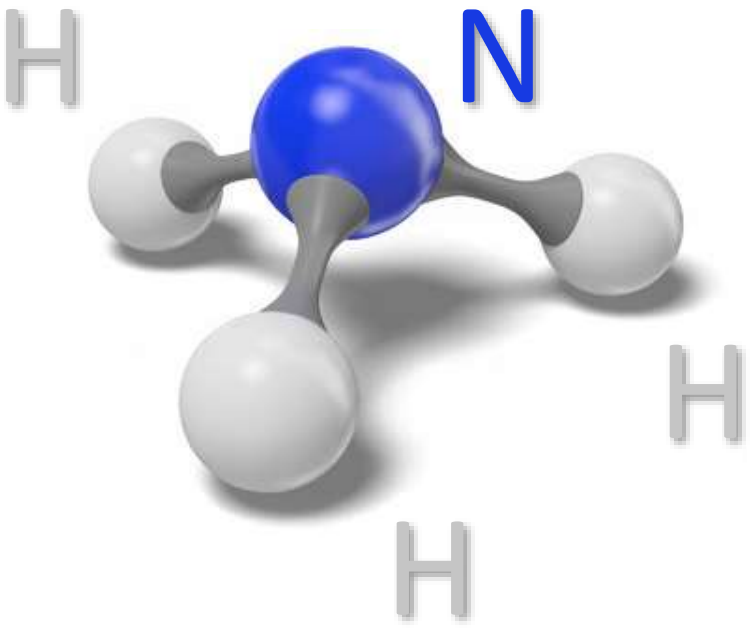
Green steel with Hydrogen from Ammonia (NH_3)



MAX-PLANCK-INSTITUT
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CORVUS FERRUM

What is ‘Green Steel’?

D. Raabe, The Materials Science behind Sustainable Metals and Alloys, Chem. Rev. 2023, 123, p. 2436
OPEN ACCESS - Free LINKS:
https://pubs.acs.org/doi/full/10.1021/acs.chemrev.2c00799
https://onlinelibrary.wiley.com/doi/full/10.1002/advs.202300111
https://www.nature.com/articles/s41586-019-1702-5

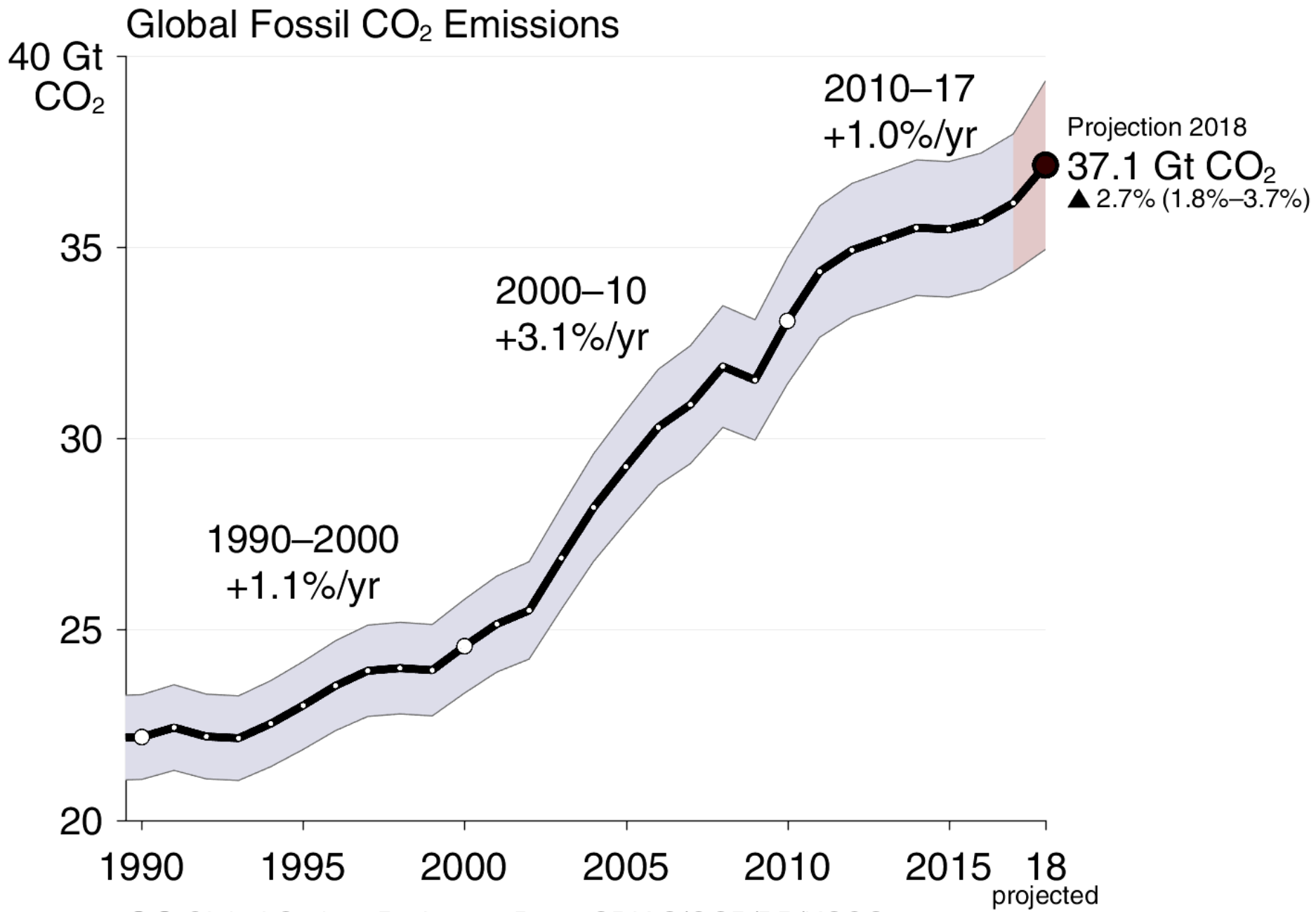
Steel with...

lower carbon footprint

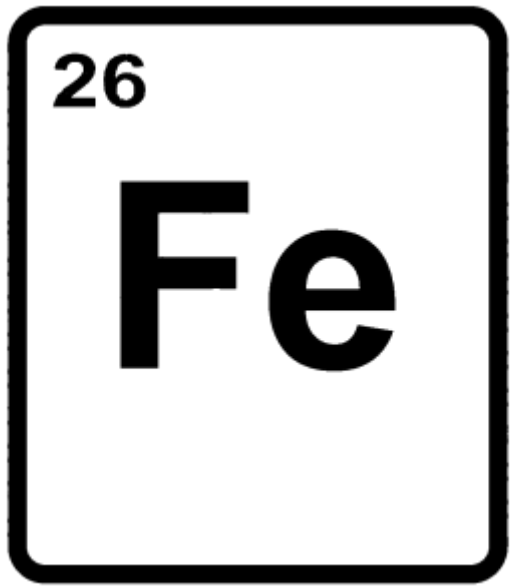
lower energy use

less byproducts

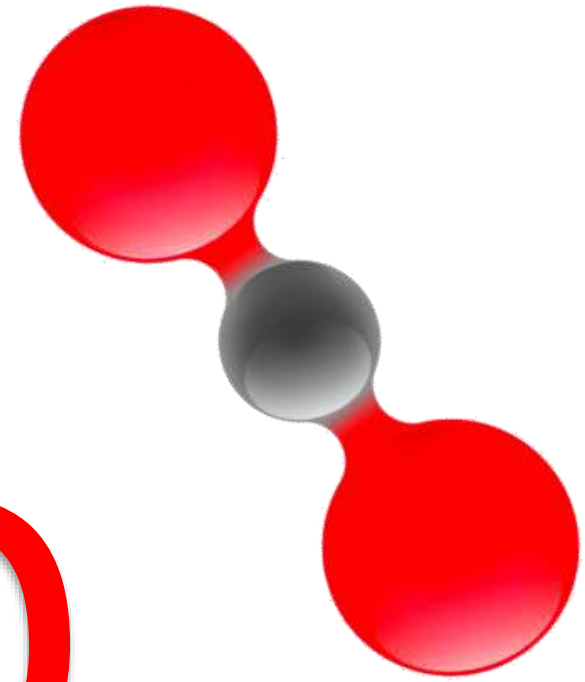
higher efficiency


Global Fossil CO_2 Emissions
40 Gt CO_2
35
30
25
20
1990–2000
+1.1%/yr
2000–10
+3.1%/yr
2010–17
+1.0%/yr
Projection 2018
37.1 Gt CO_2
▲ 2.7% (1.8%–3.7%)
1990
1995
2000
2005
2010
2015
18
projected
Global Carbon Project • Data: CDIAC/GCP/BP/USGS

Steel: 8 % of all global CO_2 emissions



Today:

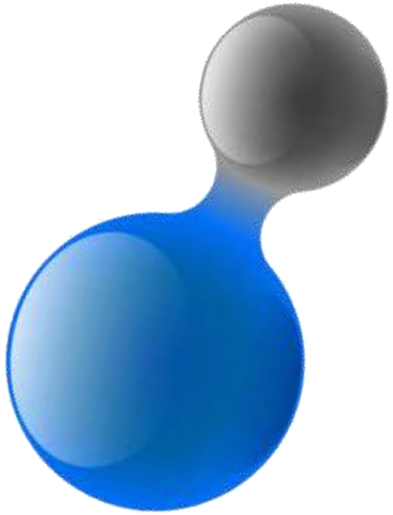


2 tons CO_2

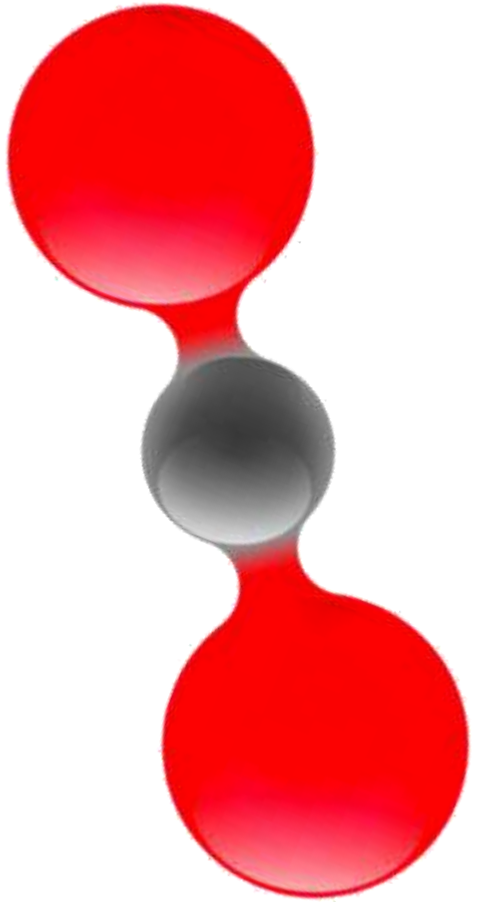
per ton of steel

Why has steel such a high carbon footprint ?

Redox reaction



$$3\ CO + Fe_2O_3 \rightarrow 3\ CO_2 + 2\ Fe$$



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The Materials Science behind Sustainable Metals and Alloys

Dierk Raabe*

Cite This: *Chem. Rev.* 2023, 123, 2436–2608

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Review

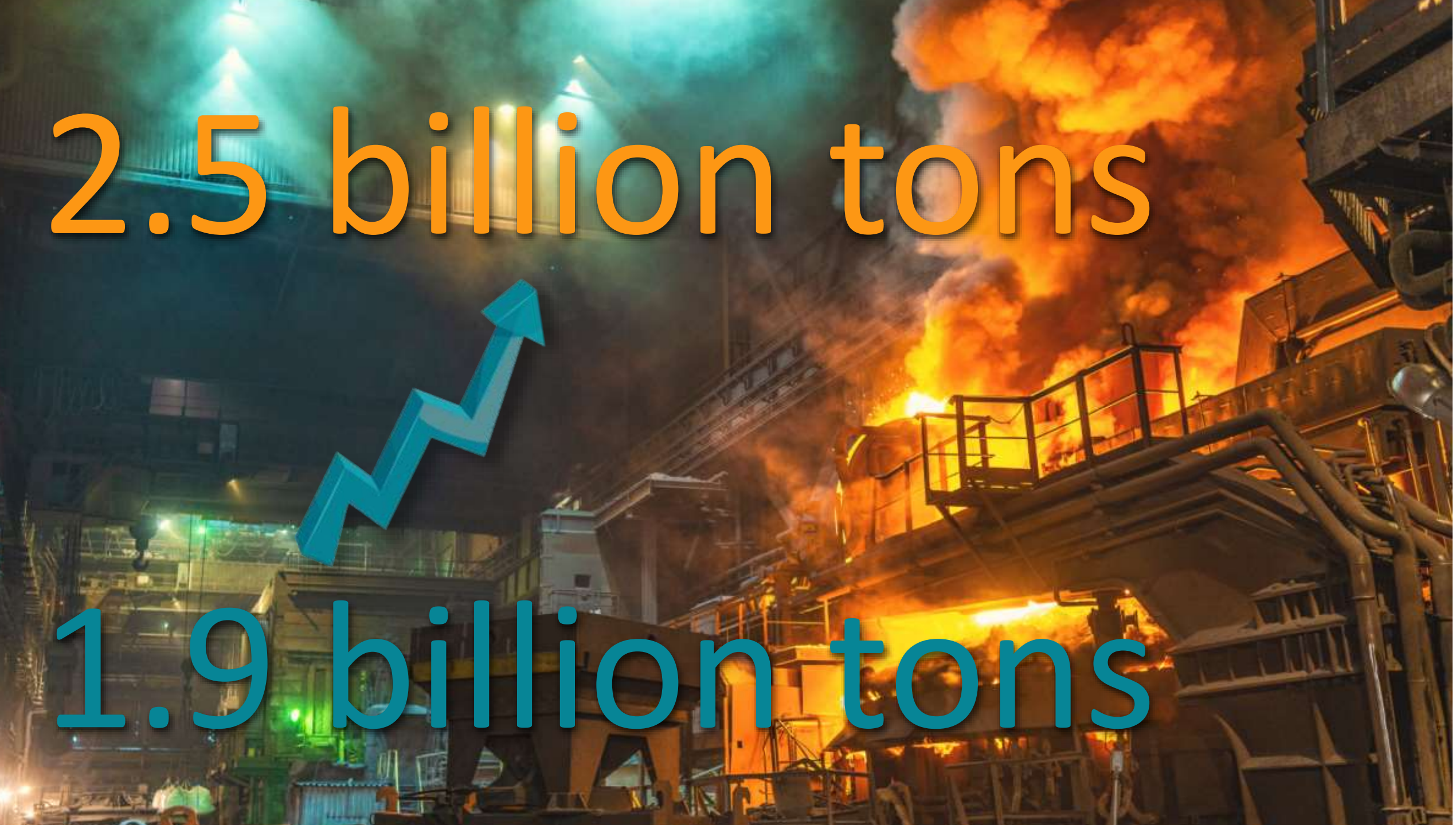
Strategies for improving the sustainability of structural metals

https://doi.org/10.1038/s41586-019-1702-5

Dierk Raabe[1]*, C. Cem Tasan[2]* & Elsa A. Olivetti[2]*

1.9 billion tons steel / year

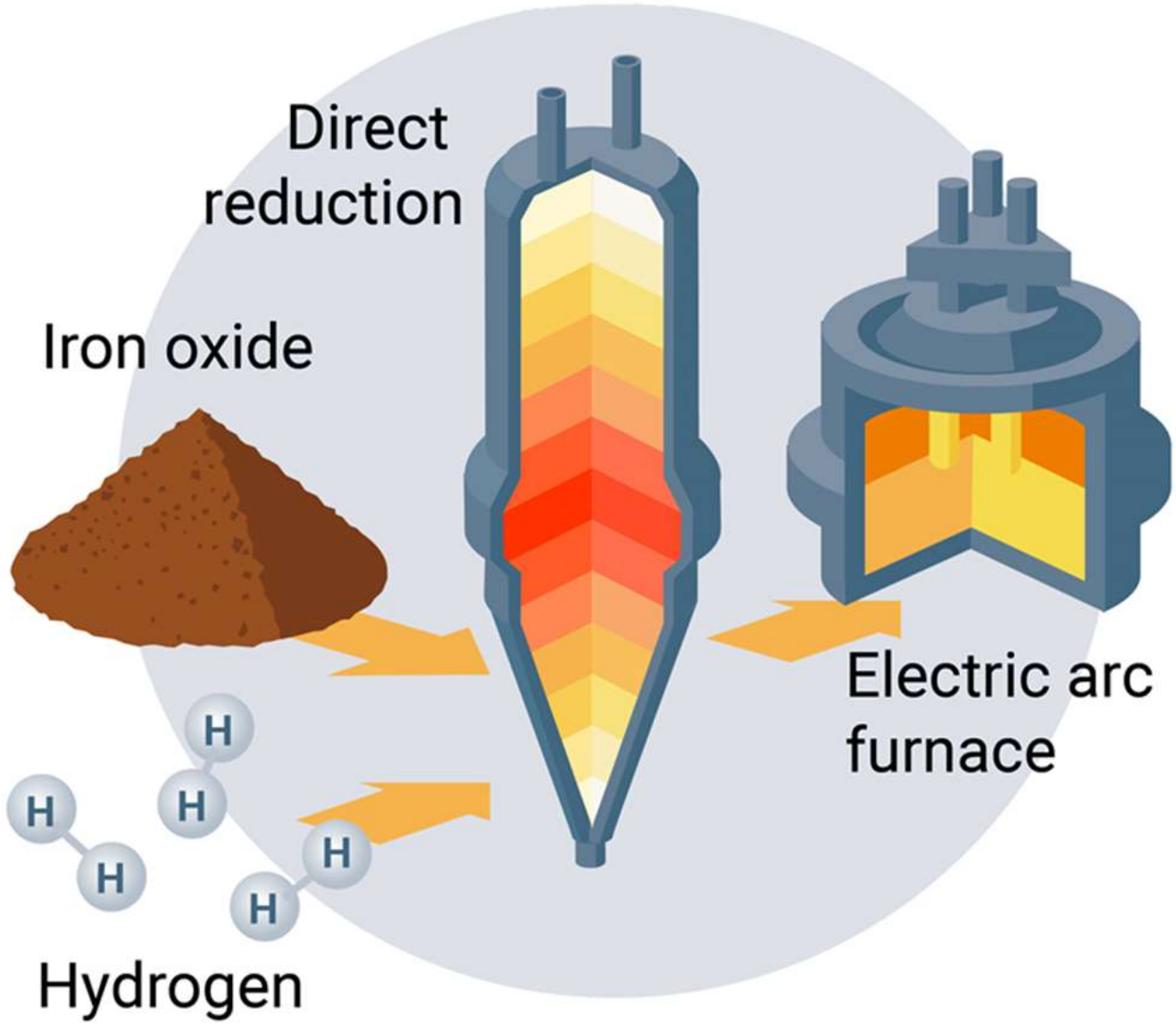
D. Raabe, The Materials Science behind Sustainable Metals and Alloys, Chem. Rev. 2023, 123, p. 2436

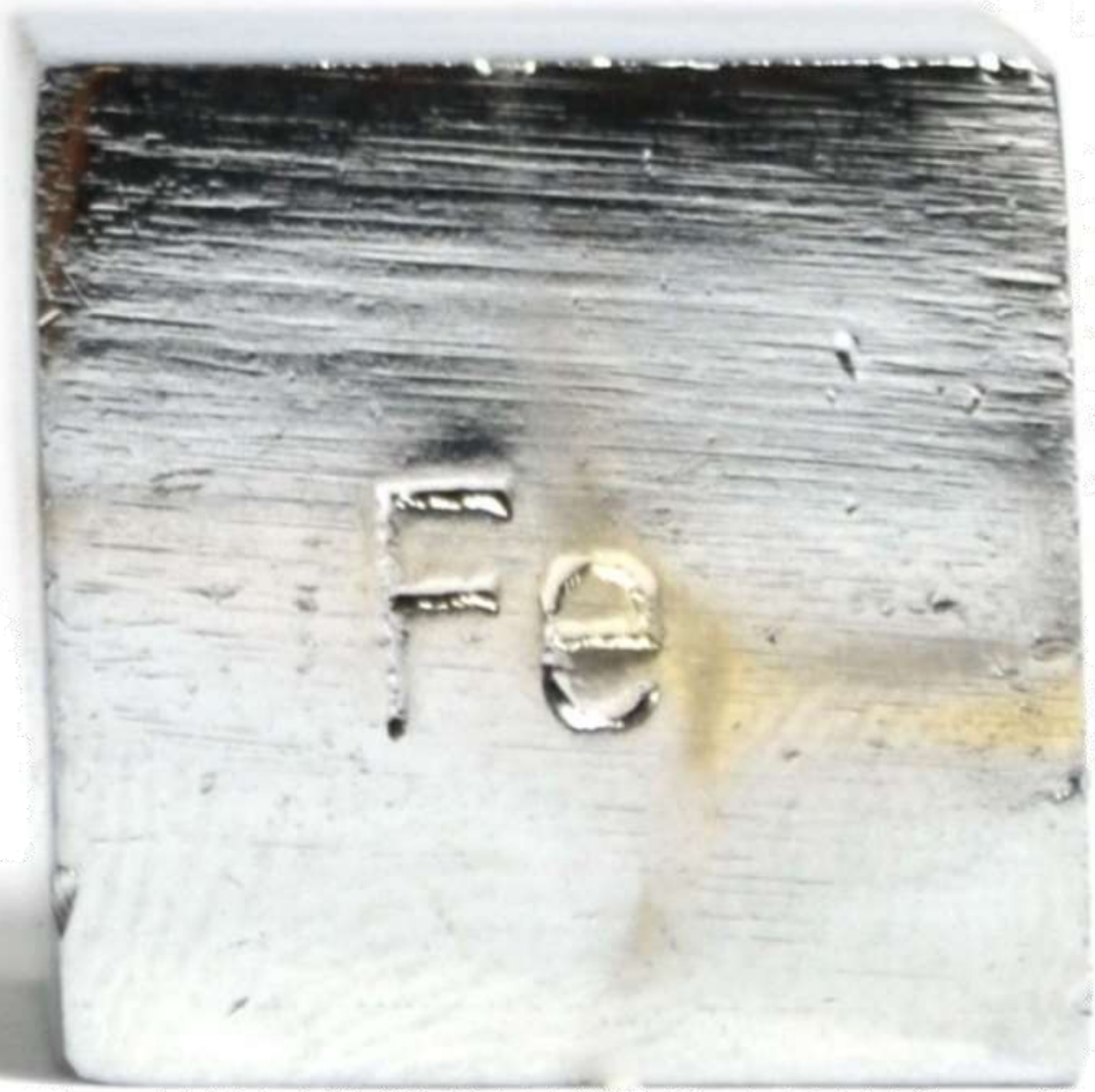

2.5 billion tons
1.9 billion tons

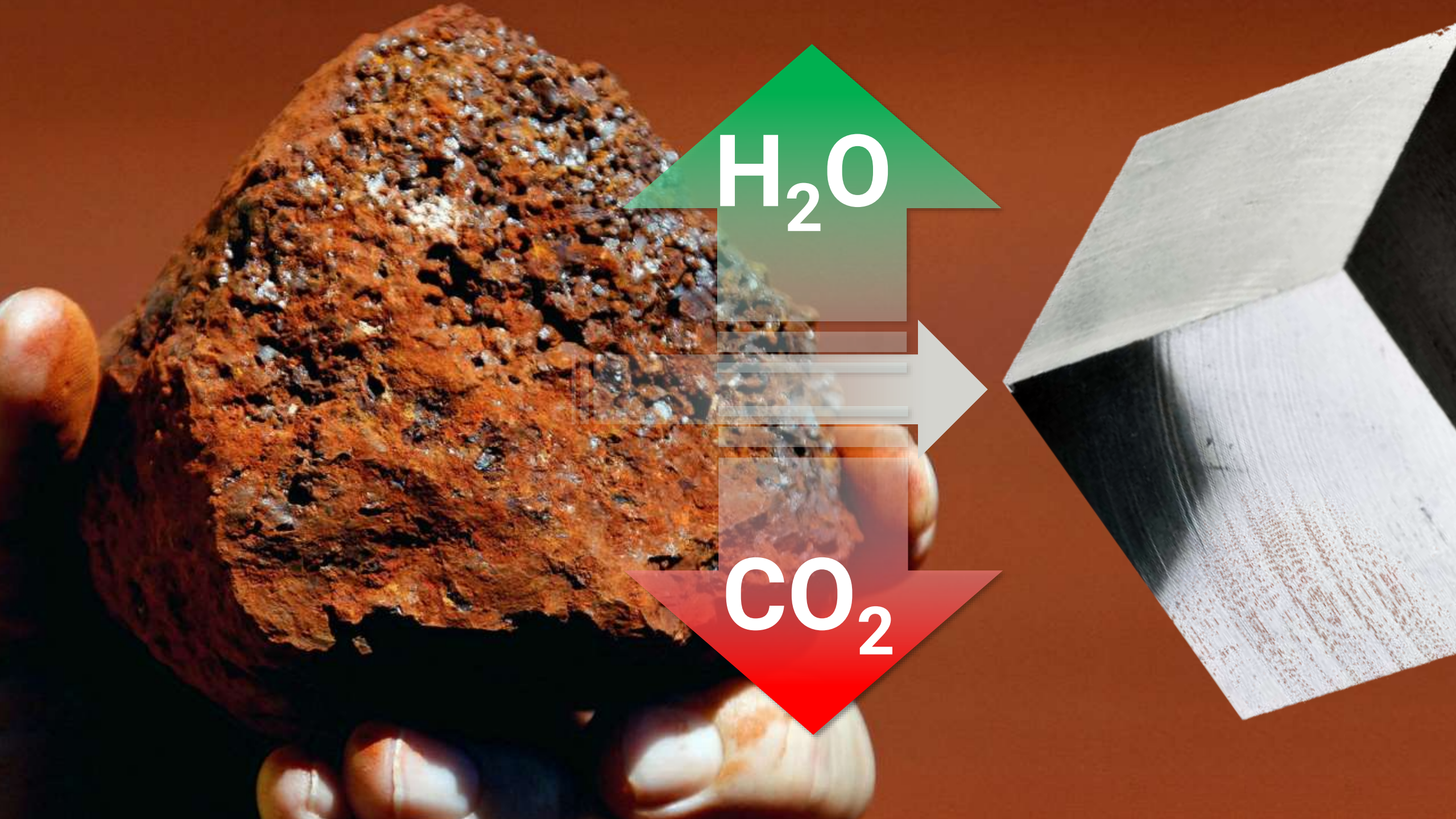
$Fe_2O_3 + 3\ CO \rightarrow 2\ Fe + 3\ CO_2$

$Fe_2O_3 + 3\ H_2 \rightarrow 2\ Fe + 3\ H_2O$

Direct reduction & electric arc
70-80% less CO_2 when using H_2



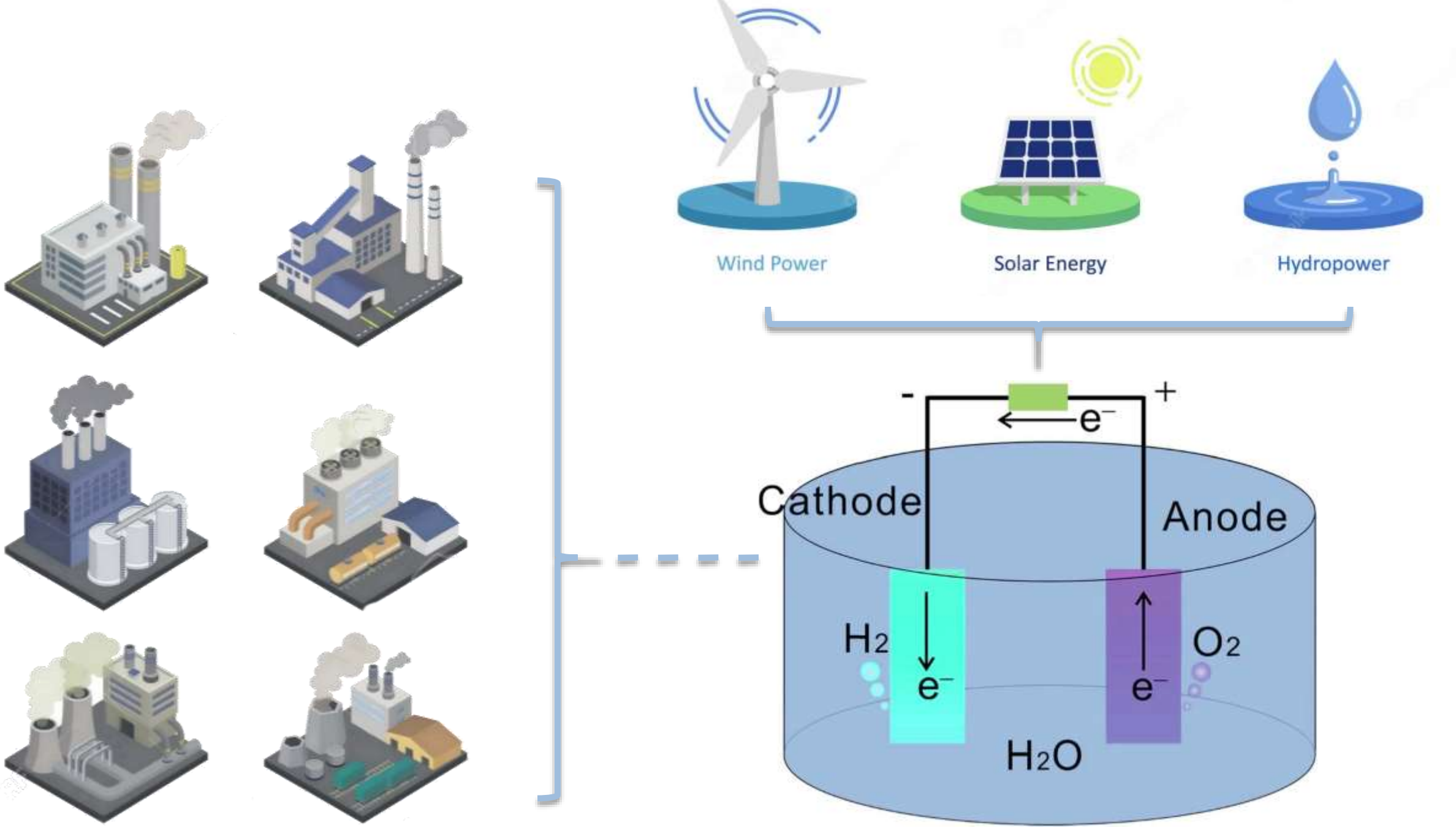



H_2O
CO_2

Where does all the green hydrogen come from?

(>250 Million tons H_2 required)

Ma, Y.; Bae, J. W.; Kim, S.; Jovi˘, M.; Li, K.; Vogel, D.; Ponge, D.; Rohwerder, M.; Gault, B.; Raabe, D. Reducing Iron Oxide with Ammonia: A Sustainable Path to Green Steel. Adv. Sci. 2023, 2300111, 1–7



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Producing 1 kg hydrogen, which has a specific energy of 143 MJ/kg, requires 50-55 kW h (180- 200 MJ/kg)

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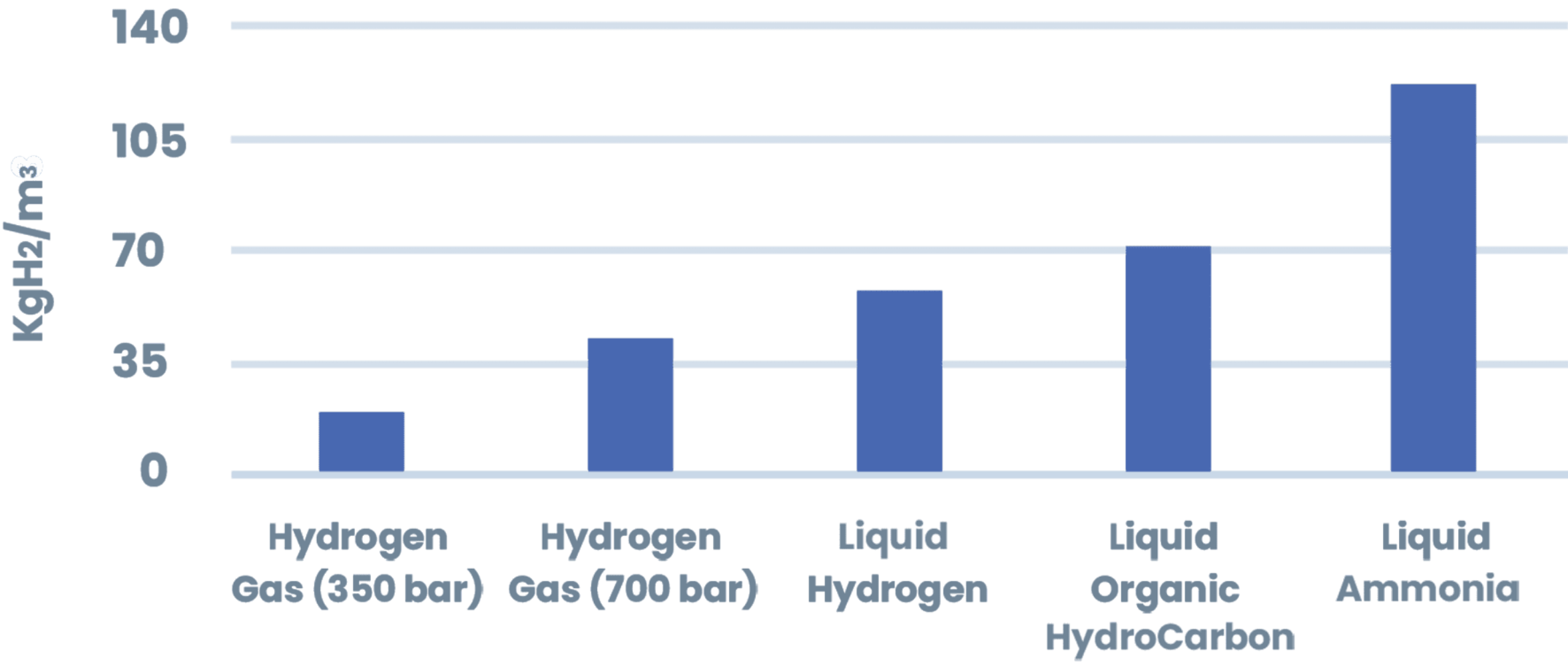
Water splitting by polymer electrolyte membrane or alkaline electrolysis:

70-80% efficiency

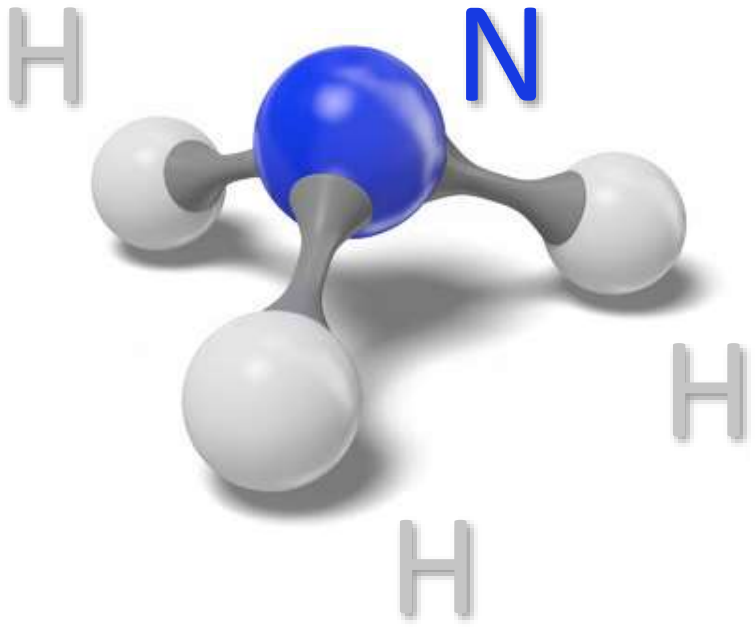
Liquefaction to −253°C costs 35% of its energy

Hydrogen density per m^3



Liquefaction of hydrogen:
consumes 35% of its energy
i.e.
liquid hydrogen transport
is inefficient !

Is Ammonia



an alternative / vector to

Hydrogen?

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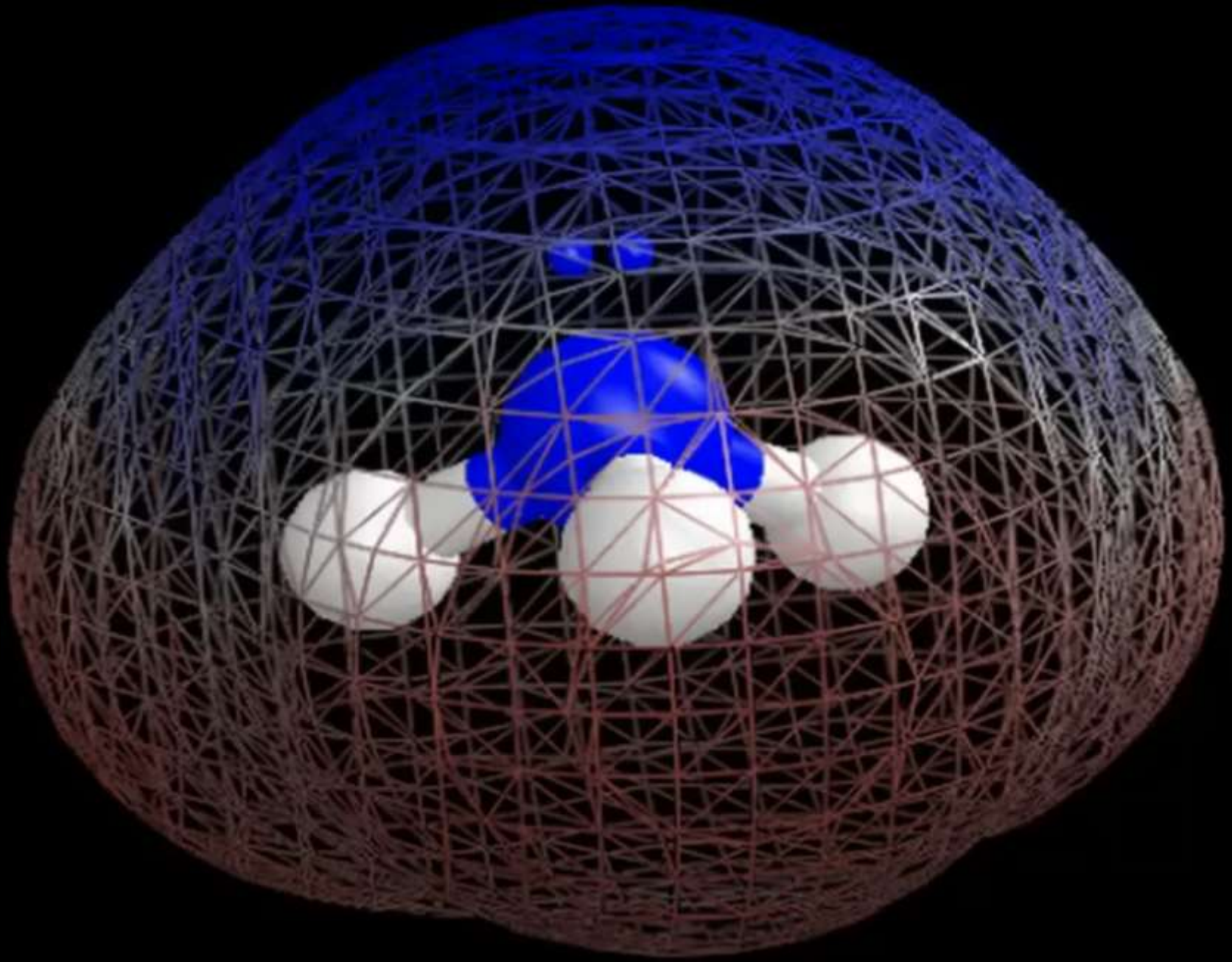
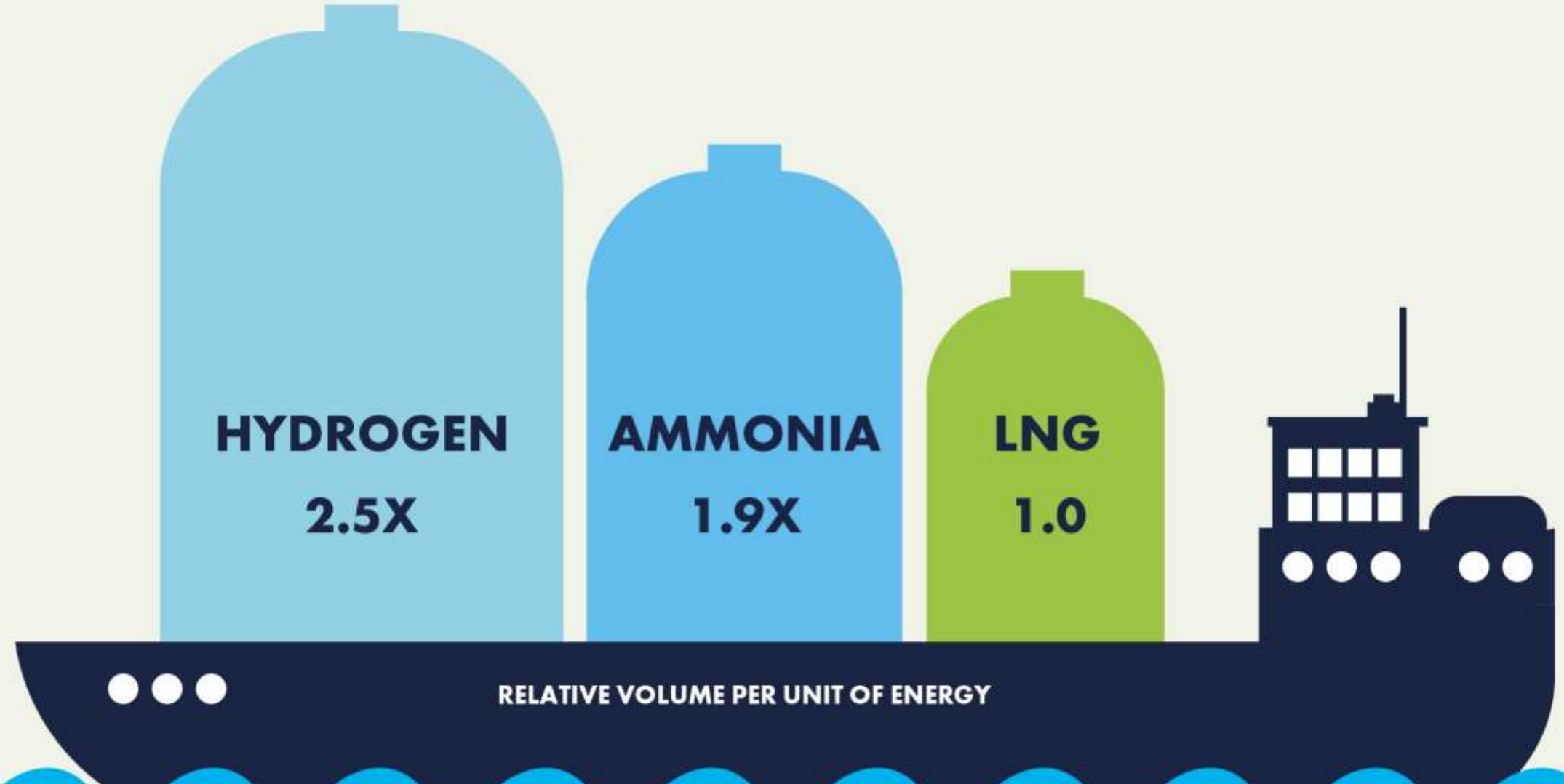
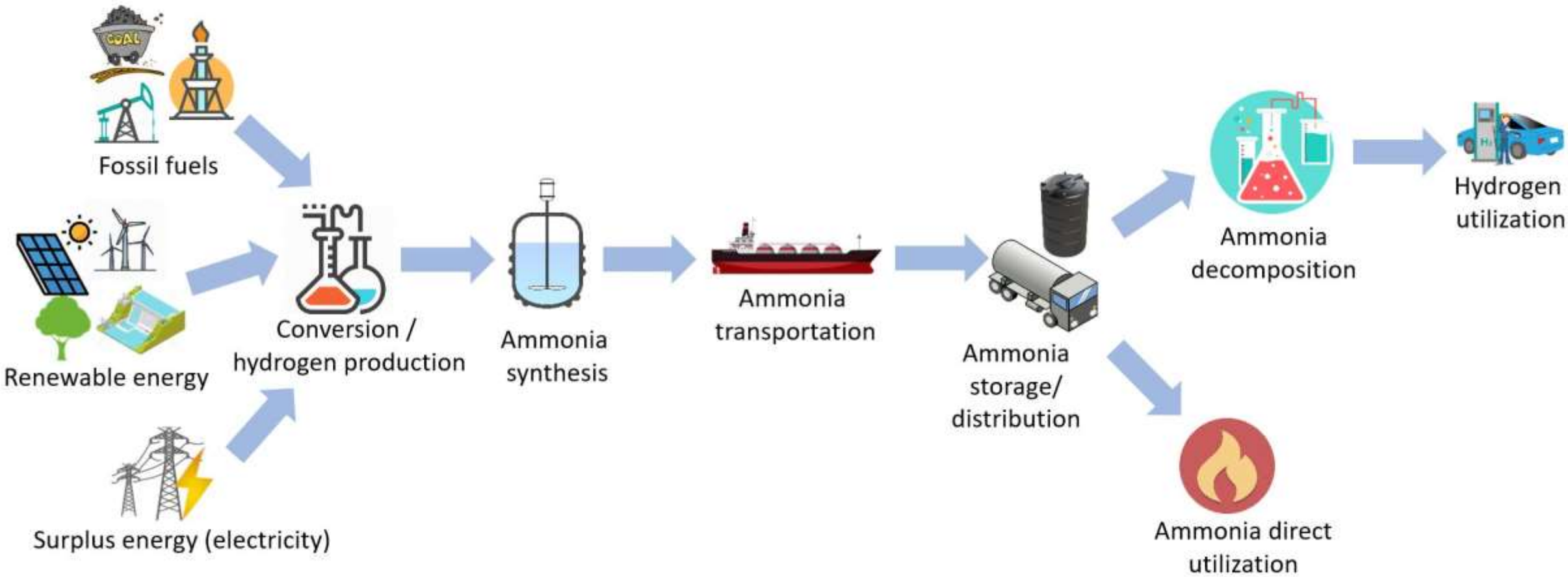
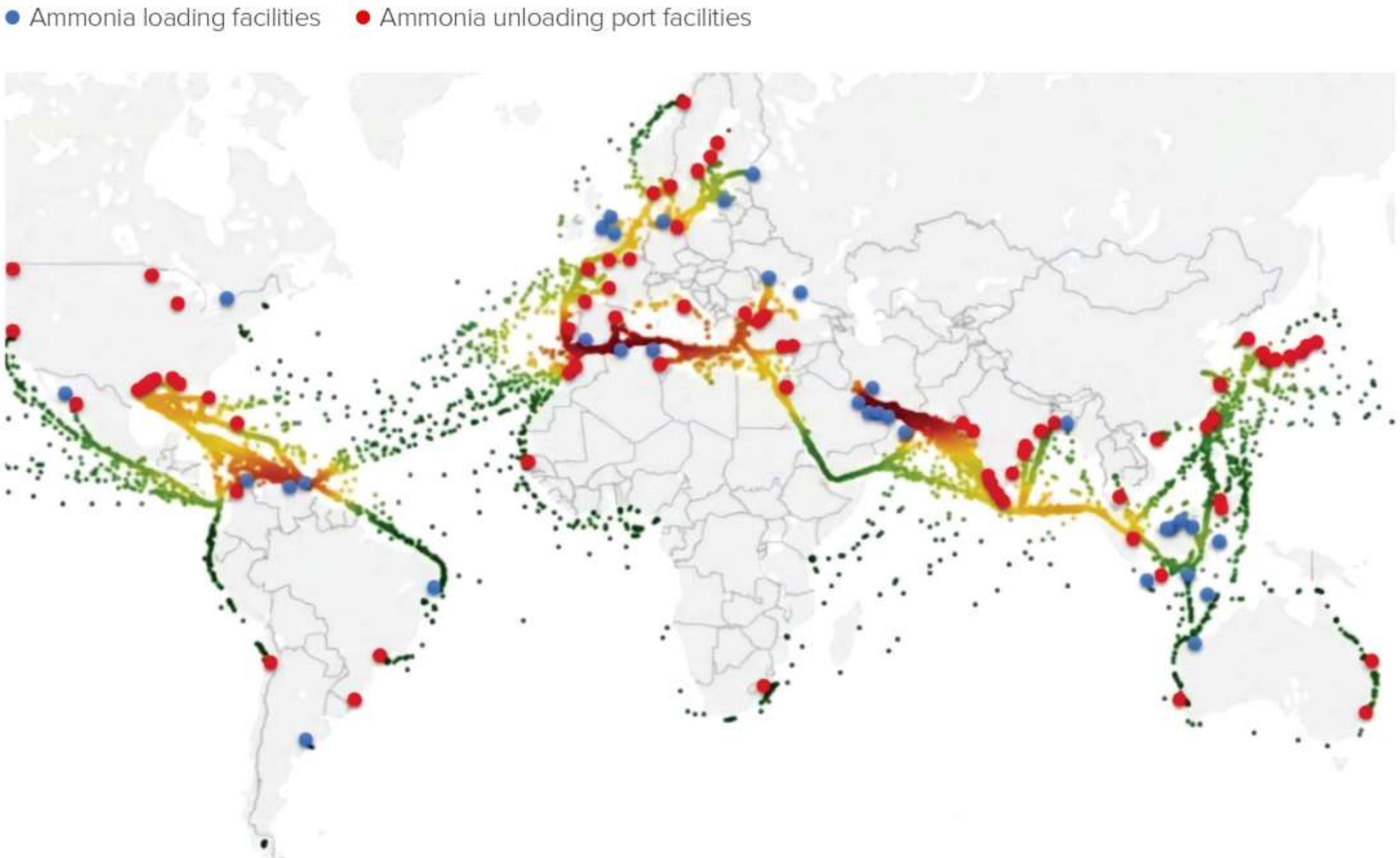


TANKS SIZE MATTERS



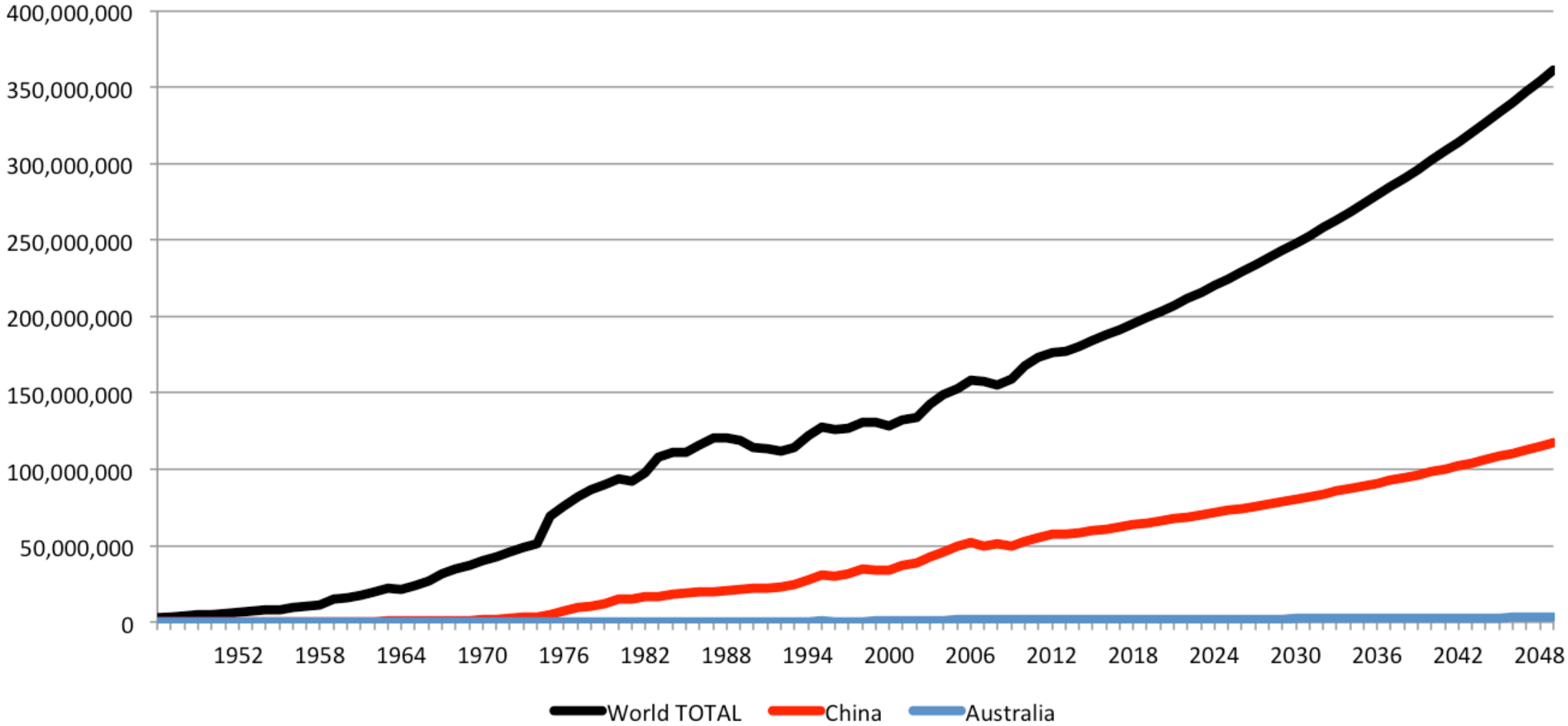

Fossil fuels
Renewable energy
Surplus energy (electricity)
Conversion / hydrogen production
Ammonia synthesis
Ammonia transportation
Ammonia storage/ distribution
Ammonia decomposition
Hydrogen utilization
Ammonia direct utilization

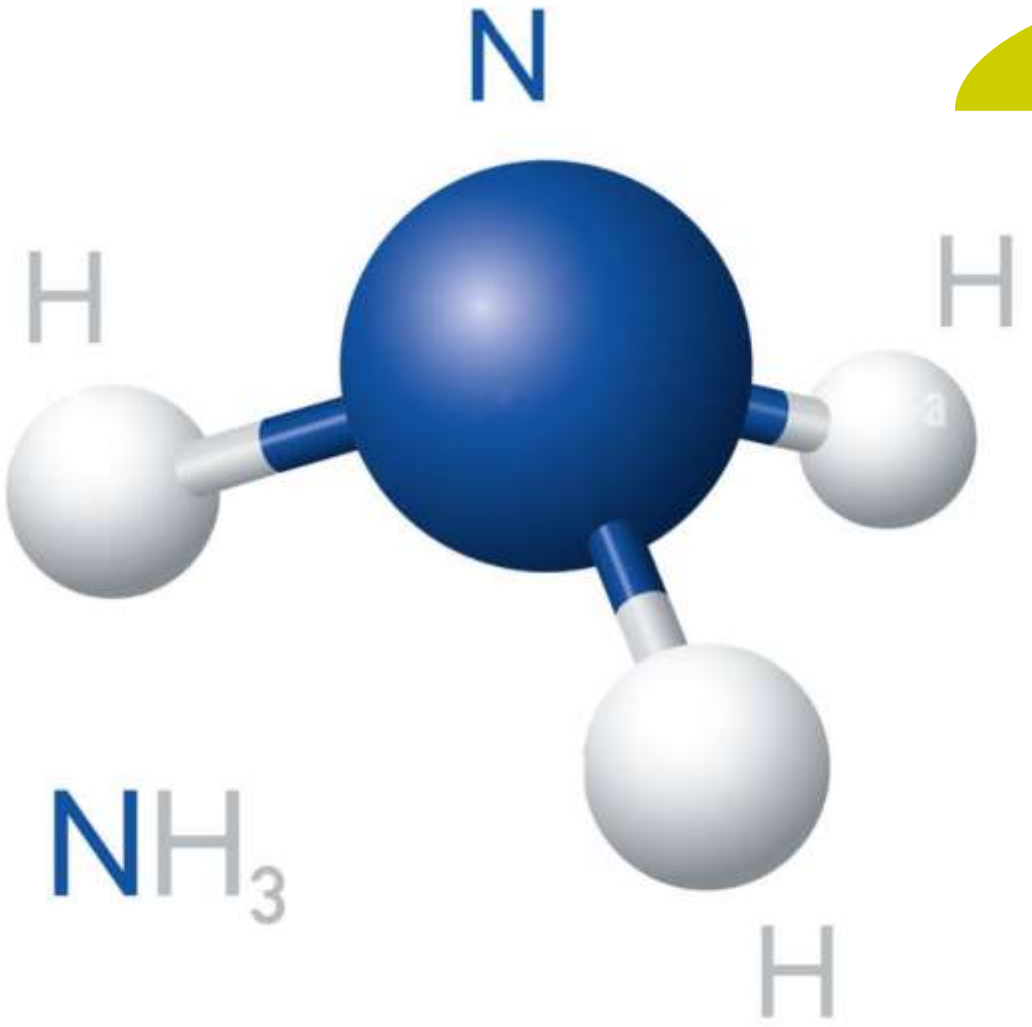


Ammonia: zero-carbon fertiliser, fuel and energy store, February 2020 DES5711, ISBN: 978-1-78252-448-9, The Royal Society

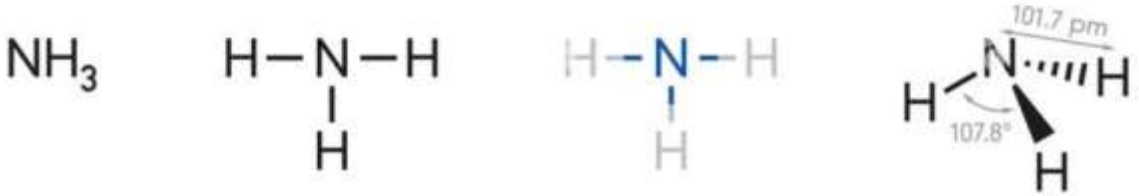
Global Ammonia Production, forecast to 2050 @ 2% growth

Units: metric tons of ammonia. Source: US Geological Survey (1947-2014) / AmmoniaIndustry.com, March 2018





$$Fe_2O_3 + 3\ H_2 \rightarrow 2\ Fe + 3\ H_2O$$



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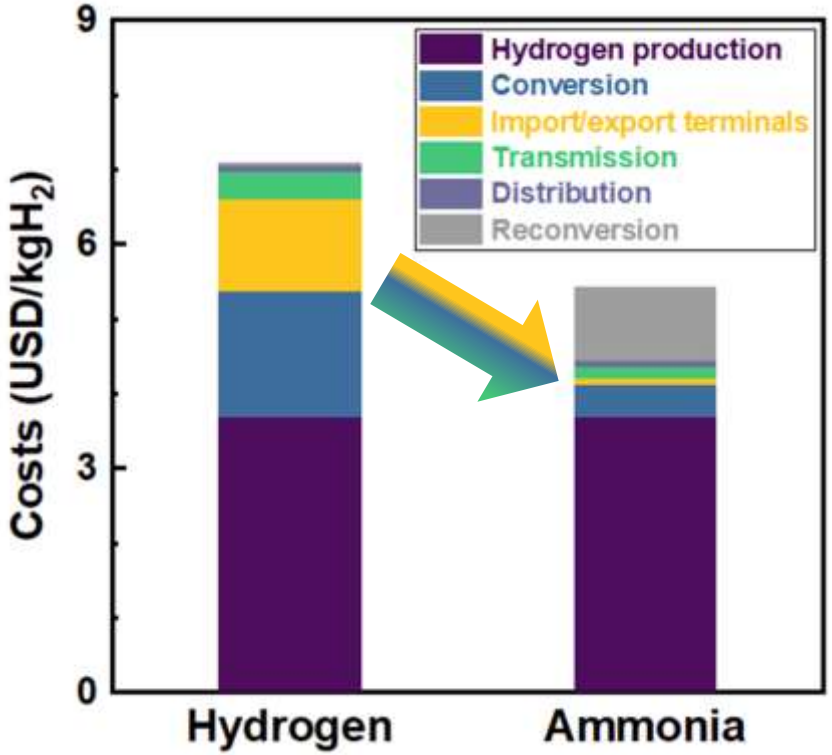
Reducing Iron Oxide with Ammonia: A Sustainable Path to Green Steel

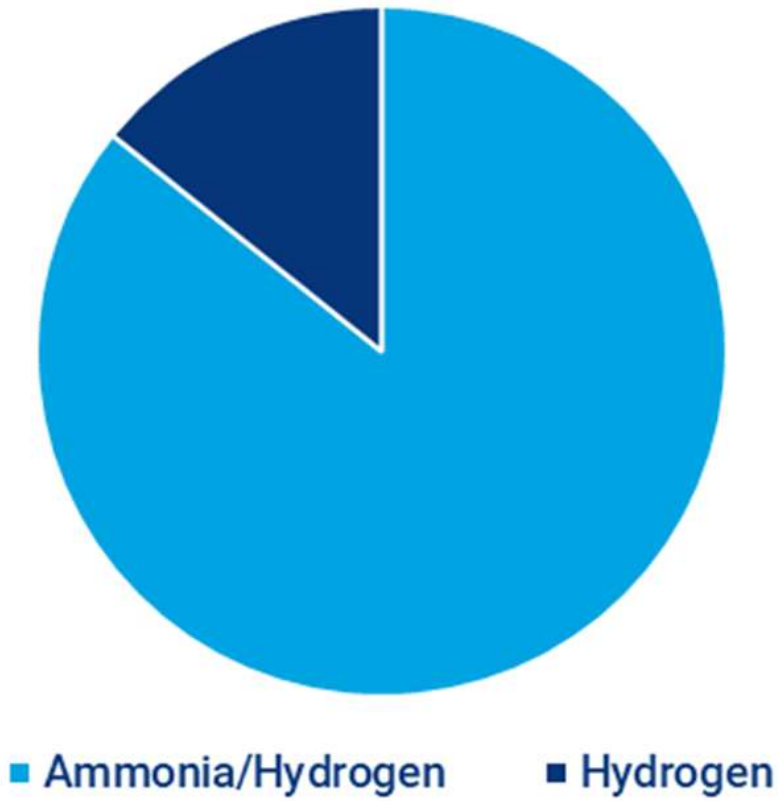
Yan Ma, Jae Wung Bae, Se-Ho Kim, Matic Jovičević-Klug, Kejiang Li, Dirk Vogel, Dirk Ponge, Michael Rohwerder, Baptiste Gault, and Dierk Raabe**



renewable carbon-free reductants and electricity. Here, the authors show how to make sustainable steel by reducing solid iron oxides with hydrogen released from ammonia. Ammonia is an annually 180 million ton traded chemical energy carrier, with established transcontinental logistics and low liquefaction costs. It can be synthesized with green hydrogen and release hydrogen again through the reduction reaction. This advantage connects it with green iron making, for replacing fossil reductants. the authors show that ammonia-based reduction of iron oxide proceeds through an autocatalytic reaction, is kinetically as effective as hydrogen-based direct reduction, yields the same metallization, and can be industrially realized with existing technologies. The produced iron/ mixture can

Energy density is a key factor in ammonia's role as a hydrogen carrier

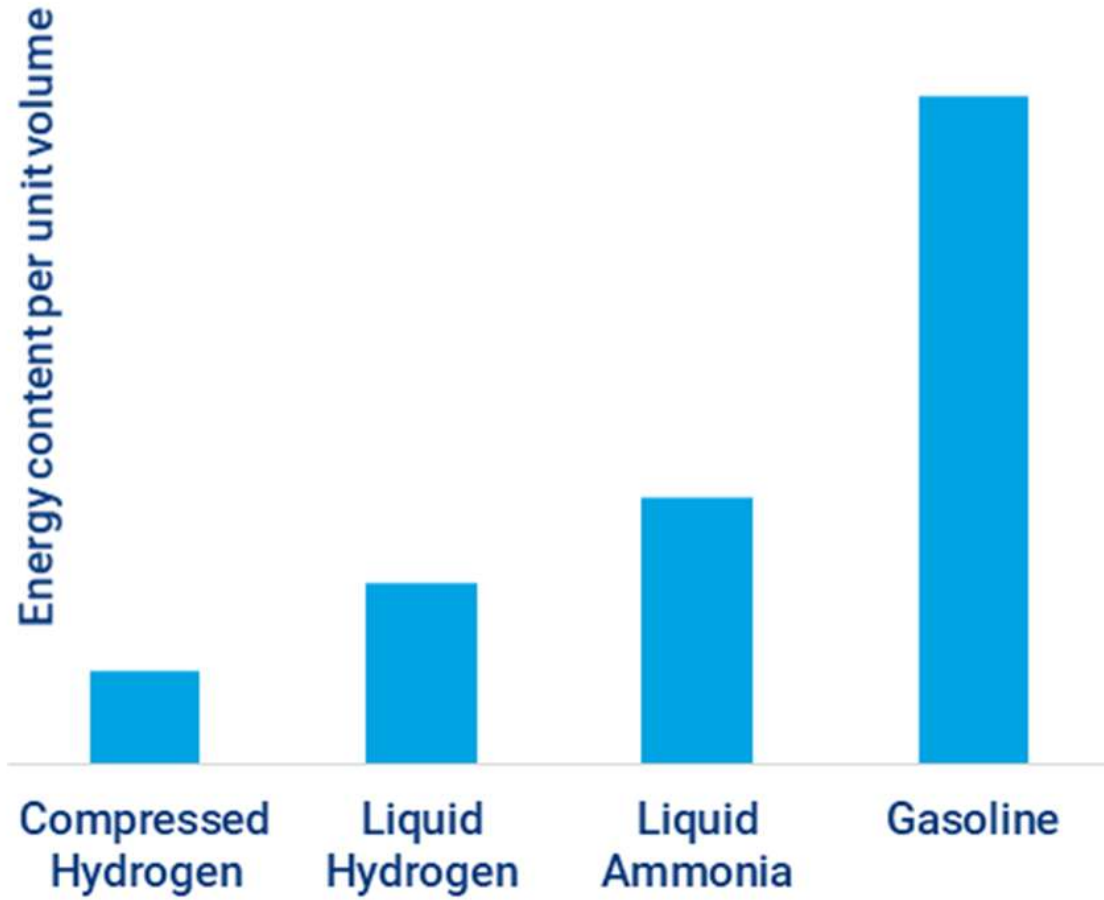
Announced hydrogen projects by capacity*



*In Australia, the Middle East, Africa and Latin America.

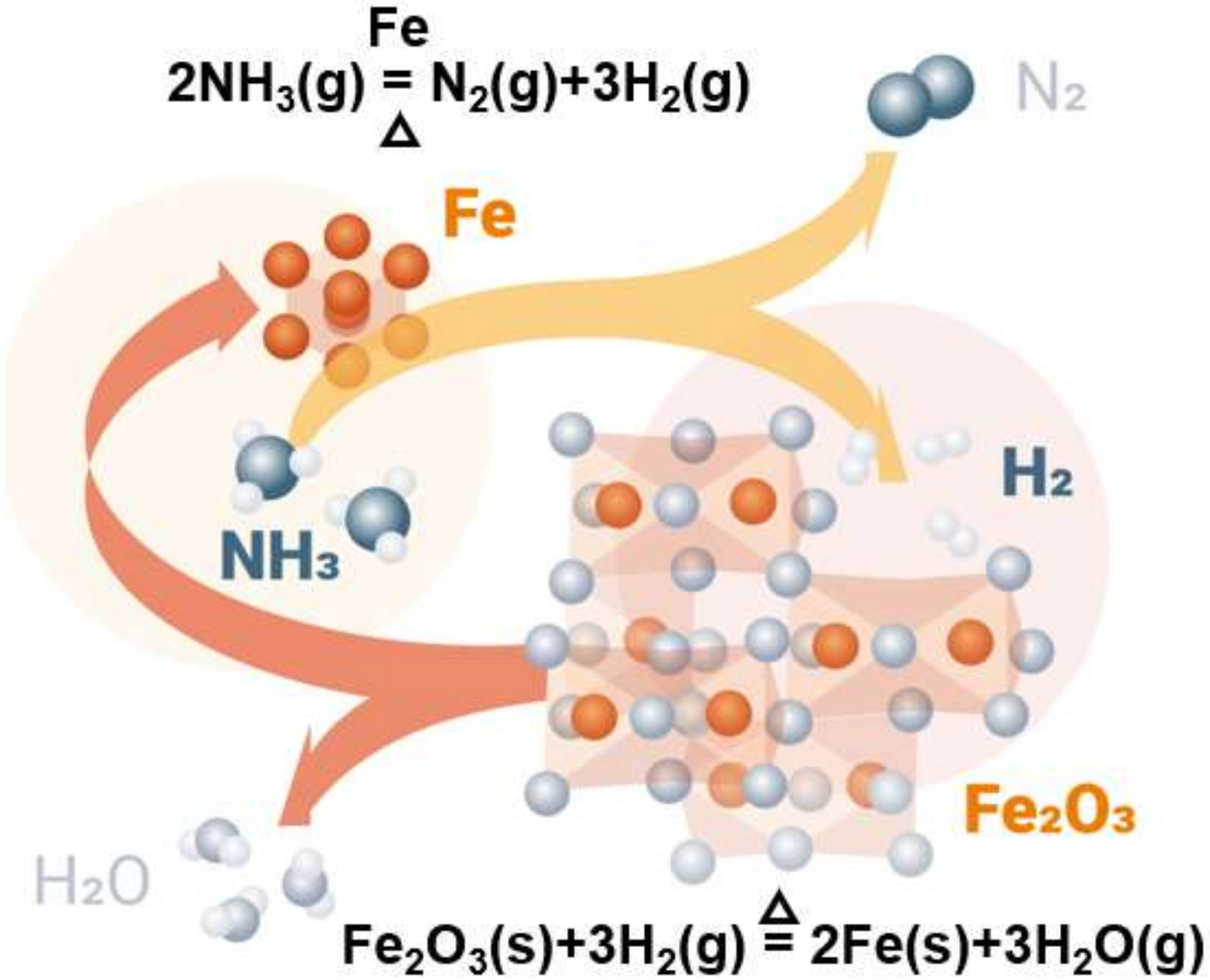
Source: Wood Mackenzie Hydrogen Project Tracker

Relative energy density of selected fuels



Source: Wood Mackenzie

Green hydrogen from Green Ammonia



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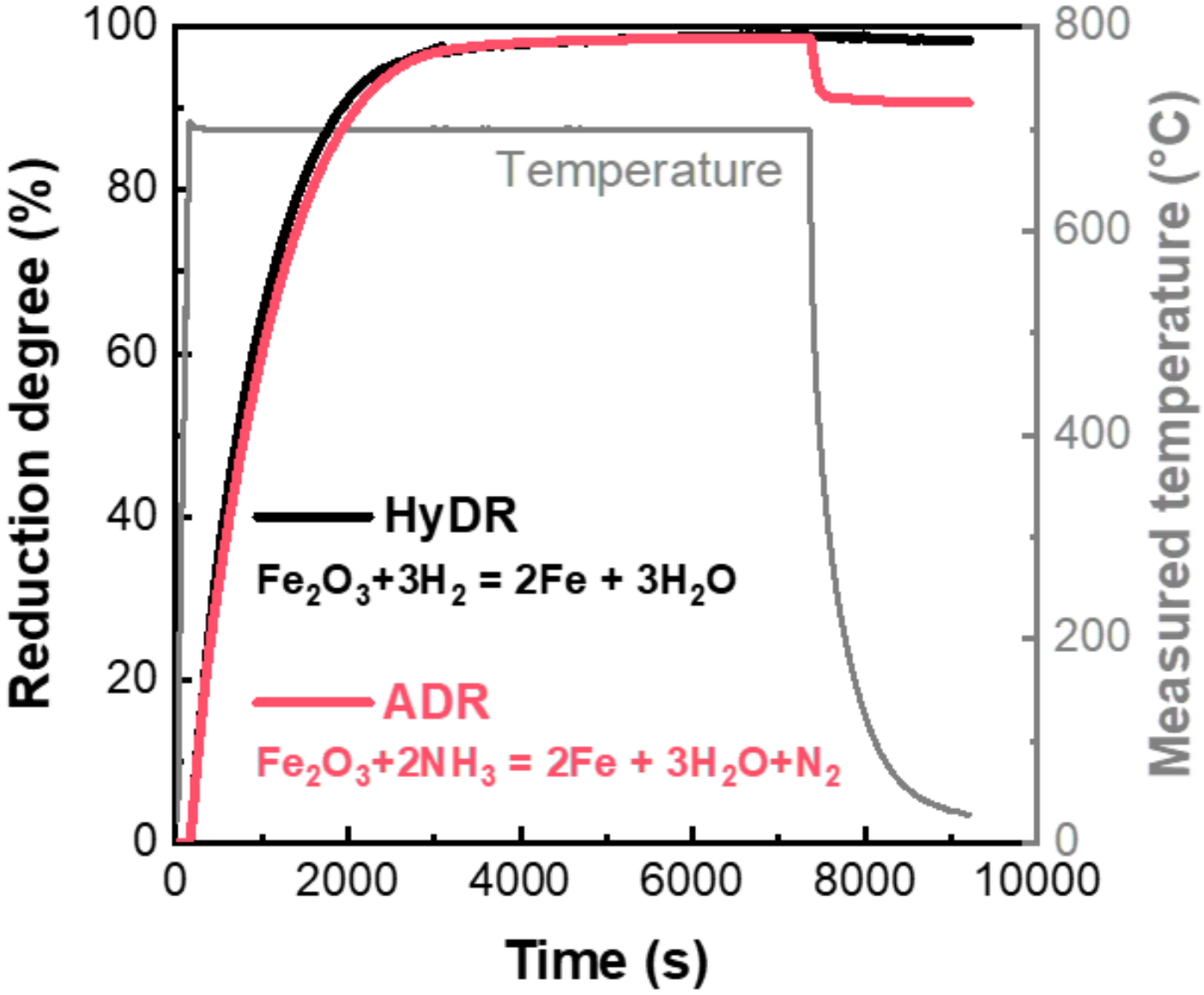
What is the kinetics?



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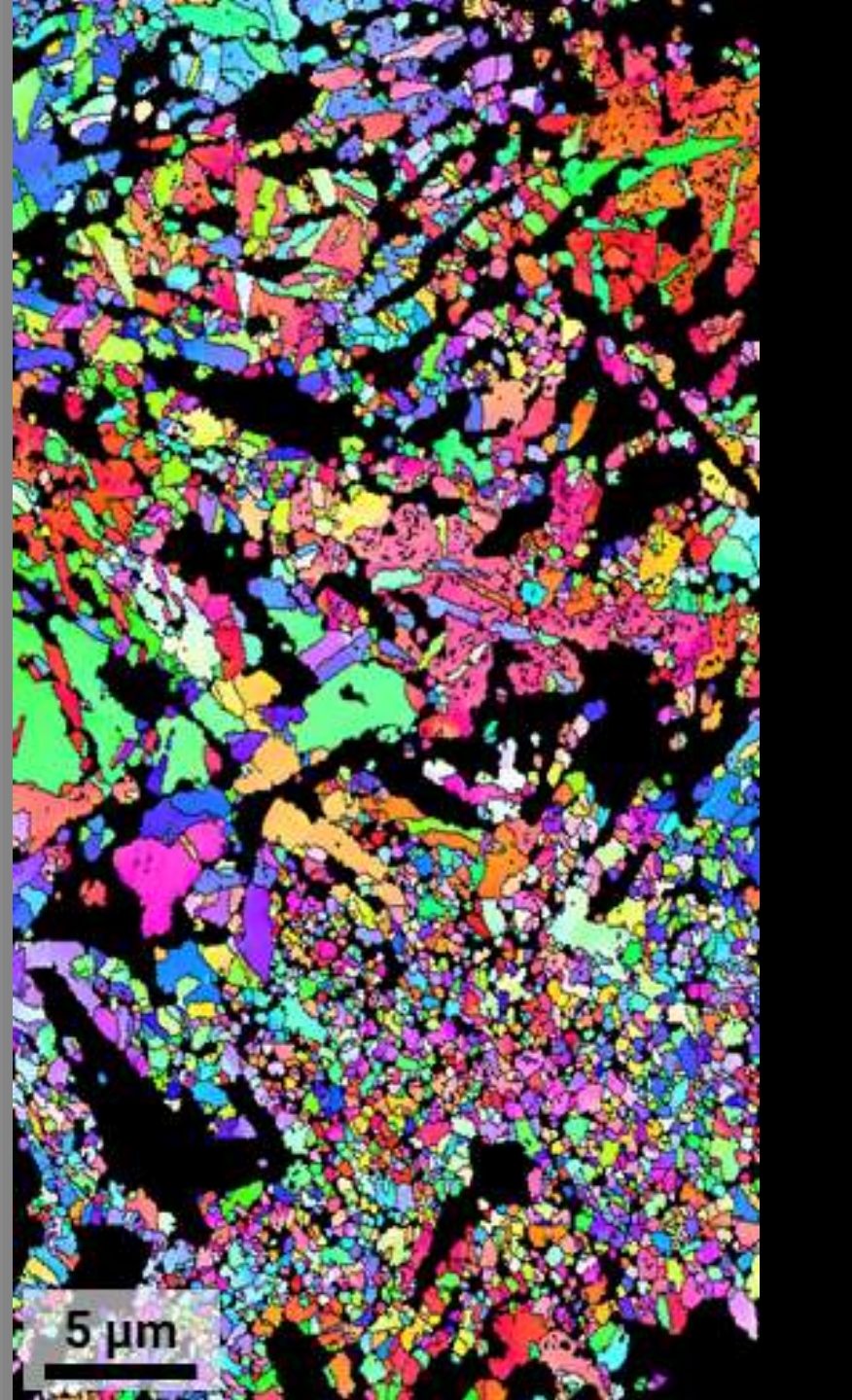
What kind of steel do we get from ammonia-based direct reduction



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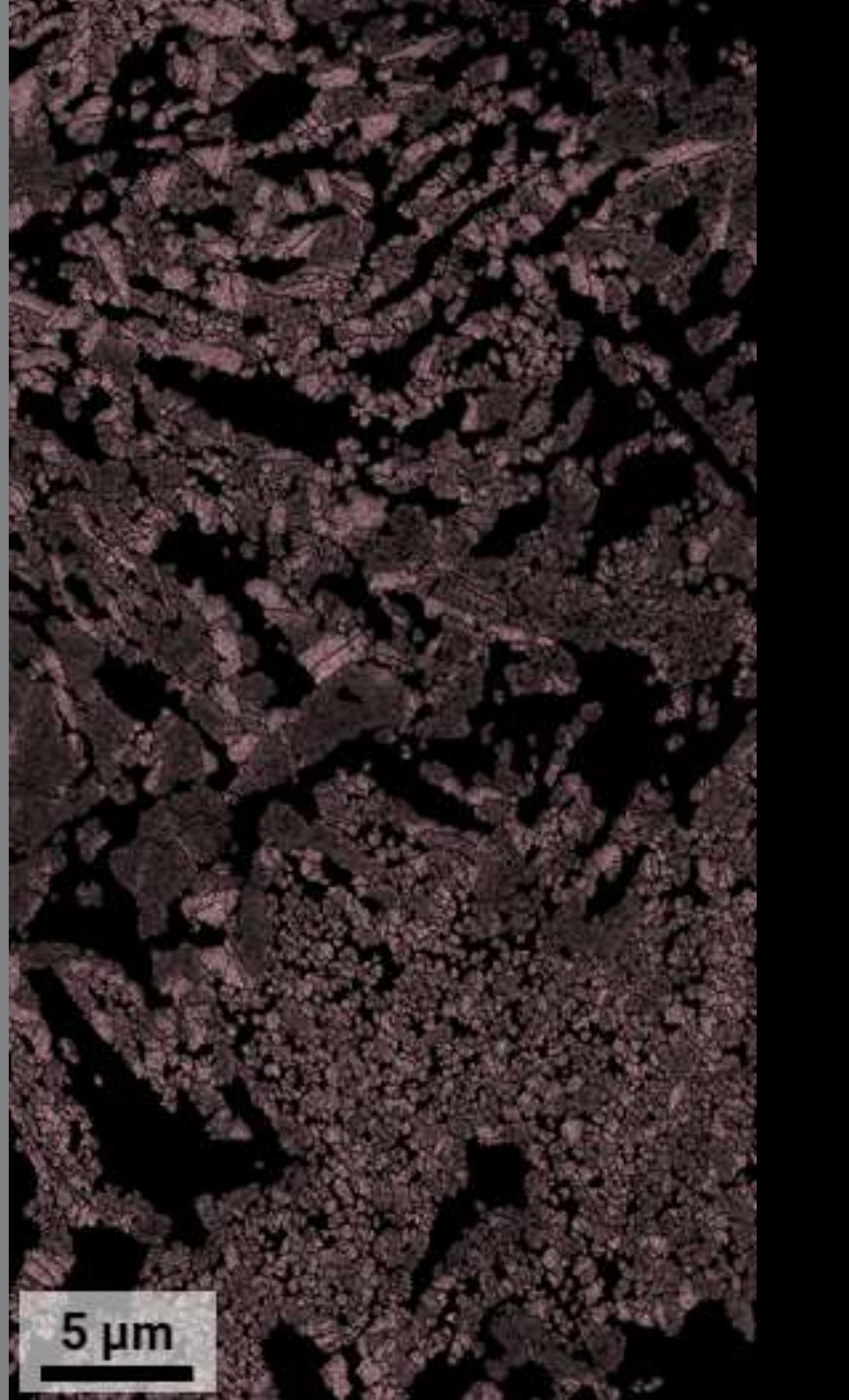
Nitrogen in the steel



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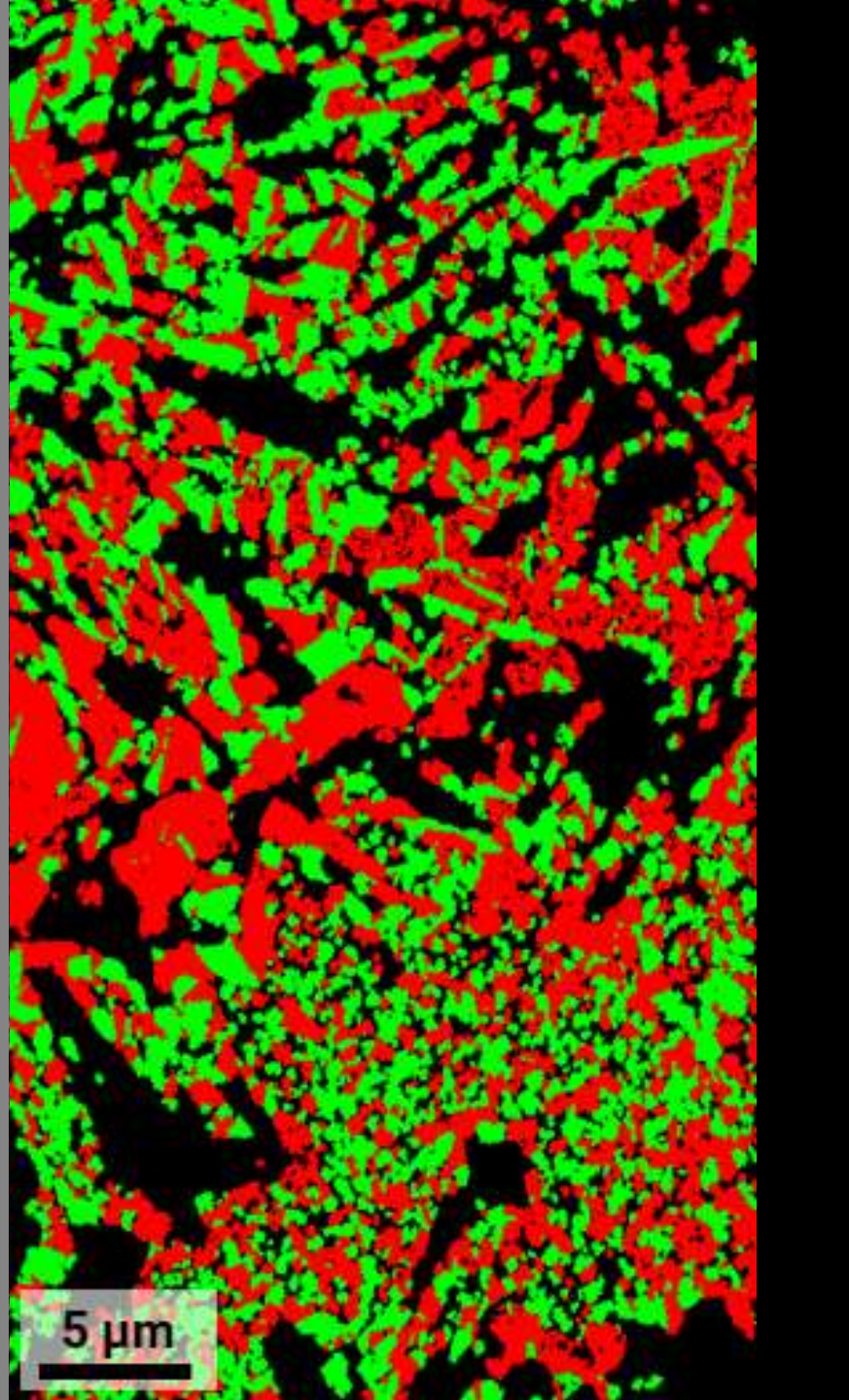
Nitrides in the steel



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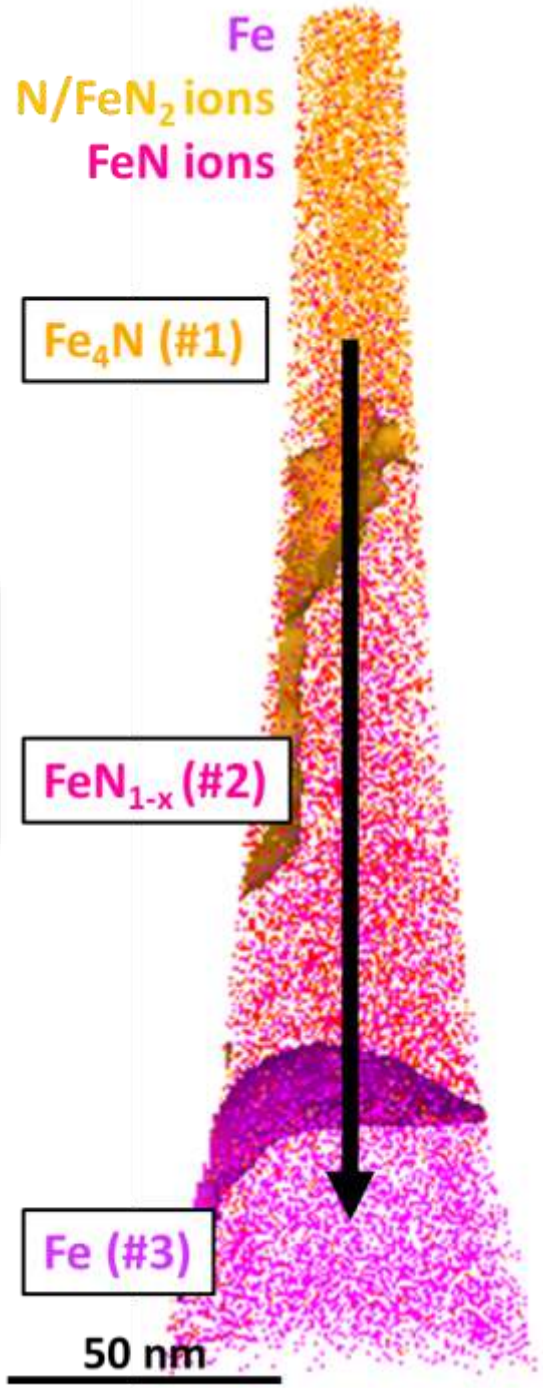
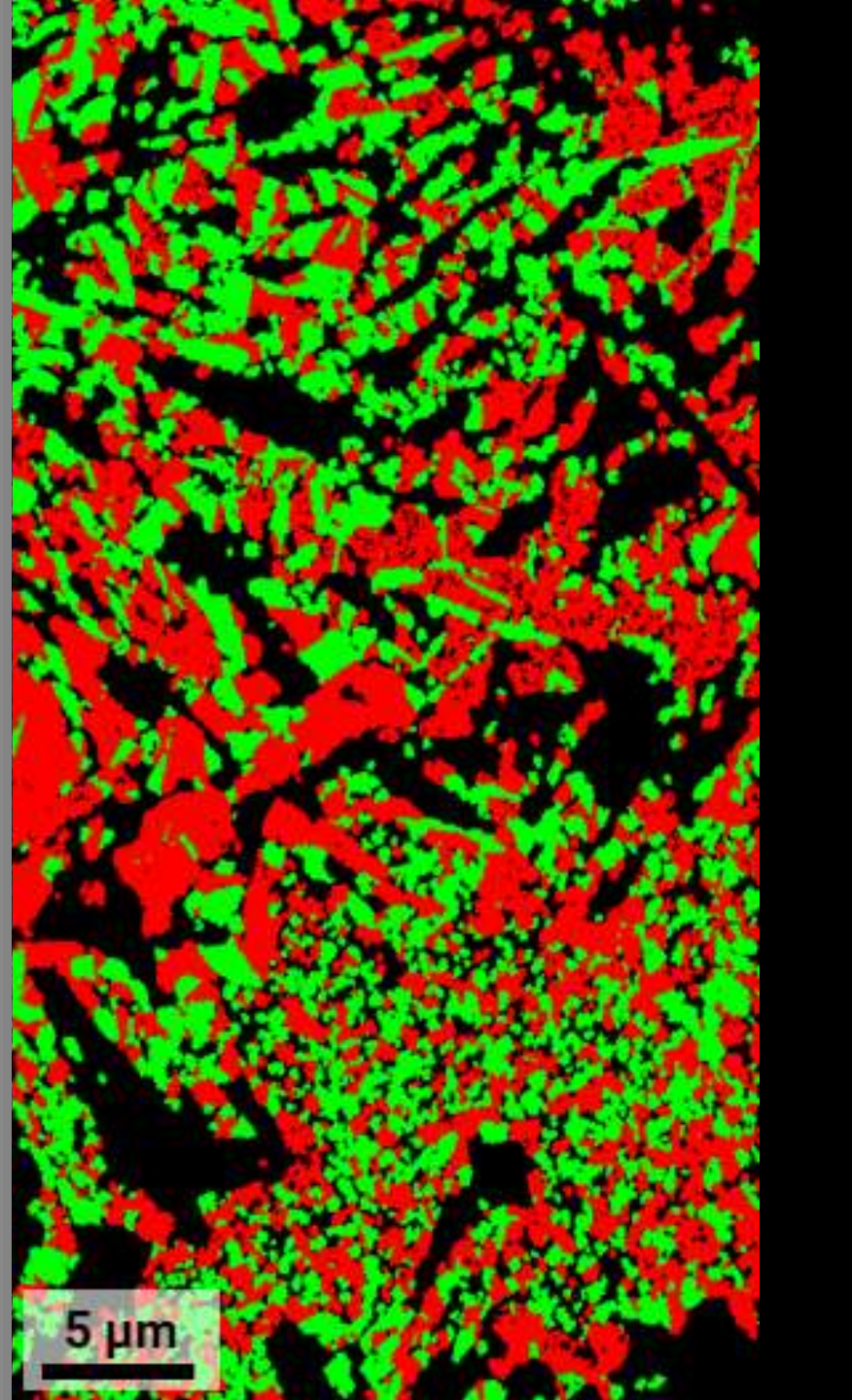
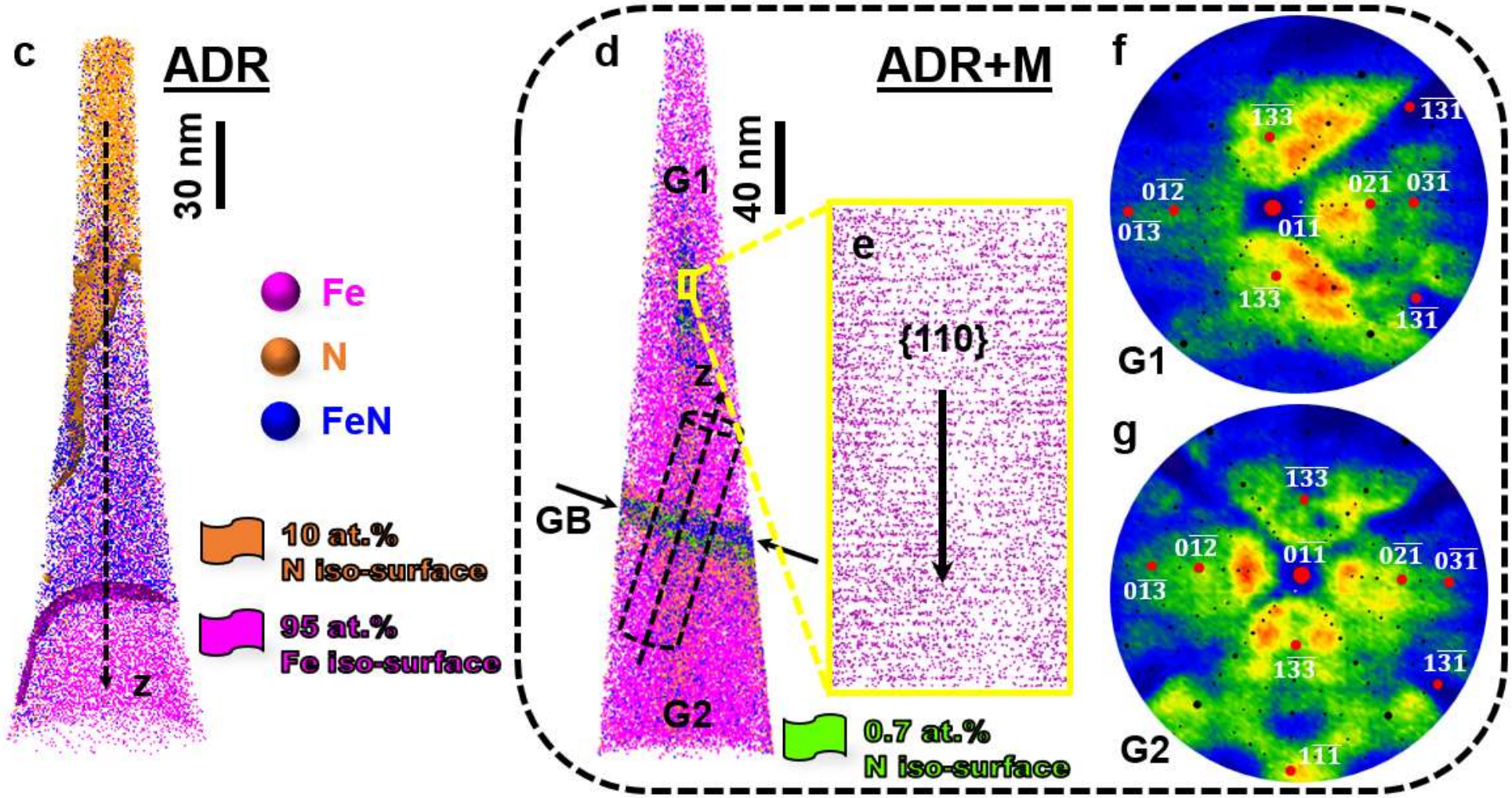




Nitrides in the steel



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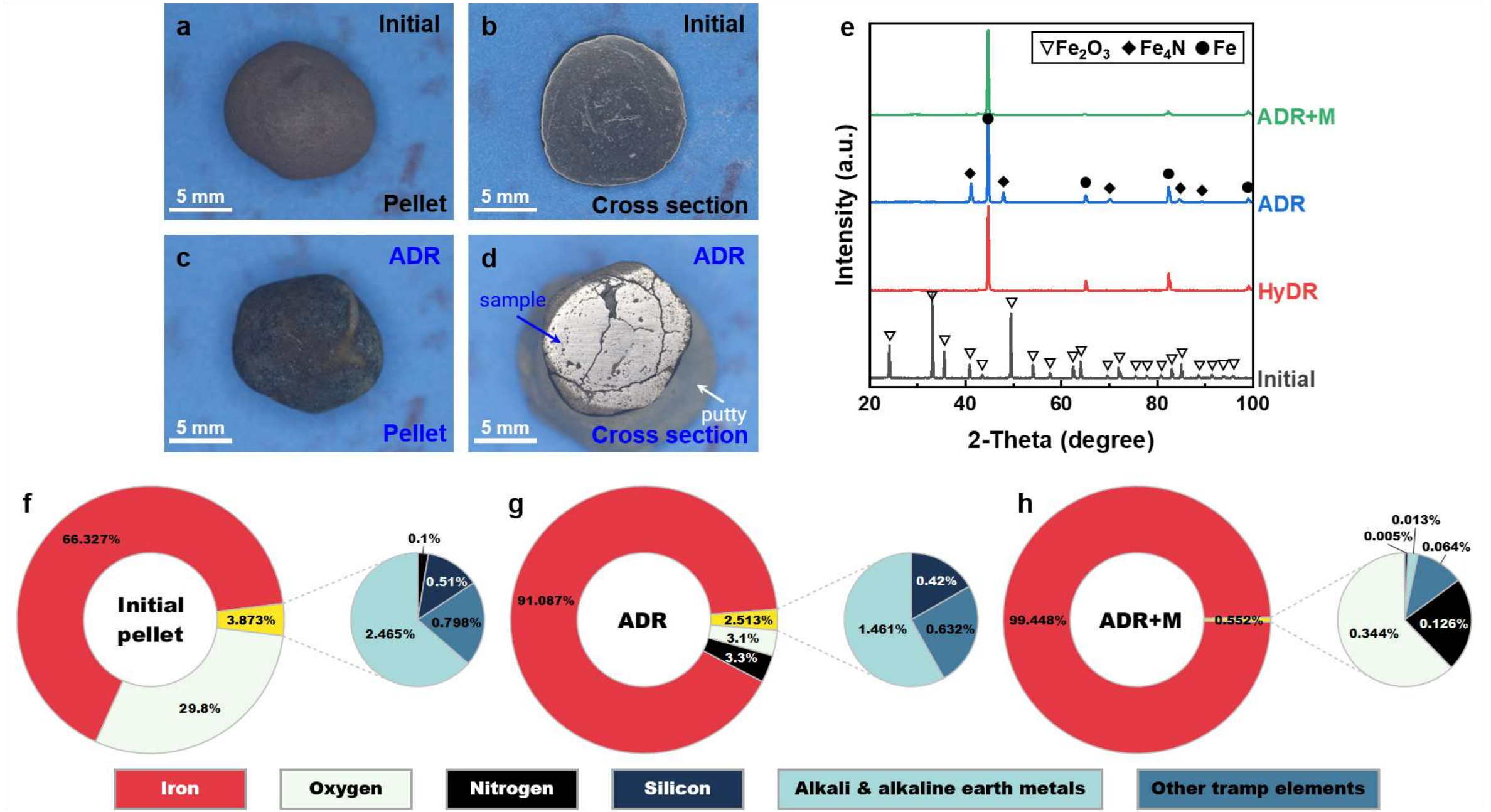

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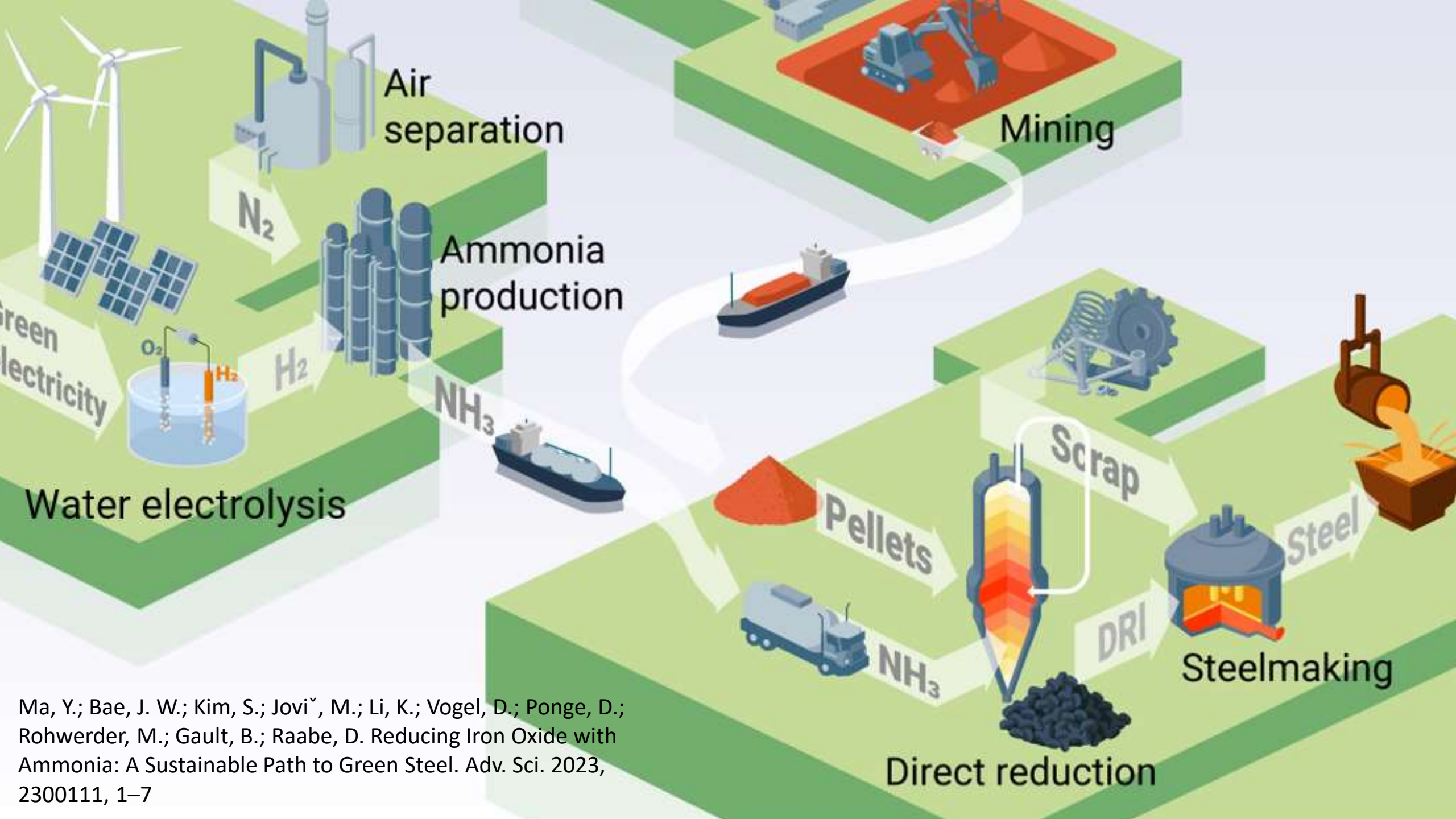

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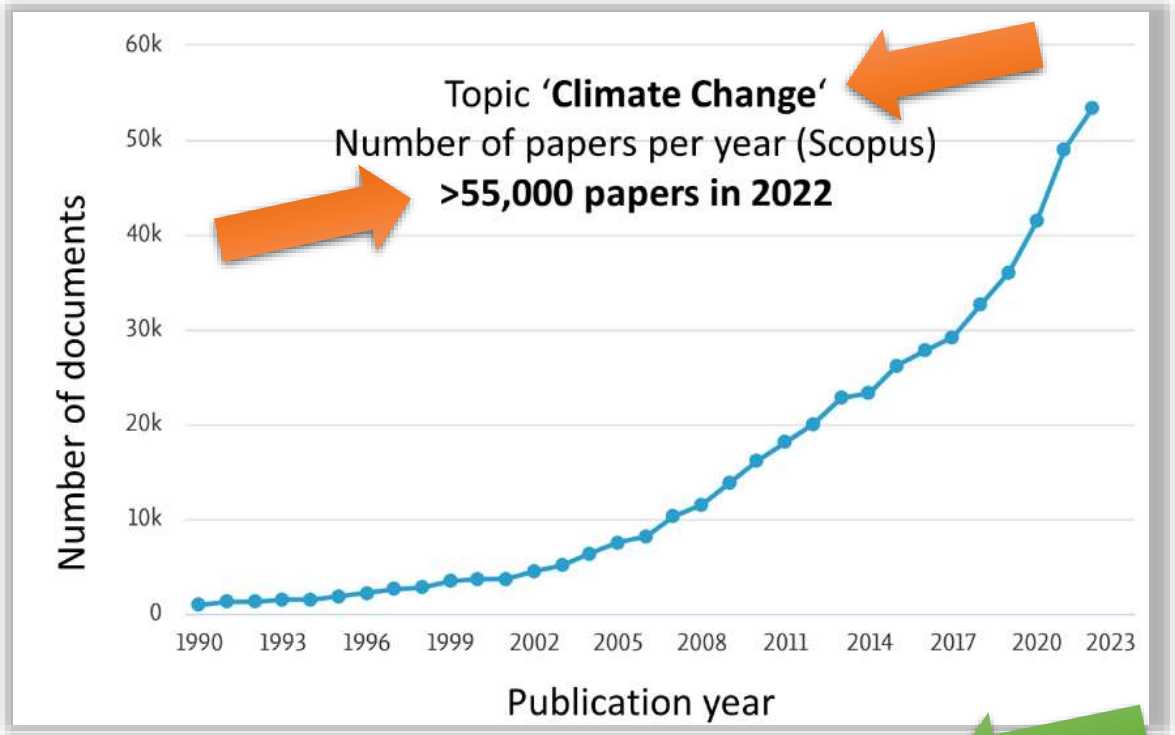
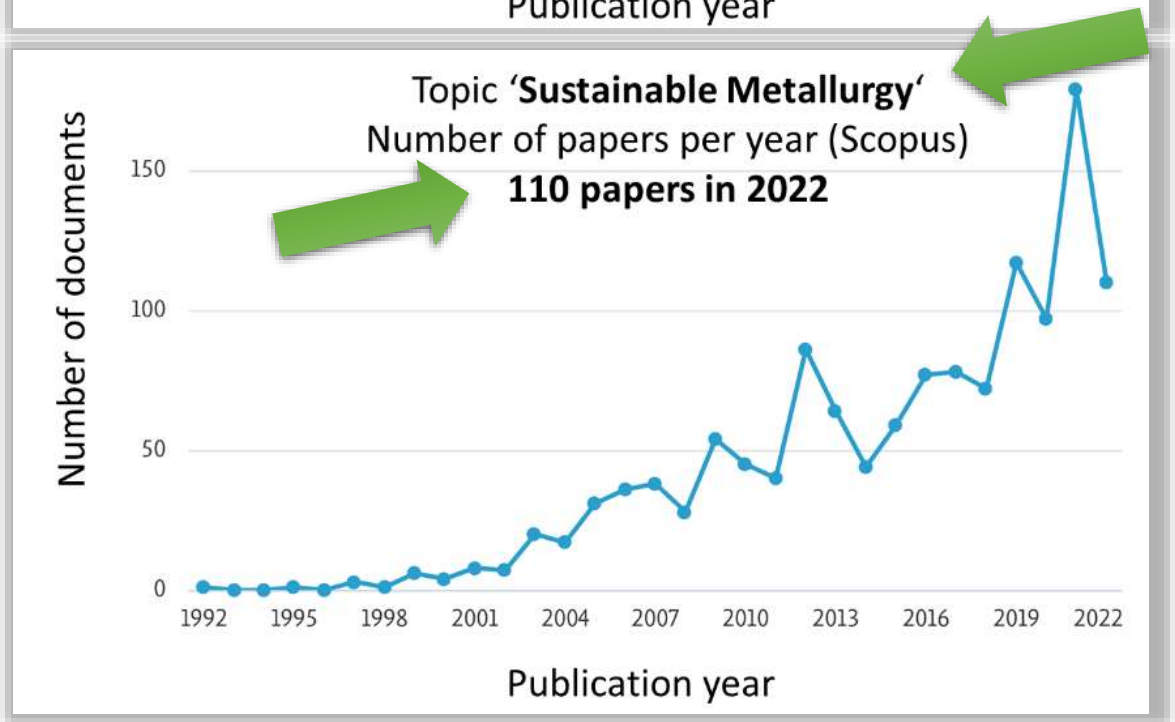
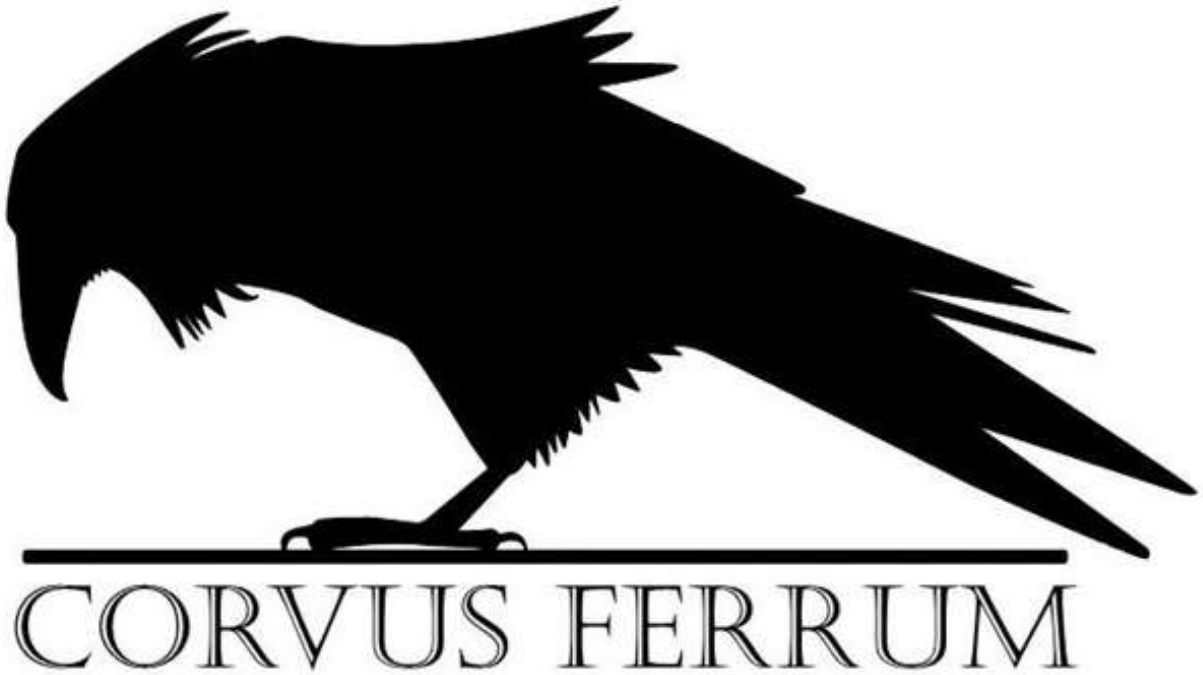




Lots of headroom for research that helps to

REDUCE CO_2

Decide !



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https://www.nature.com/articles/s41586-019-1702-5