The *low carbon* Blast Furnace

why it matters and *how*

Ashok Kumar
Tata Steel

Jamshedpur, 17th January, 2024

online talk at the

International Conference on Green and Sustainable Ironmaking

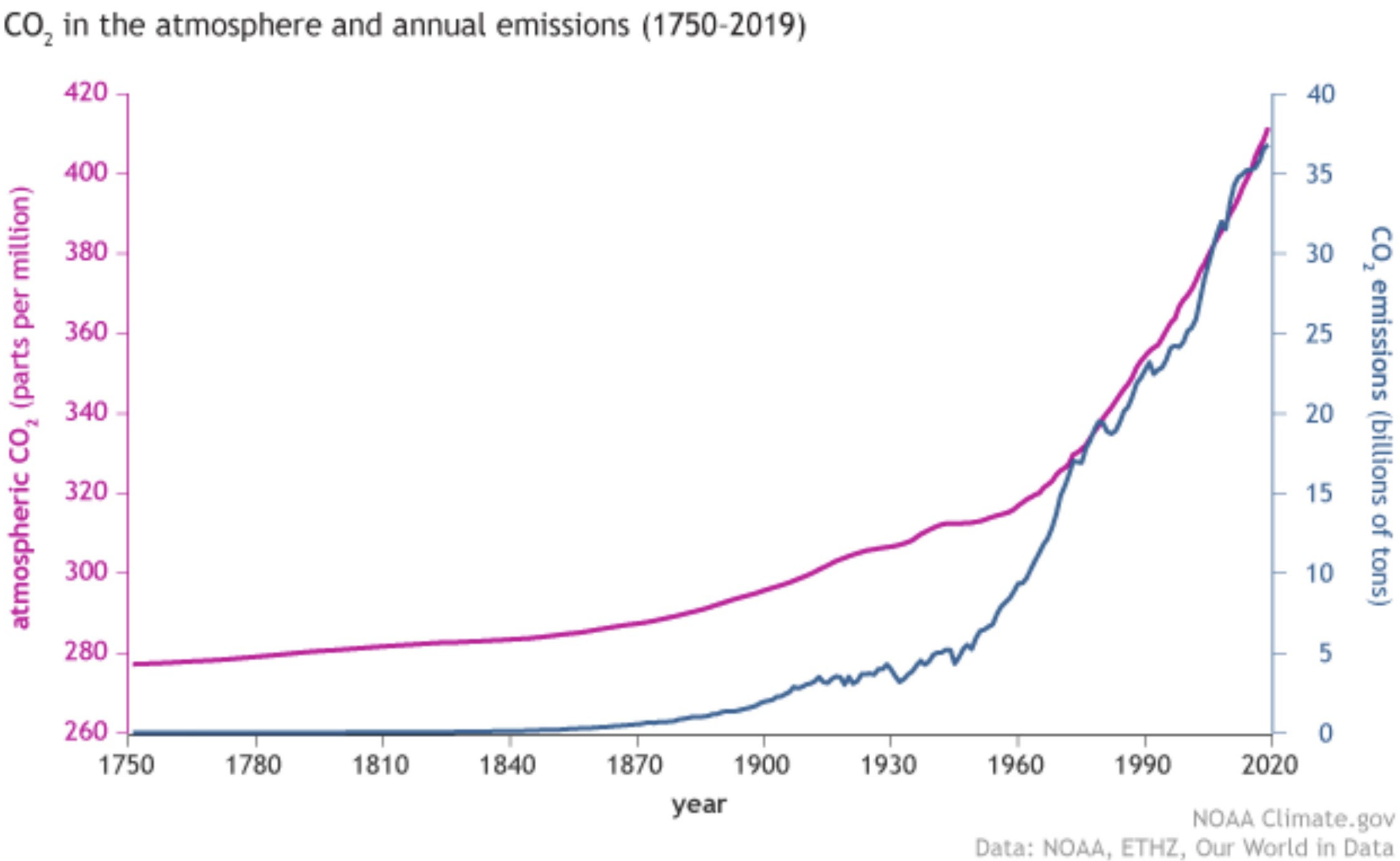
United Club

Jamshedpur

The **CO_2** rise in atmosphere

is linked to

energy related human made **emissions**



The amount of carbon dioxide in the atmosphere (raspberry line) has increased along with human emissions (blue line) since the start of the Industrial Revolution in 1750. Credit: NOAA Climate.gov plenty of '**green steel**' headlines with *two dominant themes*

➔ replace coal with *hydrogen*; ➔ replace ironmaking with *scrap*

– both calling for doing away with the ***Blast Furnace***

the

low carbon Blast Furnace

why it matters

and

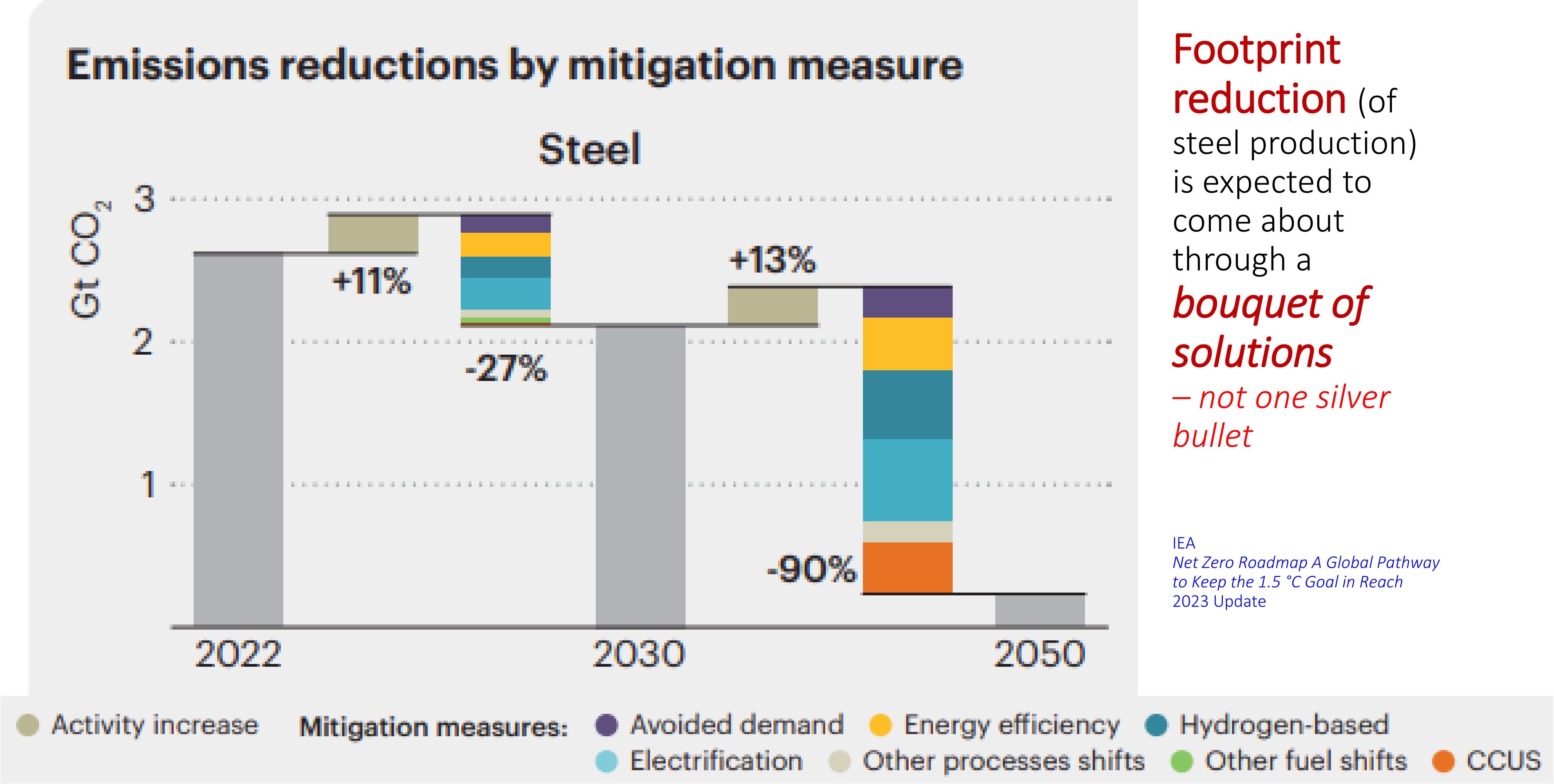
how

Changing *(rather than **killing**)* the Blast Furnace
a *better transition conversation ?*

- Leverage the broader energy transition
  - *not confined to debates about choice of reactor choice of reduction molecules ?*
  - *law of diminishing returns when focussed on one lever ? .. faster impact possible – steel industry woefully behind on emissions reduction*

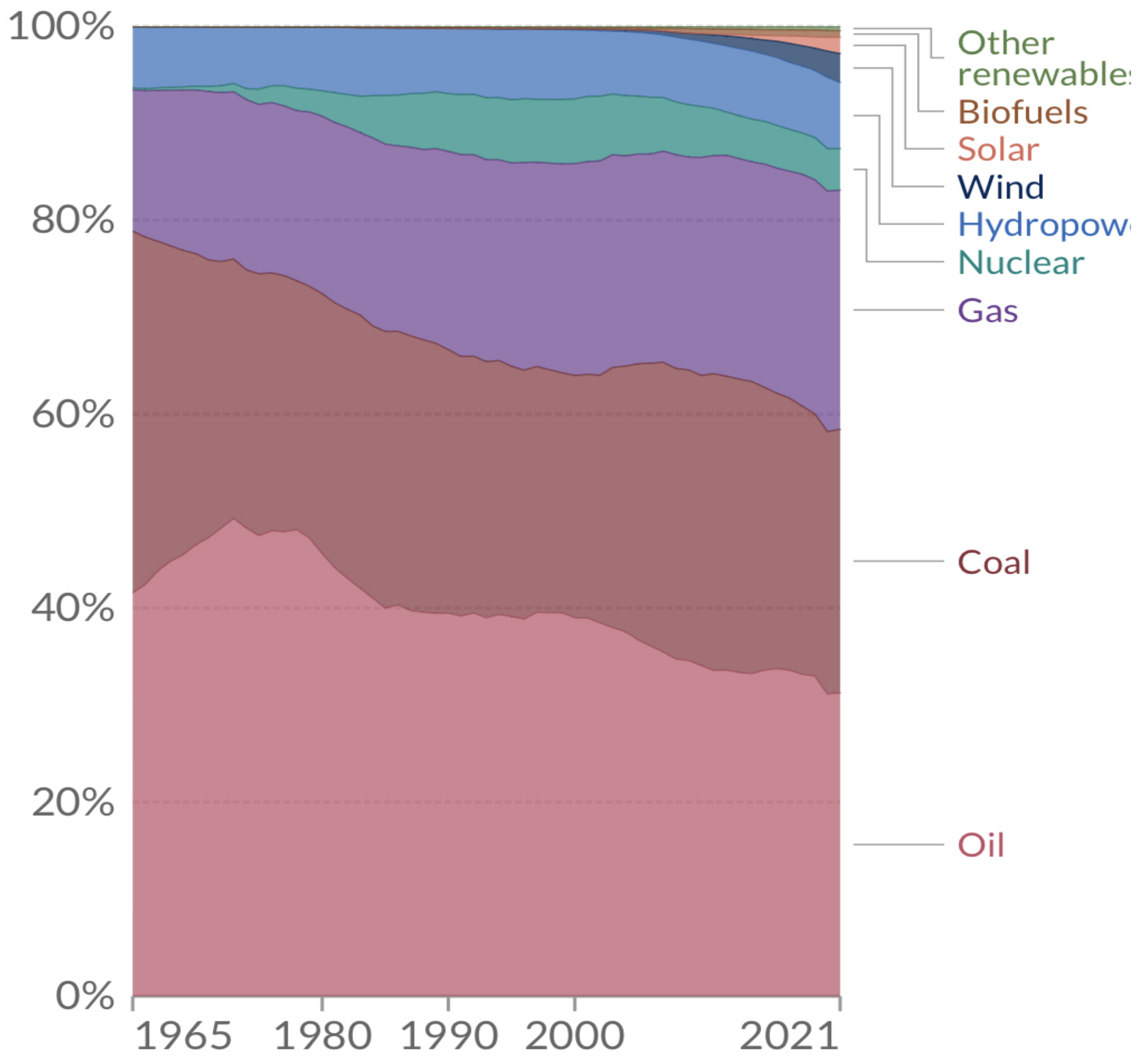
- Hydrogen not ready *to scale yet* *in much of the world..*
  - *Despite impressive progress, changing electricity mix fast enough .. net zero is still far ?*
  - *Instead a very key lever – working on 90 % of installed ironmaking capacity (BF) has gotten less attention*

- BF is essentially a good idea *for a steel plant - if we can solve its carbon footprint conundrum   .. minimal asset reconstruction*



Footprint reduction (of steel production) is expected to come about through a ***bouquet of solutions*** *– not one silver bullet*

IEA
Net Zero Roadmap A Global Pathway to Keep the 1.5 °C Goal in Reach
2023 Update



Source: BP Statistical Review of World Energy
Note: 'Other renewables' includes geothermal, biomass and waste energy.

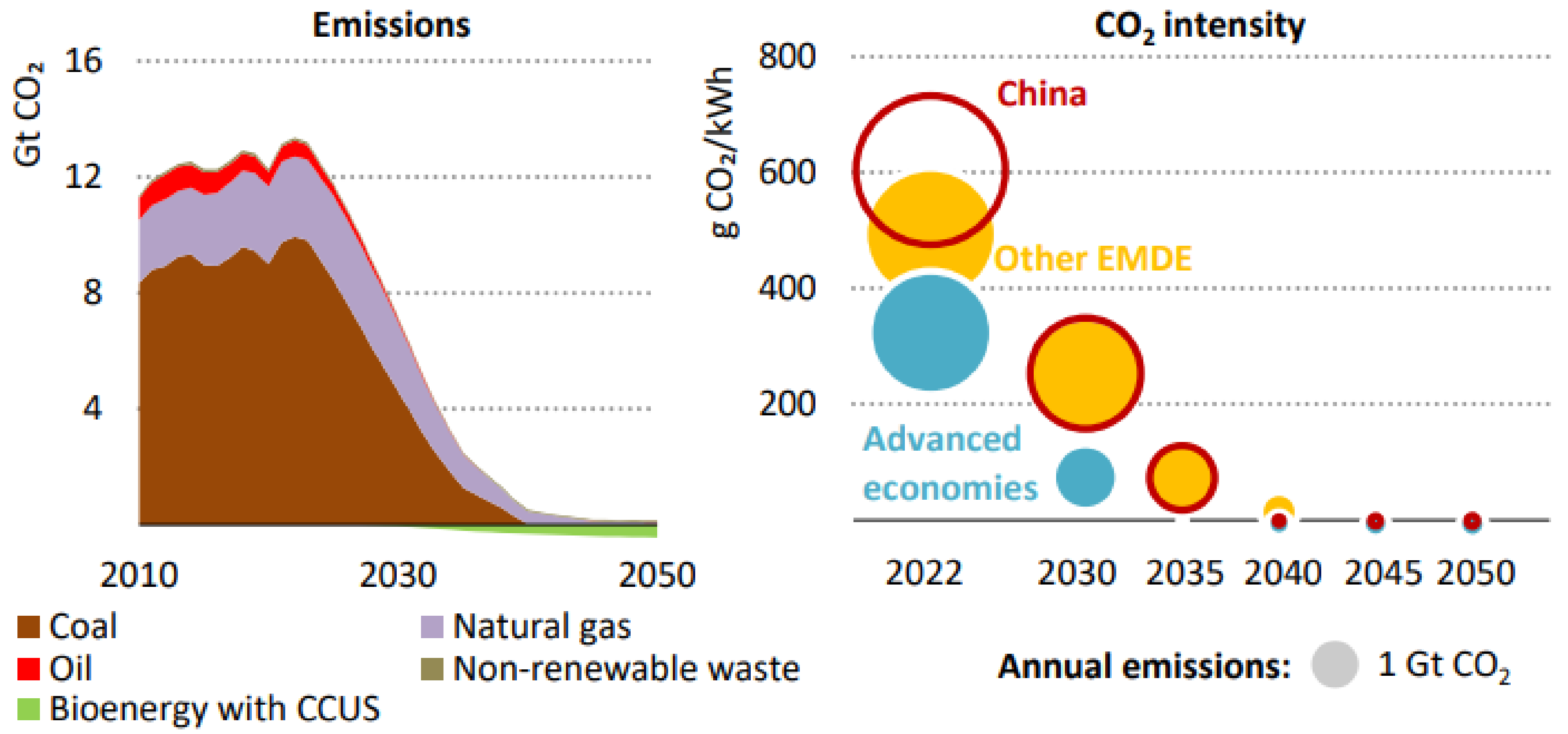
Energy consumption by source, World

Primary energy is yet *mostly fossil fuel* based

A multiple factor growth in electricity capacity would be required by most economies if *primary energy needs*, currently met by fossil fuels (coal, natural gas, oil), also have to move to renewables or nuclear energy based electricity

(credit: chart from Our World in Data based on BP Statistical Review of World Energy (2021))
Efficiency factor used to make sources comparable
own commentary

Figure 2.14 ▷ Global electricity sector emissions and CO_2 intensity of electricity generation in the NZE Scenario, 2010-2050



Electricity sector reaches net zero emissions in advanced economies in aggregate in 2035, in China around 2040 and globally before 2045

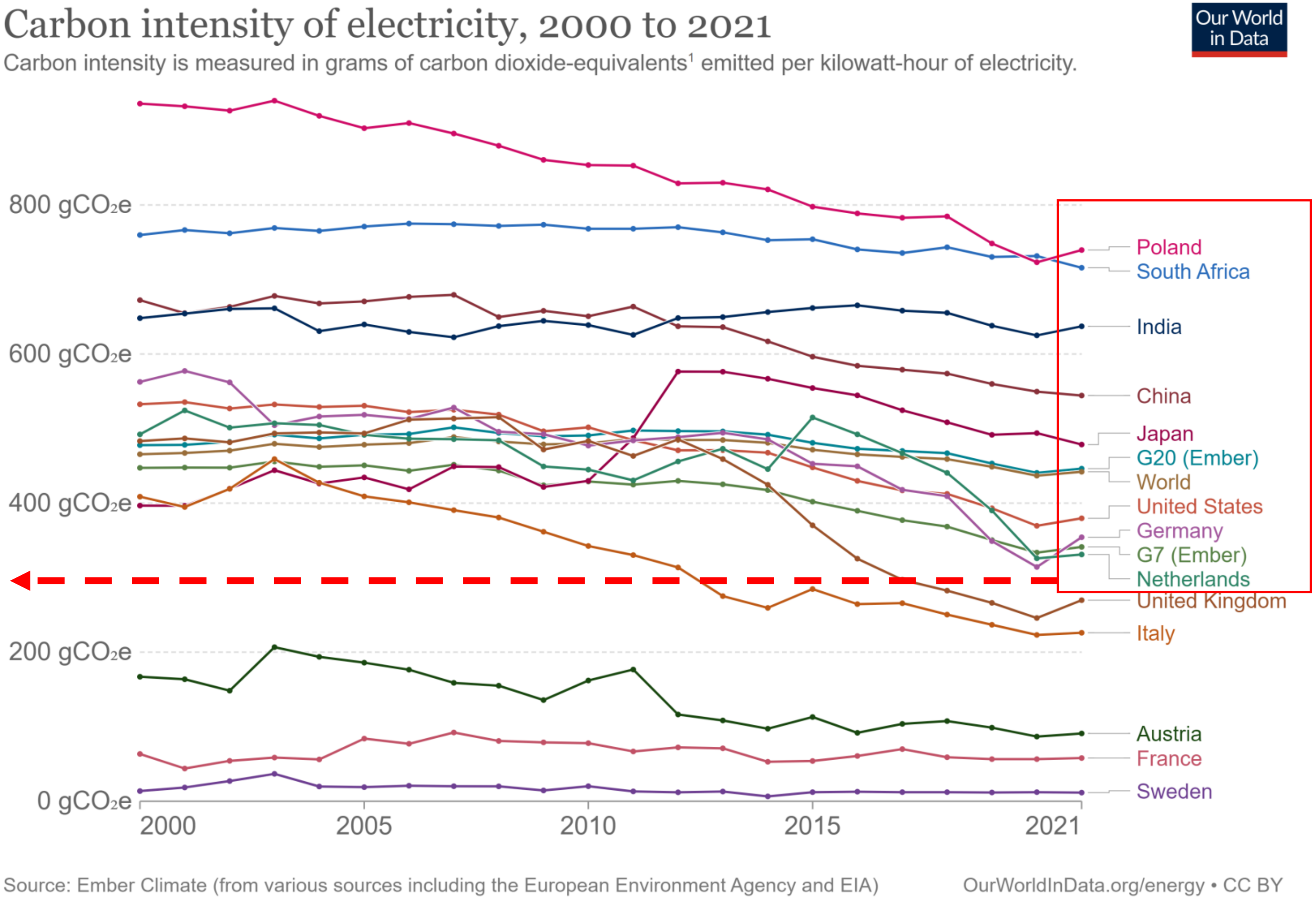
Note: g CO_2 /kWh = grammes of carbon dioxide per kilowatt-hour; other EMDE = emerging market and developing economies excluding China.

Even with impressive progress, it could take 15-25 years for bulk electricity to be 'green'

What is the carbon footprint of electricity itself ?

while reducing fast, the *current carbon footprint of electricity is yet too high* in most countries

making immediate electrification of steel industry not a useful startegy for mitigating climate change



1. **Carbon dioxide-equivalents (CO_2eq)**: Carbon dioxide is the most important greenhouse gas, but not the only one. To capture all greenhouse gas emissions, researchers express them in 'carbon dioxide-equivalents' (CO_2eq). This takes all greenhouse gases into account, not just CO_2. To express all greenhouse gases in carbon dioxide-equivalents (CO_2eq), each one is weighted by its global warming potential (GWP) value. GWP measures the amount of warming a gas creates compared to CO_2. CO_2 is given a GWP value of one. If a gas had a GWP of 10 then one kilogram of that gas would generate ten times the warming effect as one kilogram of CO_2. Carbon dioxide-equivalents are calculated for each gas by multiplying the mass of emissions of a specific greenhouse gas by its GWP factor. This warming can be stated over different timescales. To calculate CO_2eq over 100 years, we'd multiply each gas by its GWP over a 100-year timescale (GWP100). Total greenhouse gas emissions – measured in CO_2eq – are then calculated by summing each gas' CO_2eq value.

why

coal *and* *hydrogen* *(on earth)*

are not really *equivalents* ?

and

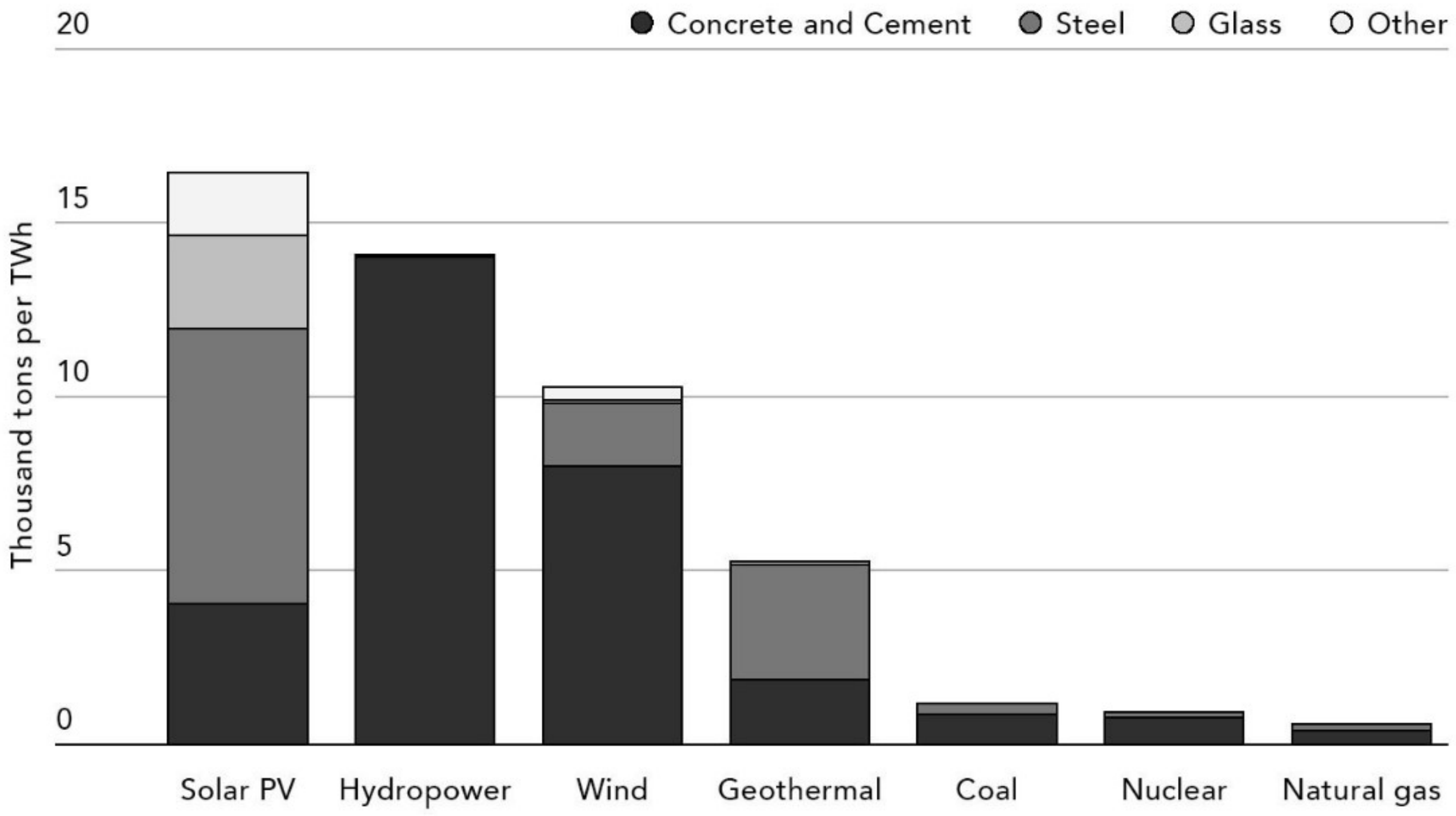
how they *can be*

Renewables based electricity is very resource intensive:

and it takes a long time to get there

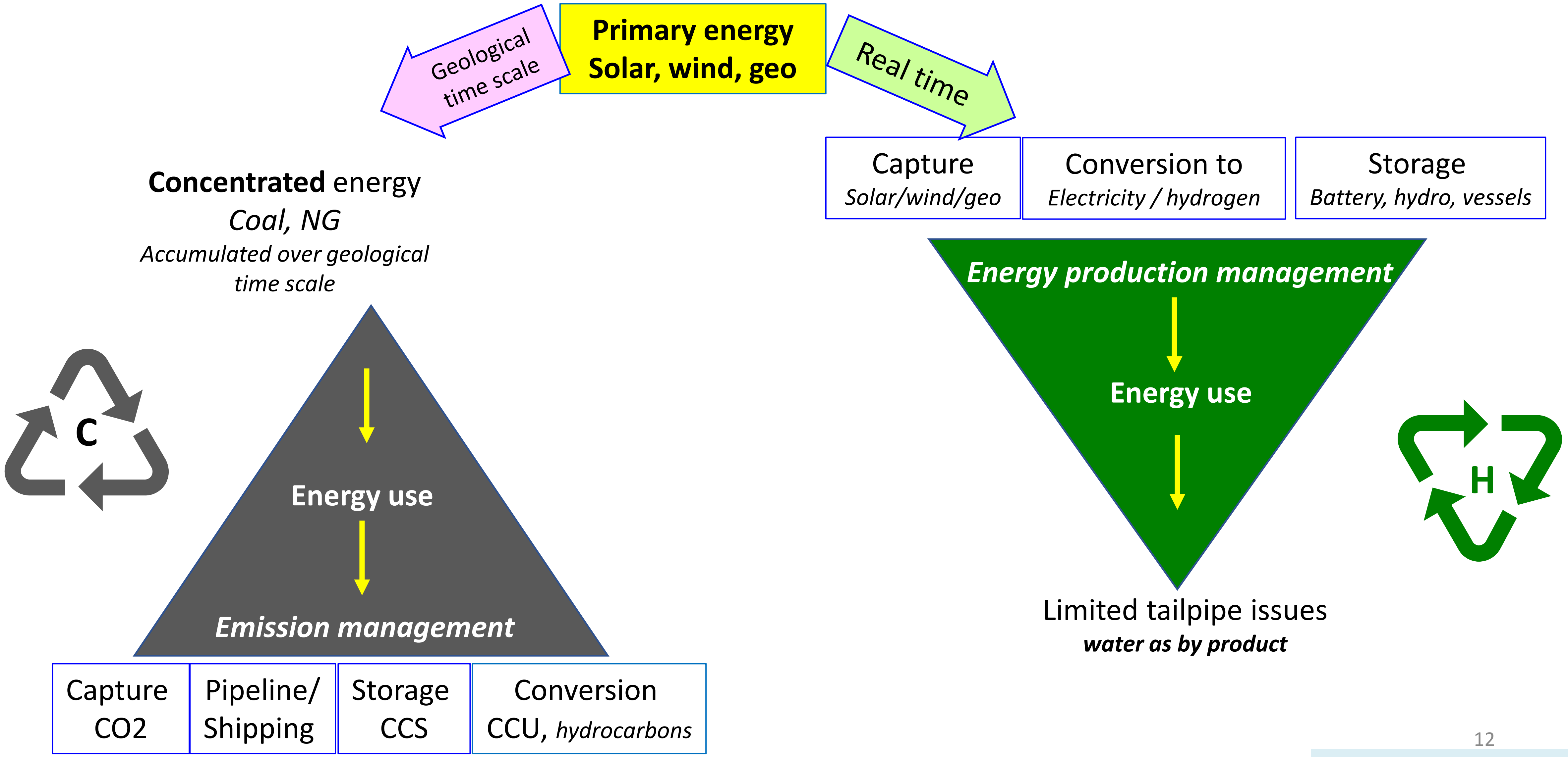
Bill Gates:
How to Avoid a Climate Disaster: The Solutions We Have and the Breakthroughs We Need

How much stuff does it take: Weight of materials, measured in metric tons, per terawatt-hour of electricity generated. "Solar PV" refers to solar photovoltaic panels, which convert light from the sun into electricity. Source: U.S. Department of Energy, Quadrennial Technology Review: An Assessment of Energy Technologies and Research Opportunities (2015), https://www.energy.gov.

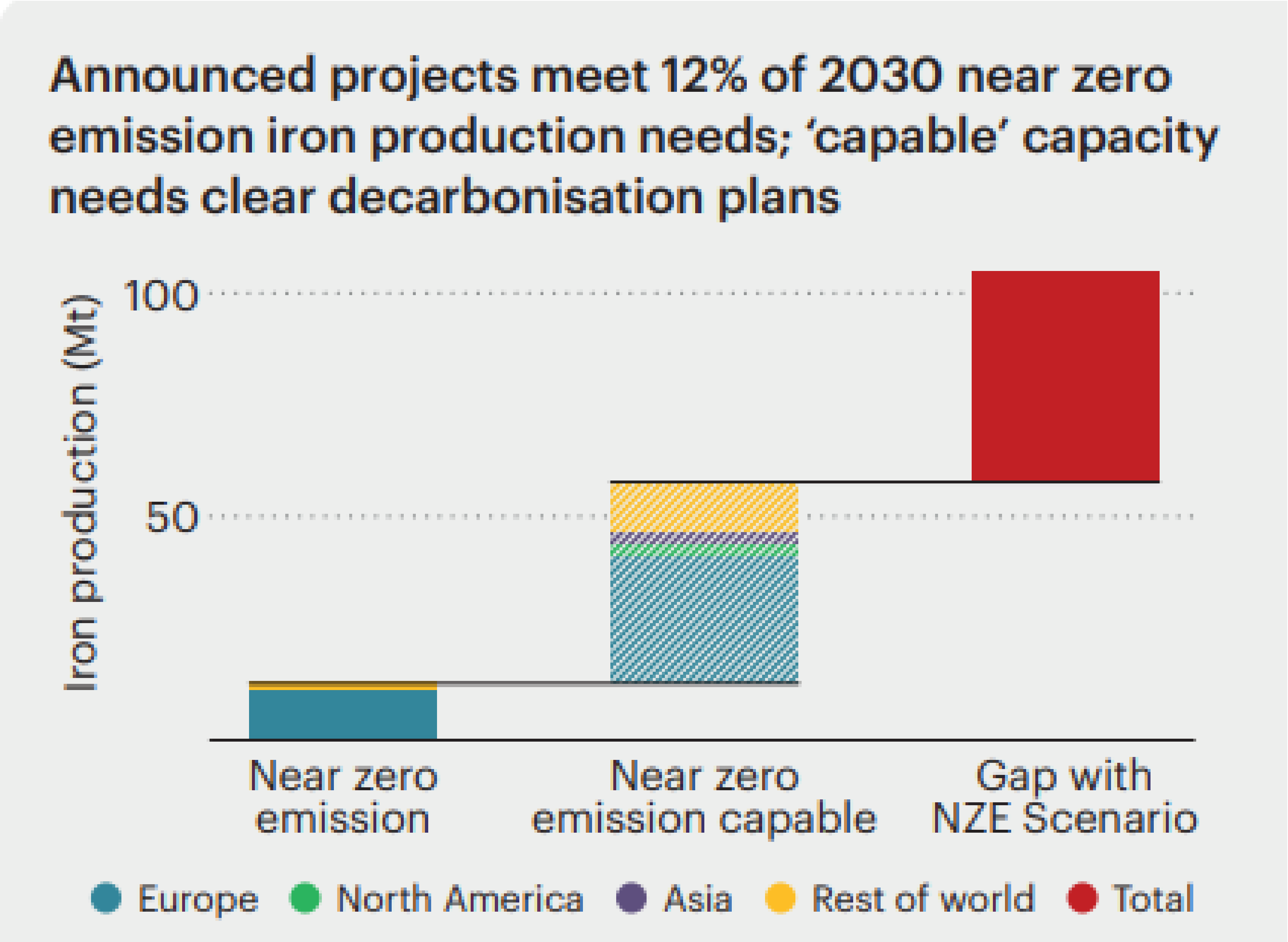


How much stuff does it take to build and run a power plant? That depends on the type of plant. Nuclear is the most efficient, using much less material per unit of electricity generated than other sources do. (U.S. Department of Energy)[12]

Managing **emissions** vs managing **energy production**
downstream vs **upstream** efforts - **C** and **H** as energy vectors



Kumar, A. DBA thesis at Sumas, Switzerland, 2022



Even with impressive progress, it could take 15-25 years for bulk electricity to be 'green'

Table 4.2 : hypothetical scenario of hydrogen based steel production for India – showing demand share of renewable electricity for hydrogen production for steel sector alone

period	2020	2030	2050	*comments*
Steel production, mtpa	100	300	470-570	Data rounded from multiple sources: TERI (2020), IEA (2020), BNEF (2020)[179]
Scrap availability, mtpa	25	50	160	
Need for primary steel, mtpa	80	260	350	
Electricity capacity, GW, needed *for following hydrogen route for all primary steel production*	104	338	455	@ 1.3 GW per 1 mtpa – as estimated in table 1
Estimated total renewable electricity capacity, India, GW	140	350-450	650-900	BNEF (2020)[180]
Potential demand share from green hydrogen for steelmaking	75 %	80 %	60 %	Unrealistic proportion of renewable electricity would have to be dedicated to green hydrogen for steelmaking alone

even after assuming ambitious growth in scrap availability

Large scale shift to H_2-DRI-EAF

*proposition for **India***

(at least till mid-century)

- ***does not*** **reduce CO_2 footprint** based on *H_2 from expected grid electricity (without CCS)*
- ***demands unrealistic proportion*** of renewables electricity / H_2 capacity *– starving other vital sectors of economy, e.g. replacing biomass based cooking*

Kumar, A. DBA thesis at Sumas, Switzerland, 2022

Switching ironmaking from **BFs** to **DRI** shafts:

a lot more than changing reductant molecules (from C to H) ?

DRI	**Blast Furnace**
• **Iron oxide - reduction** 88-95 %	• **Iron oxide - reduction ~100 %**
❖ **Iron ore gangue** – **stays in**, either pre-melt or handle in steelmaking	✓ **de-slagging of gangue** → BF slag to cement
❖ **Carburization** - **add C** into reduction shaft or during subsequent melting	✓ **Carburization** of iron ~ **near saturation**
❖ **De-S in steelmaking**	✓ **De-S** of iron > 85 % in BF + rest at HM DeS station
❖ **Import energy** – for steelworks other users	✓ **Export energy** in gas for steelworks heating and power gen ~ 4 GJ/thm
❖ **Import energy** – for melting, refining	✓ **Energy rich liquid iron** – meet steelmaking needs + absorb 20% scrap

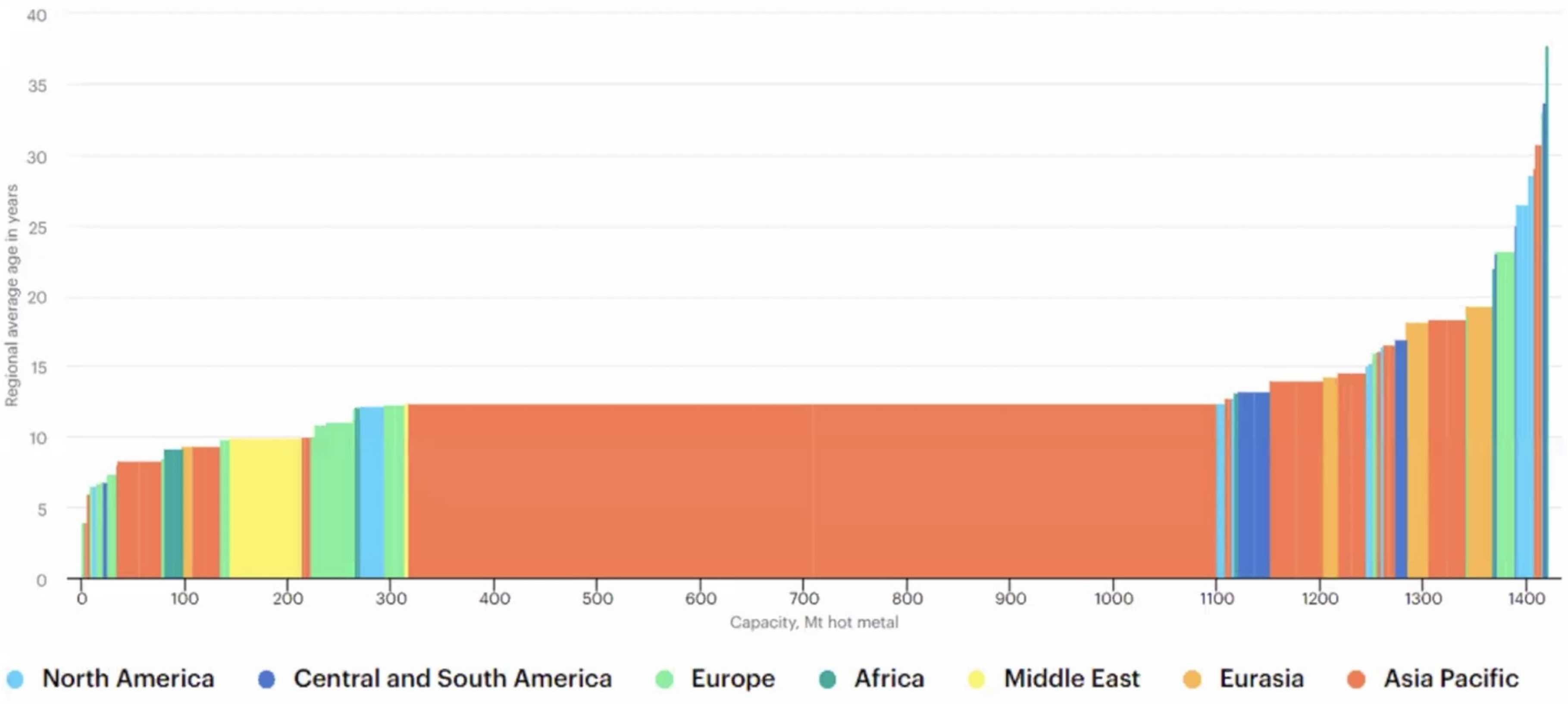
Locked in assets

World steel industry is deeply invested

in highly capital intensive assets – with lifespan of ~50 years

large part of these are less than 15 years old – *<u>in growing economies</u>* - wherein *new additions rather than replacement* is on the agenda

Replacement Agenda: Young age of BF fleet in Asia Pacific



Source: IEA

Extent of change to existing steel plants

modifying energy flows through BF vs *changing all iron and steelmaking*

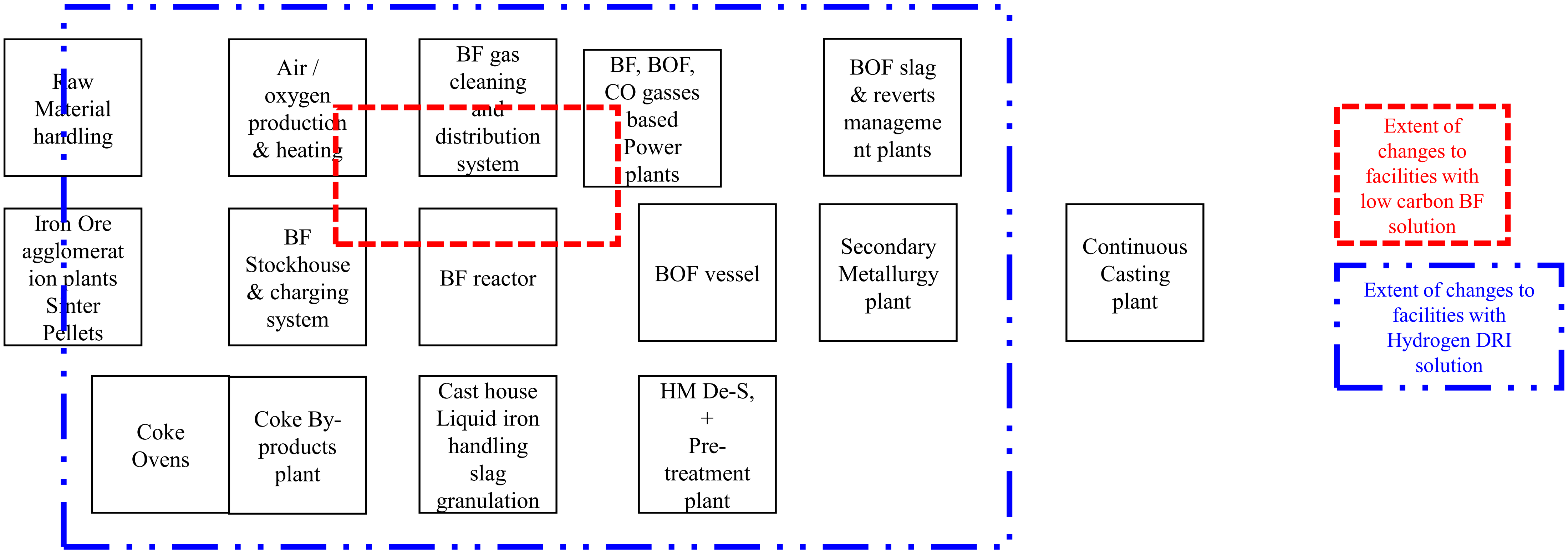


Figure 6 : Investment in integrated steel plants is spread over large number of facilities. The red and blue boxes map out the *extent of change* needed in transitioning to lower carbon footprint by following the BF decarbonization route and hydrogen based DRI-EAF route

(conceptual – based on general features and investments in integrated steel plants)

Kumar, A. DBA thesis at Sumas, Switzerland, 2022

Table 4.6:
The global metallics balance and size of decarbonization challenge now to 2050
(synthesized from data from several sources)

	Steel production billion tonnes per annum (btpa)	Scrap availability (btpa) (% of mix)	Primary production needed (btpa)	Mix footprint (bt CO_2 pa)	
Current 2020	1.9	0.65 *(30 %)*	1.4	3.5	Reference emission
Footprint t CO_2 / t		0.5	2.3		
Estimate 2050	2.5	1.1 *(45%)*	1.5	4.0	***Size of the problem*** to be solved *after accounting for increased use of scrap*
Footprint t CO_2 / t		0.5	2.3		

Increased availability and use of **scrap**

is already accounted for – in determining

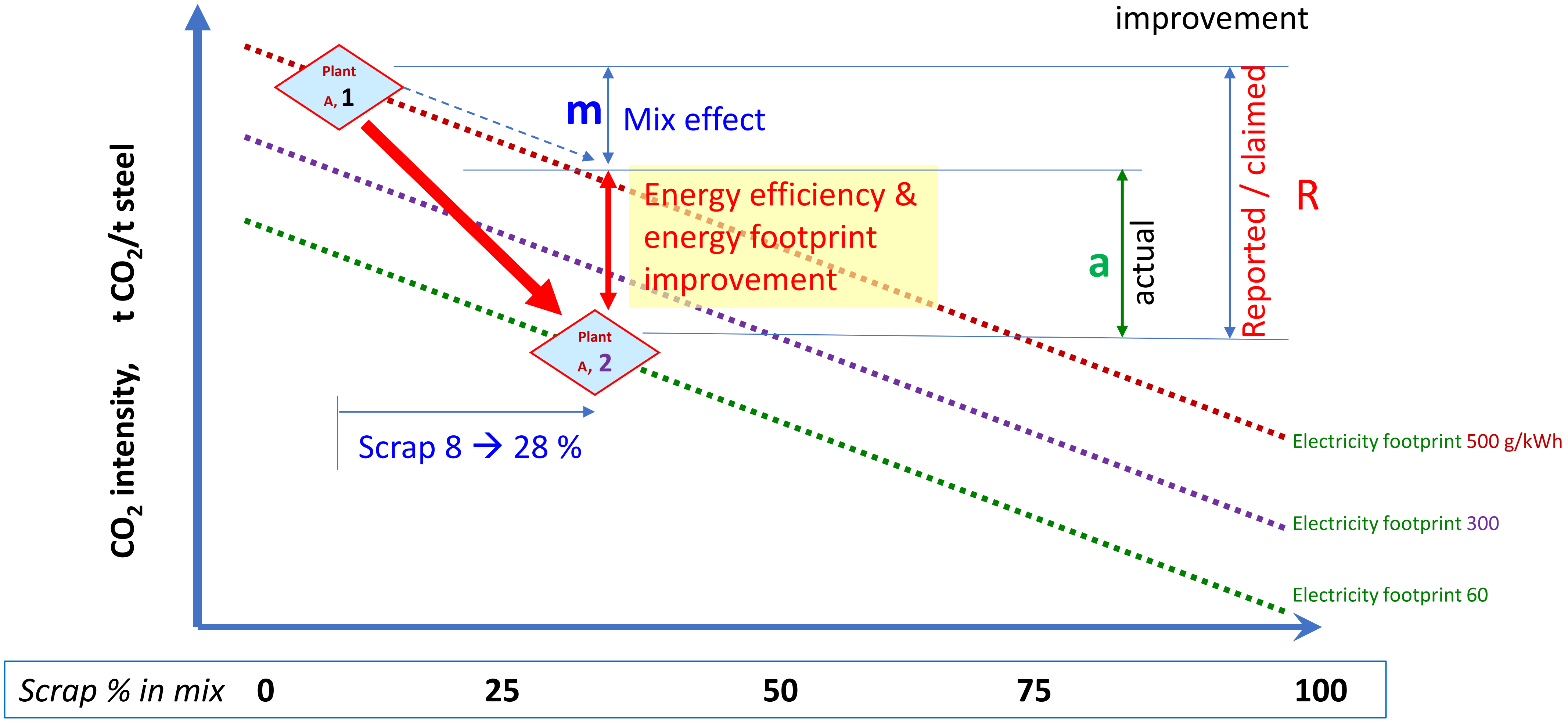
size of the challenge

and as such is

not a lever for decarbonizing
primary steel production

Kumar, A. DBA thesis at Sumas, Switzerland, 2022

A sliding scale for assessing *energy efficiency* and *energy footprint* improvements example of plant A improving from point 1 → 2 – *normalising the scrap mix effect*



Kumar, A. DBA thesis at Sumas, Switzerland, 2022

the

low carbon Blast Furnace

why it matters

and

how

Decarbonising the Blast Furnace

Key process interventions	*Potential impact on fossil carbon use*
• **DeMuGH** ***De**crease **M**olecule **u**se for **G**eneration of **H**eat* augment with renewables based heat – solar thermal, electrical, plasma • **RePuM** ***R**ecycle **P**artially **u**sed **M**olecules* recycle top gas after stripping H2O, CO2, adding heat	40-50 %
• **SwiRM** ***Swi**tch **R**eduction **M**olecules* replace fossil carbon with renewables based hydrogen / COG, and sustainable bio carbon 20 kg H2 ~ 15% + 10 % replacement by bio carbon	25 %
• CCUS	25-35 %

Blast Furnace process – *separating **reduction** and **energy** needs*

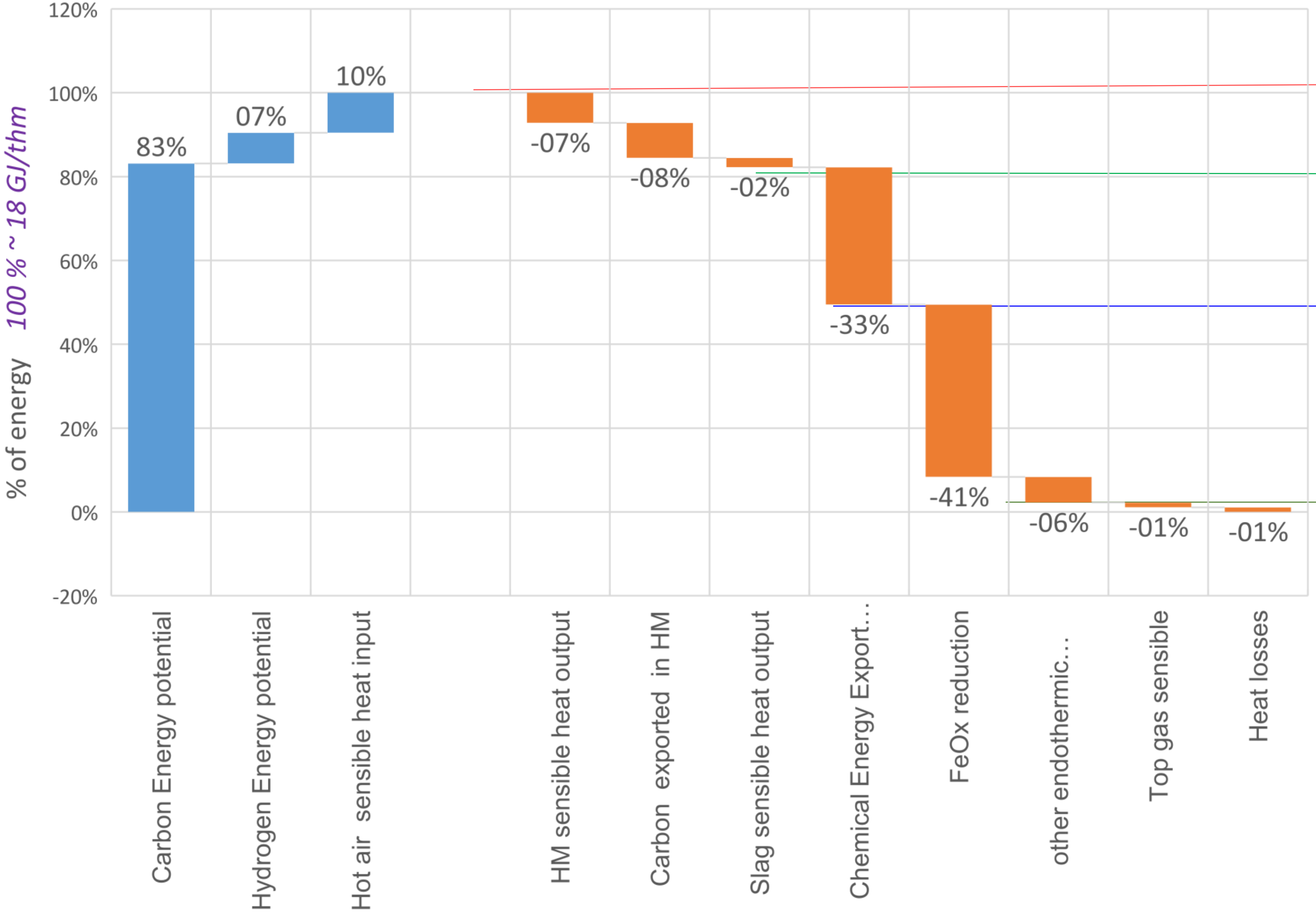
Carbon for reduction only	*Carbon as used in BF today*
$Fe_2O_3 + 1.5\ C = 2Fe + 1.5\ CO_2$ ← **energy**	$Fe_2O_3 + 4\ C + 1.5\ O_2 = 2Fe + 2\ CO + 2\ CO_2$ → **energy**
• 151 kg C / thm + 45 kg (for HM C dissolution) = **196** kg/thm	• 403 kg C / thm + 45 kg (for HM C dissolution) = **448** kg/thm
• Energy needed 8.5 GJ/thm (reactions) + 2.3 GJ/thm (heating + losses)	• Energy used 8.5 GJ/thm (reactions) + 2.3 GJ/thm (heating + losses)
	• Energy export to power + ironmaking zone & downstream heating **6** GJ/thm
augmented by 20 kg/thm hydrogen	
$Fe_2O_3 + 0.84\ C + 0.66\ H_2 = 2Fe + 0.84\ CO_2 + 0.66\ H_2O$ ← **energy**	
• 85 kg C / thm + 45 kg (for HM C dissolution) = **130** kg/thm	

Kumar, A. DBA thesis at Sumas, Switzerland, 2022

Blast Furnace - through the energy lense: INPUT = OUTPUT

typical modern BF with ~450 kg Carbon use per t HM

The **BF distributes** more energy than it uses for “**ironmaking**” per se



18 % energy available as input for steelmaking; & cement production

33 % energy exported as BF gas for heating and power generation applications

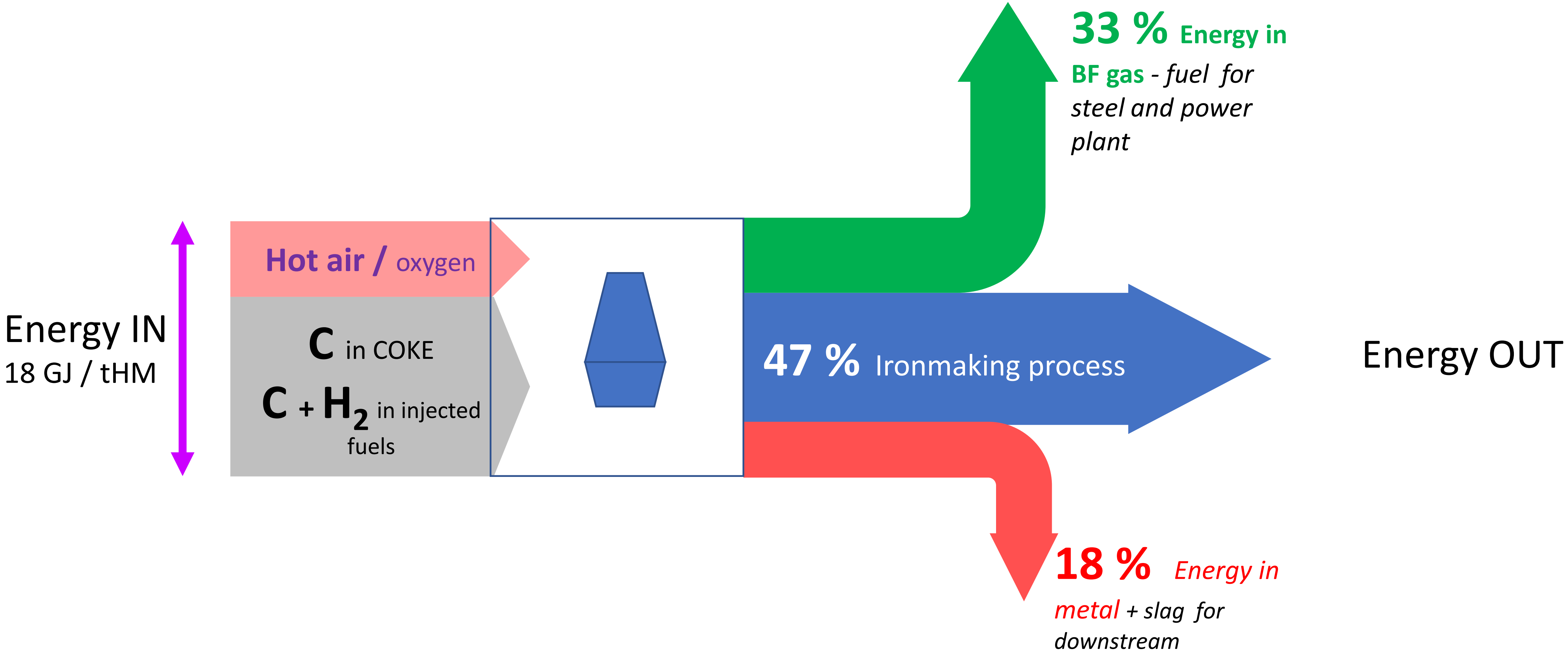
47 % energy used in ironmaking reactions and melting

2 % energy as losses

Figure 7 : An energy accounting view of inputs and outputs from the BF

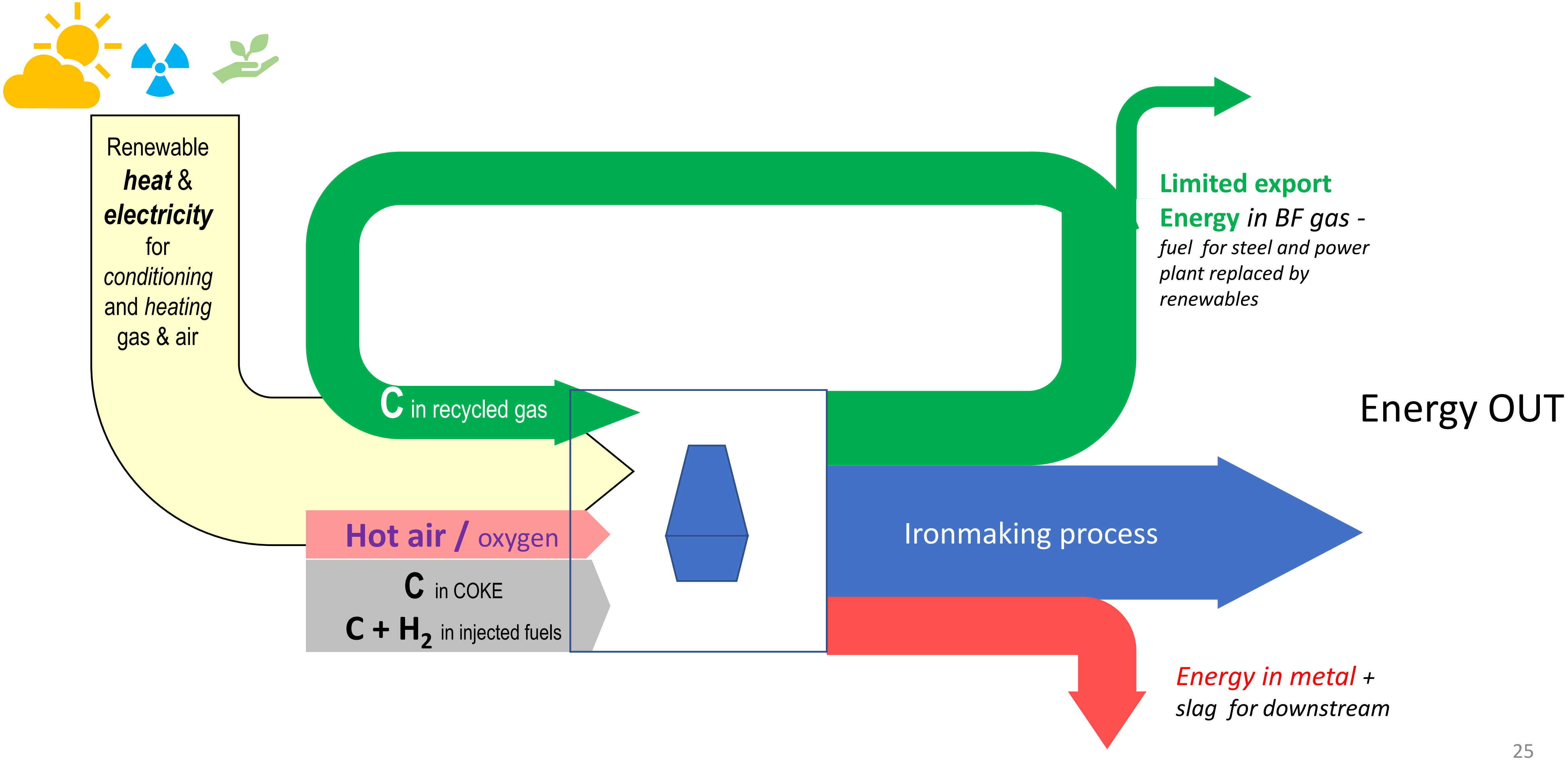
(own calculations based on first principles thermodynamic data)

Blast Furnace through the **energy** lense → *an Energy Distributor*



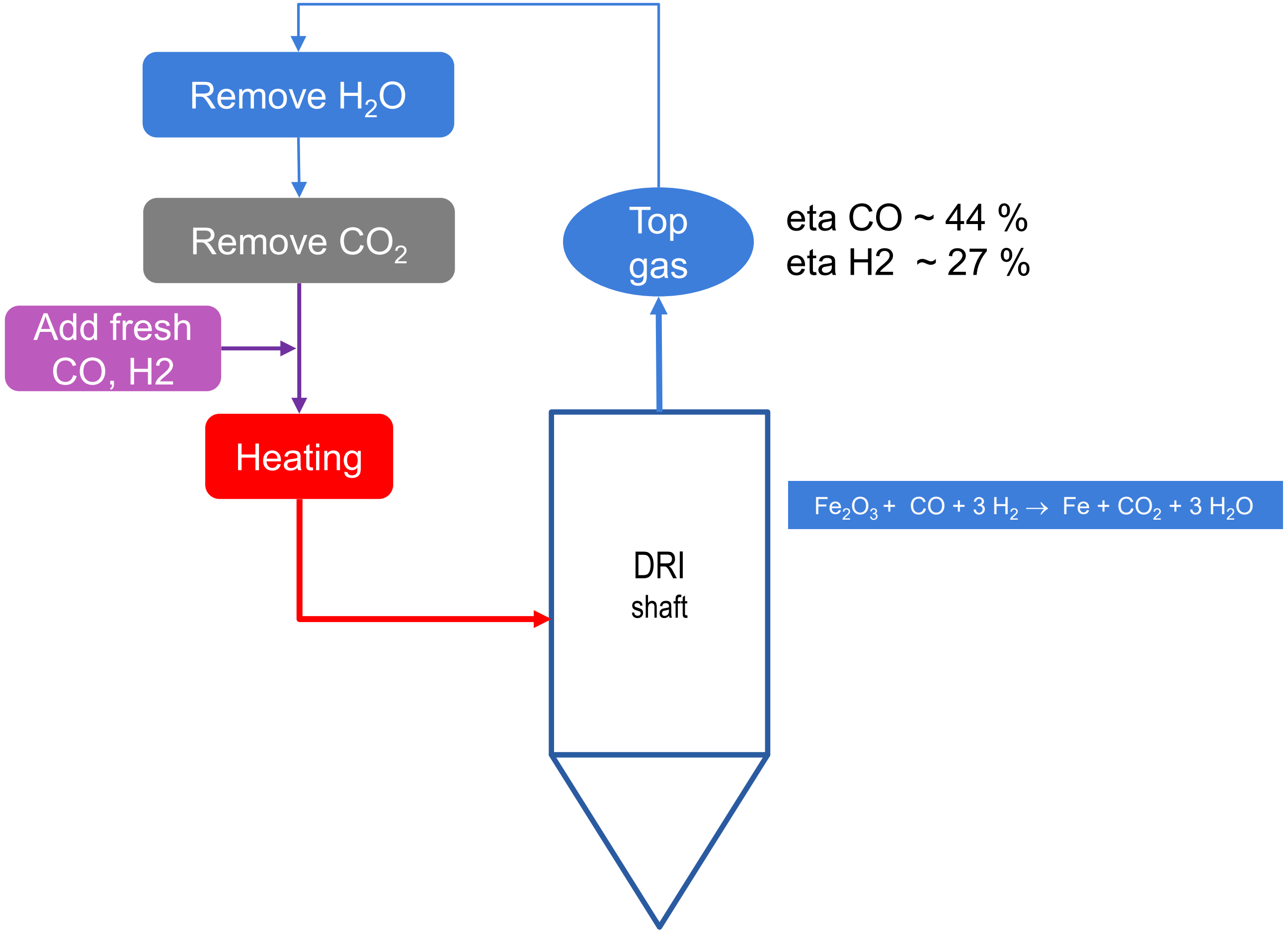
Kumar, A. DBA thesis at Sumas, Switzerland, 2022

Blast Furnace: *rearranging Energy sources & flows*



Kumar, A. DBA thesis at Sumas, Switzerland, 2022

Recycling reduction molecules is key



If the DRI shaft operated in '**one pass**' mode *(like the BF)*, the consumption of natural gas would be *three* times;

… and the CO_2 footprint to just make DRI *(using Natural Gas)* would be *higher* than that of making hot metal in the BF *(using coke / coal)* !

Blast Furnace through the CARBON lense *(case of enhanced top gas recycle)*

→ *RECYCLE **C** in export gas to BF itself, leaving general energy demands outside BF to be met by renewable energy*

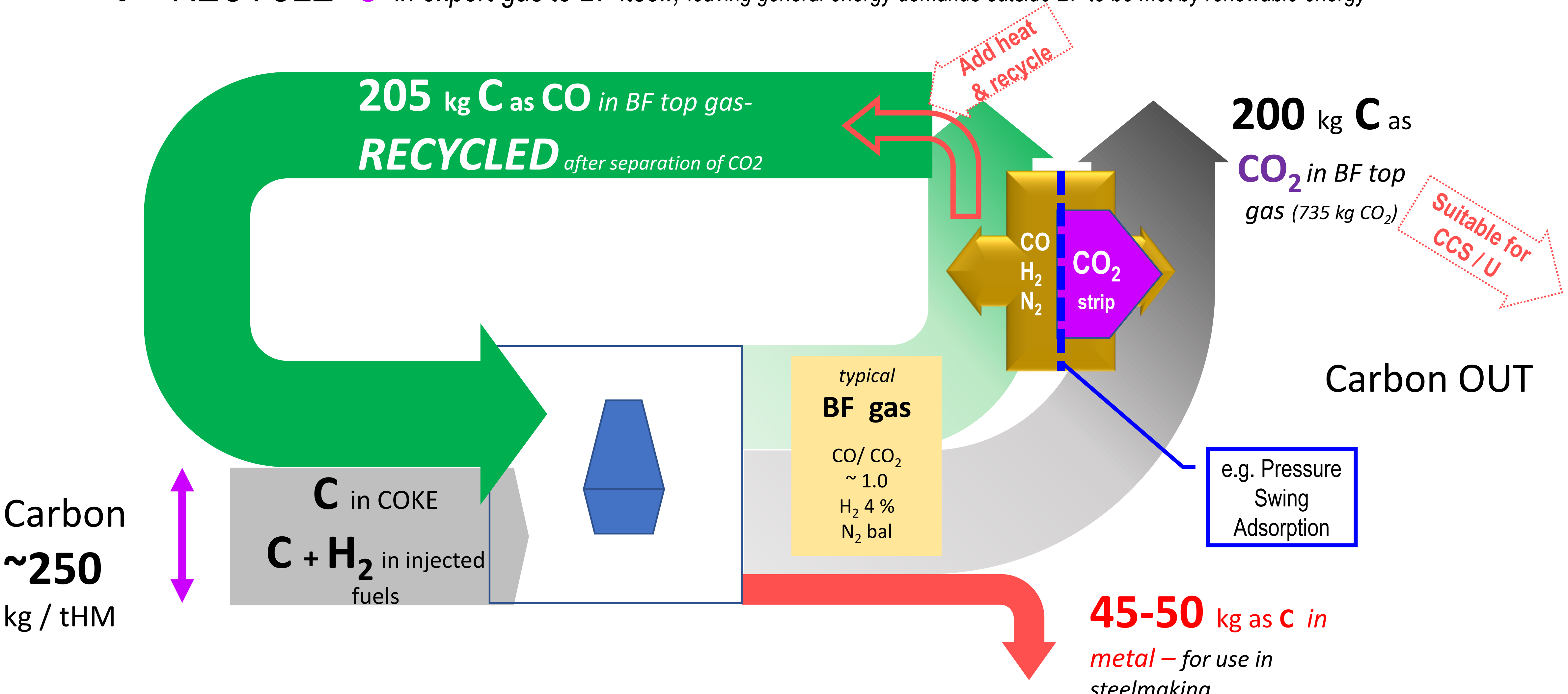


Figure 11: A vision for carbon optimized BF - *through the carbon lens* **:** recycled carbon (as CO, with added H_2 and heat) avoids ~ 200 kg/thm of fresh carbon units consumption; while 200 kg/thm of carbon units (as CO_2) get captured for CCUS. It is the sum total of *BF TGR* concept superimposed with 'renewables based' *heat* and *hydrogen*; and *CCUS*. *(own calculations based on first principles thermodynamic data)*

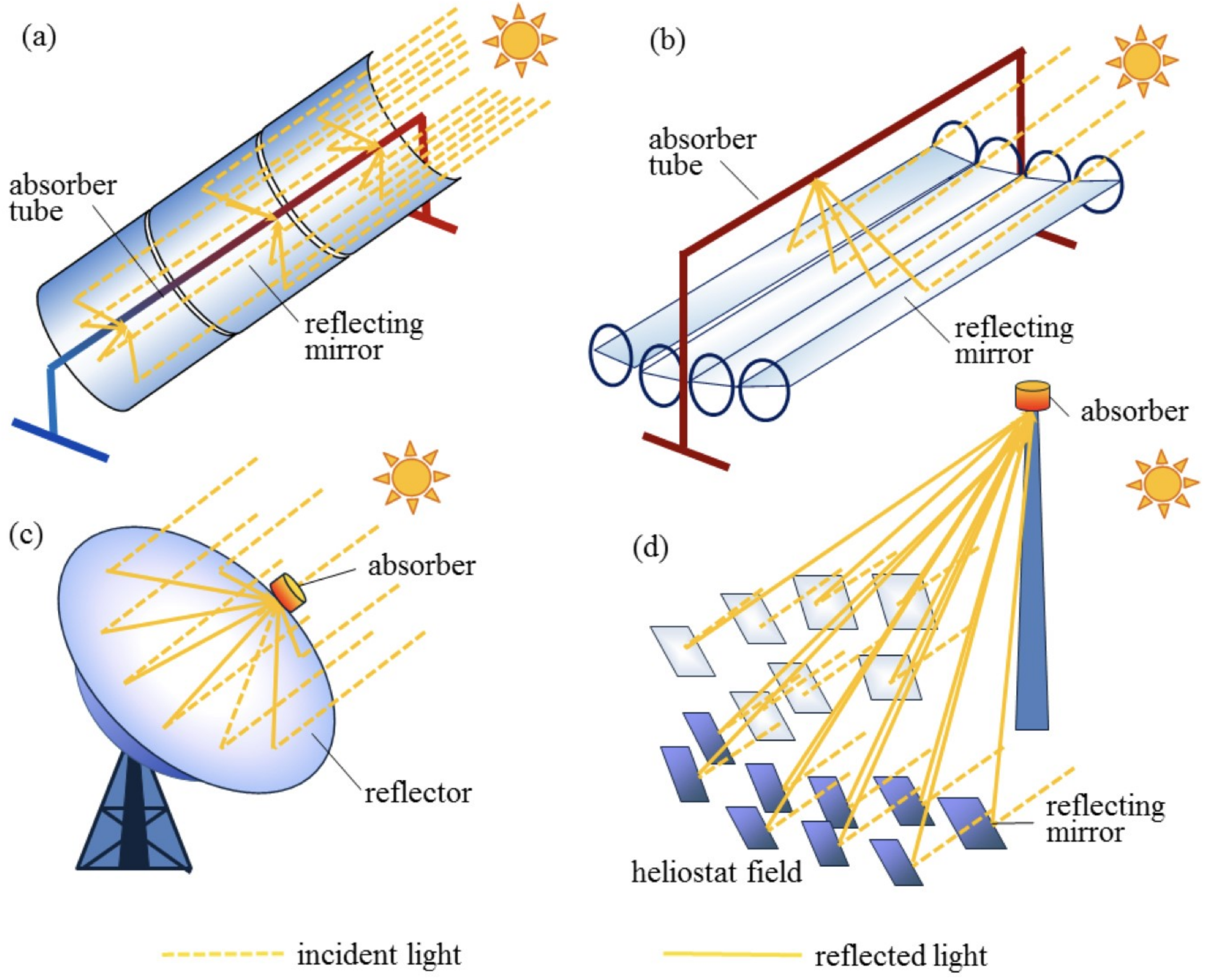


Figure 2: Four types of solar collecting systems in use: a. Parabolic Trough; b. Linear Fresnel; c. Parabolic Dish; d. Solar Tower [Modified from Quaschning (2003)]

Bypass molecule use for raising temperature ?

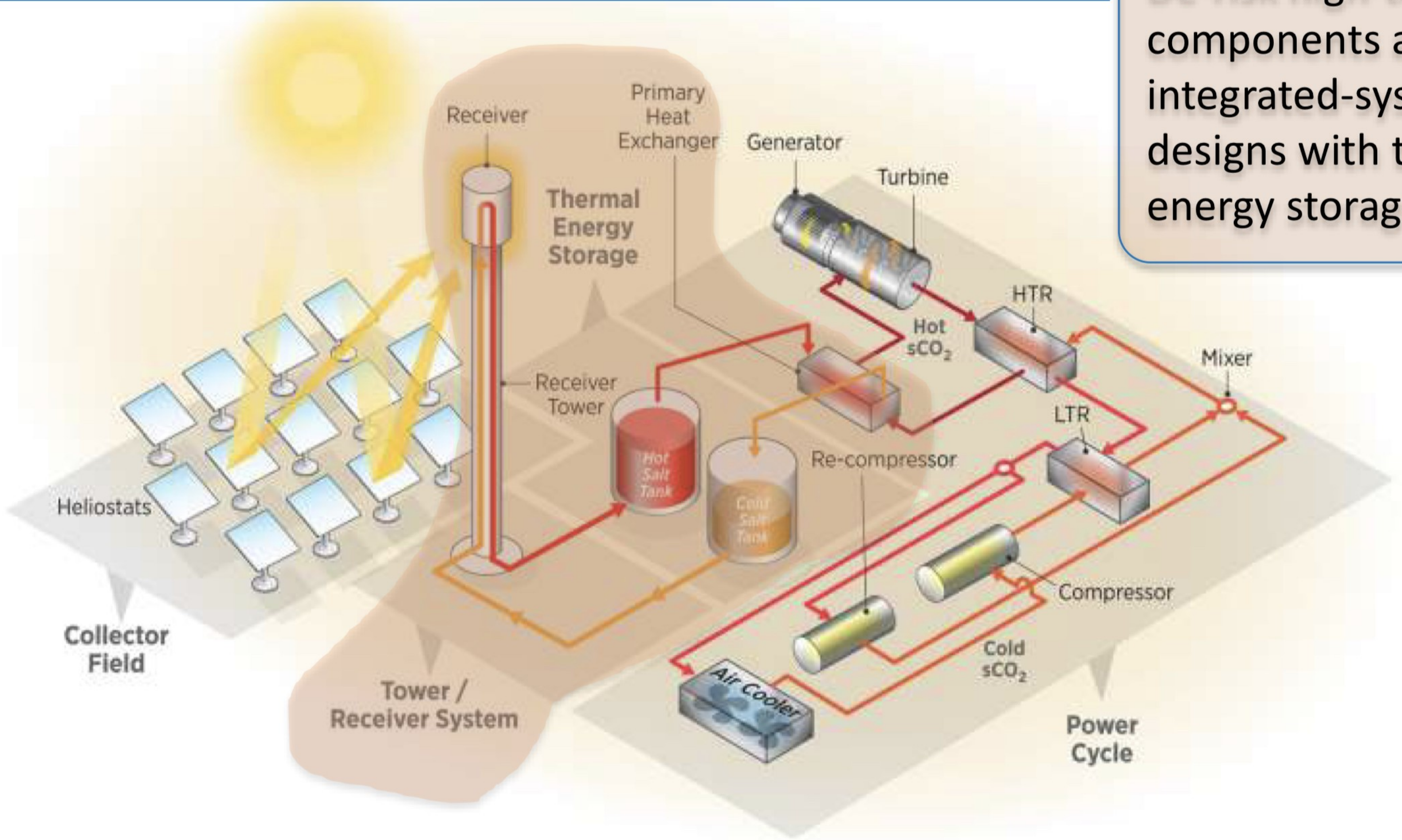
e.g.
High temperature heat ..

... directly through concentrated solar

Storage of high temperature heat *concepts…* ..

addressing intermittency problem of renewable energy

Liquid Pathway
Thermal Transfer System



Goal:
De-risk high-temperature components and develop integrated-system designs with thermal energy storage at >700 °C

Potential Solar IPH Configurations

New Solar IPH markets could open up as:

- the cost of solar technologies (CSP and PV) declines
- the cost of complementary technologies (storage, efficiency, electrification) declines

Solar technologies could meet a broad range of industrial process temperature requirements.

Solar Technologies	Temp Range	Applications
Thermal flat plate, Non-tracking compound, Solar pond, PV + heat pump or microwave	<80°C	Hot water, Space heating, Drying, Curing
Parabolic trough, Linear Fresnel, PV + infrared	<550°C (depending on HTF)	Drying and curing Steam for IPH
Heliostat/central receiver	>550°C	Steam for IPH, Lime calcining
PV + Induction	<1,100°C	Heat treating
PV + Resistance	<1,700°C + (material dependent)	Steam for IPH Glass melting
PV + Electric arc	<4,000°C	Metal melting

SETO CSP Program Summit 2019

Based on data in: Chindris and Sumper (2012) and Cheremisinoff (1996).

4

Energy needed for "heating" *does not necessarily need to come from carbon, hydrogen or even electricity* – it can simply be direct heat from solar or geothermal sources

A lot of energy for steelmaking is merely heat – and current developments in concentrated solar will answer to meeting significant part of the steel requirement

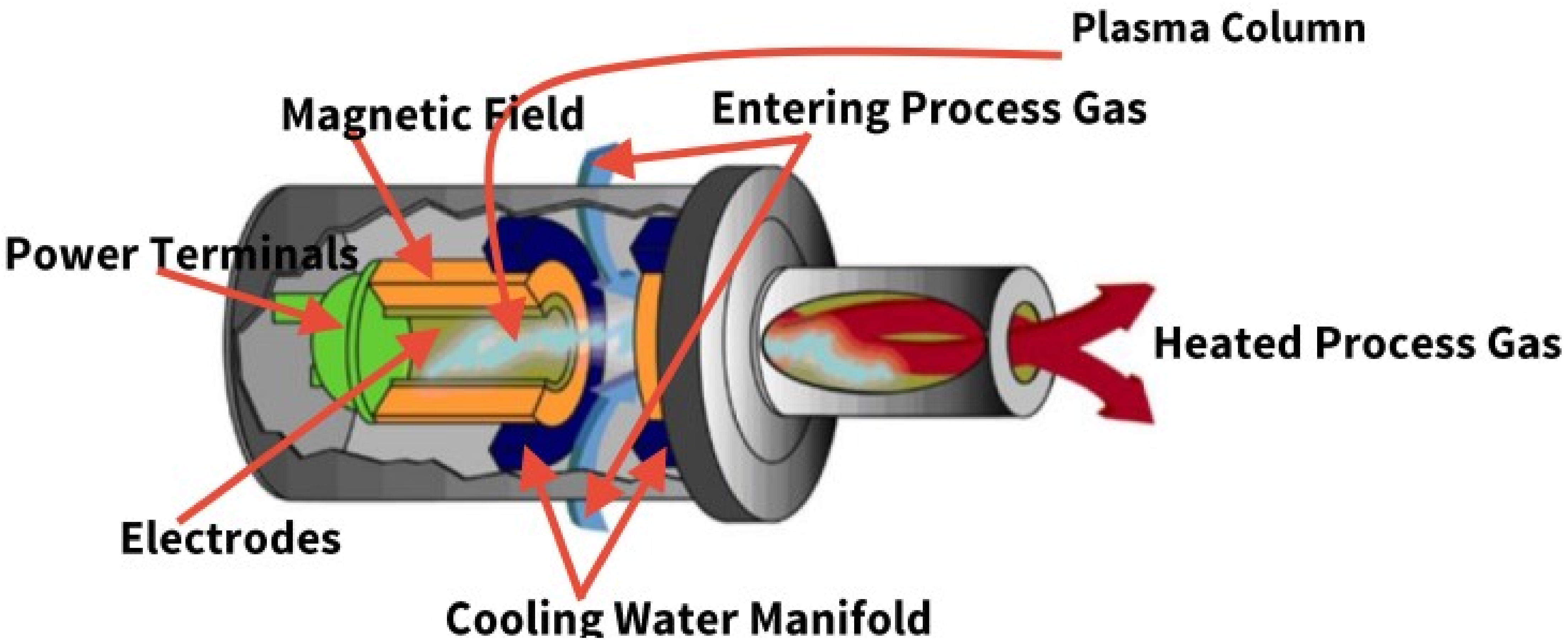
Off Grid Energy Independence

Posted on November 26, 2019

Concentrated Solar Energy to Exceed 1000 Degrees Celsius

Heliogen is transforming sunlight to create and replace fuels and has announced its launch and that it has - for the first time commercially - concentrated solar energy to exceed temperatures greater than 1,000 degrees Celsius. At that temperature, Heliogen can replace the use of fossil fuels in critical industrial processes, including the production of cement, steel, and petrochemicals, dramatically reducing greenhouse gas emissions from these activities. This singular scientific achievement was accomplished at Heliogen's commercial facility in Lancaster, California. For more information see the IDTechEx report on Distributed Generation: Minigrid Microgrid Zero Emission 2018-2038.

Plasma : electrical energy → heat



Kumar, A. DBA thesis at Sumas, Switzerland, 2022

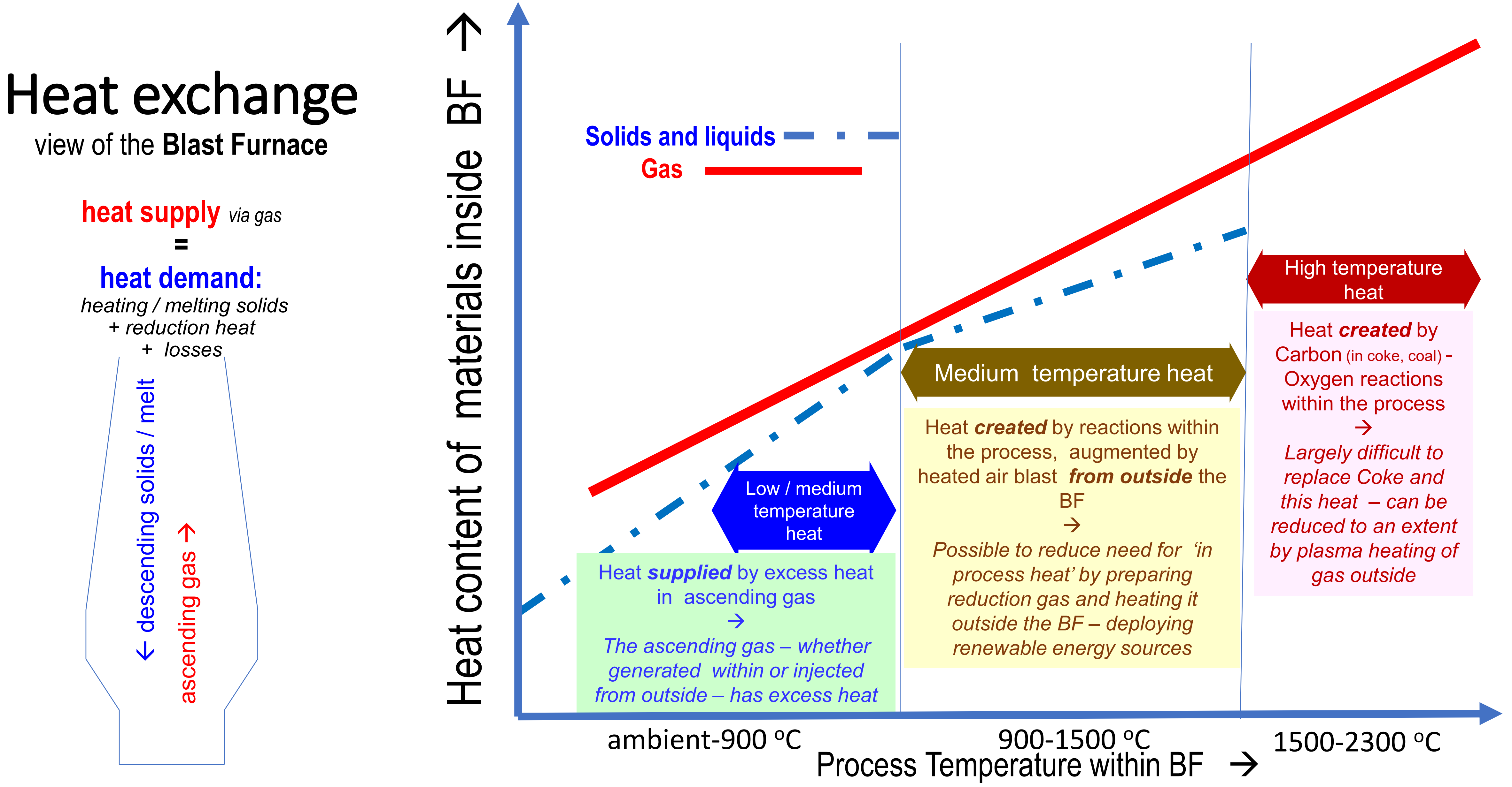


Figure 14: Heat and temperature view of BF process – categorized by 'quality of heat'. It has been assessed that the highest temperature heat within may still need to be generated in-situ – though the limit can be aspired to change over time. *(own conceptualization based on first understanding of BF process)*

Blast Furnace process – "externalising" energy sources

Limited gas generation within BF: *balancing gas amount and temperature through hot gas injection at various levels*

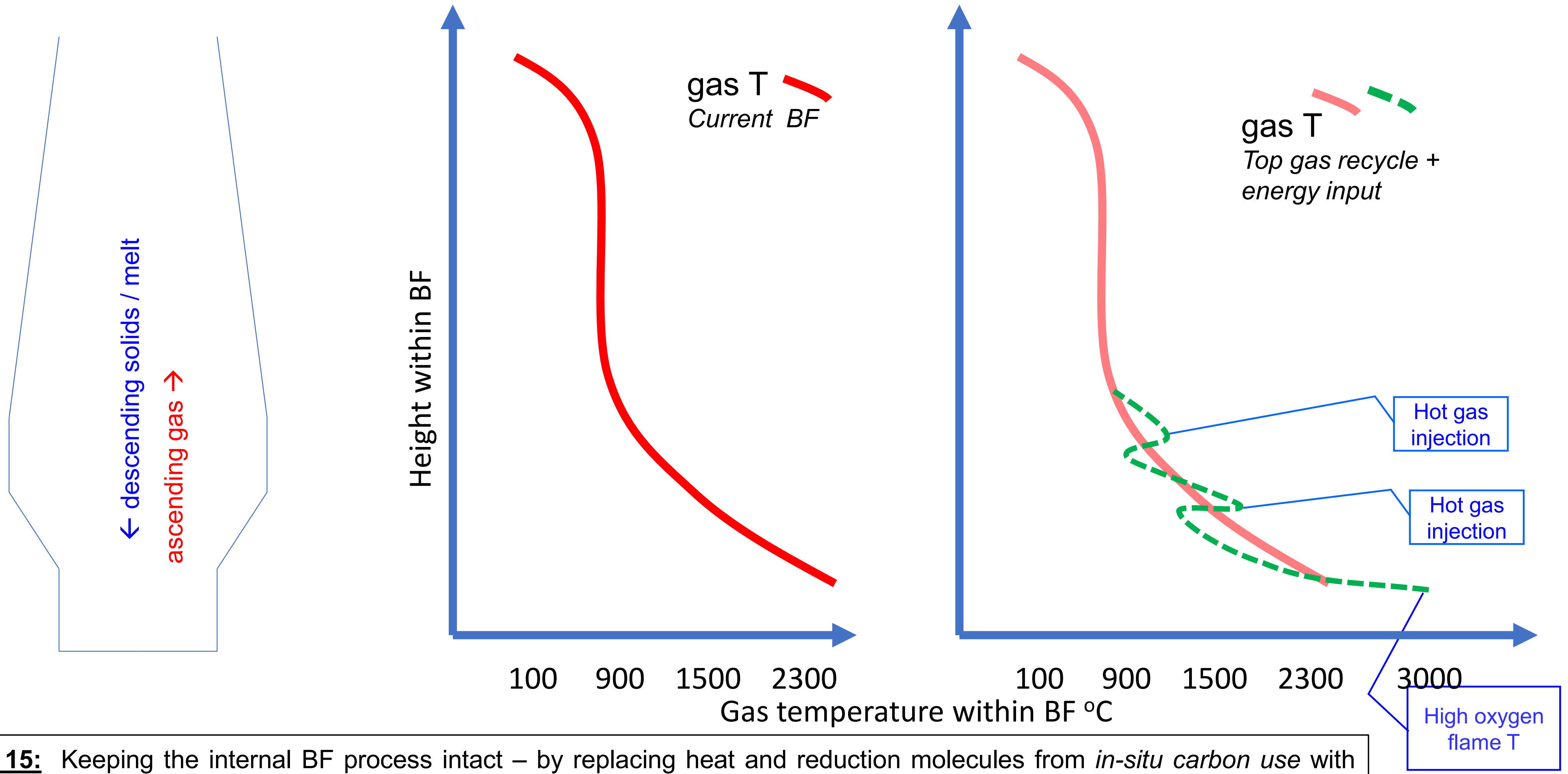
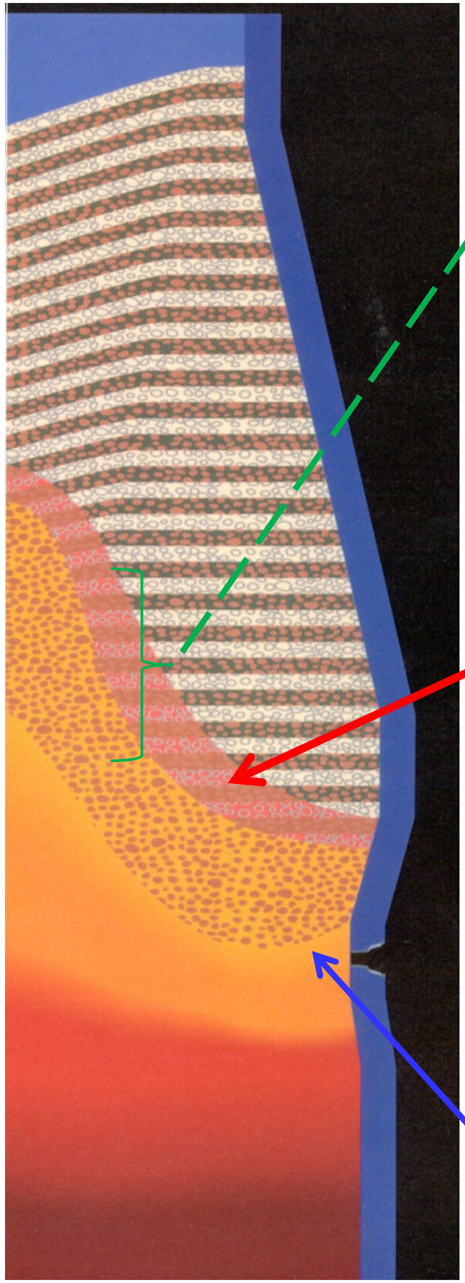


Figure 15: Keeping the internal BF process intact – by replacing heat and reduction molecules from *in-situ carbon use* with those *injected from outside (heated & recycled top gas).* *(own conceptualization based on understanding of BF process and TGR concept)*

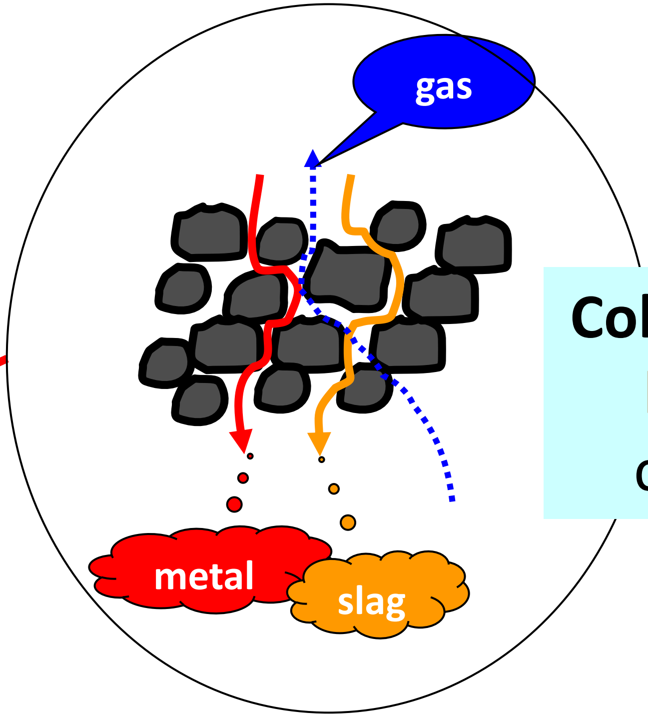
Role of Coke in the BF process



Regeneration of reducing gas

$$CO_2 + C \Leftrightarrow 2CO$$

$H_2O + C \rightarrow CO + H_2$ …



Coke bed enables **liquid** – **gas** counterflow

Generation of heat & reducing gas

$$\frac{1}{2}O_2 + C \rightarrow heat + CO$$

$C_xH_yO \rightarrow xCO + yH_2$ …

In part taken over by coal injection

Injection of conditioned reducing gas

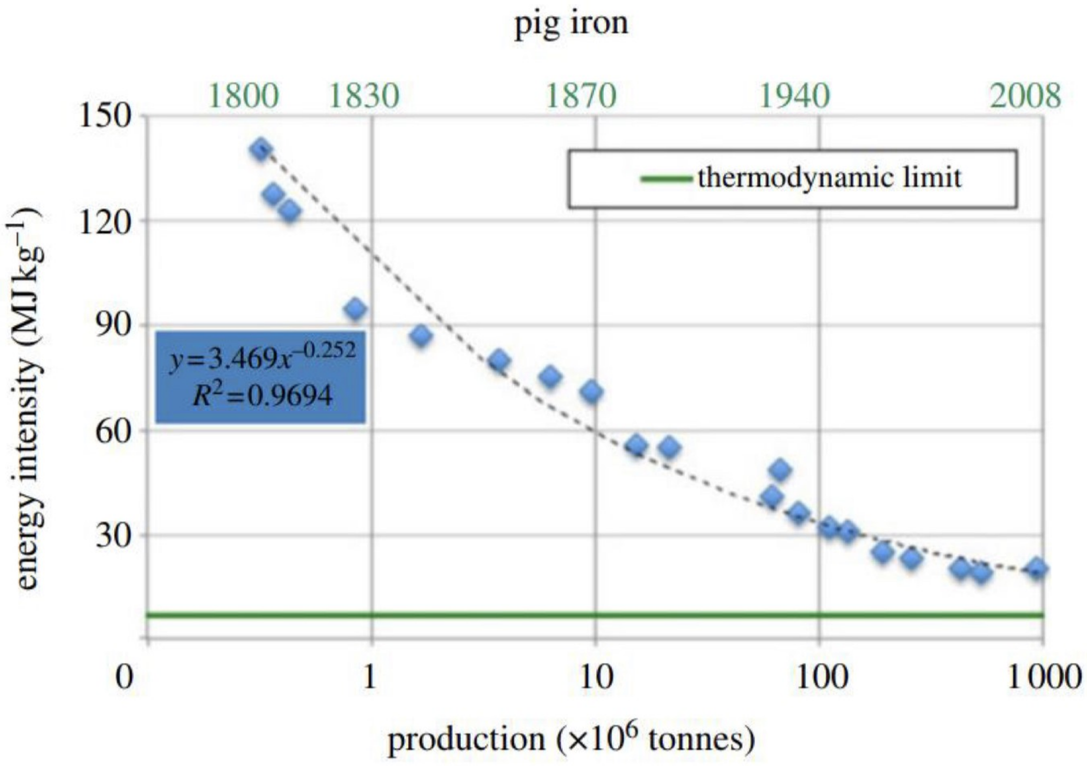
Continued role for coke

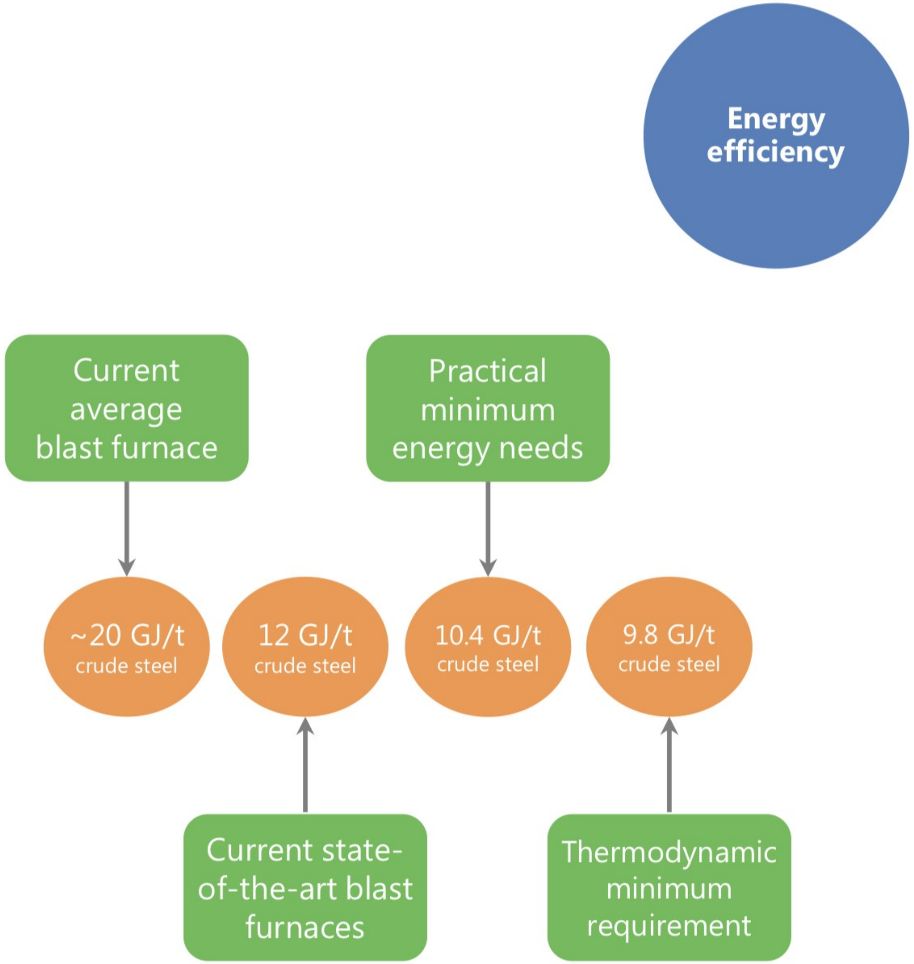
Continued role for coke

Taken over by coal injection

Replace by external heat & molecules

Enabling strategies for sustainable iron and steel production



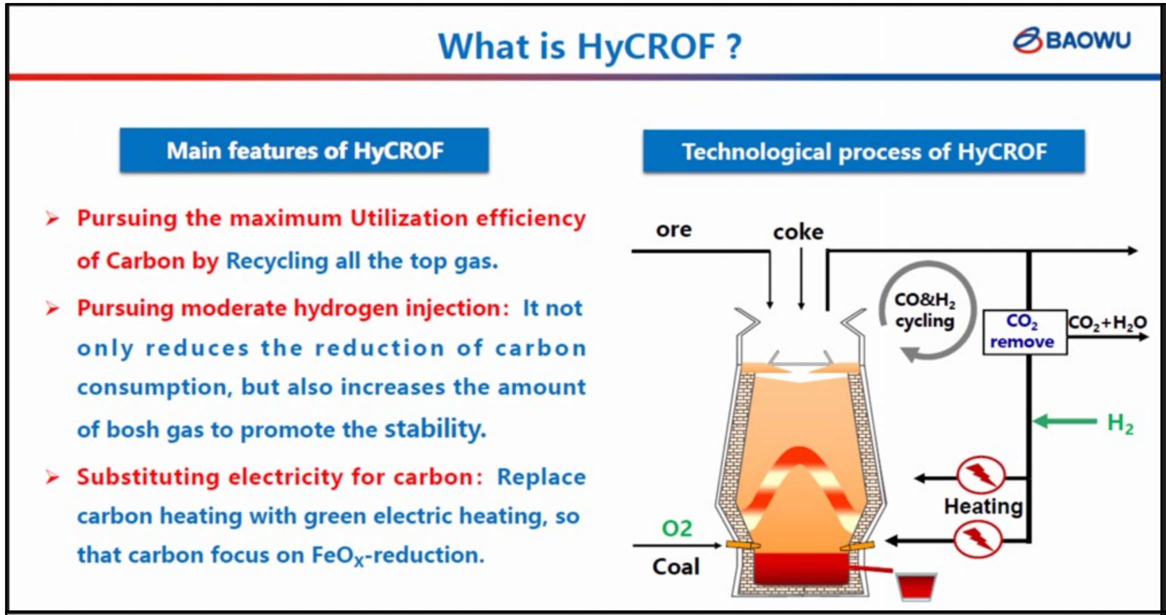


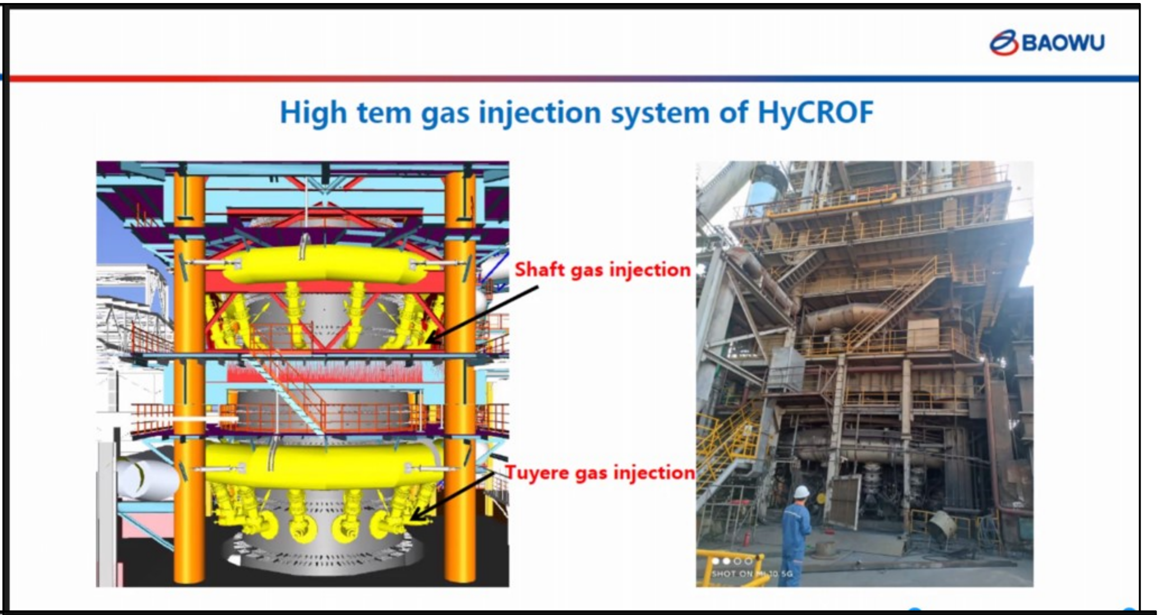
Source: Gutowski et al. (2013), "*The Energy Required to Produce Materials: Constraints on energy-intensity improvements, parameters of demand*", *Phil. Trans. R. Soc. A, 371.*

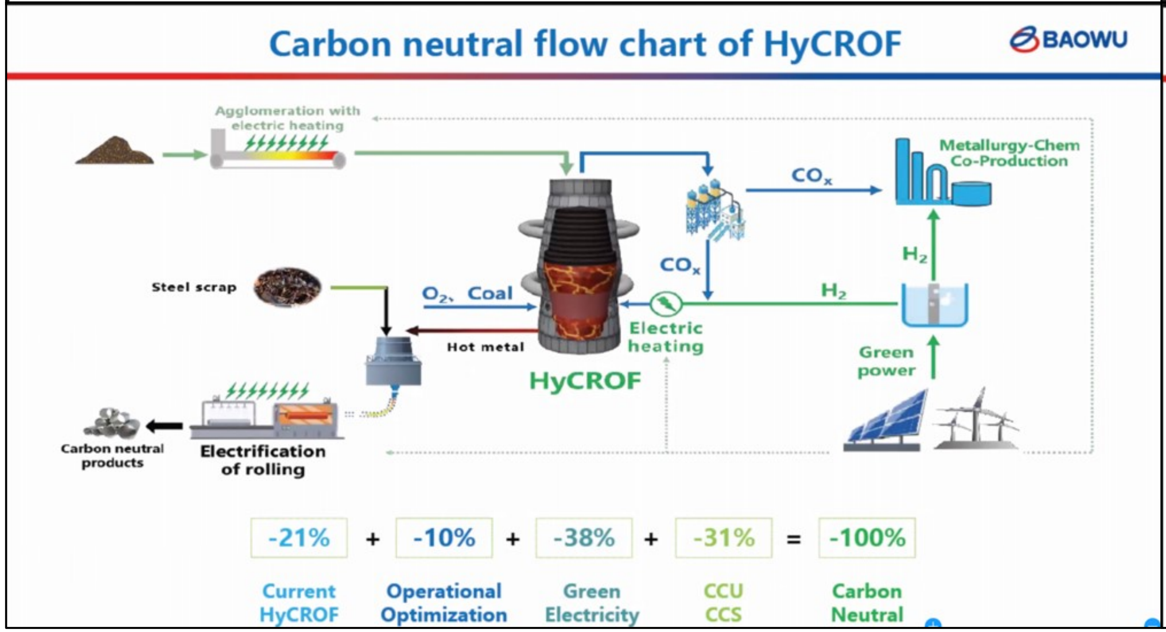
Figure 5 : Continuing evolution of the BF over 200 years – and further potential for reduction in energy consumption.

chart credit IEA source

BFs starting to change amongst large steelmakers







CO_2 accumulation in the atmosphere over the years

attributable to ***global steel industry****, with following pathways:*

Business as usual – *with projected electricity footprint improvements built in*

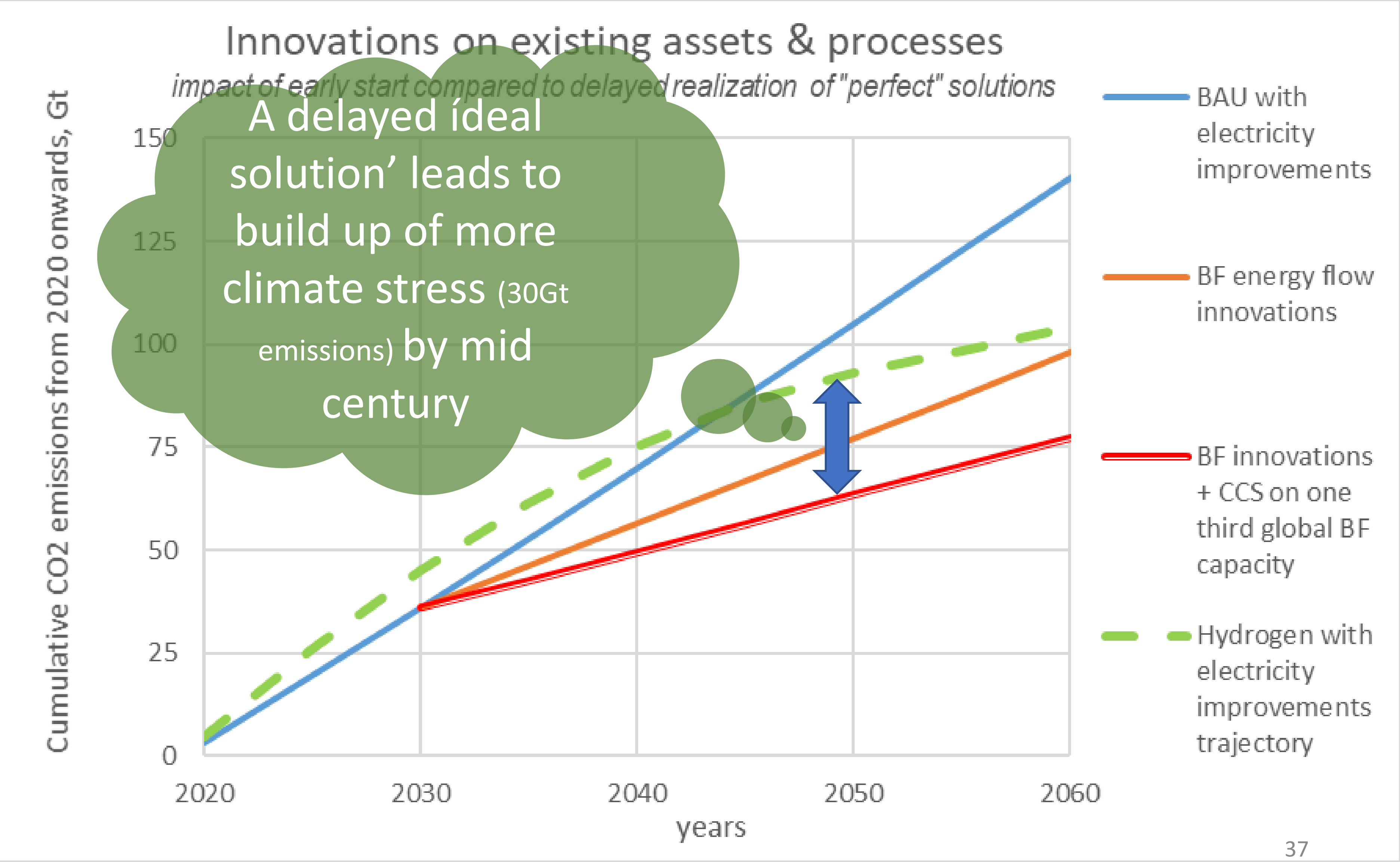
Blast Furnace System – *with* **some recycling** *innovations incorporated*

Blast Furnace System – *with* **some recycling innovations + CCS** *in one third capacity incorporated*

Electrolyser hydrogen based iron production (DRI) melted in EAF (electricity based)

Innovations on existing assets & processes

impact of ***early start*** *compared to delayed realization of "perfect" solutions*



Kumar, A. DBA thesis at Sumas, Switzerland, 2022

Findings: Climate change and Steel industry

- **Global warming** is result of accumulation of GHG molecules in the atmosphere

- **World is falling behind** in *reining in emissions* of GHGs – needed for restricting global warming.

  → Global ***steel industry*** too is amongst the laggards – facing both *technological* and *economic* hurdles to lowering CO_2 emissions from primary production

- **Steel industry** declared plans / project announcements are focused largely on *electrification* (incl *hydrogen* as energy vector). These:
  - shift the onus for providing energy to outside of the steel industry,
  - come largely from Europe - with limited appeal for other regions with diverse economic and geographical conditions;
  - demand unrealistic amounts of renewables-based electricity - many geographies do not appear to have the *luxury for allocation* or *potential for production* - of commensurate renewables based electricity capacity

Findings: Broadening the Pathways..

1. **Creating rather than 'killing' energy alternatives**

   Distinguishing between *energy*, *energy vectors*, *emissions;* Recognize *earth's carbon cycle*, *circularity, efficiency opportunity*

2. **Why the BF matters - and will continue to do so**

   Integrated *metallurgical* and *energy* efficiency, *existing capacity*, *potential*

3. **Rethinking the BF**

   Distinguishing *carbon* and *energy* functionalities, renewable *heat*, carbon *circularity*,

4. **Further process reconfiguration possibilities**

   Leveraging hydrogen better; *synthetic hydrocarbons*, *synergy across industries*

5. **Changing the BOF process**

   Absorbing increased scrap arising *without building new steel plants*

6. **Focus innovation effort**

   Direct *solar to hydrogen*, *renewable heat*, *heat storage*, *gas separation technology*, *materials*

7. **Improvements in measurement framework**

   Sliding scale primary vs secondary steel production, *cumulative emissions* over time rather than specific intensity

Kumar, A. DBA thesis at Sumas, Switzerland, 2022

Thank you