9 Hydrogen

SMR → CO_2 + H_2 @ $2/kg

Electrolyzed H_2 now $10/kg

Steam electrolysis efficient

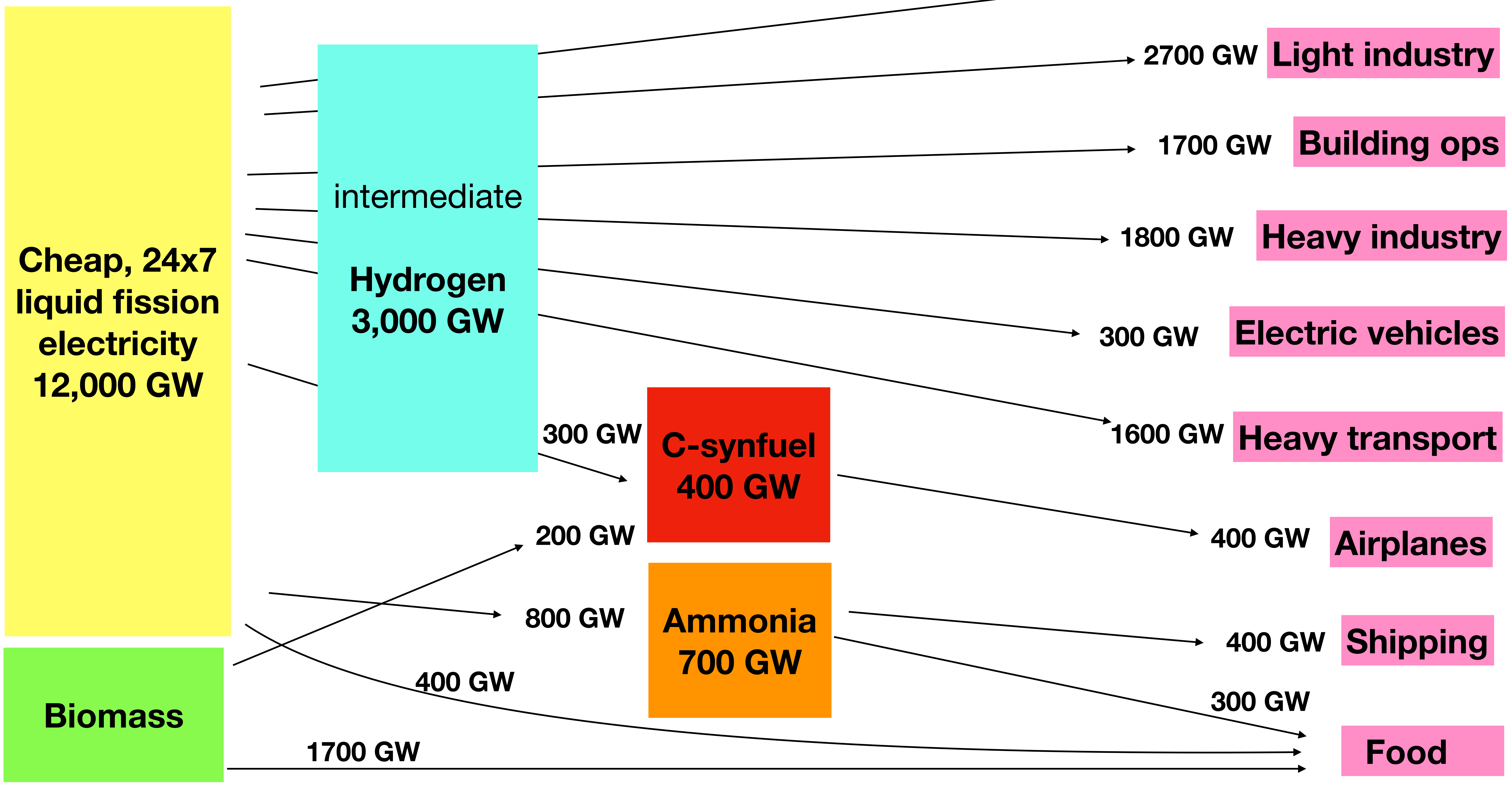
Need cheap, firm electric power

3,000 GW(t) H_2 demand

$2/kg (2030) → $1/kg

Fission is in Fashion

Transportable hydrogen energy



Steam methane reforming produces 95% of world H2.

$$CH_4 + H_2O \rightleftharpoons CO + 3\,H_2$$

$$\underline{CO + H_2O \rightleftharpoons CO_2 + H_2}$$

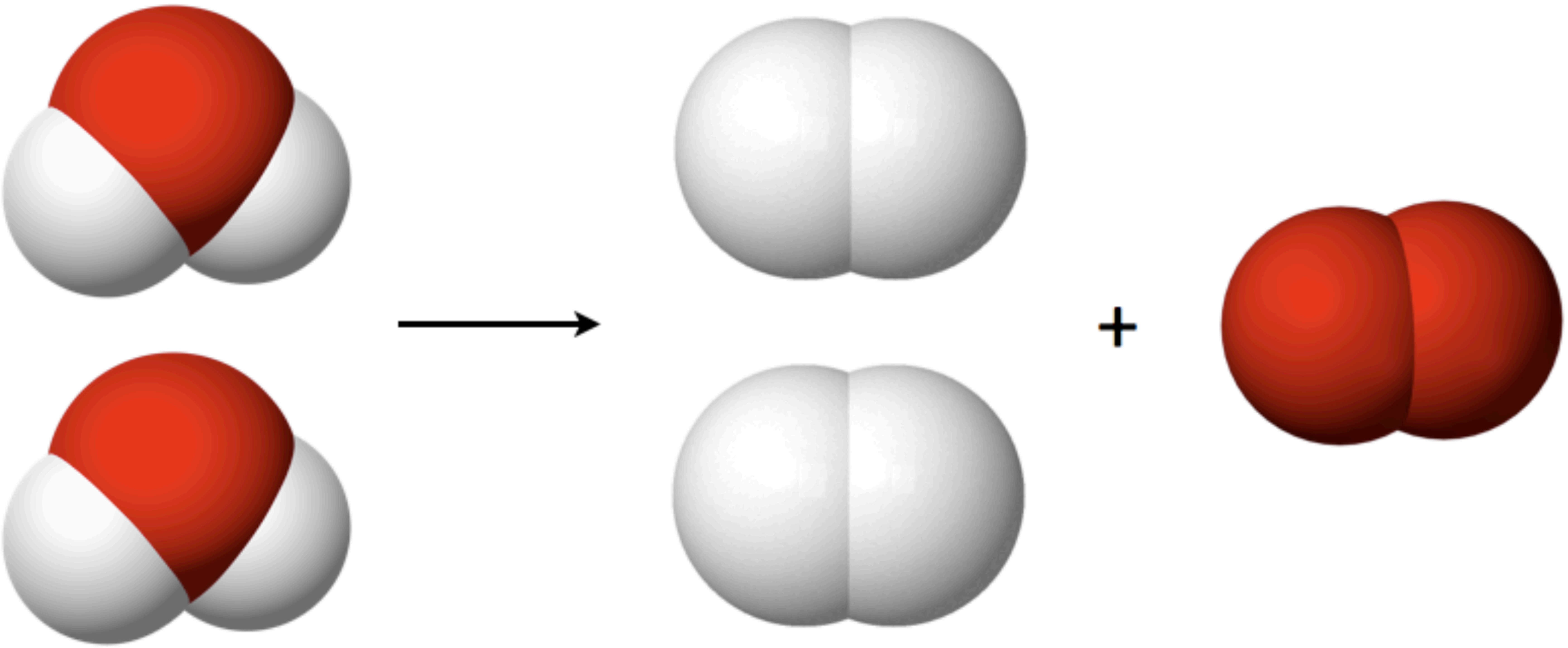
=====================

$$CH_4 + 2\,H_2O \rightleftharpoons CO_2 + 4\,H_2$$

1. SMR generates 9.3 kg-CO_2 per 1 kg-H_2.
2. Nearly 1 Gt-CO_2 released annually.
3. H_2 used in oil refining and ammonia (NH_3) production.
4. Stored chemical energy of H_2 = 143 MJ/kg or 40 kWh/kg.
5. $1.6 to $2 per kg SMR-produced H_2, varies with CH_4 cost.

https://www.sciencedirect.com/topics/engineering/hydrogen-production-cost

Electrolyzers convert H2O to H2 (and O2)



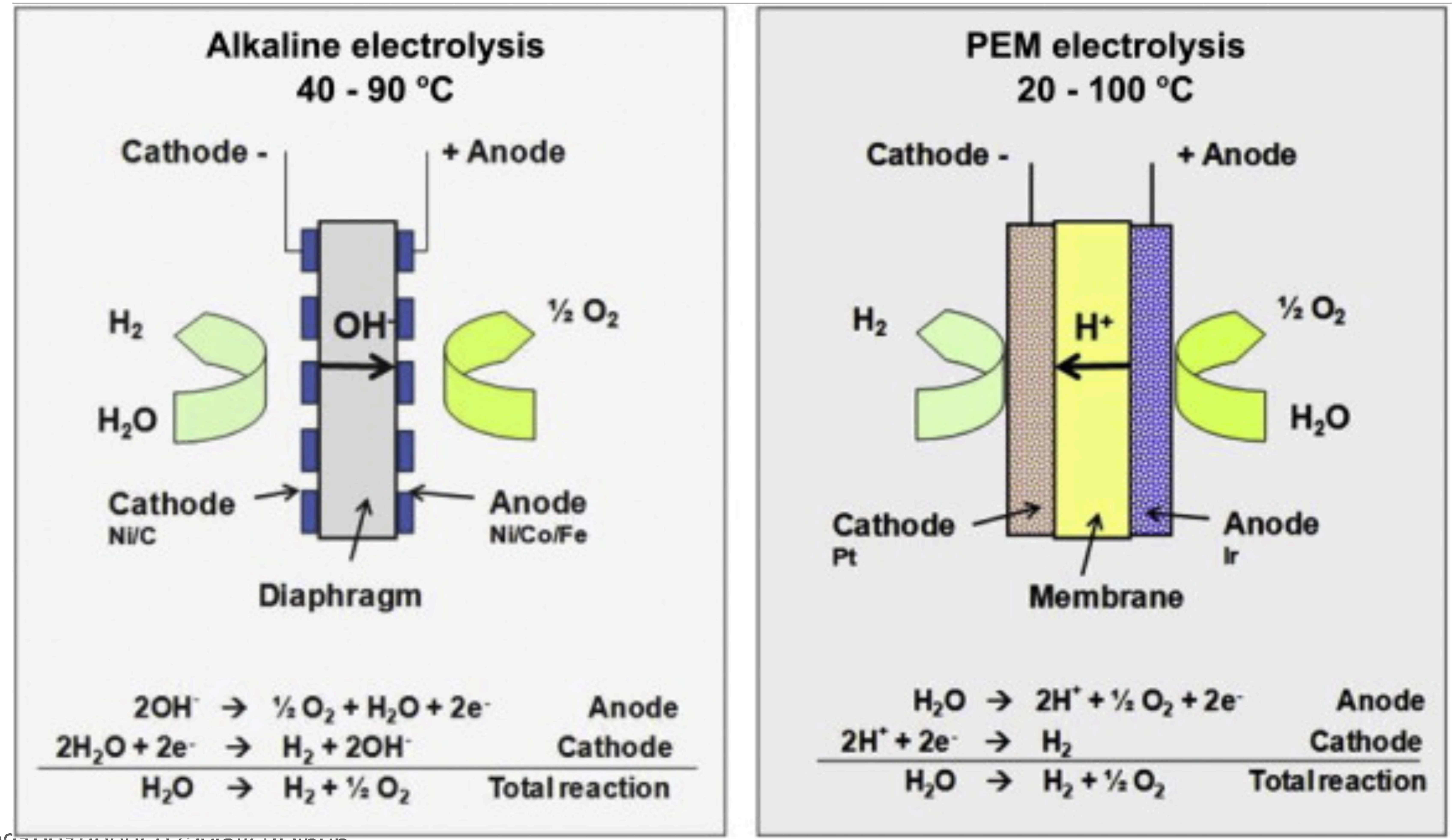
$$2H_2O \longrightarrow 2H_2 + O_2$$

Today's costs ~ $10/kg do not compete with SMR @ $2/kg.

https://www.hydrogen.energy.gov/pdfs/review19/p148B_boardman_2019_p.pdf

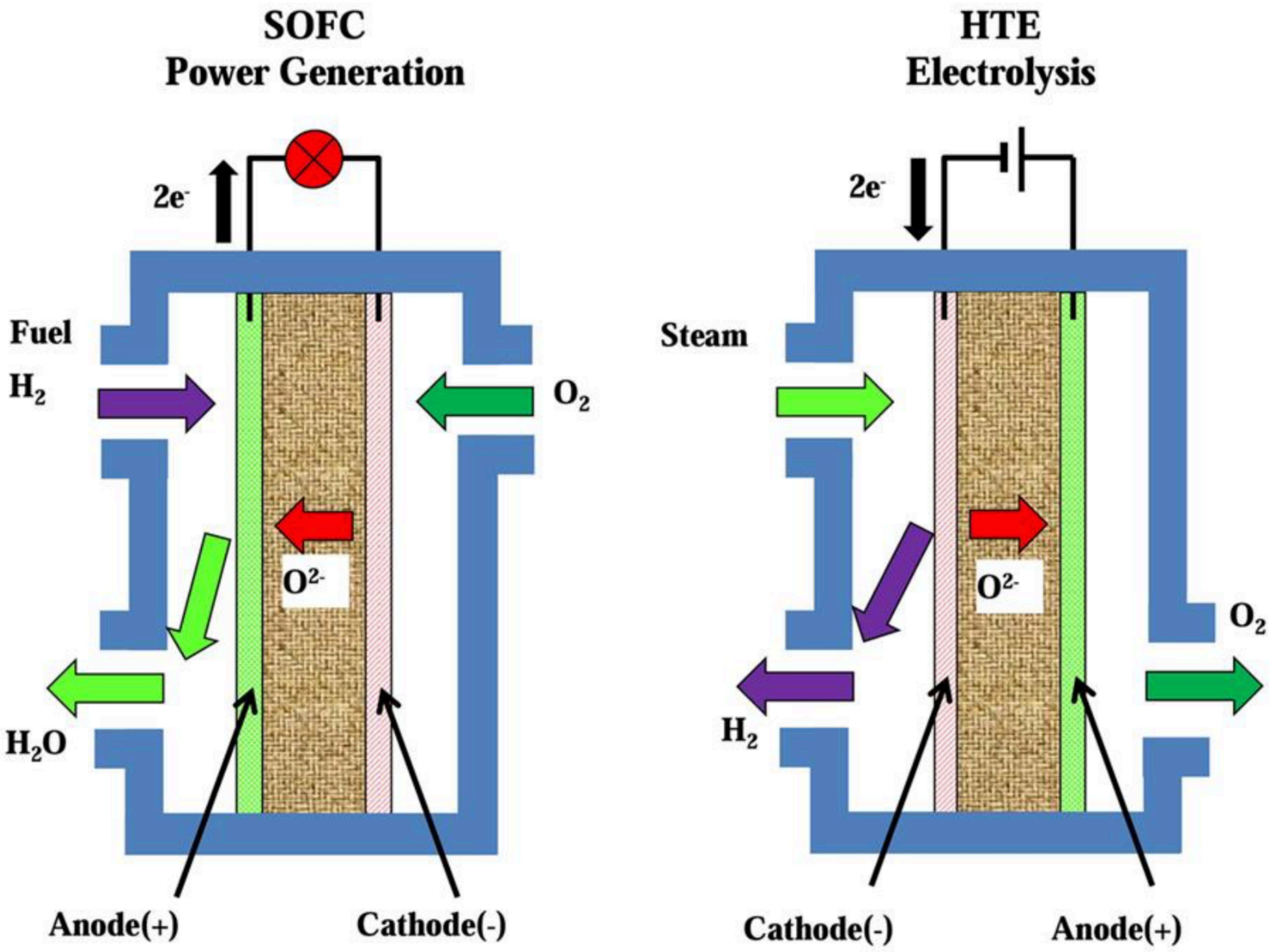
Hydrogen hype and hydrogen R&D are intensive.

A comprehensive review on PEM water electrolysis



https://www.sciencedirect.com/science/article/pii/S0360319913002607?via%3Dihub

High temperature steam electrolysis: solid oxide fuel cell in reverse.



https://learning.oreilly.com/library/view/hydrogen-economy/9780128111338/xhtml/chp002.xhtml#st0085

Sunfire SOEC electrolyzer, for H2 for steel manufacturing.

Salzgitter, Germany

steam @ 850°C

720 kW(e) input

200 Nm3/hr

= 600 kW(t) output

= 83% ‘efficiency’

$7/kg-H2

https://www.green-industrial-hydrogen.com/fileadmin/user_upload/220413_GrInHy2.0_Flyer_v6.pdf

Shell starts up Europe’s largest hydrogen electrolyser.

Cologne, Germany

$24 million

10 MW(e) input

1,300 tonnes-H2/year

= 4.9 MW(t) output

= 49% ‘efficiency’

https://www.thechemicalengineer.com/news/shell-starts-up-europe-s-largest-pem-green-hydrogen-electrolyser/

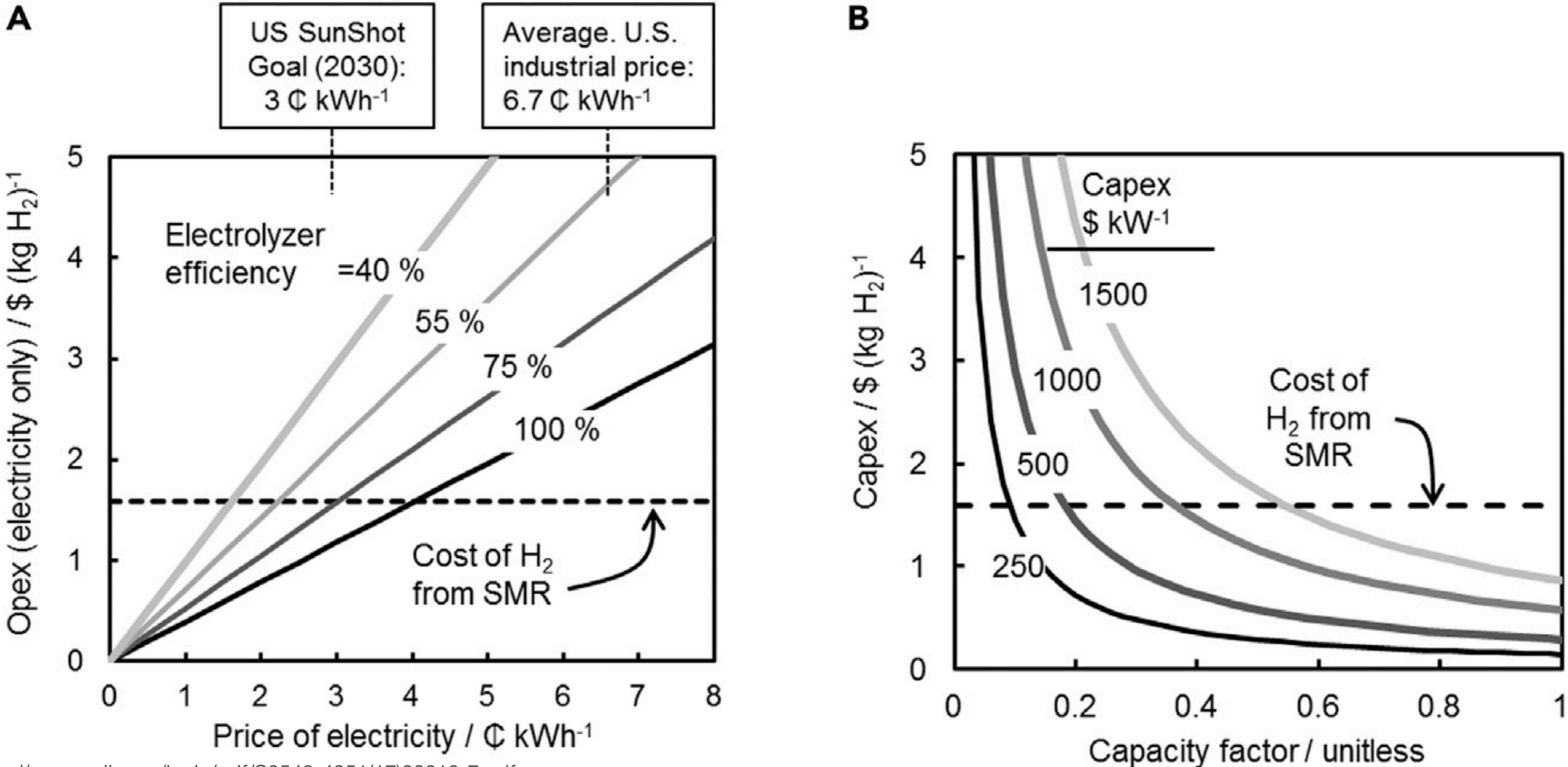
NEL manufactured > 3,500 electrolyzers

Cost of hydrogen depends on several factors.

Capital cost of electrolyzer	$250 to $1000 per kW
Electrolyzer capacity factor	30 to 90 %
Cost of electricity	3 to 10 cents per kWh
Energy conversion efficiency	60 to 95%
Water splitting technology	Alkaline, PEM, high temp

H2 cost depends on electricity price and electrolyzer utilization, illustrates Esposito.

SMR = steam methane reforming



https://www.cell.com/joule/pdf/S2542-4351(17)30010-7.pdf

DOE says $2.00/kg-H2 target for levelized cost of hydrogen from nuclear power can be met and beaten.

Lucid Catalyst: High temperature electrolysis can convert electric to H2 energy at 95% efficiency.

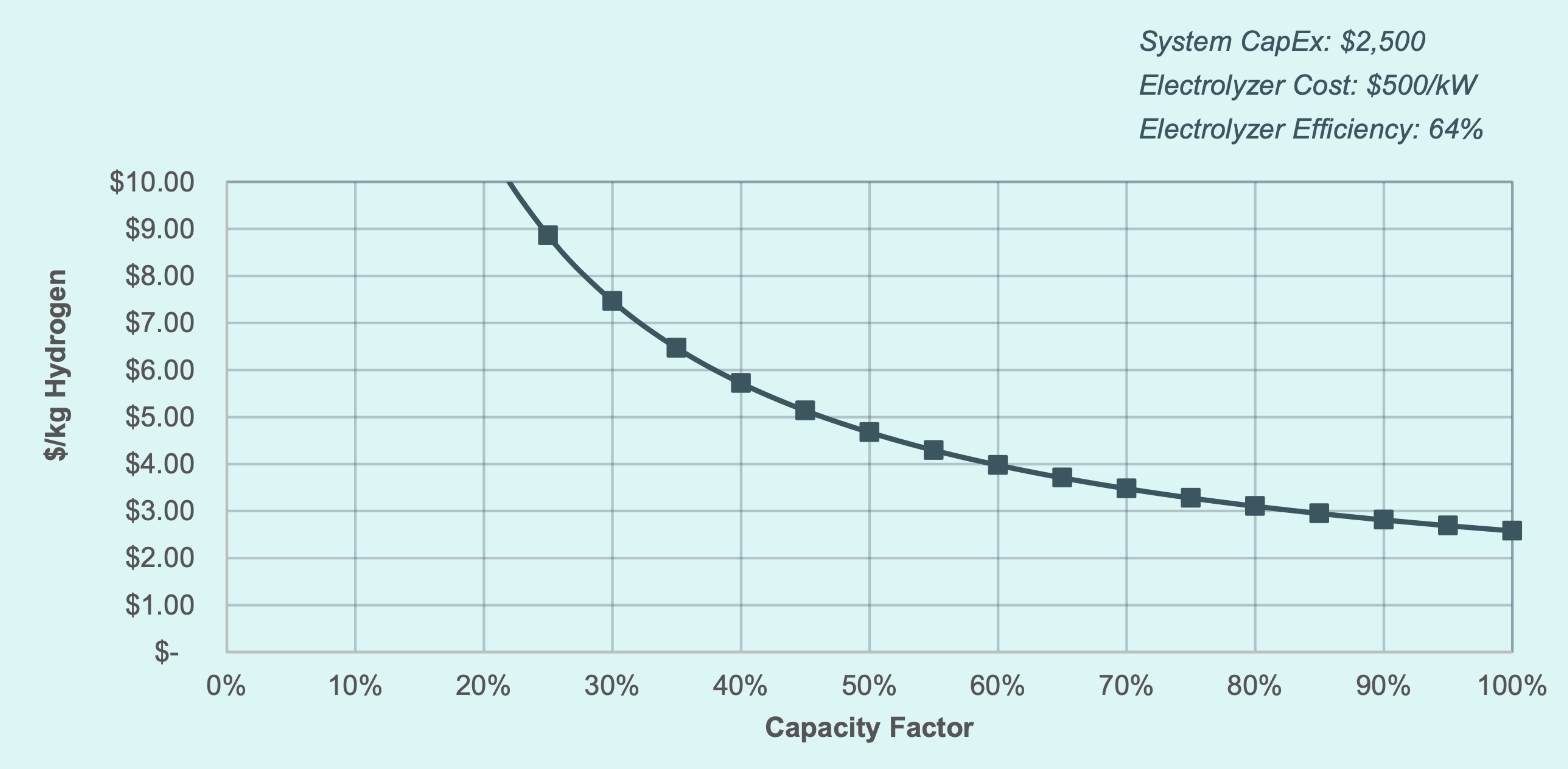
	2019	2030	2050
Low Temperature Electrolyzer Efficiency (LHV)	64% (a)	69% (a)	74% (a)
High Temperature Electrolyzer Efficiency (LHV)	95% (b)	95% (b)	95% (b)
Electrolyzer CapEx ($/kW)	$750 (c)	$400 (d)	$250 (c)

“efficiency” here means kW(thermal) out divided by kW(electric) in

LHV = lower heating value, not counting heat of vaporization of resulting water

https://85583087-f90f-41ea-bc21-bf855ee12b35.filesusr.com/ugd/2fed7a_0d2e1cc06bff412cb3031fd4bdf93cb0.pdf

Electrolyzer capacity factor affects H2 $/kg.



https://85583087-f90f-41ea-bc21-bf855ee12b35.filesusr.com/ugd/2fed7a_0d2e1cc06bff412cb3031fd4bdf93cb0.pdf

Cost of electrolytic hydrogen can be competitive with steam methane reforming.

Lucid Catalyst writes: "We find that a **new generation of advanced modular reactors**, hereafter referred to as advanced heat sources, with new manufacturing-based delivery models, could deliver hydrogen on a large scale for $1.10/kg, with further cost reductions at scale reaching the target price of $0.90/kg by 2030."

https://85583087-f90f-41ea-bc21-bf855ee12b35.filesusr.com/ugd/2fed7a_0d2e1cc06bff412cb3031fd4bdf93cb0.pdf

Thermal energy of 1 kg-H2, @ $1

- **142 MJ** (HHV)
- **120 MJ (**LHV, lower heating value)
- **33 kWh** (t)
- **1 gallon** gasoline or diesel (approx)
- **1 GJ** costs $7
- **1 kWh** (t) costs 3 cents

https://afdc.energy.gov/files/pdfs/hyd_economy_bossel_eliasson.pdf

Energy Transitions Commission estimates mid-century H2 production of 500 to 800 Mt/year (2,000 GW).

H2 for direct use or making ammonia or synfuels.

500 Mt/year @ 33 kWh/kg =
1,900 GW(t) chemical potential energy flow, requiring
2,000 GW(e) if 95% efficient electrolyzers,

If 800 Mt/year H2 needed, costing $800 billion/year...
~ 3,000 GW(e)

https://www.energy-transitions.org/wp-content/uploads/2020/09/Making-Mission-Possible-Full-Report.pdf https://afdc.energy.gov/files/pdfs/hyd_economy_bossel_eliasson.pdf

Bloomberg New Energy Finance makes similar H2 production estimates.

Strong policy estimate is 99 EJ/year, @ 95% electrolyzer efficiency, requires
~ 3300 GW(e)

Scaling-up hydrogen

Requires	Which should drive the delivered cost of clean hydrogen down to	Delivered costs could fall further to	Which would make clean hydrogen
$150 billion	**$15/MMBtu**	**$7.4/MMBtu**	**competitive**
of cumulative subsidies to 2030	in many parts of the world by 2030	by 2050	with current natural gas prices in China, India, Brazil and Germany

BNEF estimates H2 cost of $15/MMBtu = $14/GJ or $2/kg in 2030, dropping to **$1/kg** by 2050

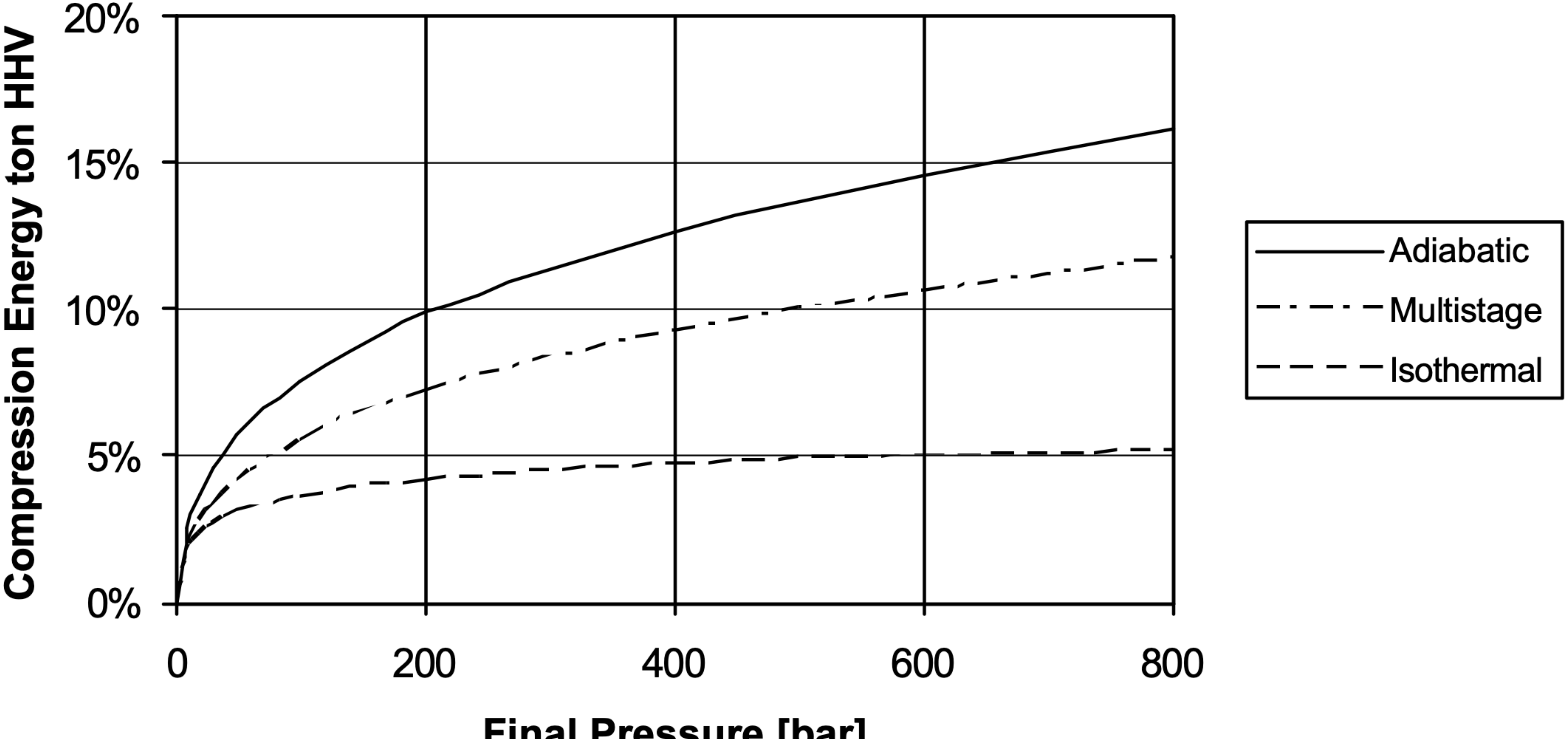
https://data.bloomberglp.com/professional/sites/24/BNEF-Hydrogen-Economy-Outlook-Key-Messages-30-Mar-2020.pdf

Hydrogen storage and distribution is challenging.

- Hydrogen liquefaction is costly.
- Storage at -253°C is lossy.
- Metal containers embrittle.

http://en.wikipedia.org/wiki/Hydrogen_economy

Fuel-cell vehicles tanks want H2 compressed to 350 or 700 bar, using ~8-16% of energy value.



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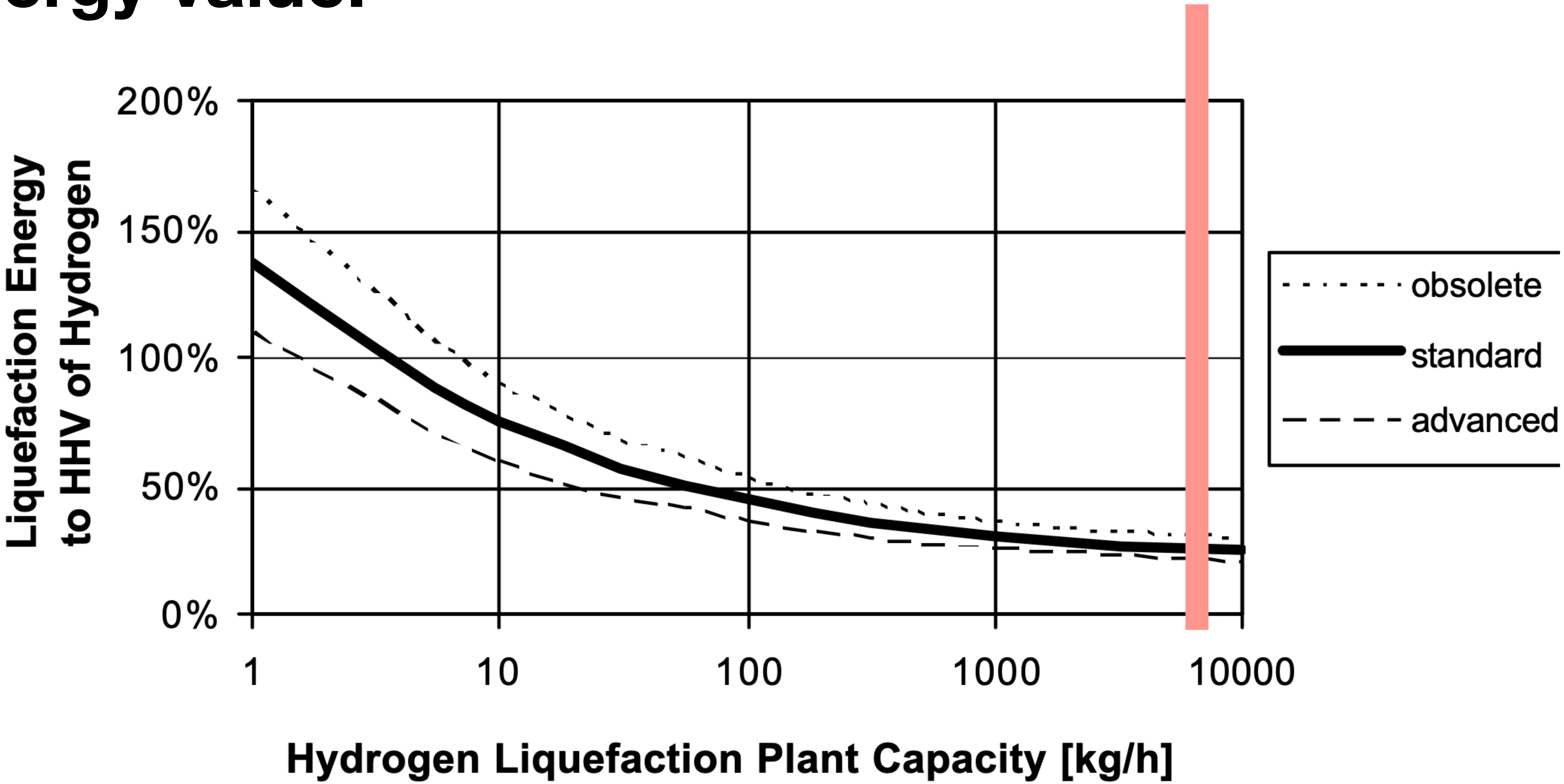
Liquefaction of H2 to -253°C costs 30% of its energy value.



https://afdc.energy.gov/files/pdfs/hyd_economy_bossel_eliasson.pdf

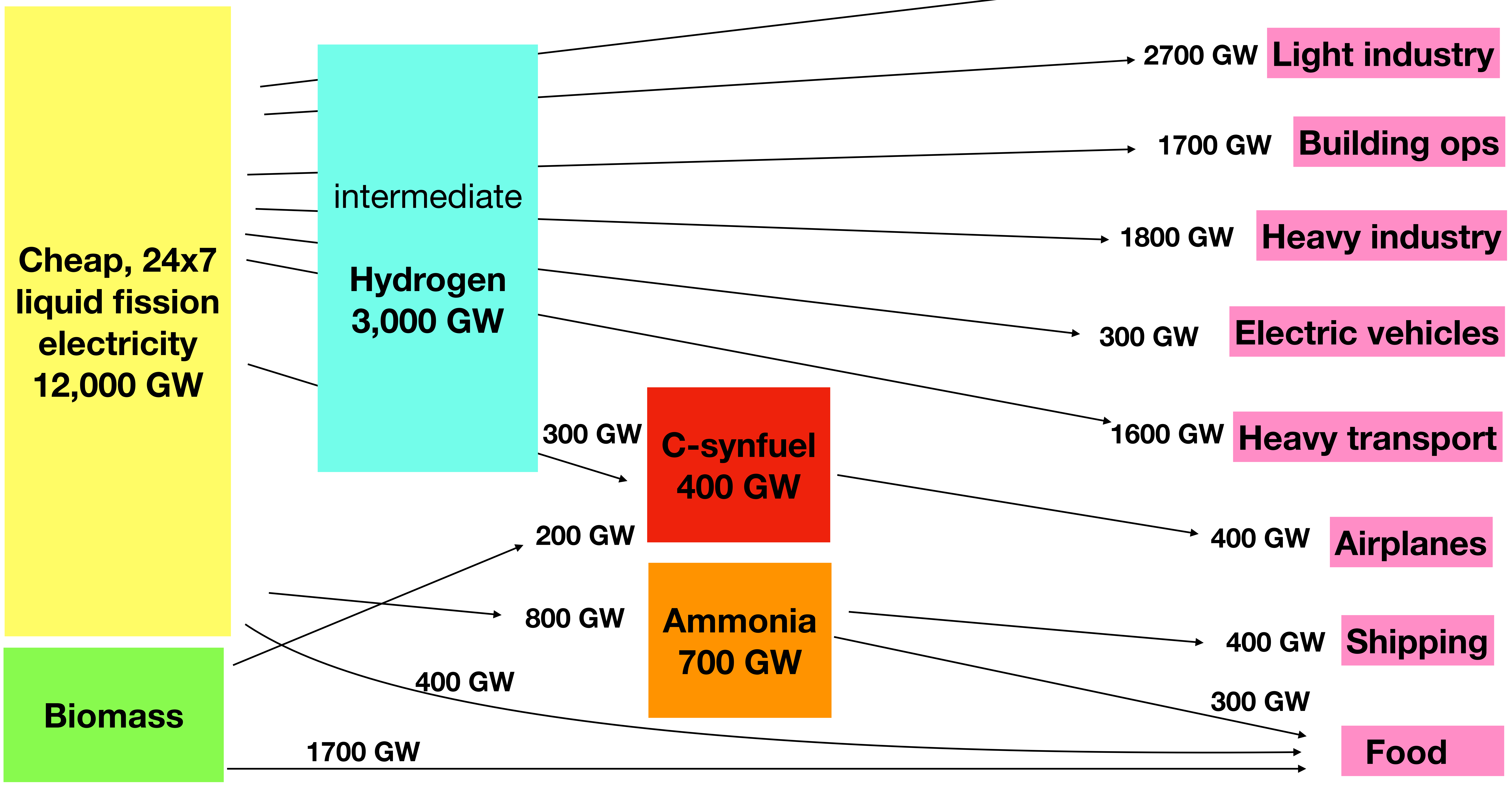
Bloomberg NEF estimates H2 storage costs.

	Gaseous state			
	Salt caverns	Depleted gas fields	Rock caverns	Pressurized containers
Main usage (volume and cycling)	Large volumes, months-weeks	Large volumes, seasonal	Medium volumes, months-weeks	Small volumes, daily
Benchmark LCOS ($/kg)[1]	$0.23	$1.90	$0.71	$0.19
Possible future LCOS[1]	$0.11	$1.07	$0.23	$0.17

https://data.bloomberglp.com/professional/sites/24/BNEF-Hydrogen-Economy-Outlook-Key-Messages-30-Mar-2020.pdf

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

Transportable hydrogen energy



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