New Nuclear is Hot!

Session 3

Transportation fuel, sea CO2, hydrogen, pH swing, SOEC, seafineries, $

Literally red hot!
Cheaper than coal.
Lets developing nations prosper.
Cuts rapacious minerals mining.
Zeros electric power CO2.

Public support

Five supporters per opponent.
Relieves energy security concerns.

Seafuel

Net-zero gasoline for your car.
Climate-neutral diesel for industry.
Guilt-free jet flights.
Uses existing combustion engines.
Zeros transportation CO2.

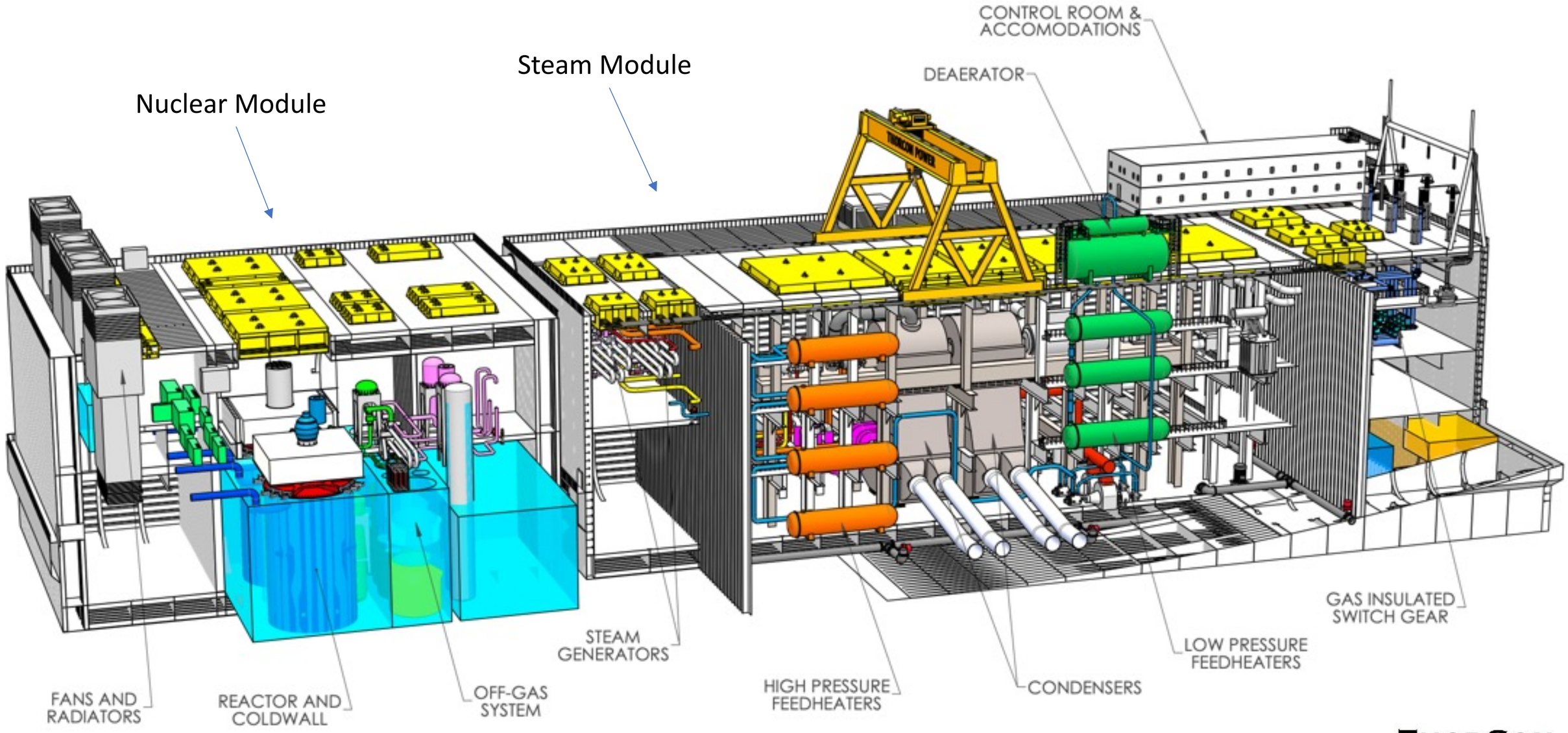
Robert.Hargraves@gmail.com

Seafuel™

Net-zero gasoline for your car.
Climate-neutral diesel for industry.
Guilt-free jet flights.
Uses existing combustion engines.
Zeros transportation CO2.

What can we do with cheap fission energy?

Heat @ $0.01/kWh, Electricity @ $0.03/kWh; Investment $1 billion/GW(e)



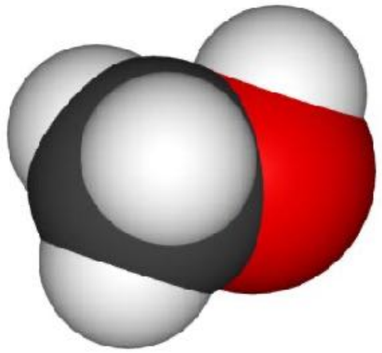
THORCON
POWERING UP OUR WORLD

Fuel weight and volume are critical for vehicles.

Fuel	kWh/kg	kWh/L
Gasoline, Diesel	13	11
Hydrogen liquid, -253°C	33	2.4
Hydrogen gas, 700 bar	33	1.2
Methane, CH4, 250 bar	15	9
Methanol, CH3OH	6	5
Dimethyl ether, CH3OCH3	9	7
Lithium ion battery, kWh(e)	0.2	

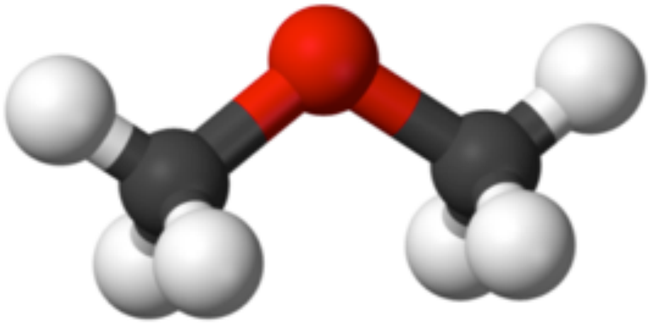
https://en.wikipedia.org/wiki/Energy_density

Transportation is fueled by hydrocarbons.



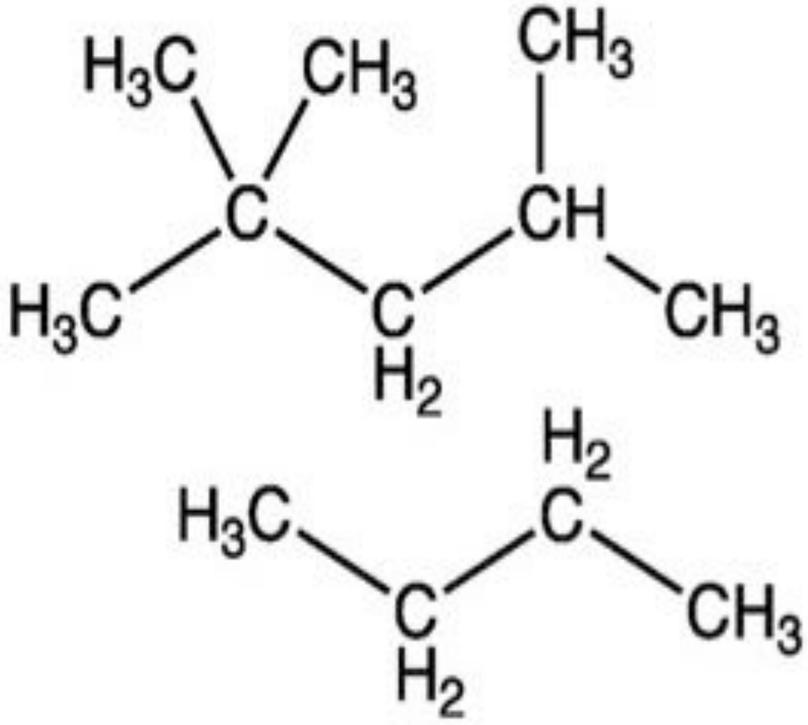
CH_3OH

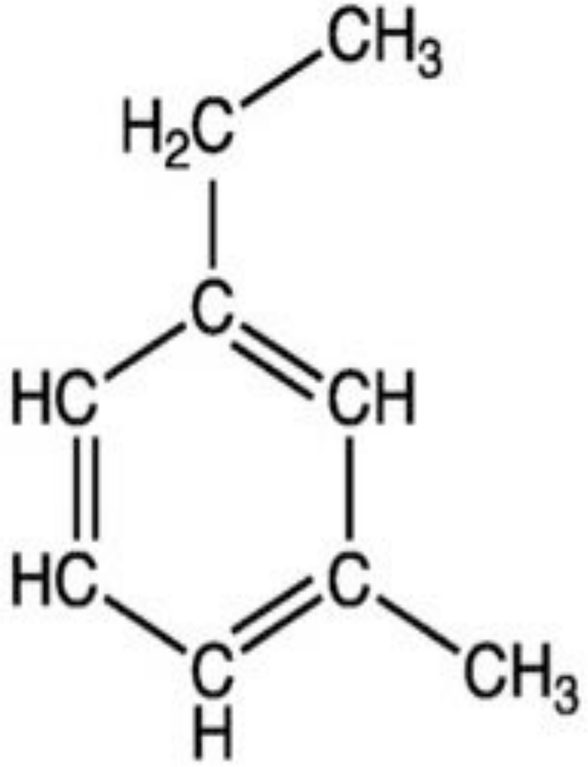
Methanol



H_3COCH_3

Dimethyl ether





Gasoline: 5 to 11 C atoms

Jet fuel: 12 to 15 C atoms

Diesel: 14 to 20 C atoms

Premium is paid for *portable* hydrocarbon energy.

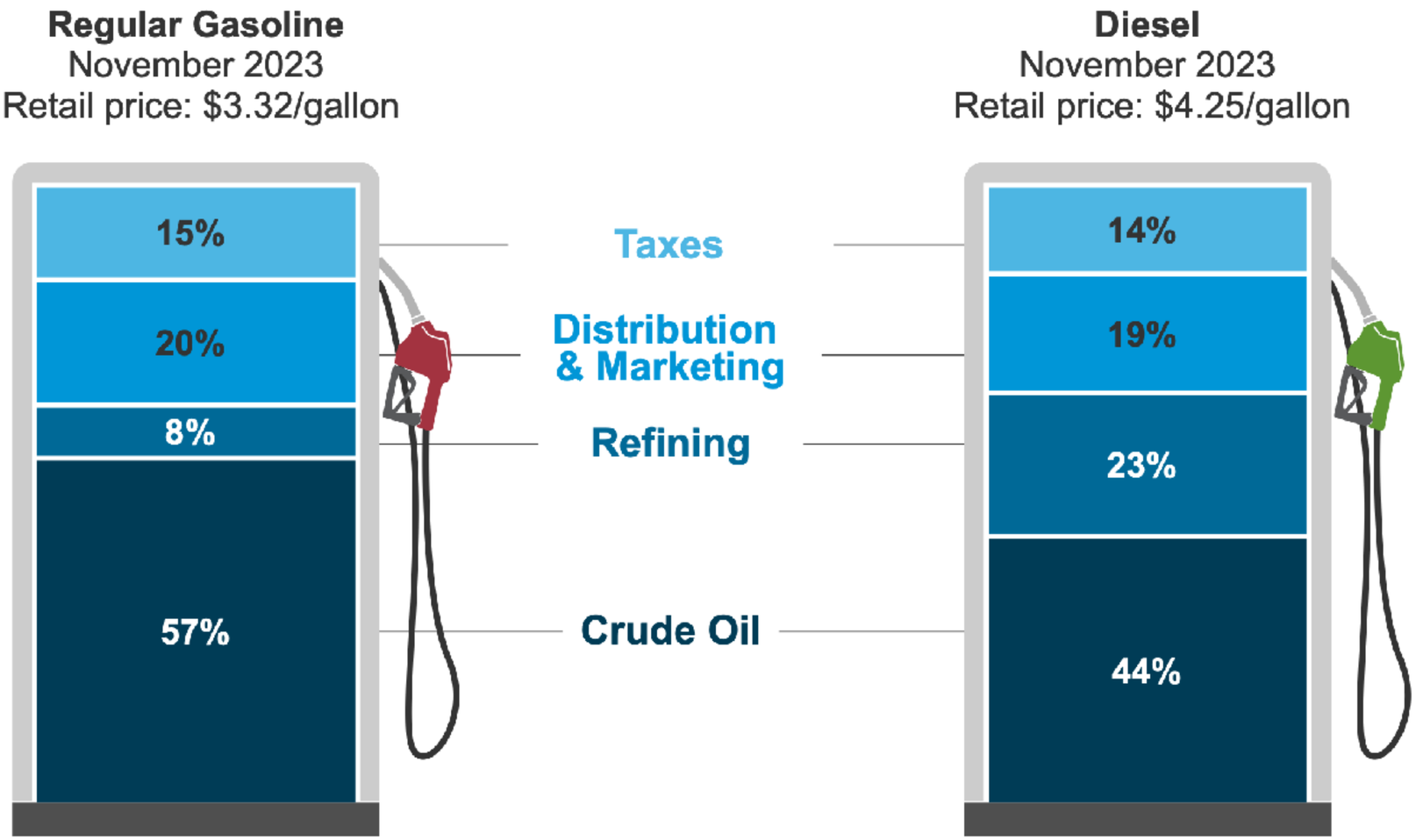
New nuclear power plant supplies cheap energy on site.

Electric energy	$0.03/kWh
Heat energy	$0.01/kWh

Portable energy sells at a premium.

Gasoline	$3.00/gallon =
Heat energy	$0.09/kWh
Premium	$ 0.08/kWh

Half retail fuel price is for crude oil energy.



$72/bblcrude

1700 kWh/bbl crude

$0.042/kWh

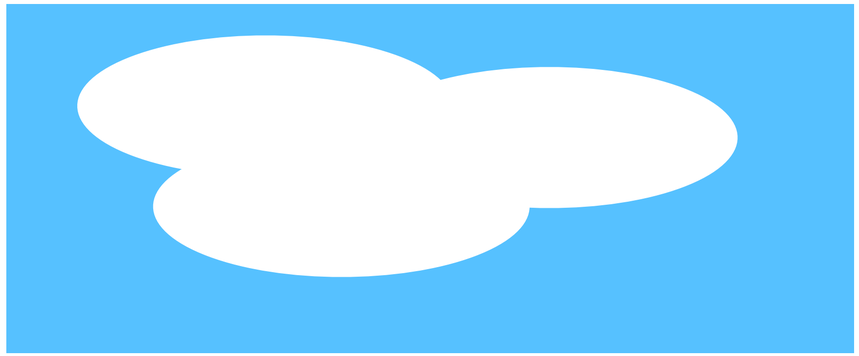
Refining costs vary with scale, age, typically $10/bbl, or **$0.006/kWh**

Retail gasoline sells for **$0.09/kWh**

https://www.eia.gov/petroleum/gasdiesel/

https://link.springer.com/chapter/10.1007/978-3-030-86884-0_3#Sec9

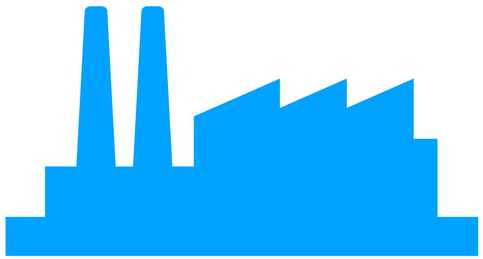
Seafuel, net zero hydrocarbon fuel, made from…



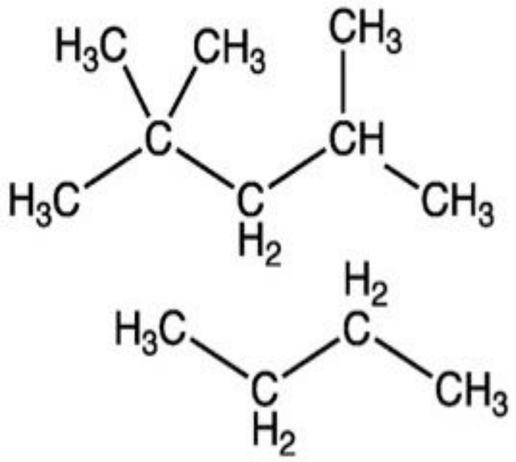
Captured Carbon

Water split Hydrogen

Cheap Energy



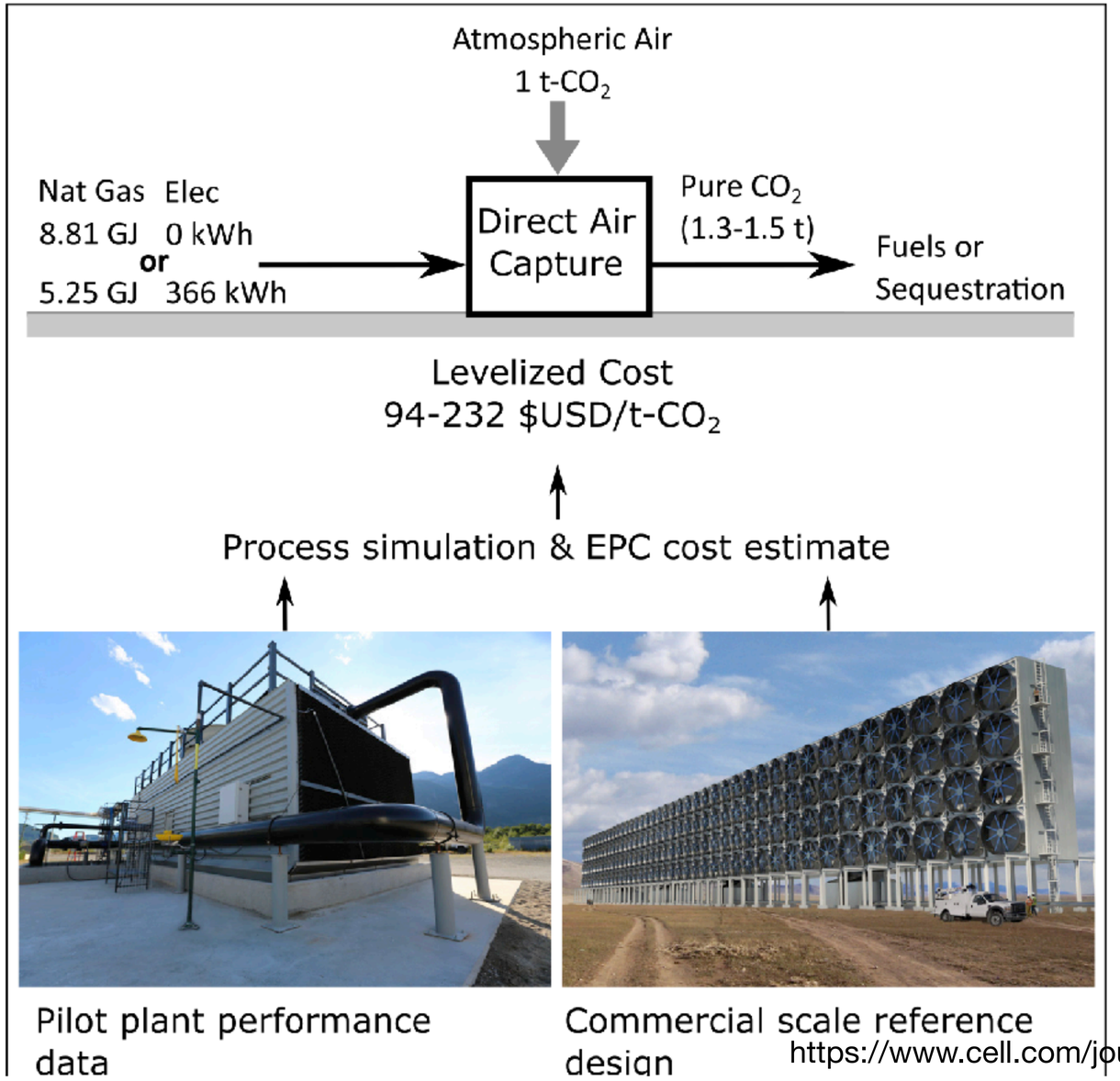
Seaside refinery,
paid by fuel premium



Where do we get the carbon?

CO_2

Direct Air Capture is expensive: $94-232 $/t-CO2 (Keith)



David W. Keith, Geoffrey Holmes, David St. Angelo, Kenton Heidel

keith@carbonengineering.com

HIGHLIGHTS

Detailed engineering and cost analysis for a 1 Mt-CO_2/year direct air capture plant

Levelized costs of $94 to $232 per ton CO_2 from the atmosphere

First DAC paper with commercial engineering cost breakdown

Full mass and energy balance with pilot plant data for each unit operation

https://www.cell.com/joule/pdf/S2542-4351(18)30225-3.pdf

600-1,000 $/t-CO2 (Herzog)

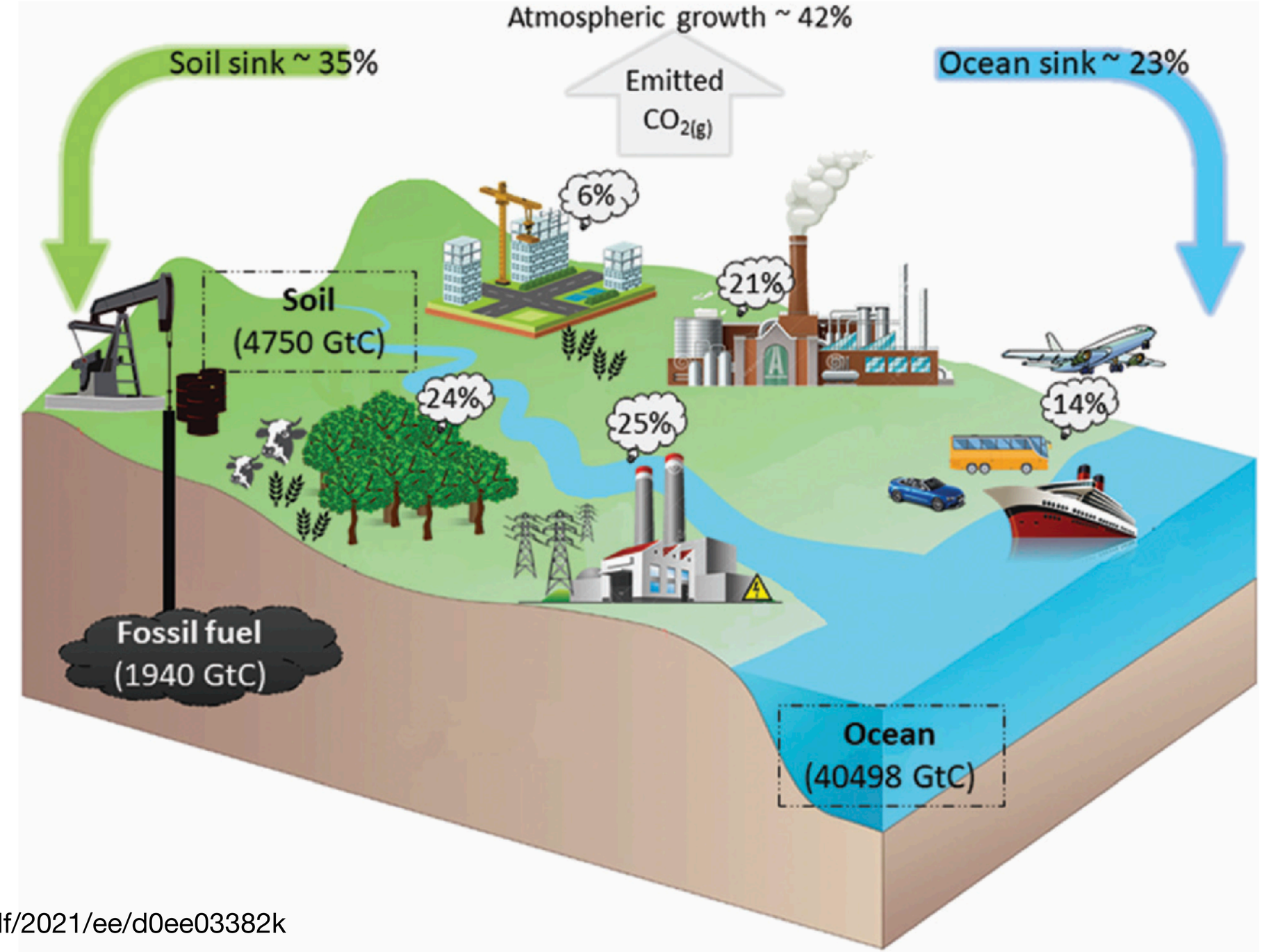
Occidental Petroleum acquired Carbon Engineering for $1.1 billion.

CO2 in the air dissolves into the ocean

until the air/sea CO2 partial pressures balance

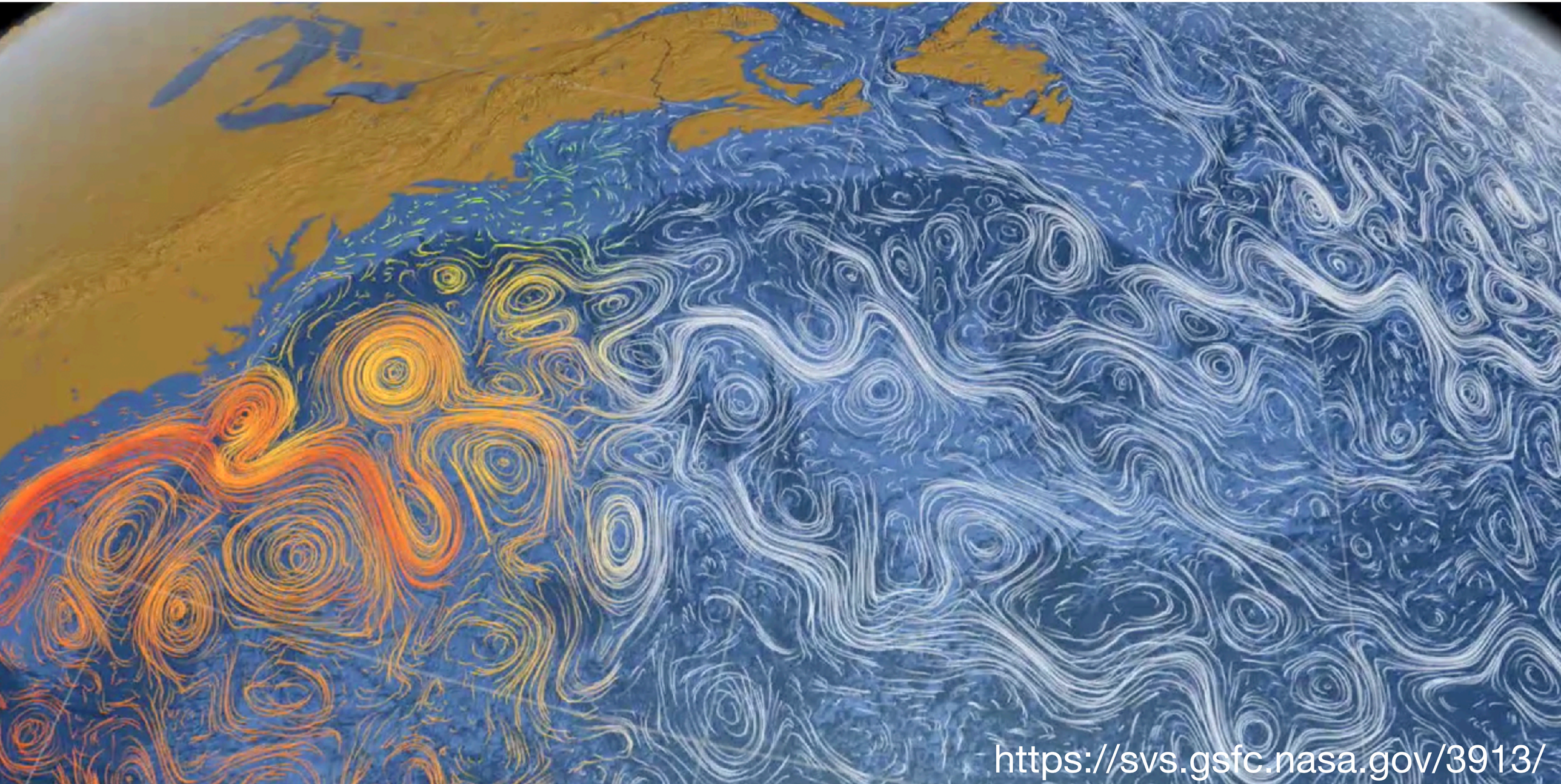
in ~ 1 year

adding 9 Gt-CO2/ yr to ocean.

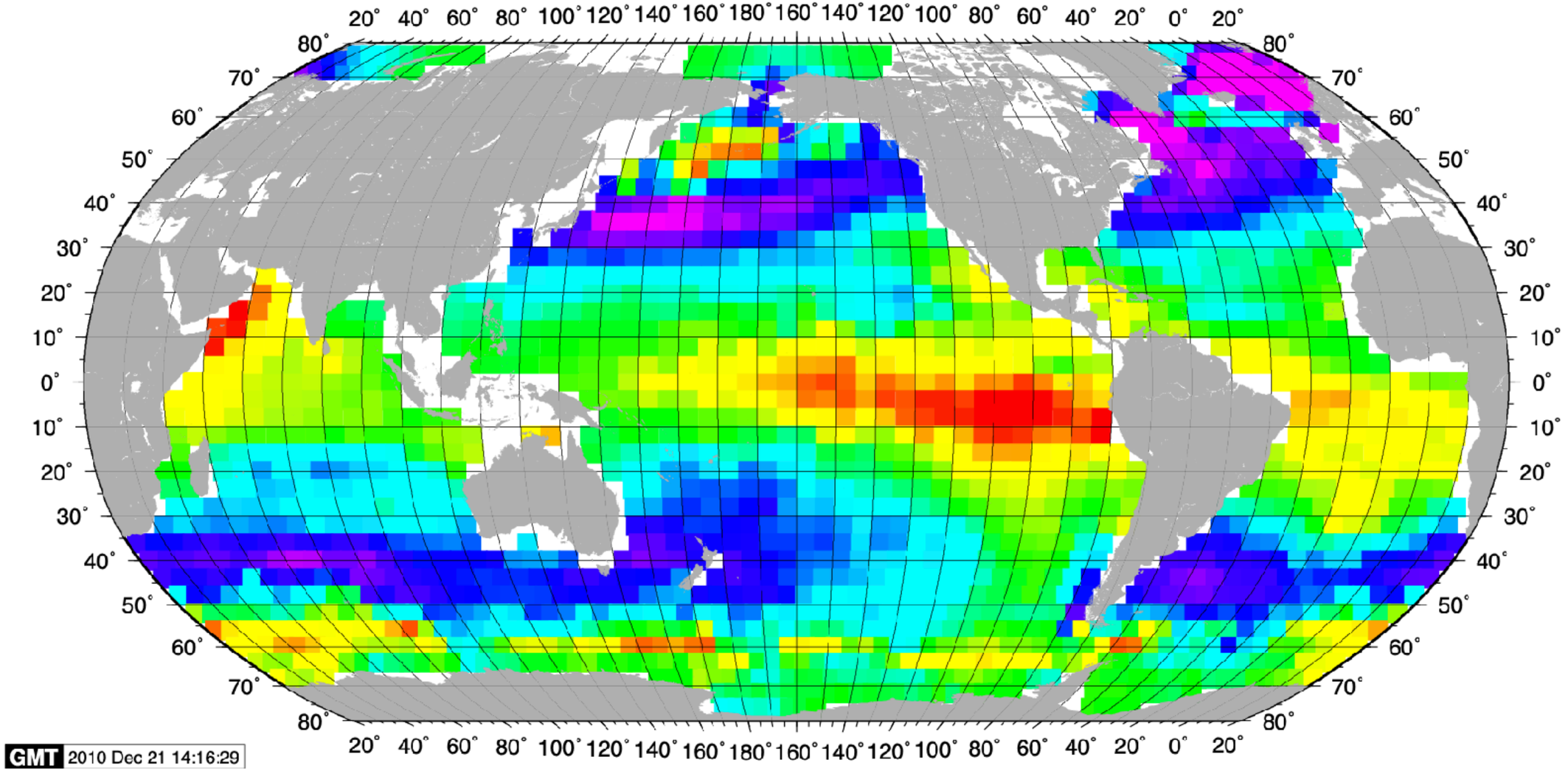


https://pubs.rsc.org/en/content/articlepdf/2021/ee/d0ee03382k

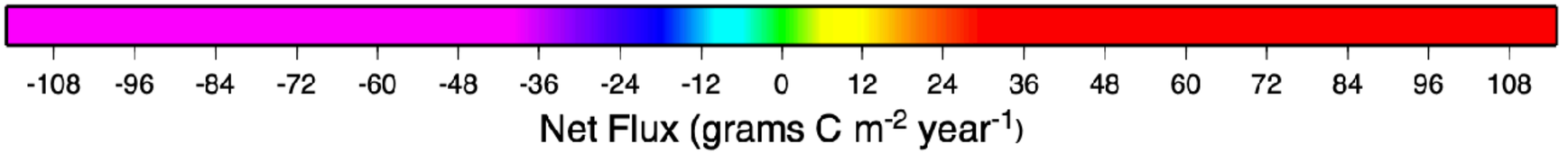
Ocean currents distribute dissolved CO2 worldwide.



CO2 flows into cold ocean water, out of warm water.



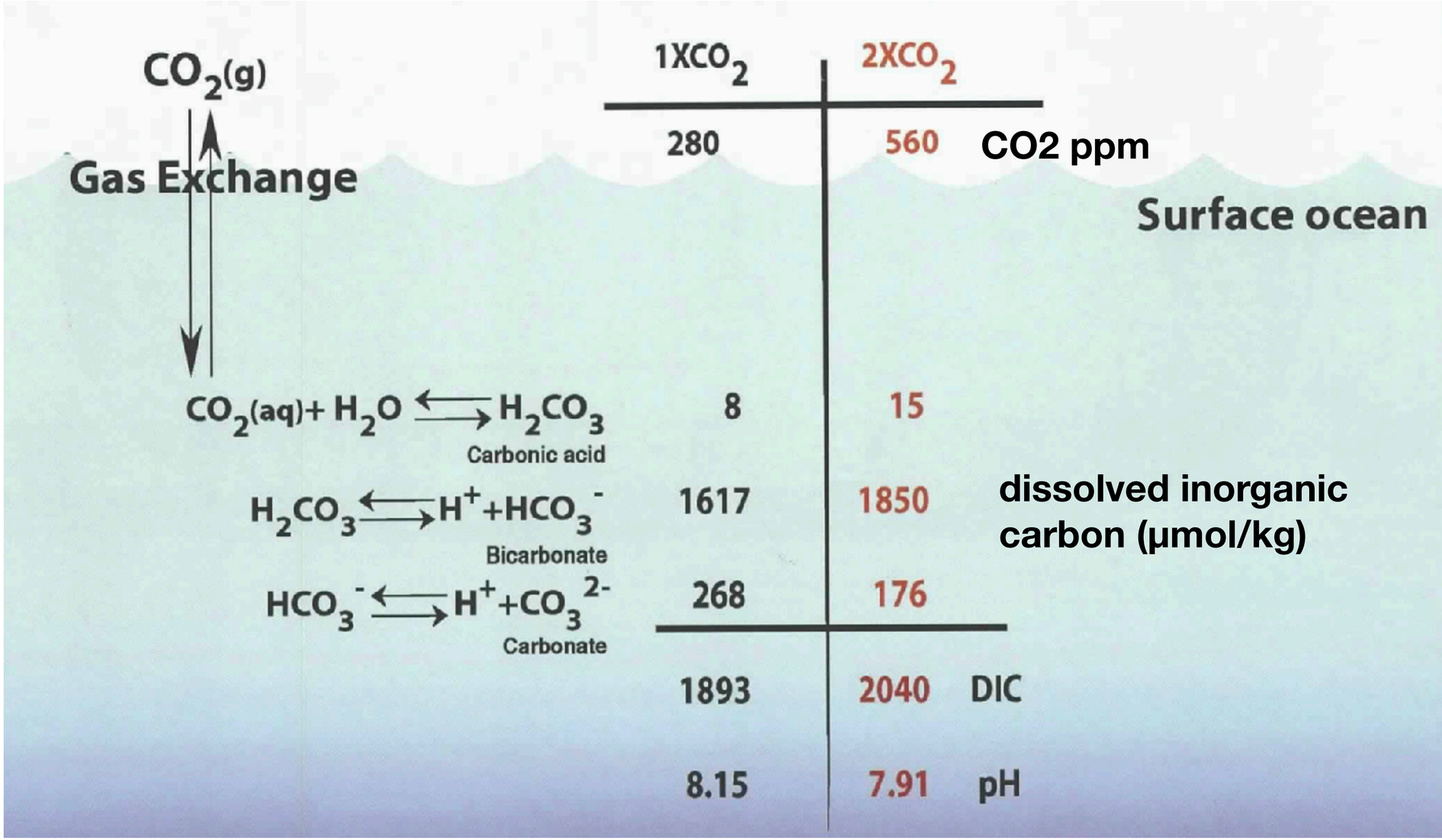
https://www.ldeo.columbia.edu/res/pi/CO2/carbondioxide/pages/air_sea_flux_2000.html



CO2 in the sea is 140X denser than in the air.

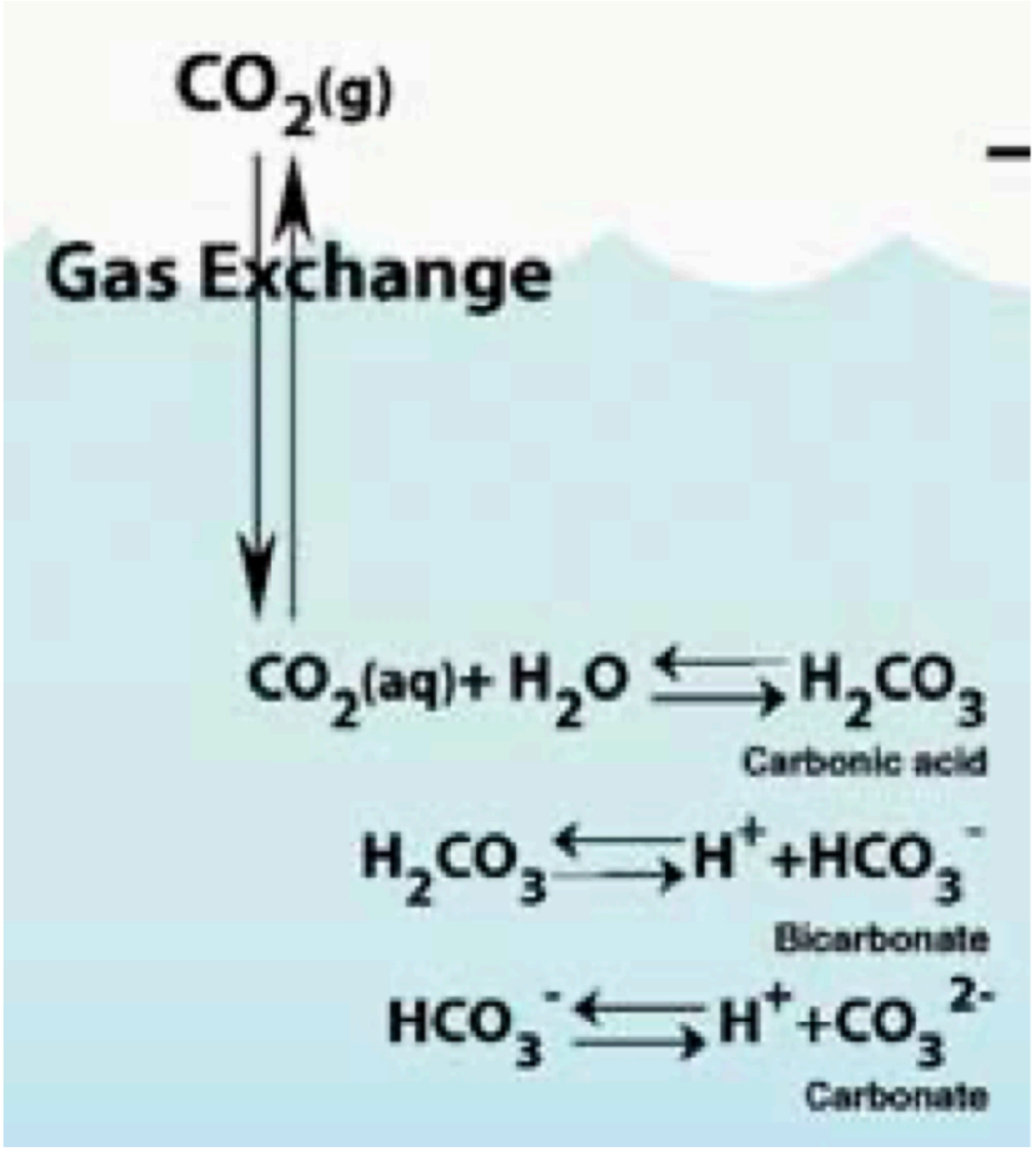
Dissolved inorganic carbon forms

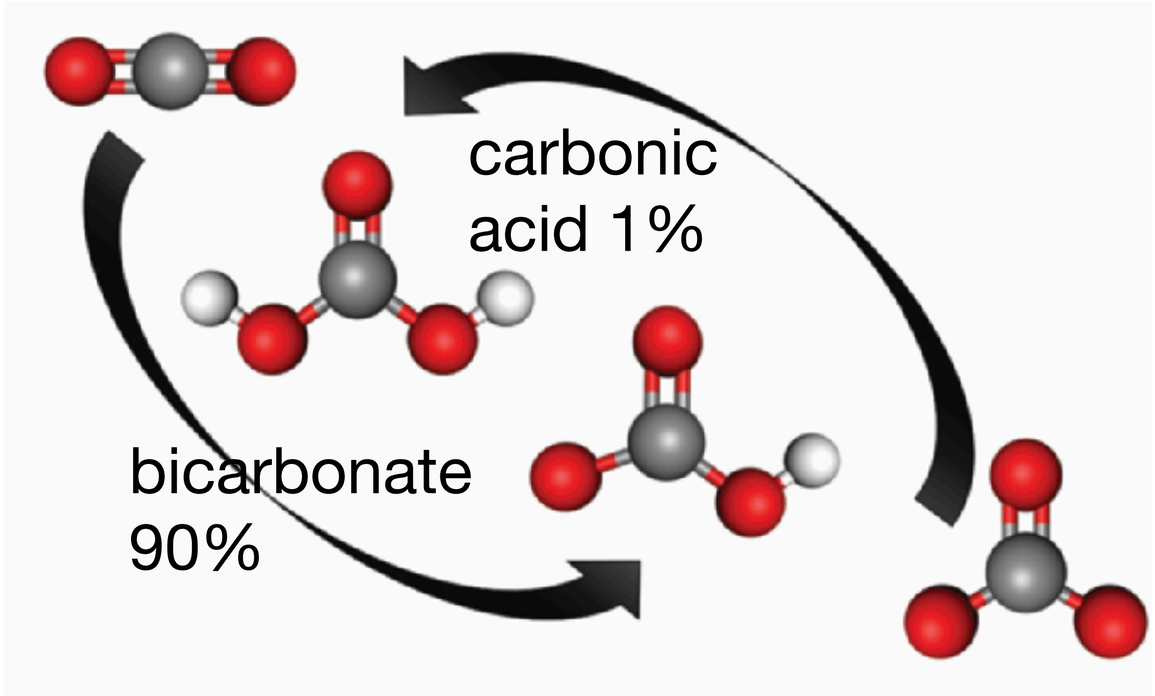
- CO2 (aq)
- H2CO3 carbonic acid
- HCO $^{-}$ bicarbonate
- CO3 $^{--}$ carbonate



https://usjgofs.whoi.edu/62987_ocean.pdf

CO2 in water becomes mostly bicarbonate ions.





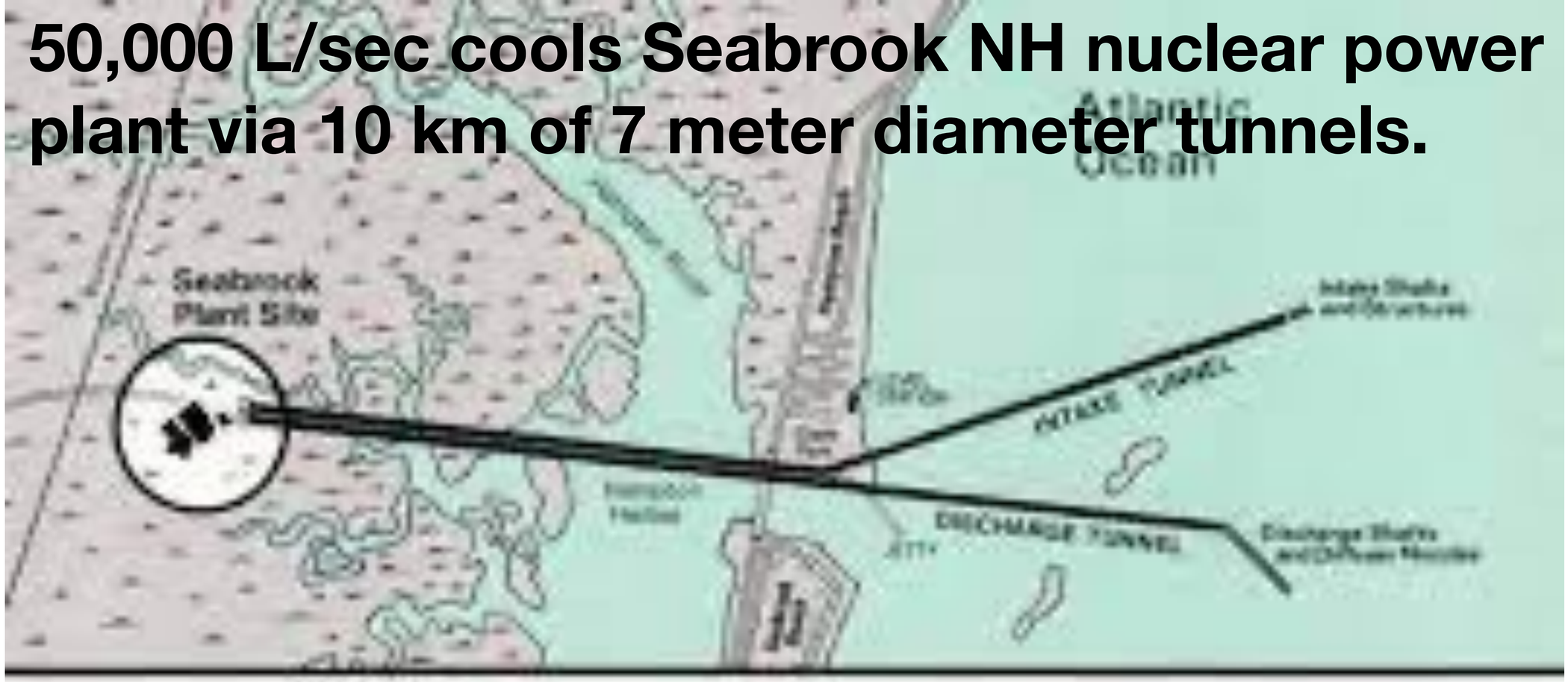
<< Acidic pH . . . . . Basic pH >>

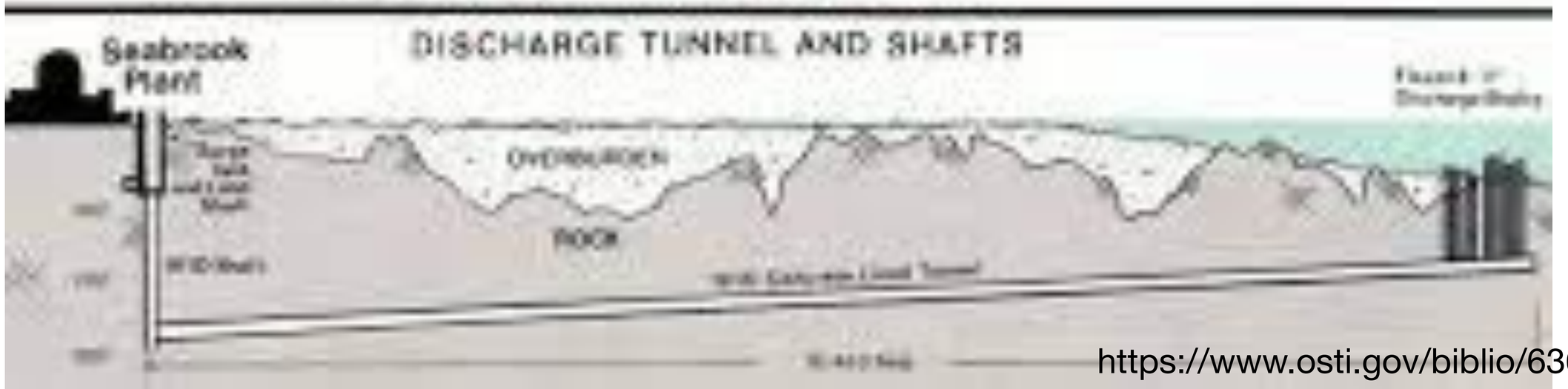
Increasing acidity reverts dissolved bicarbonate back to CO2, that can be bubbled out by vacuum pumps.

https://usjgofs.whoi.edu/62987_ocean.pdf

https://pubs.rsc.org/en/content/articlepdf/2021/ee/d0ee03382k

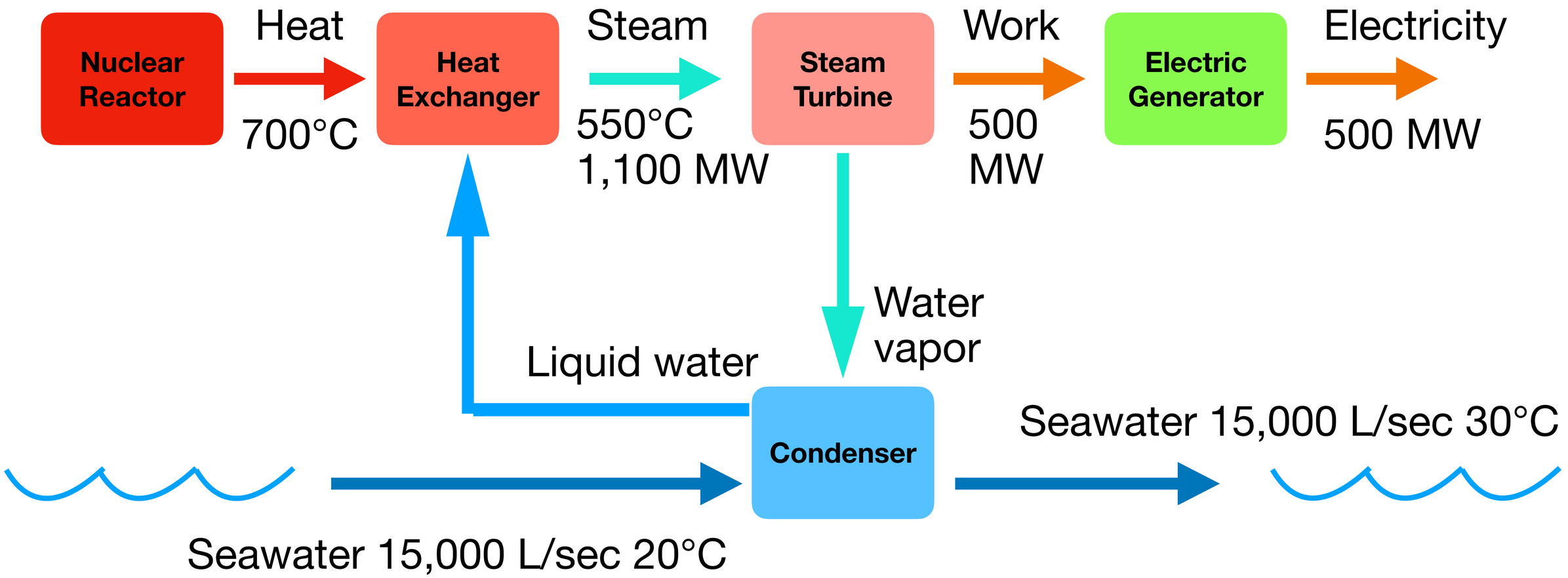
50,000 L/sec cools Seabrook NH nuclear power plant via 10 km of 7 meter diameter tunnels.



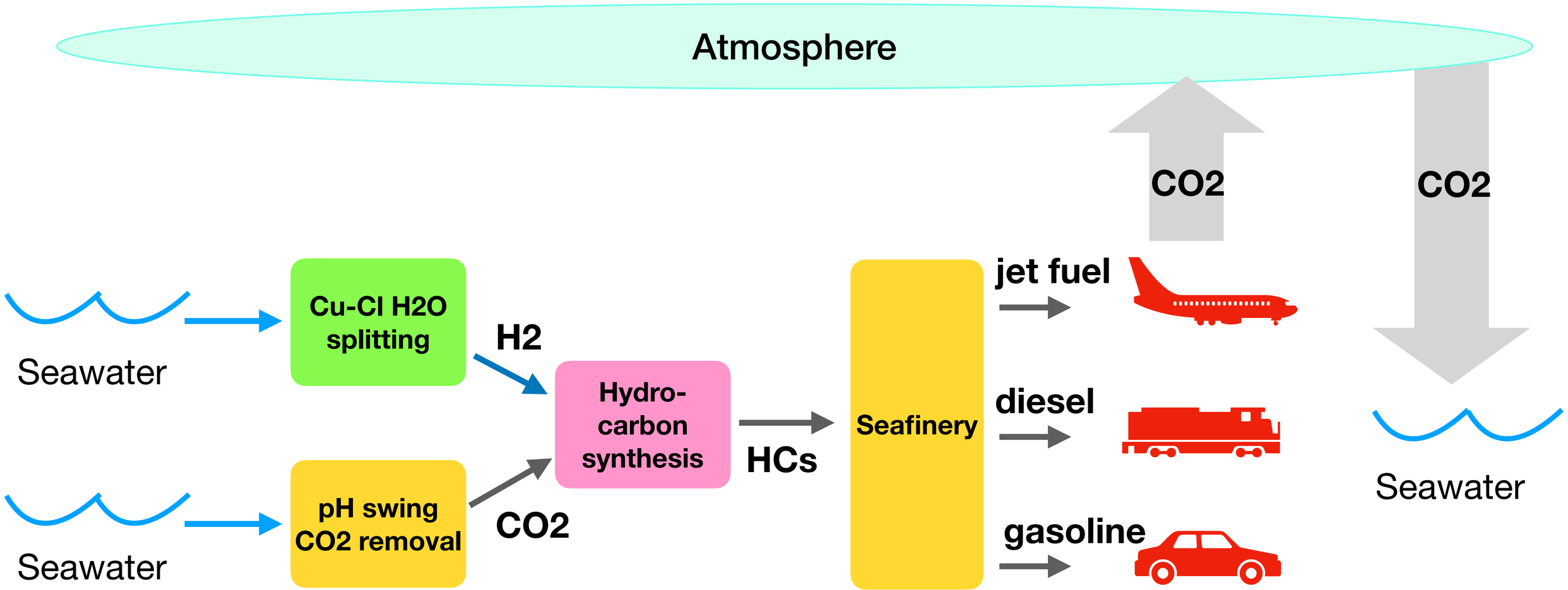


https://www.osti.gov/biblio/6367683

Seawater cooled, *new nuclear* power plant.

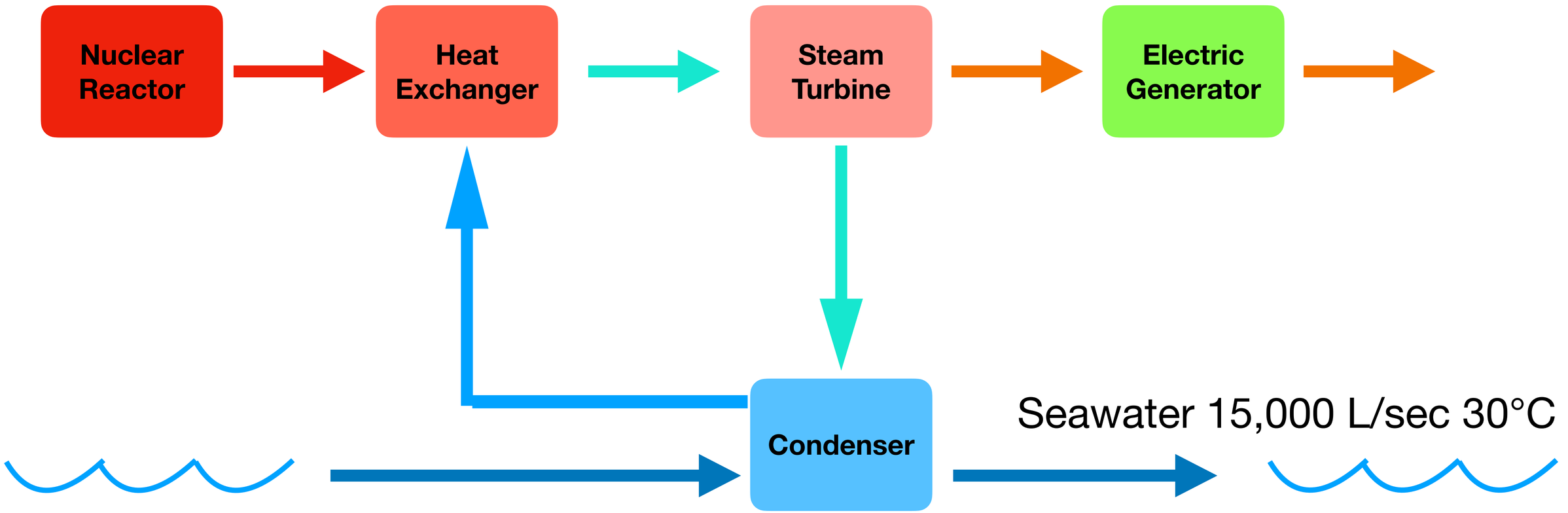


Net zero Seafuel for combustion engines.



Sea re-absorbs CO2 removed a year before.

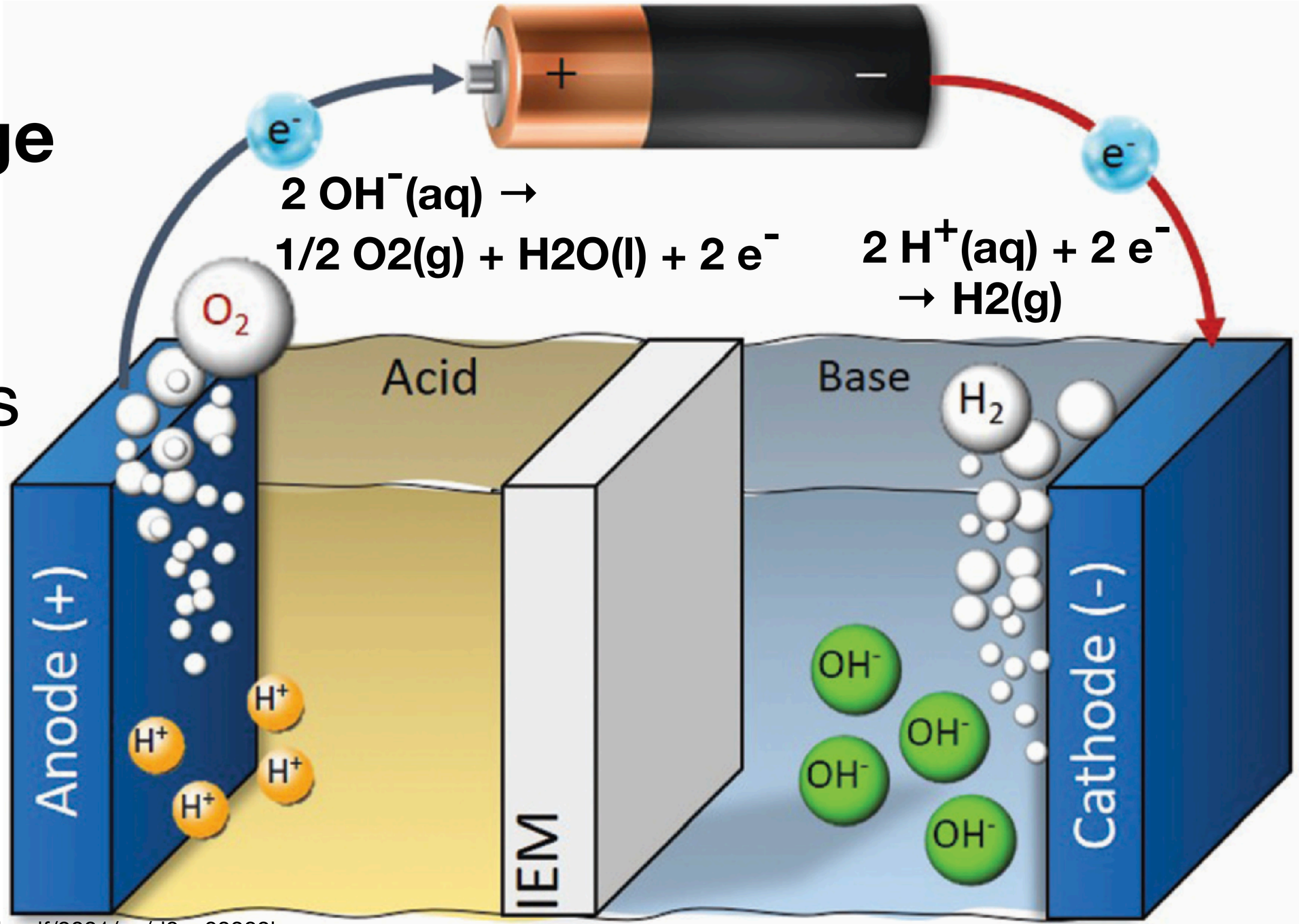
Flowing seawater supplies CO2.



https://www.lenntech.com/composition-seawater.htm

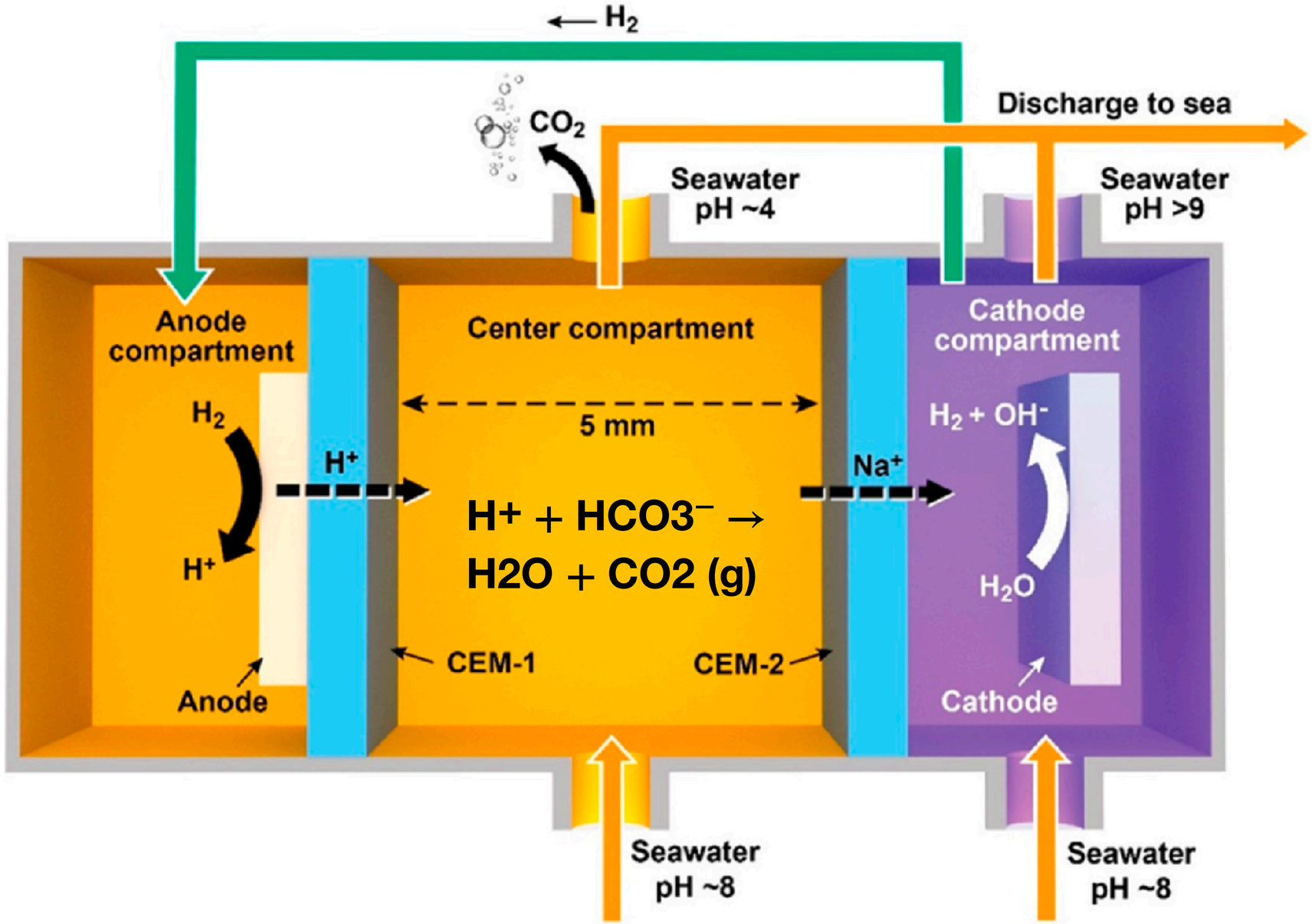
Electricity can change acidity.

Electrolysis example



https://pubs.rsc.org/en/content/articlepdf/2021/ee/d0ee03382k

CO2 removal by pH swing (Yan)



Increasing acidity reverts dissolved bicarbonate to CO2.

H+ + HCO3⁻ → H2O + CO2 (g)

CO2 bubbled out by vacuum pumps.

Electrolysis energy

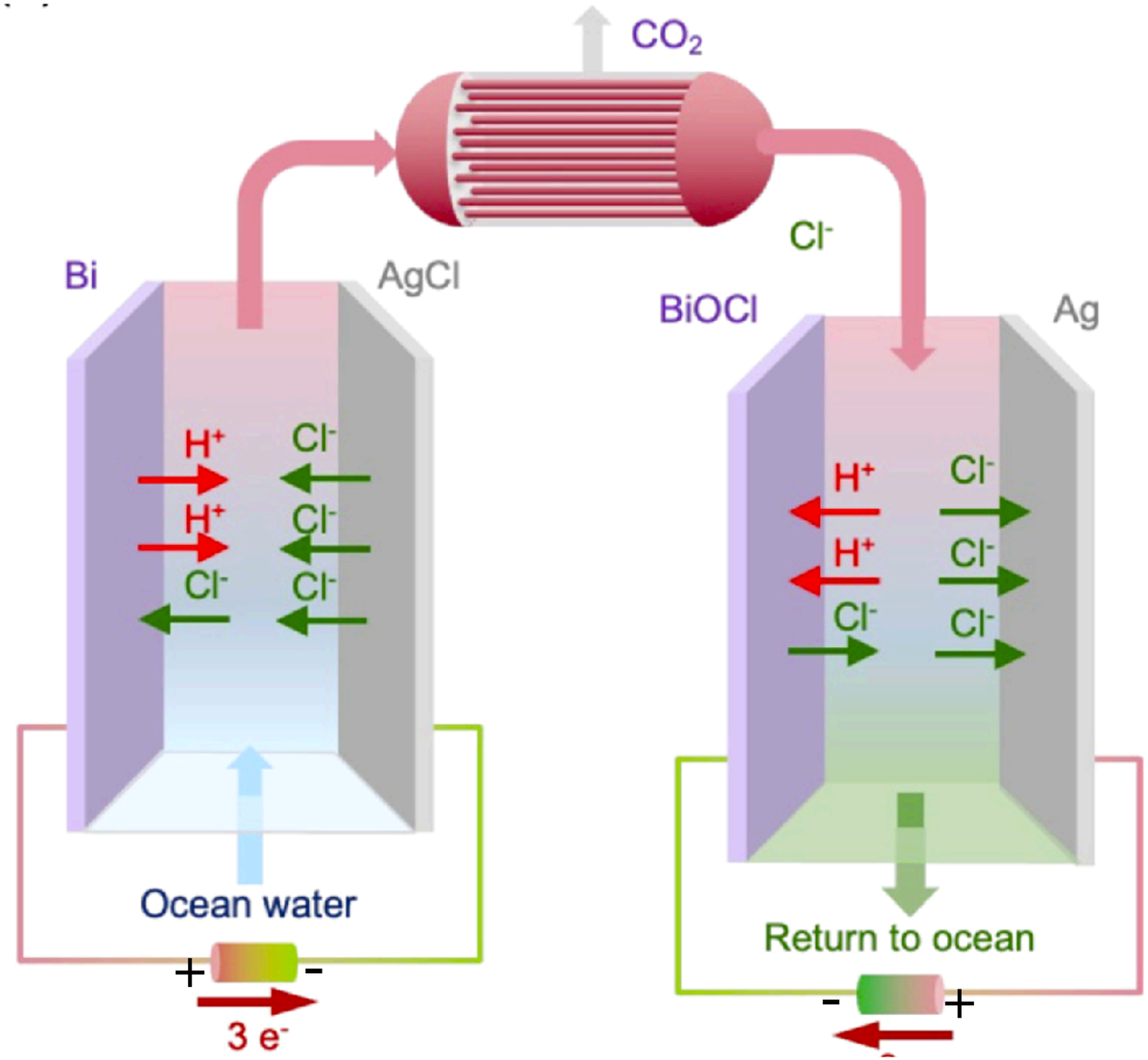
0.66 kWh(e)/kg-CO2

@ $0.03/kWh

$20.00/ton-CO2

Yan et al An Electrochemical Hydrogen-Looping System… https://pubs.acs.org/doi/10.1021/acsenergylett.2c00396?ref=pdf

CO2 removal by pH swing (Kim)



Electrolysis energy

122 kJ	per 44 g-CO2
2.77 MJ	per kg-CO2
0.77 kWh	per kg-CO2
@ $0.03	per kWh
$23	per ton-CO2

System energy (Kim)

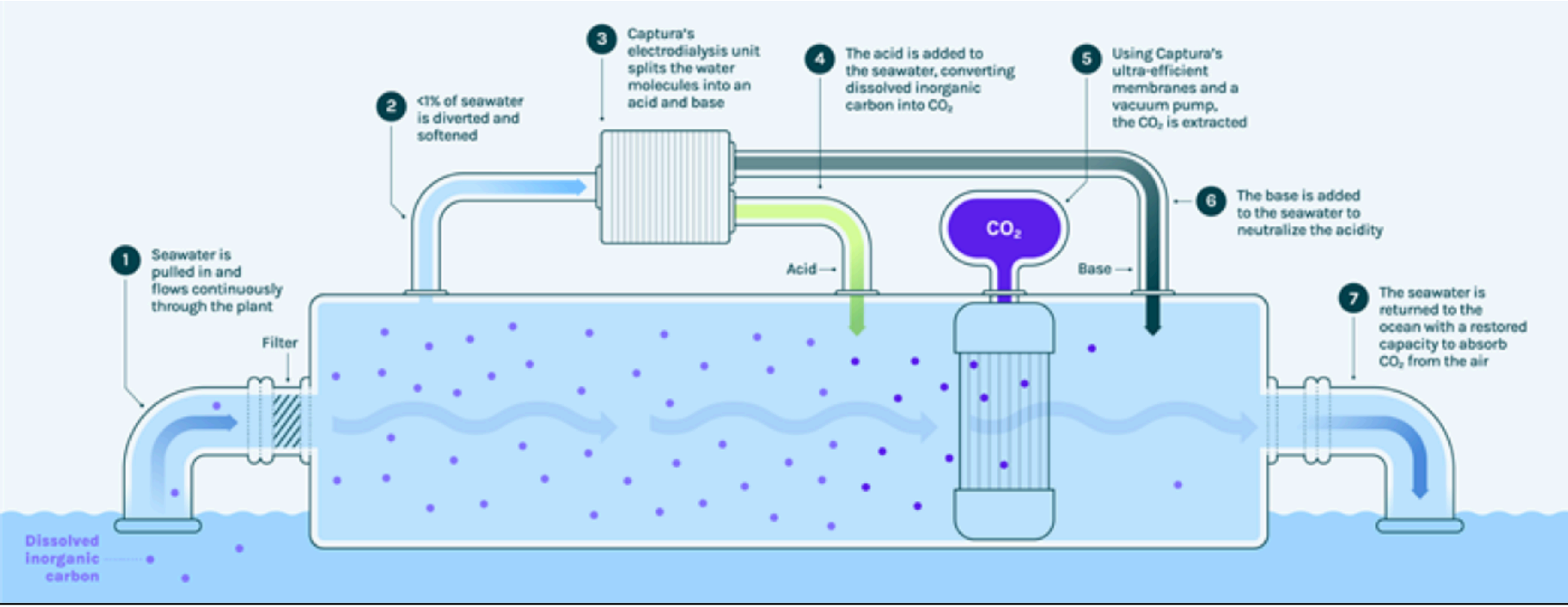
$56	ton-CO2

$$Bi + 3AgCl + H2O \rightleftarrows BiOCl + 3Ag + 2Cl^- + 2H^+$$

https://pubs.rsc.org/en/content/articlelanding/2023/EE/D2EE03804H

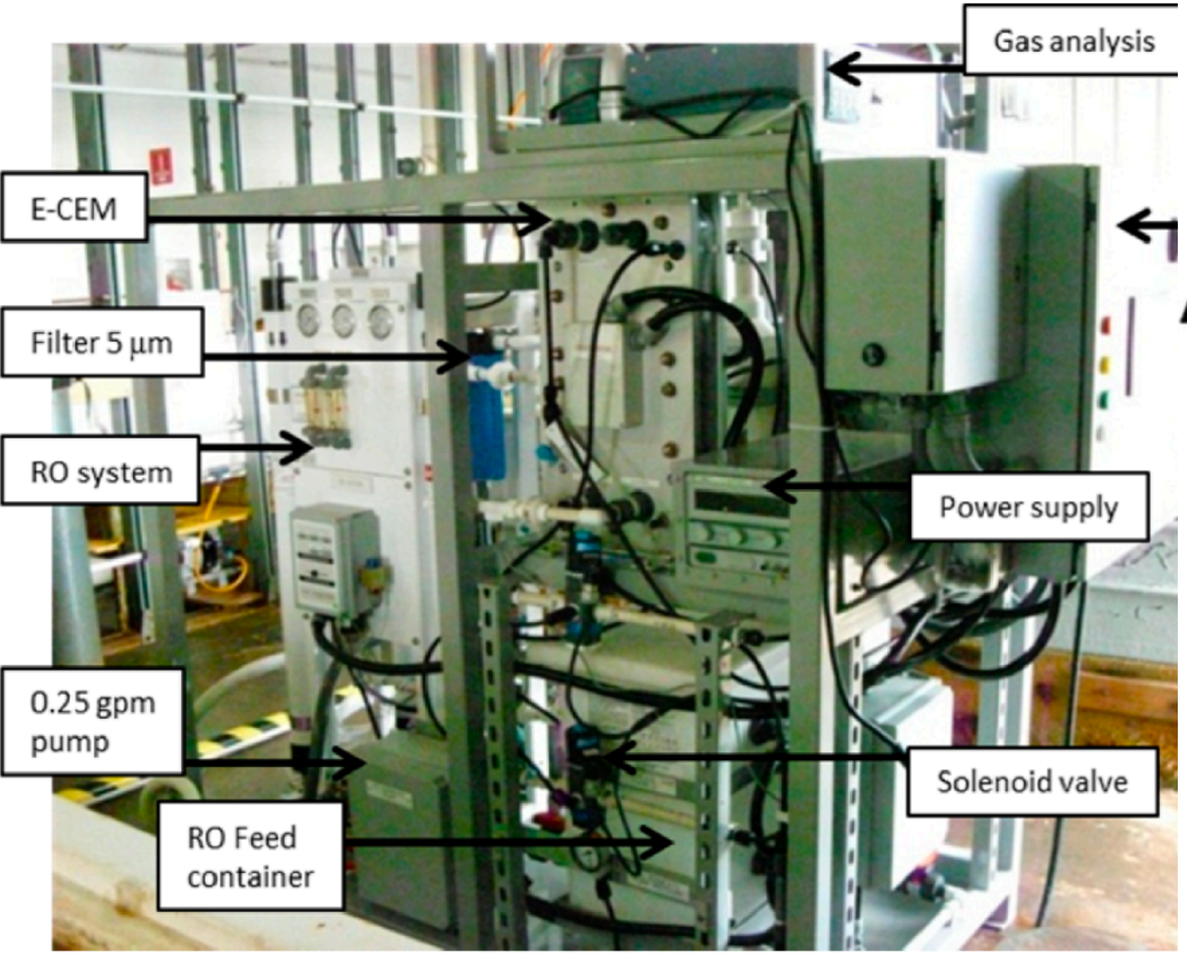
Captura and Equatic testing pH-swing in Pacific.

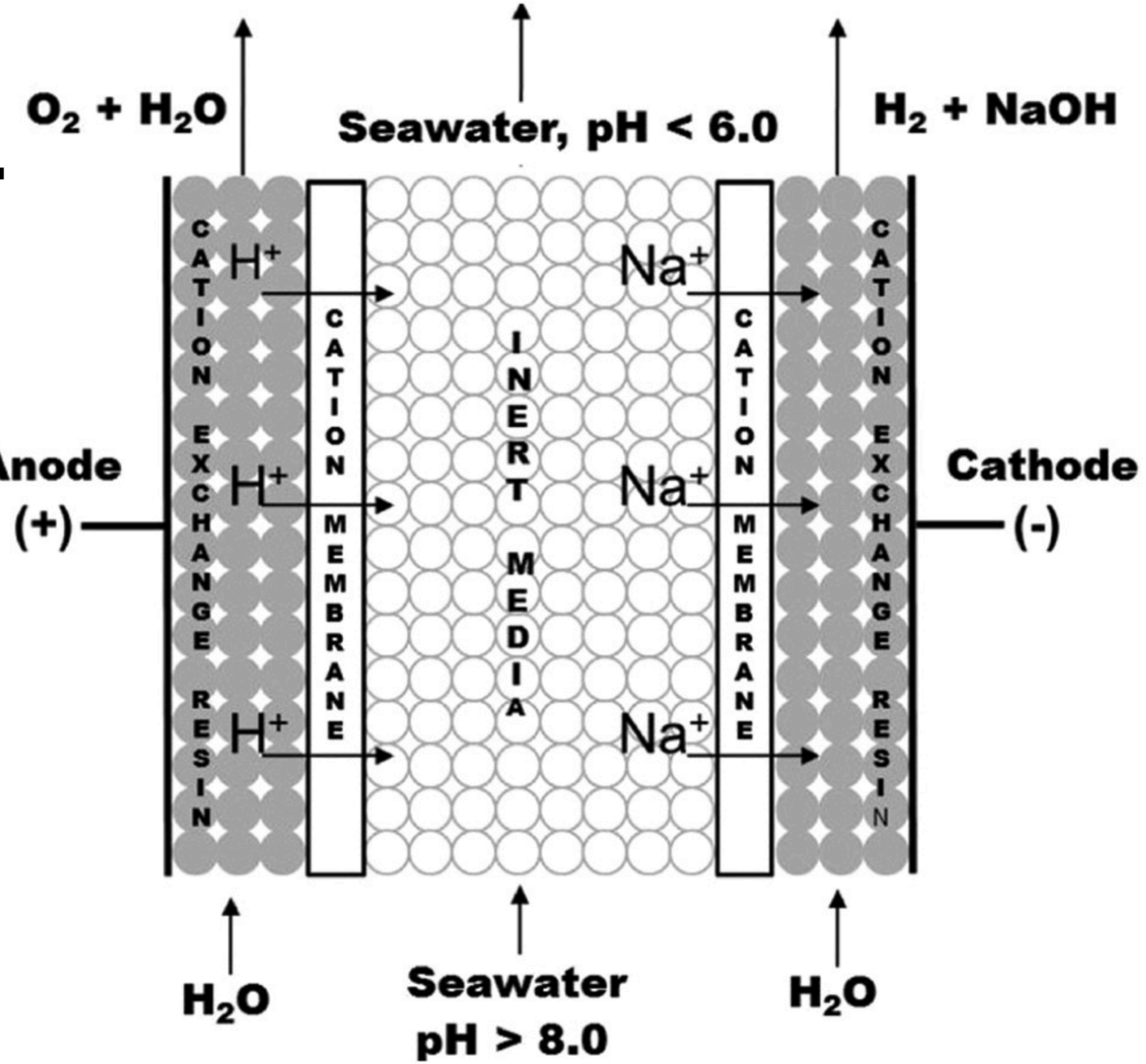
- $100/t-CO2 goals



https://www.chemistryworld.com/news/the-start-ups-taking-on-climate-change-by-extracting-carbon-dioxide-from-the-sea/4019062.article

US Navy Research Lab electrolysis cell frees both CO2 and H2 from seawater.





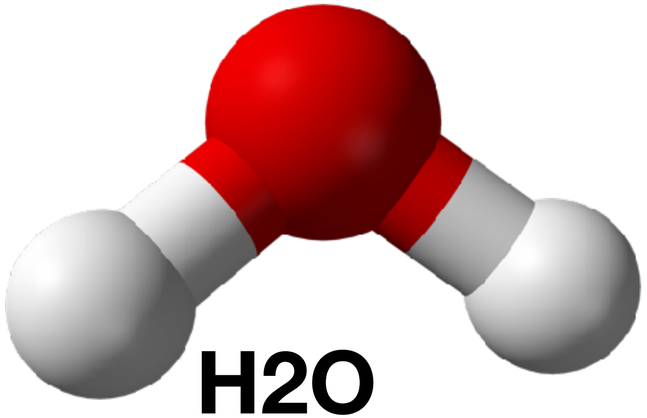
https://pubs.acs.org/doi/10.1021/ie502128x#

Where do we get the hydrogen?

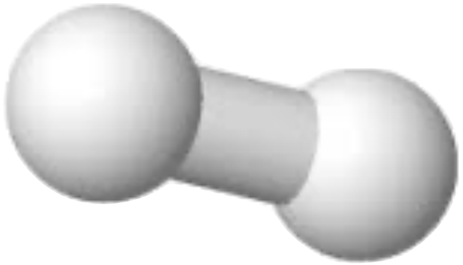
Where do we get the hydrogen?

$$H2O \longrightarrow \mathbf{H2} + O$$

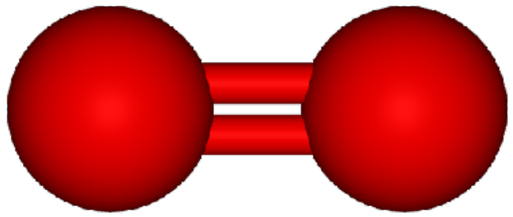
The energy to make hydrogen from water vapor is 242 kJ per mol (18 grams).



H2O



H2



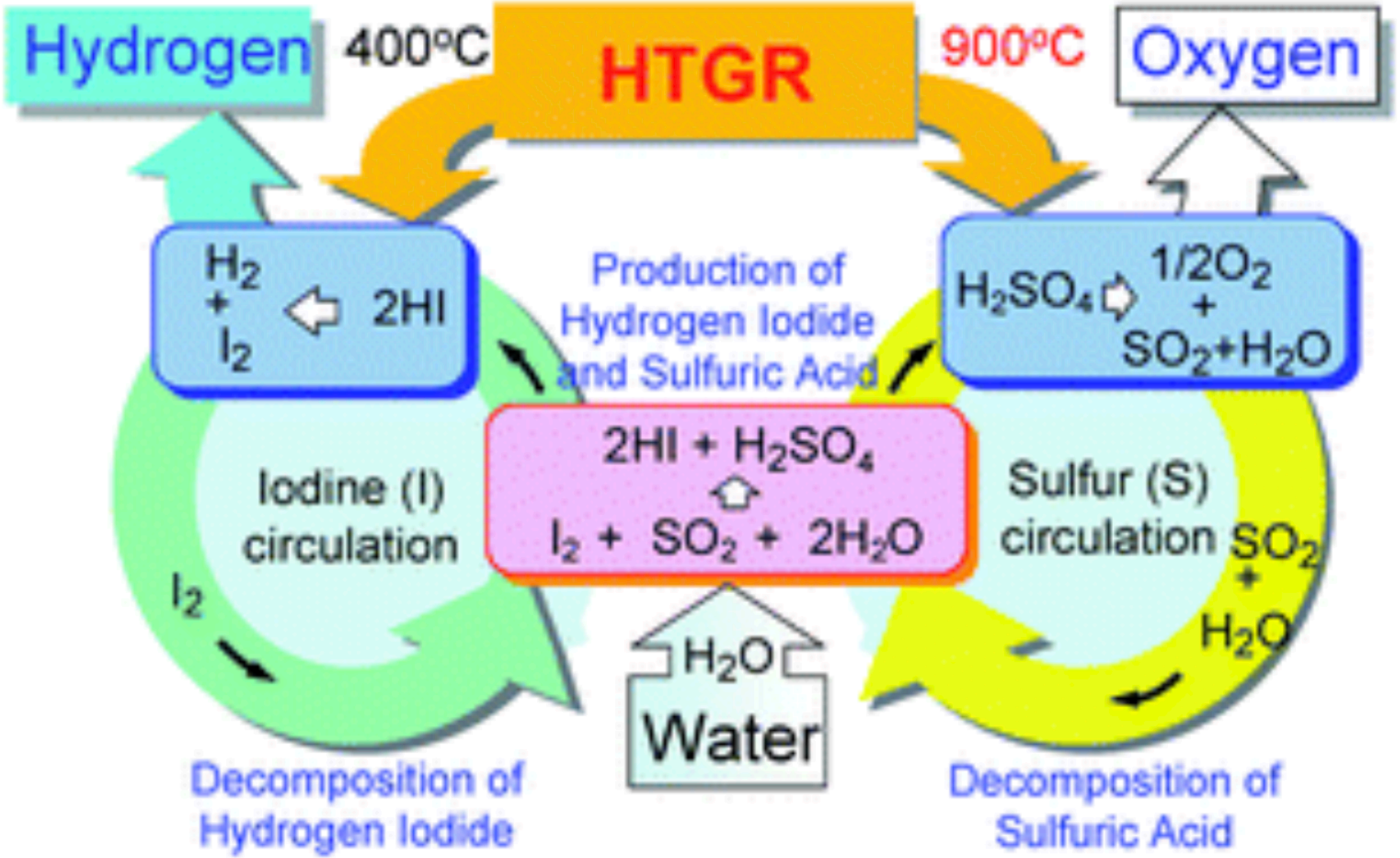
1/2 O2

242 kJ per 18 g H2O
242 kJ per 2 g H2
121 MJ per kg H2
34 kWh per kg H2
@ $0.03 per kWh(e)
$1.02 per kg H2

compare to

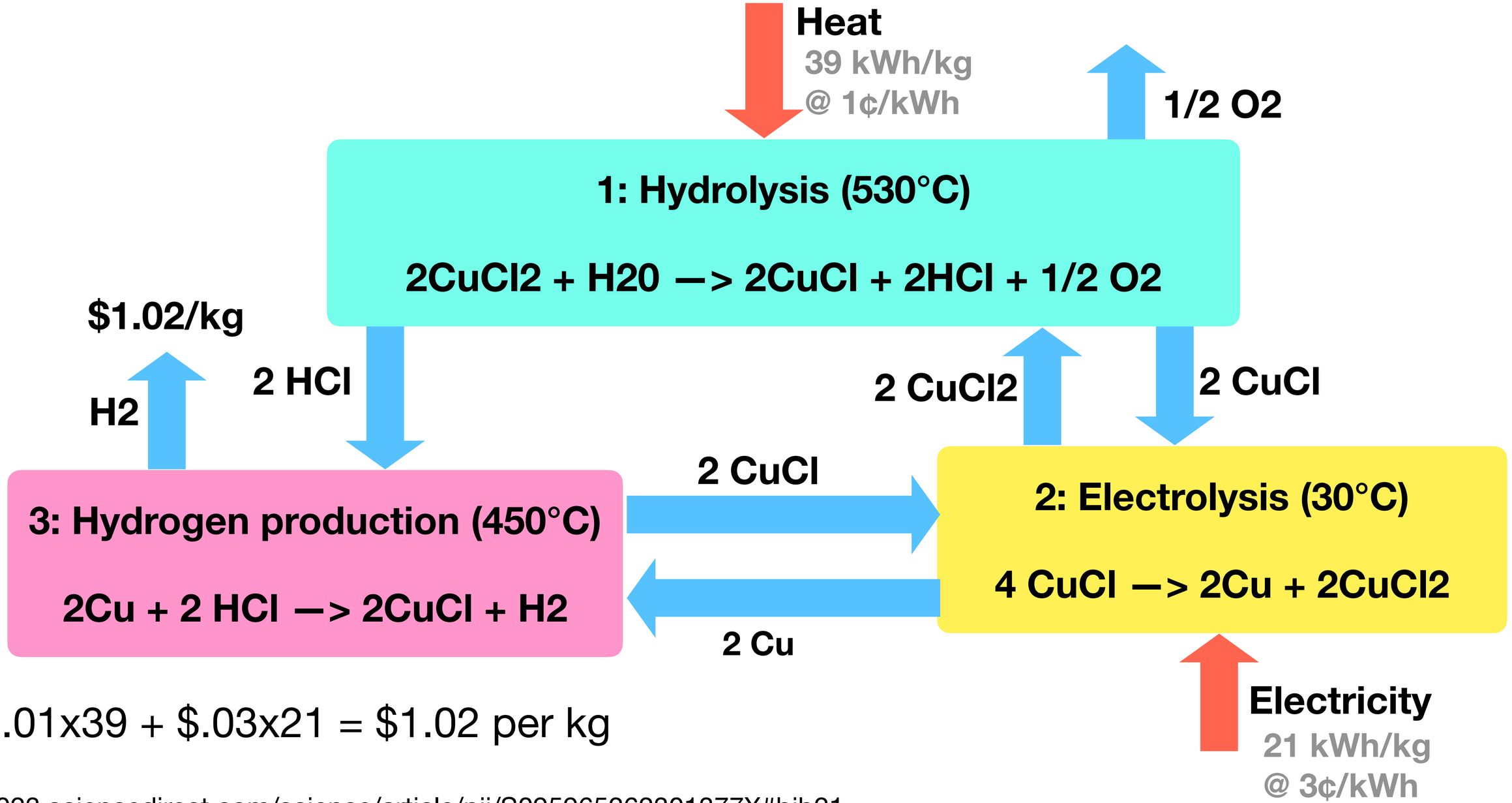
$1.03 per kg (Razi)
$1.00 DOE goal

Razi 2023 sciencedirect.com/science/article/pii/S095965262301377X#bib21



Why not H2 via 1970 Sulfur-Iodine cycle? https://pubs.rsc.org/en/content/articlelanding/2009/EE/b821113m

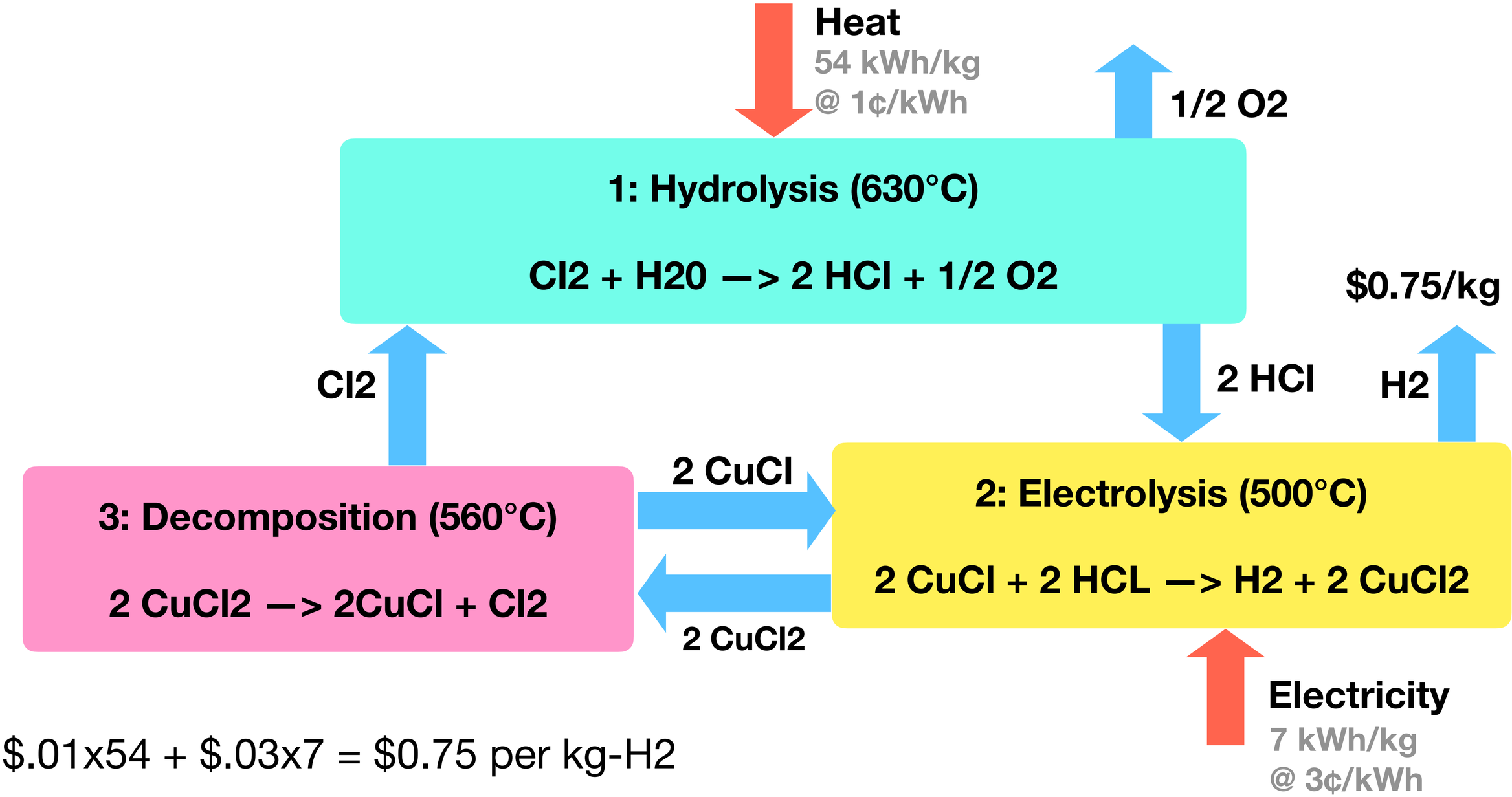
Hydrogen from three step Cu-Cl water splitting (Razi)



$.01x39 + $.03x21 = $1.02 per kg

Razi 2023 sciencedirect.com/science/article/pii/S095965262301377X#bib21

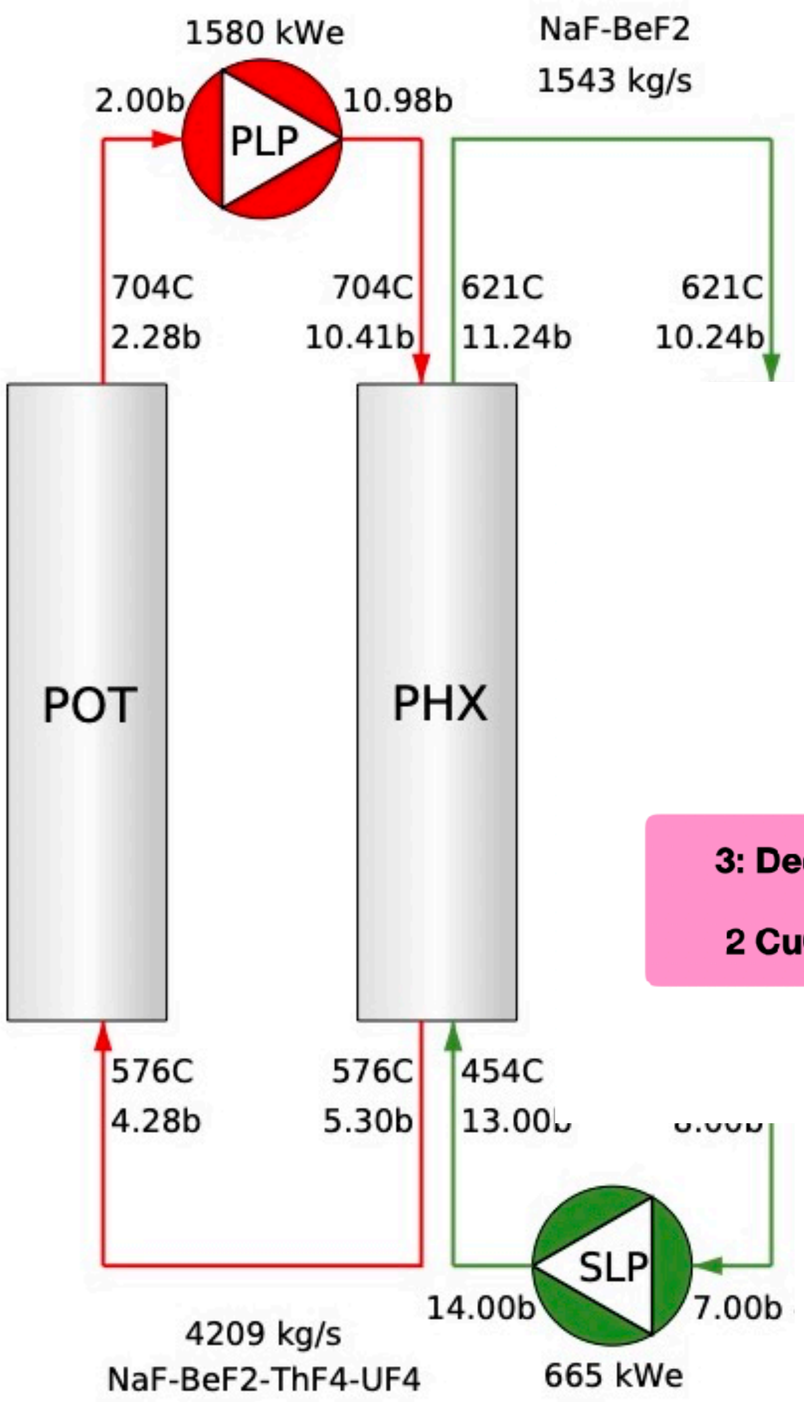
Hydrogen from H2O via 630°C 3-step Cu-Cl process?

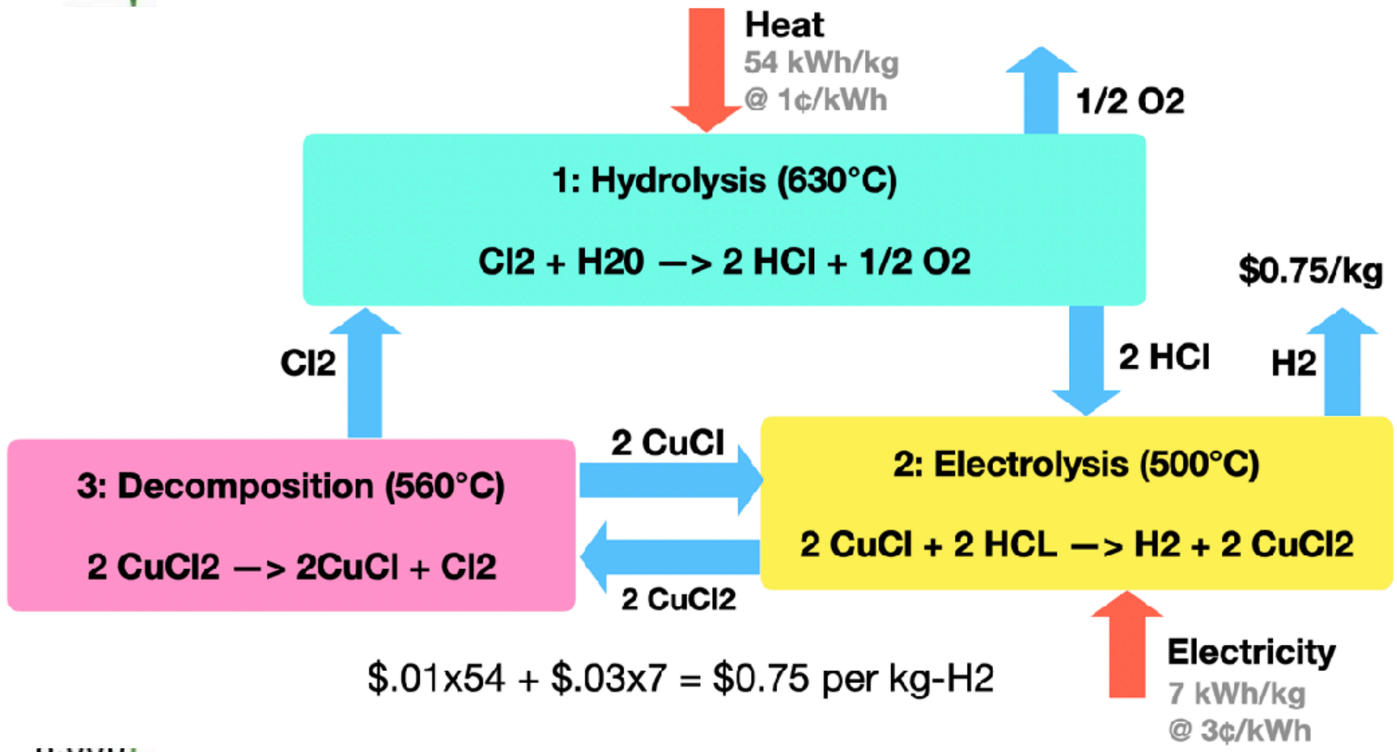


$.01x54 + $.03x7 = $0.75 per kg-H2

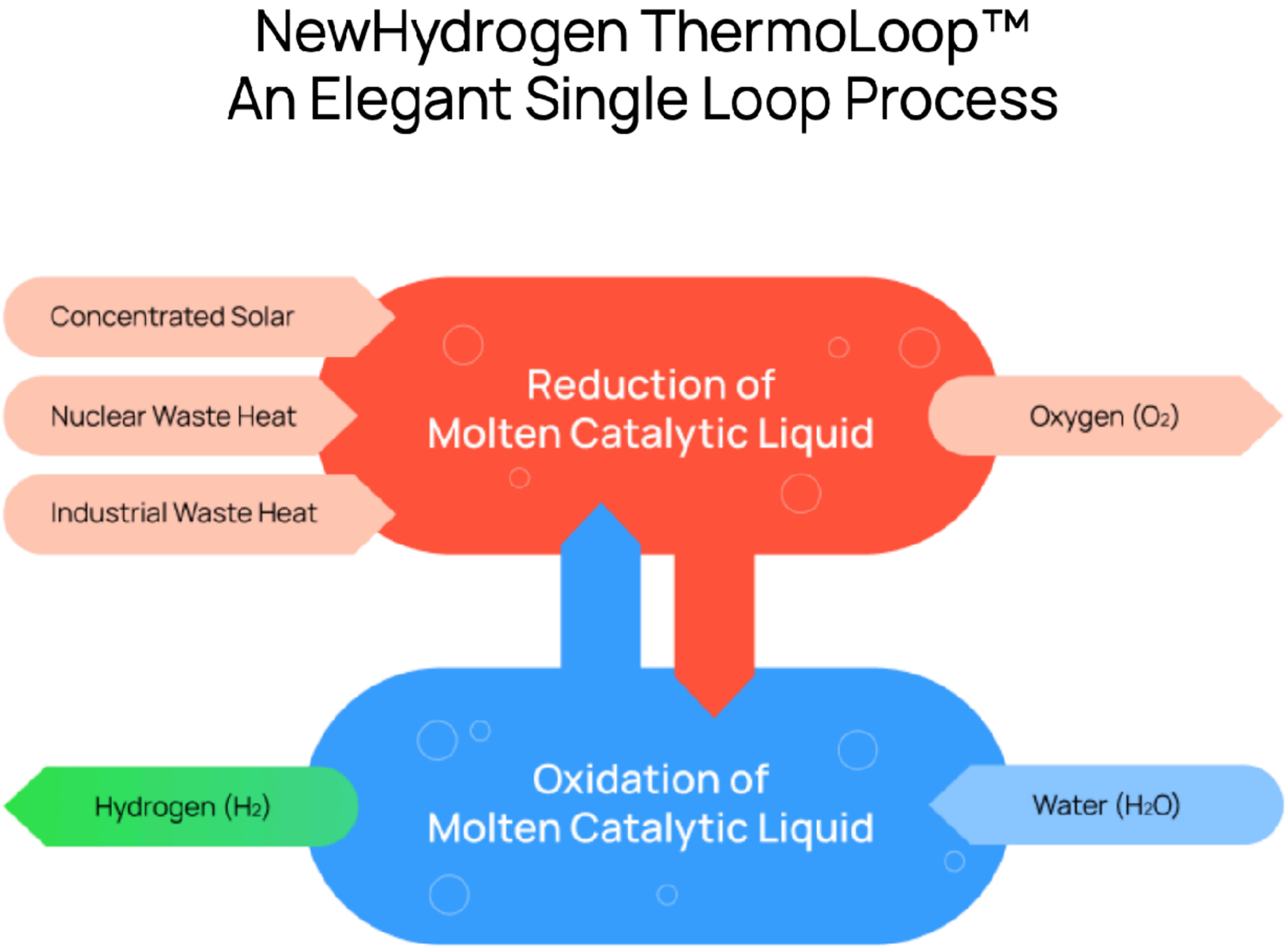
Razi 2023 sciencedirect.com/science/article/pii/S095965262301377X#bib21

ThorCon molten salt reactor secondary loop heat @ 621°C



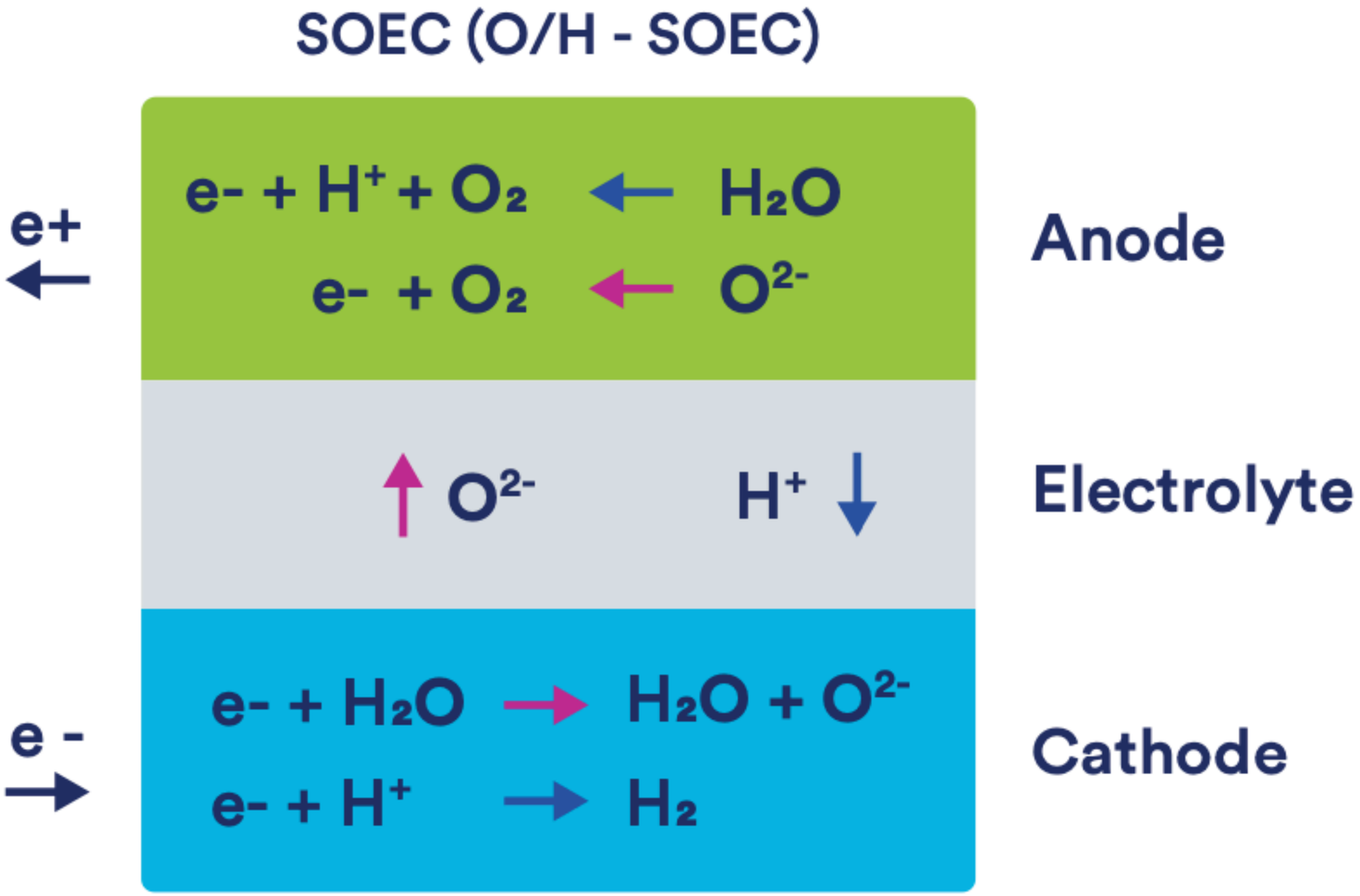


H2 from H2O @ <1000°C via UCSB public start-up?



https://newhydrogen.com/breakthrough-tech

Solid Oxide Electrolysis Cells (SOEC) use high temperature heat.

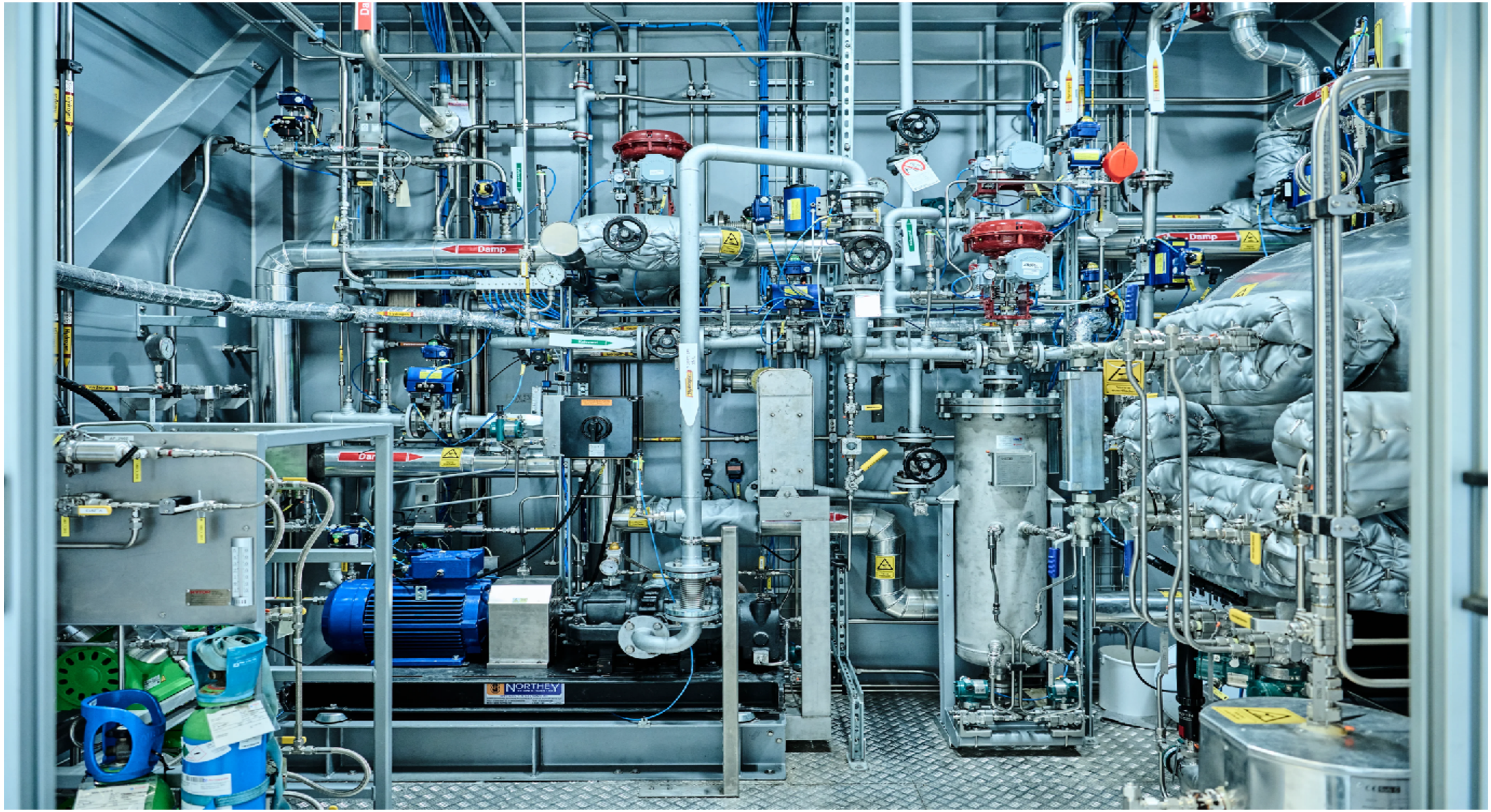


"SOECs can be used to electrolyze other combinations of molecules …

A notable combination would be steam and carbon dioxide, which, when electrolyzed, produces a mixture of carbon monoxide, hydrogen, and steam."

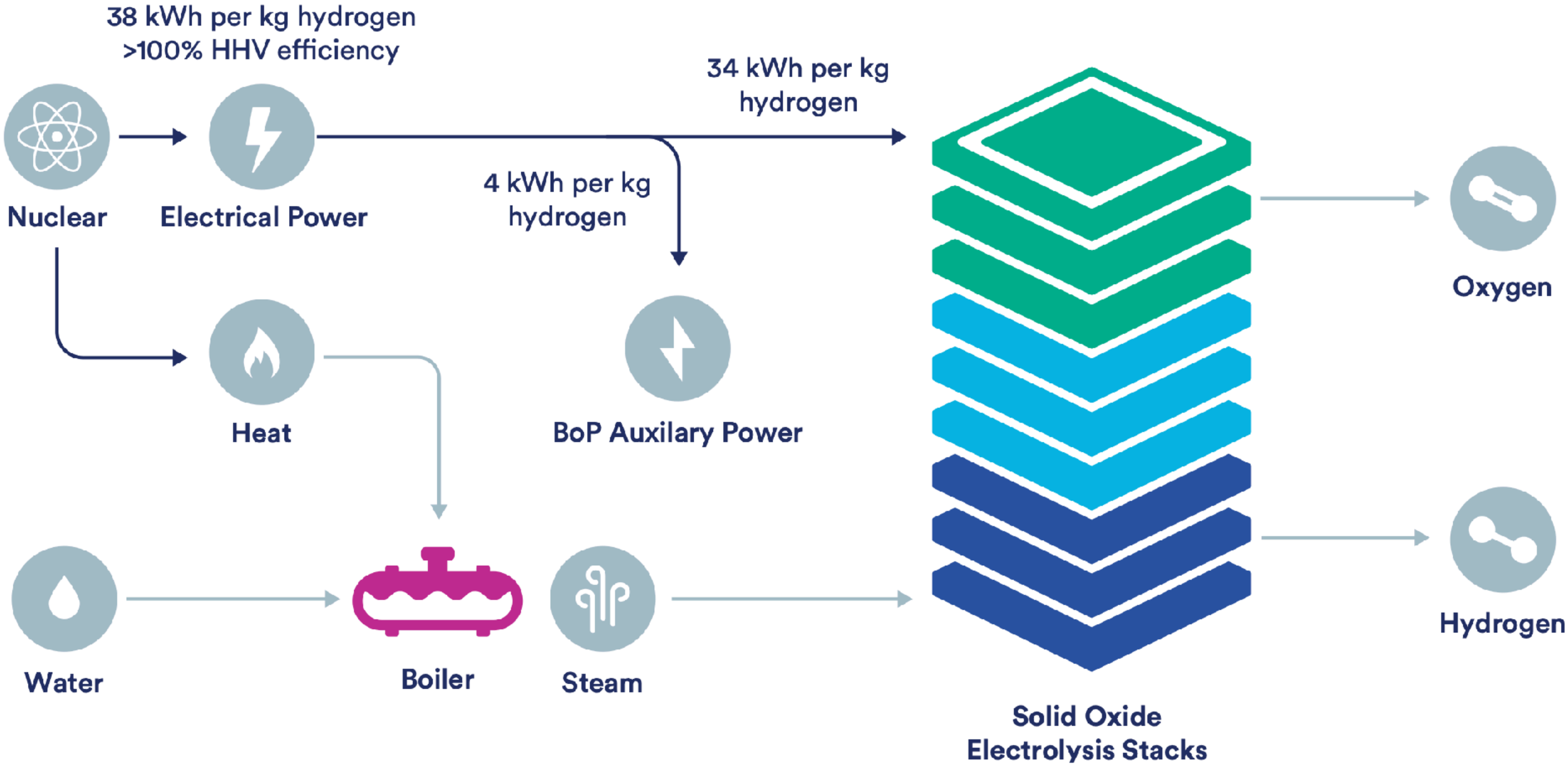
https://cdn.catf.us/wp-content/uploads/2023/11/15092028/solid-oxide-electrolysis-report.pdf

Haldor Topsoe test of hydrogen SOEC: 36 kWh/kg-H2.



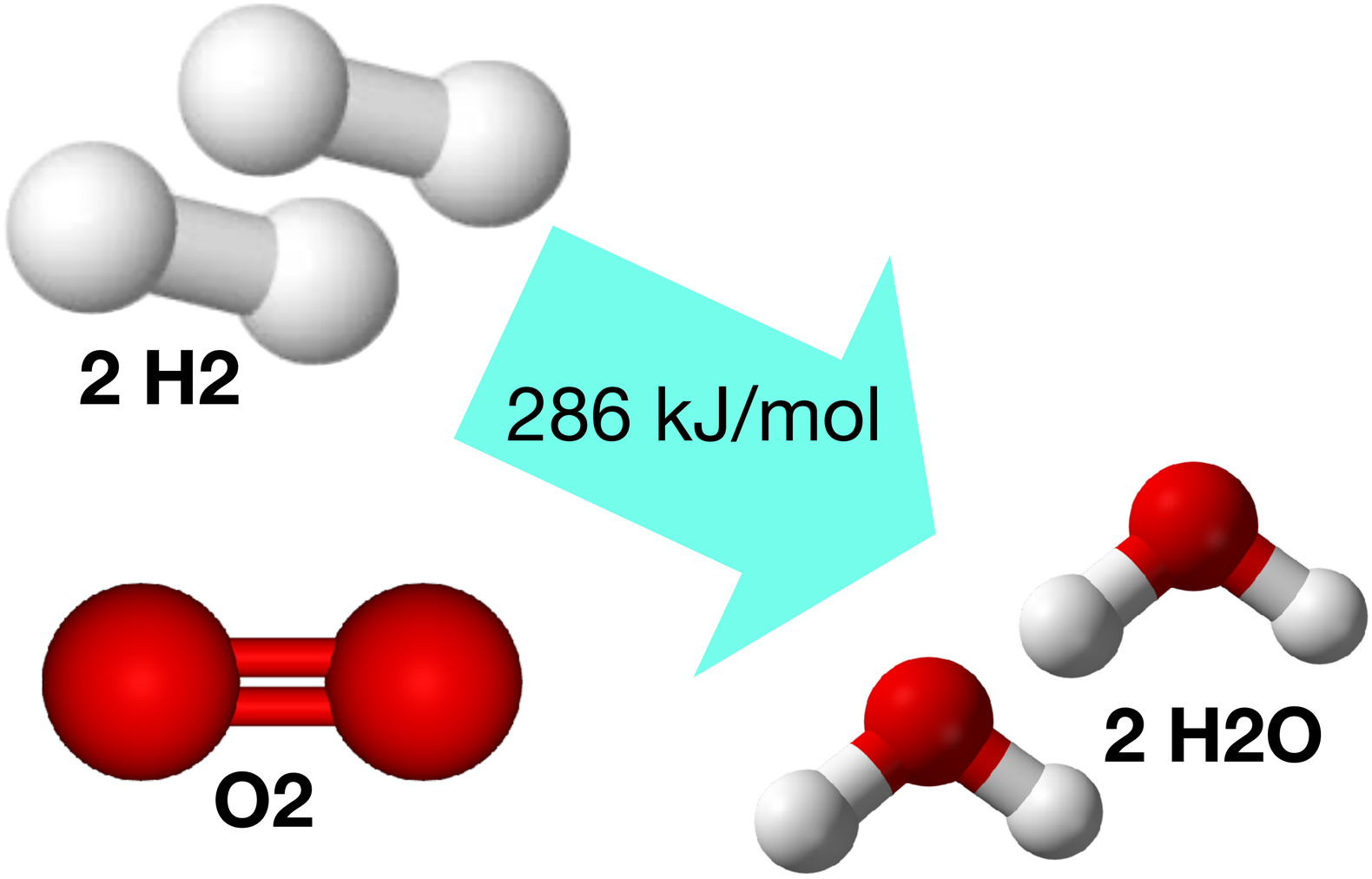
https://www.topsoe.com/blog/breakthrough-in-green-hydrogen-topsoes-soec-demo-reveals-strong-results

FuelCell Energy SOEC Electrolyzer with Nuclear Power



https://cdn.catf.us/wp-content/uploads/2023/11/15092028/solid-oxide-electrolysis-report.pdf

Hydrogen combustion delivers 142 MJ/kg (heat) but as fuel H2 is hard to transport or store.



Heat of combustion

142 MJ per kg-H2

39 kWh per kg-H2

@ $1.00 per kg-H2

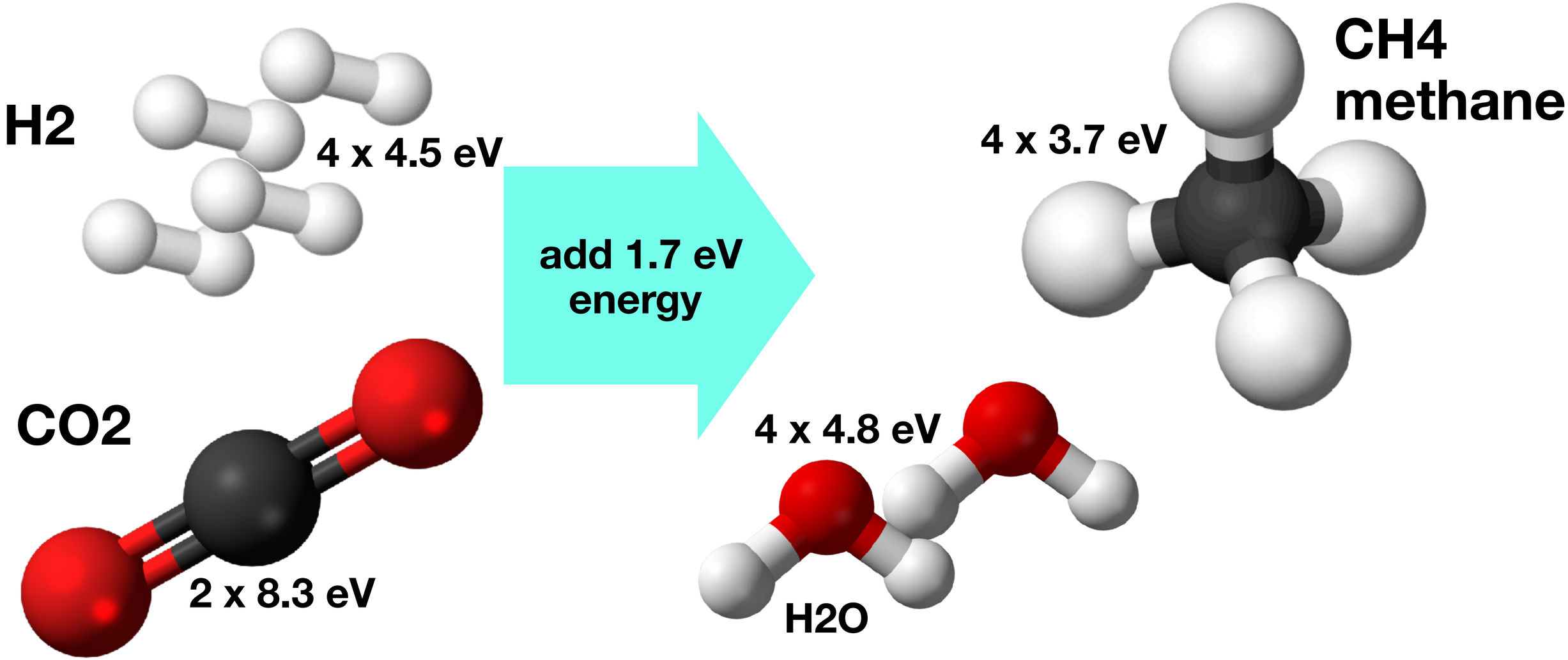
$0.026 per kWh

compare to gasoline

$0.09 per kWh

Russia's Tupolev-155 with liquid hydrogen fuel flew in 1988.

Hydrogen frees carbon from oxygen's bonds.

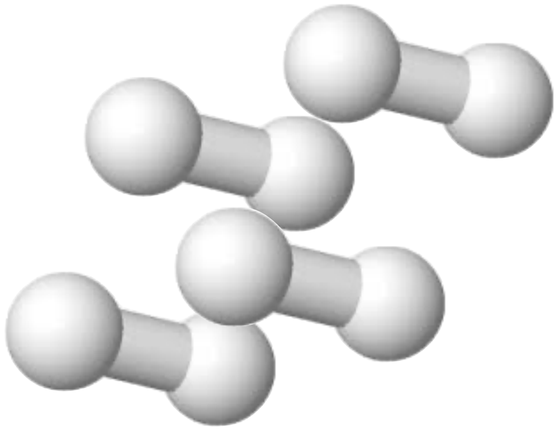


Bond energies in electron volts, 1 eV = 96 kJ/mol

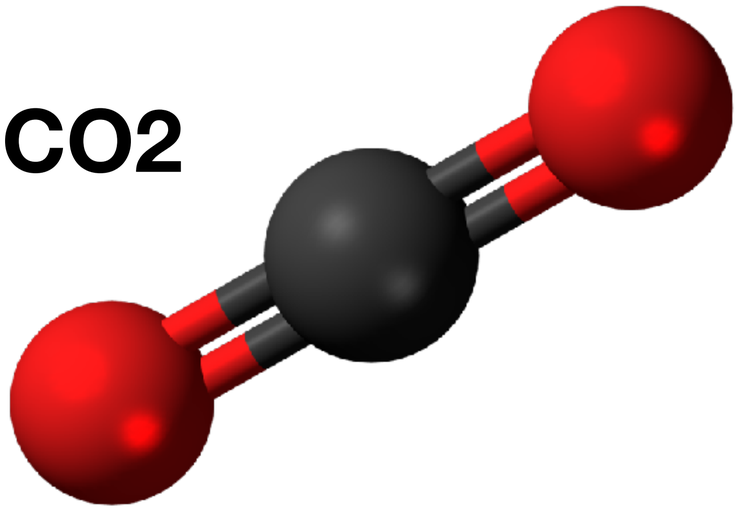
https://www.sciencedirect.com/science/article/pii/S2212982019309916

Hydrogen can convert CO2 to methane.

H2

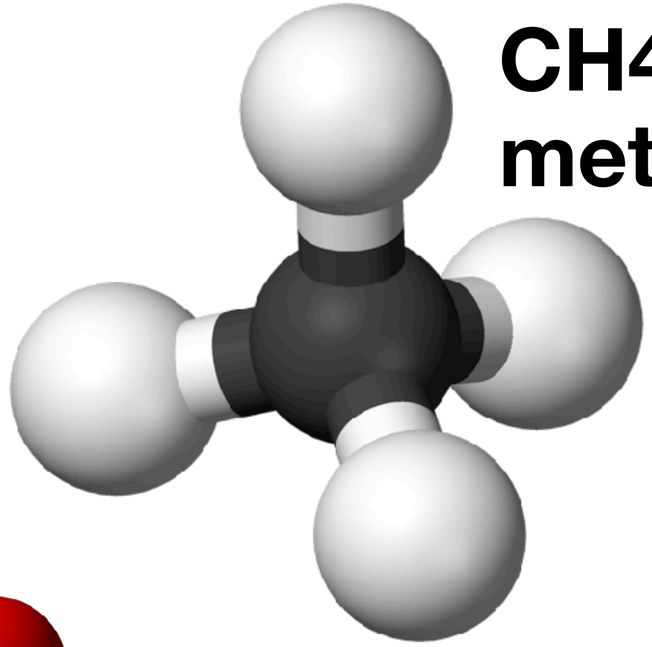


CO2

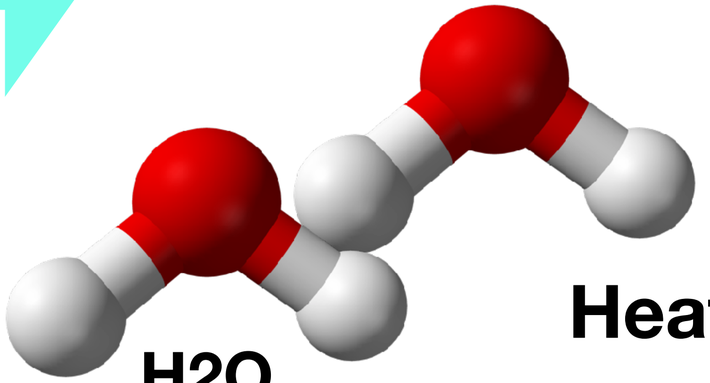


add 1.7 eV energy

CH4 methane



H2O



Heat of of combustion

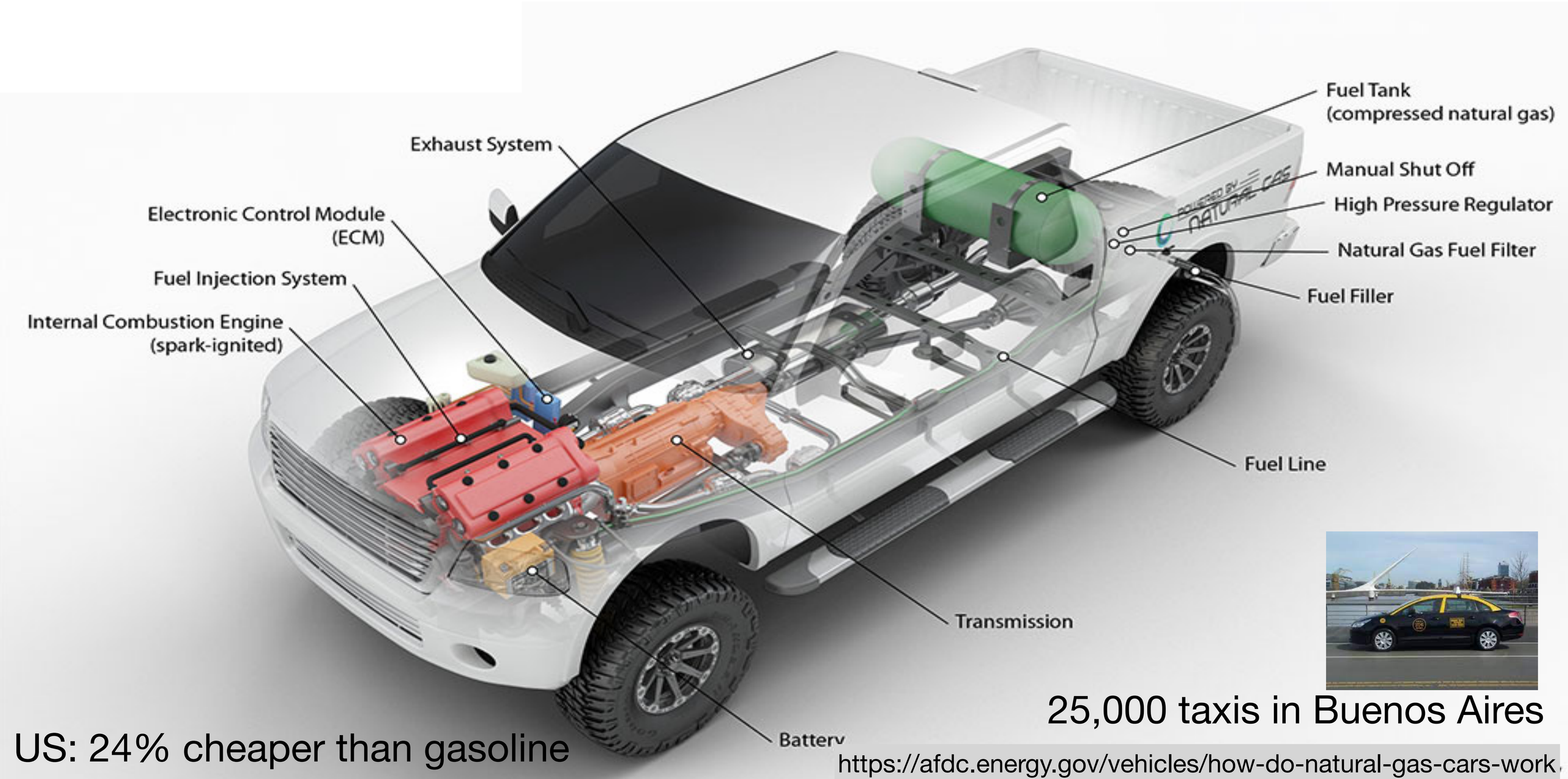
56 MJ per kg-CH4

16 kWh per kg-CH4

Bond energies in electron volts, 1 eV = 96 kJ/mol

https://www.sciencedirect.com/science/article/pii/S2212982019309916

23 million vehicles run on methane fuel.

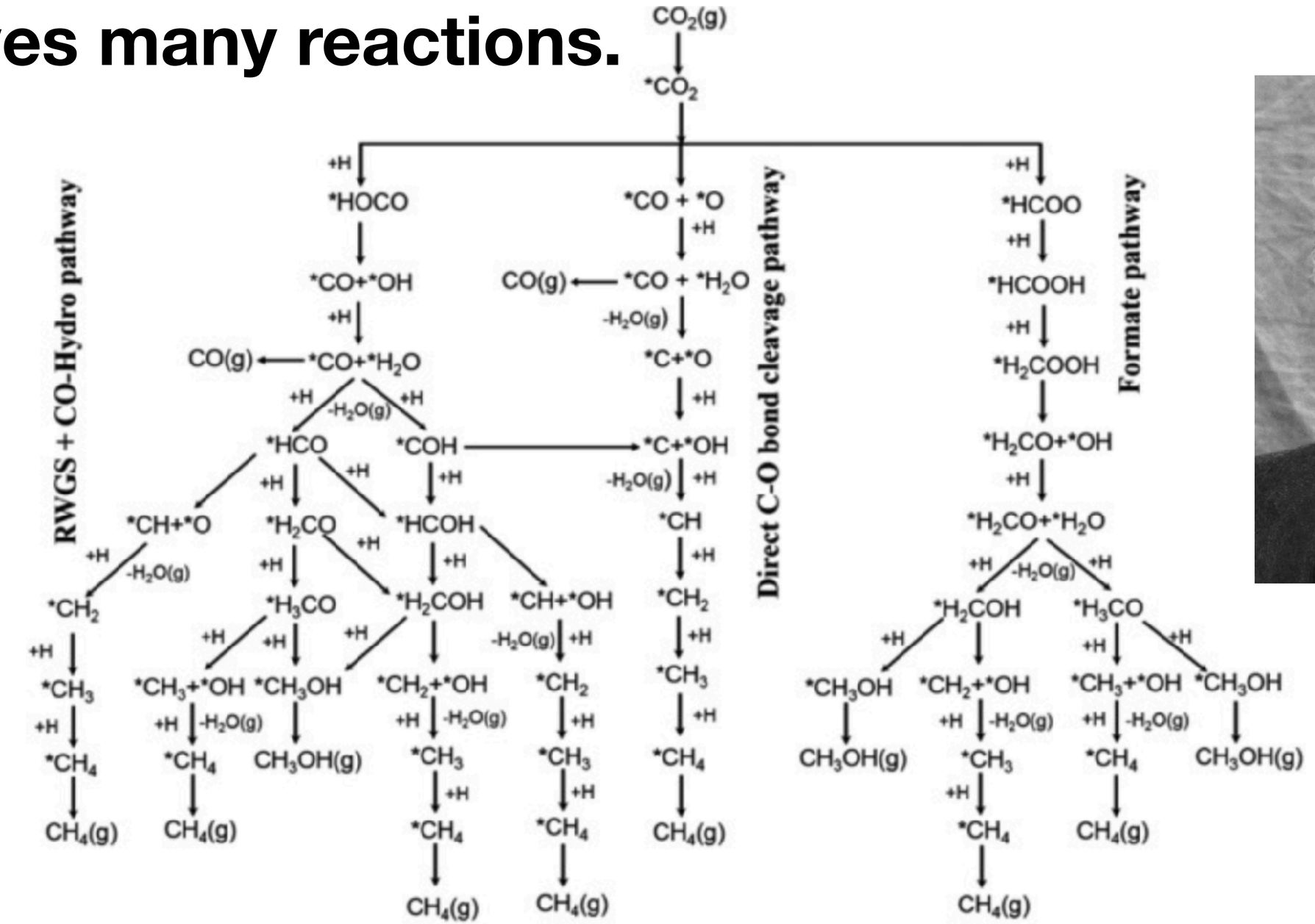


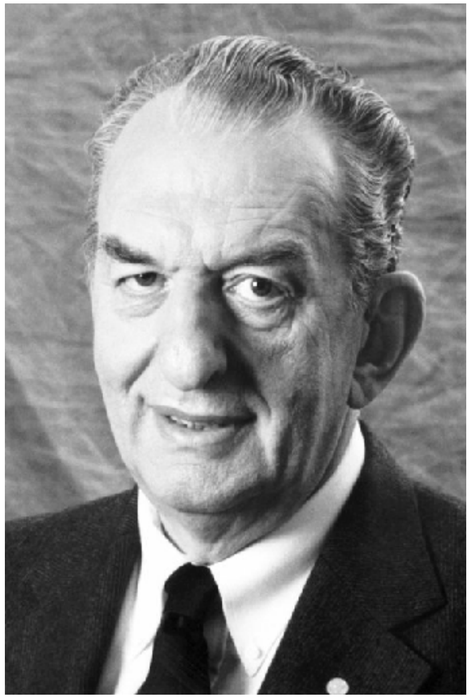
25,000 taxis in Buenos Aires

US: 24% cheaper than gasoline

https://afdc.energy.gov/vehicles/how-do-natural-gas-cars-work

Synthesizing methane, $CO_2 + 4\ H_2 \rightarrow CH_4 + 2\ H_2O$, **involves many reactions.**

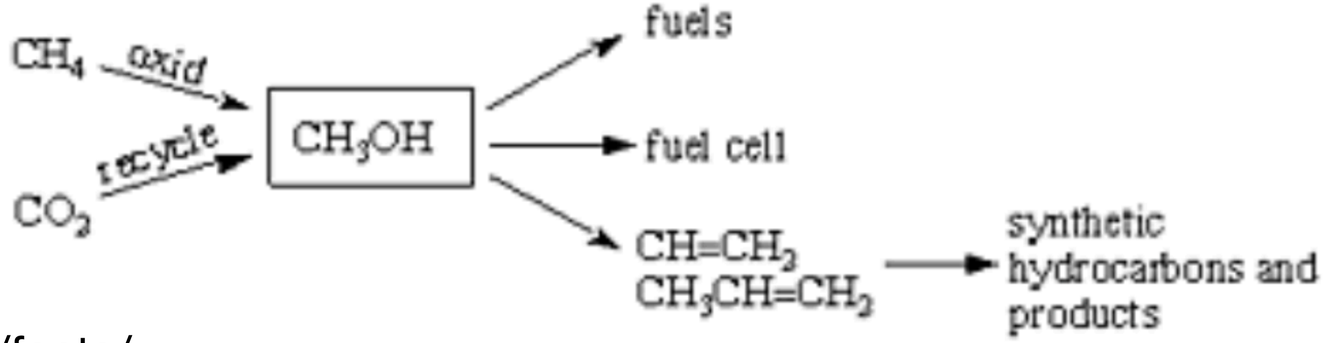




https://www.sciencedirect.com/science/article/abs/pii/B9780323903868000401

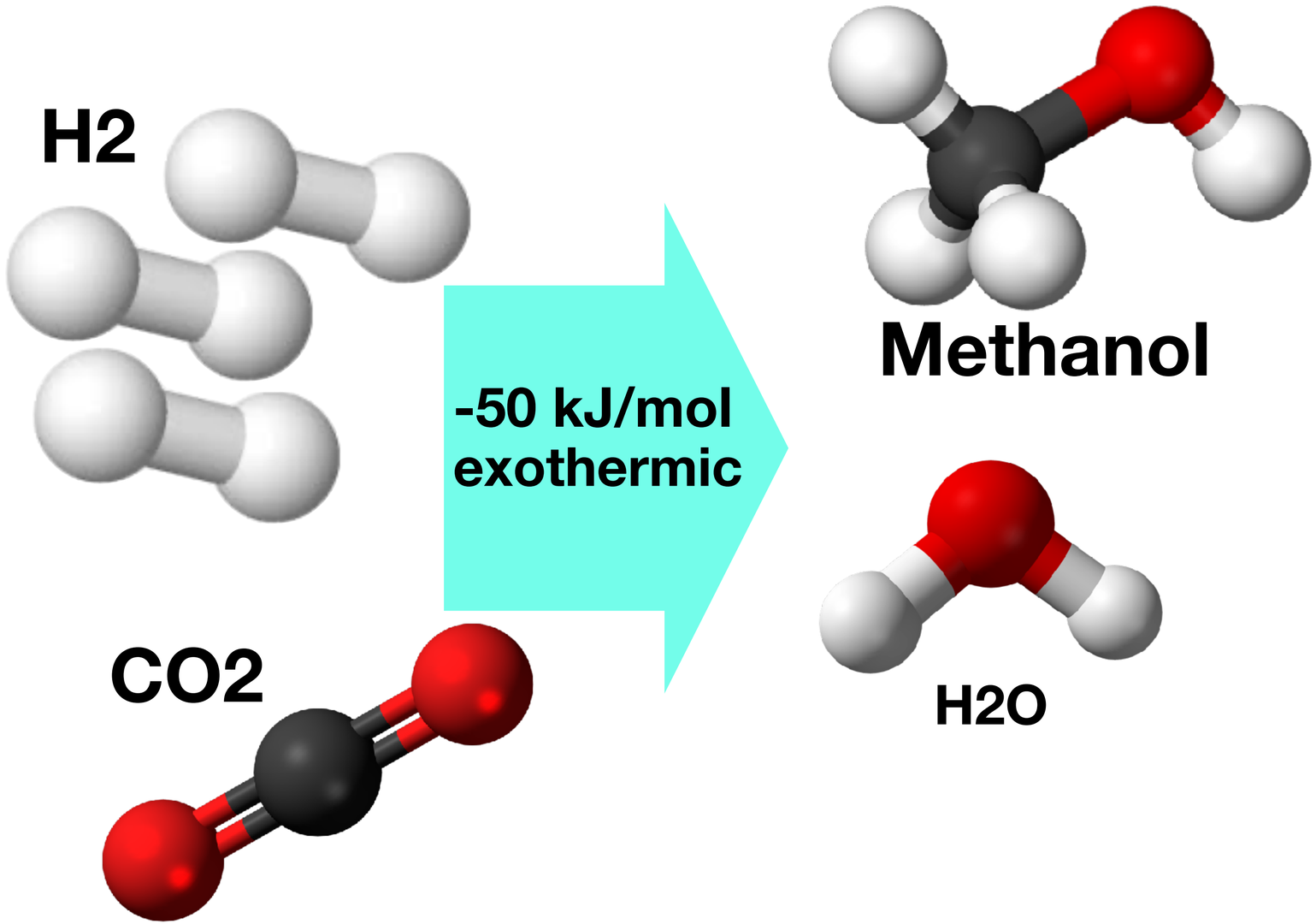
George Olah Nobel Prize acceptance essay:

"As **atmospheric carbon dioxide** is available to all people on the Earth this will enable **mankind to liberate itself from dependence on fossil fuels**. Substantial energy is of course necessary to generate the needed hydrogen for methanol production. This **energy could come from safe nuclear power plants** as well as all alternative energy sources such as sunlight, wind, geothermal, etc. At the same time, this approach will **also diminish the danger of global warming** by removing and recycling the rising carbon dioxide content of the atmosphere."



https://www.nobelprize.org/prizes/chemistry/1994/olah/facts/

George Olah envisioned a methanol economy.



Heat of combustion

23 MJ per kg-CH3OH

6.3 kWh per kg-CH3OH

compare to gasoline

13 kWh per kg-gasoline

https://www.amazon.com/Beyond-Oil-Gas-Methanol-Economy/dp/3527338039

Carbon Recycling International CO2-to-methanol plants.

Svartsengi, Iceland: 4,000 tons/year

China: 110,000 tons/year

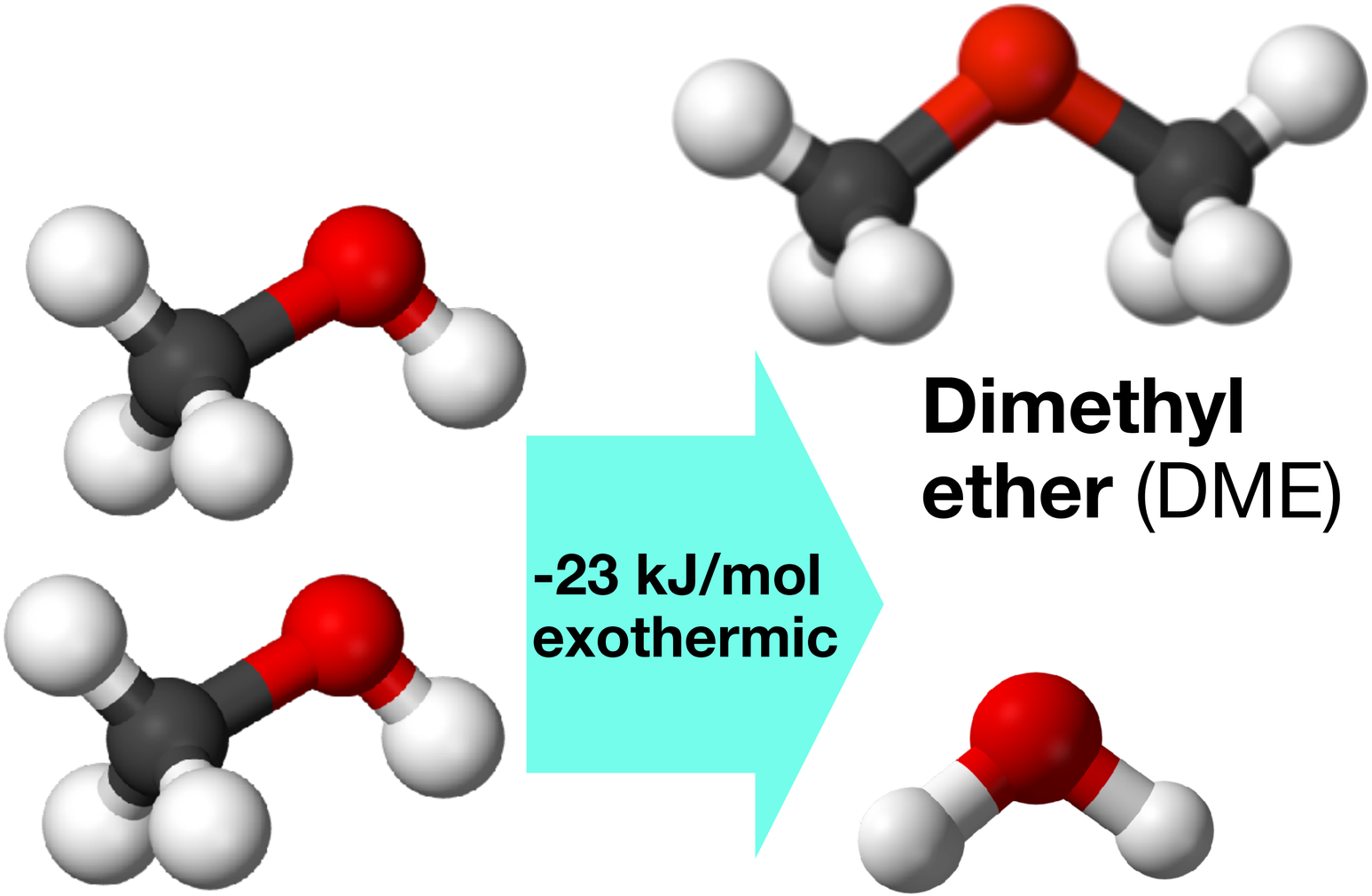
https://www.carbonrecycling.is/news-media/worlds-largest-co2-to-methanol-plant-starts-production

298 ships with alternative fuel propulsion were ordered in 2023

10 89,000 DWT Methanol Fueled Bulk Carriers Ordered in China

https://methanol.sharepoint.com/_layouts/15/stream.aspx?id=/Shared Documents/MEDIA/Videos/XCMG MeOH miniing truck.mp4&ga=1&referrer=StreamWebApp.Web&referrerScenario=AddressBarCopied.view

Dimethyl ether (DME) can fuel existing diesel engines.



Methanol

-23 kJ/mol exothermic

Dimethyl ether (DME)

H2O gas

Heat of combustion

37 MJ per kg-DME

10 kWh per kg-DME

6.5 kWh per L-DME

13 kWh per kg-diesel

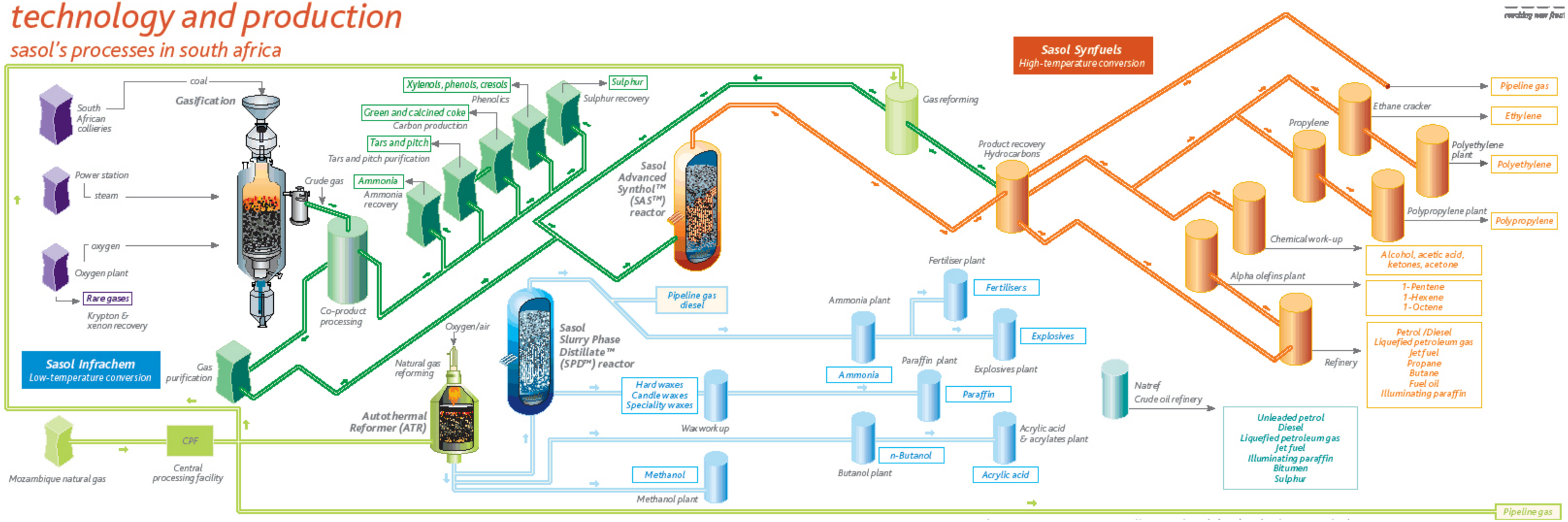
10.2 kWh per L-diesel

https://www.amazon.com/Beyond-Oil-Gas-Methanol-Economy/dp/3527338039

SASOL converts South Africa coal to gasoline since 1955.

WW II born, Fischer Tropsch process starts with coal gasification.

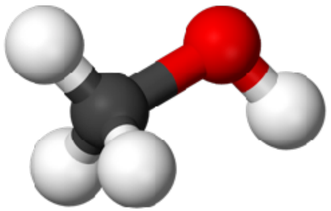
C + H2O —> CO + H2



https://www.netl.doe.gov/research/carbon-management/energy-systems/gasification/gasifipedia/sasol

https://www.netl.doe.gov/sites/default/files/2021-03/OVERVIEW OF COAL TO LIQUDS - A HISTORICAL PERSPECTIVE.pdf

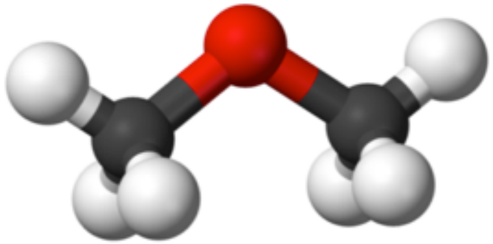
ExxonMobil methanol-to-gasoline process



CH_3OH

Methanol

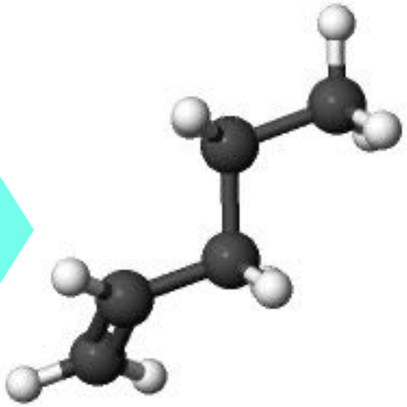
C=1



H_3COCH_3

Dimethyl ether

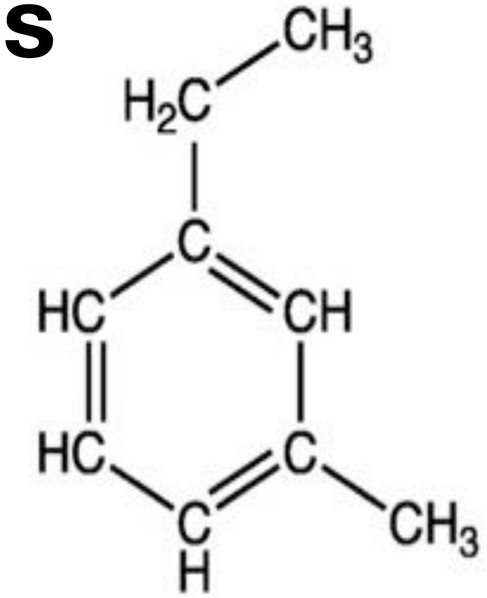
C=2



1-pentene

light olefins example

C=5



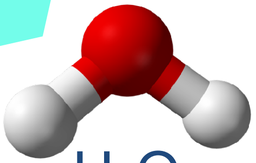
gasoline

aromatic example

C= 7 to 11

Feedstock can be syngas from water on hot coal.

C + H2O —> CO + H2



H_2O

Water

New Zealand converted natural gas to gasoline at 15,000 bbl/day in the 1980s.

ExxonMobil fixed bed reactor produces 12,500 bbl/day in China since 2016.

https://www.exxonmobilchemical.com/en/catalysts-and-technology-licensing/methanol-to-gasoline-technology https://pubs.acs.org/doi/10.1021/ef502667d

Haldor Topsoe gas-to-gasoline process.

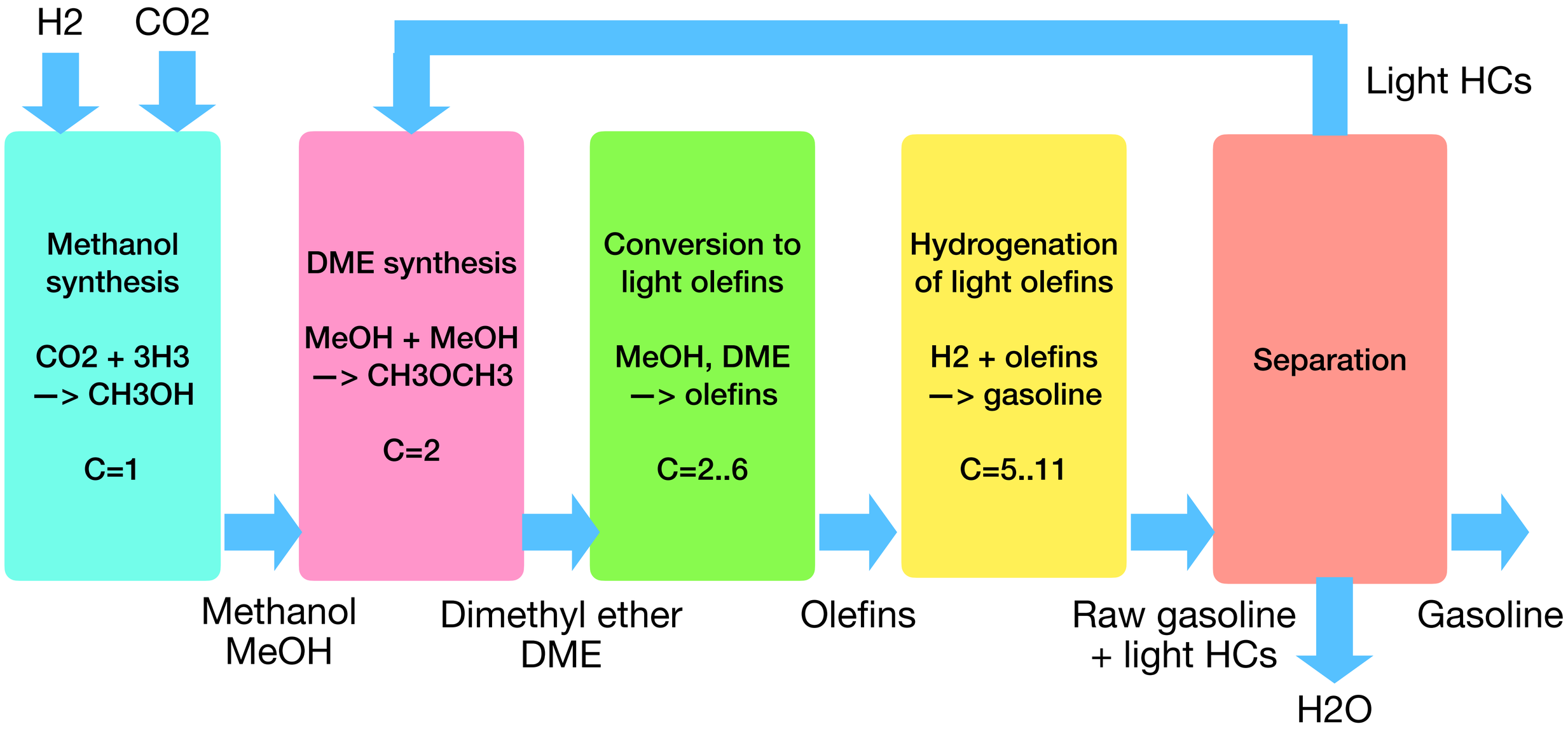
Synthetic Fuels | Methane-rich gas to gasoline

TIGAS™ (Topsoe Improved Gasoline Synthesis) makes it possible to produce high-quality, high-value gasoline from natural gas, shale gas, or associated gas.

After the 1973 oil crisis sparked a surge of interest in synthetic fuels, that interest soon waned as oil prices began to fall. However, today's high energy prices and a volatile energy supply have rejuvenated interest in synthetic fuels. And, as gasoline specifications reach new levels of stringency, Topsoe has responded to the needs of the market with TIGAS™ – Topsoe Improved Gasoline Synthesis.

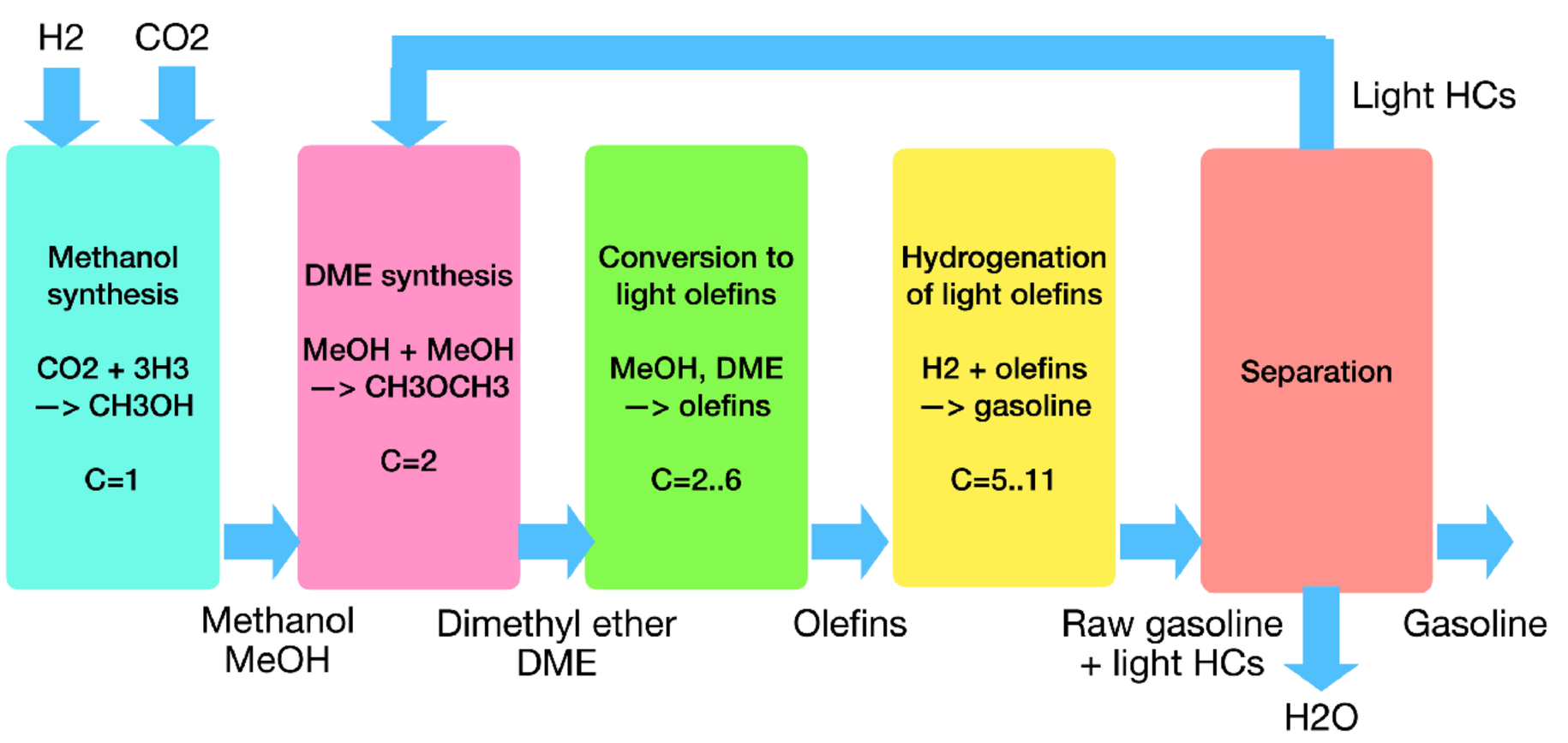
https://www.topsoe.com/processes/synthetic-fuels/methane-rich-gas-to-gasoline

Seafinery: H2 + CO2 —> gasoline



Szdzygiel sciencedirect.com/science/article/abs/pii/S0959652620328353 sciencedirect.com/science/article/pii/S0959652620328353

Chemical engineers optimize each reactor.



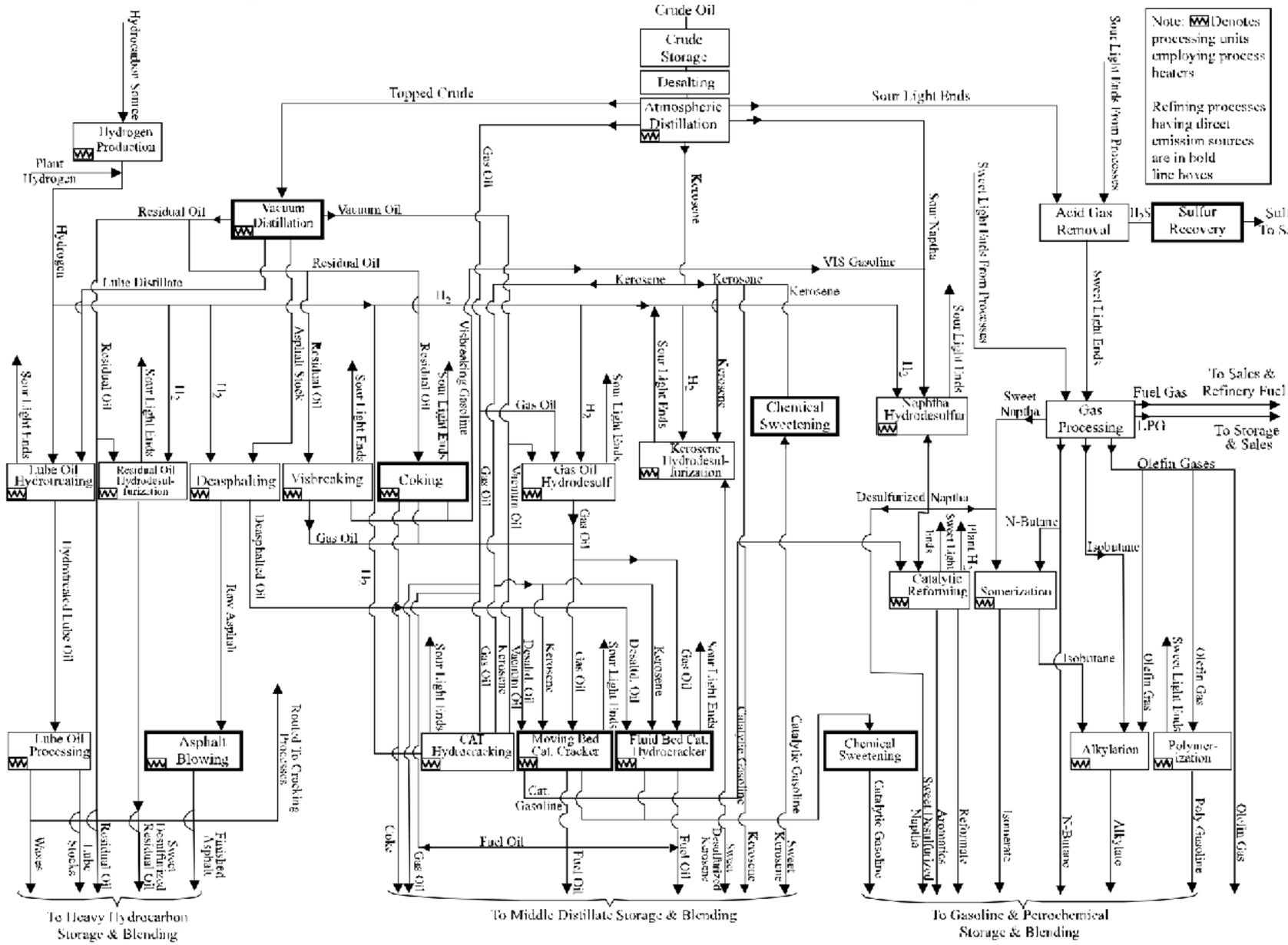
Variables …

Note: reactions are exothermic

Catalyst	Fixed bed	Temperature
Promoter	Fluid bed	Pressure
Substrate	Slurry	Cooling
Feed rates	Heat exchangers	Flow speeds

Seafinery benefits vs petroleum refinery:

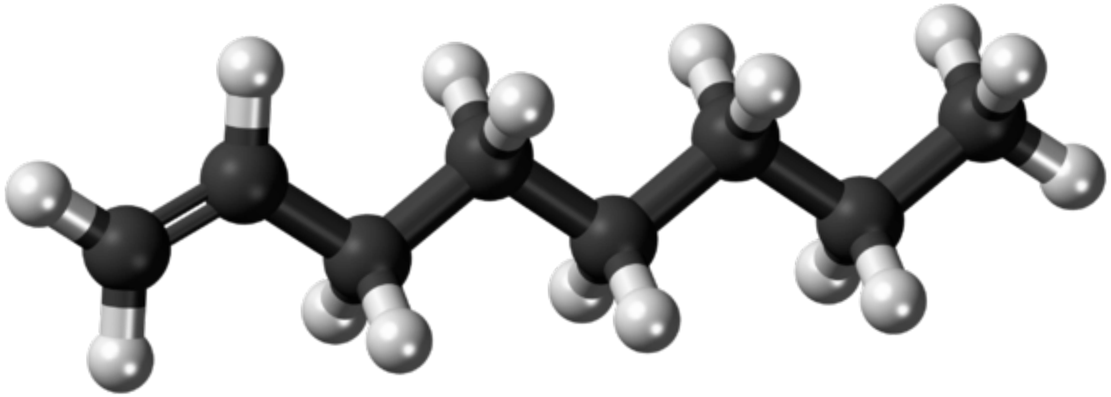
- No sulfur removal required
- No cracking of long-chain HC molecules
- Makes antiknock additive MeOH
- No crude oil sourced contaminants in fuel.



https://gaftp.epa.gov/ap42/ch05/s01/final/c05s01_jan1995.pdf

Seafuel from H2 and CO2: octene example

Octene is one of over a hundred hydrocarbon molecules in gasoline.



8 x (CO2 + 3H2) —> 16 H2O + C8H16

8x44 g-CO2 + 8x6 g-H2 —> 16x18 g-H2O + 112 g-C8H16

solve for octene, C8H16

1 kg-octene needs 3.14 kg-CO2 + 0.43 kg-H2

Seafuel input energy, cost

1 kg-octene composed of 3.14 kg-CO_2 + 0.43 kg-H_2

Octene Ingredients	Quantity kg	Electricity kWh(e)/kg	kWh(e)	Elect Cost $/kWh @0.03	Heat kWh(t)/kg	kWh(t)	Heat cost $/kWh @ 0.01	Energy cost
CO_2	3.14	0.66 (Yan)	2	$0.06	0			$0.06
H_2	0.43	21 (Razi)	9	$0.27	39 (Razi)	17	$0.17	$0.44
Totals, per kg-octene			11	$0.33		17	$0.17	$0.50

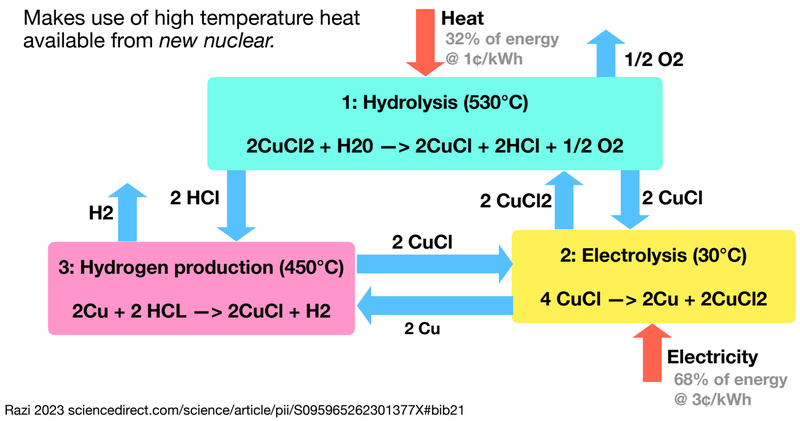
Seafuel heat of combustion: 13 kWh/kg

1 kg Seafuel from 11 kWh(e) + 17 kWh(t), costing $0.50, or **$0.04/kWh**

Cost numbers may be low; e-technology is new.

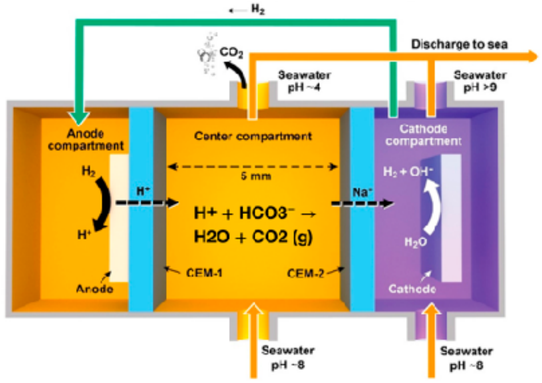
(Catalysts, reaction speeds, pressures needed, membrane life?)

Hydrogen from three step Cu-Cl water splitting (Razi)



Razi 2023 sciencedirect.com/science/article/pii/S095965262301377X#bib21

CO2 removal by pH swing (Yan)



Increasing acidity reverts dissolved bicarbonate to CO2.

H+ + HCO3⁻ → H2O + CO2 (g)

CO2 bubbled out by vacuum pumps.

Electrolysis energy

0.66 kWh(e)/kg-CO2

@ $0.03/kWh

$20.00/ton-CO2

Yan et al An Electrochemical Hydrogen-Looping System… https://pubs.acs.org/doi/10.1021/acsenergylett.2c00396?ref=pdf

H2 @ $1.00/kg

88% of $

Seafuel energy
@ $0.04/kWh

12% of $

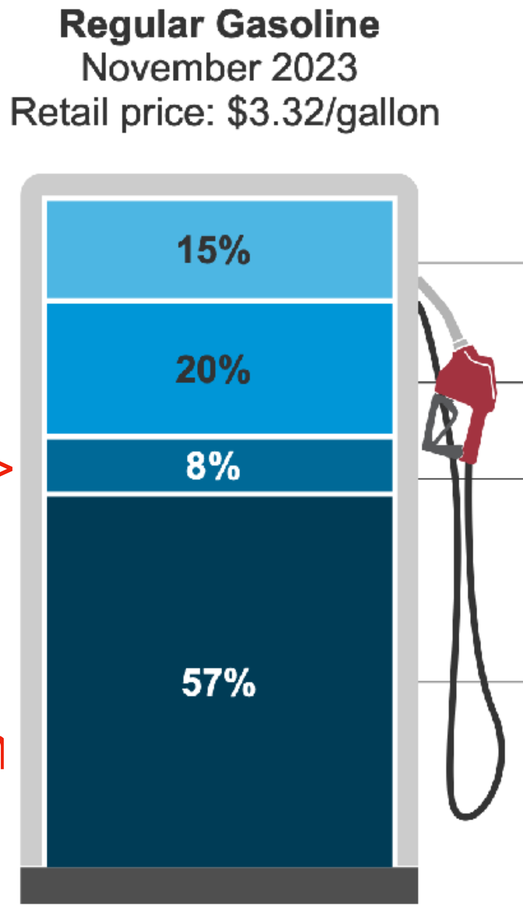
CO2 @ $20/ton

Low cost sensitivity

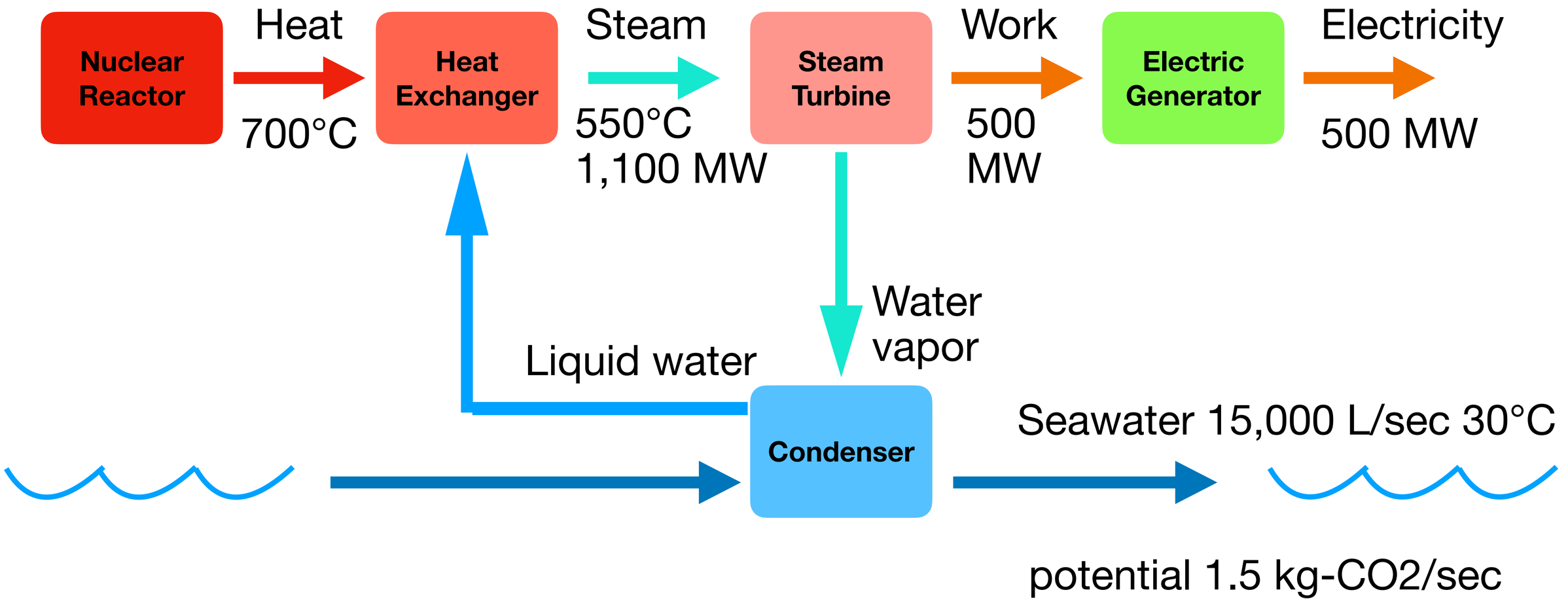
gasoline value —>
$0.09/kWh

refining
$0.006/kWh —>

crude
$0.04/kWh



Seafuel co-production is limited by power plant condenser seawater CO2 flow.



potential 1.5 kg-CO2/sec

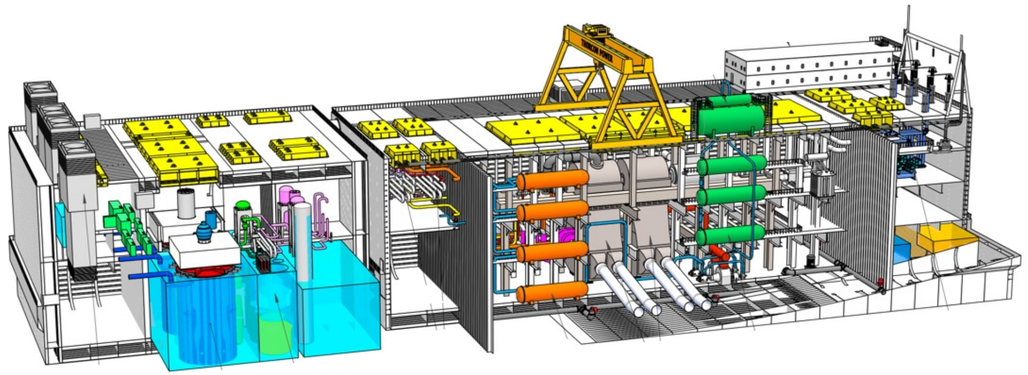
Assume 1.0 kg-CO2/sec extractable.

Such a nuclear electric power plant can make Seafuel as a by-product.

Seafuel output 0.32 kg/sec

@ density 119 kg/bbl

Seafuel output 230 bbl/day



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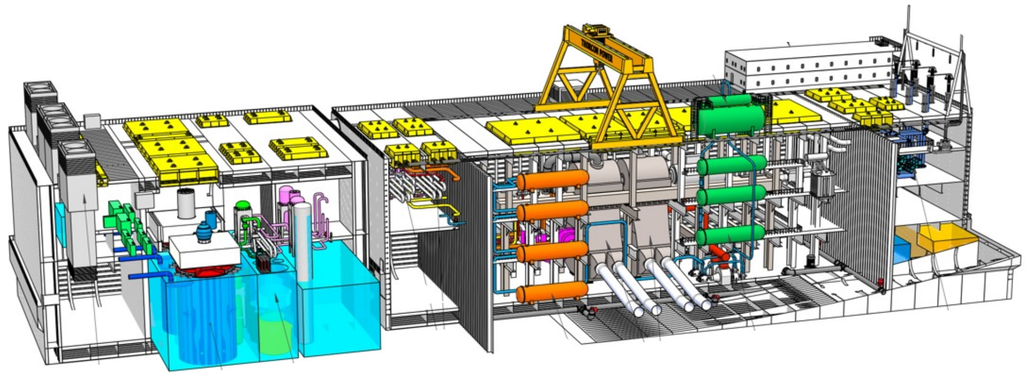


World crude refining 93,000,000 bbl/day

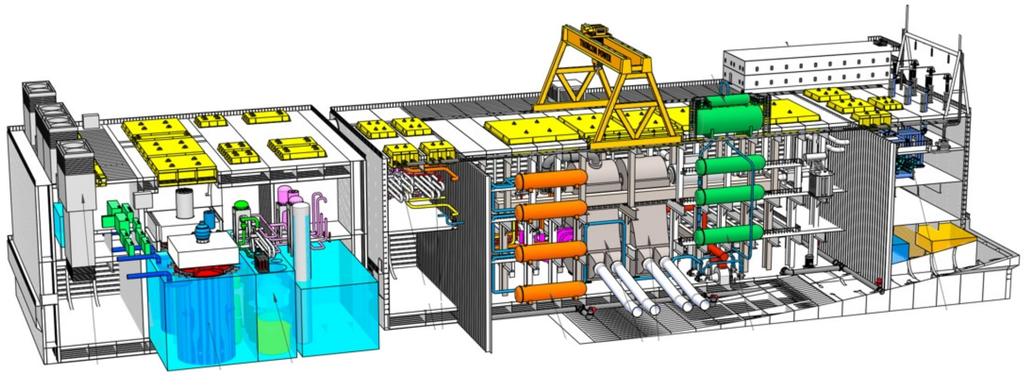
World airline fuel 5,600,000 bbl/day

A plant *dedicated* to produce Seafuel could take CO2 from 25X more seawater flow.

Seafuel output 8 kg/sec

Seafuel output 5,800 bbl/day

World airline fuel 5,600,000 bbl/day

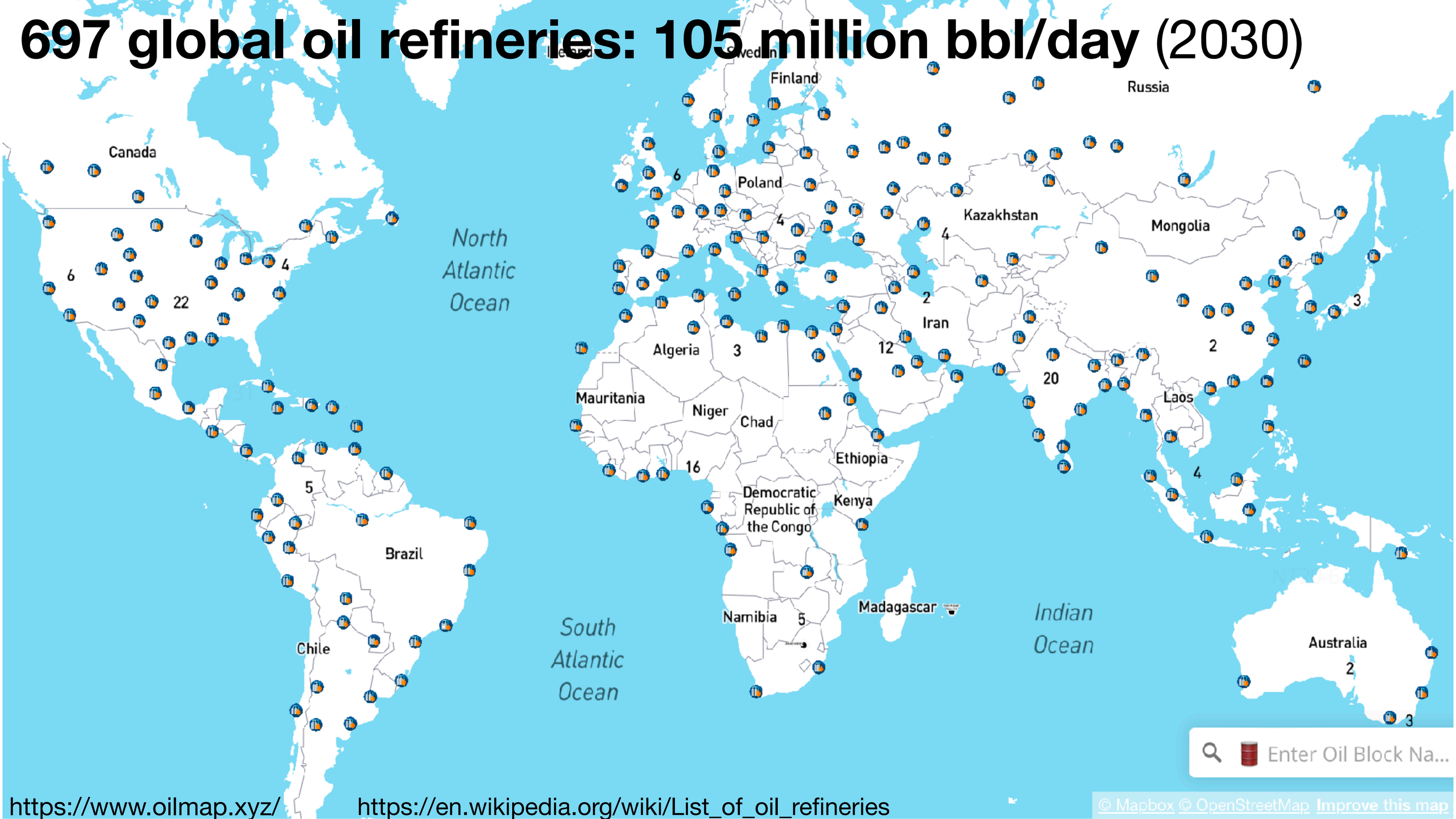


1000 such Seafuel-dedicated plants required for airline fuel.

$500 million per ThorCon 500.

Is $500 billion a lot of money?

697 global oil refineries: 105 million bbl/day (2030)



https://www.oilmap.xyz/ https://en.wikipedia.org/wiki/List_of_oil_refineries

2023 Dangote refinery

650,000 bbl/day crude

10.4 Mt/year gasoline

4.6 Mt/year diesel fuel

4.0 Mt/year jet fuel

27 GW-fuels out

https://www.hydrocarbons-technology.com/projects/dangote-refinery-lagos/

2023 Dangote refinery

650,000 bbl/day crude

10.4 Mt/year gasoline

4.6 Mt/year diesel fuel

4.0 Mt/year jet fuel

27 GW-fuels out

Capital measures

$19 billion investment

$29,000 per (bbl/day)

$2/bbl (if 40 year lifetime)

$700/kW-fuels out

$0.001/kWh

https://www.hydrocarbons-technology.com/projects/dangote-refinery-lagos/

Shell Pearl gas-to-liquids refinery

Natural gas liquids (..butane, propane..) extracted.

Remaining natural gas converted to liquid fuels.

24 reactors, each with 26,000 tubes of cobalt synthesis catalyst.

Catalyst surface area 18 times the land area of Qatar.

https://www.shell.com.qa/about-us/projects-and-sites/pearl-gtl.html

Shell Pearl gas-to-liquids refinery.

Pearl Capacities

1.6 billion cu ft per day gas in
120,000 bbl/day NGL out
140,000 bbl/day liq fuels out
3 billion bbl lifetime out
8 GW-NGL power out
10 GW-GTL fuels power out

https://www.shell.com.qa/about-us/projects-and-sites/pearl-gtl.html

Shell Pearl gas-to-liquids refinery.

Pearl Capacities

1.6 billion cu ft per day gas in
120,000 bbl/day NGL out
140,000 bbl/day liq fuels out
3 billion bbl lifetime out
8 GW-NGL power out
10 GW-GtL fuels power out

Capital measures

$19 billion investment
$73,000 per (bbl/day)
$6/bbl (60 year lifetime)
$1,000/kW-power out
$0.004/kWh-out (60 years)

https://www.shell.com.qa/about-us/projects-and-sites/pearl-gtl.html

Capital invested in world oil refineries ~ $3 trillion.

$29,000/(bbl/day) x 105 million bbl/day

Replacement with gas-to-liquid refineries?

$73,000/(bbl/day) x 105 million bbl/day ~ **$8 trillion?**

30,200+ Oil Refinery Stock Photos, Pi...
iStock

276,229 Refinery Images, Stock Photos, ...
Shutterstock

US oil refiners to defy heat, run plants a...
Reuters

Oil refinery - Wikipedia
Wikipedia

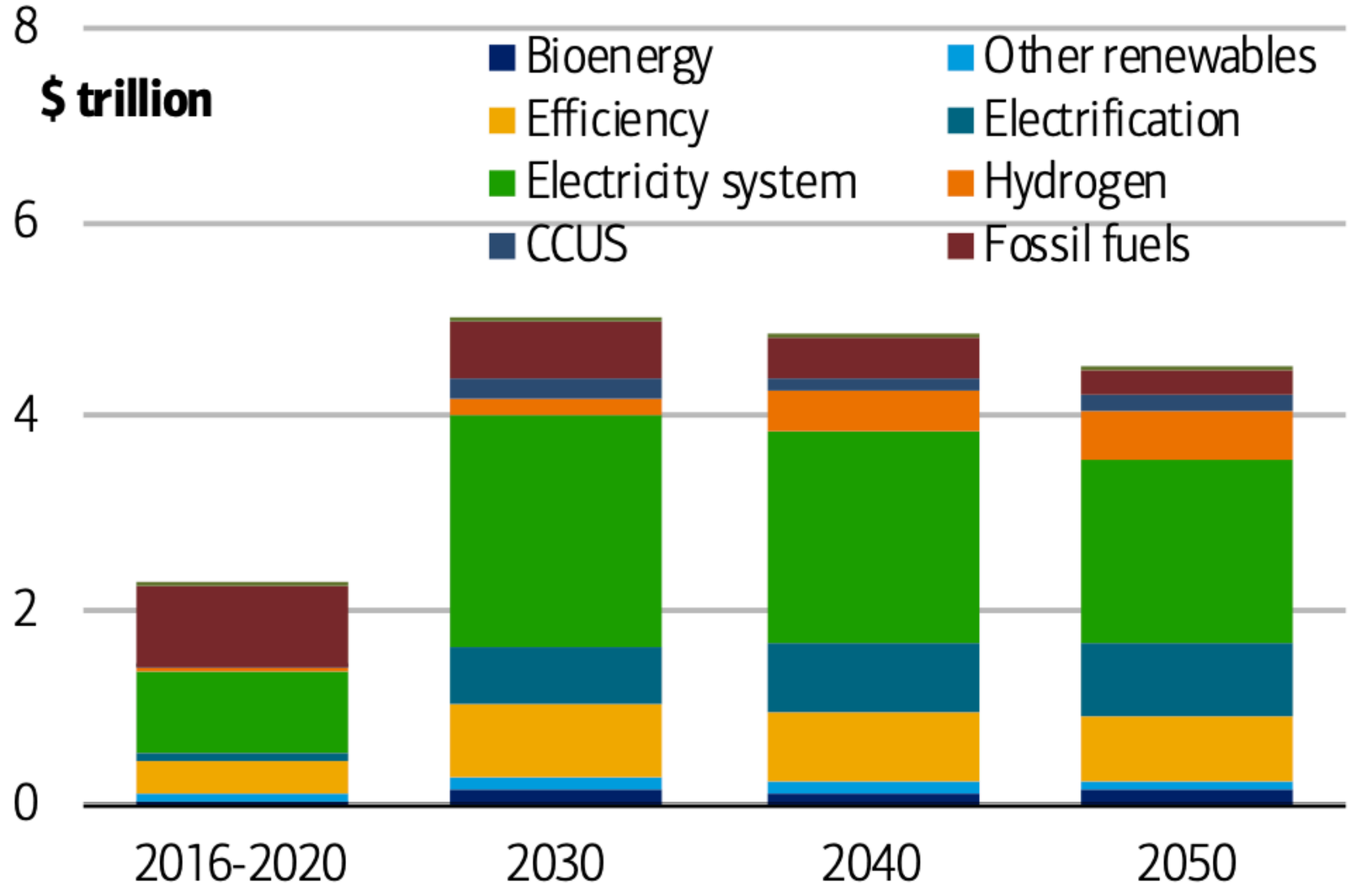
Global oil refiners crank up output as m...
Reuters

276,229 Refinery Images, Stock Photos, ...
Shutterstock

The Refining Process - How Oil Refinin...
Science | HowStuffWorks

Refinery Photos, Download The BE...
Pexels

BofA: Green energy transition costs $150 trillion, $5 trillion/year.



Source: International Energy Agency (2021), Net Zero by 2050, IEA, Paris

"Even in global terms and over a 30-year span, $150 trillion is a gargantuan amount.

The latter number is almost twice the total global GDP in 2019…"

https://news.yahoo.com/fighting-climate-change-a-150-trillion-battle-bank-of-america-report-163422676.html

Note: no fission power.

https://business.bofa.com/content/dam/boamlimages/documents/articles/ID21_1543/Net_Zero_Redacted_Note_Updated_Final.pdf

Possible improvements

1. Increase efficiency of **harvest of CO2** from seawater.
2. Use more thermal **hydrolysis**, less electricity.
3. Investigate combined **CO2/H2 cells** further.
4. Colocate Seafuel with **desal** plants.
5. Locate floating plants in **CO2-rich** Humboldt current.
6. **Fund** Seafuel demonstration plants ASAP.

Industry expertise is key to Seafuel success.

Challenges

Technology readiness level

Will processes scale up?

Reaction kinetics

Overpotential energy losses

Ion exchange membrane life

Catalyst lifetimes

Way forward

Increase public support for R&D for hydrogen and carbon chemistry.

Overturn unscientific regulations preventing cheap fission power.

Arrange multi-billion-dollar funding, longer than election cycles.

Attract and engage expert chemical and petroleum engineering firms.

Seafuel innovators, investors? Who else?

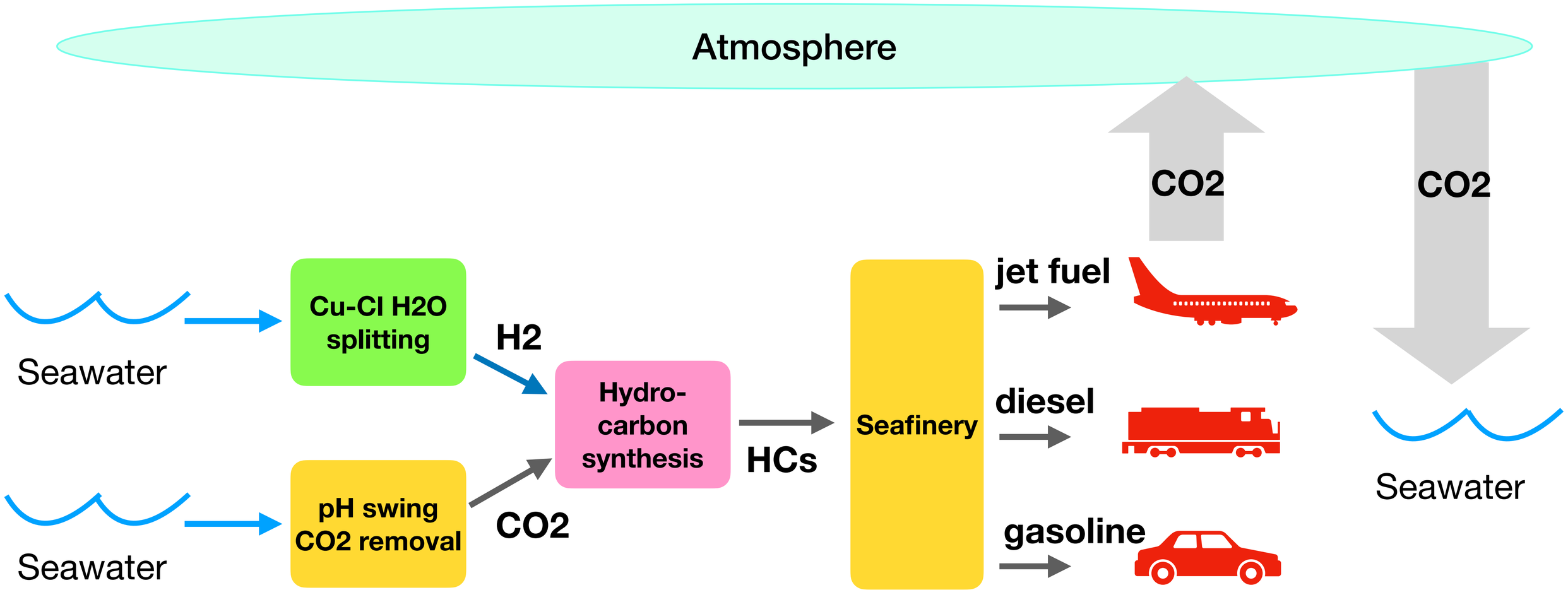
Chevron invested in Zap fusion energy.

Occidenal Petroleum CEO “I’d love to” expand into nuclear.

Shell investing in H2 via solid oxide electrolysis cells

Chemical plant to use X-energy high temp nuclear power

Net zero Seafuel for combustion engines?



Sea re-absorbs CO2 removed a year before.

Seafuel™

Net-zero gasoline for your car.
Climate-neutral diesel for industry.
Guilt-free jet flights.
Uses existing combustion engines.
Zeros transportation CO2.

Seafuel™

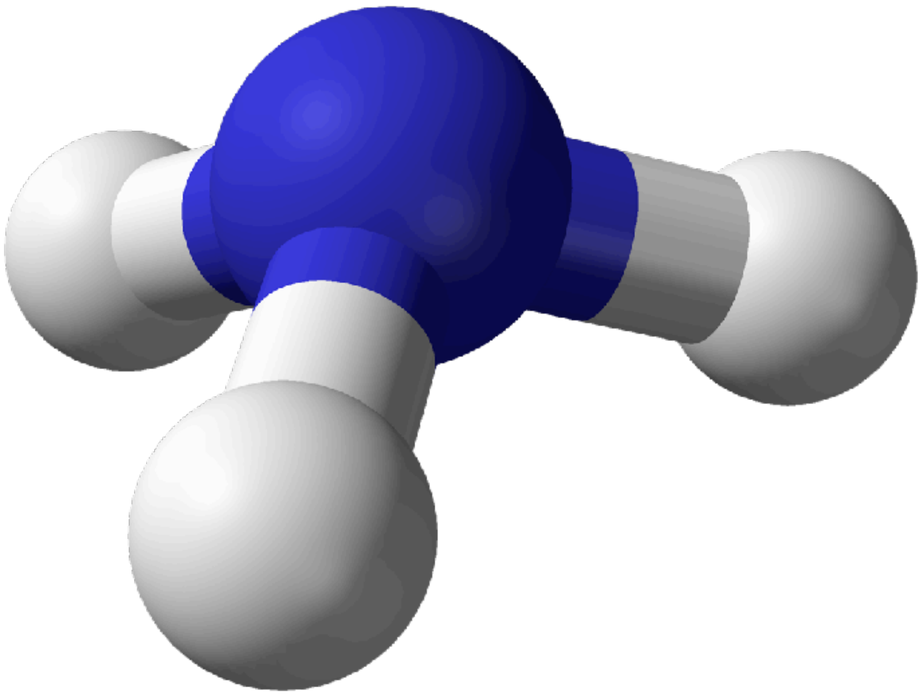
Who will commercialize Seafuel?

I’m ready to help.

Robert.Hargraves@gmail.com

Discards

Ammonia, NH3



- High octane, low flame temperature, high-compression ICE **fuel** with little NOx emissions.
- Nitrogen is 78% of the atmosphere.
- Ammonia can be stored at **15 bar** in pressurized tanks, like propane tanks.
- 11.5 MJ/liter **energy density, 1/3** that of diesel.

https://www.energy.gov/sites/prod/files/2015/01/f19/fcto_nh3_h2_storage_white_paper_2006.pdf

Ammonia fertilizer feeds half the world.

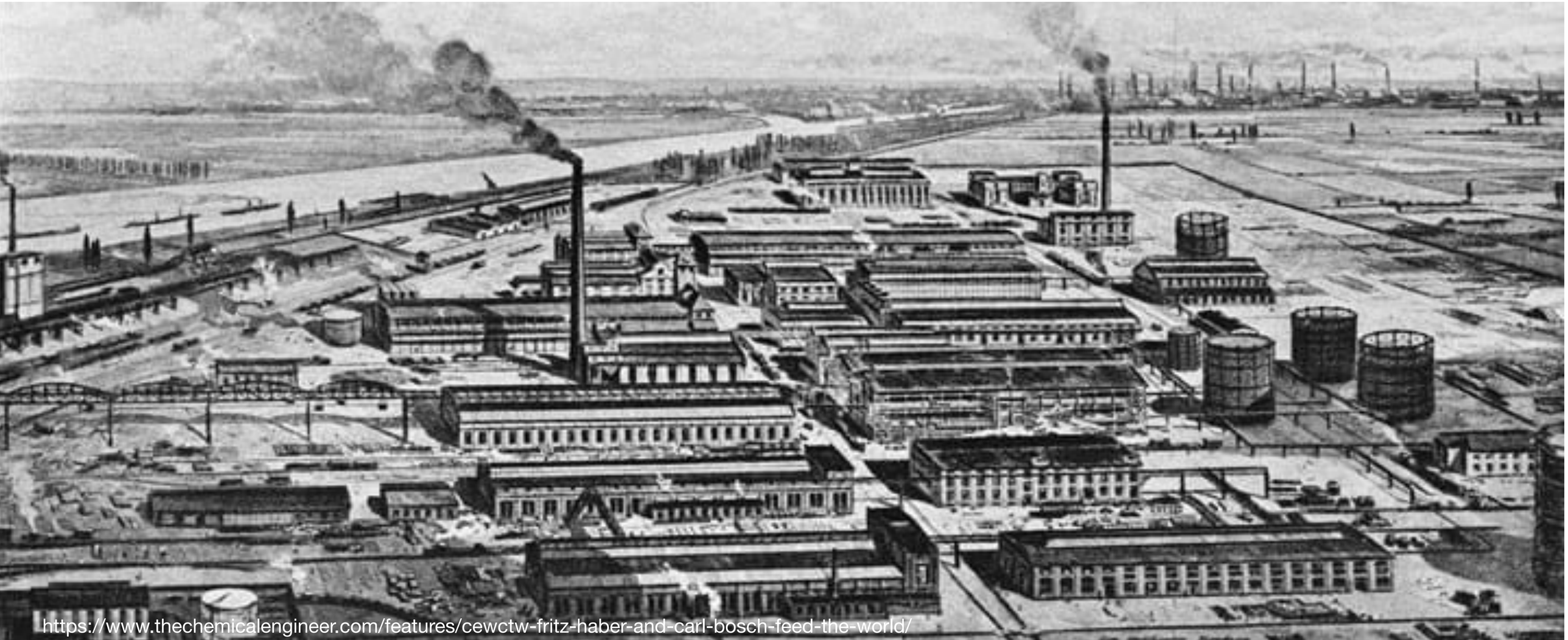
- The knife slices the soil and injects the fertilizer 6 to 8 inches into the soil.
- The ammonia (NH3) ions react with moisture in the soil and convert to ammonium (NH4).
- Ammonium ions are bonded to negatively charged soil particles like clay and organic matter.
- These ammonium ions can be taken in by plants and used directly in proteins.
- In time they convert to nitrate (NO3) fertilizer.

https://iowaagliteracy.wordpress.com/2019/03/20/why-do-they-do-that-anhydrous/

Century-old Haber-Bosch process transforms methane to ammonia.

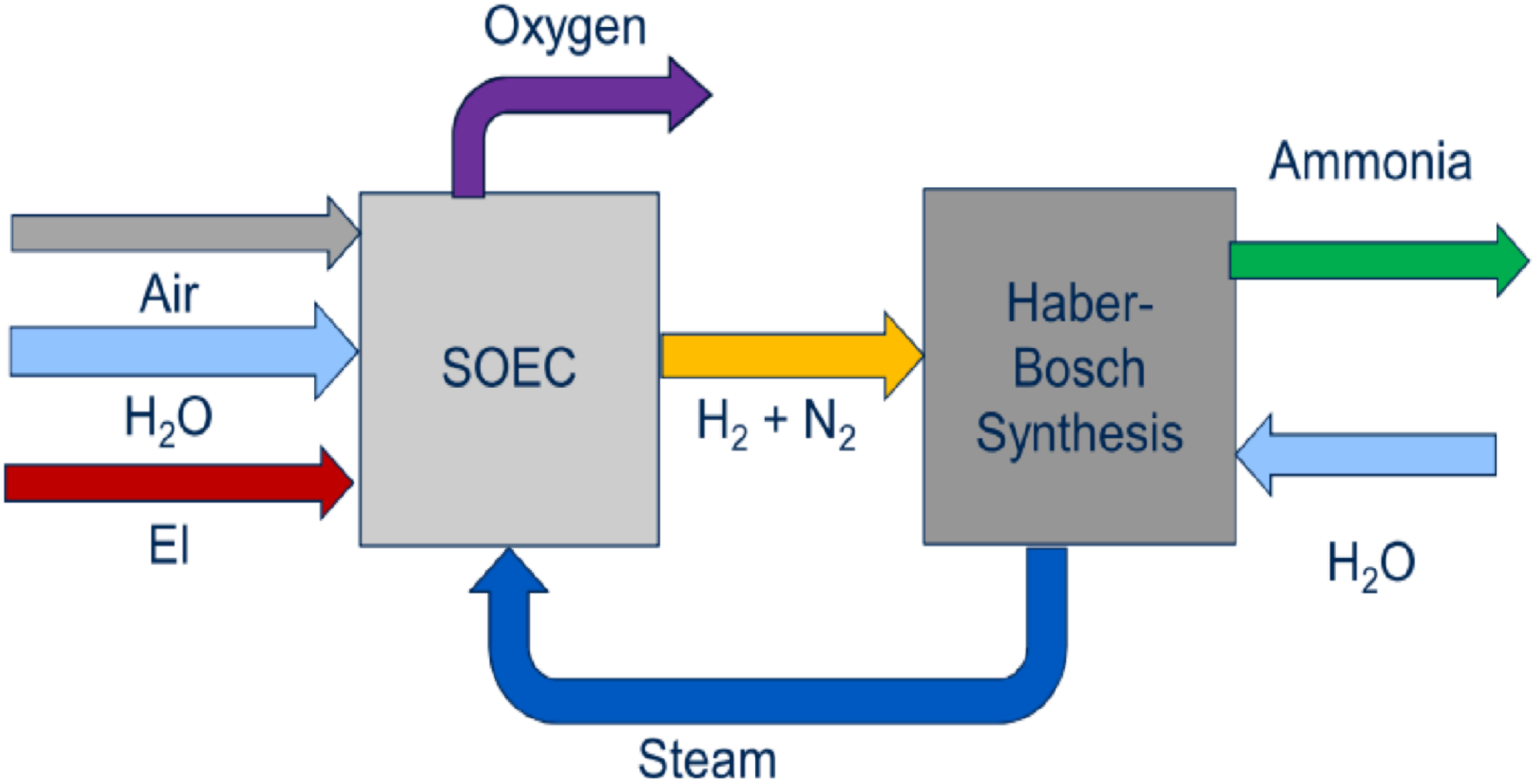
$$CH_4 + O_2 \rightarrow CO_2 + 2H_2$$

$$N_2 + 3H_2 \rightarrow 2NH_3$$



https://www.thechemicalengineer.com/features/cewctw-fritz-haber-and-carl-bosch-feed-the-world/

Haldor Topsoe Solid Oxide Electrolysis Cell (SOEC) for ammonia svnthesis



https://www.ammoniaenergy.org/wp-content/uploads/2019/08/20191112.0800-NH3-Topsøe.pdf

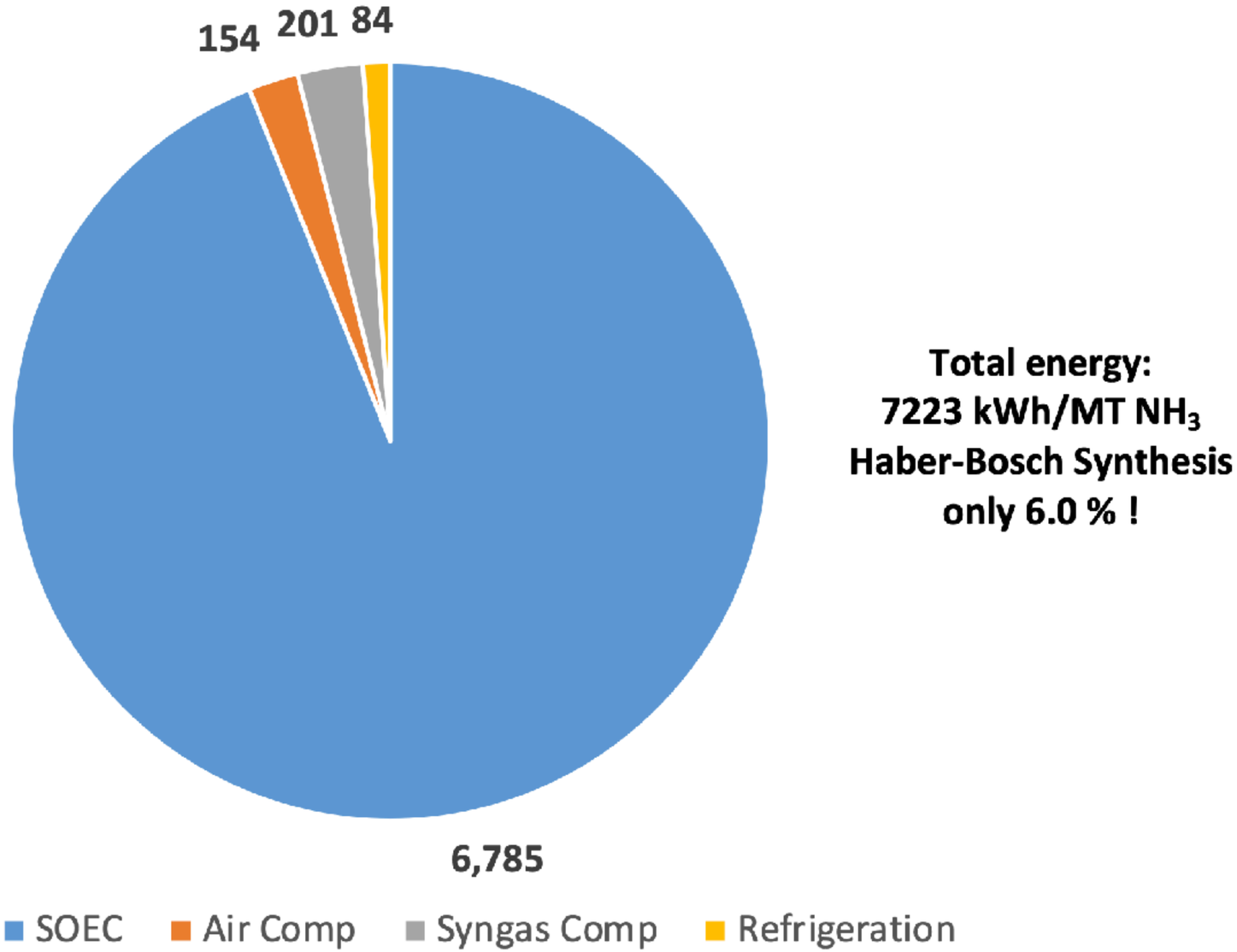
Haldor Topsoe ammonia synthesis process: 7.2 kWh/kg

At $0.03/kWh

electrolytic ammonia costs **22 cents/kg**

+ operation costs
+ capital deprec

US market price (2024) ~ **60 cents/kg**



https://www.ammoniaenergy.org/wp-content/uploads/2019/08/20191112.0800-NH3-Topsøe.pdf

Seafuel™

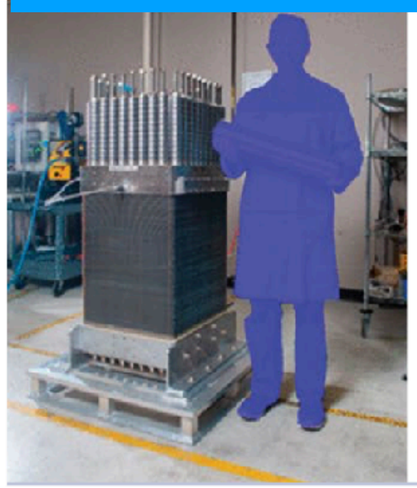
New Nuclear is ***HOT!*** robert.hargraves@gmail.com https://seafuel.energy

Introductory publications

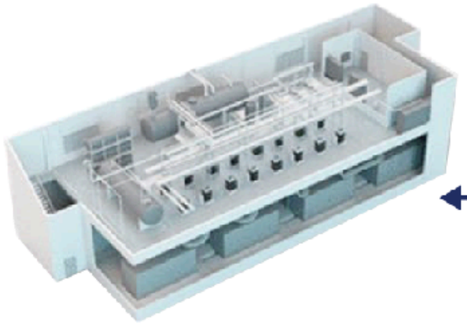
NETL 2000 Overview of coal to liquids: a historical perspective https://www.netl.doe.gov/sites/default/files/2021-03/OVERVIEW OF COAL TO LIQUDS - A HISTORICAL PERSPECTIVE.pdf
Woods Hole Oceanographic Institute 2001 Ocean Biogeochemistry and the Global Carbon Cycle: An Introduction to the U.S. Joint Global Ocean Flux Study https://usjgofs.whoi.edu/62987_ocean.pdf
Yan et al 2022 An Electrochemical Hydrogen-Looping System for Low-Cost CO2 Capture from Seawater https://pubs.acs.org/doi/10.1021/acs.chemrev.1c00412?ref=pdf https://pubs.acs.org/doi/10.1021/acsenergylett.2c00396
Razi et al 2023 Exergoeconomic performance evaluation of three, four, and five-step thermochemical copper-chlorine cycles for hydrogen production https://www.sciencedirect.com/science/article/abs/pii/S095965262301377X?via=ihub
Hargraves 2004 New Nuclear is HOT; https://seafuel.energy

SOEC industry: Bloom,

NEL



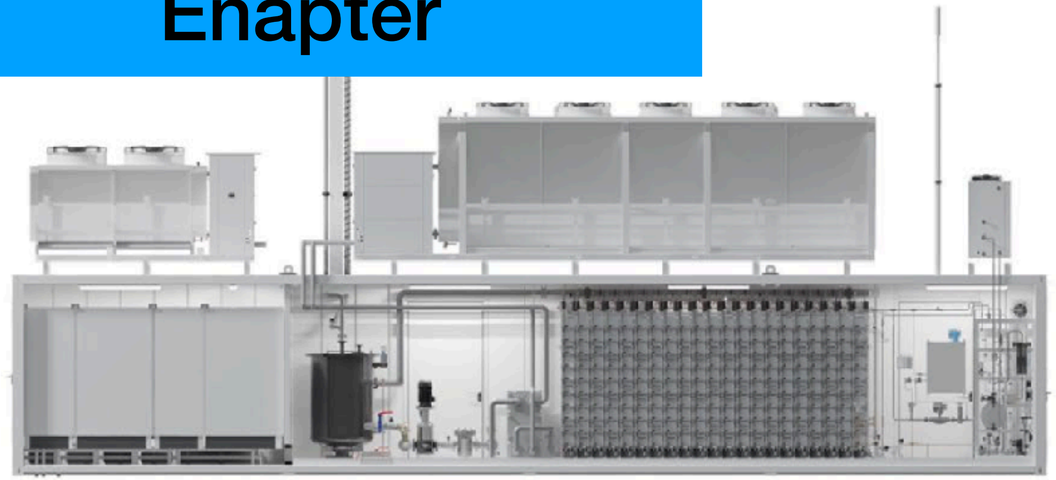
M series
1.25-2.5 MW solution →



Larger Installations
← 5-25 MW solution

Cummins

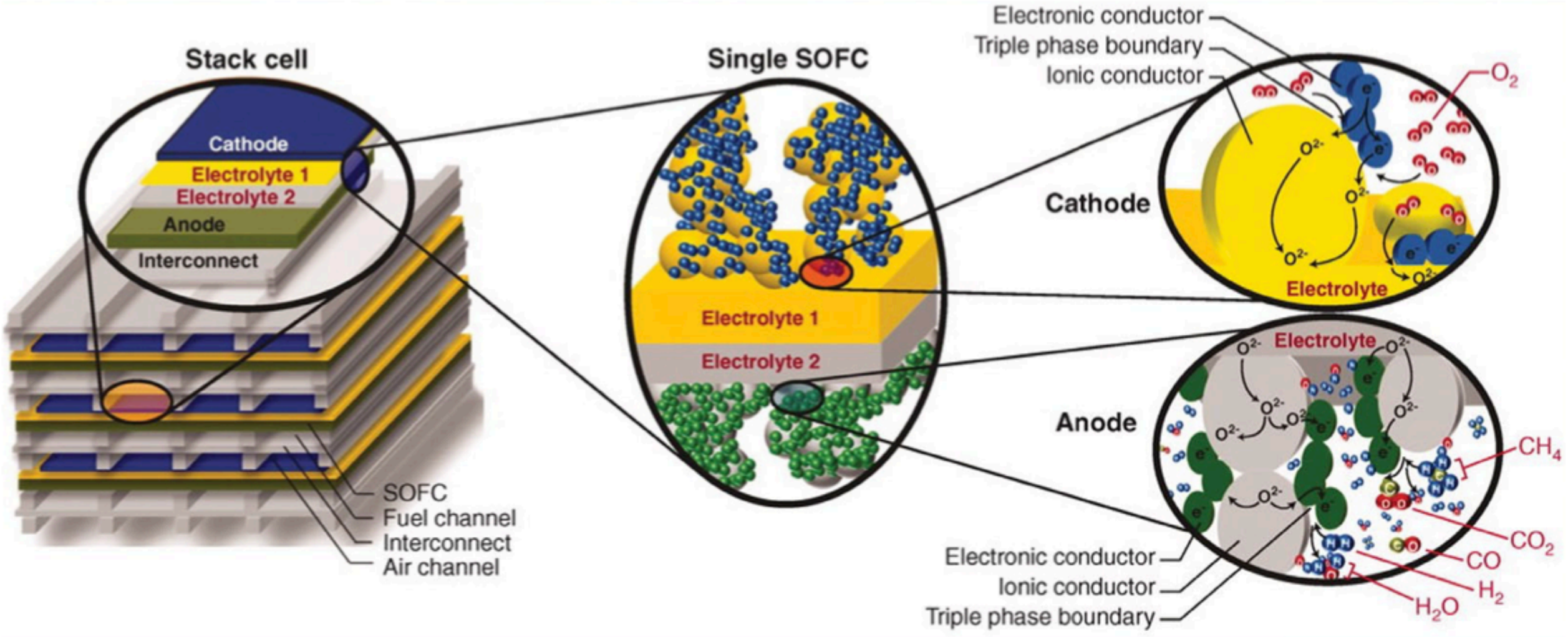
Enapter



Sunfire

https://cdn.catf.us/wp-content/uploads/2023/11/15092028/solid-oxide-electrolysis-report.pdf

100 kW module of 10 stacks of 5 layers of 10cmx10cm cells



https://cdn.catf.us/wp-content/uploads/2023/11/15092028/solid-oxide-electrolysis-report.pdf

Thinking Big

World electric power: Now **3,000 GW(e)** from **6,800 GW(t)** of combustion heat (coal, nat gas), plus nuclear/wind/solar/hydro. The 6,800 GW(t) could be replaced by 2,300 GW(e) of nuclear, plus 3,000 GW(e) as poor nations develop. Cost: **$5.3 trillion**.

World liquid fuel power: Now **7,000 GW(t)** from combustion could be replaced by Seafuel from **6,000 GW(e)** plus **9,000 GW(t)** from fission. Cost: $6 trillion for electric power plus $3 trillion for heat, = **$9 trillion**.

15 MW(t)$_{Seafuel}$ requires 13 MW(e) + 20 MW(t)$_{fission}$

	Flow rate kg/sec	Electricity kWh(e)/kg	MW(e)	Heat kWh(t)/kg	MW(t)
CO2 in	1.00	0.66 (Yan)	2.4	0	0
H2 in	0.14	21 (Razi)	10.6	39 (Razi)	20
Seafuel out	0.32				-15

Each MW(e) requires 2.2 MW(t)$_{fission}$ @ 46% e/t efficiency

1 MW(t)$_{Seafuel}$ requires 3.2 MW(t)$_{fission}$

Cost estimates for renewable methanol

Estimated cost of H2 from PEM electrolysis (@6.88 c/kWh)	4.23 $/kg_H2	[1]
Fraction of electricity in H2 cost above	3.46 $/kg_H2	
Projected electricity cost from a wind farm	2.35 c/kWh	[2]
Estimate of H2 from PEM electrolysis with windfarm electricity	1.95 $/kg_H2	
Cost of H2 in MeOH (3H2 + CO2 → CH3OH + H2O)	**1.1 $/gal_MeOH**	[3]
Cost of captured CO2	40 $/MT = 0.04 $/kg_CO2	[4]
Cost of CO2 in MeOH (3H2 + CO2 → CH3OH + H2O)	**0.17 $/gal_MeOH**	[3]
Cost of Methanol synthesis (based on production from NG)		
Capital + Fixed O&M + Variable O&M	**0.50 $/gal_MeOH**	[5]
Total estimated cost of renewable MeOH	**1.8 $/gal_MeOH ($4 /gge)**	[6]

Max Lyubovsky, Journal of Energy Security, Oct 2017. www.ensec.org

- Cost of renewable methanol is in the range of the market prices
- Renewable H_2 production constitutes ~60% of the product cost
- Cost of CO_2 capture is a small fraction of the overall cost

1. DOE Hydrogen and Fuel Cells Program Record, forecourt future case https://www.hydrogen.energy.gov/pdfs/14004_h2_production_cost_pem_electrolysis.pdf
2. 2014 Wind Technologies Market Report, p 56 http://www.energy.gov/sites/prod/files/2015/08/f25/2014-Wind-Technologies-Market-Report-8.7.pdf
3. Assuming stoichiometric conversion
4. DOE Office of Fossil Energy projections to 2020-2025, http://www.energy.gov/fe/science-innovation/carbon-capture-and-storage-research/carbon-capture-rd
5. Baseline Analysis of Crude Methanol Production from Coal and Natural Gas, October 15, 2014, p.1 http://www.netl.doe.gov/energy-analyses/temp/BaselineAnalysisofCrudeMethanolProductionfromCoalandNaturalGas_101514.pdf
6. 116,000 BTU/gal LHV for gasoline vs. 57,250 BTU/gal LHV for methanol.

https://media.licdn.com/dms/document/media/C562DAQEYfqnXaBEj3g/profile-treasury-document-pdf-analyzed/0/158405404
e=1704931200&v=beta&t=CnjsQUpL8ZWtT9G0549SD2p3n9drOIKT7ghh-udxKdw
https://www.methanol.org/wp-content/uploads/2019/08/Methanol-Renewable-Hydrogen-Carrier-Fuel-.pdf

Max Lyubovsky methanol cost estimates

Cost of H_2 production by PEM electrolysis at 1500 kg/day scale	$4.23 /kg_$H_2$
Electricity component in electrolysis H_2 cost @ $0.0688 /kWh	$3.46 /kg_$H_2$
Levelized PPA for onshore wind power	$0.0235 /kWh
Cost of H_2 production by PEM electrolysis @ $0.0235 /kWh	$1.95 /kg_$H_2$
H_2 in MeOH (kg H_2 per kg MeOH)	0.19 kg/kg
Cost of H_2 in MeOH	**$1.10 /gal MeOH**
Assumed cost of CO_2 capture	$40 /tonne_$CO_2$
CO_2 in MeOH (kg CO_2 per kg MeOH)	1.38 kg/kg
Cost of CO_2 in MeOH	**$0.17 /gal MeOH**
Capital and O&M cost in MeOH synthesis	**$0.5 /gal MeOH**
Cost of MeOH produced from H_2 and CO_2	$1.77 /gal

http://www.ensec.org/index.php?option=com_content&view=article&id=604:shifting-the-paradigm-synthetic-liquid-fuels-offer-vehicle-for-monetizing-wind-and-solar-energy&catid=131:esupdates&Itemid=414