Iron & Steel:
Can We Take Emissions Down to Zero?

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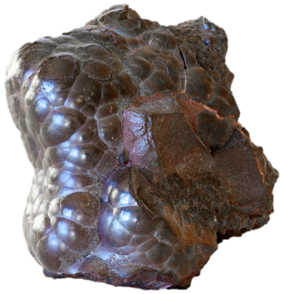
7% of world energy
(36 quads)[1]

7% of world CO_2e
(3.5 Gt CO_2)[2]

2% of US energy
(2 quads)[3]

4% of US CO_2e
(>0.2 Gt CO_2)[4]

→ Plus imports[5]...



Fe_2O_3*
Iron Ore

Can we reduce energy and carbon intensities of this process?

Soup Can

*Iron ore is often found in the form of magnetite (Fe_3O_4), hematite (Fe_2O_3), and other forms.

Please see the end of the presentation for all references.

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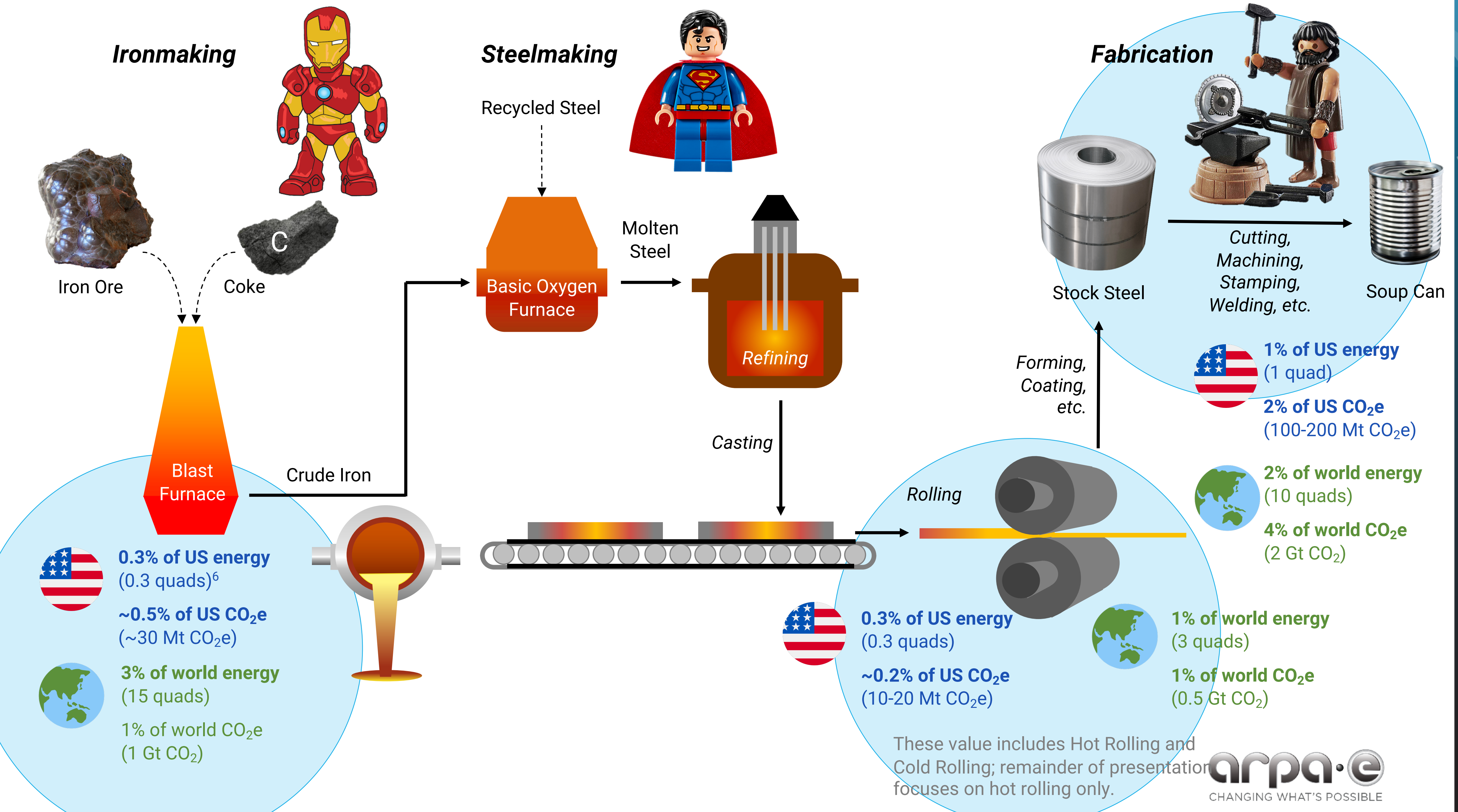
Ironmaking
Iron Ore
C
Coke
Blast Furnace
Crude Iron
0.3% of US energy
(0.3 quads)[6]
~0.5% of US CO_2e
(~30 Mt CO_2e)
3% of world energy
(15 quads)
1% of world CO_2e
(1 Gt CO_2)
Steelmaking
Recycled Steel
Basic Oxygen Furnace
Molten Steel
Refining
Casting
Rolling
0.3% of US energy
(0.3 quads)
~0.2% of US CO_2e
(10-20 Mt CO_2e)
1% of world energy
(3 quads)
1% of world CO_2e
(0.5 Gt CO_2)
These value includes Hot Rolling and Cold Rolling; remainder of presentation focuses on hot rolling only.
Forming, Coating, etc.
Fabrication
Stock Steel
Cutting, Machining, Stamping, Welding, etc.
Soup Can
1% of US energy
(1 quad)
2% of US CO_2e
(100-200 Mt CO_2e)
2% of world energy
(10 quads)
4% of world CO_2e
(2 Gt CO_2)
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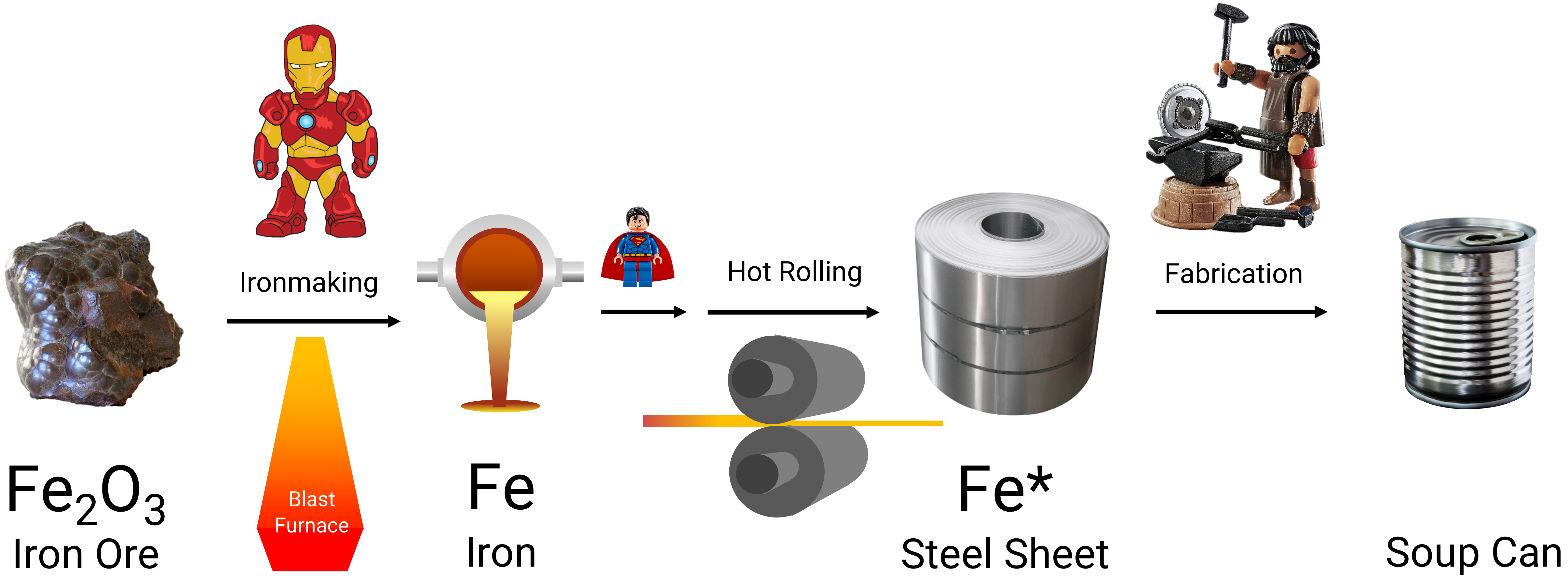

*Steel is an alloy of iron and any combination of carbon and several other elements, depending on the desired properties of the steel.

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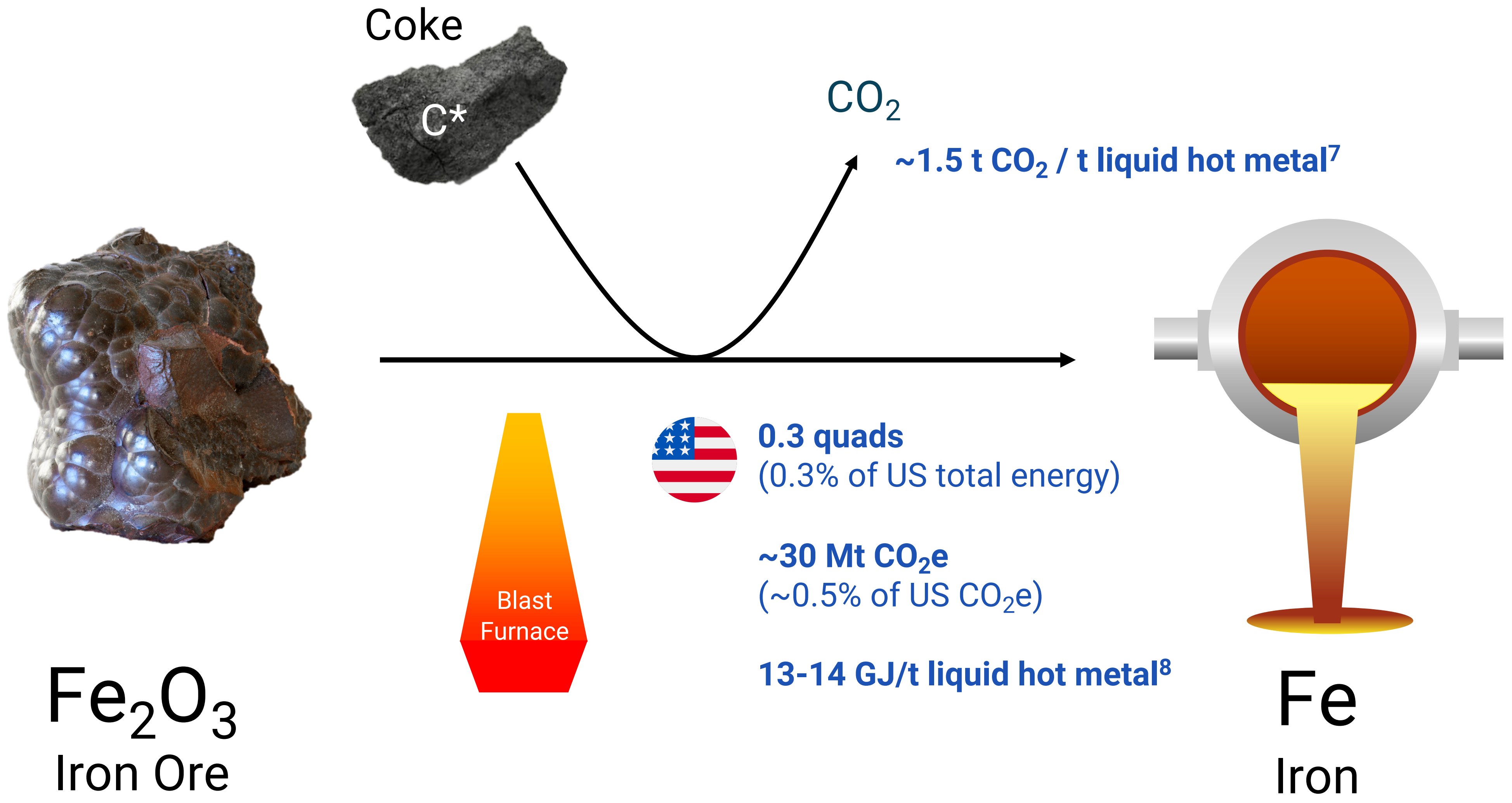
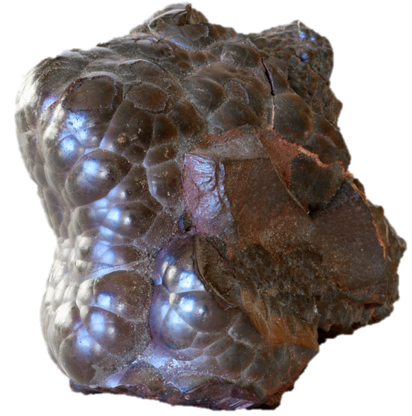


* The reactions in this presentation are given without the stoichiometric coefficients.



Fe_2O_3

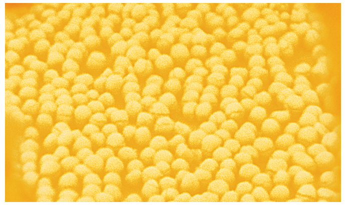
Iron Ore

$CH_4 \rightarrow CO + H_2$ → CO_2

Direct Reduced Iron

10-11 GJ/t Fe[9]

MIDREX, Hyl-ENERGIRON FASTMET, ITmk3, FINMET, CIRCORED,...

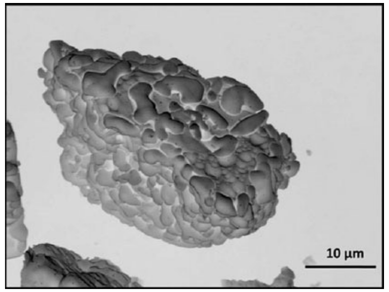


Midrex[10]

H_2 (CO_2e) → H_2O

Hydrogen Reduction

HYBRIT (SSAB, LKAB, Vattenfall), HyL-3, MIDREX, Corex, FIT, Romelt, ArcelorMittal, Thyssentrupp, Primetals, Salzgitter, Verbund (Siemens), POSCO...



Wang and Sohn[11]

→ O_2

Electrowinning, Electrolysis

>7-10 GJ/t Fe[12]

(CO_2e)

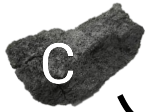
SIDERWIN, Boston Metal,...

SIDERWIN[13]

C → CO_2

”Bio” reductants (charcoal etc.)

Plantar Siderúrgica



C → CO_2 capture

Carbon Capture

HIsarna, Emirates Steel, Ternium (Praxair), PT Krakatau Steel (RMI),Saldanha Steel ...

?

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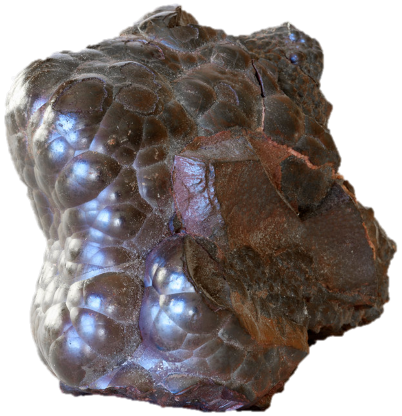
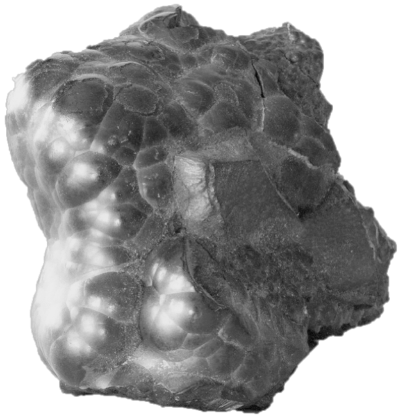


O_2 no CO_2

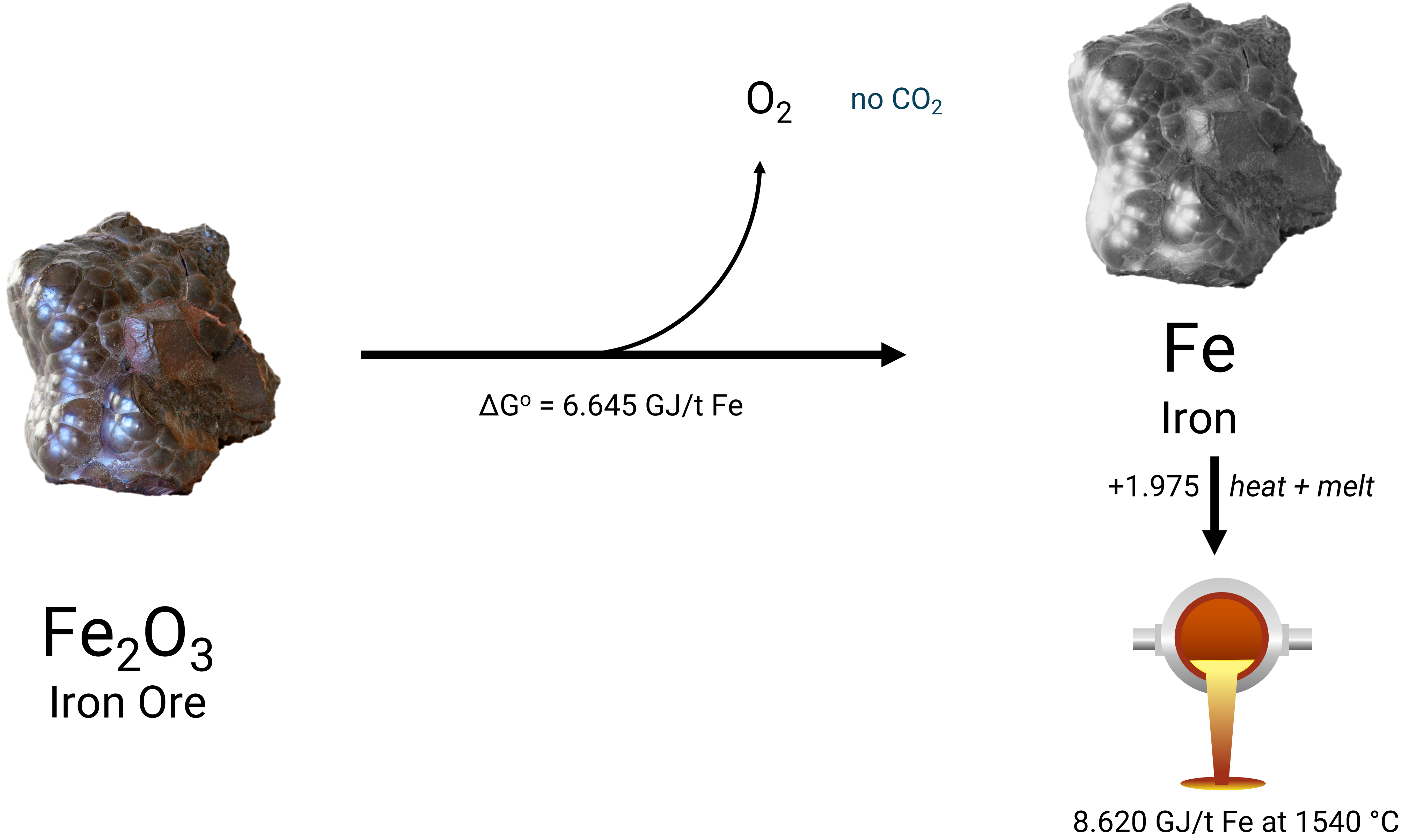
$\Delta G^{o} = 6.645$ GJ/t Fe



Fe_2O_3
Iron Ore

Fe
Iron

Thermodynamic minima from ref. 15



Thermodynamic minima from ref. 15

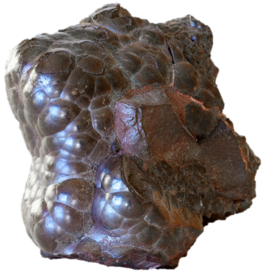
Can we rethink how iron is produced?

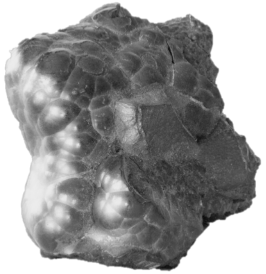
Can other reductants be proposed?

Inorganic reductants: H_2, NH_3, H_2S, O^{2-}…?
(Scrap) metals?
Renewable or waste hydrocarbons?
…?

Reductant, R → RO_x

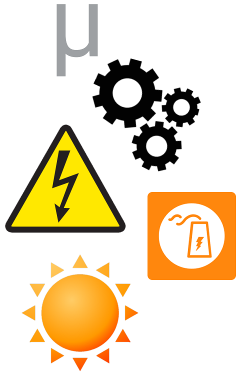
Fe_2O_3
Iron Ore





Fe
Iron

Can other energy sources/carriers be used?



Chemical potential?
Mechanical energy forms?
Electrical energy?
Induction heating?
Waste heat?
Solar energy?
…?

Lower heat requirement?

Recover heat?

Drop into existing infrastructure?

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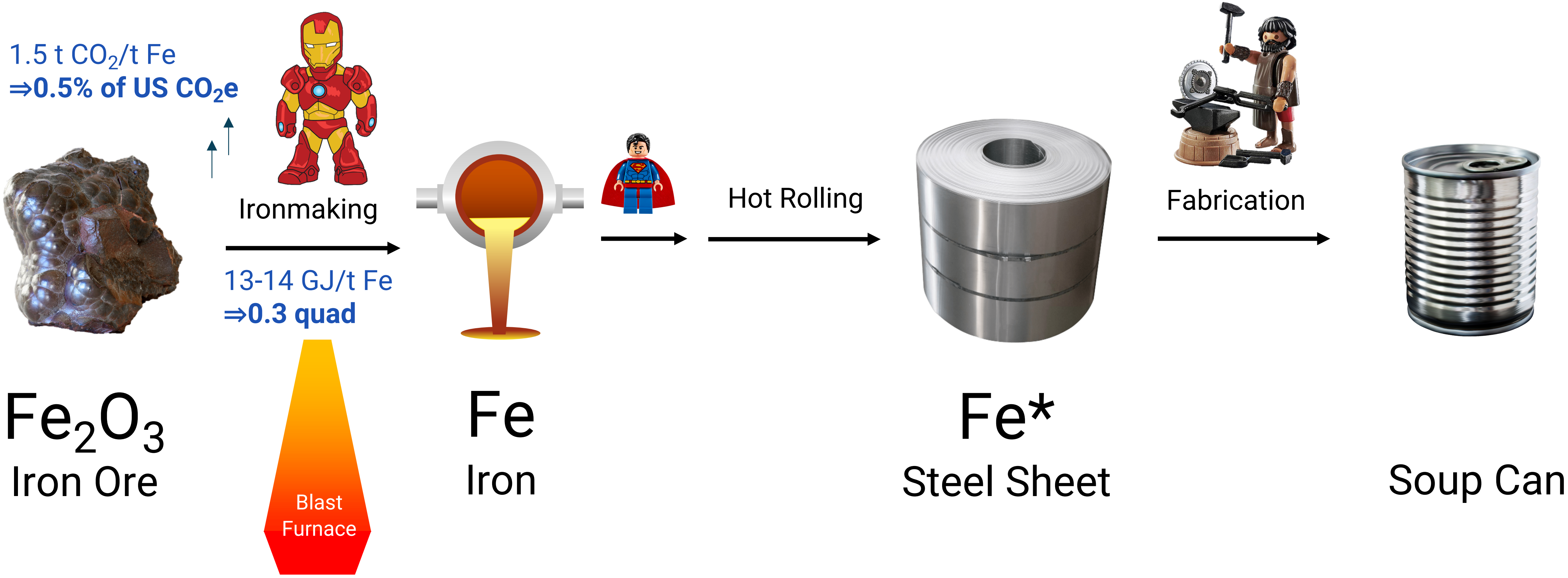
ARPA-E is not endorsing Robert Downey, Jr.

What new technologies could decrease energy and emissions of the existing supply chain?



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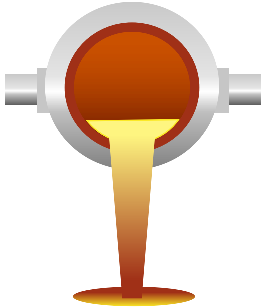
0.1 t CO_2/t steel

⇒ **0.1% of US CO_2e**



Fe*

Steel

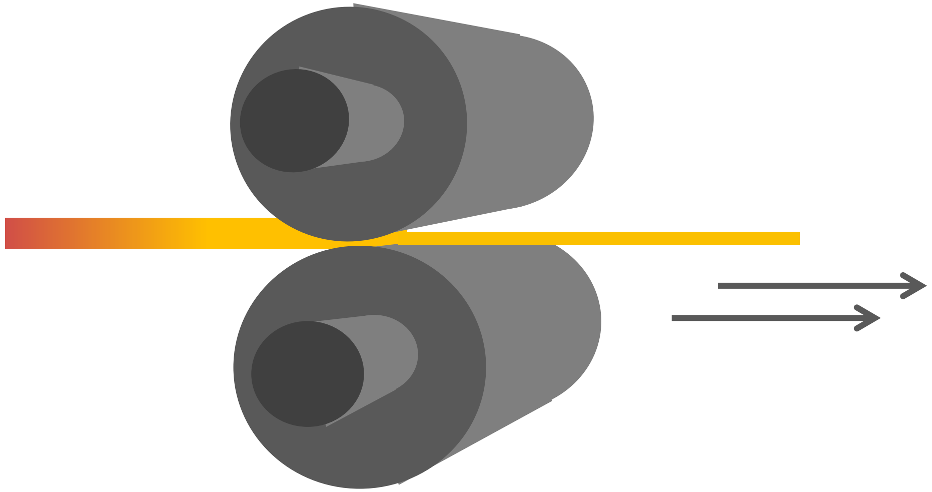
Hot Rolling

3 GJ/t steel

⇒ **0.22 quad**[16]

Fe*

Steel Sheet



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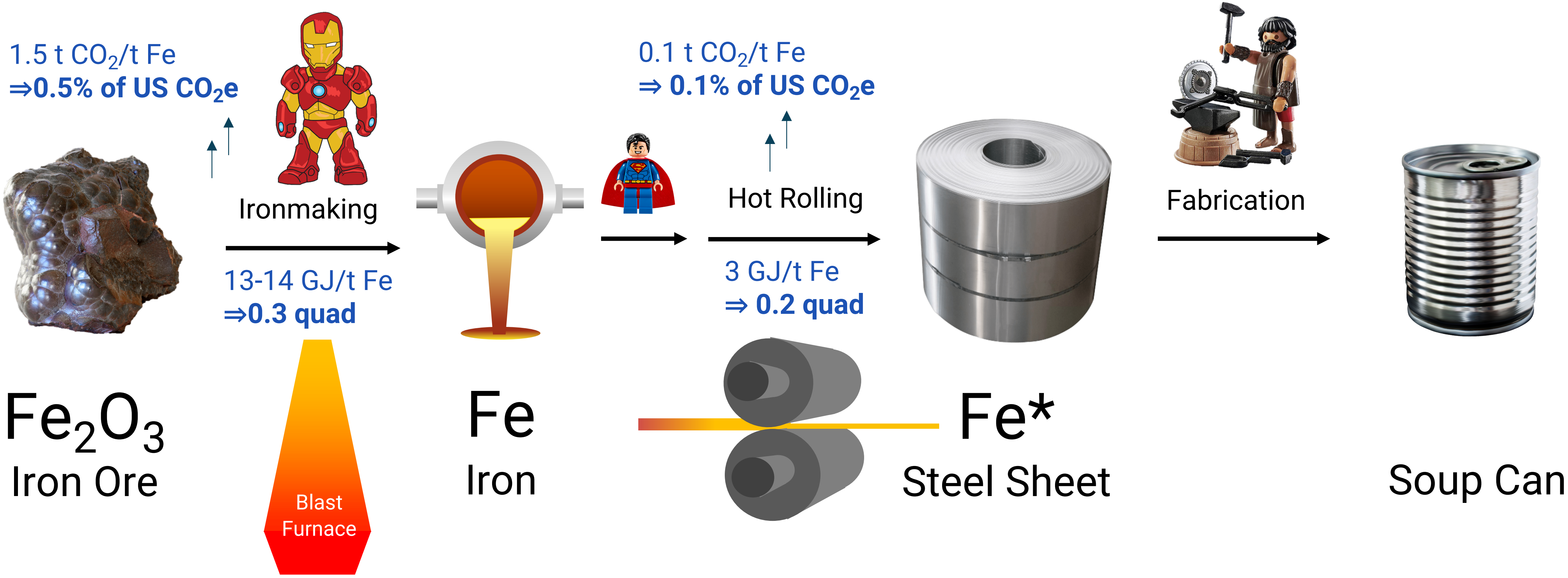

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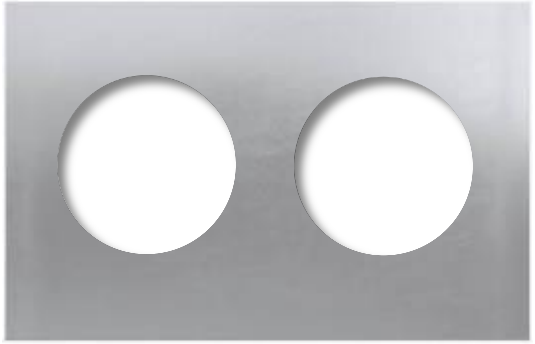
Fe*

Steel Sheet

Fabrication

1 t CO_2/t steel product
⇒2% of US CO_2e

10 GJ/t Fe
⇒ 1 quad[17]



Net energy wasted[18]
⇒ 0.1 quad

Soup Can

- Can new technologies allow us to increase material utilization of steel during fabrication, while maintaining the desired steel material properties?
- Can clean cuts can be achieved without the need for a sacrificial skeleton, allowing better component tessellation on the stock?

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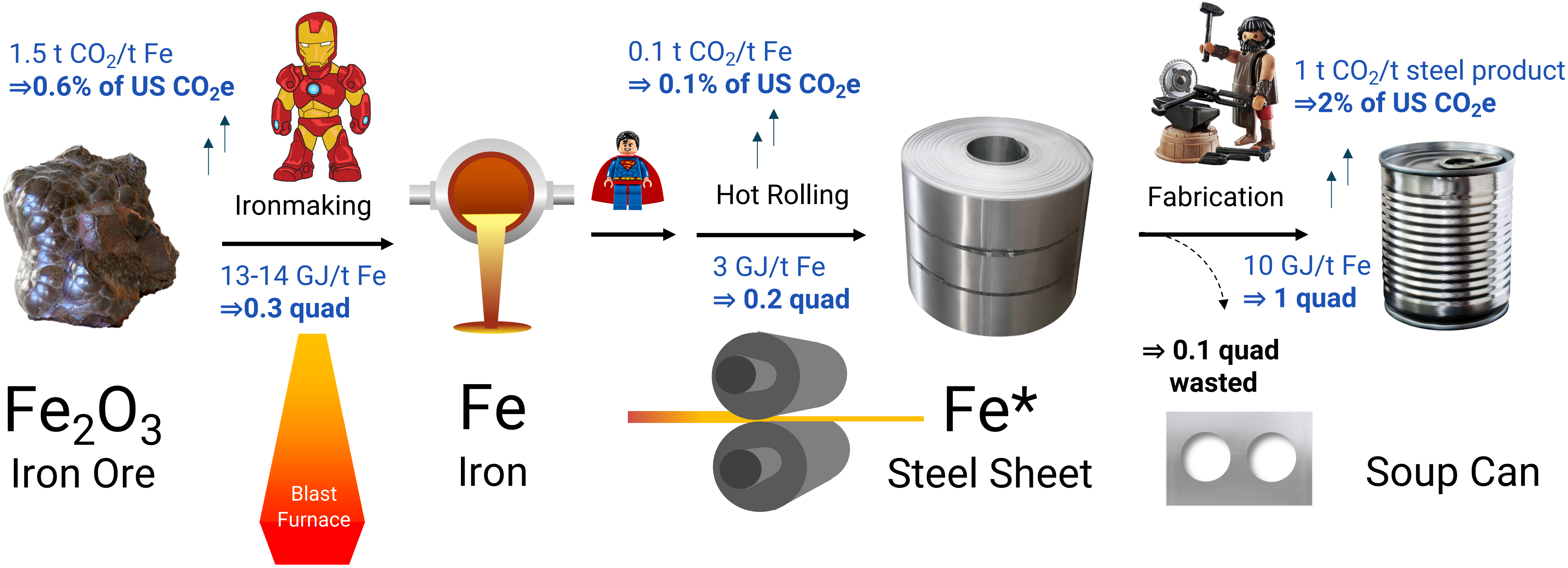
What new technologies could decrease energy and emissions of the existing supply chain?



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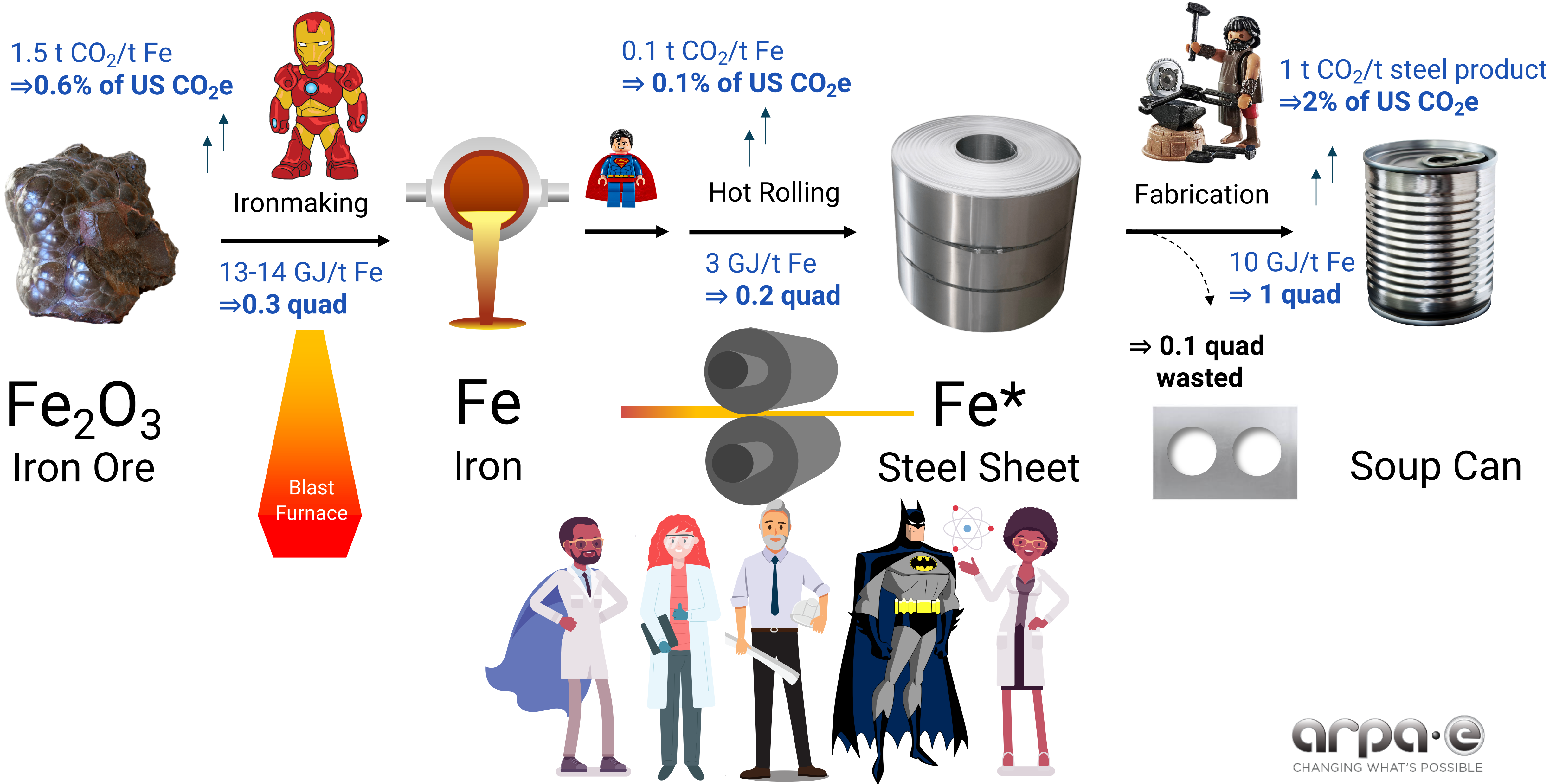
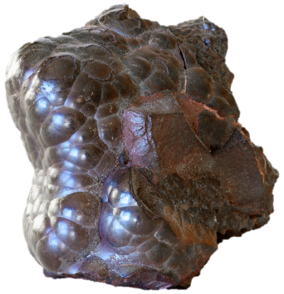
What new technologies could decrease energy and emissions of the existing supply chain?



Can we reinvent the process from iron ore to steel product?



Fe_2O_3

Iron Ore

Can we take emissions down to zero?

Can new, low-T processes convert ore directly to products?

Can near-net-shape parts be made from ore or metal powders?

What other energy challenges in iron and steel must be solved?

Soup Can

Several considerations:

- Any new processes must meet the same stringent requirements for mechanical properties and performance.
- Though the steel industry is changing, which types of steels will experience increased demand, and how can we decarbonize those?
- Where might the United States aim for strategic technical niche -- in terms of material, product, and process classes that match our strengths and resources?

https://arpa-e.energy.gov

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References (1)

1. Global steel production energy use is about 37.5 EJ. See pg 72 of Allwood J. M. and Cullen J. M., Sustainable Materials Without the Hot Air, 2015.
2. Global CO_2e from steel production is about 3.5 Gt CO_2e. See Bloomberg New Energy Finance 2020 New Energy Outlook Economic Transition Scenario plot, year 2019 (includes Scope 1 and 2 emissions). Global total CO_2e is ~52 Gt CO_2e from IPCC, Climate Change 2014 Synthesis Report Summary for Policymakers, Figure SPM.2.
   - As another reference which may use a different system boundary for CO_2 accounting, steel accounts for 8% of global CO_2 emissions according to a recent McKinsey article: https://www.mckinsey.com/industries/metals-and-mining/our-insights/decarbonization-challenge-for-steel.
3. U.S. steel production energy use is about 2 quads.
   - For several processes totaling approximately 1 quad, see the Advance Manufacturing Office's Bandwidth Study on Energy Use and Potential Energy Saving Opportunities in U.S. Iron and Steel Manufacturing (June 2015) (see Table 6-2 on pg. 46).
   - U.S. fabrication energy of steel products at another 1 quad is own internal estimate using pg 72 of Allwood J. M. and Cullen J. M., Sustainable Materials Without the Hot Air, 2015, and assuming global specific energy use in steel products fabrication (~10 GJ/t steel, itself calculated by dividing 37.5 EJ by the 1088 million tonnes of global steel demand on p. 54 of Allwood and Cullen) is roughly equal to the domestic value, and multiplying by 118 Mt of steel products fabricated in the U.S. (see World Steel Association, Steel Statistical Yearbook 2018).
   - U.S. total primary energy use is about 100.2 quads. See https://www.eia.gov/energyexplained/us-energy-facts/.
4. U.S. steel production emissions are about 200-300 Mt/year. This is a rough approximation calculated by summing the following values:
   - The EPA 2012 report, "Available and Emerging Technologies for Reducing Greenhouse Gas Emissions from the Iron and Steel Industry" Table D-4 gives 117 Mt CO_2e as emissions from U.S. steel sector for several processes.
   - U.S. fabrication CO2e of steel products were calculated at ~107 Mt CO_2e via own internal estimate. The global specific energy use of steel products fabrication of 10 GJ/t steel (see #3 above) was partitioned into 70% of this energy from electricity and 30% from fuel, in accordance with the same reference, Allwood and Cullen, p. 73. To calculate carbon intensity of this energy mixture in the U.S., 150 lbs CO2 per million BTU of energy was assumed for US fuel burning (https://www.eia.gov/tools/faqs/faq.php?id=73&t=11) and 460 g CO_2e/kWh were assumed for the U.S. electric grid, which was approximately the U.S. grid emission factor in 2016 (IGES 2019, Moro and Lonza 2018).
5. U.S. domestic steel production and use is approx. 80 Mt, net imports of semifinished steel are 29 Mt, and net imports of steel inside goods are 14 Mt (World Steel Association Steel Statistical Yearbook 2015, values reported for year 2013).
6. Image on this set of slides made in-house, inspired by: McQueen,* Woodall,* Psarras, and Wilcox, doi: 10.1039/9781788012744-00353. Data on these slides are from: US Crude Steel Production in 2017 (WSA Steel Statistical Yearbook 2018), Bandwidth Study on Iron & Steel Mfg, US Adv. Mfg. Office, 2015, and Allwood J. M. and Cullen J. M., Sustainable Materials Without the Hot Air, 2015.
7. Freuhan, Ortini, Paxton and Brindle, "Theoretical Minimum Energies to Produce Steel for Selected Conditions," May 2000.
8. Bandwidth Study on Iron & Steel Mfg, US Adv. Mfg. Office, 2015.

References (2)

9. Cavaliere, P., “Clean Ironmaking and Steelmaking Processes,” Springer, 2019, doi: 10.1007/978-3-030-21209-4
10. www.midrex.com/
11. Wang and Sohn, 10.1007/s11663-012-9754-z
12. Several estimates are provided for the energy required for various electrolytic methods. See for example: Carpenter, A. “CO_2 Abatement in the iron and steel industry.” 2012, IEA Clean Coal Centre; Kleiner K (2006) *Electrolysis may one day provide ‘green iron’*. Available at: www.newscientist.com/article/dn9878-electrolysis-may-one-day-provide-green-iron.html 2 pp. (30 Aug 2006)
13. Cavaliere, P., “Clean Ironmaking and Steelmaking Processes,” Springer, 2019, doi: 10.1007/978-3-030-21209-4; Allanore A, Ortiz LA, Sadoway R (2011) Molten oxide electrolysis for iron production: identifi- cation of key process parameters for largescale development. In: Energy technology 2011: carbon dioxide and other greenhouse gas reduction metallurgy and waste heat recovery. Wiley, Hoboken, NJ, pp 120–129
14. SIDERWIN: https://www.siderwin-spire.eu/, METEC 2019
15. ΔG^o was calculated using the CRC Standard Thermodynamic Properties of Chemical Substances. The thermodynamic minimum energy to produce molten iron from Fe_2O_3 is available in Freuhan, Ortini, Paxton and Brindle, ”Theoretical Minimum Energies to Produce Steel for Selected Conditions,” May 2000.
16. Freuhan, Ortini, Paxton and Brindle, ”Theoretical Minimum Energies to Produce Steel for Selected Conditions,” May 2000.
17. 10 GJ/t Fe is an approximate value for Fabrication energy use; see Ref #3 on prior page.
18. The bodied energy of steel scrap depends on the steel stock material, the country of origin, and other factors. Average values for the bodied energy of steel may be found at various sources. See for example: Ashby, M. F., 2013: *Materials and the Environment – Eco-Informed Material Choice*, 2nd ed.; and Milford, R.L., Allwood, J. M., and Cullen, J. M., “Assessing the potential of yield improvements, through process scrap reduction for energy and CO2 abatement in the steel and aluminum sectors”, Resources, Conservation and Recycling 55 (2011) 1185–1195; and https://www.energy.gov/sites/prod/files/2013/11/f4/steel_energy_use.pdf.; Steel prompt scrap amount reported in Mineral Commodities Summary 2019. Net energy wasted calculated by subtracting the approximate embodied energy of steel made from virgin ore (~19 GJ/t) from the approx. embodied energy of steel made by recycled route (~8GJ/t) and multiplying by prompt scrap amount in the US (~15 Mt/yr)