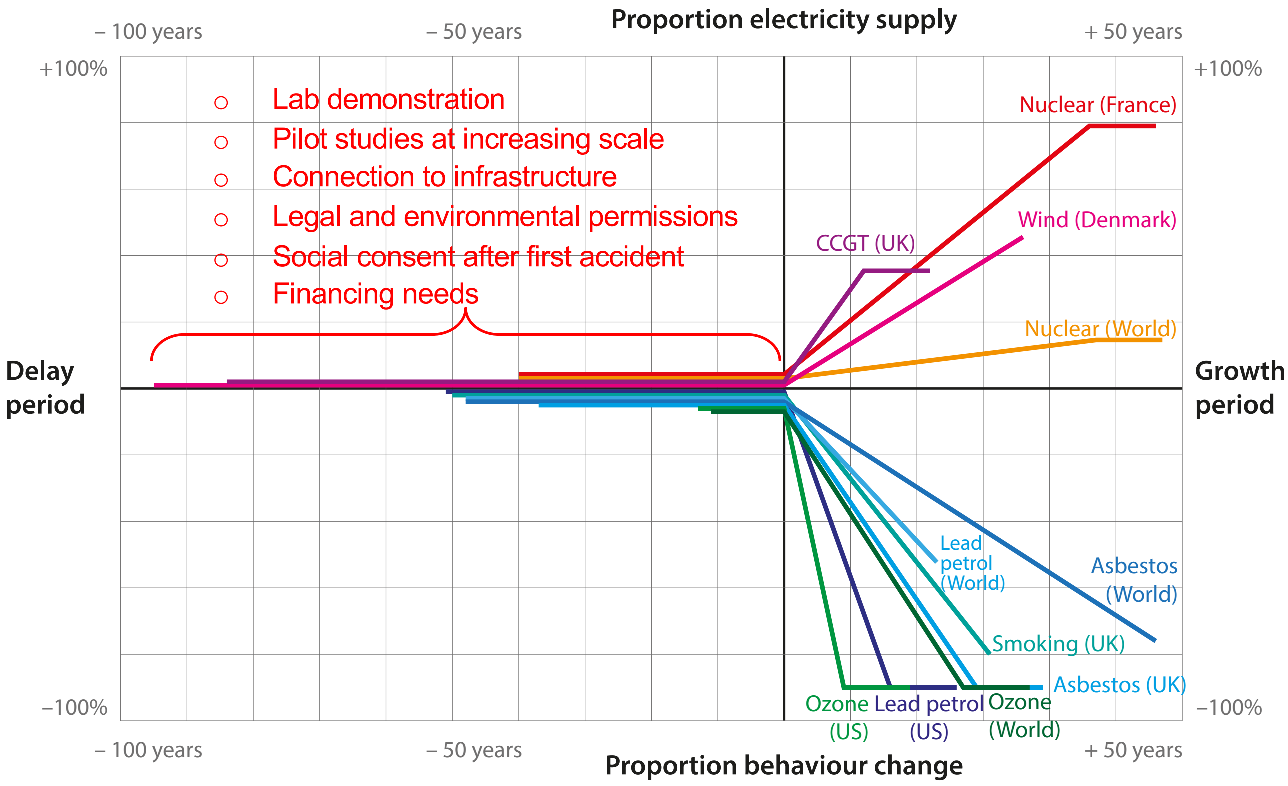


Source Zhou et al. (2018)

Deployment rates



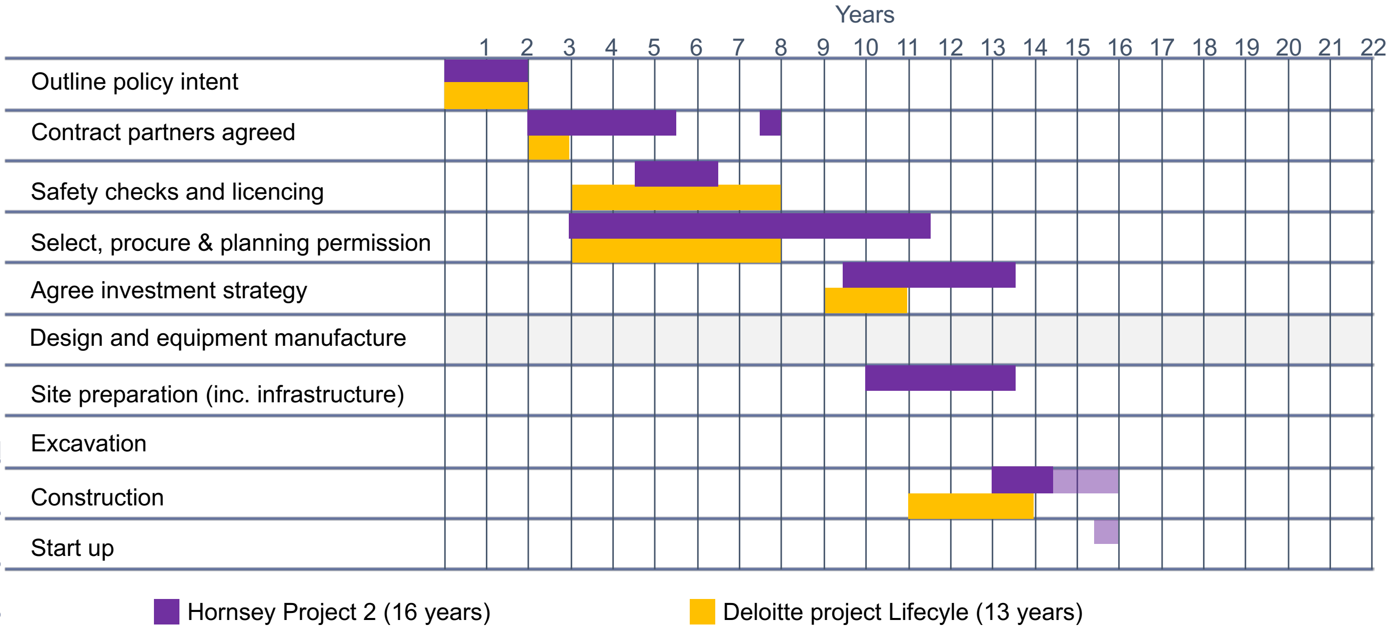
Sources: Smil (2014), update BP World energy statistics (2022)



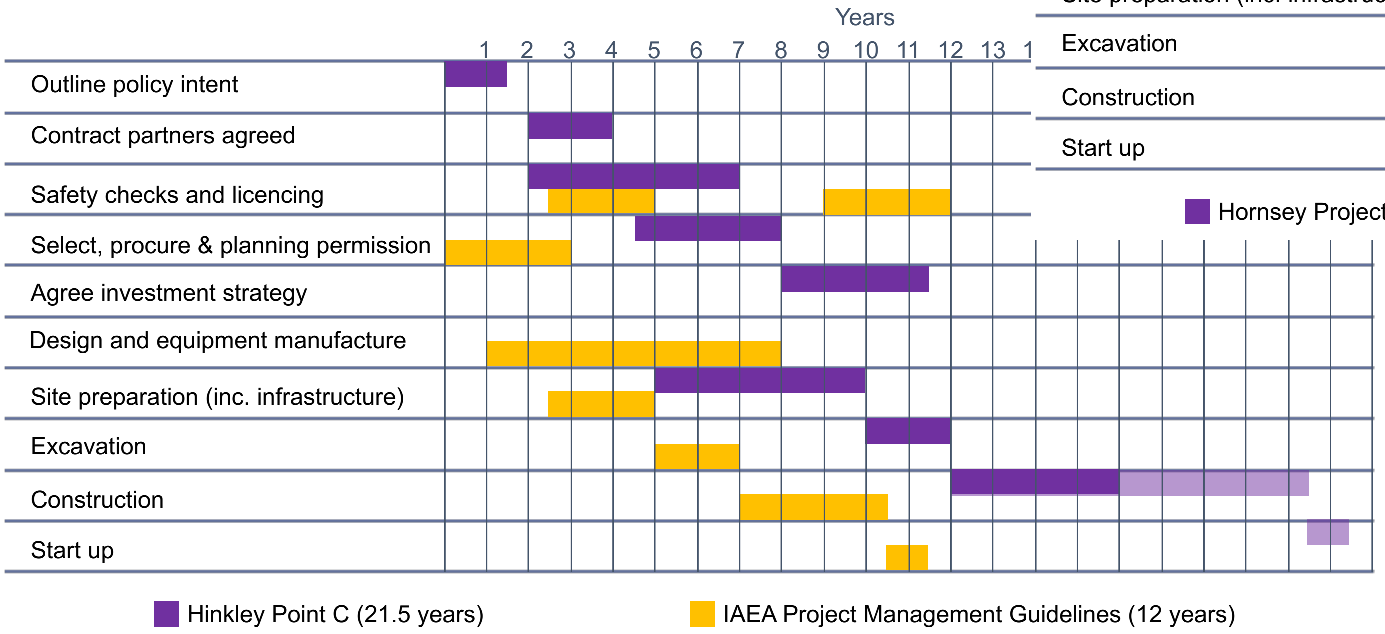
Source: Nelson & Allwood (2021)

Project examples

Offshore Wind Power Timeline

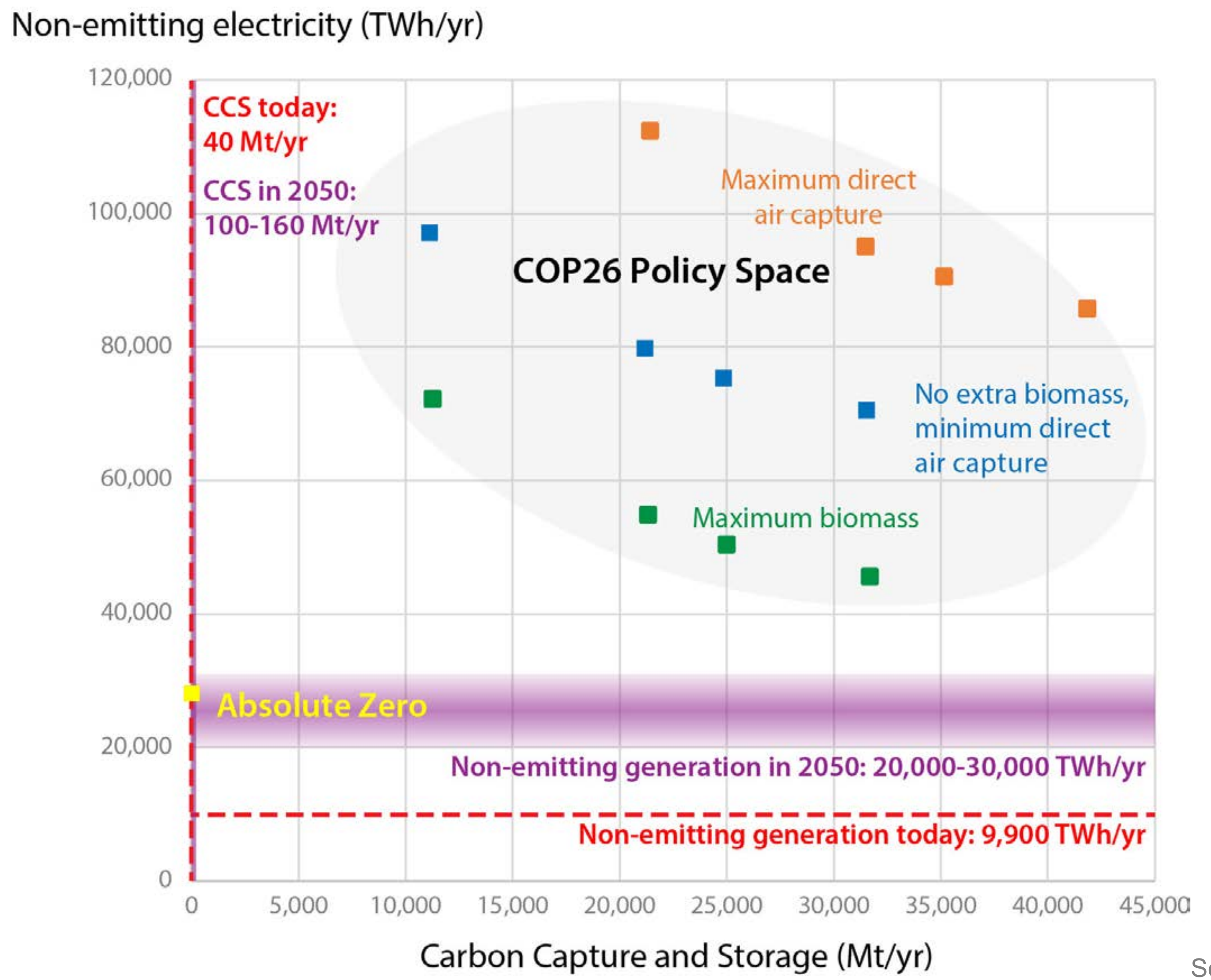


Nuclear Power Timeline



Source: Use Less Group analysis

Preliminary result: policy will be constrained by resources

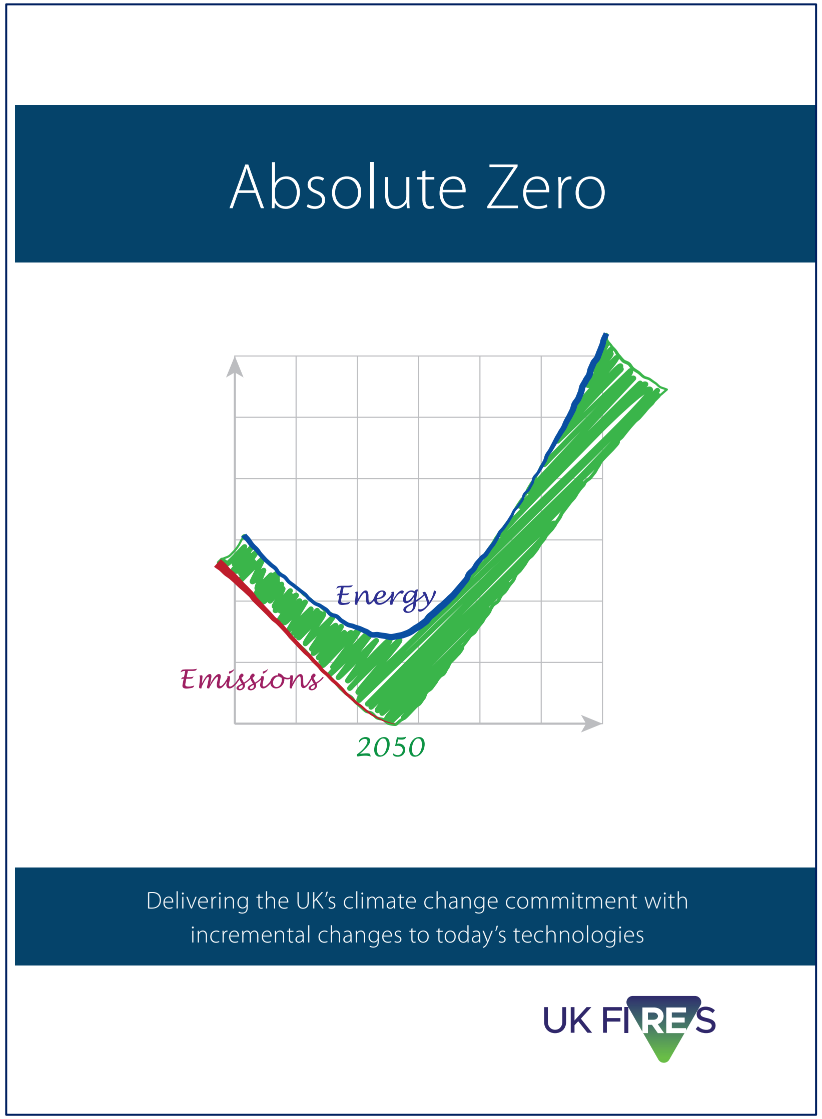


Source: https://ukfires.org/blog-cop26/

Resource-constrained climate policy

The big picture in the UK:

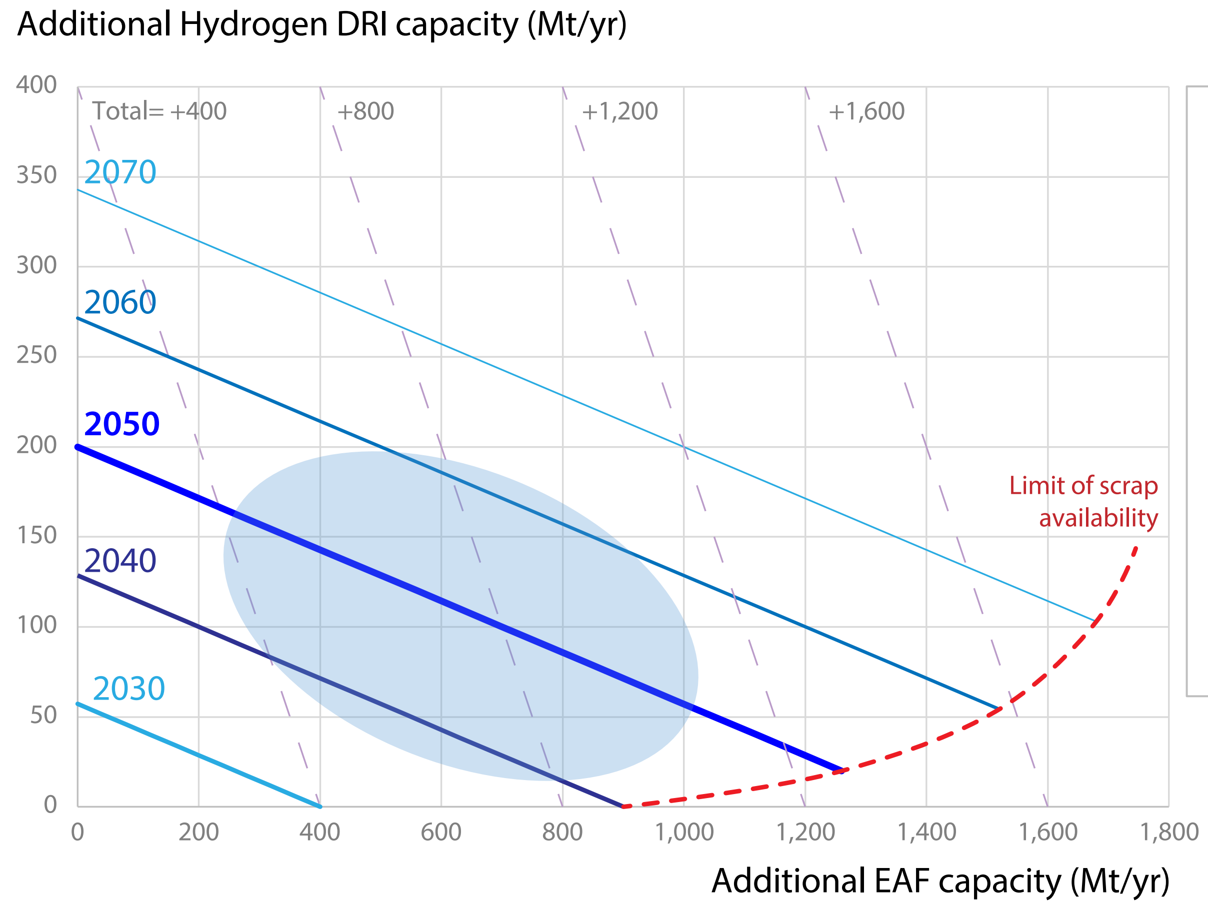
- By 2050 we will have ~ 2.5x as much emissions-free electricity as today
- We will have no significant carbon storage, surplus biomass, hydrogen or negative emissions technologies
- We have to electrify everything possible, close anything else, and use ~60% as much electricity as we'd otherwise like
- For householders only 4 actions matter - stop using:
  - fossil boilers,
  - fossil cars,
  - fossil planes,
  - ruminants.

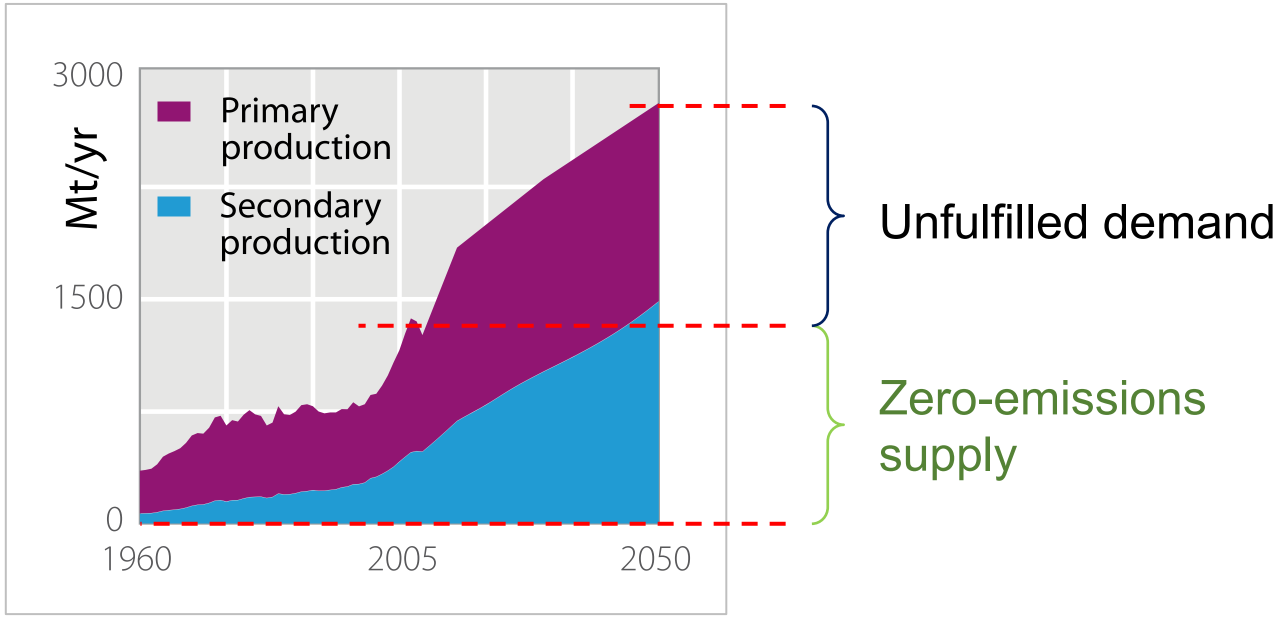


https://ukfires.org/absolute-zero/

Resource constrained future steel production

Steel





Assuming additional non-emitting electricity allocated across sectors in proportion to current emissions

Resource constrained future aluminium production

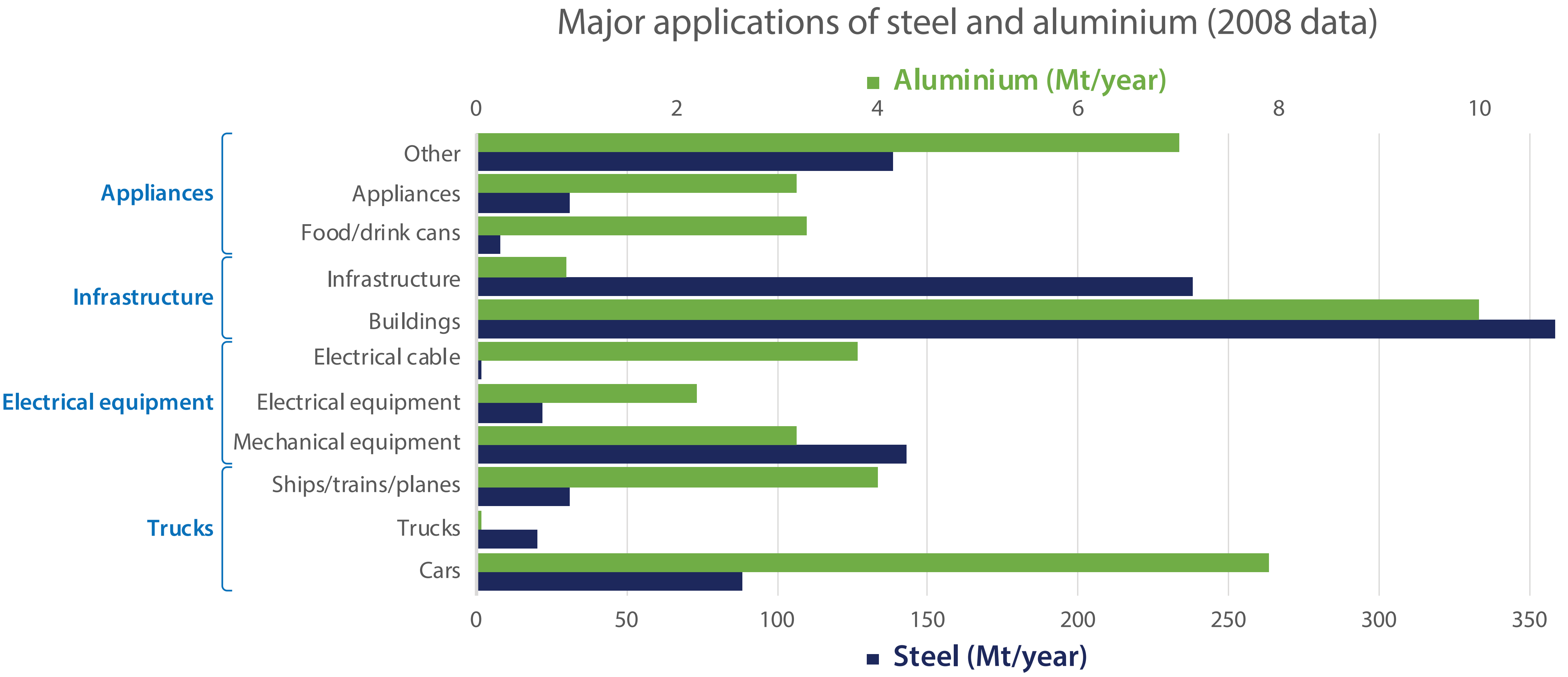
Aluminium

- Roughly one third of today's electricity supply is decarbonised
- As zero-emissions electricity expands, we can expect primary production to remain ~constant
- Recycling will grow with scrap supply

Resource efficiency and metal forming:

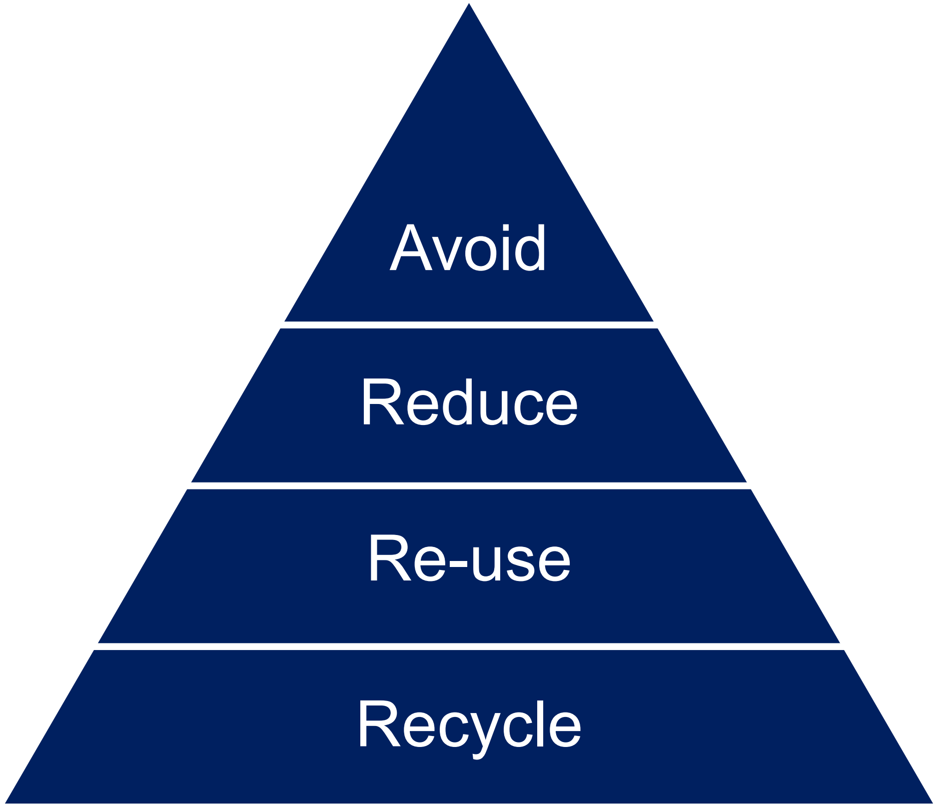
Opportunity in restraint

Priority applications

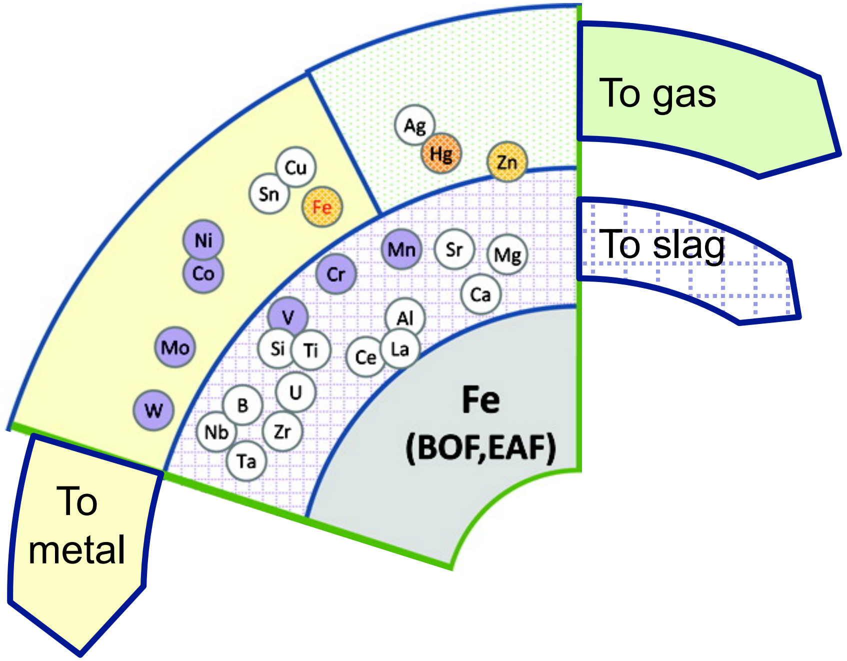


Sources: Cullen et al. (2012), Cullen et al. (2013)

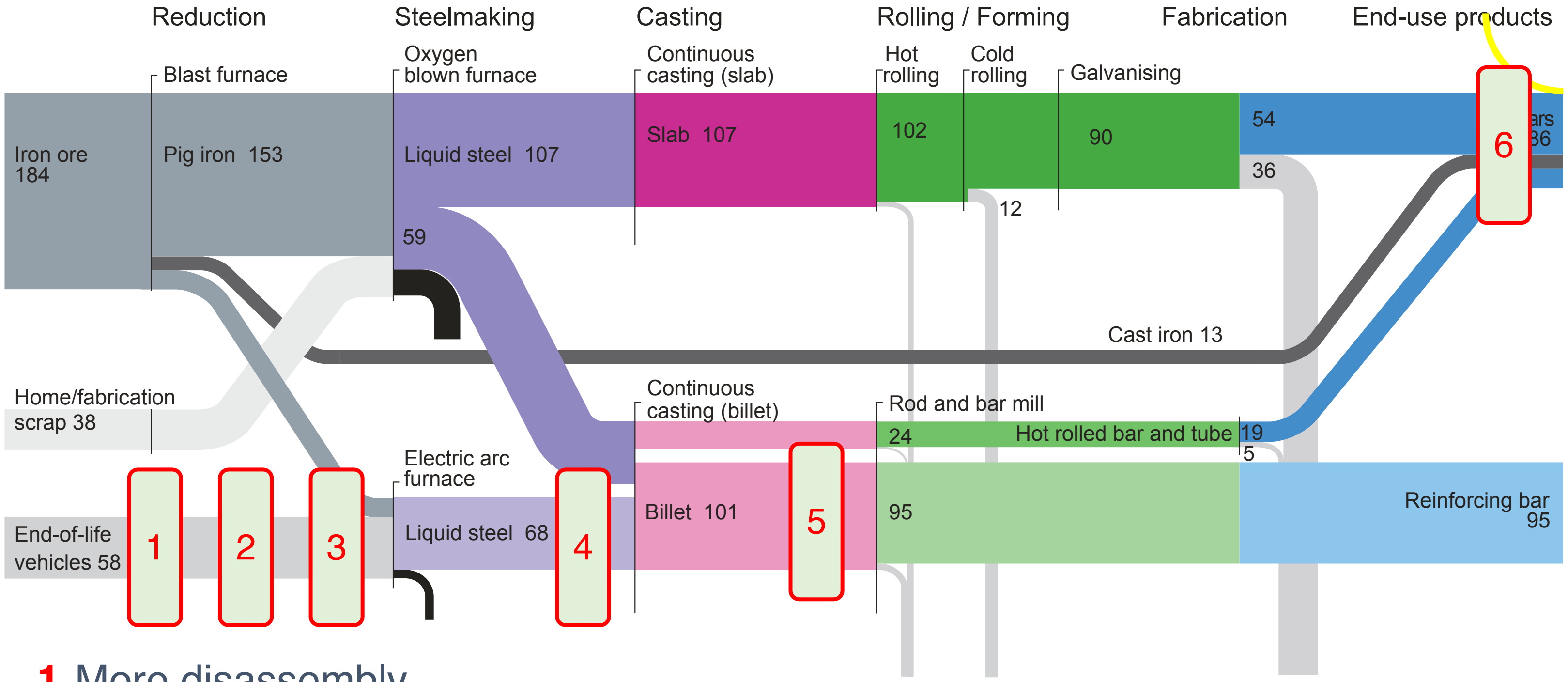
The ‘pyramid’ of resource efficiency



Recycling and quality



Source Nakajima et al. (2010)



1 More disassembly

2 Alternative shredding

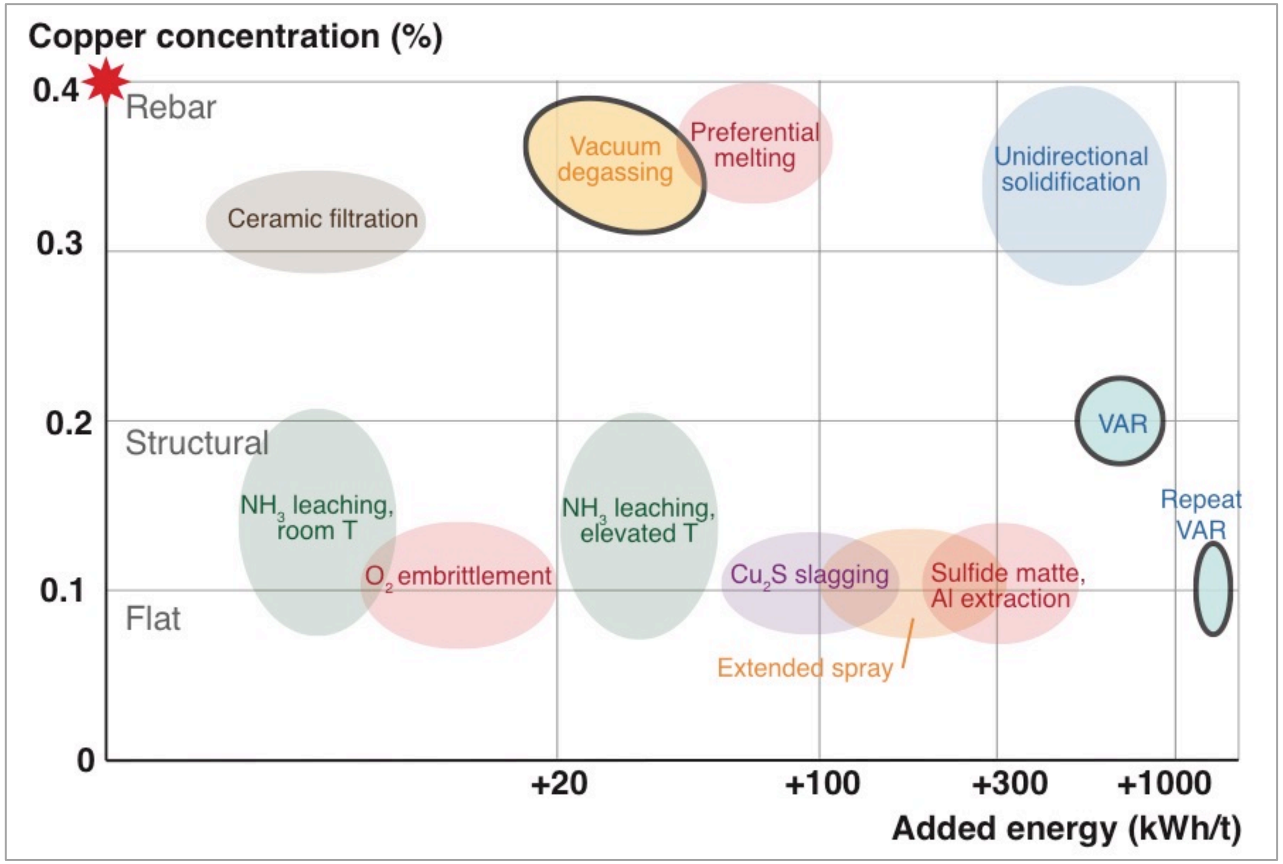
3 Better sorting

4 Melt control

5 Cu tolerant casting

6 Reduce Cu content in new cars

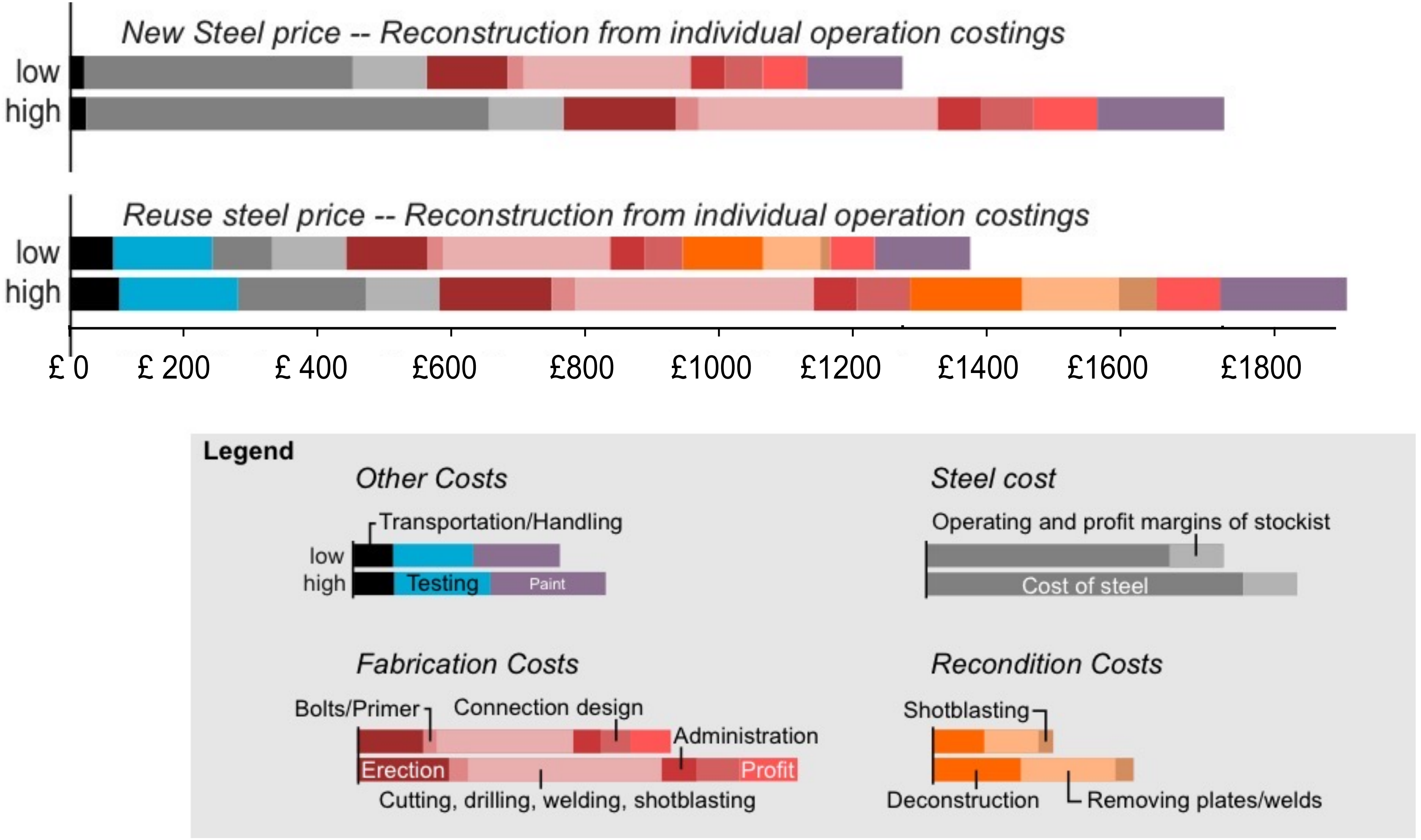
Recycling and quality



Source Daehn et al. (2019)

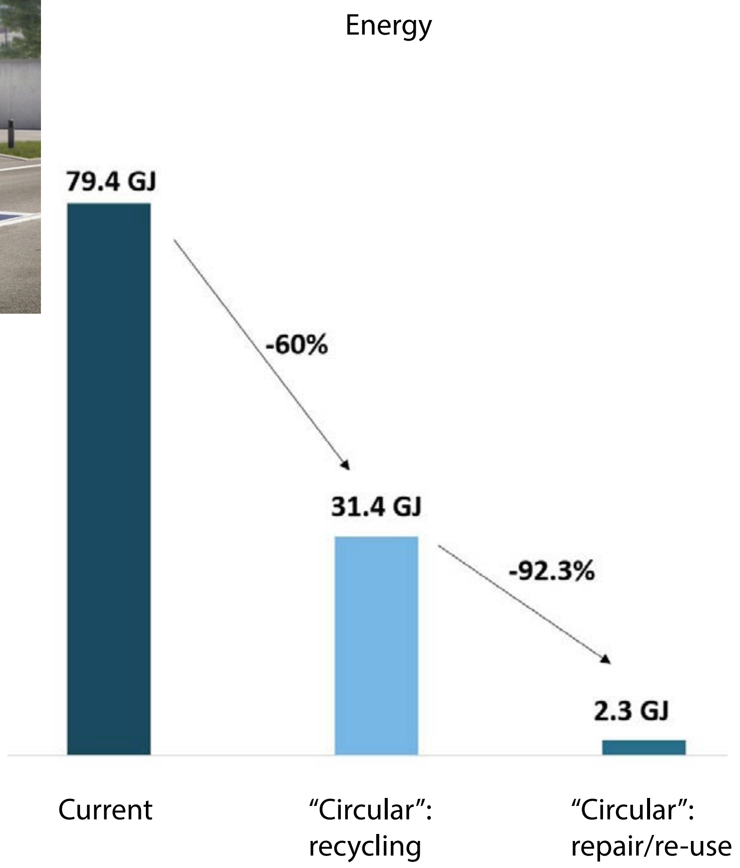
- To date, copper contamination has not been a problem because it can be absorbed in rebar
- It will become a global problem ~2040-50
- There is a technology opportunity for innovation in removing copper from recycled steel or coping with it

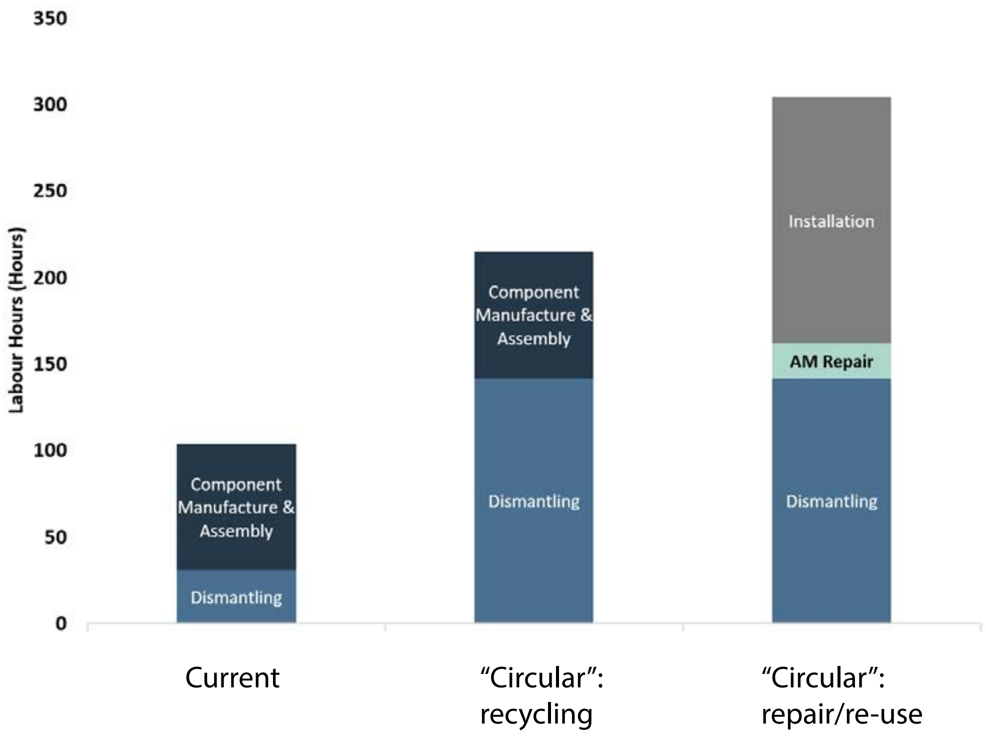
Re-use



Source Dunant et al. (2018a)

A truly circular car

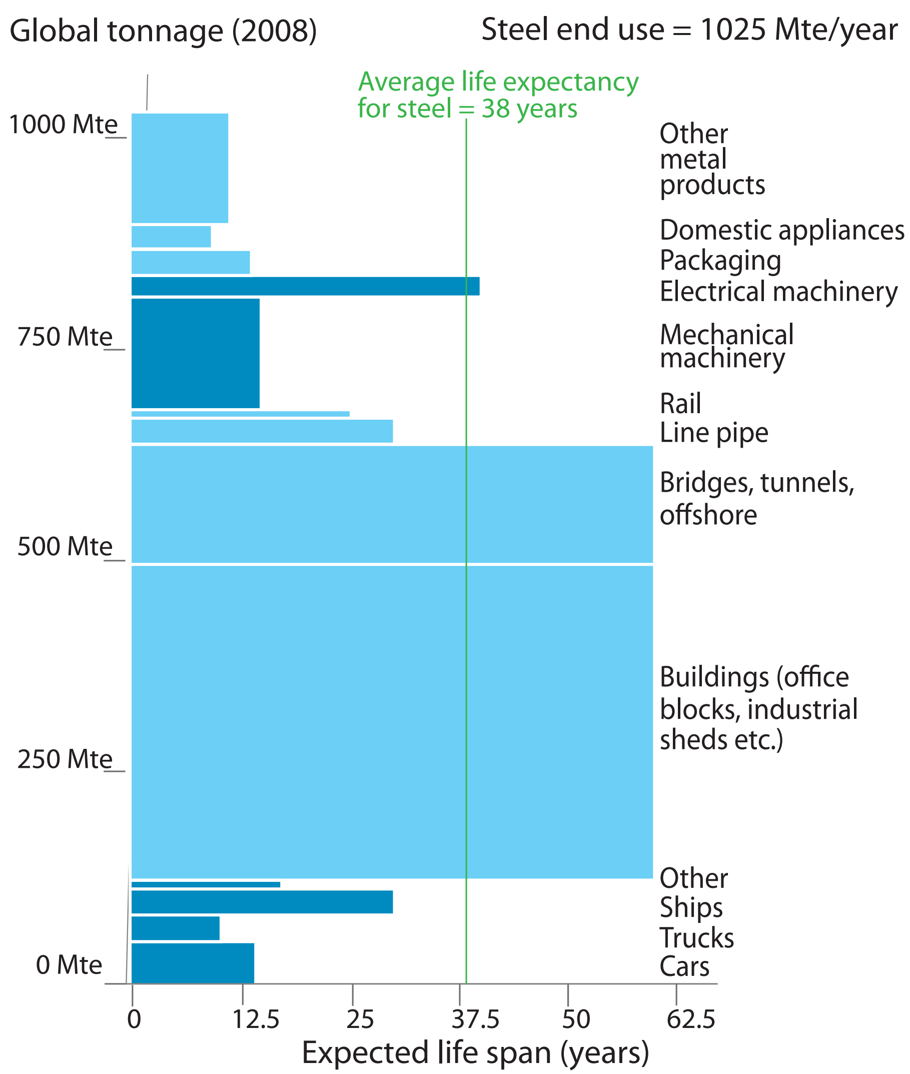




Source Keh (2021)

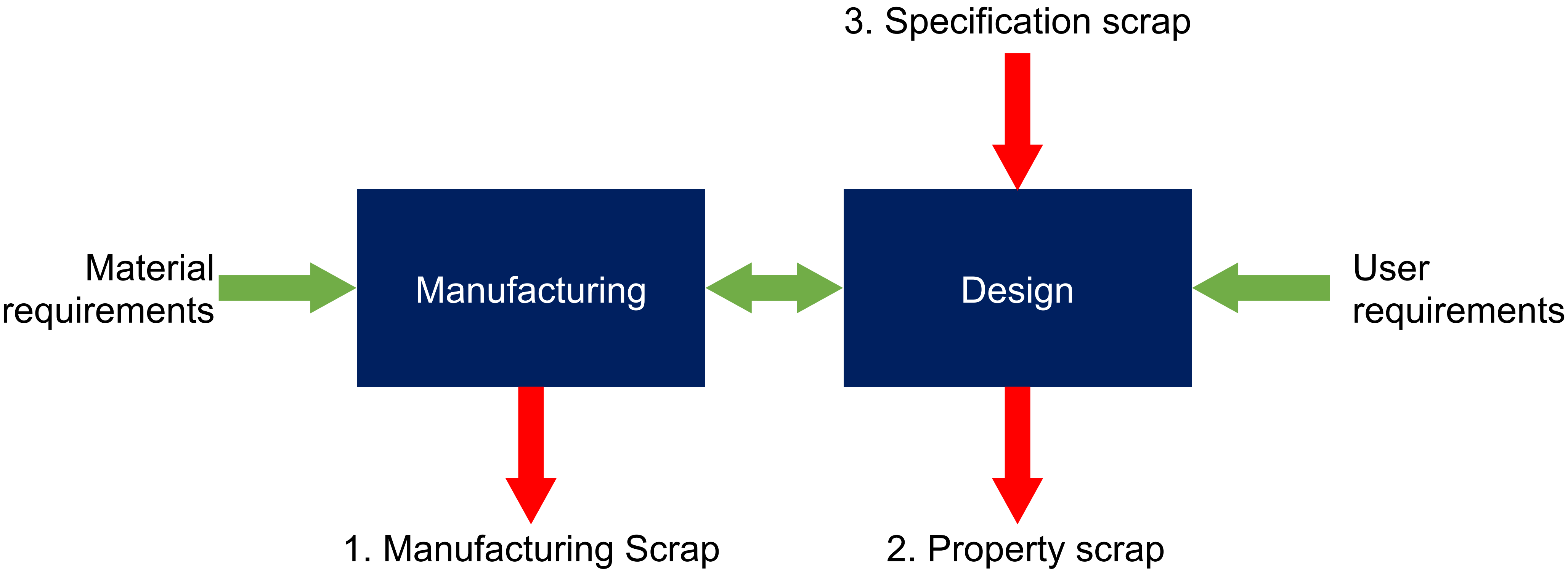
Avoid

- Longer life
- More intense use
- Material substitution
- Product substitution

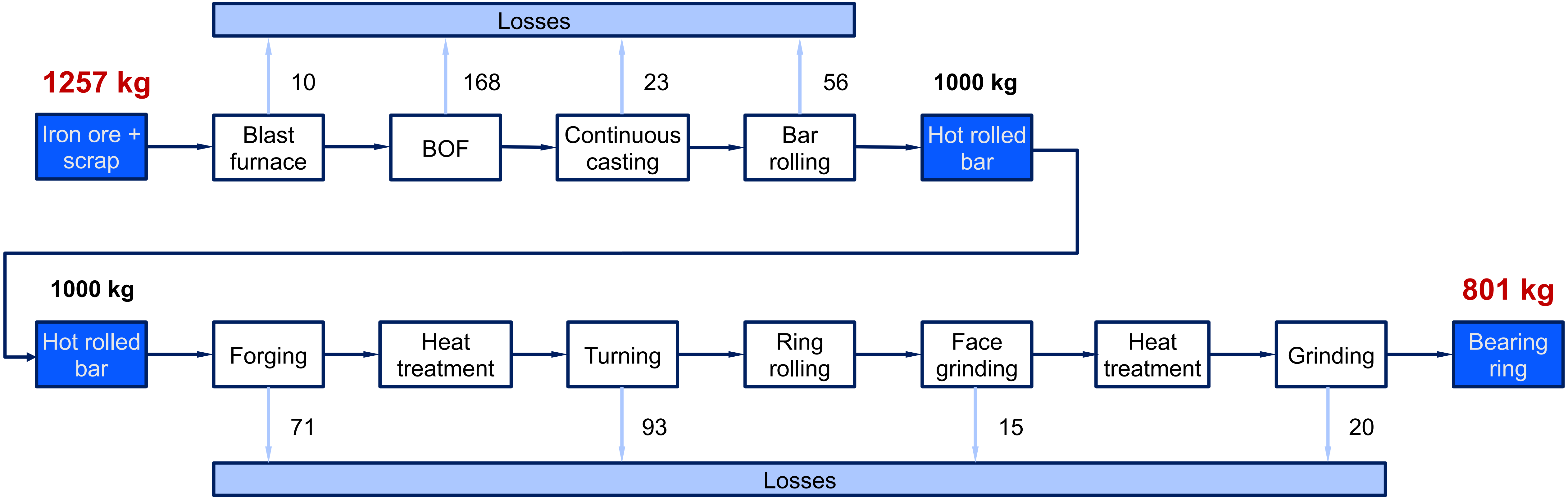


Source Cooper et al. (2014)

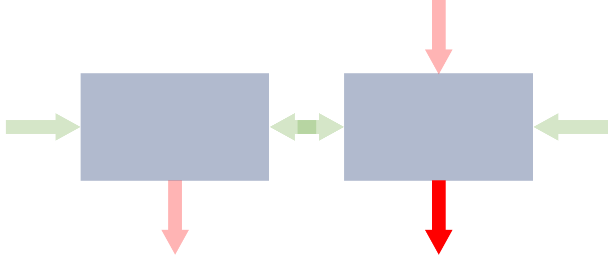
Reduce: three forms of scrap

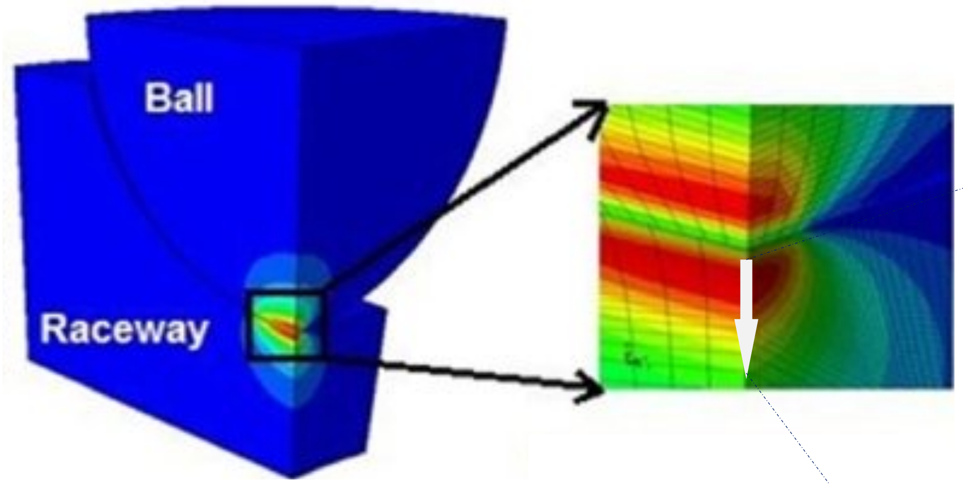


Manufacturing scrap: bearings example

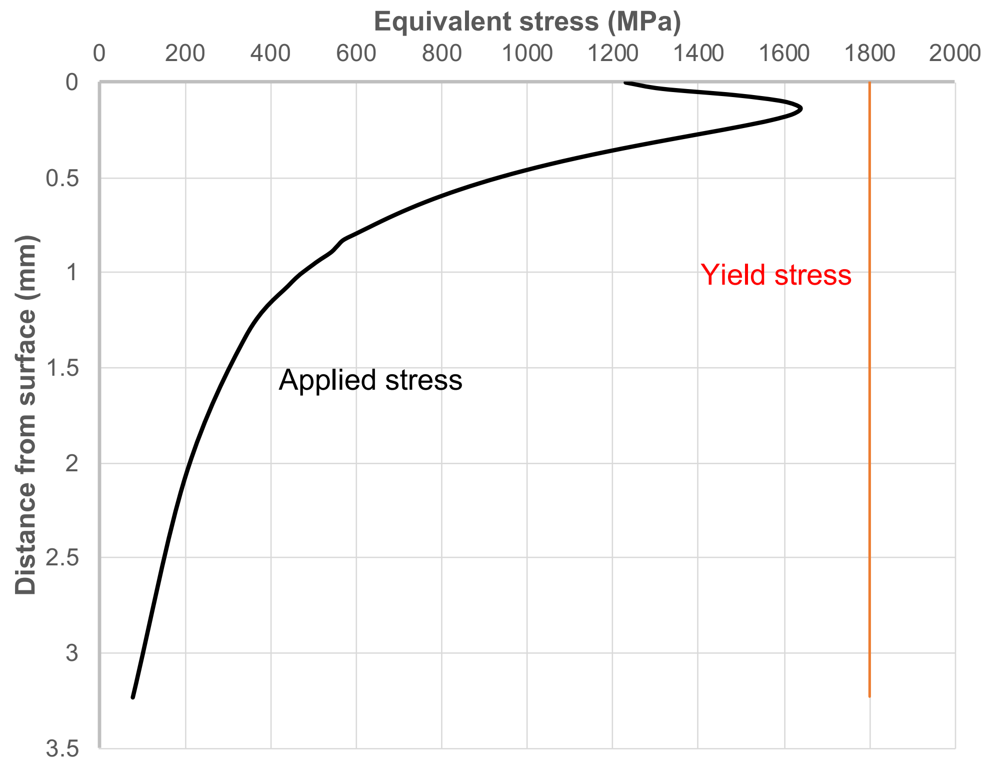


Property scrap: bearings example



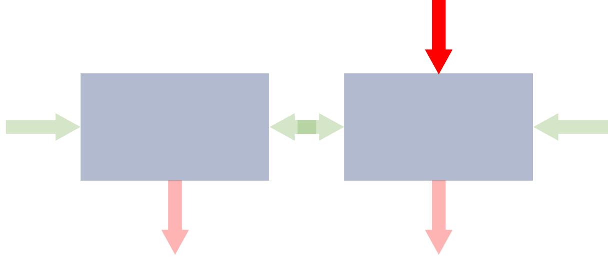


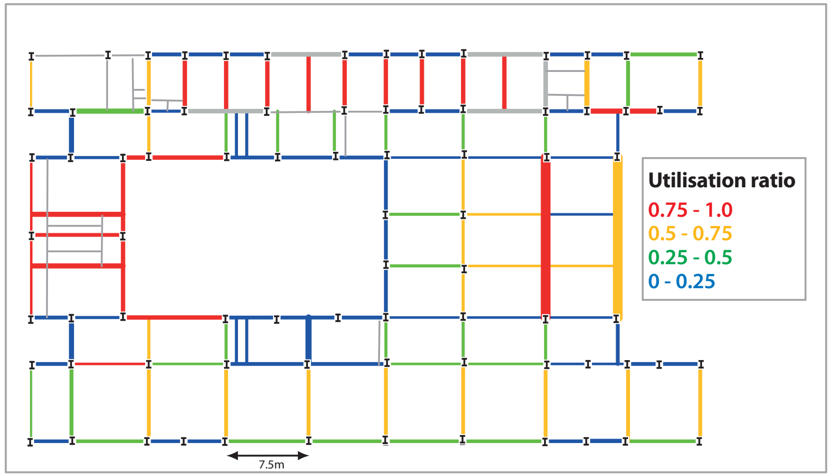
Equivalent stress in a bearing



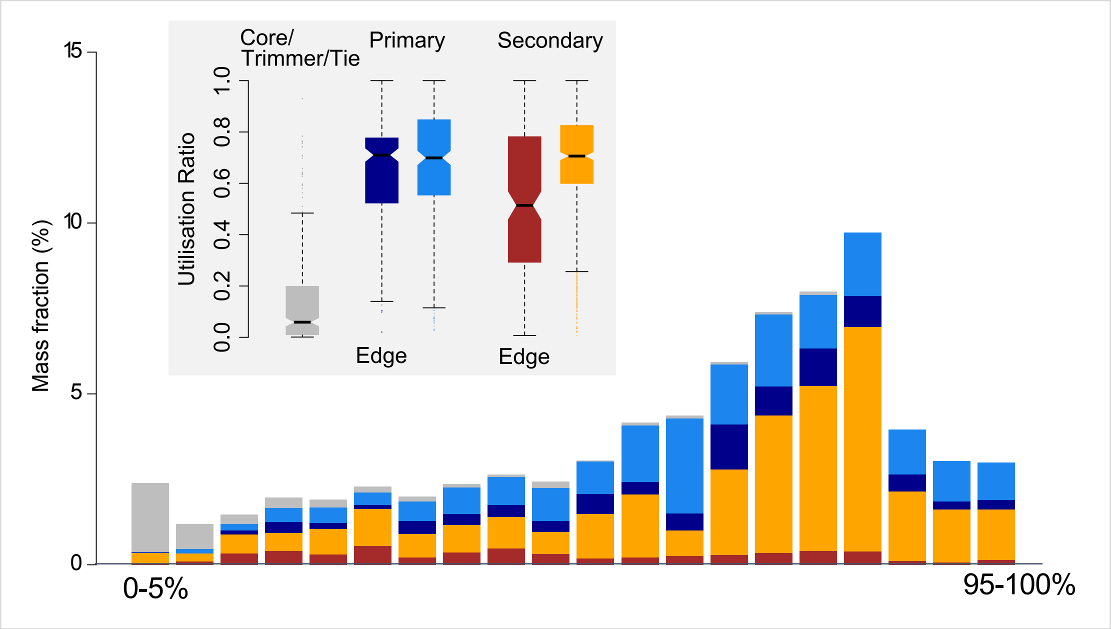
Equivalent stress and yield through inner ring

Specification scrap: construction & cars

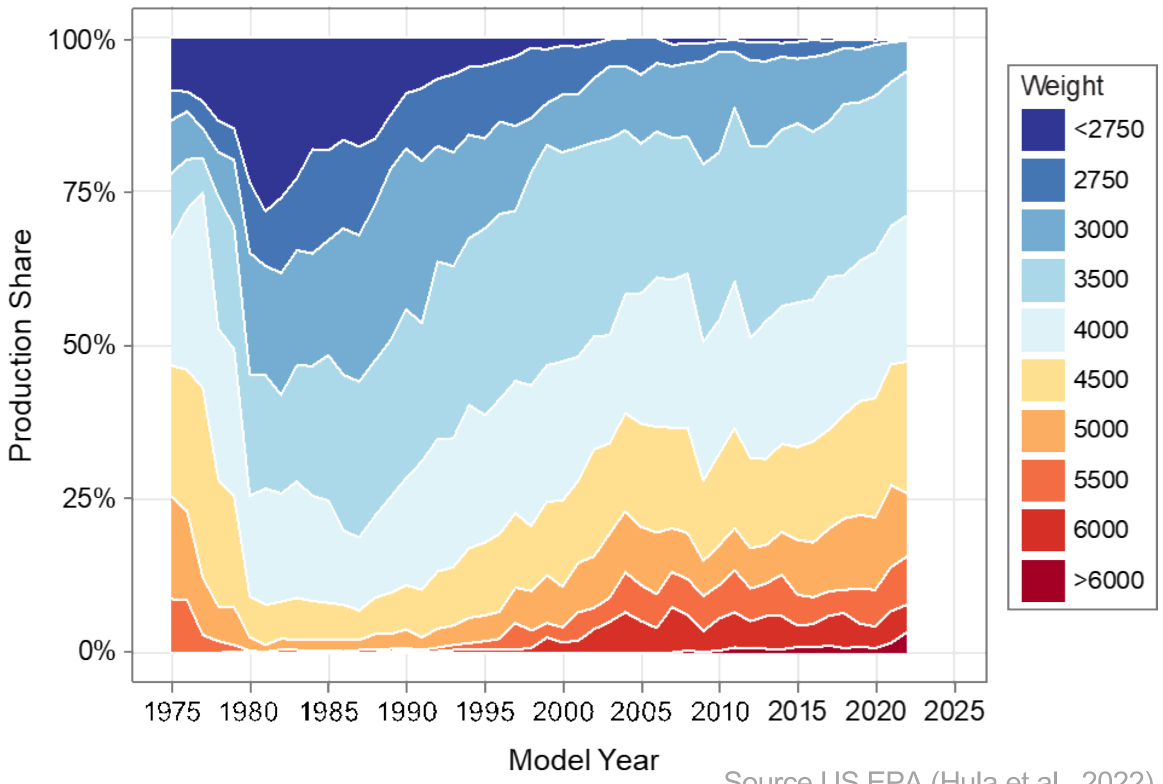




Source Moynihan & Allwood (2014)

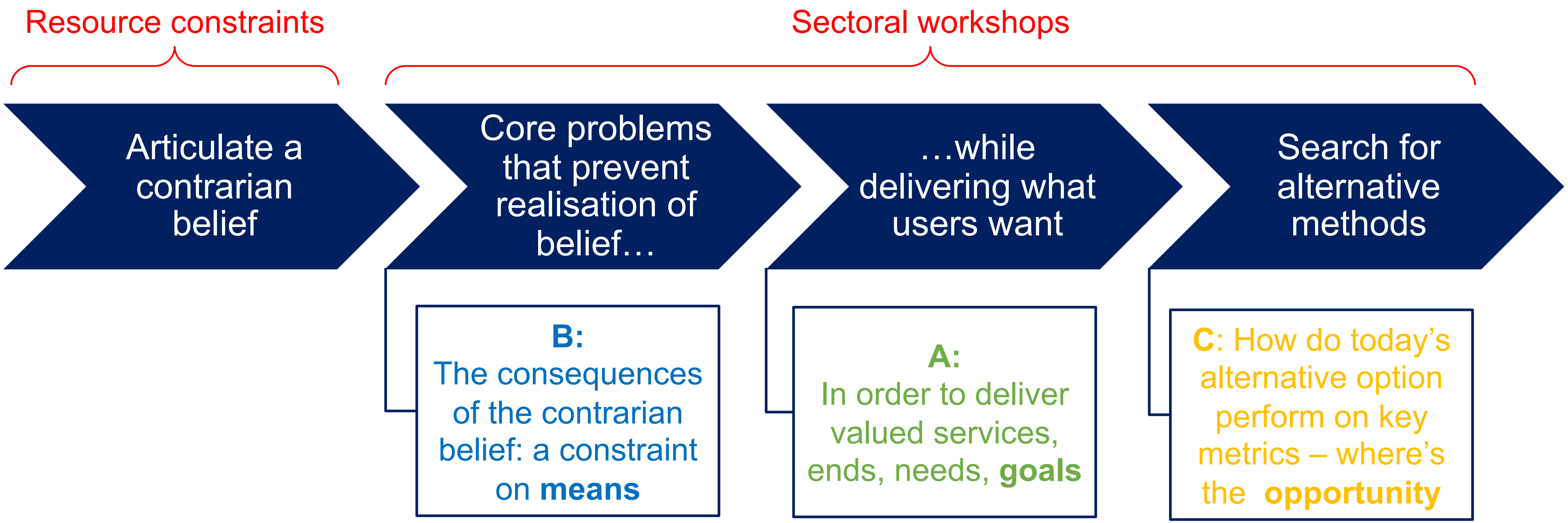


Source Dunant et al. (2018b)



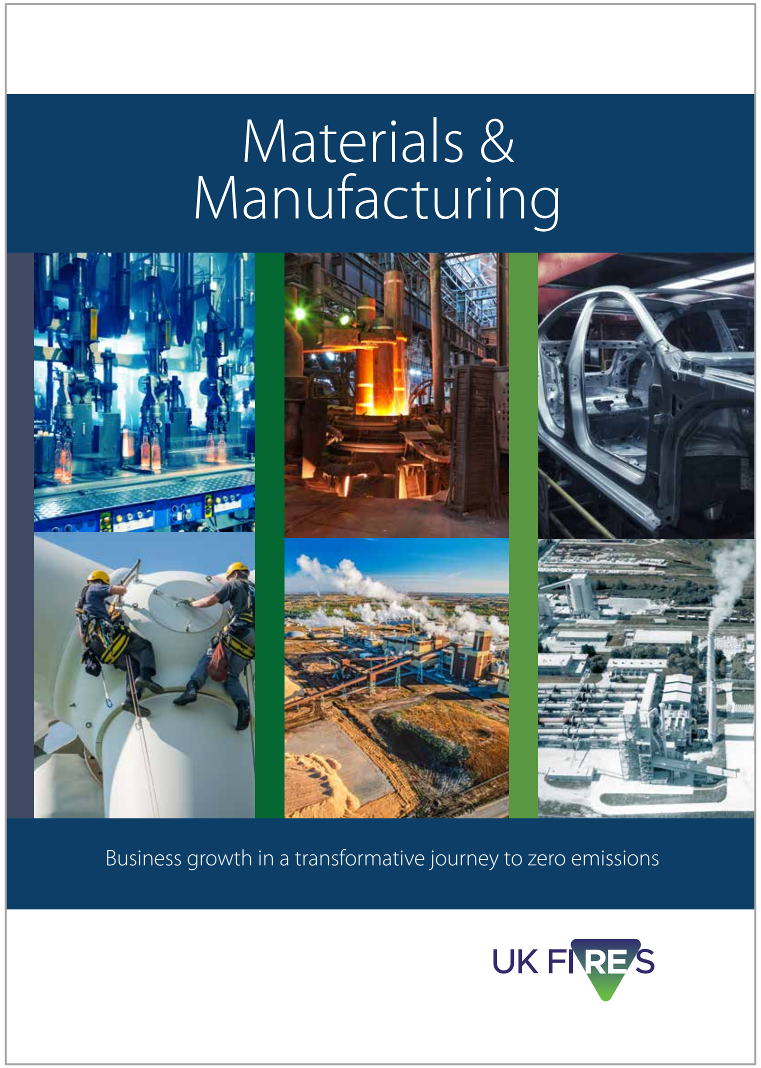
Source US EPA (Hula et al., 2022)

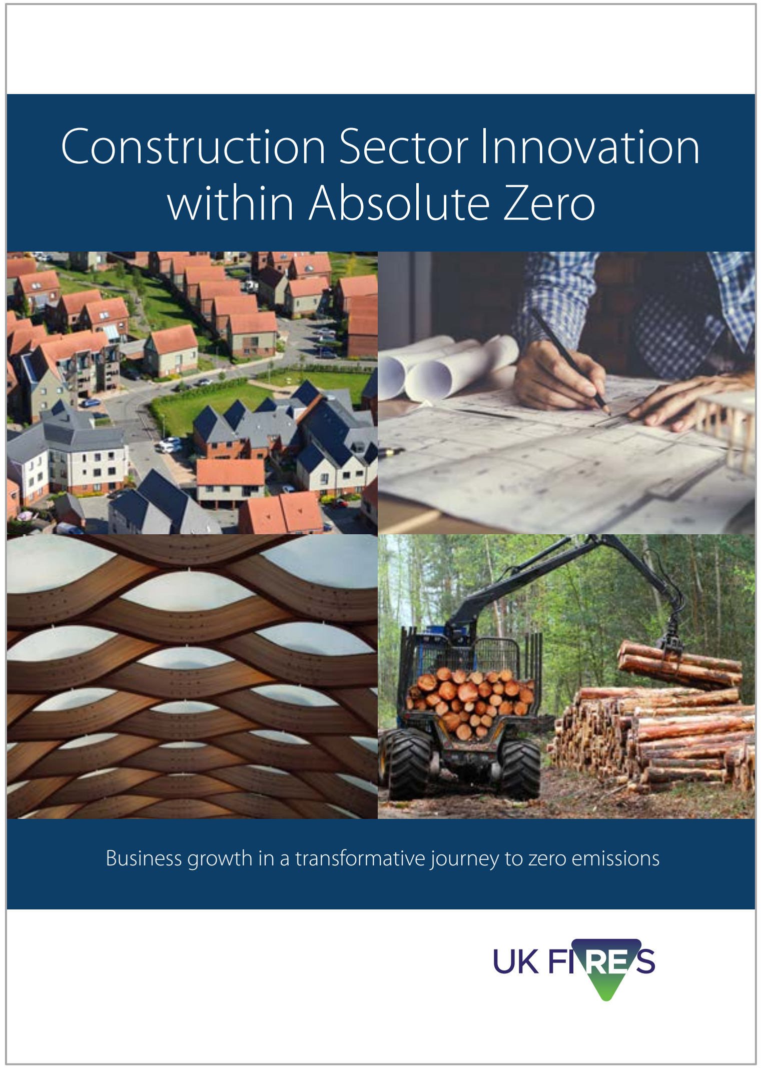
Opportunity search



Sub-problems: "End-users" would like to do A but can't because of B

Innovation opportunities

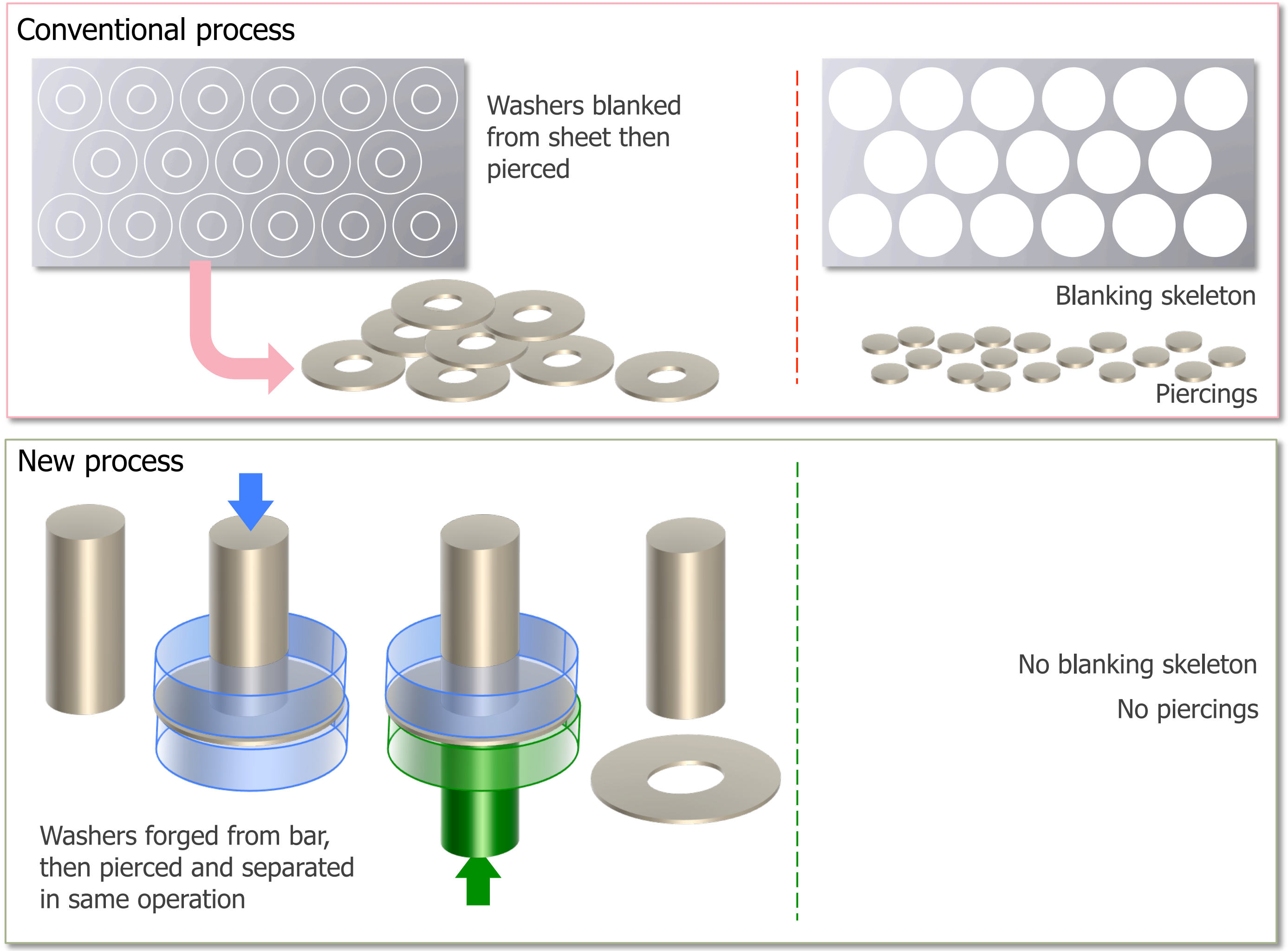




www.ukfires.org

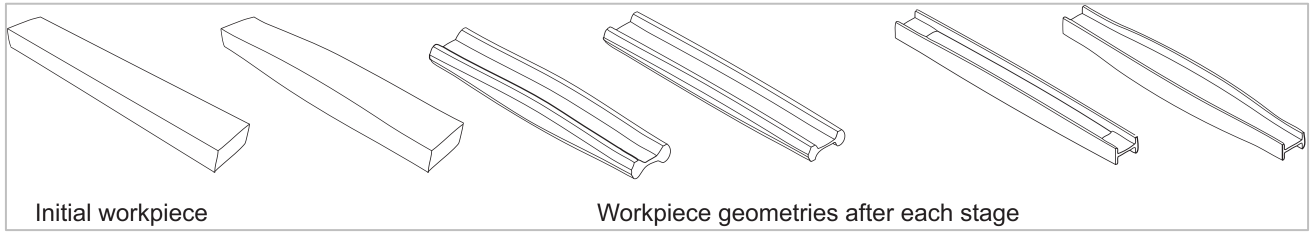
Examples

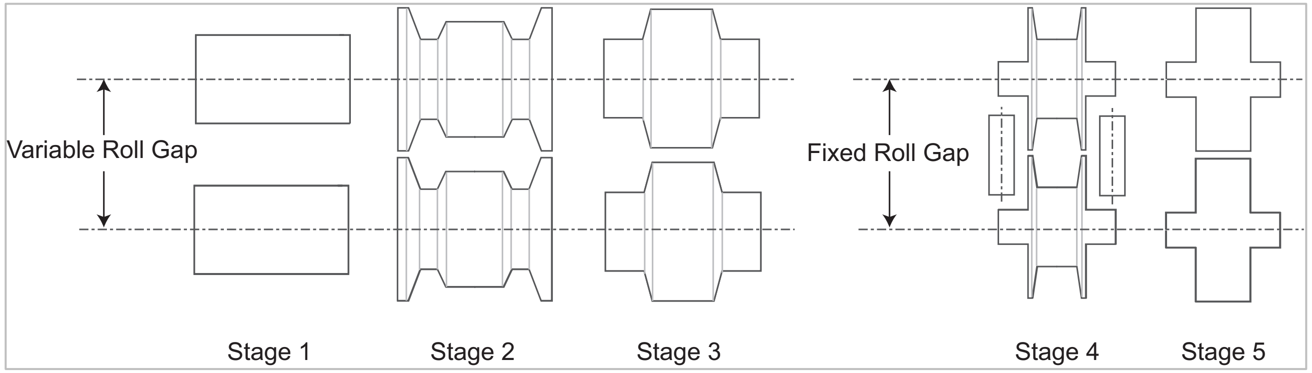
Washers without scrap



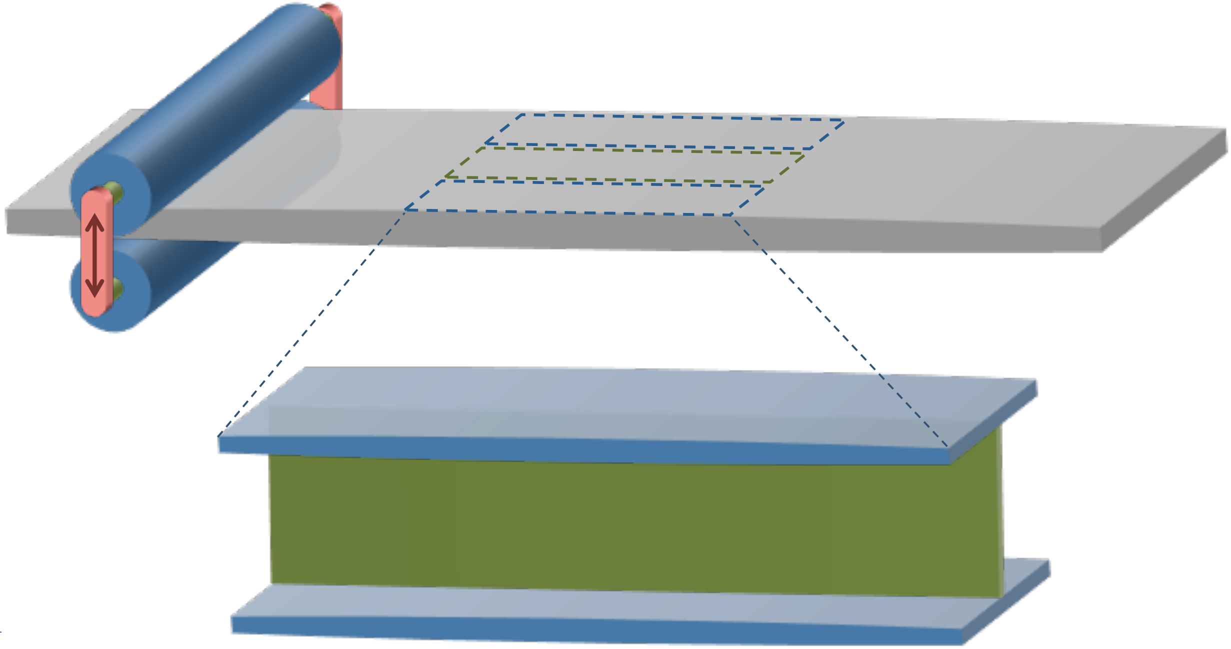
San Shing Fastech Company in Taiwan

Beams that track the bending moment diagram

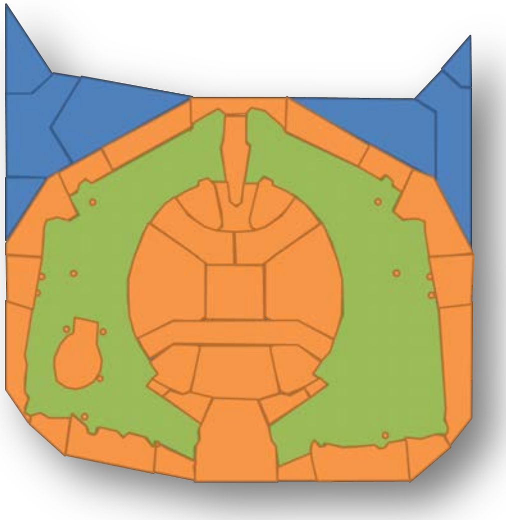


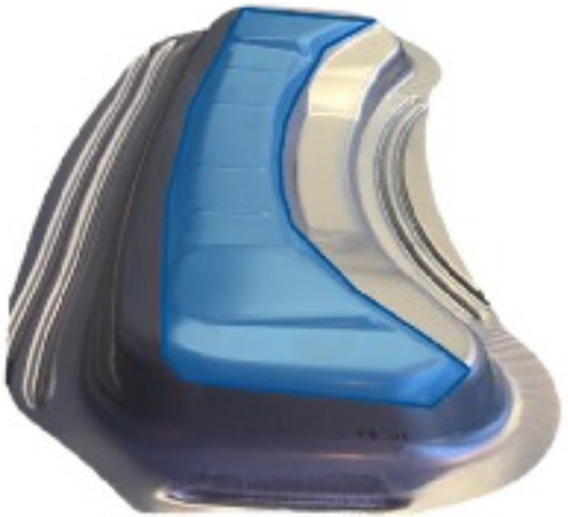


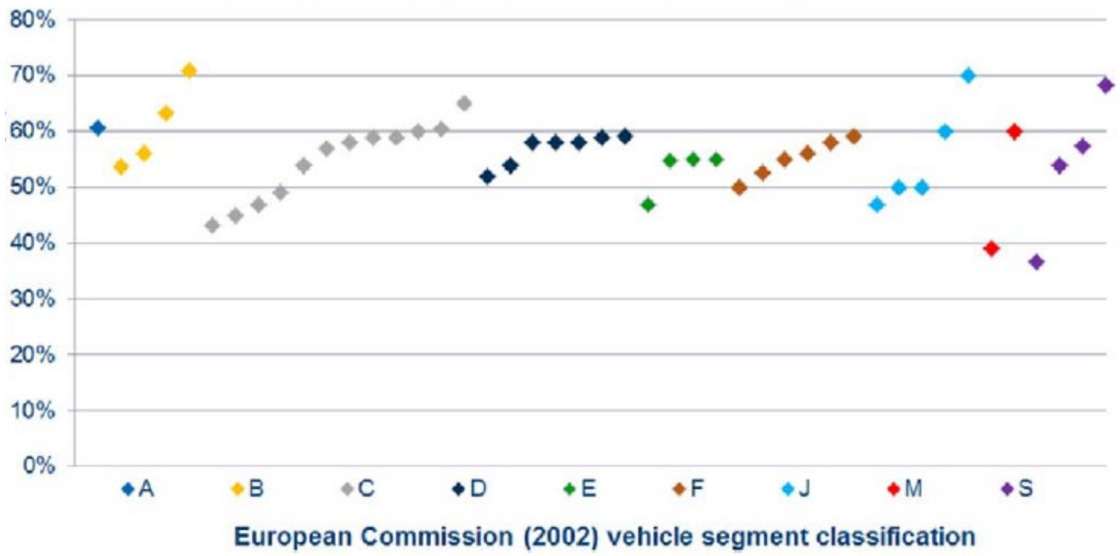
Source: Carruth and Allwood (2011)

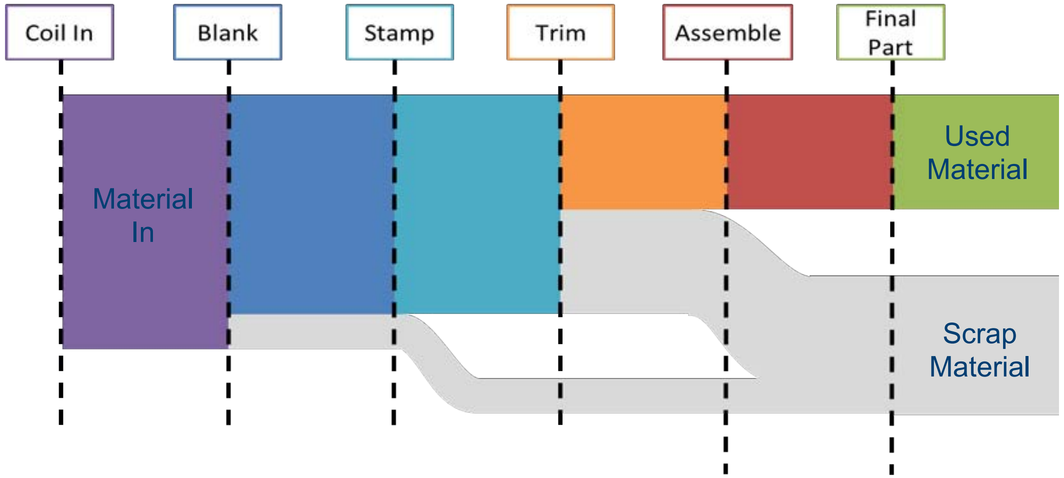


Folding-Shearing



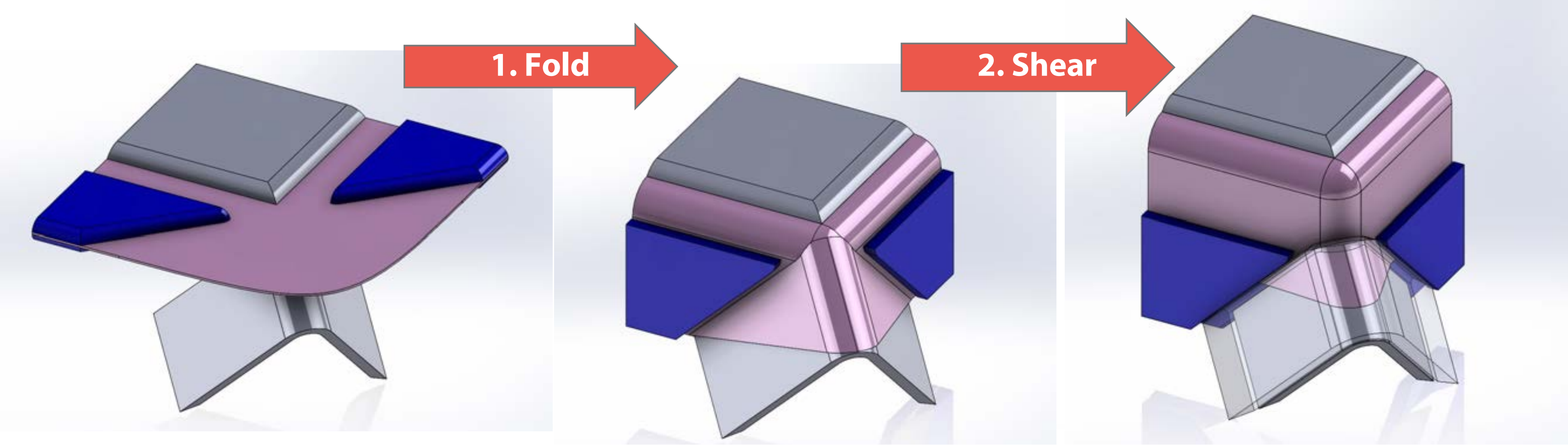






Source: Horton and Allwood (2017)

Folding-Shearing

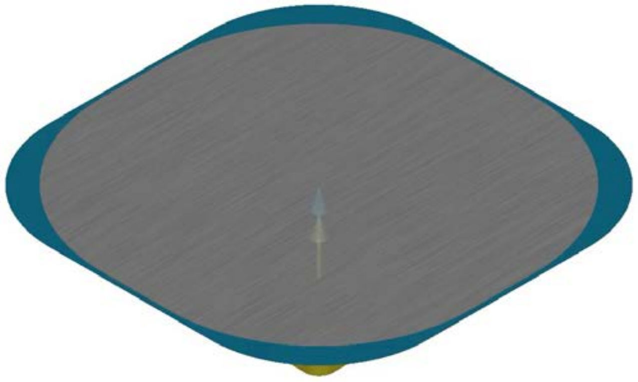


Source: Allwood et al. (2019), Cleaver et al. (2022)

Folding-shearing compared to deep-drawing

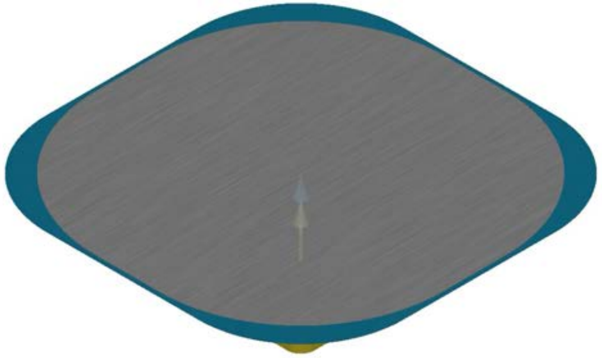
Drawing with blankholder

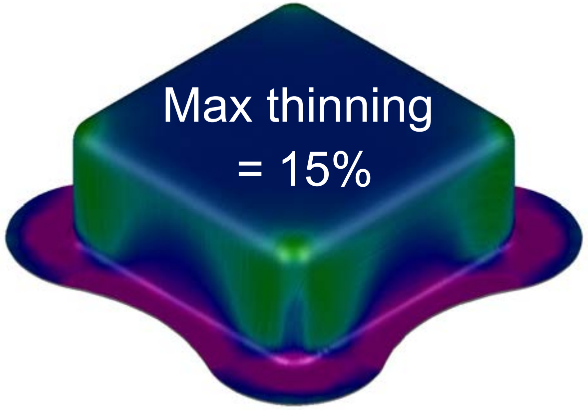
BHF = 15 kN



Drawing with blankholder

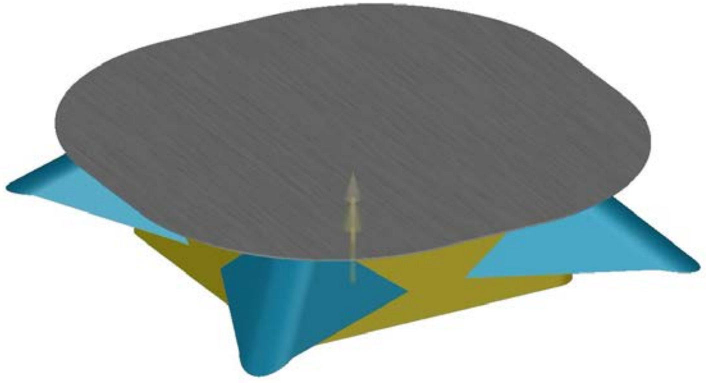
BHF = 50 kN

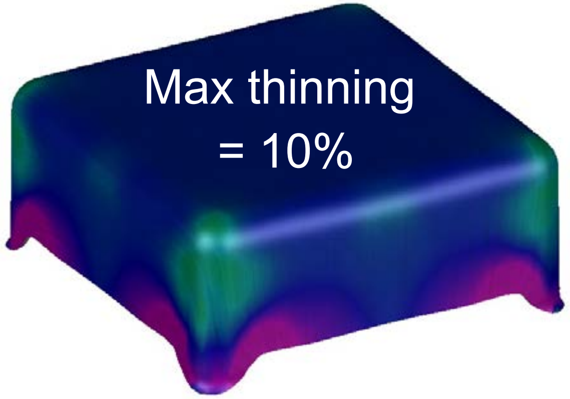




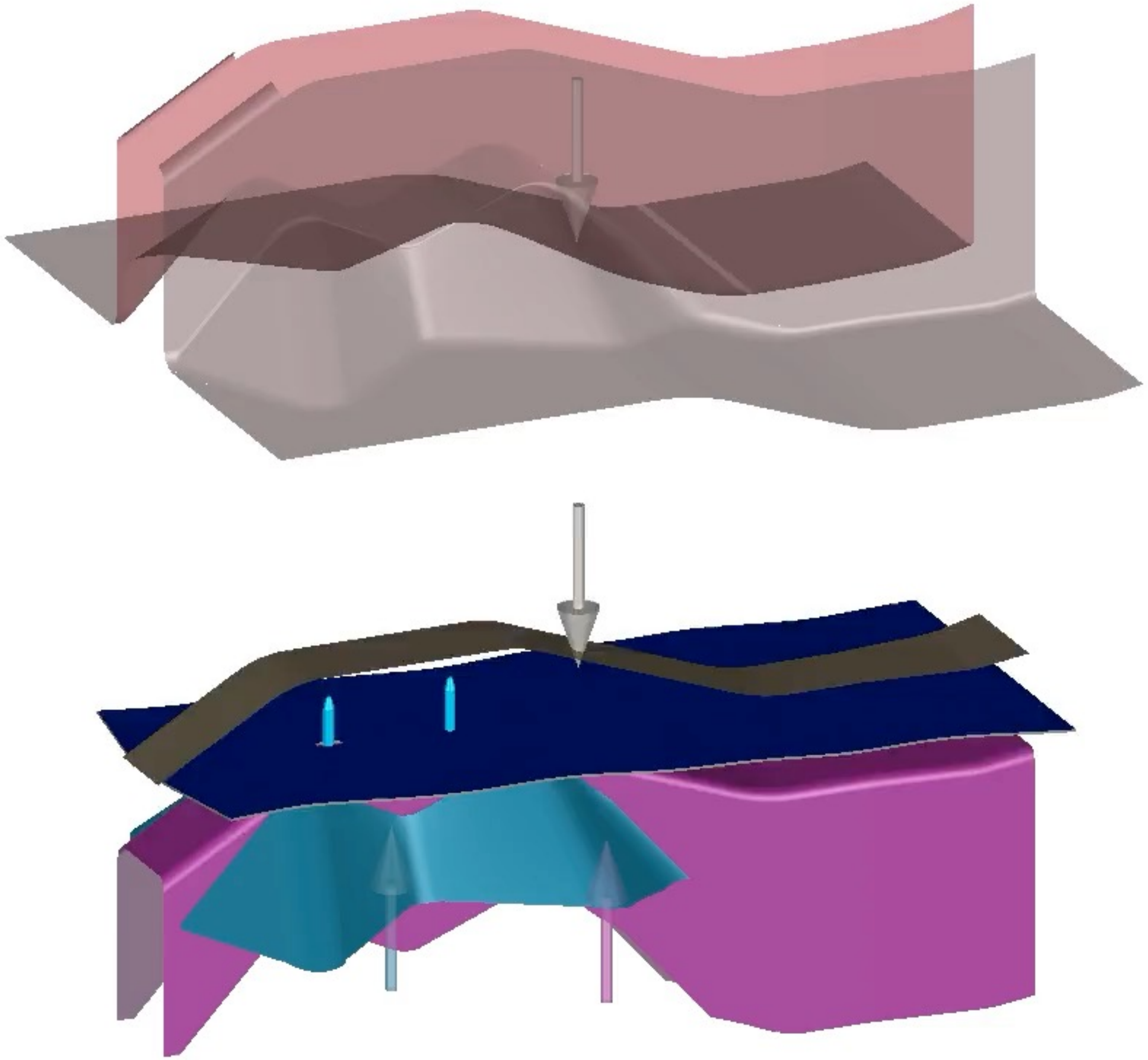
Folding-shearing

BHF = 15 kN





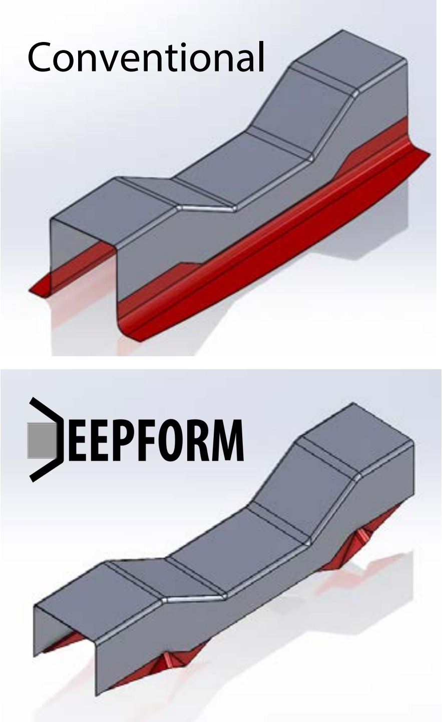
Folding-Shearing

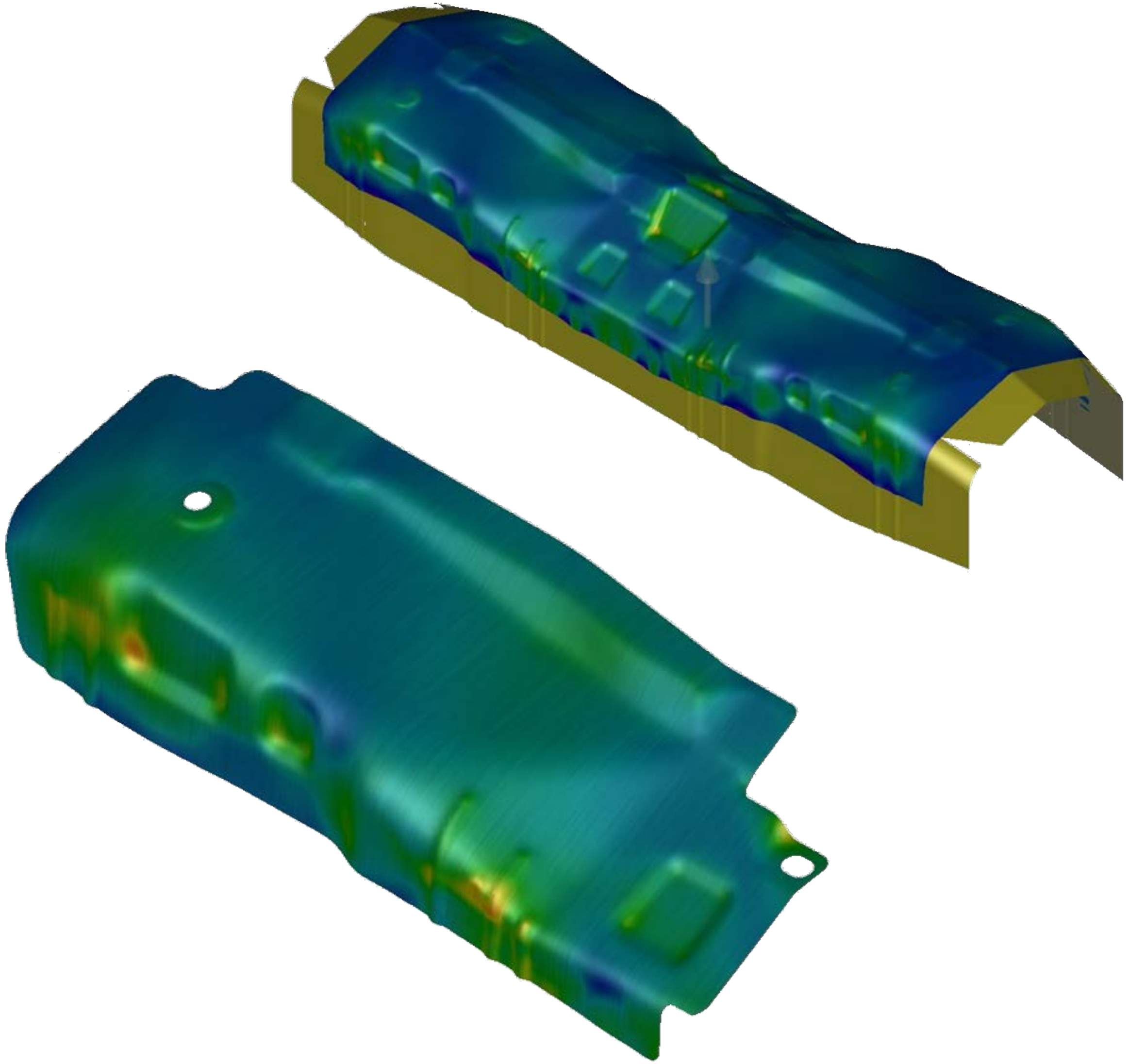


Folding-Shearing: DeepForm Ltd.

- 75% reduction in trimming **scrap**
- **Environmental benefit**: 30% reduction in embodied emissions per part
- **Cost savings**: 20% reduction in piece cost

DeepForm





Conclusion

Sustainable metals: science and systems

Scientific discussion meeting
Part of the Royal Society scientific programme

Organised by Professor Julian M Allwood FREng
and Professor Dierk Raabe.

5 – 6 February 2024

The Royal Society
6 – 9 Carlton House Terrace, London, SW1Y 5AG

Find out more at **royalsociety.org/events/for-scientists**

THE ROYAL SOCIETY

Image: © zephylwer0 from Pixabay.

Conclusion

- Current climate policy will not deliver due to resource constraints
- Zero-emissions metal supply will be much lower than demand in medium future
- Restraint creates opportunity
- There are rich business and research opportunities in making more use of less material
- A whole-systems view is required to identify meaningful opportunities

References used in the talk:

Allwood J.M. and Cullen J.M. (2012) Sustainable Materials: with both eyes open, UIT Cambridge, England, pp 384.

Allwood, J.M., Cleaver, C.J., Loukaides, E.G., Music, O. and Nagy-Sochacki, A. (2019) Folding-shearing: Shrinking and stretching sheet metal with no thickness change, *CIRP Annals* **68(1)** 285-288

BP (2021) Statistical Review of World Energy 2021, 70th Edition, www.bp.com

Carruth, M.A. and Allwood, J.M. (2012) The development of a hot rolling process for variable cross-section I-beams, *Journal of Materials Processing Technology* **212(8)** 1640-1653

Cleaver, C.J., Arora, R., Loukaides, E.G., Allwood, J.M. (2022) Producing isolated shrink corners by folding-shearing, *CIRP Annals,* **71,** 217-220

Cooper, D.R., Skelton, A.C.H., Moynihan, M.C. and Allwood, J.M. (2014), Component level strategies for exploiting the lifespan of steel in products, *Resources Conservation and Recycling,* **84** 24-32

Cullen, J.M. and Allwood, J.M. (2013). Mapping the global flow of aluminium: from liquid aluminium to end-use goods, *Environmental Science and Technology,* **47**, 3057–3064

Cullen, J.M., Allwood, J.M. and Bambach, M. (2012). Mapping the global flow of steel: from steelmaking to end- use goods, *Environmental Science and Technology* **46(24)**, 13048-13055

Daehn, K.E., Serrenho, A.C. and Allwood, J.M. (2019) Finding the most efficient way to remove residual copper from steel scrap, *Metallurgical Transactions B,* **50B**, 1225-1240.

Dunant, C.F., Drewniok, M.P., Eleftheriadis, S., Cullen, J.M. and Allwood, J.M. (2018b) Regularity and optimisation practice in steel structural frames in real design cases, *Resources Conservation and Recycling,* **134**, 294-302

Dunant, C.F., Drewniok, M.P., Sansom, M., Corbey, S., Allwood, J.M. and Cullen, J.M. (2018a) Options to make steel reuse profitable: An analysis of cost and risk distribution across the UK construction value chain, *Journal of Cleaner Production*, **183**, 102-111

Global CCS Institute (2021) Global Status of CCS 2021, www.globalccsinstitute.com

Horton, P.M. and Allwood, J.M. (2017) Yield Improvement Opportunities for Manufacturing Automotive Sheet Metal Components, *Journal of Materials Processing Technology,* **249**, 78-88

Hula, A., Maguire, A., Bunker, A., Rojeck, T., & Harrison, S. (2022). The 2022 EPA Automotive Trends Report: Greenhouse Gas Emissions, Fuel Economy, and Technology Since 1975 (No. EPA-420-R-22-029).

References used in the talk:

HYBRIT (2017) Summary of findings from HYBRIT Pre-Feasibility Study 2016-17, https://dh5k8ug1gwbyz.cloudfront.net/uploads/2021/02/Hybrit-broschure-engelska.pdf

IAI (2018) https://international-aluminium.org/statistics/greenhouse-gas-emissions-aluminium-sector/

International Energy Agency. (2022). *Global Hydrogen Review 2022*. OECD Publishing.

IPCC SRCCL (2019) IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems, www.ipcc.ch

Keh, Z.H. (2021) Circular Cars, *MEng thesis, University of Cambridge.*

Moynihan, M.C. and Allwood, J.M. (2014), Utilisation of structural steel in buildings, *Proceedings of the Royal Society A,* **470** no. 2168 20140170

Nakajima, K., Takeda, O., Miki, T., Matsubae, K., Nakamura, S., & Nagasaka, T. (2010). Thermodynamic analysis of contamination by alloying elements in aluminum recycling. *Environmental science & technology*, *44*(14), 5594-5600.

Nelson, S.K. and Allwood, J.M. (2021) The technological and social timelines of climate mitigation: lessons from 12 past transitions, *Energy Policy,* **152**, 112155

Smil, V. (2014). The long slow rise of solar and wind. *Scientific American*, *310*(1), 52-57.

UK Govt (2022) UK Government GHG Conversion Factors for Company Reporting, https://www.gov.uk/government/publications/greenhouse-gas-reporting-conversion-factors-2022

Watari, T., Cabrera Serenho A., Gast, L., Cullen, J.M. and Allwood J.M. (2023). Feasible supply of bulk materials within a carbon budget is likely to fall short of expected global demand. *Environmental science & technology*, *under review*.

Zhou, C., Elshkaki, A., & Graedel, T. E. (2018). Global human appropriation of net primary production and associated resource decoupling: 2010–2050. *Environmental science & technology*, *52*(3), 1208-1215.

A pdf of the slides used in this talk can be downloaded from:

www.uselessgroup.org/about-us/blog

Allwood-office@eng.cam.ac.uk