Sustainable Fuels and Batteries for Mobile Applications

MIT Mobility Forum

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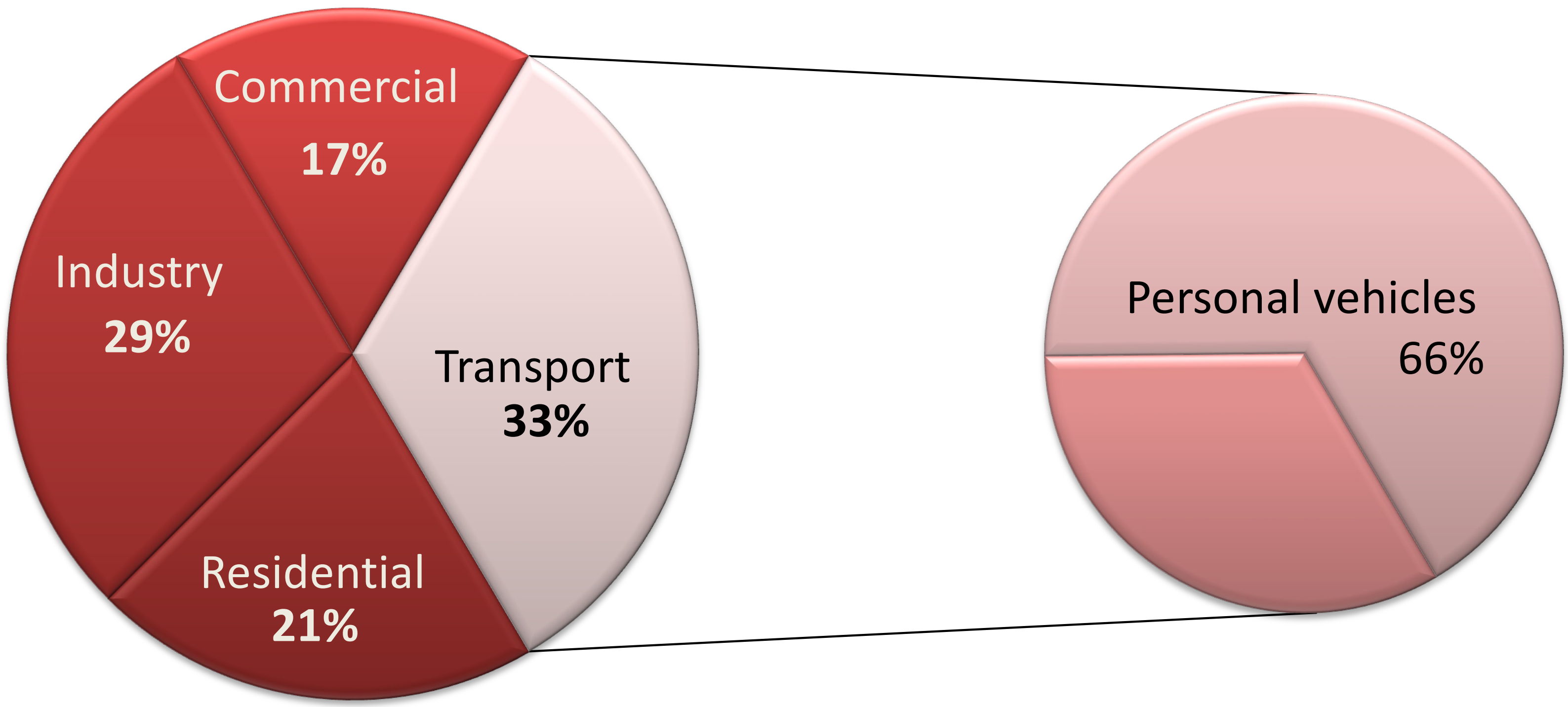
Transportation accounts for 33% of end-user CO_2 emissions



Source: EPA

Hydrogen packs more energy than any other fuel

fuel	specific energy (kWh/kg)	energy density (kWh/L)
liquid hydrogen	33.3	2.37
hydrogen (200 bar)	33.3	0.53
liquid natural gas	13.9	5.6
natural gas (200 bar)	13.9	2.3
petrol	12.8	9.5
diesel	12.6	10.6
coal	8.2	7.6
$LiBH_4$	6.16	4.0
methanol	5.5	4.4
wood	4.2	3.0
electricity (Li-ion battery)	0.55	1.69

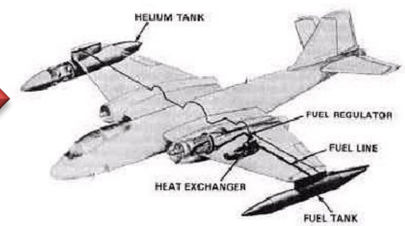
⇨ CO_2 emmissions potentially eliminated, NO_x emmissions drastically reduced

Hydrogen Cars are Older than Gasoline Cars

1807 – Ivaz
Internal combustion
100 m range

1860 – Hippomobile
300-400 produced, 9 km/h

1933 – Norsk Hydro
concept, NH_3 reforming



1956 – B-57 Bomber
Cryo LH_2

1967 – GM Electrovan
LH_2, FC, 200 km range
105 km/h top speed

1970 – Kodesch
300 km range, CGH_2

1977 – Billings Cadillac Seville
Metal Hydride, Internal Combustion

1978 – BMW S7
CGH_2, Internal Combustion

2010 – Hyundai Tucson
6.5 kg H2 in 2 tanks @ 70 Mpa
Range 650 km
Top Speed 160 km/h
PEM-FC, LiPoly Battery
Delivery in the thousands in 2012

Hydrogen is losing the battle as a green alternative to fossil fuels for transportation (for now…)

ChatGPT generated panoramic image of a fleet of hydrogen buses abandoned in a field, rusting and covered in bird dung

How Many Hydrogen Transit Trial Failures Are Enough?

3 weeks ago Michael Barnard 64 Comments

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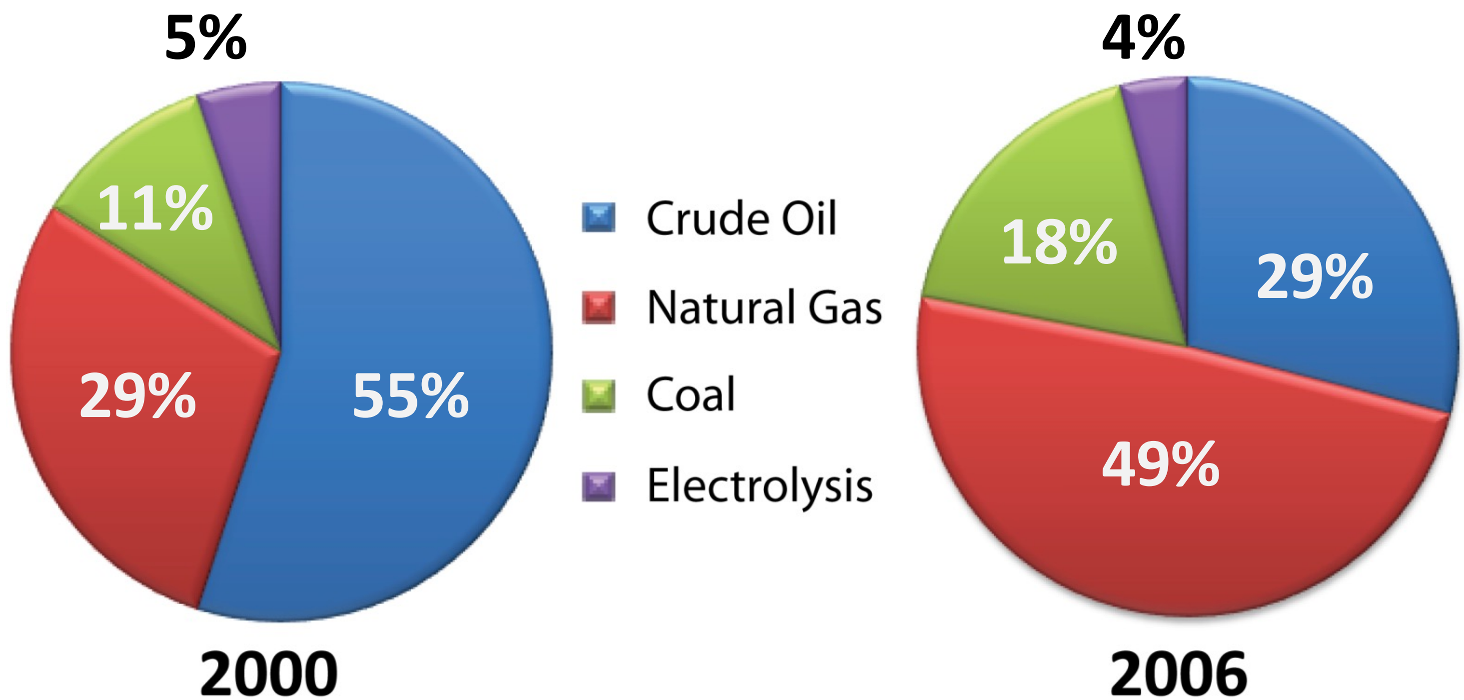
Oct 2024

https://cleantechnica.com/2024/10/24/how-many-hydrogen-transit-trial-failures-are-enough/

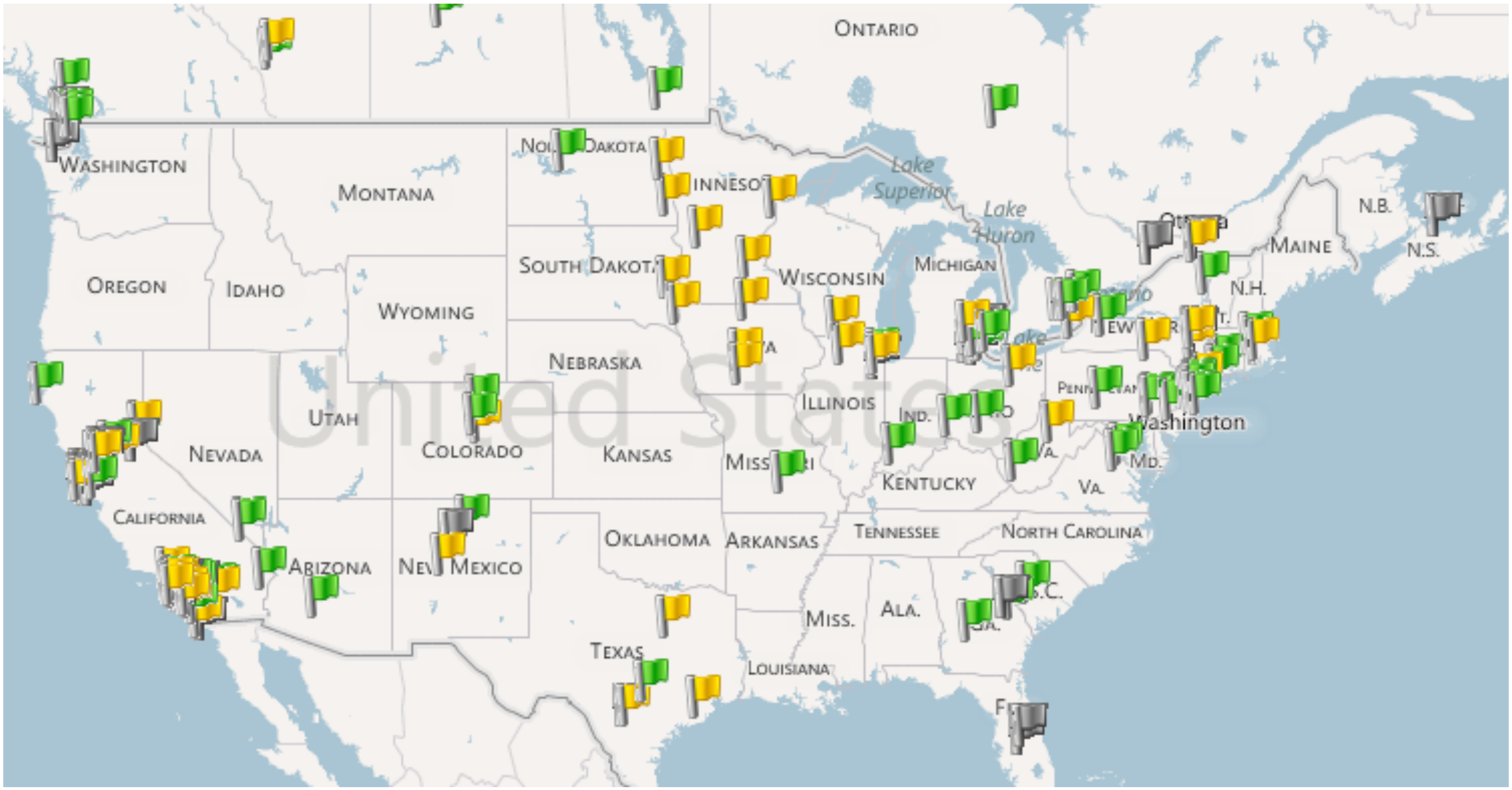
H_2 production relies almost exclusively on fossil fuels



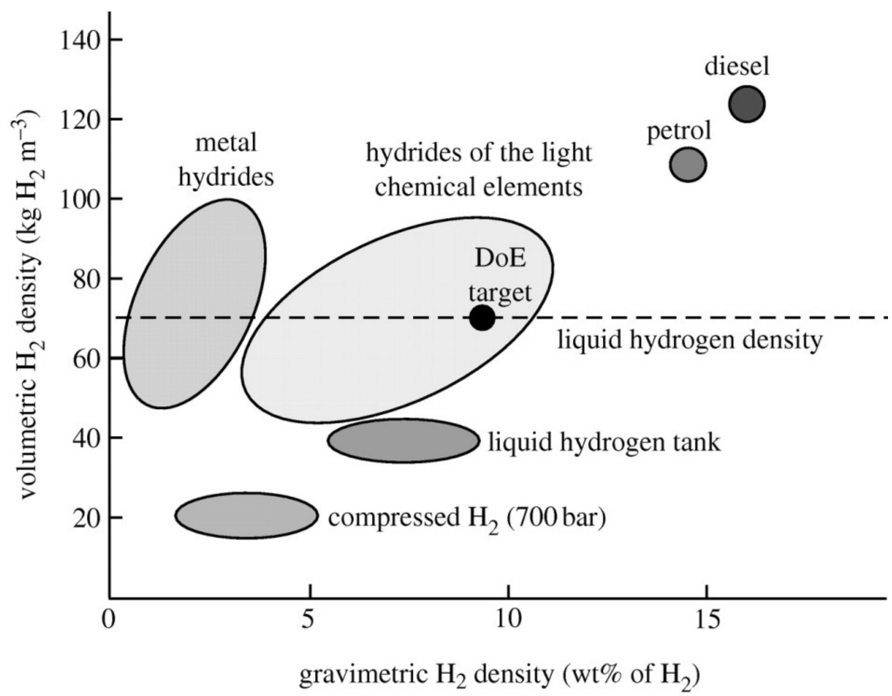
World H_2 production not monitored, but estimated at ~ 50 million tonnes

H_2 distribution in the United States

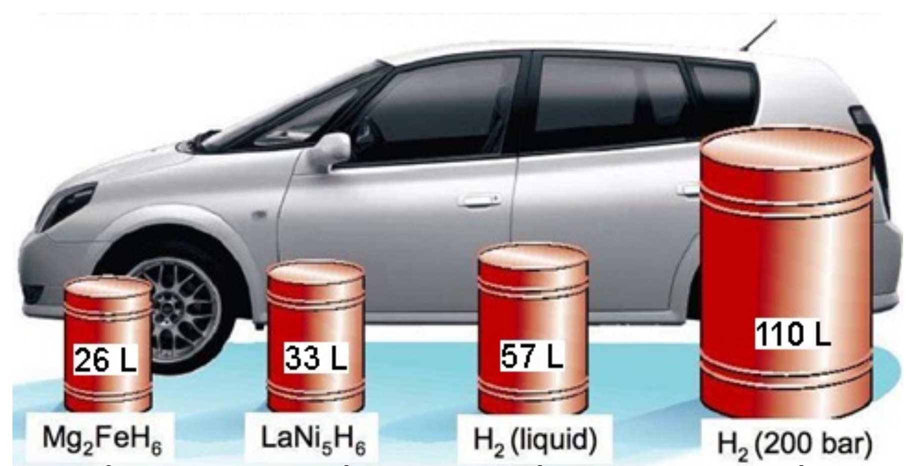
- ~ 40 existing stations, with ~ 50 planned



CGH2 and LH2 do not meet DOE targets

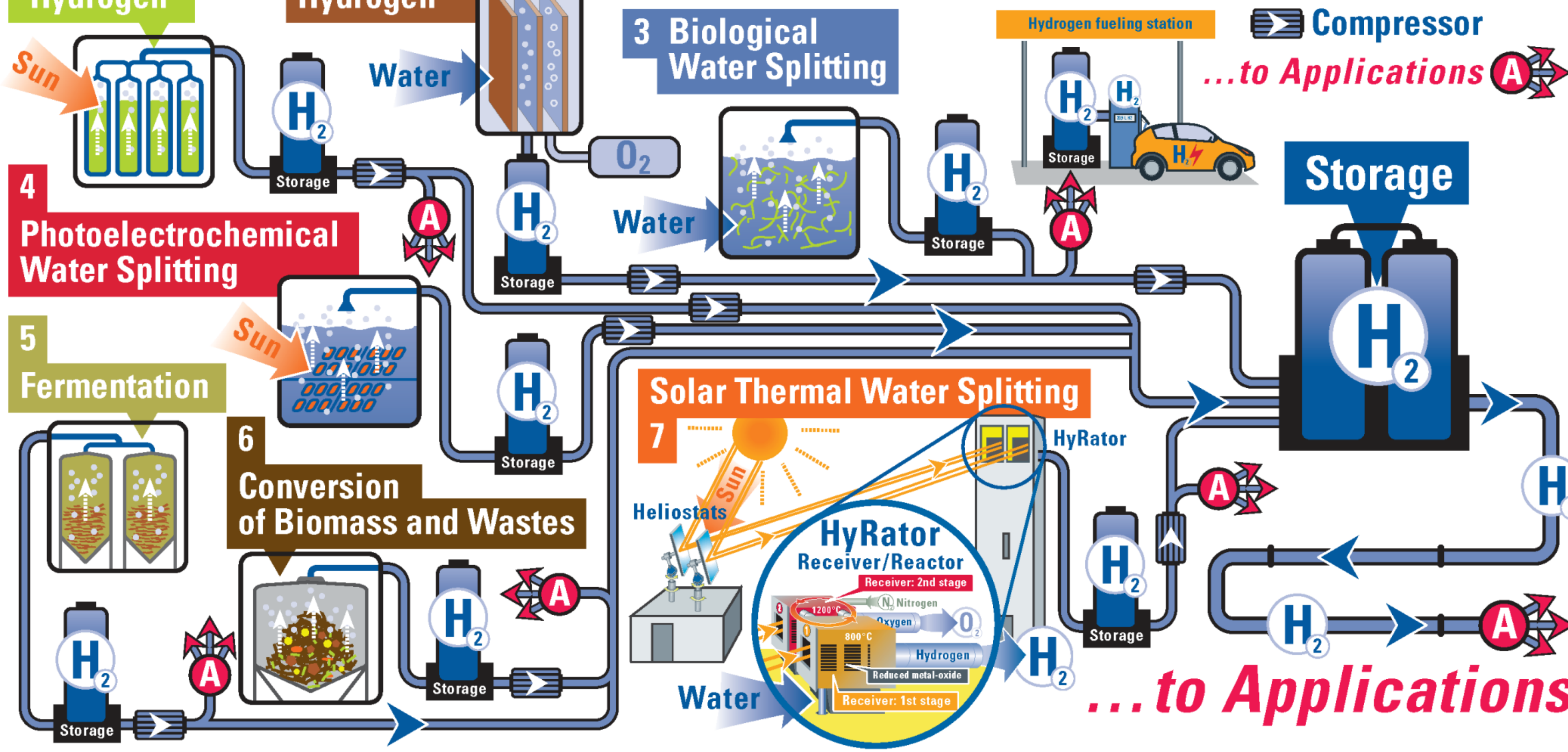


Edwards *Phil. Trans. R. Soc. A* **2007**, *365, 1043-1056*



Schlapbach, Züttel *Nature* **2001**, *414*, 353.

Production of Hydrogen without electricity from renewables



Go to where the market is! www.fair-pr.com

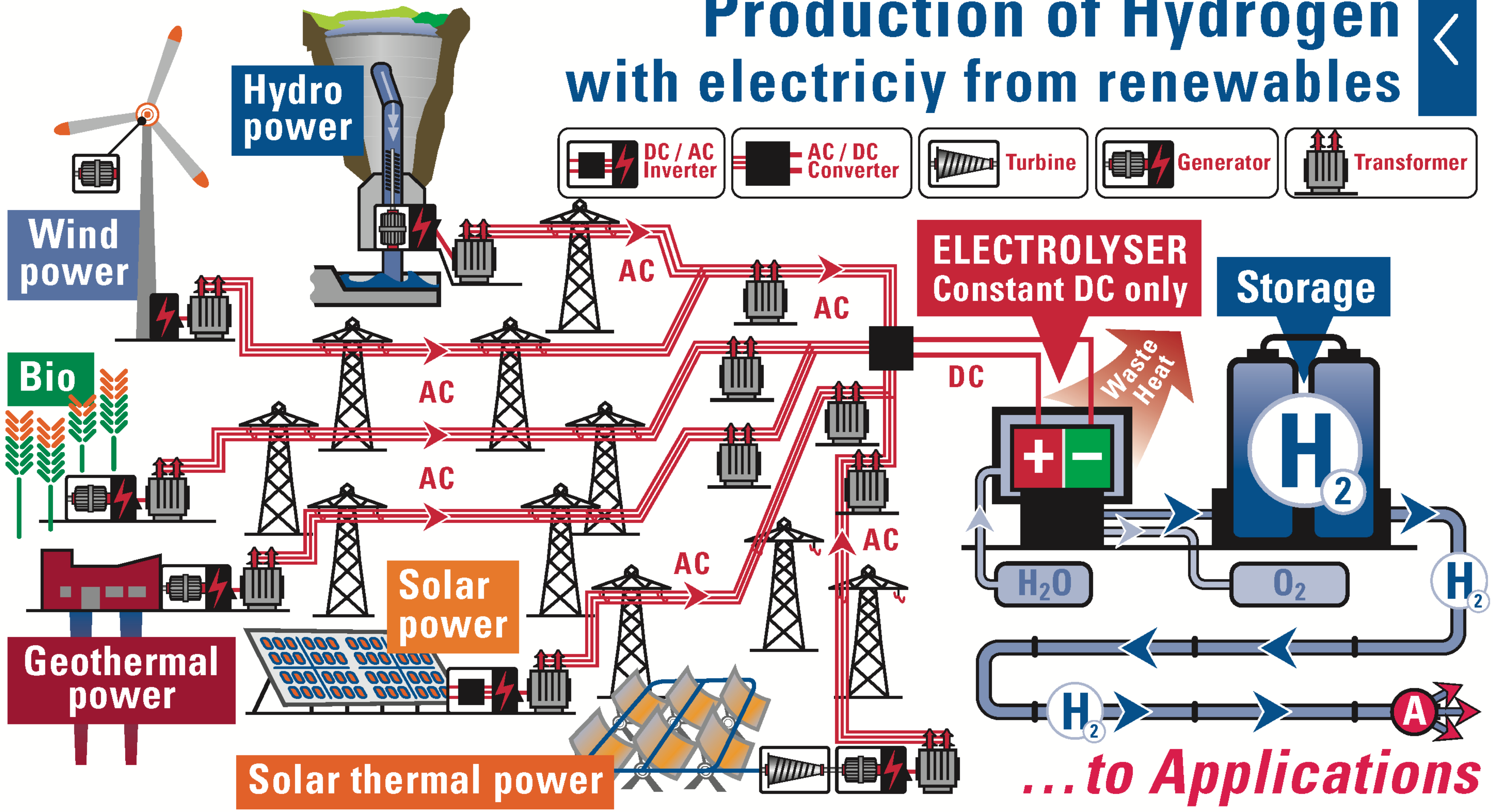
I M P L E M E N T I N G N E W I D E A S

Data Sources: Own Research

EVERS

First released: February 2010

Production of Hydrogen with electriciy from renewables

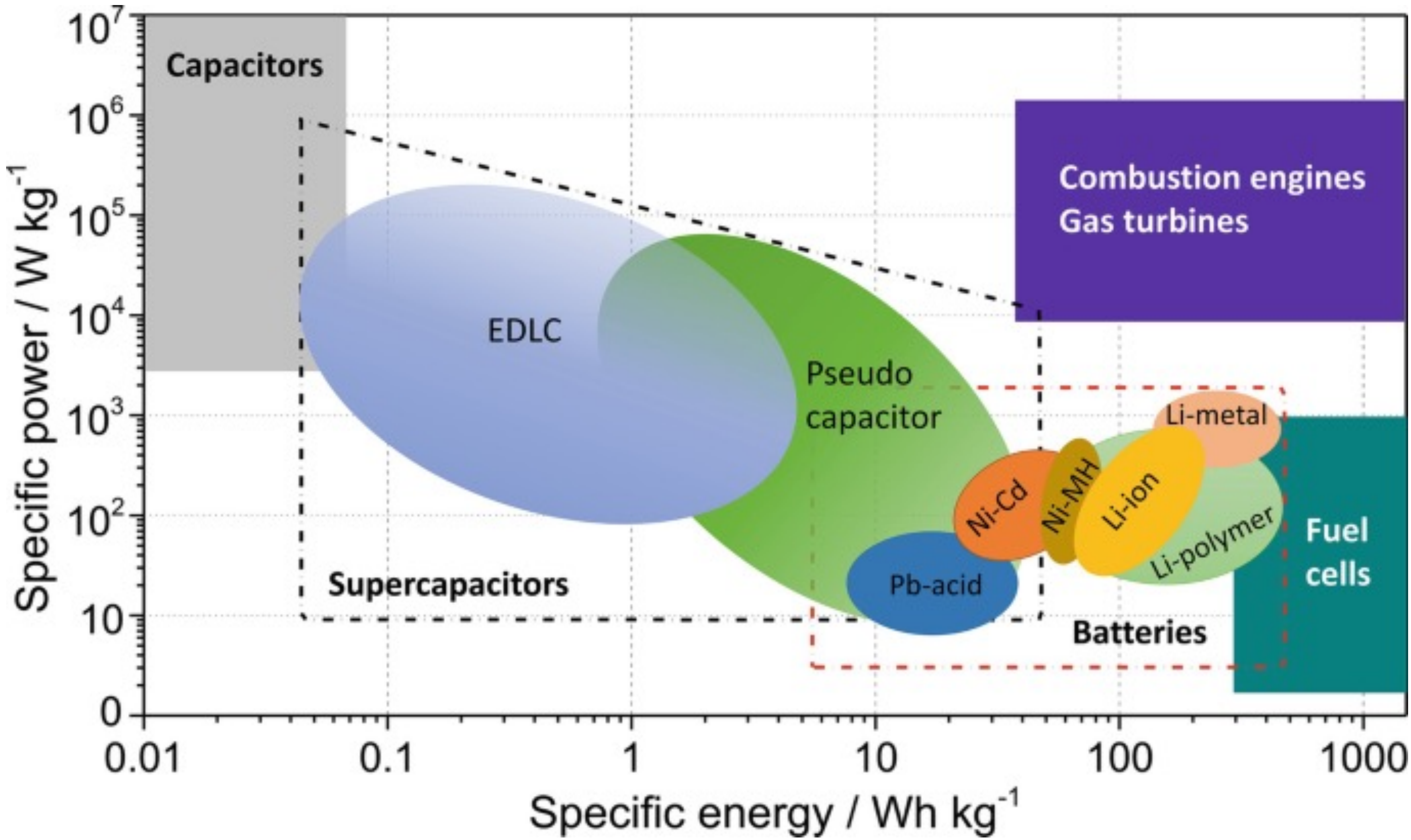


Go to where the market is! www.fair-pr.com I M P L E M E N T I N G N E W I D E A S

Data Sources: Own Research

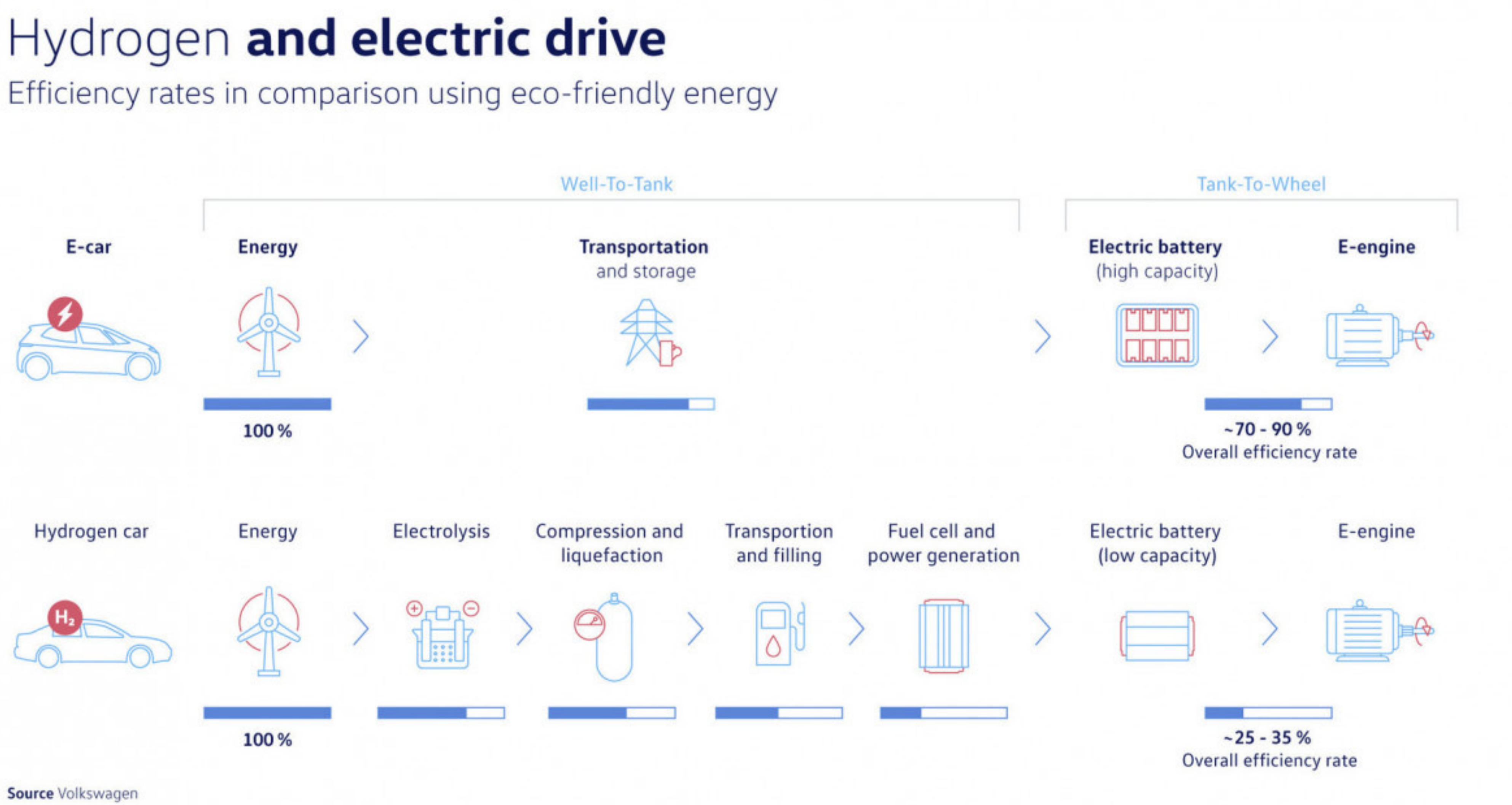
First released: February 2010

If not hydrogen, and not fossil fuels, then what?

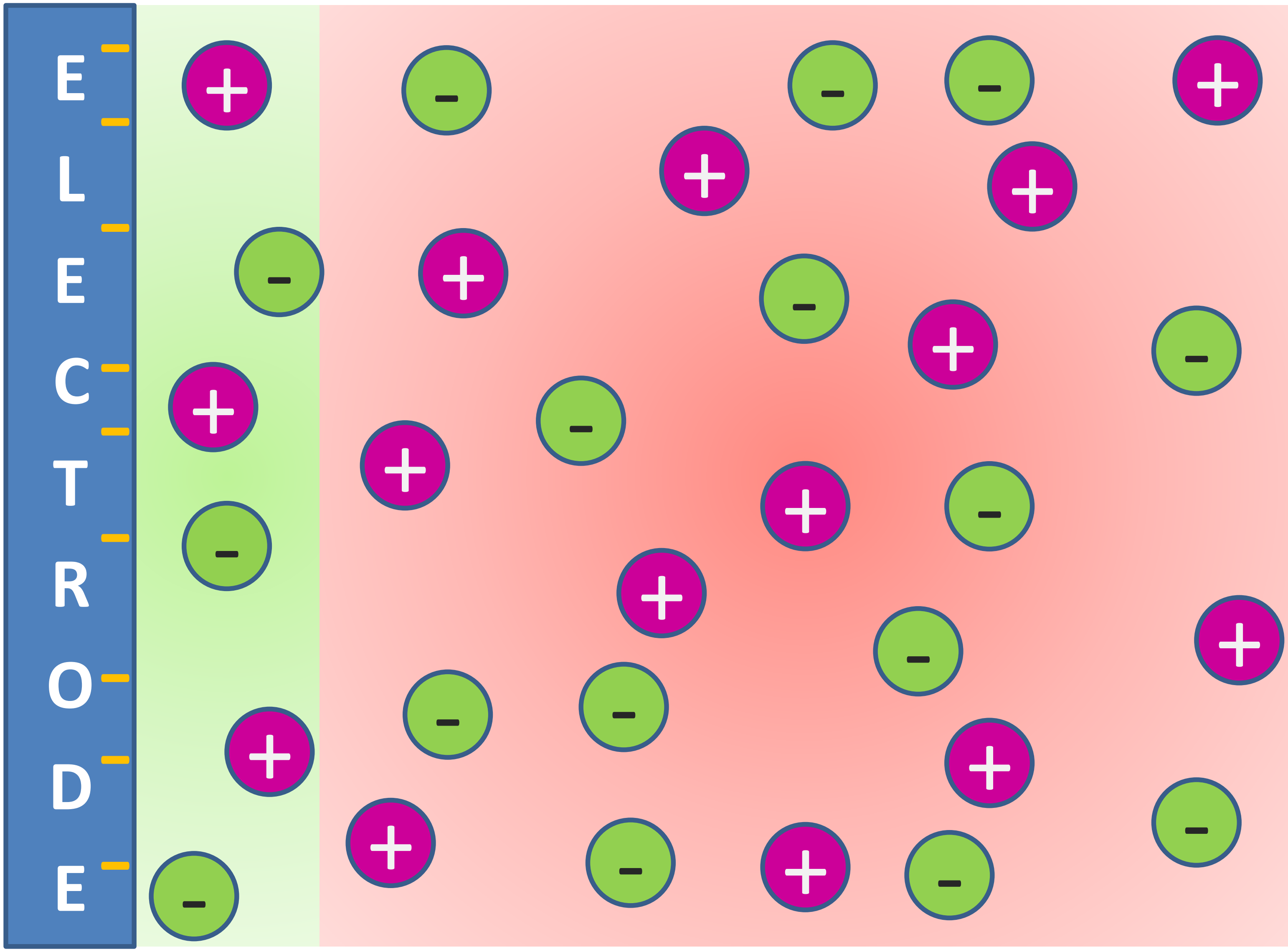


https://link.springer.com/chapter/10.1007/978-3-662-58675-4_2

Hydrogen FCEVs vs EVs

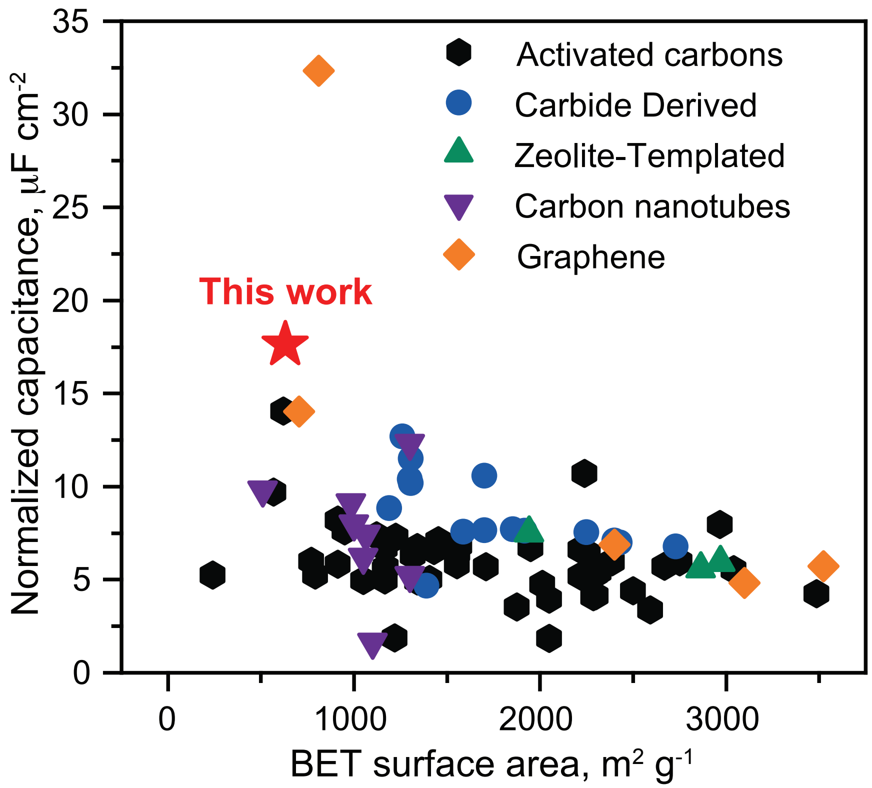


Electrical double layer supercapacitors (EDLC)



Cells exhibit very large area-normalized capacitance

Surface area normalized capacitance 18 μF cm^{-2}



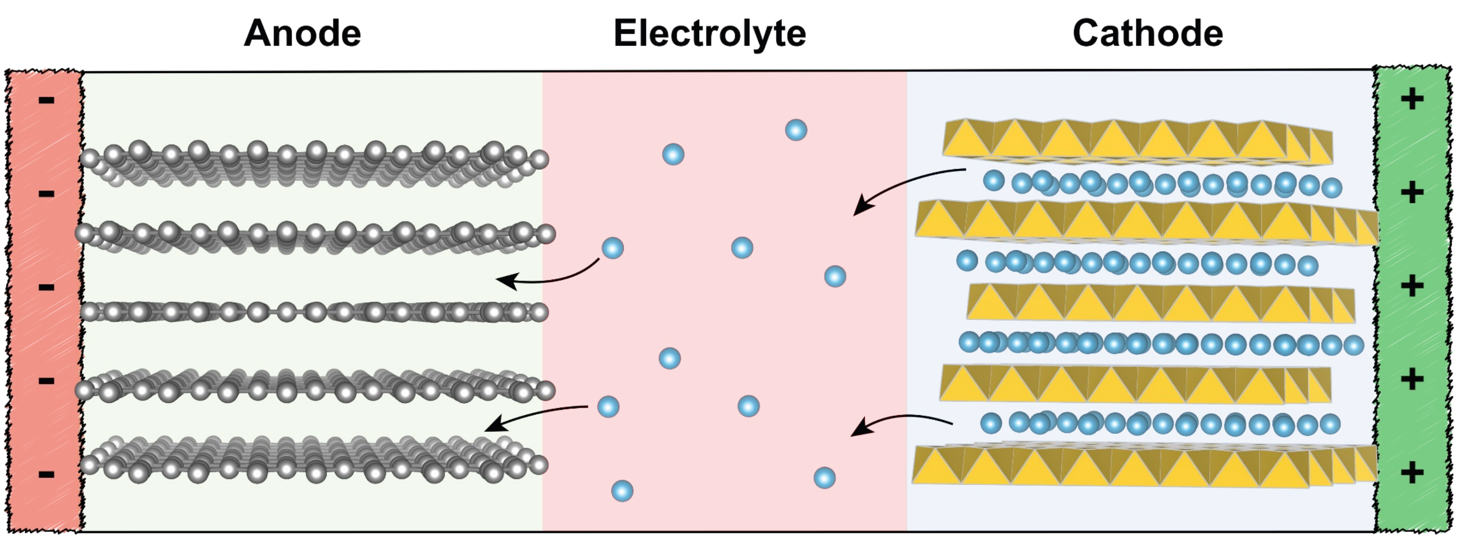
Material (Areal loadings >2.5 mg cm^{-2})	Capacitance gravimetric, F g^{-1} (Conditions)
$Ni_3(HITP)_2$	**111 (1V, 50 mA g^{-1})** **70 (1V, 1 A g^{-1})**
Activated carbon	80~140
Chemically reduced graphene	165 (3.6V 1.4 A g-1) 150 (2.6V 0.8 A g-1)
Single-walled CNTs arrays	160 (4V, 1A g^{-1}) 68 (2V, 1A g^{-1})
Activated graphene	202 (2.7V, 1A g^{-1})
Holey Graphene	262 (3.5V, 1A g^{-1})
Electrolyte-mediated graphene	167 (3.5V, 1A g^{-1})

Sheberla, Bachman, Elias, Shao-Horn, Dincă, *Nature Mater.* **2017**, *16*, 220-224.

The world’s most expensive supercap for…

the world’s most exotic car

Innovations are focused on Electrolytes, processing of traditional cathodes and anodes



Silicon/Graphite

- More than 40 start-ups
- Sila Nanotechnologies
- Storedot

Solid-state

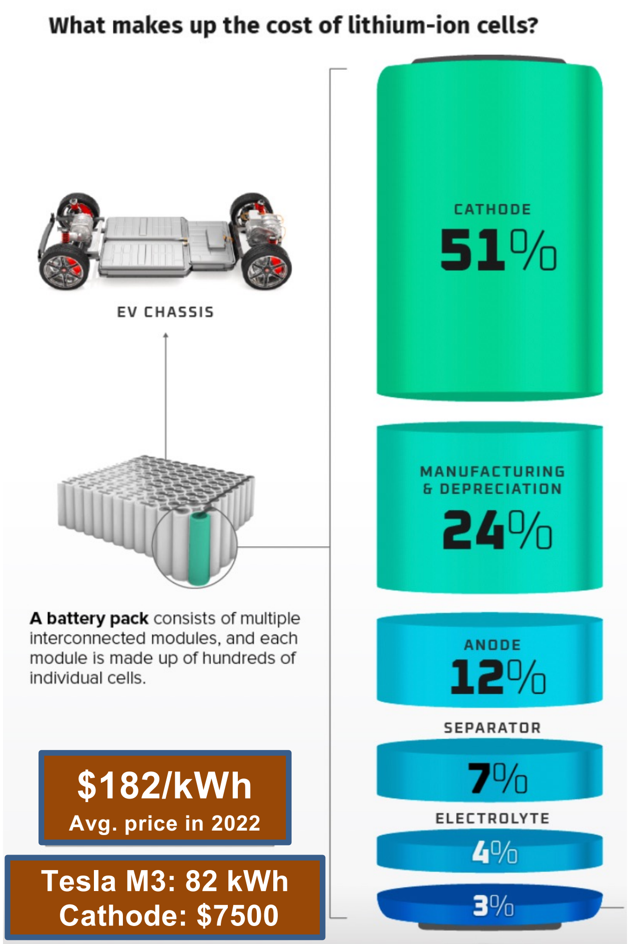
- Quantumscape
- Solid Power
- Factorial

Optimizing NMC compositions

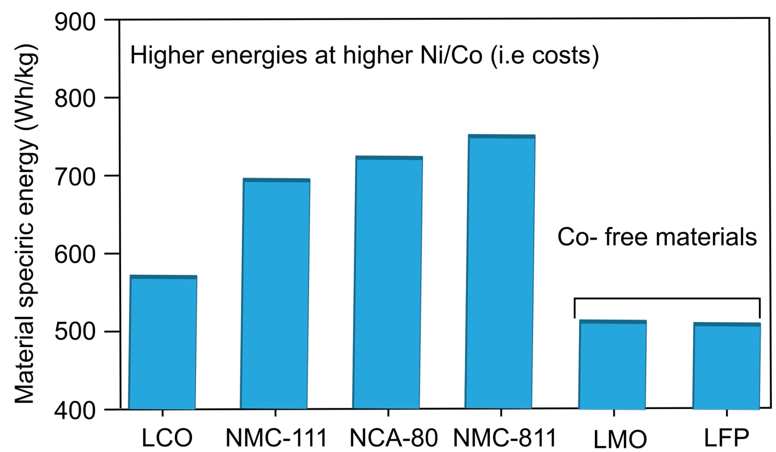
- Large players (eg: CATL)
- Engineering better cells
- Supply chain optimization

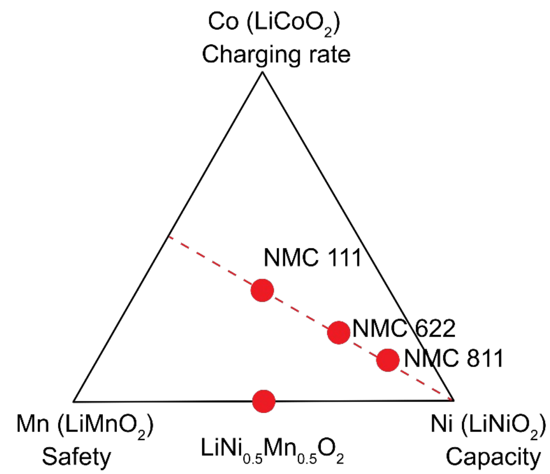
A new technology that replaces NMC cathodes sustainably would truly change the game

Cathodes drive battery costs and performance, are hardest to innovate



Source: Bloomberg





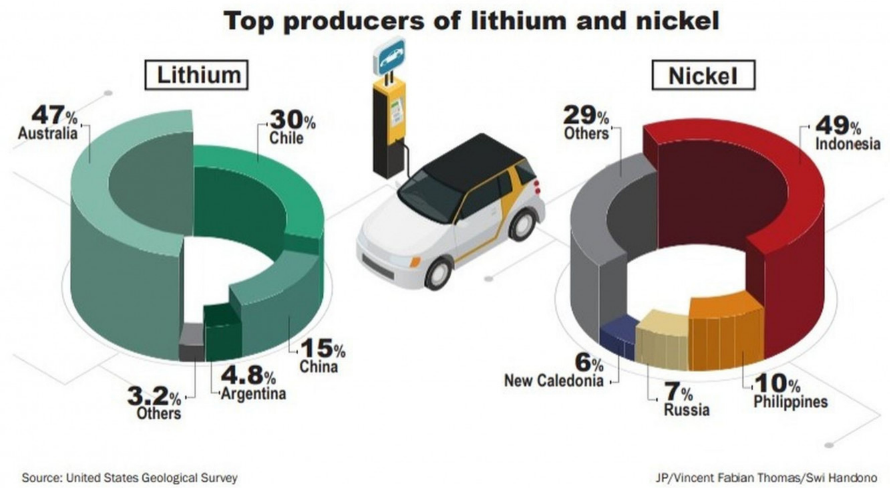
Cathodes dictate energy and power of a battery

Slow charging of cathodes – long wait times

Commercial cathodes are limited by the metal phase compositions

Critical material mining: cobalt, nickel, and phosphate

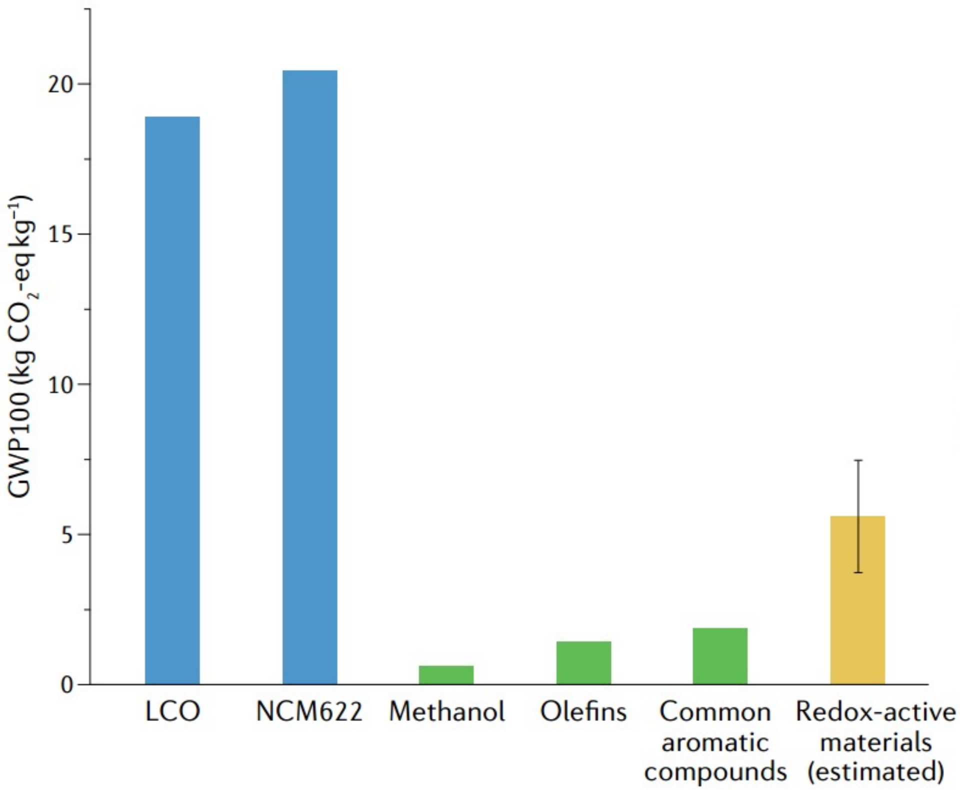
- 73% DRC
- 5% Indonesia
- 3% Australia
- 3% Philippines
- 3% Cuba
- 13% ROW



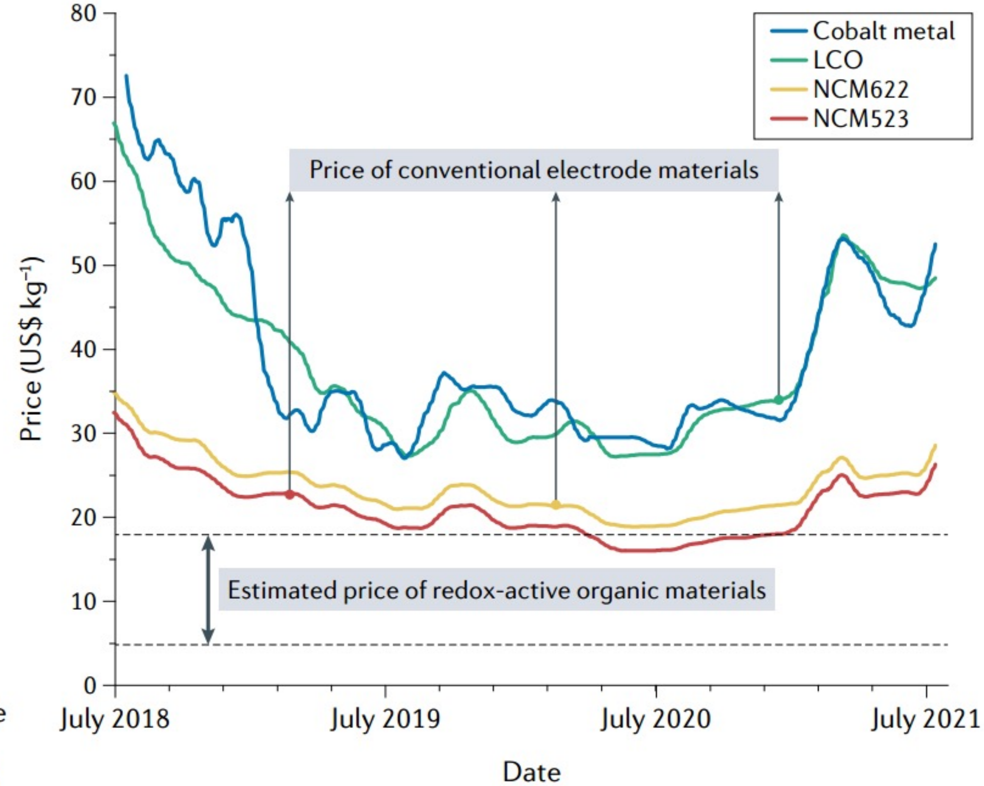
Rank	Country	Reserves (in thousand metric tons)	Share (%)
1	Morocco	50,000,000	69.4%
2	Egypt	2,800,000	3.9%
4	Tunisia	2,500,000	3.5%
5	Algeria	2,200,000	3.1%
6	China	1,900,000	2.6%
7	Brazil	1,600,000	2.2%
8	South Africa	1,600,000	2.2%
9	Saudi Arabia	1,400,000	1.9%
10	Australia	1,100,000	1.5%

Organic Redox Active Materials More Cost-Effective and Environmentally Friendly than Inorganics

Organic redox molecules are greener



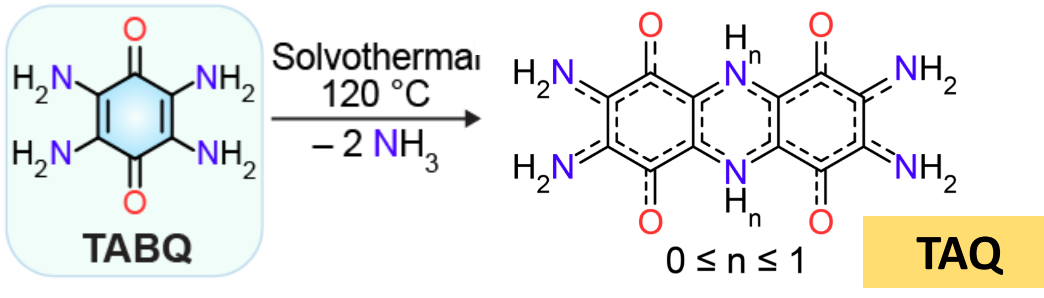
Organic redox molecules are more affordable

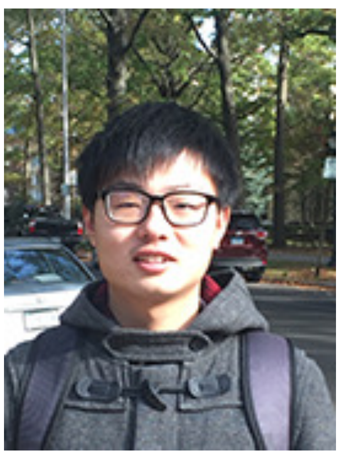


- Organic cathodes **cycle poorly** because of solubility
- Organic cathodes are **not conductive**, thus requiring high additive/binder content, which **lowers their overall cathode metrics**

Kim, J., *et al. Nat. Rev. Mater.*, **2023**, 8, 54-70.

TAQ has strong intermolecular H-bonding and interlayer π–stacking



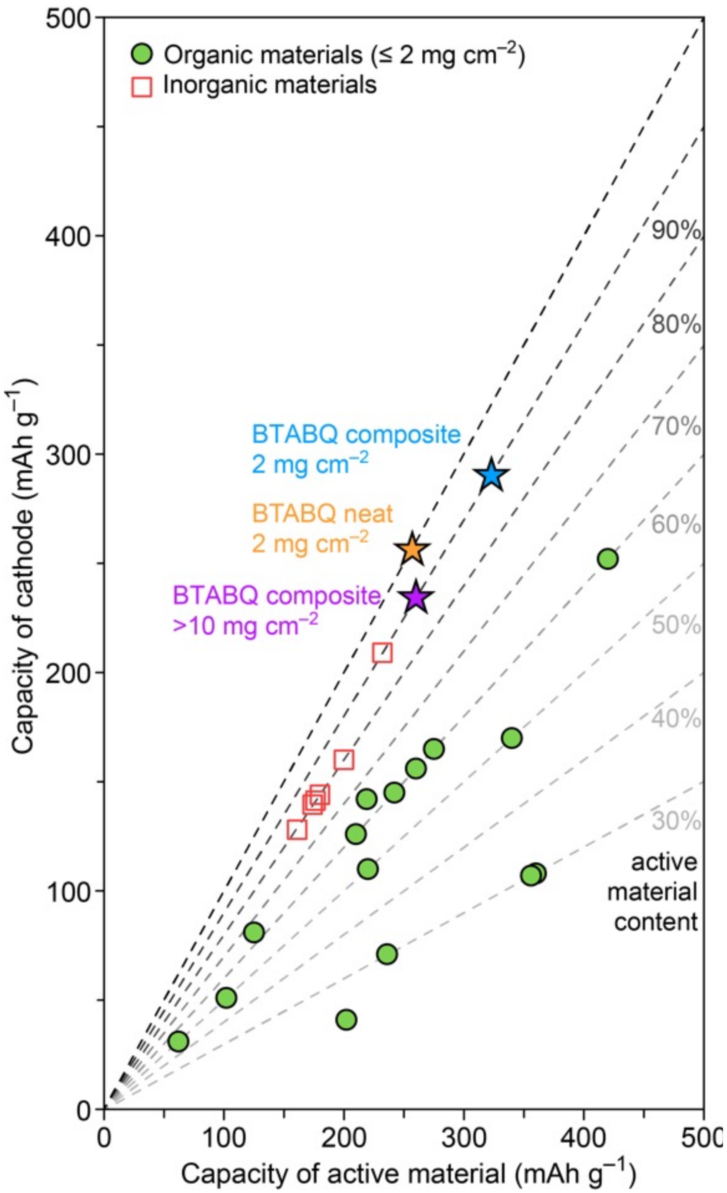


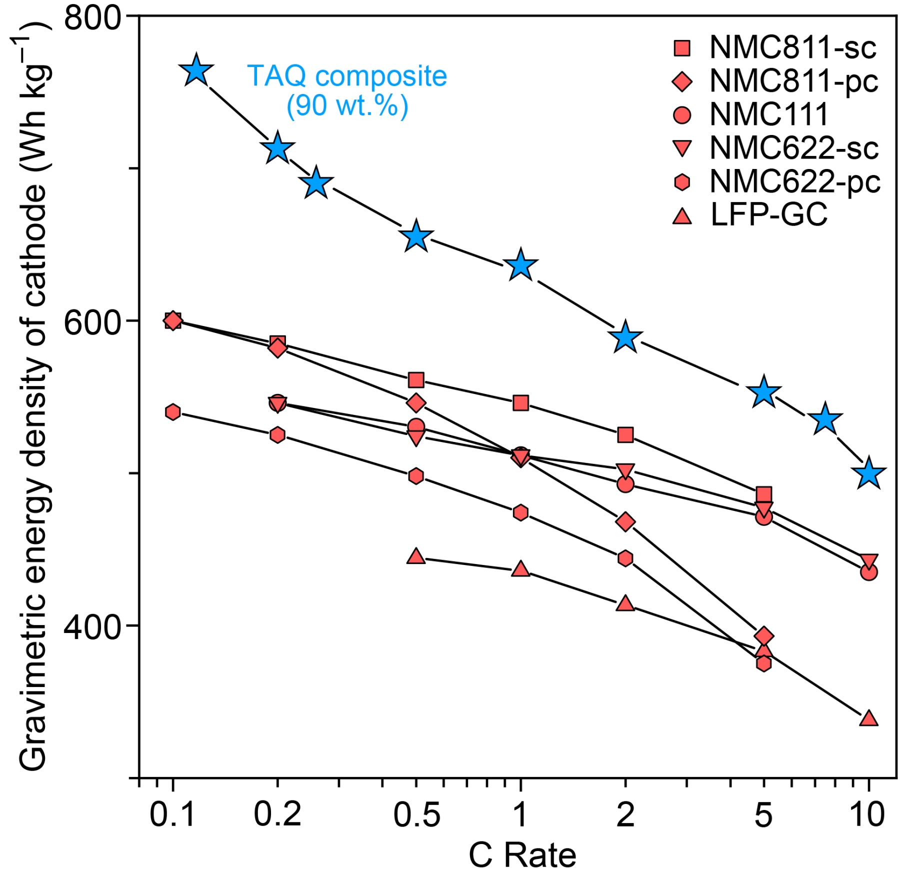
Tianyang Chen

Harish Banda

Chen, Banda, Dincă *et al Joule* **2023**, *7*, 986-1002.

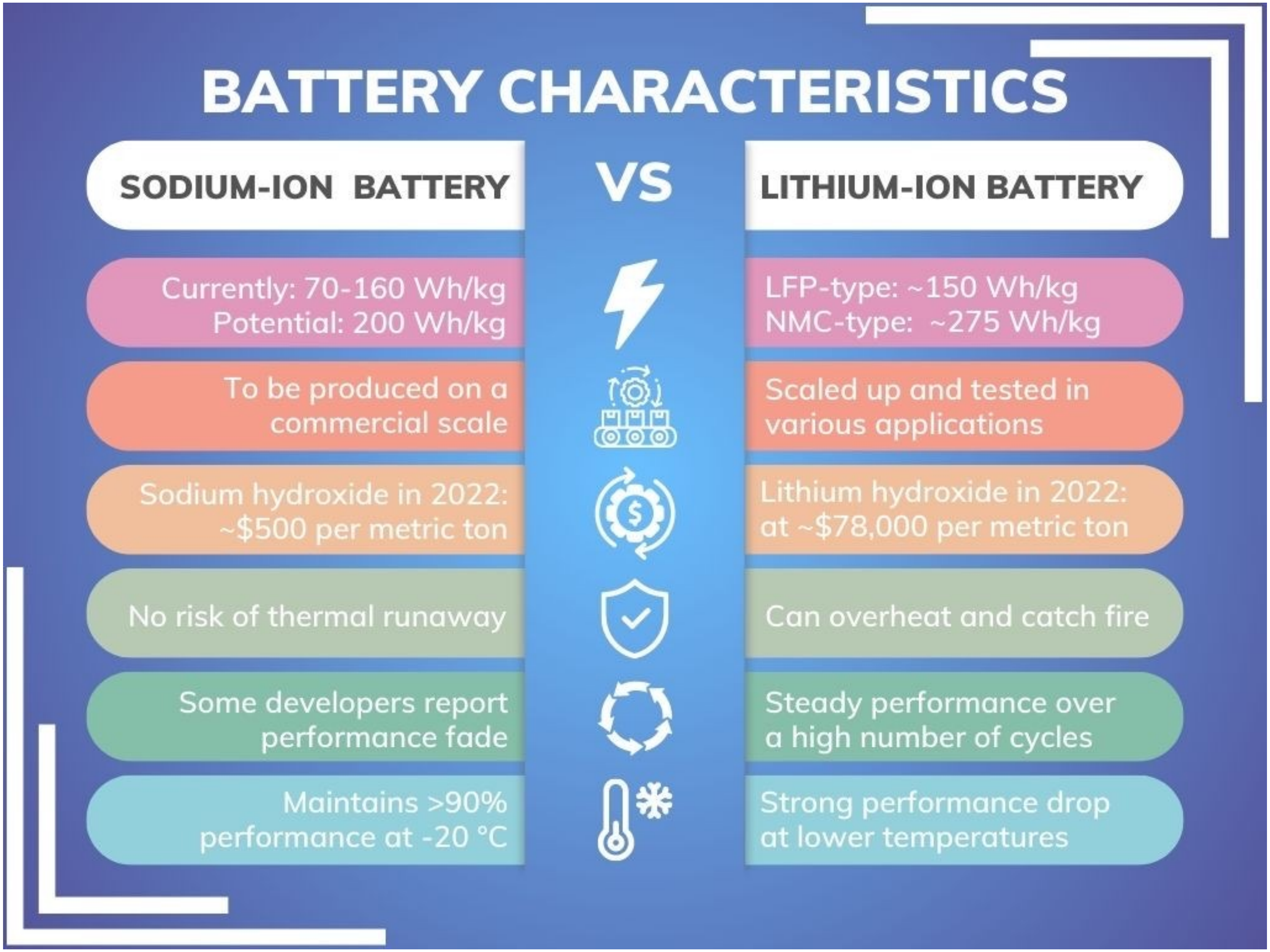
TAQ composite electrodes exhibit excellent electrode-level metrics



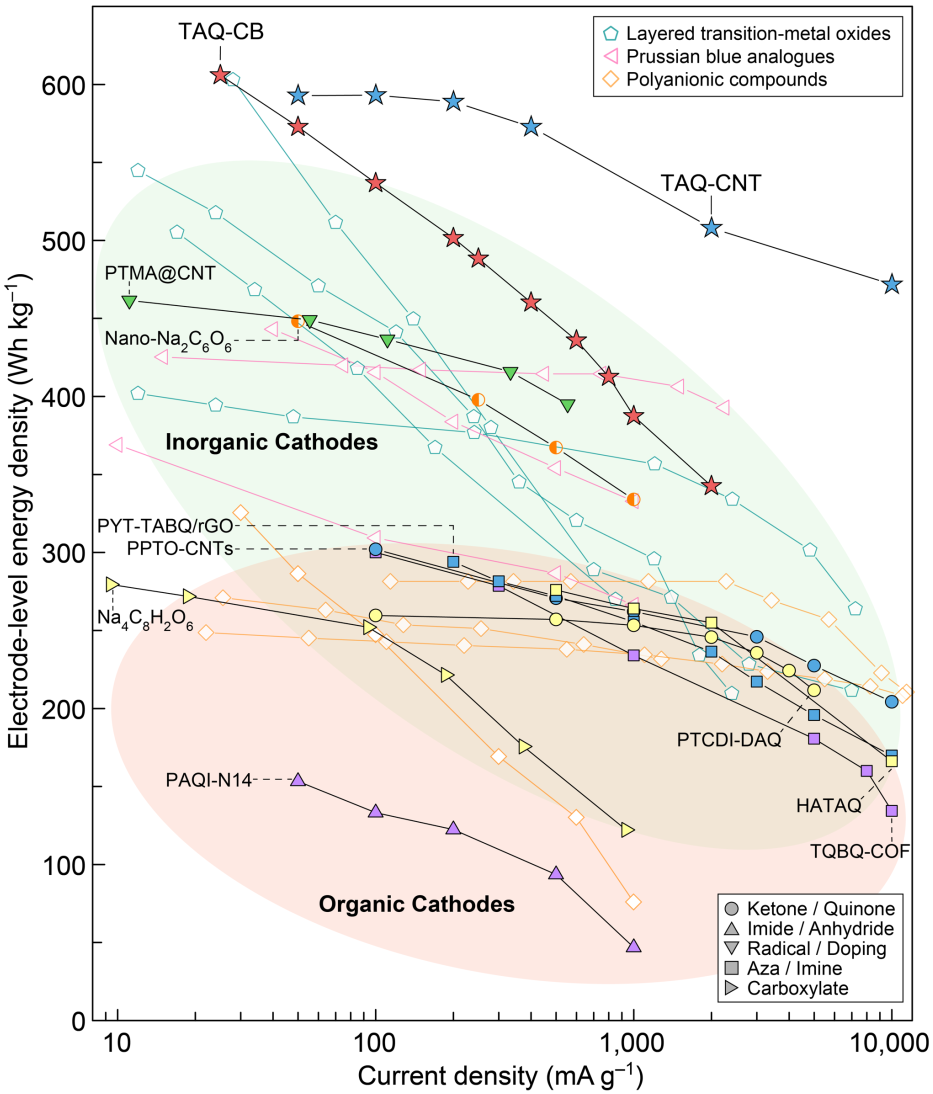


Chen, Banda, Dincă *et al* – *ACS Cent. Sci.* **2024**, *10*, 569

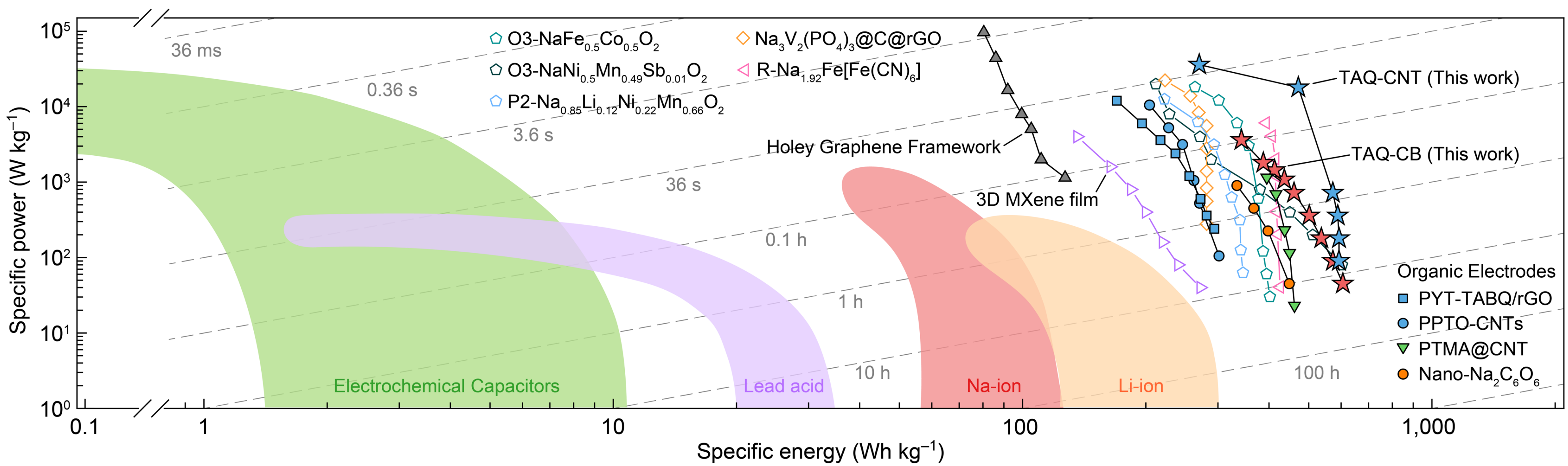
So we got rid of Co, Ni, Phosphate: **what about Lithium?**



TAQ in Sodium Ion Batteries



A high-performance battery from just oil and seawater!



Sustainable Batteries for Mobile Applications, 11/15/22

ChenAn Shen

Part I. Literature (for further reading about organic cathode materials)

Chen, T., Banda, H., Wang, J., Oppenheim, J. J., Franceschi, A., & Dincă, M. (2024). A layered organic cathode for high-energy, fast-charging, and long-lasting Li-Ion Batteries. *ACS Central Science*, *10*(3), 569–578. https://doi.org/10.1021/acscentsci.3c01478

Cui, J., Guo, Z., Yi, J., Liu, X., Wu, K., Liang, P., Li, Q., Liu, Y., Wang, Y., Xia, Y., & Zhang, J. (2020). Organic cathode materials for rechargeable zinc batteries: Mechanisms, challenges, and perspectives. *ChemSusChem*, *13*(9), 2160–2185. https://doi.org/10.1002/cssc.201903265

Lyu, H., Sun, X.-G., & Dai, S. (2020). Organic cathode materials for lithium-ion batteries: Past, present, and future. *Advanced Energy and Sustainability Research*, *2*(1). https://doi.org/10.1002/aesr.202000044

Zhang, H., Gao, Y., Liu, X., Yang, Z., He, X., Li, L., Qiao, Y., Chen, W., Zeng, R., Wang, Y., & Chou, S. (2021). Organic cathode materials for sodium-ion batteries: From Fundamental Research to potential commercial application. *Advanced Functional Materials*, *32*(4). https://doi.org/10.1002/adfm.202107718

Part II. Recent News

Aesar, S. by A. (2024, August 23). *Environmentally friendly battery materials for lithium-ion and alternative battery technologies*. AZoM. https://www.azom.com/article.aspx?ArticleID=23877

Anne Trafton | MIT News. (n.d.). *Cobalt-free batteries could power cars of the future*. MIT News | Massachusetts Institute of Technology. https://news.mit.edu/2024/cobalt-free-batteries-could-power-future-cars-0118

Richard, I. (2024, January 22). *Lamborghini licenses MIT's new Taq battery-fast charging, organic, and more features*. Tech Times. https://www.techtimes.com/articles/300850/20240121/lamborghini-licenses-mit-s-new-taq-batteryfast-charging-organic-more.htm

Part III. Q&A Summary

---Jinhua---

Q: Can you tell us about the discovery/design process of TAQ? What inspired you to use it as an organic material? Also, how long would it take to move from scientific research to pilot and commercial usage?

A: The discovery is a "cool story of scientific serendipity." During work with Lamborghini, two students noticed a black precipitate that most researchers would have discarded. Instead of throwing it away, they had the insight to test it in batteries before fully understanding its composition due to its black, potentially conductive appearance. It worked remarkably well, leading them to backtrack and investigate why. The material is now being commercialized.

Q: Regarding hydrogen technology, you mentioned it's not really a technical issue but more about logistics and consumer preferences. The technology existed even earlier than IC and electric cars but stopped around 2010. Was it due to poor process design, and what can we do to revitalize hydrogen as a meaningful path forward?

A: Distribution is the major challenge. While companies like Toyota and Nissan have working hydrogen cars and fuel cells function well, the main problem is hydrogen accessibility. Storage, though bulky (taking half the car's storage space), is manageable. Current hydrogen production is "blue hydrogen" from hydrocarbons with lower CO_2 emissions and could potentially be "green" using solar water splitting. Home-scale solutions like electrolyzers exist but require maintenance and are more complex than simply plugging in an electric car.

Q: From a strategic perspective, looking at all possibilities (hydrogen, gas, diesel, battery, capacitor), is the scientific community covering most interesting grounds, or are there major unexplored areas with potential?

A: The scientific community is covering most potential areas, with research into various fuels including ammonia (as a hydrogen carrier), methanol fuel cells, and engineering innovations like solar-electric hybrids. Market adoption ultimately depends on cost and efficiency, which is why EVs are currently leading. While EVs appear to be the most practical solution now, the speaker remains hopeful about hydrogen's future potential.

---Audience---

Q: What is the role of government in investing in core technology innovation and commercialization? Based on your experience with Lamborghini, are we putting our investments in the right place to reduce CO_2 emissions?

A: From an informed observer's perspective, some government actions are positive, like investing in domestic manufacturing for independence in critical technologies. However, the single most important policy would be pricing carbon, which would drive adoption of sustainable materials in batteries. This would naturally push towards technologies with lower CO_2 footprints (like organics with 1/4 the footprint of cobalt oxide) and have societal benefits like reducing cobalt production in Congo. Policy can be more important than technology, as demonstrated by the air conditioning industry where lack of policy incentives has kept inefficient technology in place despite better alternatives being available.

Q: Would carrying the liquid hydrogen tank be as heavy as an EV car, considering batteries add significant weight compared to gas cars?

A: While a direct comparison hasn't been made, hydrogen systems might be slightly lighter, but they're more problematic from an engineering perspective. Liquid hydrogen requires cylindrical tanks due to engineering constraints, while batteries can be shaped and placed flexibly in the car.

Additionally, liquid hydrogen faces significant loss issues - a car left in the sun for a month might lose its hydrogen, while batteries don't face this problem.

Q: Is there a market where hydrogen is feasible, perhaps marine applications?

A: No definitive answer, but there probably are markets better suited for hydrogen applications.

Q: How do organic and inorganic redox materials compare in terms of kilowatt-hours of lifetime use rather than per kilogram of material (life cycle greenhouse gases)?

A: With similar lifetimes (e.g., 5,000 cycles), organic materials still outperform in terms of CO2 footprint. The presented materials have at least as long-life cycles as inorganic ones, making them much better in terms of overall CO2 footprint.

Q: Any thoughts on lithium capacitors?

A: While many capacitors use lithium, the speaker wasn't sure about specific commercial applications.

Part IV. Summary of Memos

Most memos share insights on:

- Success requires addressing multiple challenges simultaneously
- Technical solutions must be paired with supportive policy frameworks
- Need to balance immediate practicality with long-term sustainability
- Importance of considering both local and global impacts
- Role of interdisciplinary approaches in solving complex problems

Here are the detailed key themes emerged across the memos:

1. Technical Innovation & Scientific Discovery
    a. Discovery of TAQ:
        i. Found as a "black unidentified precipitate" that most would have discarded
        ii. Students made batteries from it before understanding its composition
        iii. Demonstrates value of investigating unexpected results
    b. Research Methodology:
        i. Sequential testing proved more efficient than parallel experimentation for battery development
        ii. Each test was expensive, and results were highly interconnected
    c. Technical Achievements:
        i. TAQ overcame two main challenges of organic cathodes: solubility and conductivity
        ii. Delivers higher energy density than conventional metal oxides
        iii. Maintains capacity over thousands of charge cycles
2. Policy & Market Forces
    a. Carbon Pricing Impact:
        i. Could drive adoption of materials with lower CO2 footprint

        ii. Would help internalize environmental costs
        iii. Example of air conditioning industry showing market inertia without policy intervention
    b. Economic Considerations:
        i. Cost remains primary barrier to adoption of new technologies
        ii. Need to balance upfront costs with long-term benefits
        iii. Market dynamics influence technology choice more than technical superiority
3. Human & Social Factors
    a. Public Perception:
        i. Hydrogen storage fears linked to Hindenburg disaster
        ii. Technical excellence doesn't guarantee adoption
        iii. Need for public education and awareness
    b. Consumer Behavior:
        i. Resistance to change despite better alternatives
        ii. Role of comfort and convenience in technology adoption
        iii. Impact of historical experiences on current choices
4. Geopolitical & Resource Considerations
    a. Critical Materials:
        i. 73% of cobalt from Democratic Republic of Congo
        ii. Human rights concerns in mining operations
        iii. Resource concentration creating geopolitical dependencies
    b. Supply Chain Issues:
        i. Need for domestic manufacturing capability
        ii. Resource scarcity driving innovation
        iii. Complex international supply networks
5. Implementation & Infrastructure Challenges
    a. Hydrogen Infrastructure:
        i. Only ~40 existing stations in US
        ii. ~50 planned stations
        iii. Distribution and storage complications
    b. EV Charging Network:
        i. Limited charging infrastructure
        ii. Capacity constraints
        iii. Range anxiety concerns
    c. Scale-up Challenges:
        i. Production capacity needs
        ii. Integration with existing systems
        iii. Manufacturing process development
6. Sustainability & Environmental Impact
    a. Environmental Benefits:
        i. Organic materials reduce CO_2 emissions in production (5kg vs 200kg CO_2/kg)
        ii. Less reliance on mining
        iii. Potential for circular economy
    b. Life Cycle Considerations:

    i. Need for cradle-to-grave analysis
    ii. Impact of raw material sourcing
    iii. End-of-life recycling and disposal

These themes reflect the complexity of transitioning to sustainable transportation technologies and the need for integrated solutions that address technical, social, and economic challenges simultaneously.

Part V. Other Information

The documentary film "Who Killed the Electric Car?" directed by Chris Peck reveals another layer of socio-economic complexity behind sustainable energy. The film examines California's Zero Emission Vehicle (ZEV) mandate from 1990 and its eventual weakening and effective reversal in the early 2000s. The documentary follows the creation and then withdrawal of General Motors' EV1, one of the first modern mass-produced electric vehicles, which was introduced in response to the mandate but later recalled and destroyed by GM. The film explores various factors that contributed to the mandate's failure, including resistance from auto manufacturers, oil industry influence, hydrogen fuel cell promotion, and battery technology limitations at the time. The competition between hydrogen and battery electric vehicles (BEVs) was a key part of the story.

In 1990, California's Air Resources Board (CARB) passed the Zero Emission Vehicle mandate, requiring automakers to sell an increasing percentage of zero-emission vehicles. Initially, major automakers like GM developed battery electric vehicles like the EV1 to comply with this mandate.

The documentary argues that hydrogen fuel cells were used strategically by automakers and oil companies to delay BEV adoption.

1. Around 2000-2003, automakers began heavily promoting hydrogen as the "future technology," arguing that BEVs were just a steppingstone. They presented hydrogen as a more practical long-term solution.

2. GM particularly shifted its focus from the EV1 program to hydrogen fuel cell development. The film suggests this was partly a deliberate strategy to move away from a ready-now technology (BEVs) to a future technology that would take many years to develop.

3. The Bush administration in 2003 announced a $1.2 billion hydrogen initiative, which helped automakers make the case that hydrogen was the preferred zero-emission solution.

The film contends that this hydrogen push was partly responsible for CARB's decision to weaken the ZEV mandate in 2003, effectively ending the first wave of modern electric vehicles. Some points raised in the film about hydrogen vs. BEVs include:

- Infrastructure challenges: Hydrogen would require an entirely new fueling infrastructure, while electricity infrastructure already existed

- Energy efficiency: Converting electricity to hydrogen and back to electricity in fuel cells is less efficient than using electricity directly in batteries

- Cost considerations: Both the vehicles and hydrogen fuel would be more expensive than BEVs and electricity

This film shows once again the complexity behind the adoption of new technology, especially energy technology.