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energy innovation summit

March 22-24, 2023 • Washington, D.C.

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Ashes to Ashes, Coke to Coke:

Drop-in Fuels for Circular Industrial Decarbonization

Jonathan "Jo" Melville, PhD
ARPA-E Fellow

March 22nd, 2023

Clean Coal 2.0

for real this time i promise

where are you going wait come back

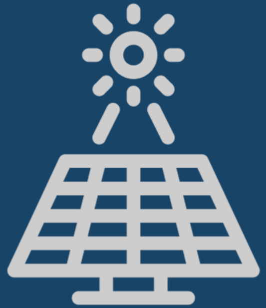
Jonathan "Jo" Melville, PhD

ARPA-E Fellow

March 22nd, 2023

Carbon consumption circumscribes contemporary civilization

Batteries
(phosphorus)



Solar Panels
(silicon)

Aviation
(titanium)

Fertilizers
(phosphorus)

Computers
(silicon)

Bioimplants
(titanium)

Cars, Ships, Buildings
(iron, aluminum)

Metall. Mater. Trans. B **2020**, *51*, 1315.
J. Sus. Metall. **2021**, *7*, 848.
Chem. Soc. Rev. **2021**, *50*, 87.

Periodic Table of the Elements

Refined (directly or indirectly) using solid carbon

1 IA 1A	2 IIA 2A	3 IIIB 3B	4 IVB 4B	5 VB 5B	6 VIB 6B	7 VIIB 7B	8	9 VIII 8	10	11 IB 1B	12 IIB 2B	13 IIIA 3A	14 IVA 4A	15 VA 5A	16 VIA 6A	17 VIIA 7A	18 VIIIA 8A
1 H Hydrogen 1.008																	2 He Helium 4.003
3 Li Lithium 6.941	4 Be Beryllium 9.012											5 B Boron 10.811	6 C Carbon 12.011	7 N Nitrogen 14.007	8 O Oxygen 15.999	9 F Fluorine 18.998	10 Ne Neon 20.180
11 Na Sodium 22.990	12 Mg Magnesium 24.305											13 Al Aluminum 26.982	14 Si Silicon 28.086	15 P Phosphorus 30.974	16 S Sulfur 32.066	17 Cl Chlorine 35.453	18 Ar Argon 39.948
19 K Potassium 39.098	20 Ca Calcium 40.078	21 Sc Scandium 44.956	22 Ti Titanium 47.867	23 V Vanadium 50.942	24 Cr Chromium 51.996	25 Mn Manganese 54.938	26 Fe Iron 55.845	27 Co Cobalt 58.933	28 Ni Nickel 58.693	29 Cu Copper 63.546	30 Zn Zinc 65.38	31 Ga Gallium 69.723	32 Ge Germanium 72.631	33 As Arsenic 74.922	34 Se Selenium 78.971	35 Br Bromine 79.904	36 Kr Krypton 83.798
37 Rb Rubidium 85.468	38 Sr Strontium 87.62	39 Y Yttrium 88.906	40 Zr Zirconium 91.224	41 Nb Niobium 92.906	42 Mo Molybdenum 95.95	43 Tc Technetium 98.907	44 Ru Ruthenium 101.07	45 Rh Rhodium 102.906	46 Pd Palladium 106.42	47 Ag Silver 107.868	48 Cd Cadmium 112.414	49 In Indium 114.818	50 Sn Tin 118.711	51 Sb Antimony 121.760	52 Te Tellurium 127.6	53 I Iodine 126.904	54 Xe Xenon 131.294
55 Cs Cesium 132.905	56 Ba Barium 137.328	57-71	72 Hf Hafnium 178.49	73 Ta Tantalum 180.948	74 W Tungsten 183.84	75 Re Rhenium 186.207	76 Os Osmium 190.23	77 Ir Iridium 192.217	78 Pt Platinum 195.085	79 Au Gold 196.967	80 Hg Mercury 200.592	81 Tl Thallium 204.383	82 Pb Lead 207.2	83 Bi Bismuth 208.980	84 Po Polonium [208.982]	85 At Astatine 209.987	86 Rn Radon 222.018
87 Fr Francium 223.020	88 Ra Radium 226.025	89-103	104 Rf Rutherfordium [261]	105 Db Dubnium [262]	106 Sg Seaborgium [266]	107 Bh Bohrium [264]	108 Hs Hassium [269]	109 Mt Meitnerium [278]	110 Ds Darmstadtium [281]	111 Rg Roentgenium [280]	112 Cn Copernicium [285]	113 Nh Nihonium [286]	114 Fl Flerovium [289]	115 Mc Moscovium [289]	116 Lv Livermorium [293]	117 Ts Tennessine [294]	118 Og Oganesson [294]

Lanthanide Series	57 La Lanthanum 138.905	58 Ce Cerium 140.116	59 Pr Praseodymium 140.908	60 Nd Neodymium 144.243	61 Pm Promethium 144.913	62 Sm Samarium 150.36	63 Eu Europium 151.964	64 Gd Gadolinium 157.25	65 Tb Terbium 158.925	66 Dy Dysprosium 162.500	67 Ho Holmium 164.930	68 Er Erbium 167.259	69 Tm Thulium 168.934	70 Yb Ytterbium 173.055	71 Lu Lutetium 174.967
Actinide Series	89 Ac Actinium 227.028	90 Th Thorium 232.038	91 Pa Protactinium 231.036	92 U Uranium 238.029	93 Np Neptunium 237.048	94 Pu Plutonium 244.064	95 Am Americium 243.061	96 Cm Curium 247.070	97 Bk Berkelium 247.070	98 Cf Californium 251.080	99 Es Einsteinium [254]	100 Fm Fermium 257.095	101 Md Mendelevium 258.1	102 No Nobelium 259.101	103 Lr Lawrencium [262]

Greenwood, N.; Earnshaw, A. *Chemistry of the Elements*; Elsevier, **2012**.

How do you remove carbon from a carbothermal reaction?

Several strategies suggest speculative sustainable solutions

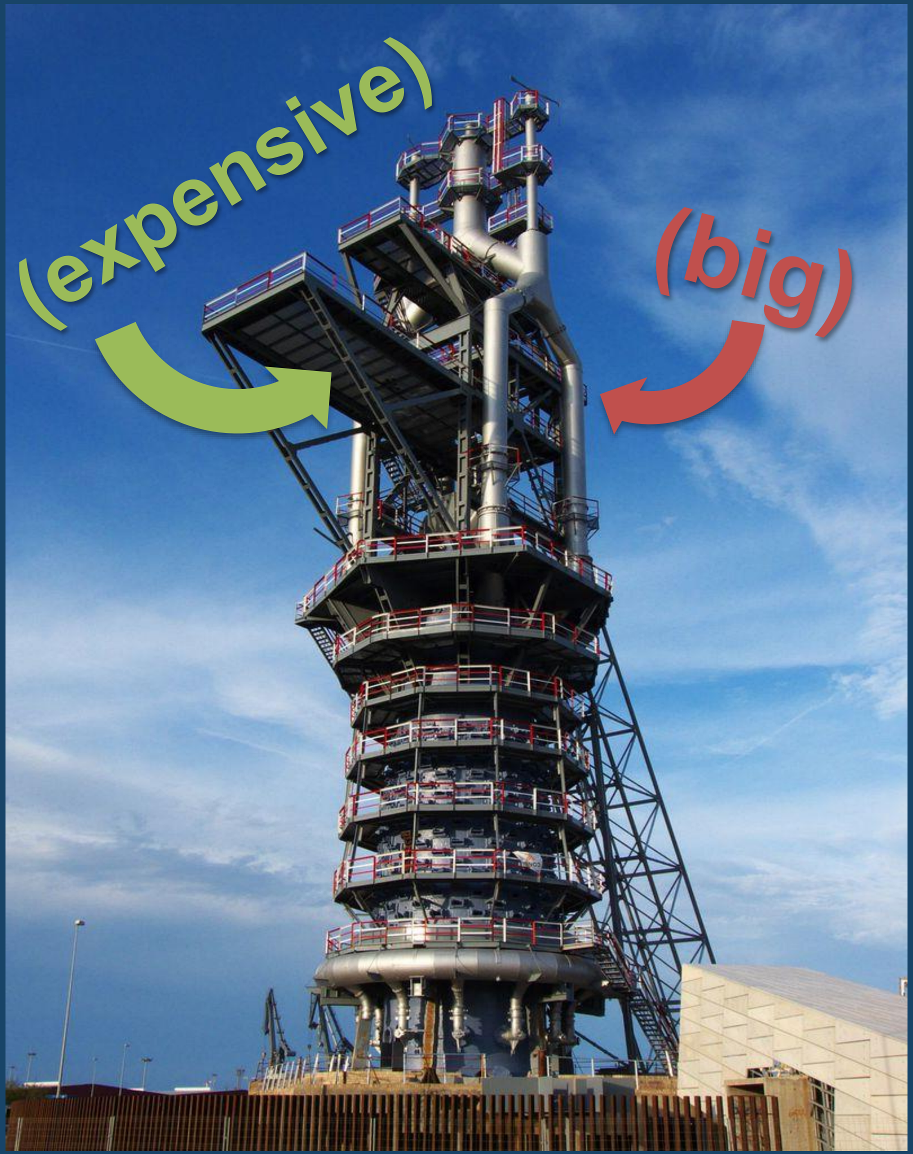
Revolutionary routes require restrictively remunerative retrofitting

(that means it's expensive)

- Furnaces are big!
  (**\$100mil** ~ **\$billions**)

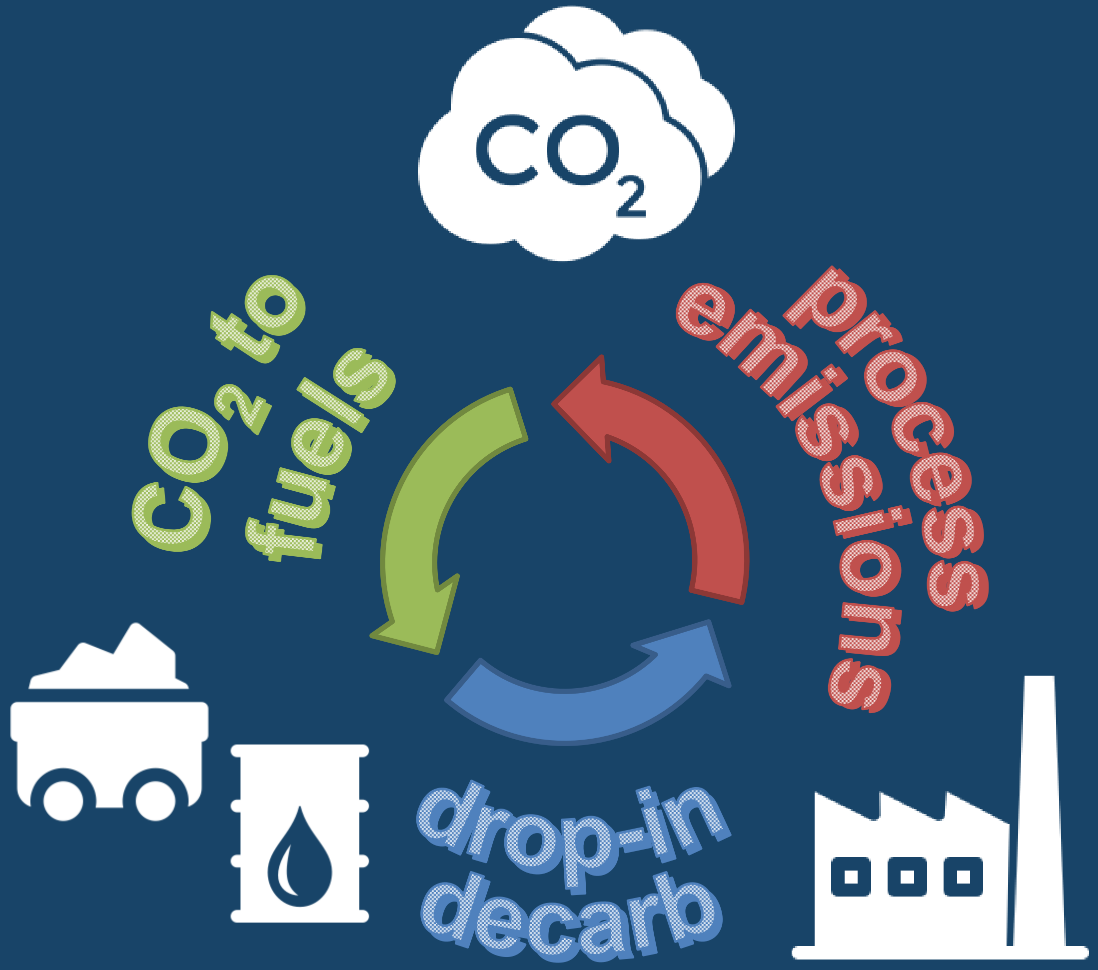
- Decarbonizing each industry is unique

- Different feedstocks, different products



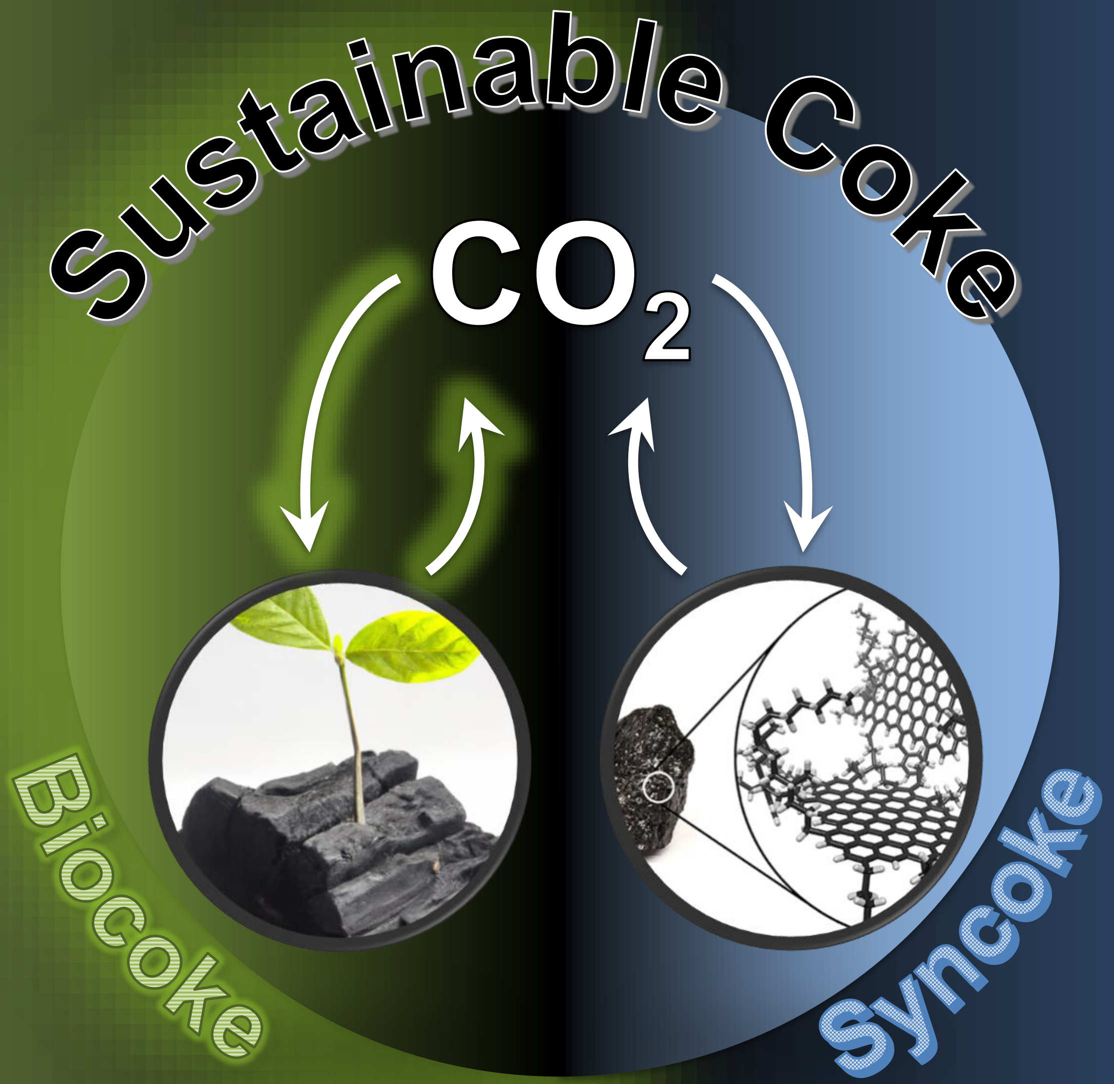
Drop-in decarbonization directly draws down detrimental discharge

(…of CO_2)



- Identical chemistry
- Identical input, identical output
- One size fits all
- Read my lips: **no sunk costs**

Sustainable coke enables drop-in industrial decarbonization



Humans have used drop-in carbon for millennia

Interdiscip. Sci. Rev. **1999**, *24*, 301.

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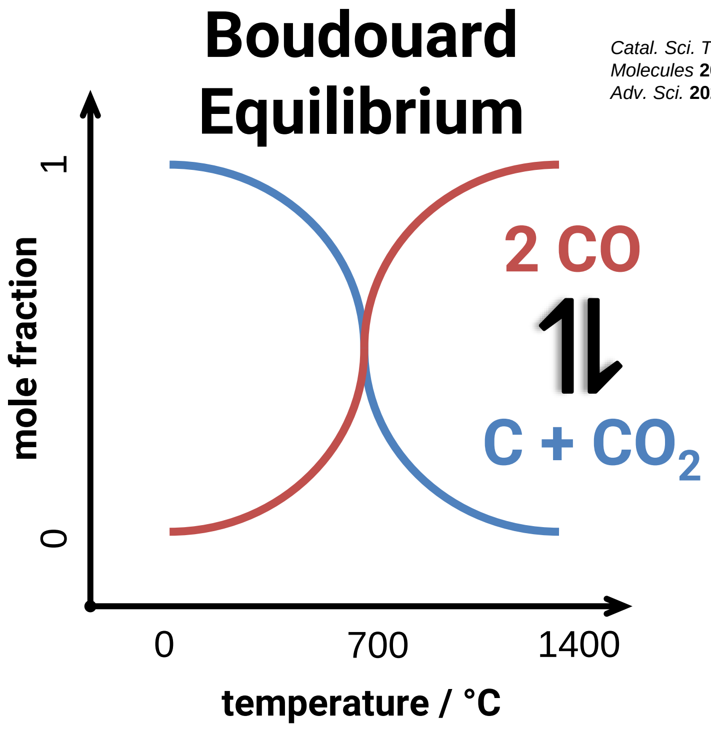
Interdiscip. Sci. Rev. **1999**, *24*, 301.

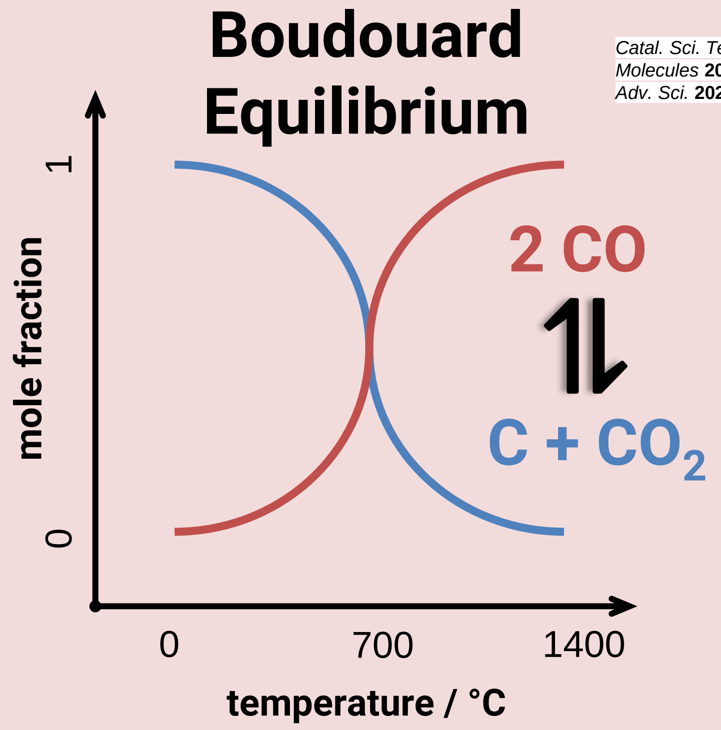
Sustainable coke enables drop-in industrial decarbonization

Multiple viable routes to syncoke production exist



Catal. Sci. Tech. **2019**, *9*, 4100.
Molecules **2021**, *26*, 1507.
Adv. Sci. **2022**, *9*, 2200217.

Multiple viable routes to syncoke production exist



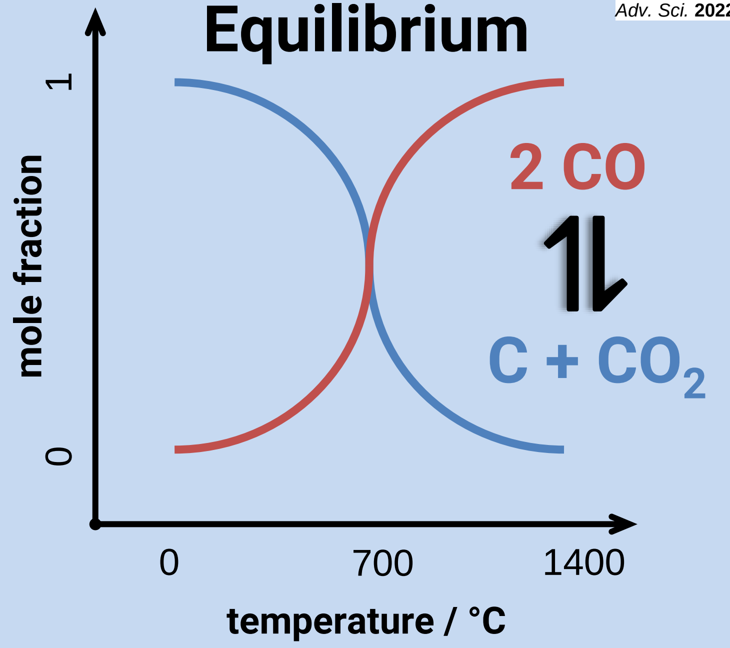
Catal. Sci. Tech. **2019**, *9*, 4100.
Molecules **2021**, *26*, 1507.
Adv. Sci. **2022**, *9*, 2200217.

Reverse Water-Gas Shift:

$CO_2 + H_2 \rightarrow CO + H_2O$

Ind. Eng. Chem. Res. **2002**, *41*, 4252.
RSC Adv. **2016**, *6*, 49675.
React. Chem. Eng. **2021**, *6*, 954.

Multiple viable routes to syncoke production exist



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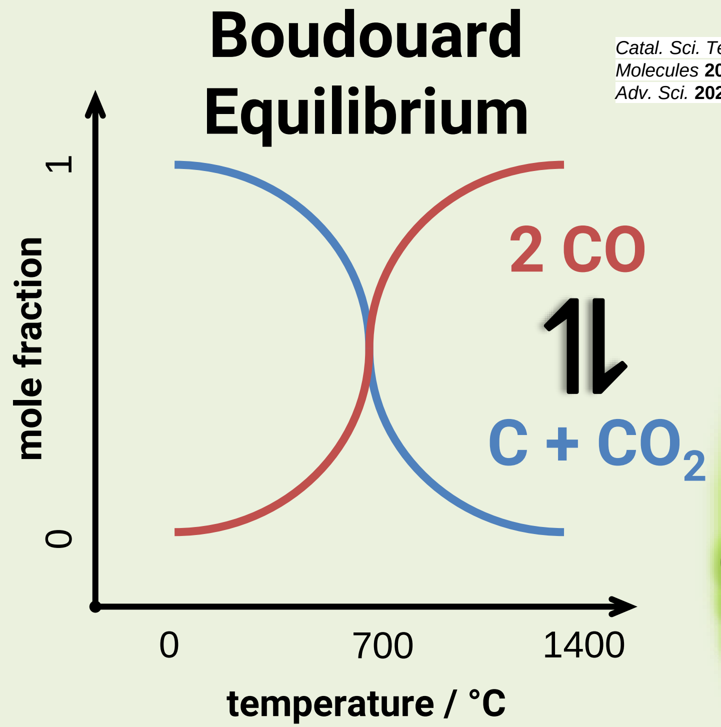
Molecules **2021**, *26*, 1507.
Adv. Sci. **2022**, *9*, 2200217.

CO$_2$ Splitting:

$CO_2 \rightarrow CO + \frac{1}{2} O_2$

Catal. Today **2021**, *364*, 211.
Energy Environ. Sci. **2022**, *15*, 806.
J. Clean. Prod. **2023**, *389*, 135963.

Multiple viable routes to syncoke production exist



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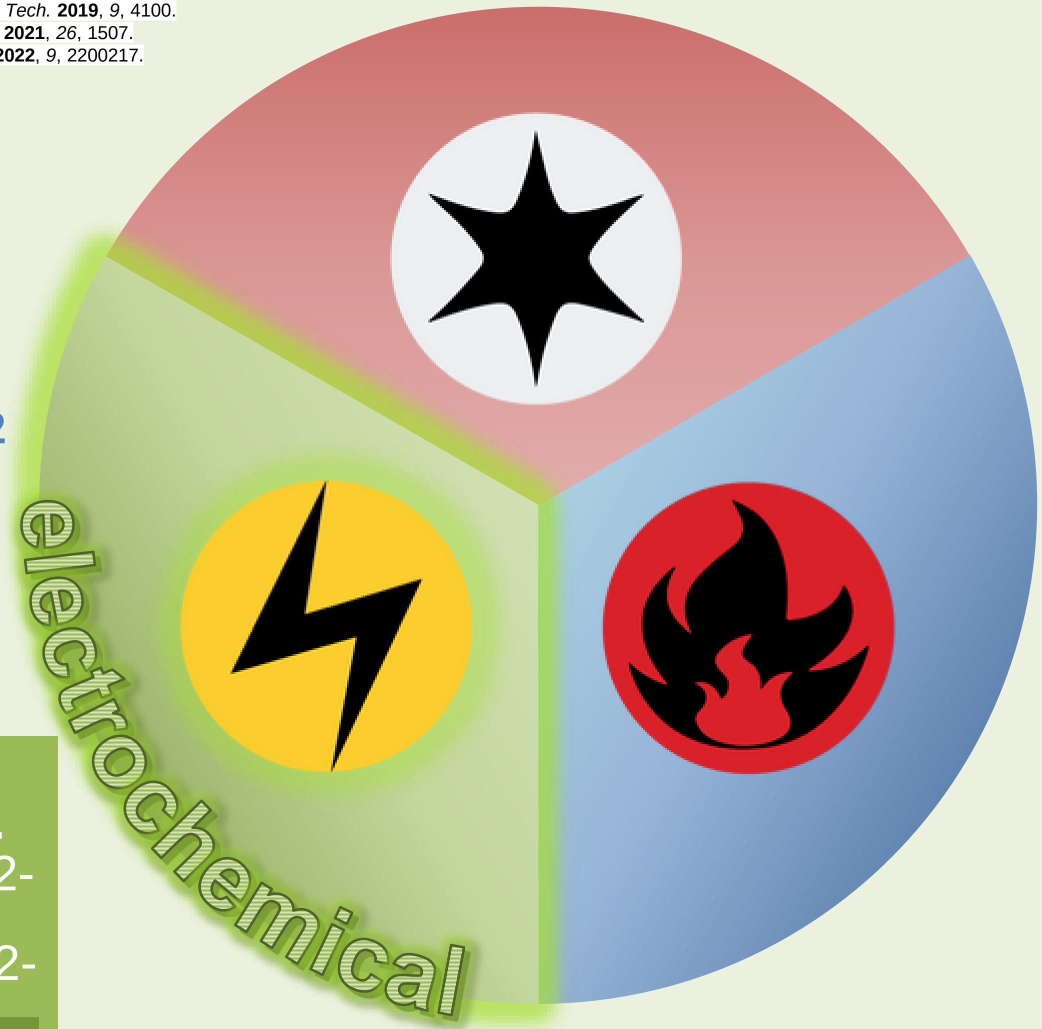
Adv. Sci. **2022**, *9*, 2200217.



CO_2 Electroreduction:

$CO_2 + 2\,e^- \rightarrow CO + O^{2-}$

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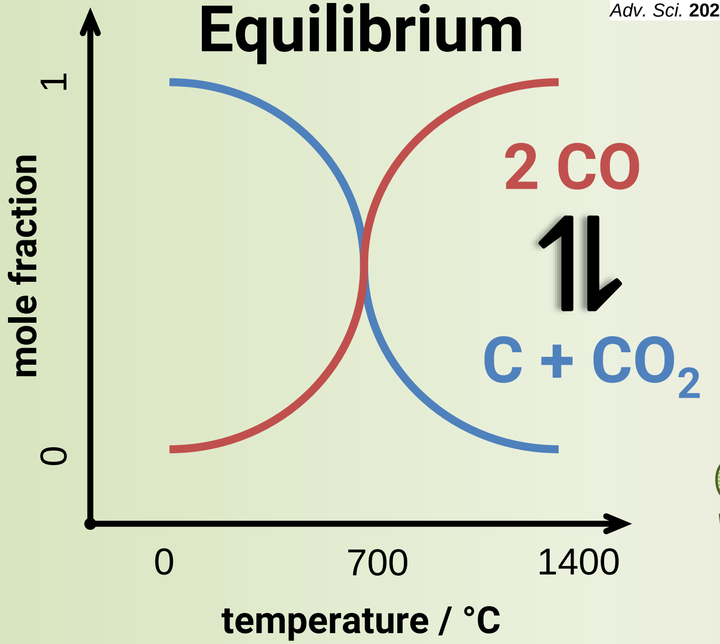
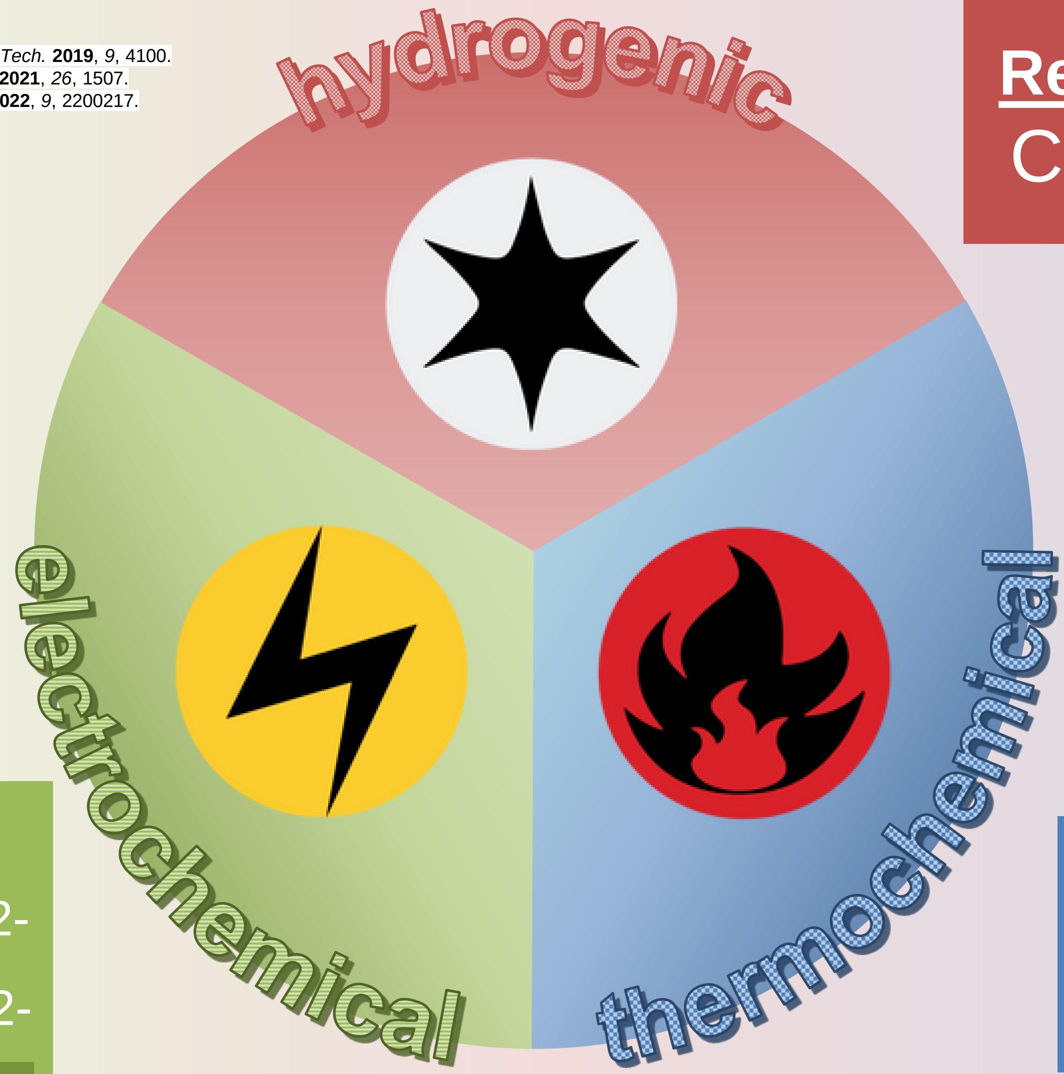
Nat. Commun. **2019**, *10*, 865.
Curr. Opin. Green Sus. Chem. **2019**, *16*, 47.
Chem. Eng. Sci. **2021**, *234*, 116403.

Multiple viable routes to syncoke production exist

Boudouard Equilibrium



Catal. Sci. Tech. **2019**, *9*, 4100.
Molecules **2021**, *26*, 1507.
Adv. Sci. **2022**, *9*, 2200217.



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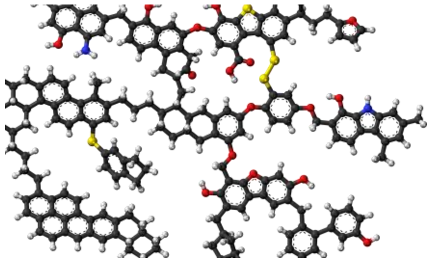
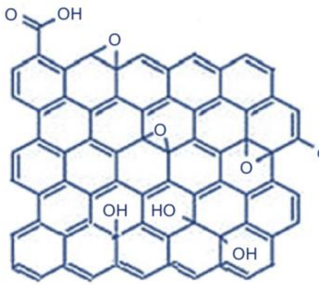
Catal. Today **2021**, *364*, 211.
Energy Environ. Sci. **2022**, *15*, 806.
J. Clean. Prod. **2023**, *389*, 135963.

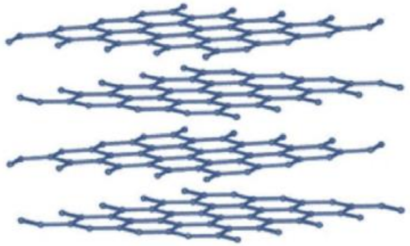
Not all carbon is created equal…



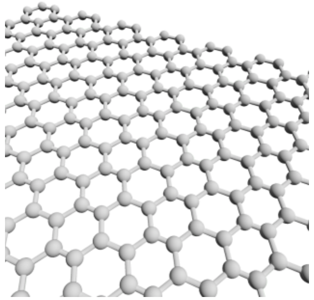
coke



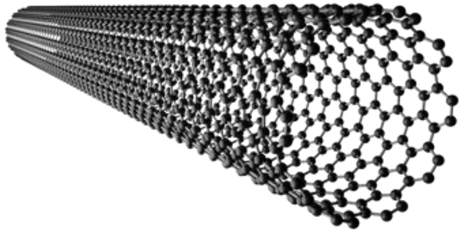
carbon black



graphite



graphene



nanotubes

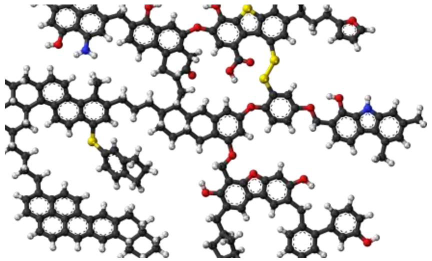
less ordered ↔ more ordered

fast synthesis ↔ slow synthesis

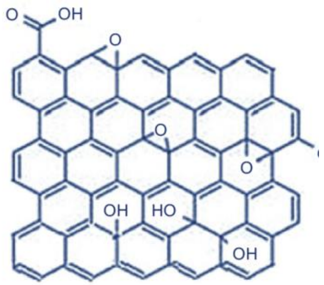
less expensive ↔ more expensive

bigger market size ↔ smaller market size

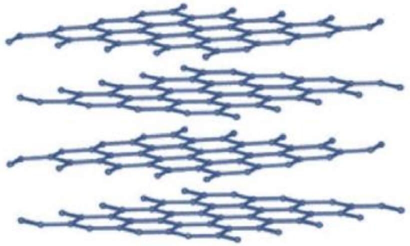
…but the blast furnace is a great equalizer



coke



carbon black



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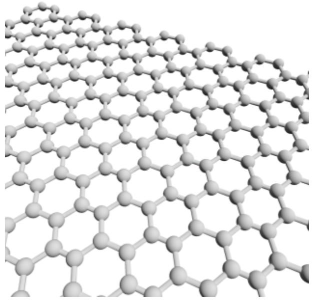
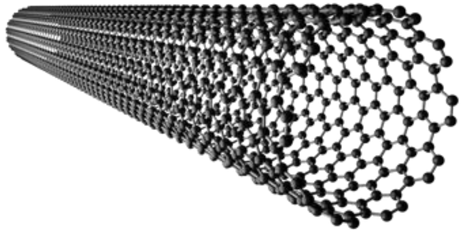


graphene



nanotubes

>95% C

>97% C

>99% C

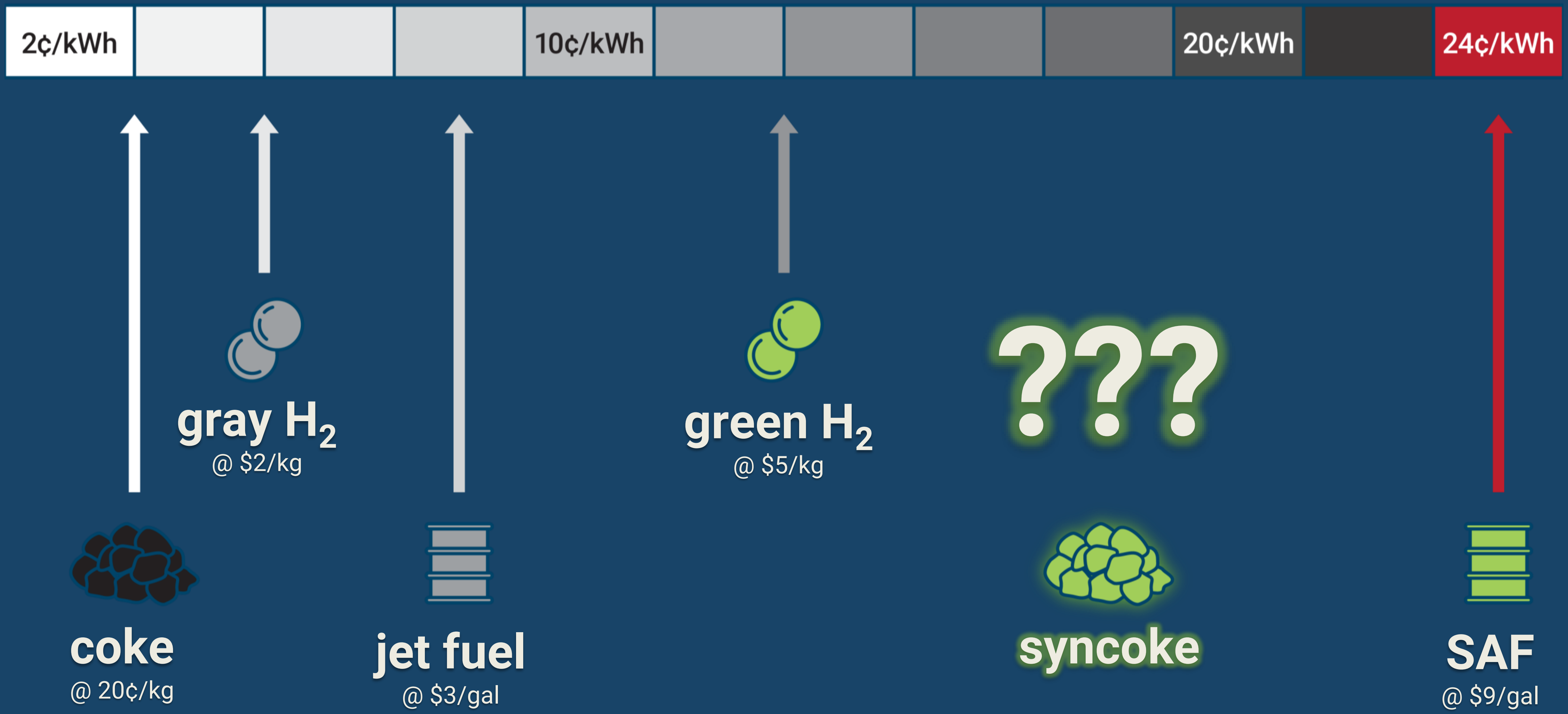
100% C

100% C


Let’s make worse
carbon *faster!*

Get real: all green fuels cost a premium

(...but how much?)



Get real: all green fuels cost a premium

(...but how much?)

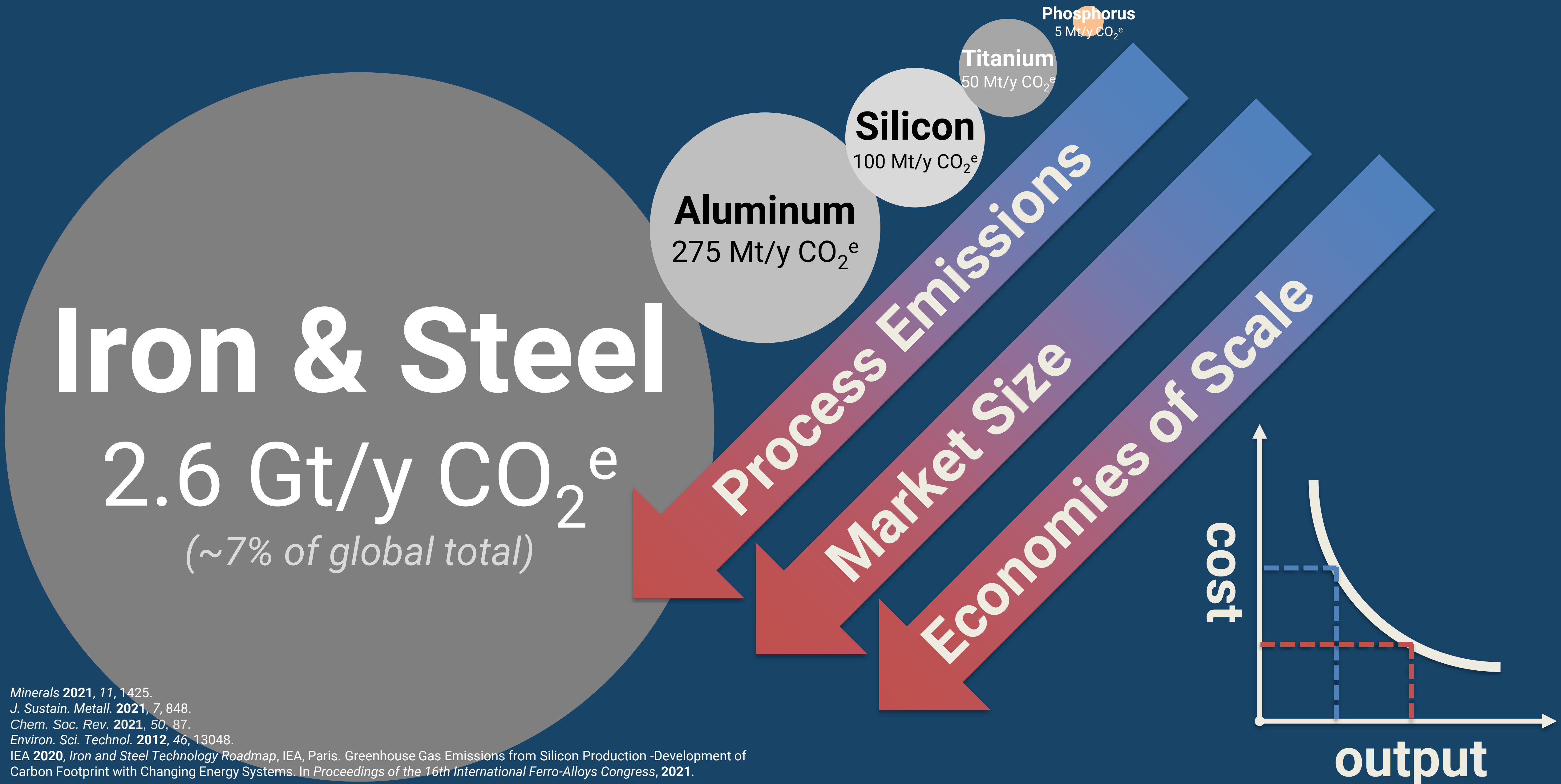
2¢/kWh				10¢/kWh					20¢/kWh		24¢/kWh

How much does syncoke cost?

We don't know.
No one's making any.

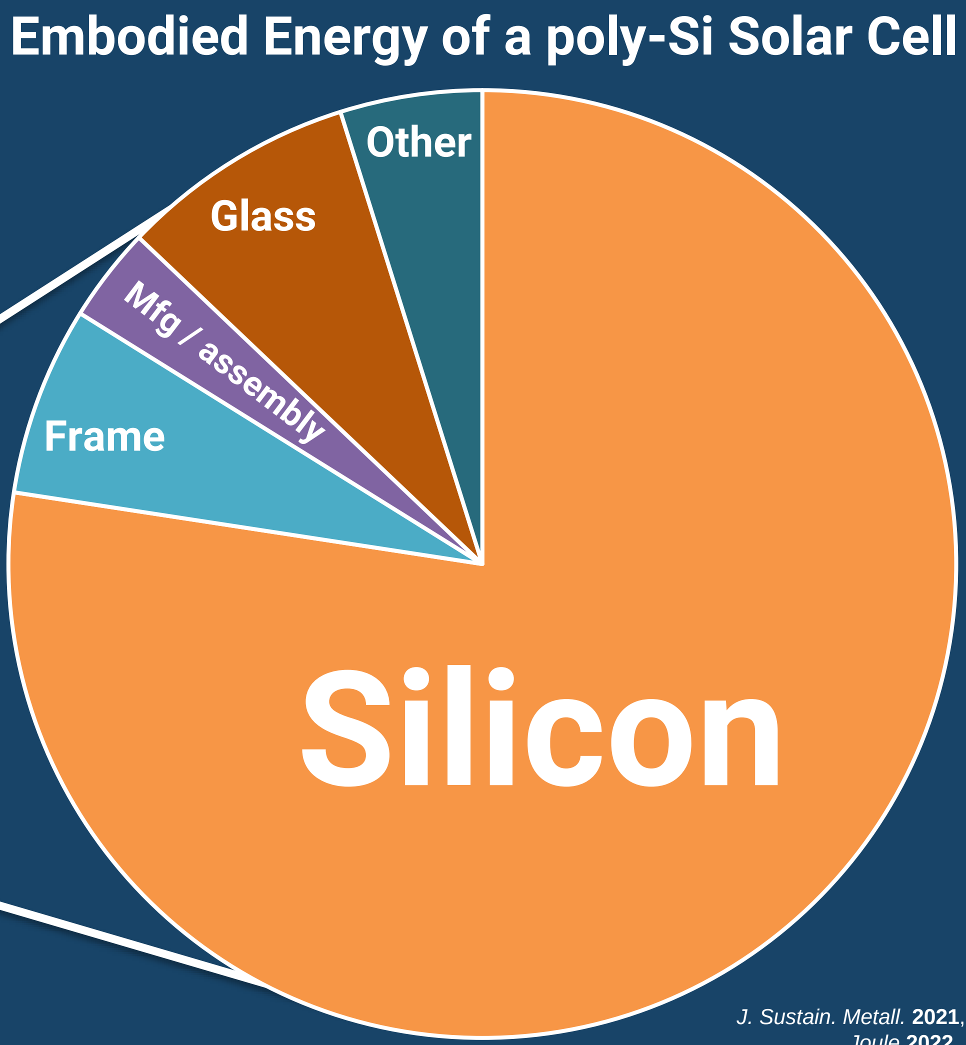
syncoke

Cross-sectoral impact offers footholds for process scaling



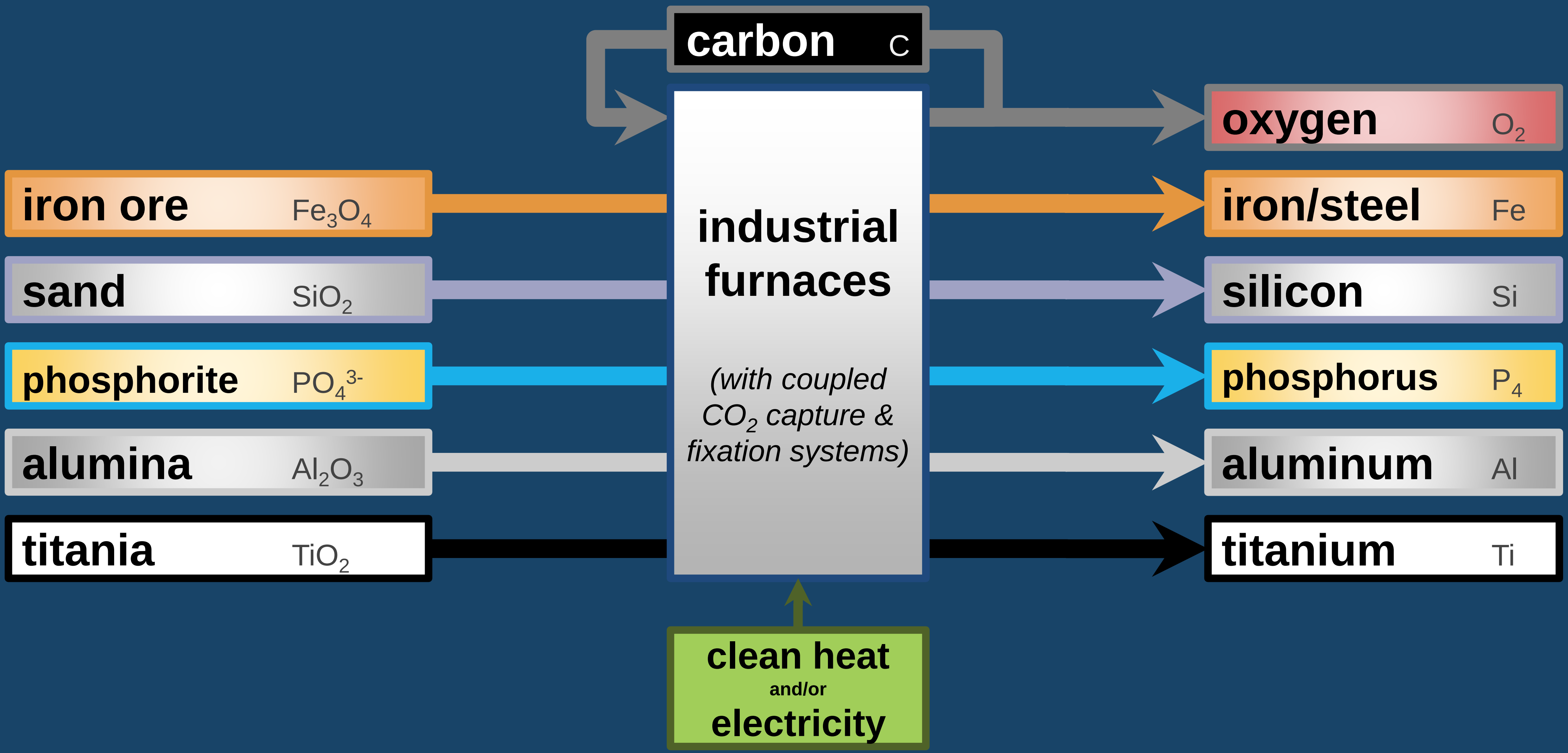
Minerals **2021**, *11*, 1425.
J. Sustain. Metall. **2021**, *7*, 848.
Chem. Soc. Rev. **2021**, *50*, 87.
Environ. Sci. Technol. **2012**, *46*, 13048.
IEA **2020**, *Iron and Steel Technology Roadmap*, IEA, Paris. Greenhouse Gas Emissions from Silicon Production -Development of Carbon Footprint with Changing Energy Systems. In *Proceedings of the 16th International Ferro-Alloys Congress*, **2021**.

Silicon solar photovoltaics: a potential beachhead industry

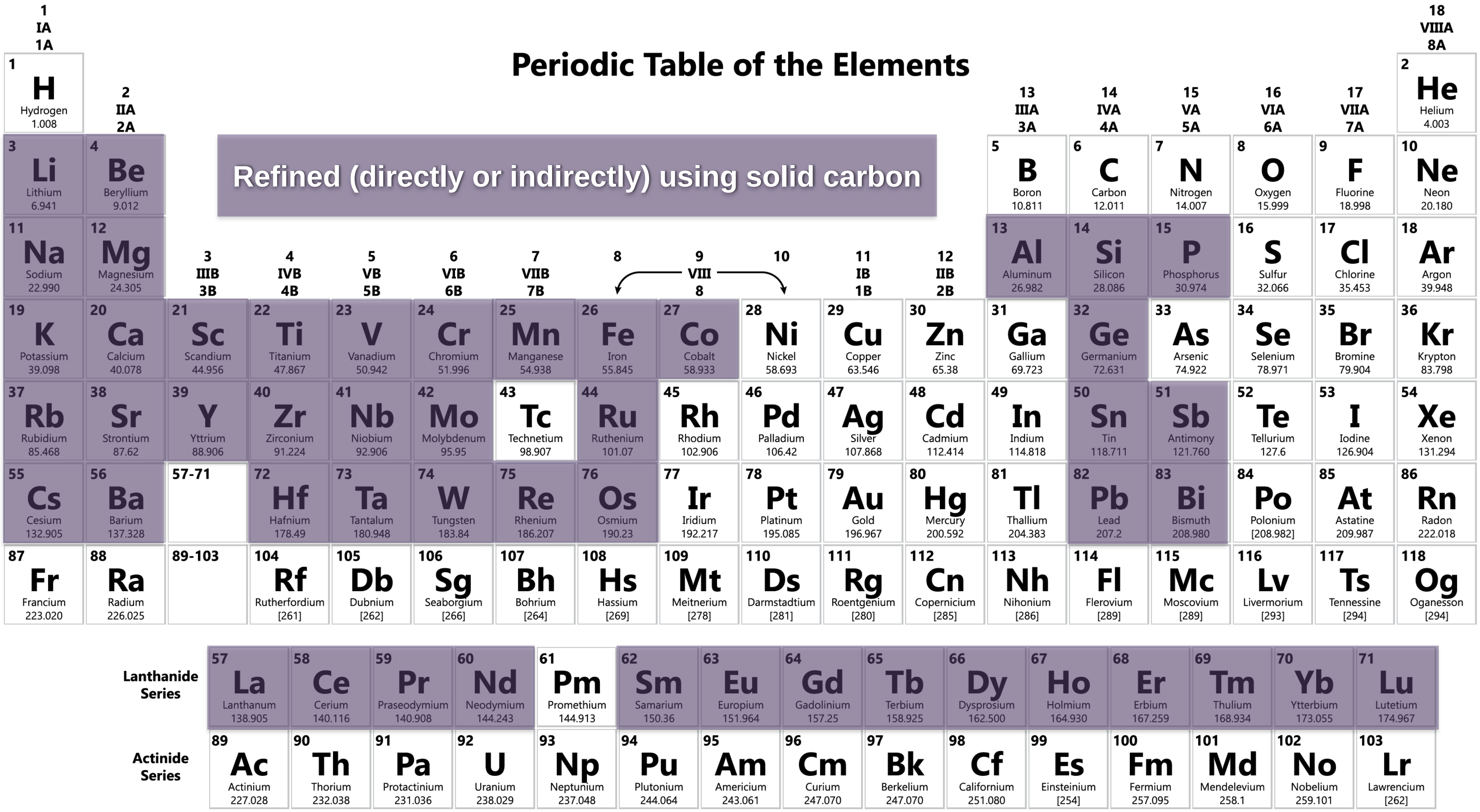


J. Sustain. Metall. **2021**, *7*, 848.
Joule **2022**, *6*, 1710

Long-term goal: total industrial carbon circularity

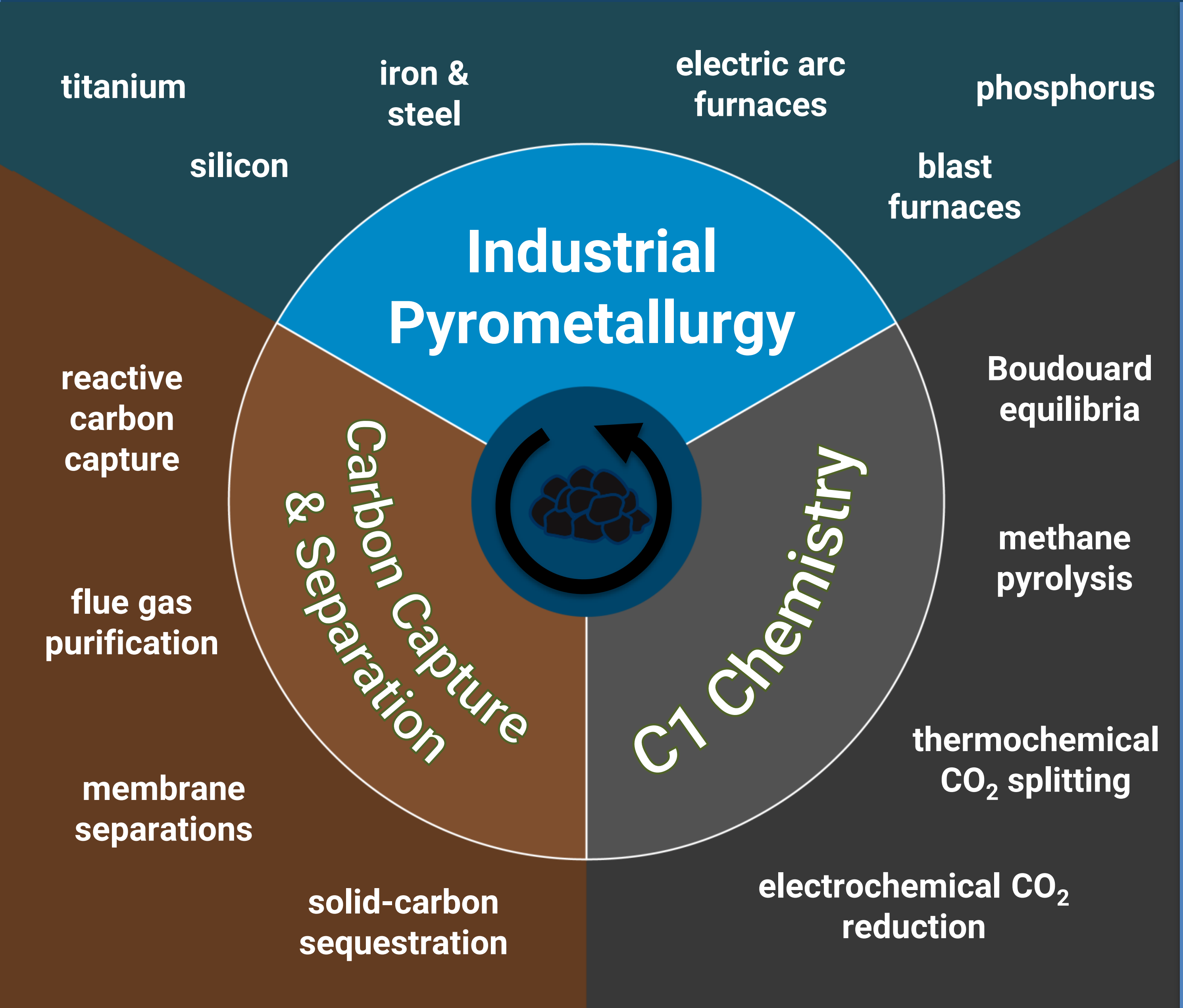


Periodic Table of the Elements



Greenwood, N.; Earnshaw, A. *Chemistry of the Elements*; Elsevier, **2012**.

Come contribute carbonaceous comments & constructive criticism!



jonathan.melville@hq.doe.gov

or find me at

COFFEE WITH ARPA-E

7:30 AM Thurs/Fri

Maryland Foyer