Prof. Harry L. Tuller, Department of Materials Science and Engineering
Massachusetts Institute of Technology

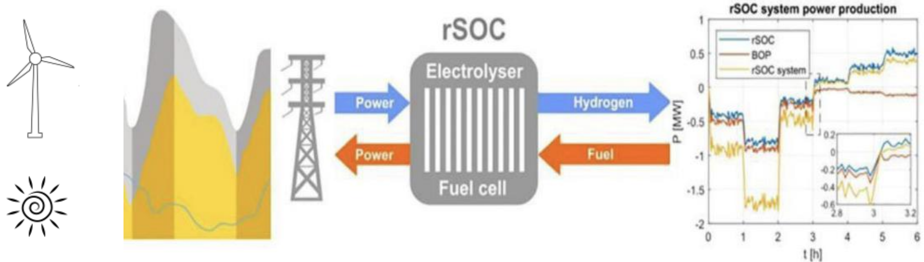
Fuel Cell Powered Vehicles – Opportunities and Challenges

Forever Technology of the Future?

MIT Mobility Forum, November 10, 2023

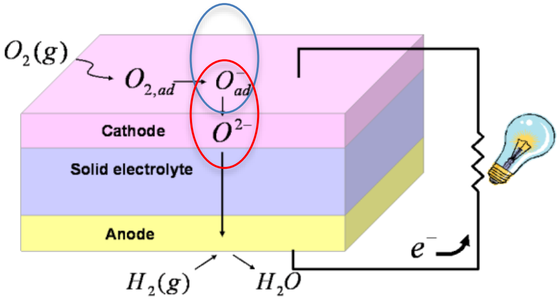
Fuel Cell Vehicle – Green Hydrogen

Intermittent energy production



Green hydrogen production

Progress in extending life of fuel/electrolysis cells
by markedly reducing susceptibility to "poisoning"



Outline

- **CO_2 induced global warming** - *how did we get there?*

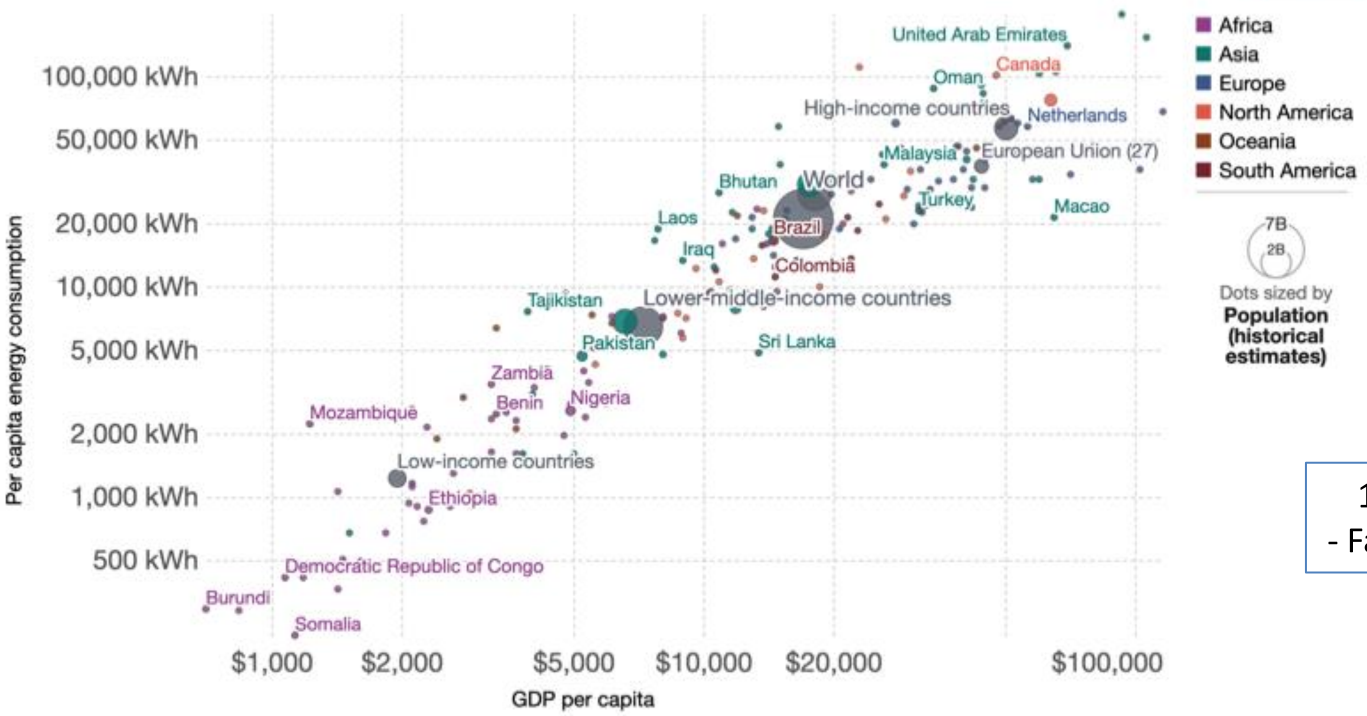
- **Transportation** – *hooked on oil.*

- **Electric vehicle options**: *battery vs fuel cell*
    - Battery vehicles- *how fast can they grow?*
    - Fuel cell vehicles –
        - *Hydrogen* generation and distribution challenges
        - *Electrolyzers* are the answer and *here's why!*

- **And now for something different - *Fundamentals*:**
    - Breakthroughs in our lab promising:
        - Fuel/electrolyzer cells with *improved performance, extended life* and less reliance on *critical materials*

Rapid increase in energy use with improved living conditions

Energy use per person vs. GDP per capita, 2021



Source: U.S. Energy Information Administration (EIA); Energy Institute Statistical Review of World Energy (2023); Data compiled from multiple sources by World Bank

Note: Energy refers to primary energy – the energy input before the transformation to forms of energy for end-use (such as electricity or petrol for transport).

OurWorldInData.org/energy • CC BY

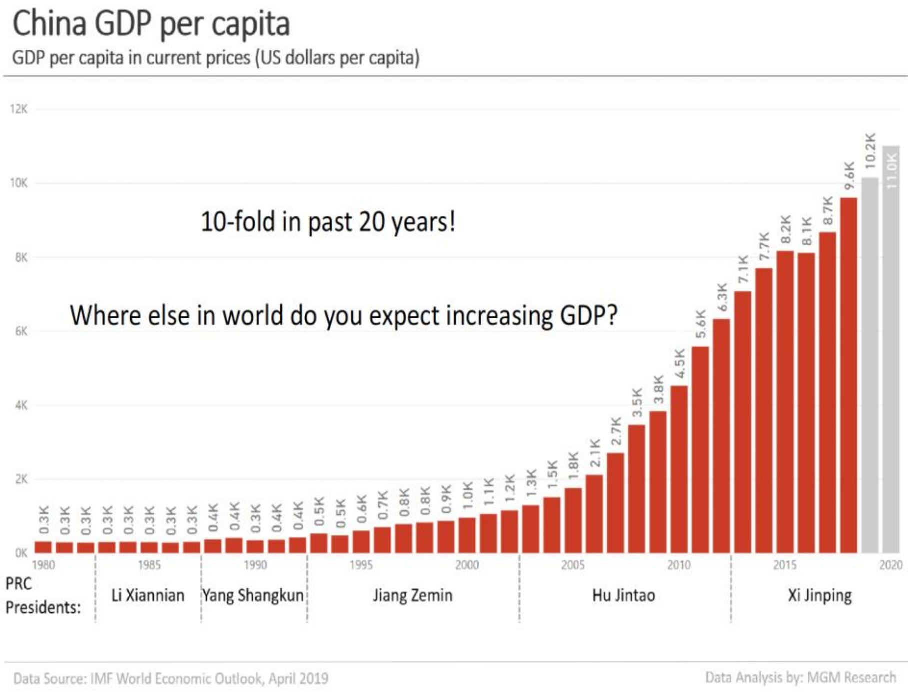
10^3-10^5 kWh

- Factor or ~100!

Focus on impact of vehicle consumption and use

https://ourworldindata.org/grapher/energy-use-per-person-vs-gdp-per-capita

Growth of GDP and Vehicle Sales



China GDP per capita

GDP per capita in current prices (US dollars per capita)

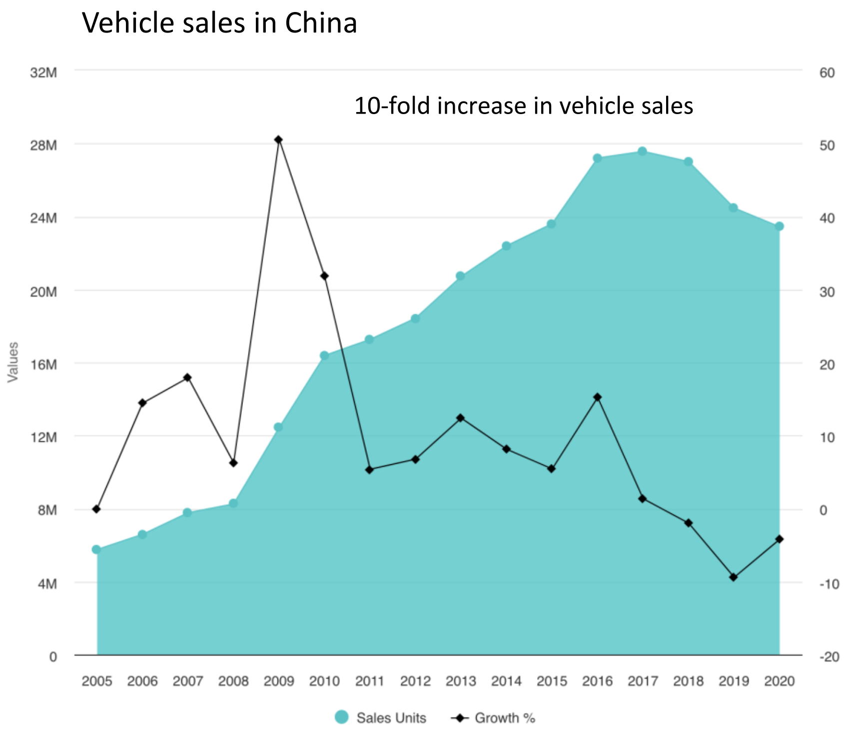
10-fold in past 20 years!

Where else in world do you expect increasing GDP?

Data Source: IMF World Economic Outlook, April 2019

Data Analysis by: MGM Research

https://mgmresearch.com/china-gdp-data-and-charts-1980-2020/



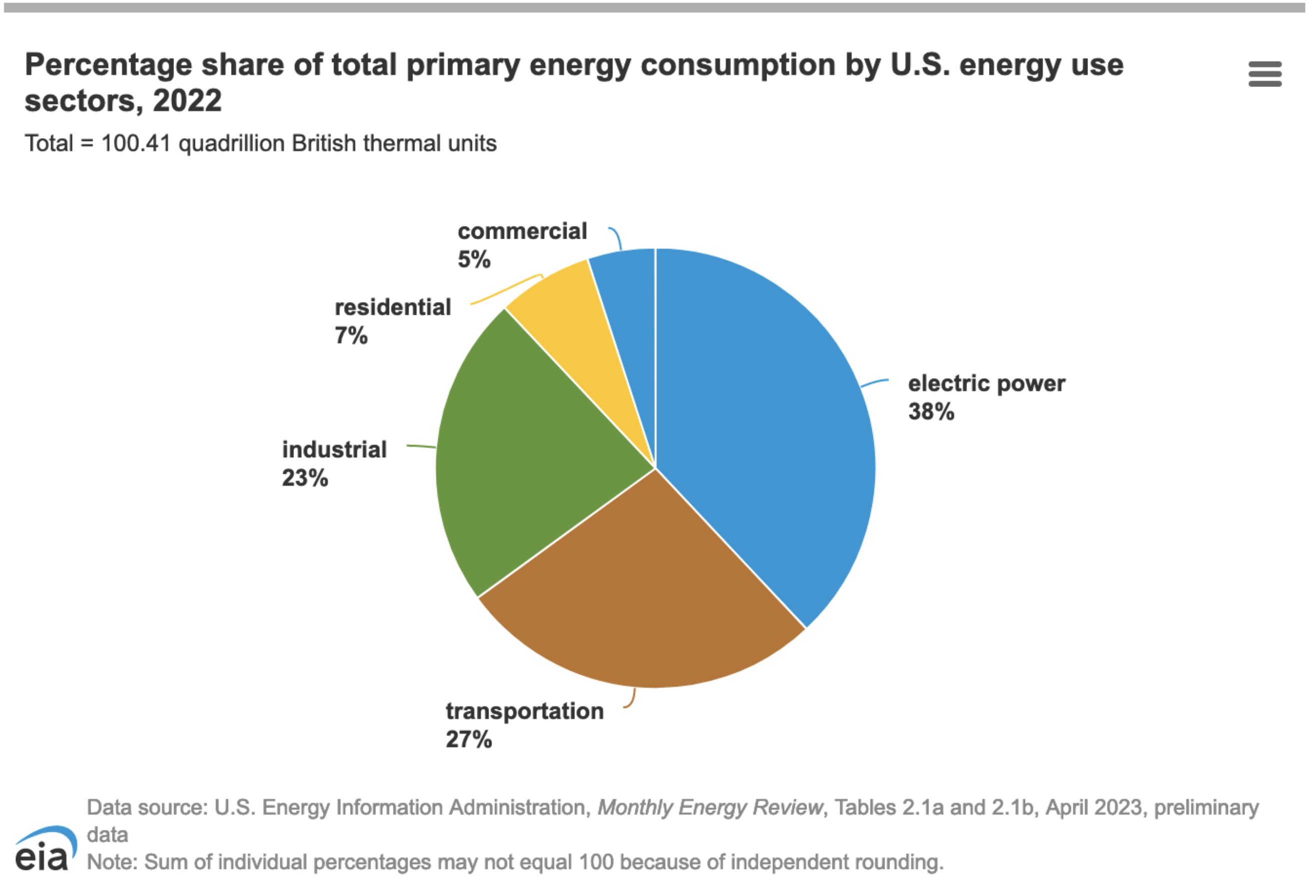
Vehicle sales in China

10-fold increase in vehicle sales

https://carsalesbase.com/china-car-sales-data-market/

GDP and population growth has led to explosive increase in fossil fuel consumption and CO_2 emissions generally!

Vehicle Energy Consumption & Impact on Emissions



Percentage share of total primary energy consumption by U.S. energy use sectors, 2022

Total = 100.41 quadrillion British thermal units

Data source: U.S. Energy Information Administration, *Monthly Energy Review*, Tables 2.1a and 2.1b, April 2023, preliminary data

Note: Sum of individual percentages may not equal 100 because of independent rounding.

Energy (largely fossil) consumption:

- 27% by vehicles → EVs
- 38% by electric power generation (coal and gas)

→ Renewables – *intermittent* PV and Wind (H_2?)

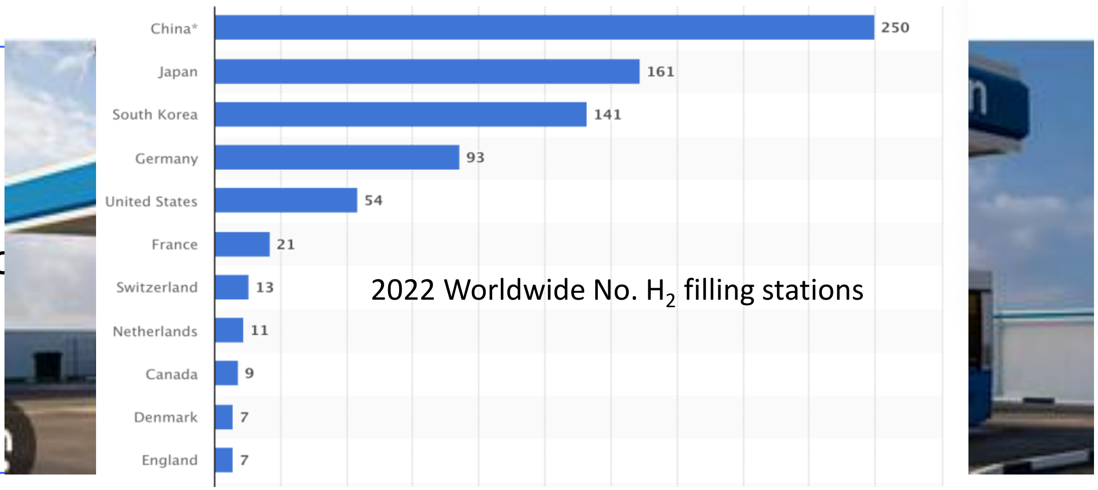
Love Affair with Fossil Fuels - Filler-up!

Fossil fuels pack big punch: high stored chemical energy, including cleaner alternatives like natural gas (largely methane).

- *Installed infrastructure* – USA
  - 145,000 filling stations (Am. Petroleum Inst.)
  - 278 million *registered* passenger *vehicles (Forbes)*
- ***Rapid refueling & extended range*** to 400 miles, low cost

Challenges:

- Non-renewable resource
- Strategic fuel
- Contamination (fracking, c
- Emissions
  - Health
  - Global warming



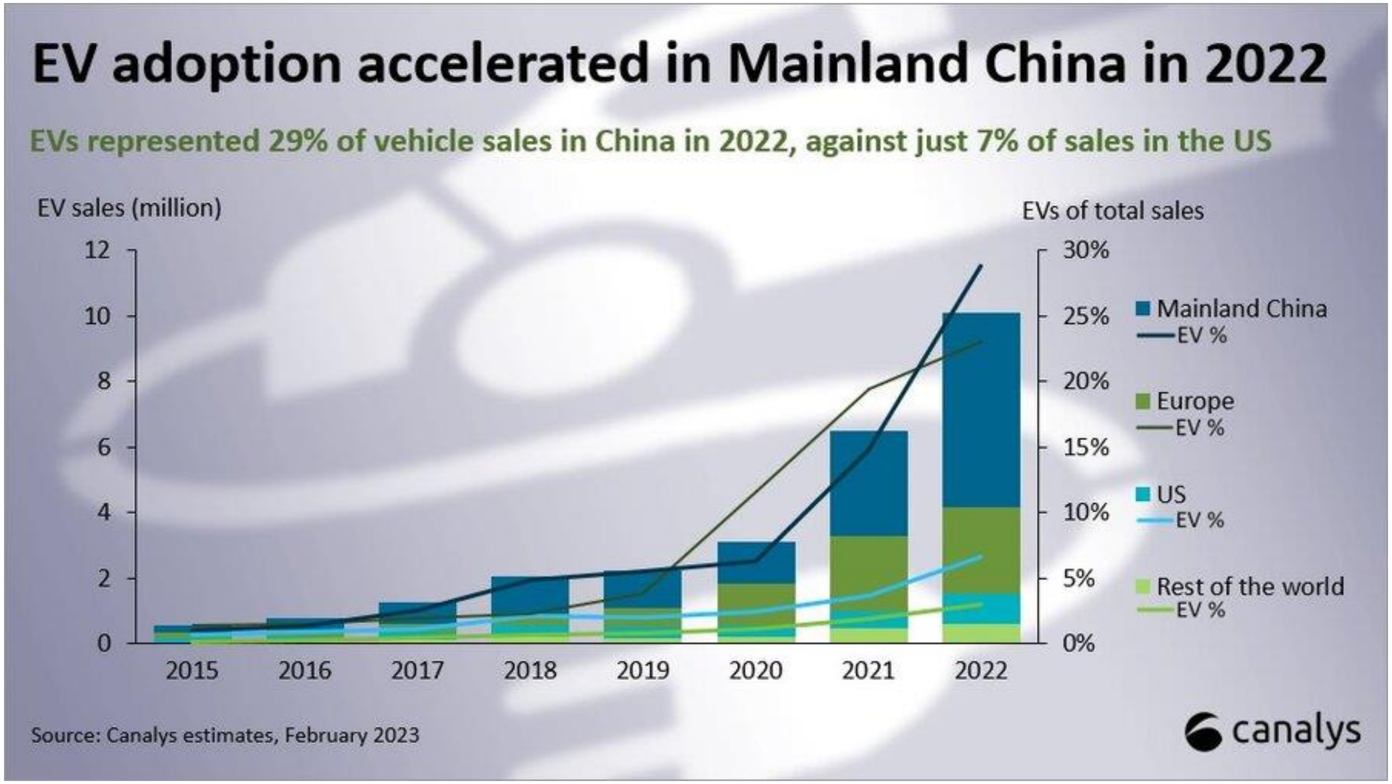
2022 Worldwide No. H_2 filling stations

Handwriting on the wall: **Government regulations/incentives to drive combustion-engined vehicles to extinction between 2035-2050**

https://www.statista.com/statistics/1026719/number-of-hydrogen-fuel-stations-by-country/

Is There a Future for Electric Vehicles?

The future is here! *EV Adoption Grew by 55% to 10.1 M in 2022*



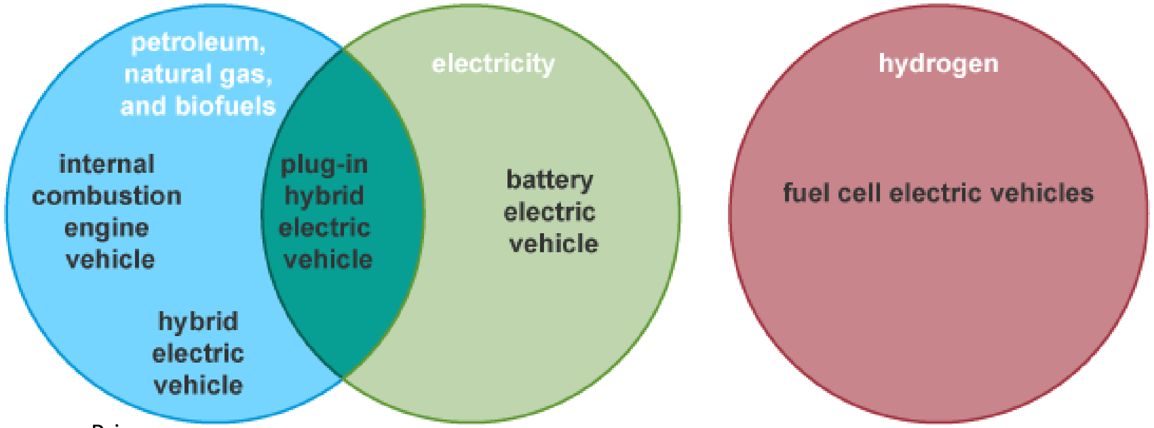
Source: Canalys estimates, February 2023

- **Mainland China: 5.9 million units ~ 60% of EVs sold worldwide. Represents 29% of all light vehicles sold in region, up from 15% in 2021.**
- **Europe has 26% share and 2.6 million units sold.**
- **US has 9% share, but rapid growth, with 920,000 EVs sold, up 72%.**

https://www.canalys.com/newsroom/global-ev-sales-2022

What are Electric Vehicle Options?

Fuel use by vehicle type



petroleum, natural gas, and biofuels

electricity

hydrogen

internal combustion engine vehicle

plug-in hybrid electric vehicle

battery electric vehicle

fuel cell electric vehicles

hybrid electric vehicle

Prius

eia Source: U.S. Energy Information Administration

Tesla S

Toyota Mirai

EV Sales Breakdown by Type & Location

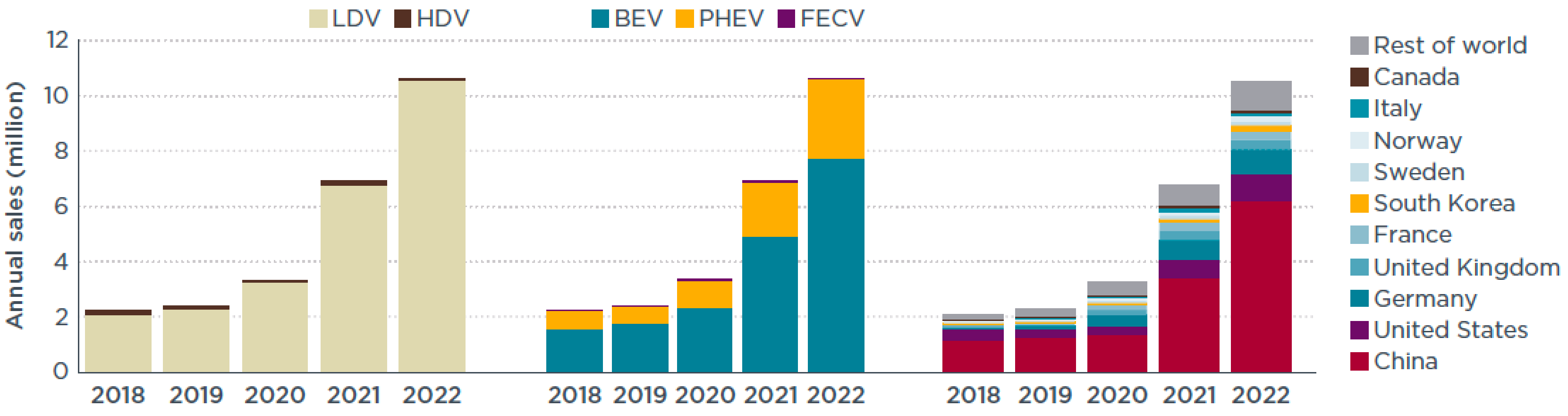
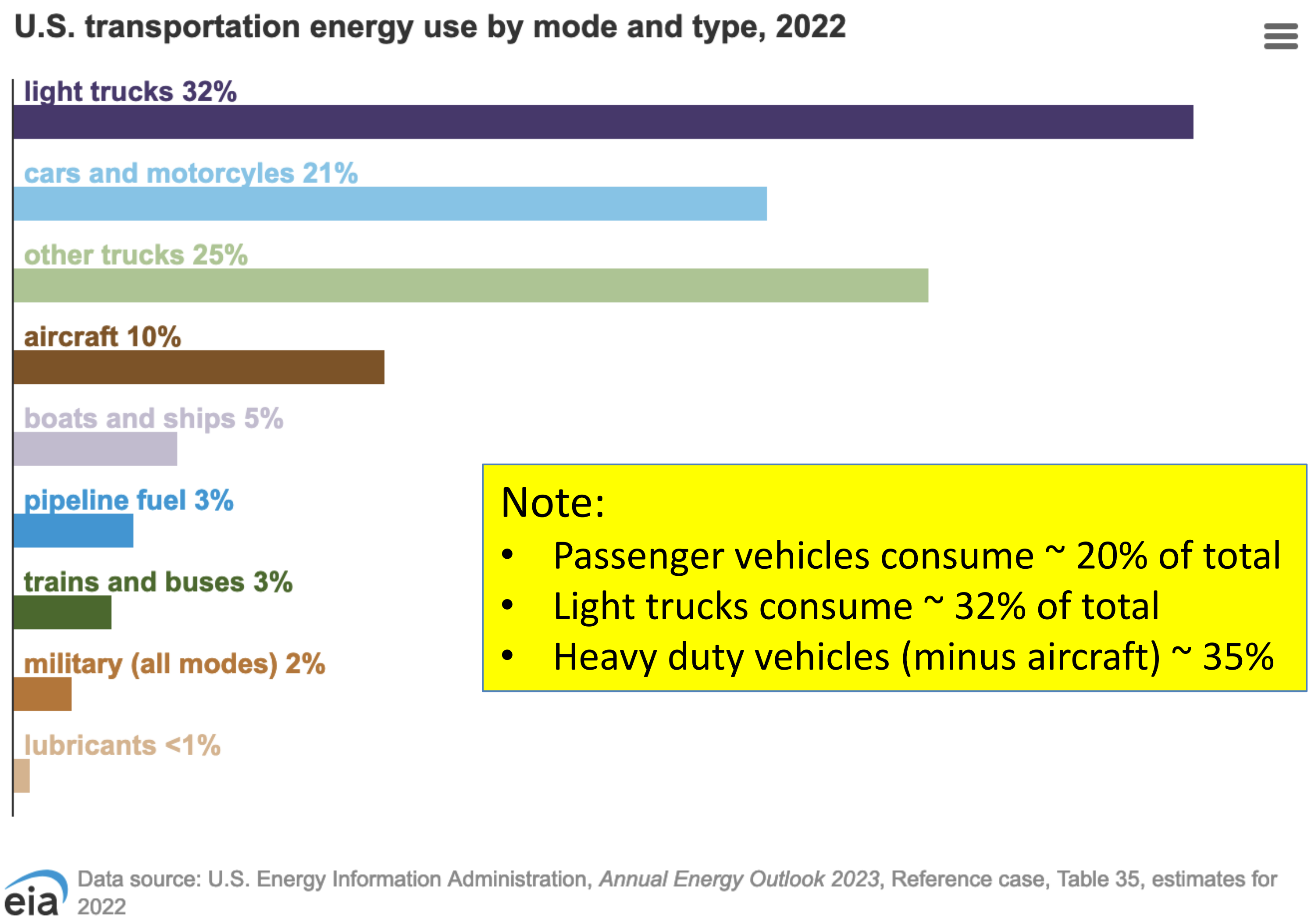


Figure 1. Annual electric vehicle sales globally by vehicle category (left), technology pathway (middle), and market (right) from 2018 to 2022.

- **Light-duty vehicles (LDVs)** and heavy-duty vehicles (HDVs)
- **Battery electric vehicles (BEVs),** plug-in hybrid electric vehicles (PHEVs), and hydrogen fuel cell electric vehicles (FCEVs).
- EVs hit milestone in 2022 with **10 million** in annual **EV sales**, 54% increase from 2021.

Y. Chu & H. Cui, Annual update on the global transition to electric vehicles: 2022, Int. Council on Clean Transportation, 2023.

US Transportation Energy Use



Data source: U.S. Energy Information Administration, *Annual Energy Outlook 2023*, Reference case, Table 35, estimates for 2022

Note:

- Passenger vehicles consume ~ 20% of total
- Light trucks consume ~ 32% of total
- Heavy duty vehicles (minus aircraft) ~ 35%

https://www.eia.gov/energyexplained/use-of-energy/transportation.php

Heavy Duty Vehicle Breakdown

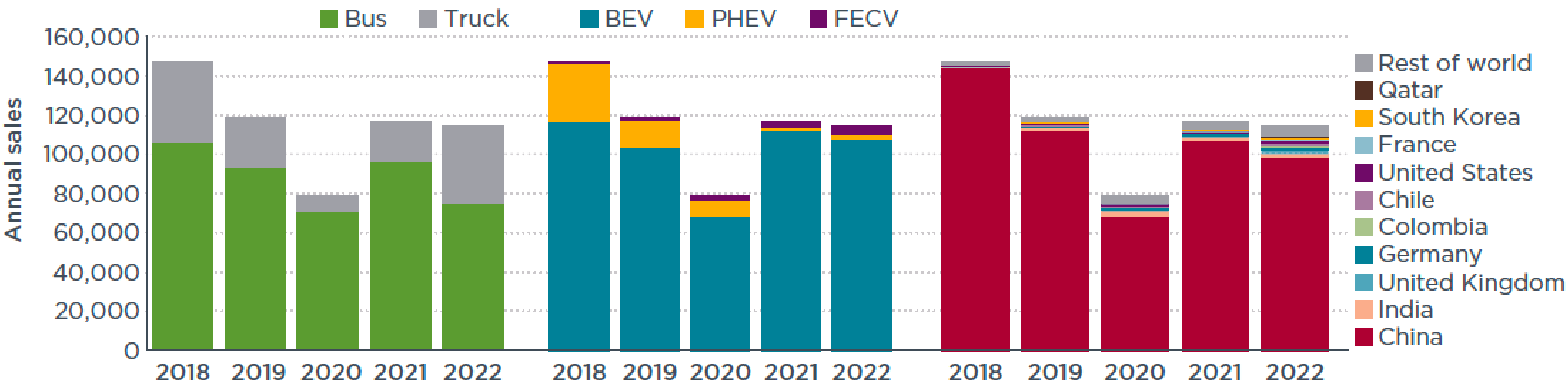


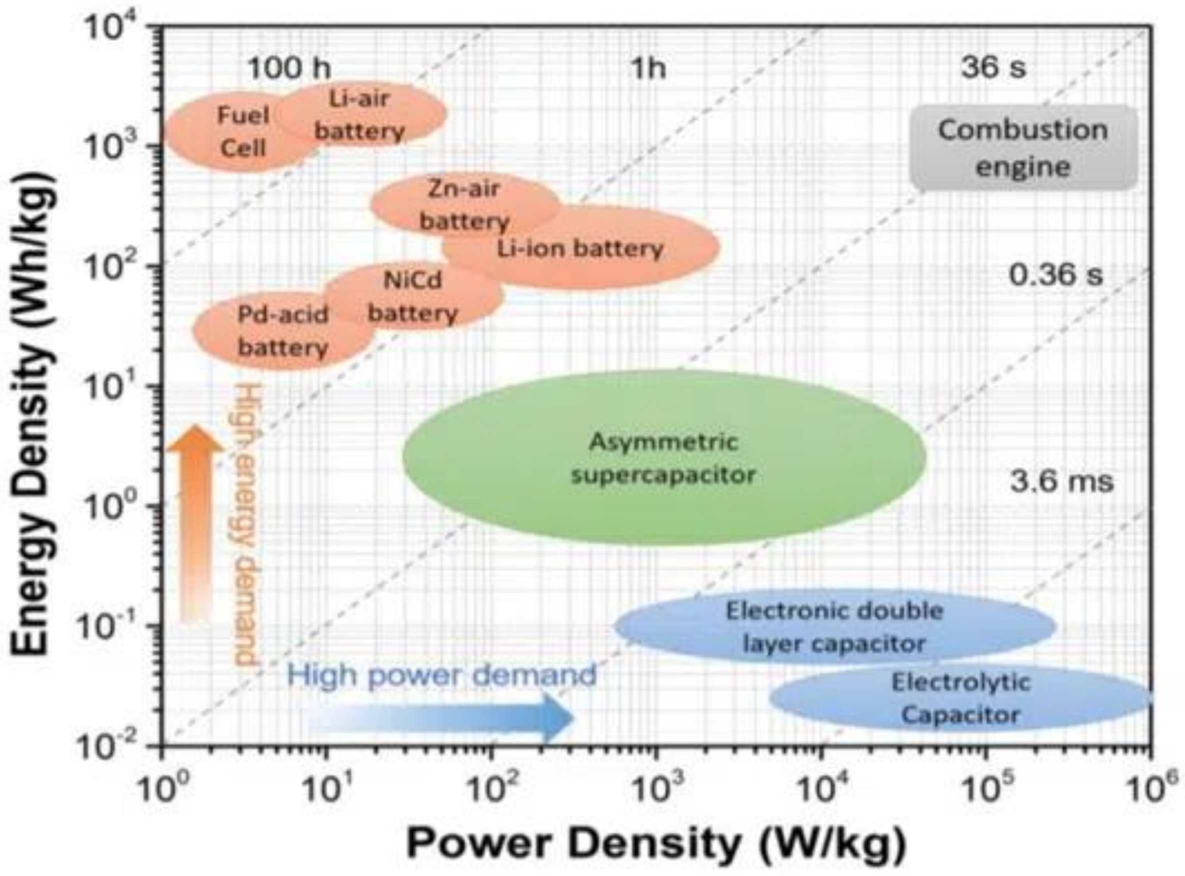
Figure 2. Annual electric heavy-duty vehicle sales by vehicle type (left), technology pathway (middle), and market (right) from 2018 to 2022.

- Electric LDVs comprised 99% of global EV sales for the year, with the other 1% were electric HDVs.
- HDVs however consume large fraction of transportation in Energy sector
- FCEV opportunities lie most strongly with HDVs – ***let's see why***

Y. Chu & H. Cui, Annual update on the global transition to electric vehicles: 2022, Int. Council on Clean Transportation, 2023.

Transportation - Specific Energy/Power – Why so difficult to get off alcohol wagon?

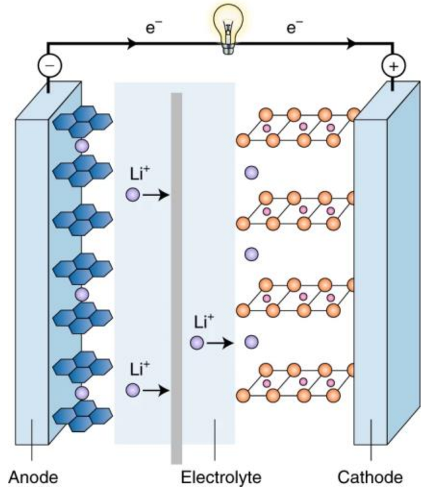
Ragone plot



Energy density – extended ***range*** with fuel cells
Power density - increased ***acceleration*** with batteries

Y. Shao, et al Chem. Rev. (2018)

High Energy Density Batteries – Self Contained

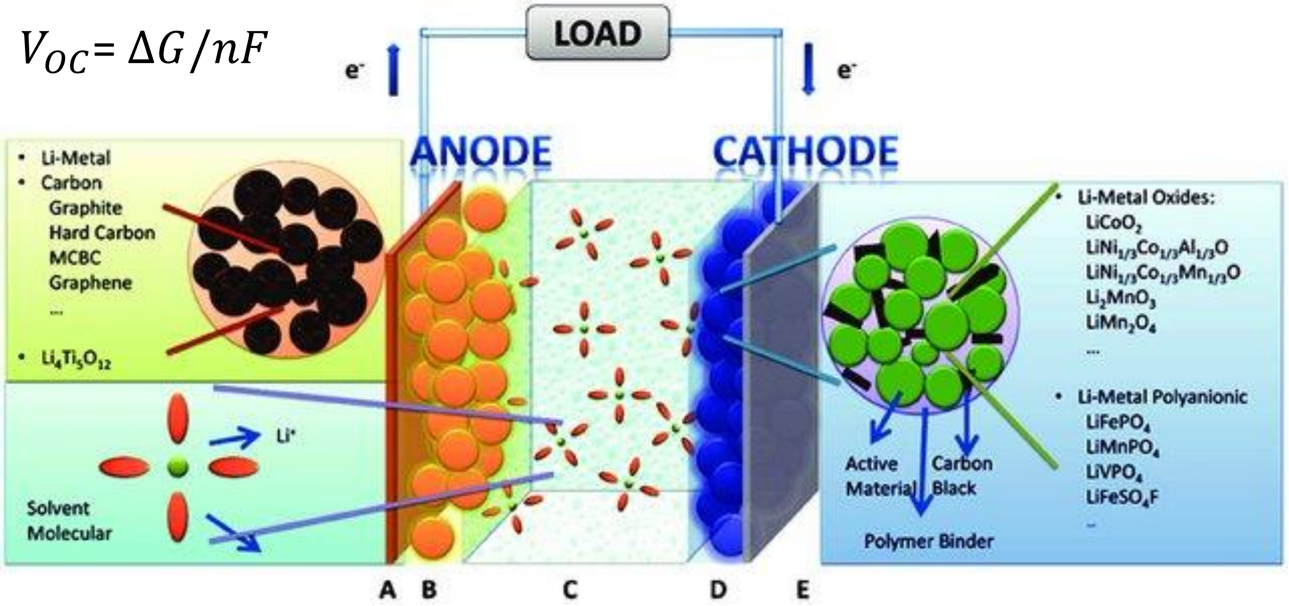


Goodenough, J.B. *Nat Electron* **1**, 204 (2018)

<u>Key parameters:</u>

- Open circuit voltage V_{OC}
- Capacity mAh/g *(Range)*
- Maximum discharge rates *(Acceleration)*
- Maximum charge rates *(Charging times)*
- Resistance to dendrite formation (*life*)
- Electrolyte chemical stability *(Safety?)*
- Critical materials content (e.g. Co, Ni, Li)

$V_{OC} = \Delta G / nF$



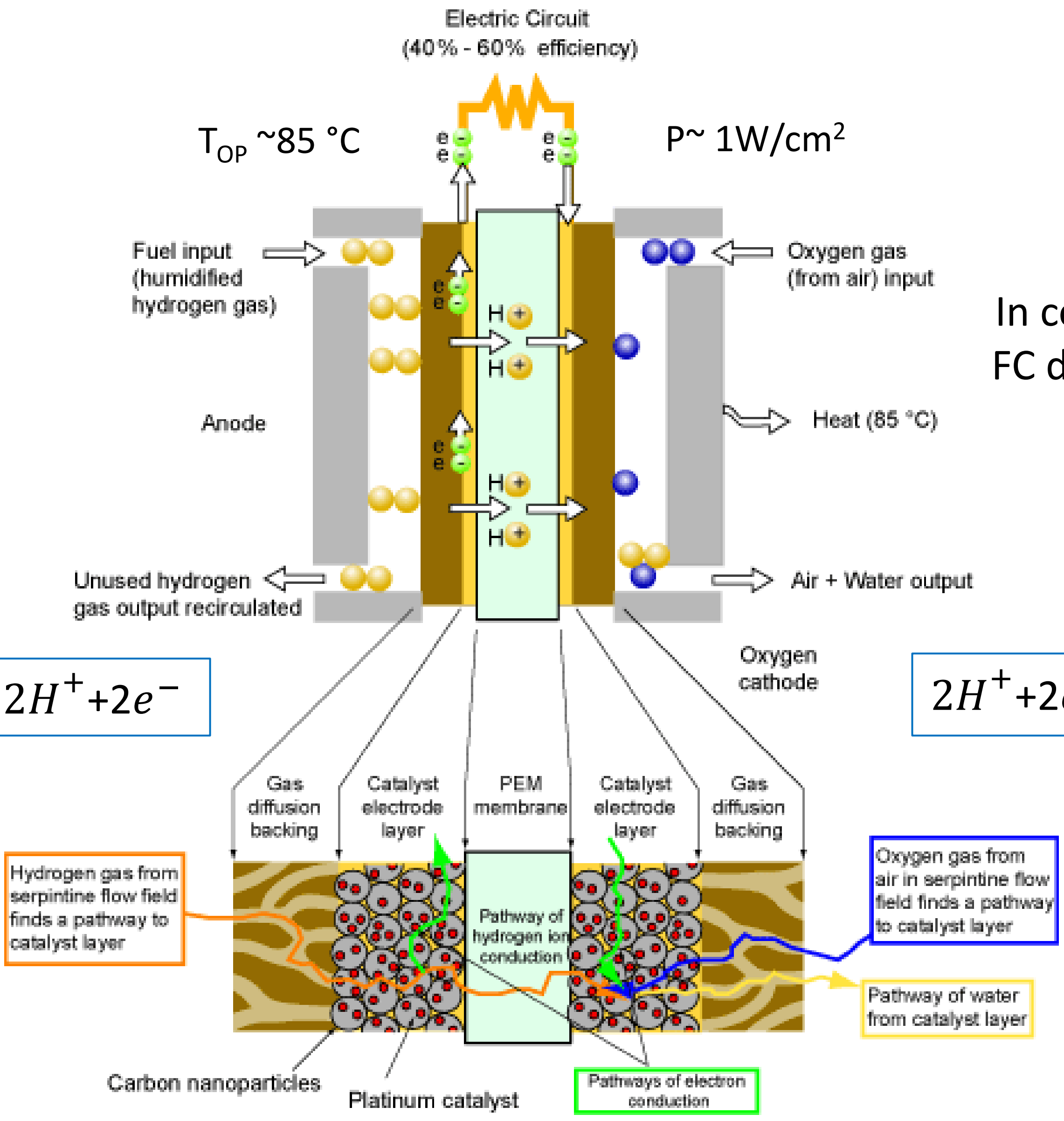
G. Jian et al, Chinese Phys B 25, 018210 (2016)

Moving towards all solid-state batteries

Polymer Electrolyte Membrane (PEM) Fuel Cell

T_{OP} ~85 °C

P~ $1 W/cm^2$



Note:
In contrast to battery,
FC doesn't carry both
"reactants"

$$H_2 \rightarrow 2H^+ + 2e^-$$

$$2H^+ + 2e^- + \tfrac{1}{2}O_2 \rightarrow H_2O$$

http://physics.nist.gov/MajResFac/NIF/pemFuelCells.html

Why PEMFC?

Polymer Electrolyte Membrane - PEM

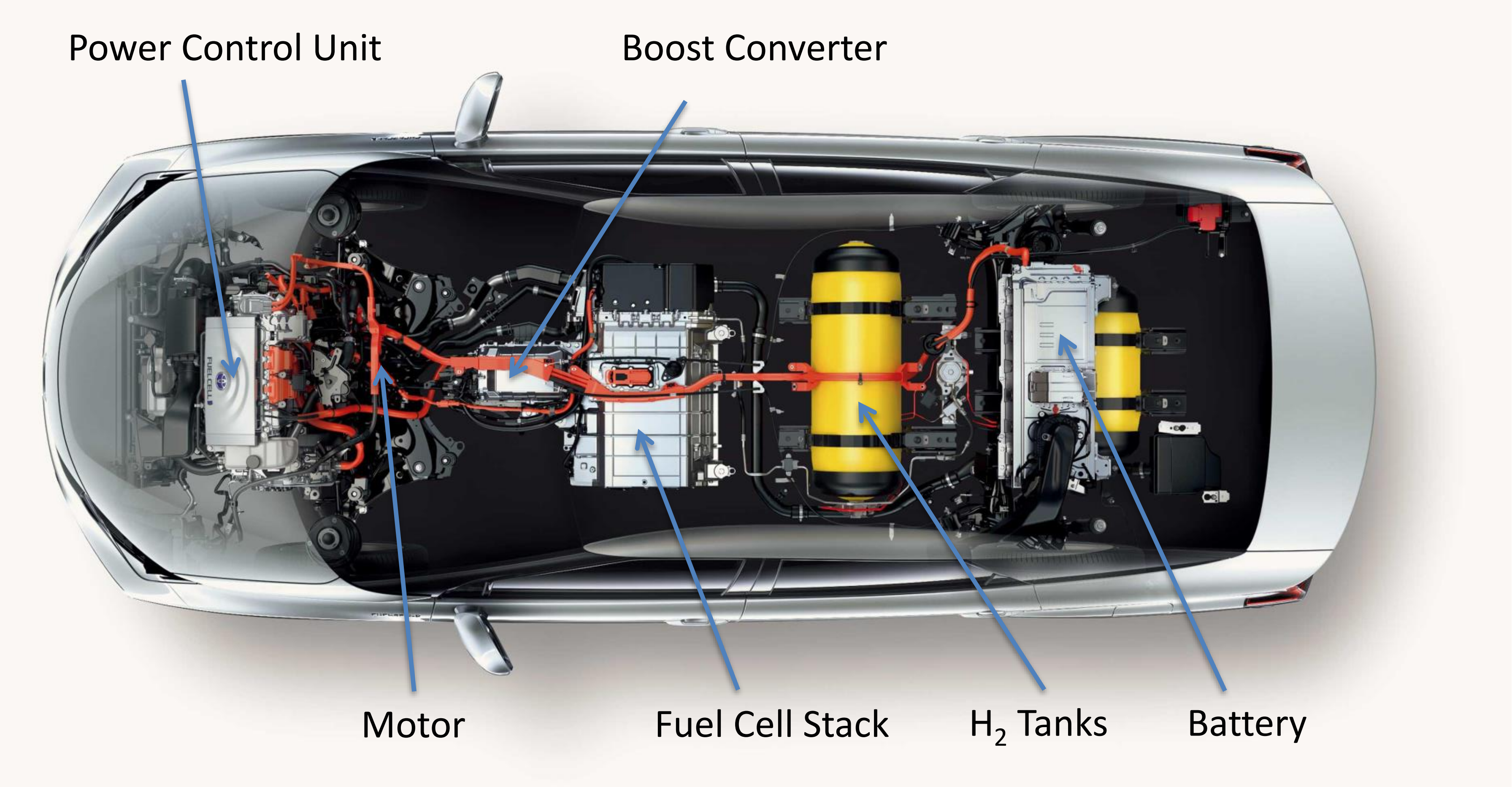
Advantages:

- High power density – *long range*
- Good start – stop capabilities
- Low temperature operation – suitable for portable applications
- *Scalable to large vehicles*

Disadvantages:

- Costly platinum catalysts/degrades
- Costly polymer membrane
- Active water management required
- Poor CO and S tolerance of Pt catalyst.
- *Require hydrogen refueling stations!*

Anatomy of Fuel Cell Vehicle



https://ssl.toyota.com/mirai/fcv.html

Toyota Mirai Fuel Cell Powered Car

- 800 km range
- 3 min refueling time
- -30°C cold-start

Roughly 2100 Mirai’s solid in 2022 in US

Lack of hydrogen Refueling Infrastructure!

Hydrogen - Electric Grid Infrastructure

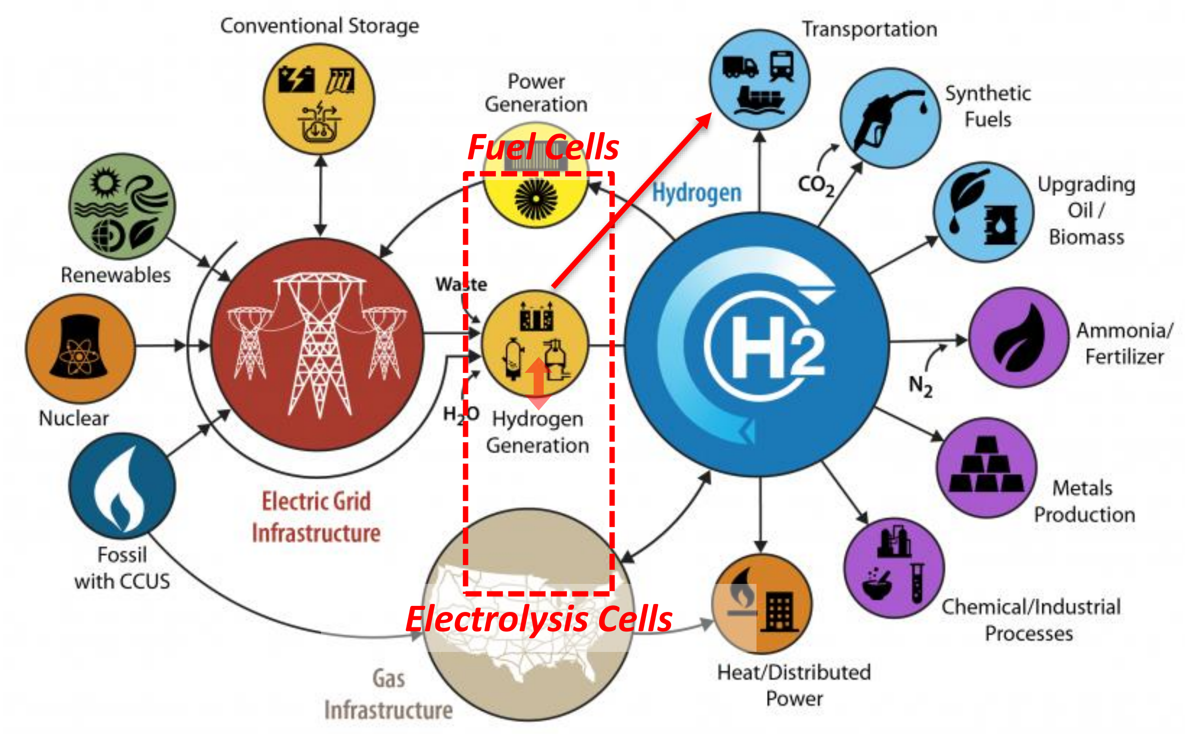
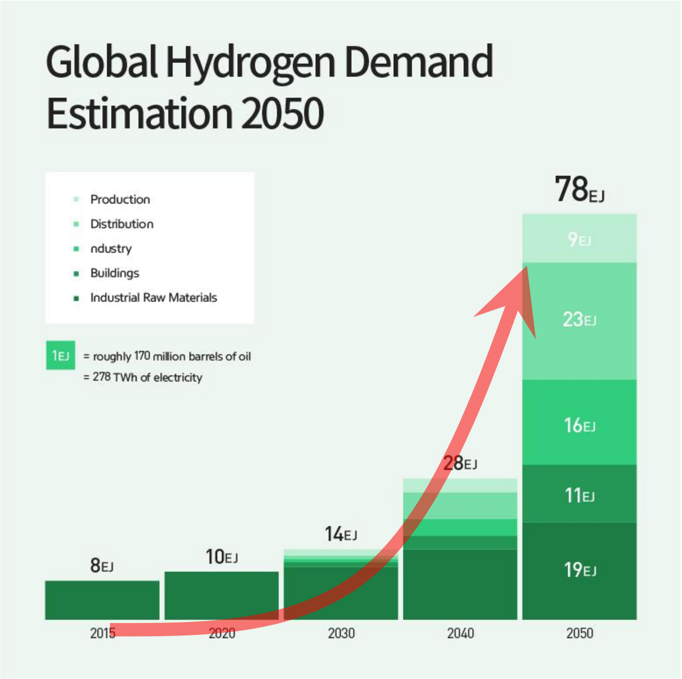
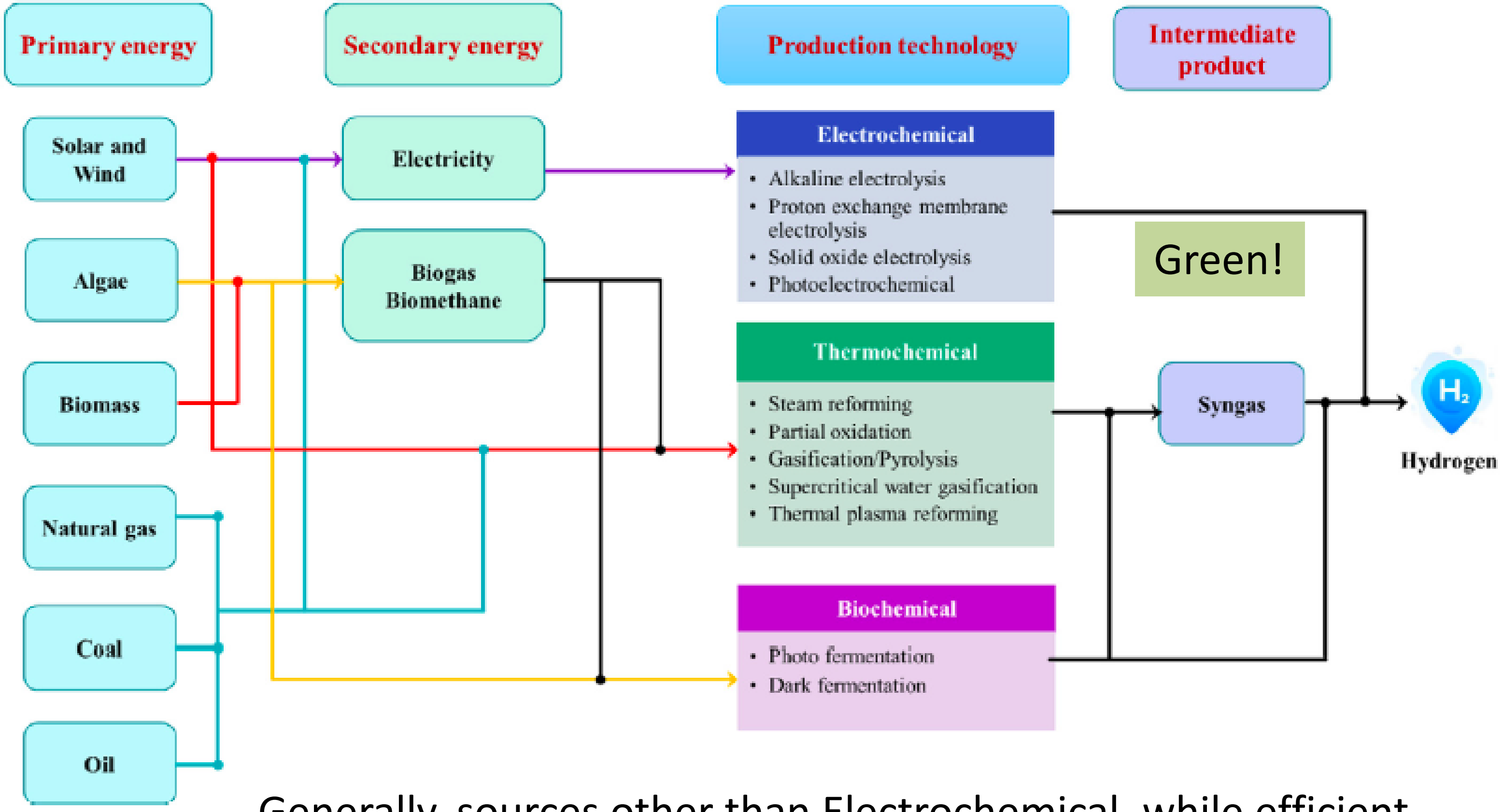


Image: *H_2@Scale, U.S. Department of Energy*



Hyundai Motor Group 2020

Hydrogen Sourcing & Distribution Channels



Green!

Generally, sources other than Electrochemical, while efficient and readily transported, lead to high CO_2 emissions

- **SMR**: CO_2 emissions of around **8-10 kg CO_2 per kg of H_2 produced**
- **Coal gasification:** CO_2 emissions of around **14-15 kg CO_2 per kg of H_2 produced**

Steam-Methane Reforming Reaction
$CH_4 + H_2O$ (+heat) → $CO + 3H_2$
Water-Gas Shift Reaction
$CO + H_2O$ → $CO_2 + H_2$ (+small amount of heat)

Halder et al, Int J Hydrogen Energy, in press (2023);
https://www.hydrogennewsletter.com/gh2-facts/

Green Hydrogen Generation

International Renewable Energy Agency (IRENA)

- Hydrogen: low carbon and ultimately **green from outset**. **Electrolysis** of water using renewable electricity. Key for *long-haul transport, shipping and aviation*, green steel & chemicals.
- *Low-cost electricity essential* for producing competitive green hydrogen;
- *Major reductions in costs of electrolysis plants* needed with 40% reductions in the short term to 80% in the long term.
- *Fundamental breakthroughs needed* in addition to standardization, economies of size and scale-up.

Doesn’t address hydrogen transport challenges!

↓

On-site hydrogen generation at refueling stations

IRENA (2020), Green Hydrogen Cost Reduction: Scaling up Electrolysers to Meet the 1.5°C Climate Goal, International Renewable Energy Agency, Abu Dhabi. ISBN: 978-92-9260-295-6

Hi-T Solid Oxide Electrolysis/Fuel Cells

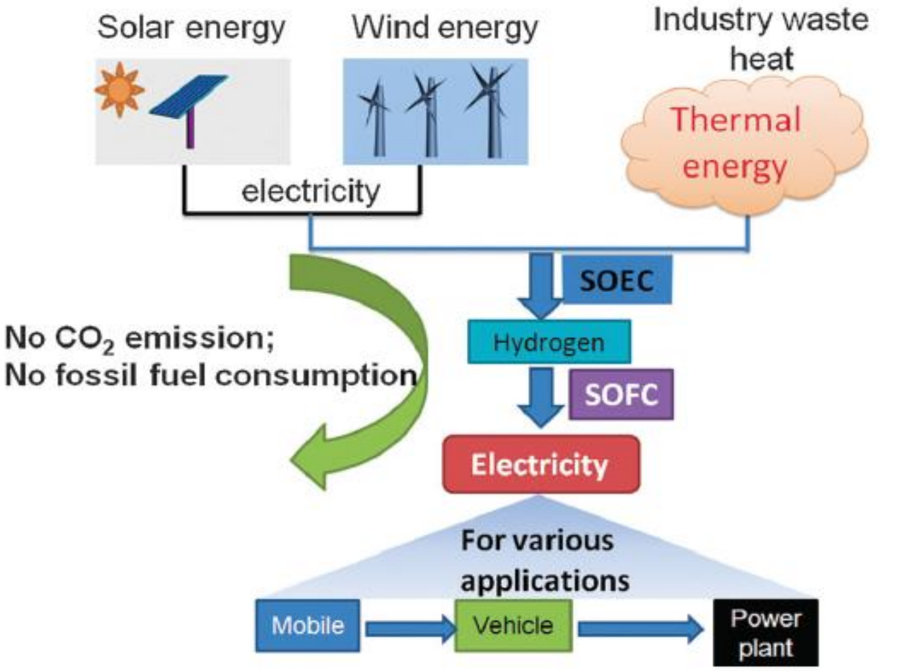
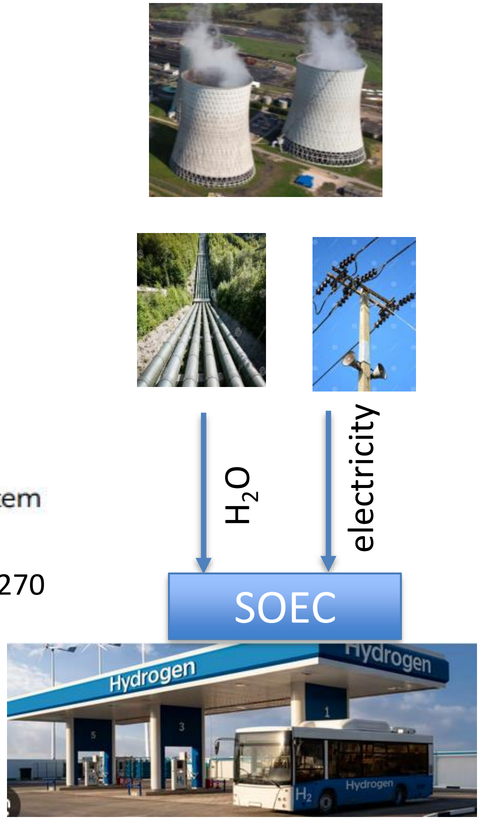


Fig. 2 Concept diagram of applications of a sustainable energy system based on SOEC/SOFC technology.

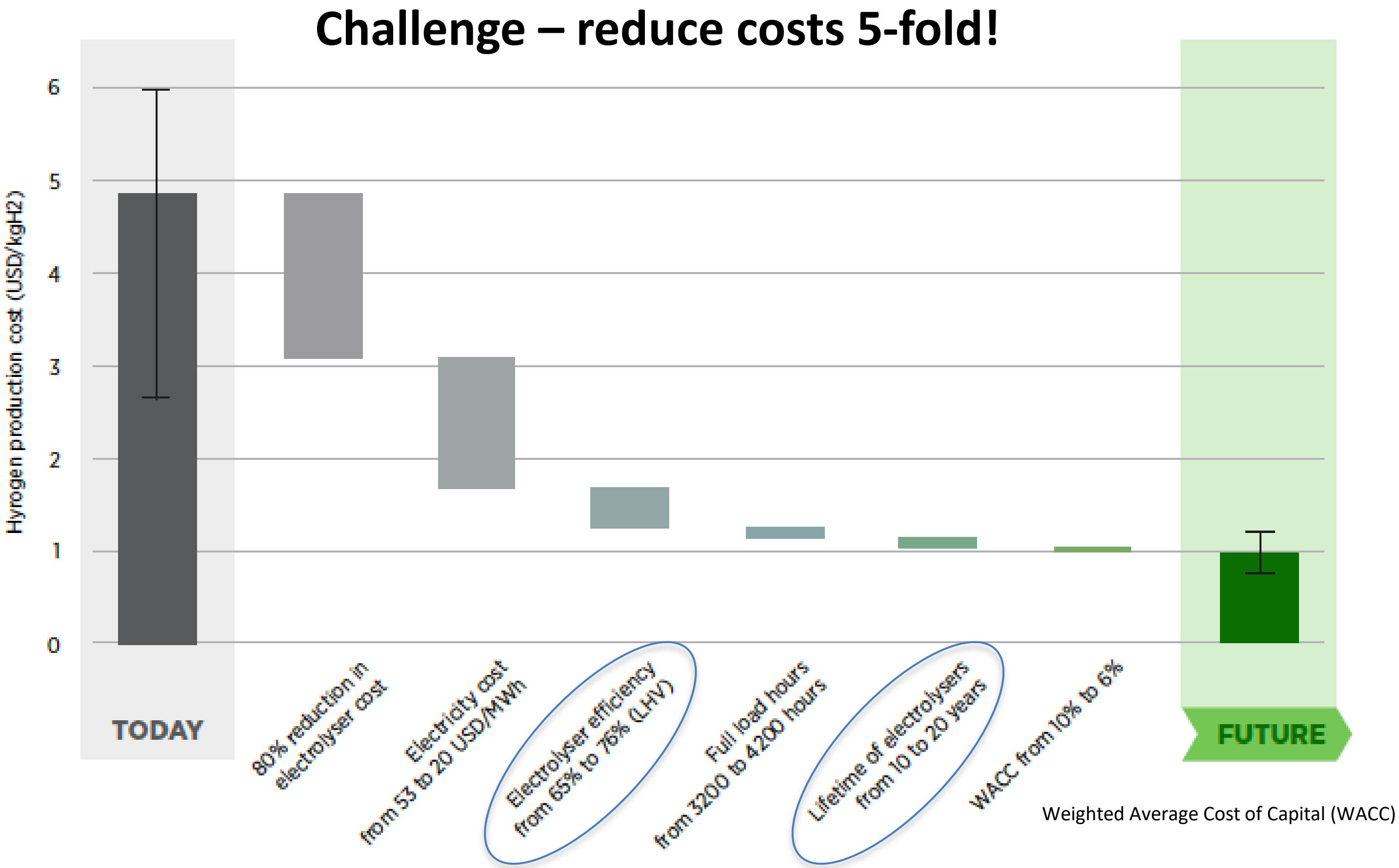
L. Bi, S. Boulfrad and E. Traversa, Chem. Soc. Rev., 2014, 43, 8255--8270



"On site generation"

- Reduced electrical energy demand
- No need for costly and sensitive noble metal catalysts
- Resistant to CO & SO_2
- No water management issues
- Reversable operation – key for energy storage of intermittent sources

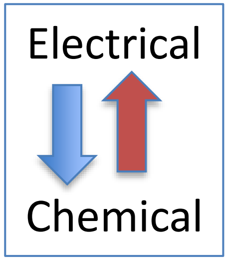
Projected H_2 Production Cost Reductions - Electrolyzers



Note: 'Today' captures best and average conditions. 'Average' signifies an investment of USD 770/kilowatt (kW), efficiency of 65% (lower heating value – LHV), an electricity price of USD 53/MWh, full load hours of 3200 (onshore wind), and a weighted average cost of capital (WACC) of 10% (relatively high risk). 'Best' signifies investment of USD 130/kW, efficiency of 76% (LHV), electricity price of USD 20/MWh, full load hours of 4200 (onshore wind), and a WACC of 6% (similar to renewable electricity today).

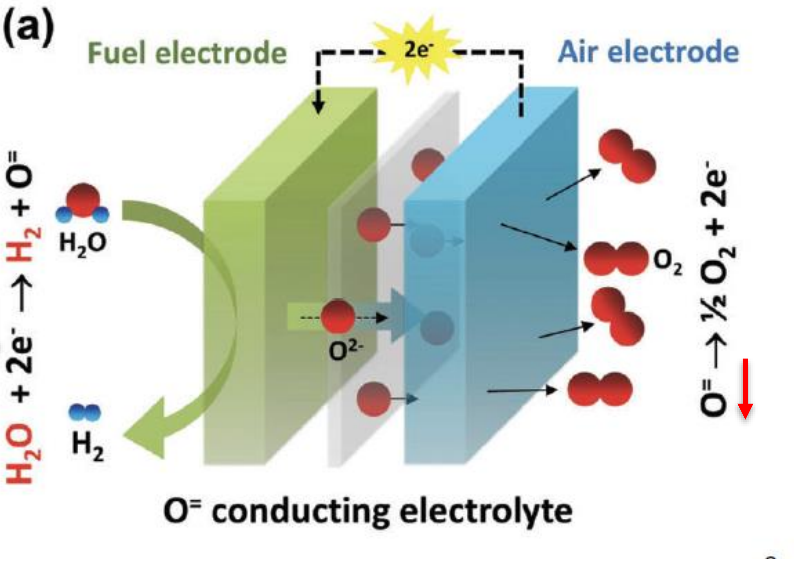
IRENA (2020), Green Hydrogen Cost Reduction: Scaling up Electrolysers to Meet the 1.5ºC Climate Goal, International Renewable Energy Agency, Abu Dhabi. ISBN: 978-92-9260-295-6

Back to Fundamentals



Electrical

Chemical



S. Choi, T.C. Davenport, S. Haile,
Energy Environ. Sc. 12, 206 (2019)

$$1/2\, O_2 + V_o^{\cdot\cdot} + 2e^- \leftrightarrow O_o^X$$

k – Surface exchange reaction coefficient

$$j_O = -\boldsymbol{k_O}(C_{O,\text{atmosphere}} - C_{O,surface})$$

- *Efficiency depends on:*

- Low overpotentials- losses at electrodes – susceptible to poisons.
- Low ohmic resistance of solid electrolyte.

- *Device **lifetime** depends on sensitivity to electrode “poisons”:*

- *Device **cost** depends on component materials criticality*

DOE Targets on SOFCs

Metric	Current	2020 Target	2025/2030 Target
System Cost (100 kW- 1MW)	**>$12,000/kWe**	**$6,000/kWe**	**$900/kWe**
Single Cell Degradation	0.2 - 0.5% per 1,000 hrs		
Cell Manufacturing Approach	Batch	Semi- Continuous	Continuous
System Degradation	**1 – 1.5% per 1,000 hrs**	**0.5 - 1.0% per 1,000 hrs**	**<0.2% per 1,000 hrs**
Fuel Reformation	Primarily external natural gas conditioning/reforming	100% integrated natural gas reformation inside cell stack	
Durability	**<2,000 hrs**	**5,000 hrs**	**5 [illegible]**
Platform	Proof-of-[illegible]	Prototype/Pilot	DG: Commercial Pilot
Configuration	Breadboard/Integrated system	Fully packaged	Fully packaged
Fuel	**Natural gas**	**Natural gas** [illegible]	**Natural gas** [illegible]
Demonstration Scale	**50 kWe – 2[illegible]**	[illegible]	**DG: MWe-class** **Utility-scale: 10 – 50 MWe**

Table: Dr. Shailesh Vora, "U.S. DOE Office of Fossil Energy Solid Oxide Fuel Cell (SOFC) Program", 2019 Fuel Cell Seminar and Exposition

If not resolved, high degradation rates are potentially show stoppers for SOFC technology to be broadly *accepted*

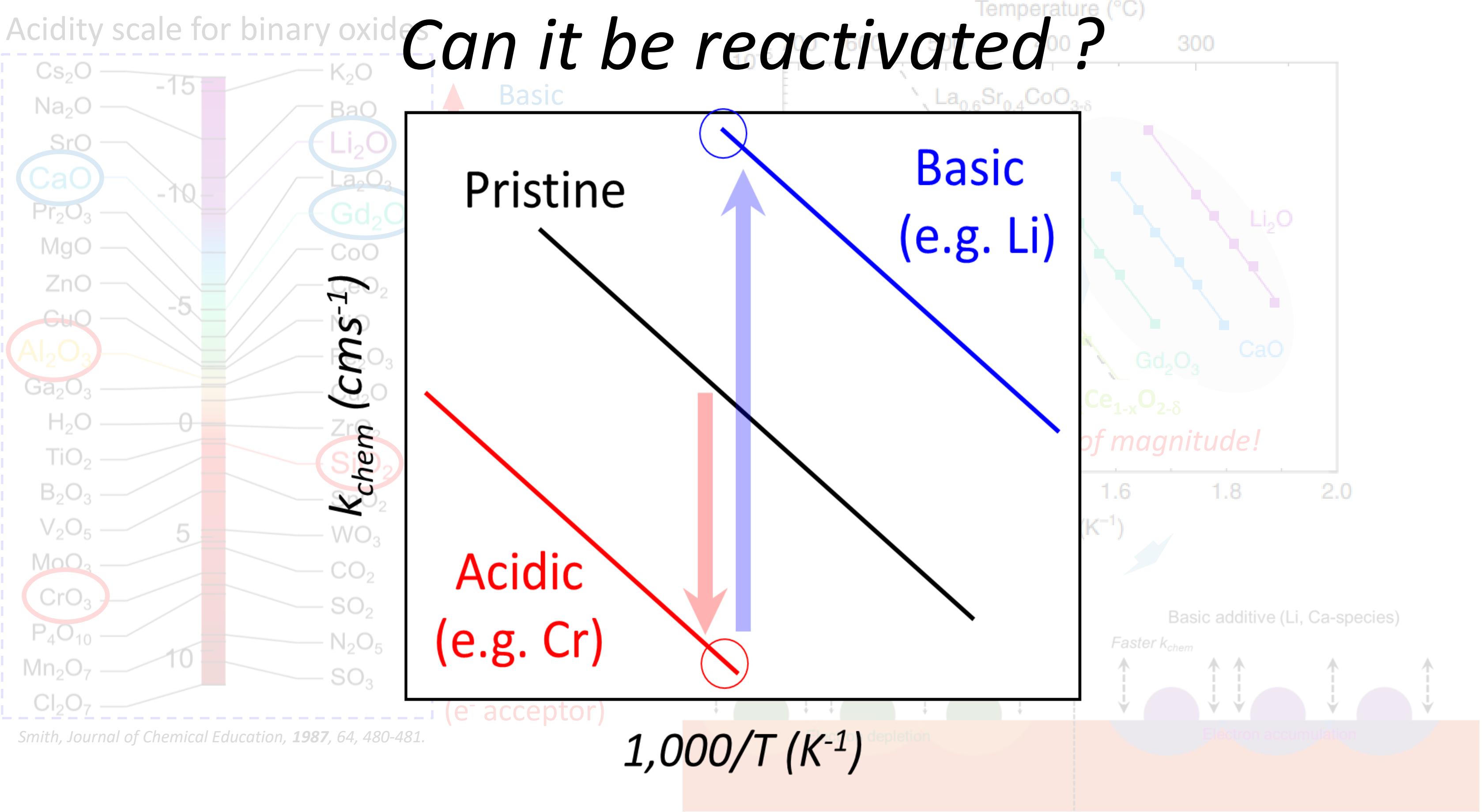
But also

Need to minimize use of critical materials to reduce costs and insure reliable supply

How to address these problems in a novel way?

Identified Descriptor Controlling Oxygen Exchange Rate: Acidity of Surface Additives

Can it be reactivated ?

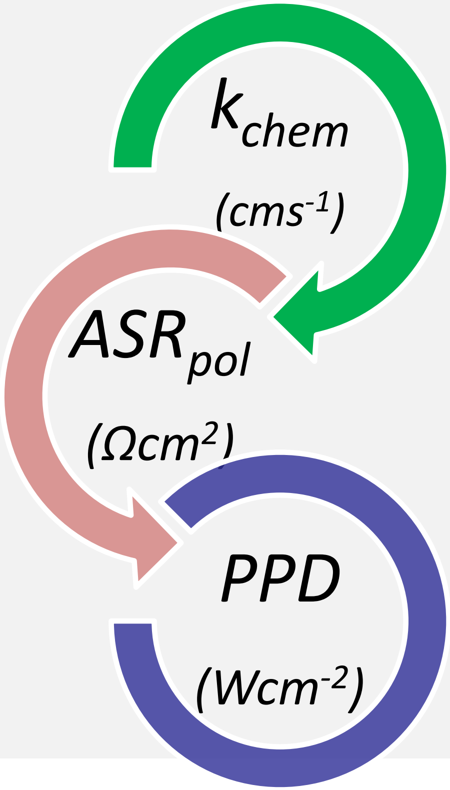


Smith, Journal of Chemical Education, 1987, 64, 480-481.

Clement Nicollet, Cigdem Toparli, George F. Harrington, Thomas Defferriere, Bilge Yildiz and Harry L. Tuller, Nature Catalysis, 3, 913-920 (2020)
Patent Pending

Approach

- Demonstrate ability to recover Cr-driven degradation in surface activity with serial infiltration of basic additives



k_{chem}

(cms^{-1})

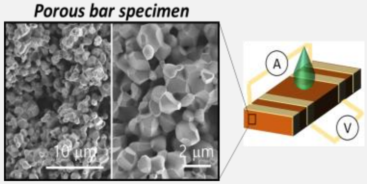
ASR_{pol}

(Ωcm^2)

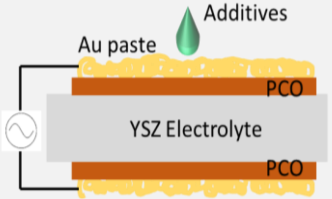
PPD

(Wcm^{-2})

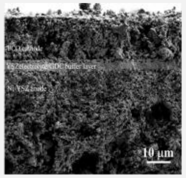
- Conductivity relaxation measurements
- *Porous bar* $(\sigma \propto P_{O_2}^{\pm\frac{1}{x}})$

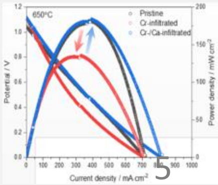

Porous bar specimen

- Electrochemical impedance spectroscopy (EIS)
- *Distribution of relaxation time (DRT)*
- *Screen-printed symmetric cells*

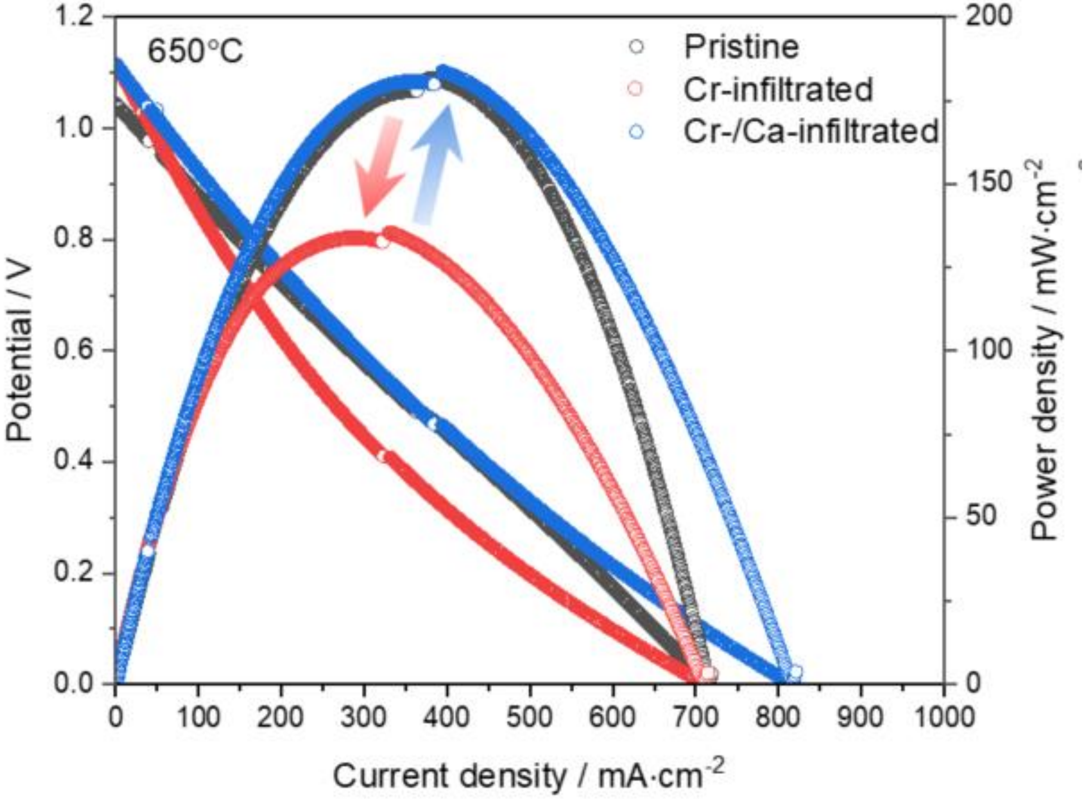


- Current-Voltage-Power curves (I-V-P)
- *Anode-supported single cells*



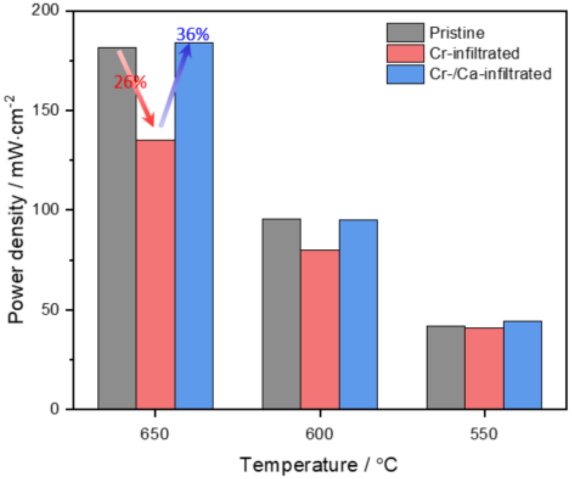


Demonstration of Cell Performance with Controlled Acidity



Measurement conditions

- *Humidified H_2 at anode*
- *Synthetic air at cathode*
- *Temperature: 650-550°C*



✓ More than 35% recovery of degraded power density!

H. G. Seo, H.L. Tuller, *et al., J. Power Sources.,* ***2022***

Hydrogen Powered Vehicles – Forever Technology of the Future?

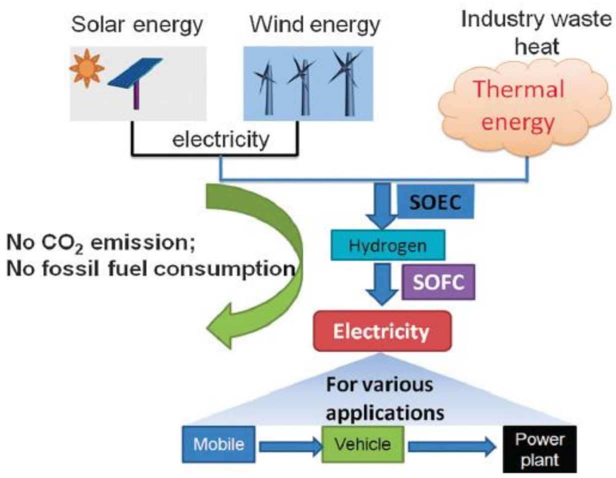
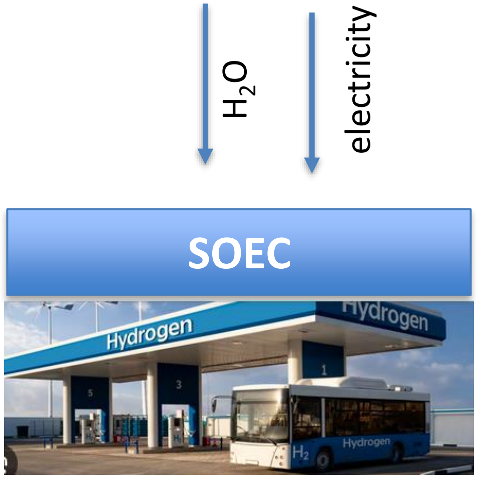


Fig. 2 Concept diagram of applications of a sustainable energy system based on SOEC/SOFC technology.



On-site generation (one man's vision!)

Long range heavy vehicles

Acknowledgements – Acidity/Basicity Research


nature catalysis ARTICLES

Acidity of surface-infiltrated binary oxides as a sensitive de… in mixed co…

Journal of Materials Chemistry A REVIEW

Silica: ubiquitous poison of metal oxide interfaces

The Influence of Cr-Additives on the Polarization Resistance of Praseodymium-Doped Ceria Cathodes for Solid Oxide Fuel Cells

Energy & Environmental Science COMMUNICATION

Reactivation of chromia poisoned oxygen exchange kinetics in mixed conducting solid oxide fuel cell electrodes by serial infiltration of lithia

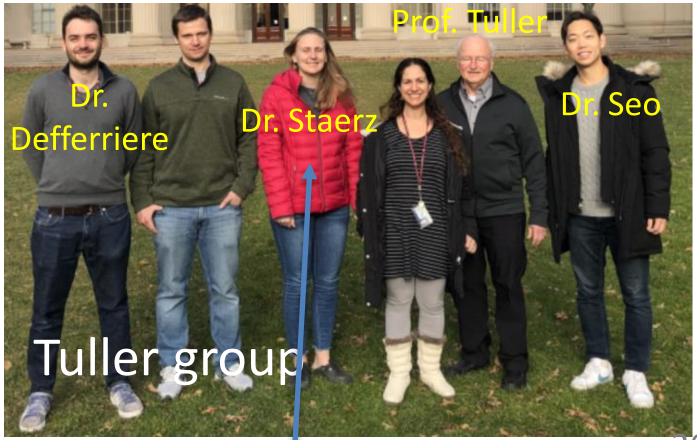
Collaborators: Profs. J. LeBeau; B. Yildiz

NATIONAL ENERGY TECHNOLOGY LABORATORY

Thank you for your attention!!

Dr. Nicollet

Nantes

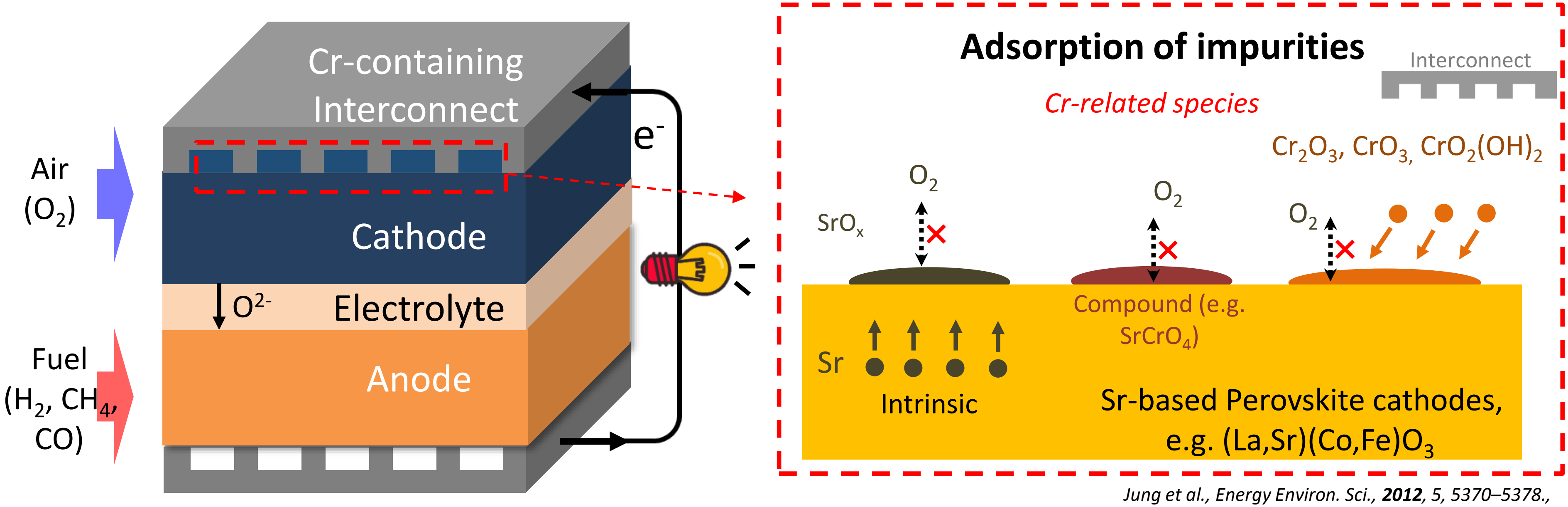


Colorado School of Mines

Questions?

Solid Oxide Fuel Cells (SOFCs) and Cr-poisoning

$$1/2\,O_2 + V_O^{\cdot\cdot} + 2e^- \leftrightarrow O_O^X$$



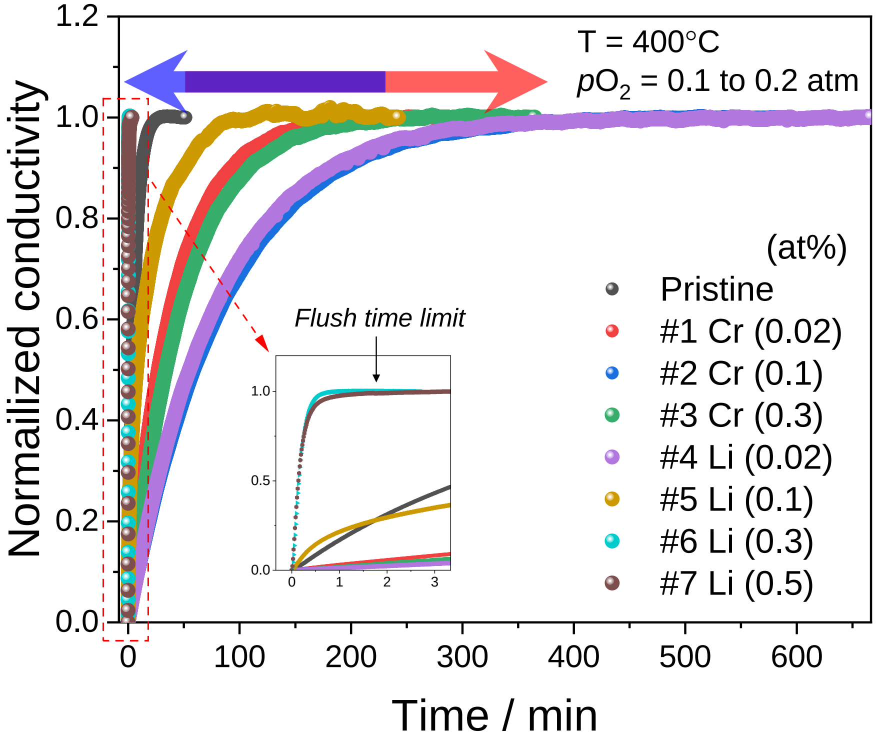
Jung et al., Energy Environ. Sci., ***2012****, 5, 5370–5378.,*
Chen et al., Faraday Discuss., ***2015****, 182, 457-476*

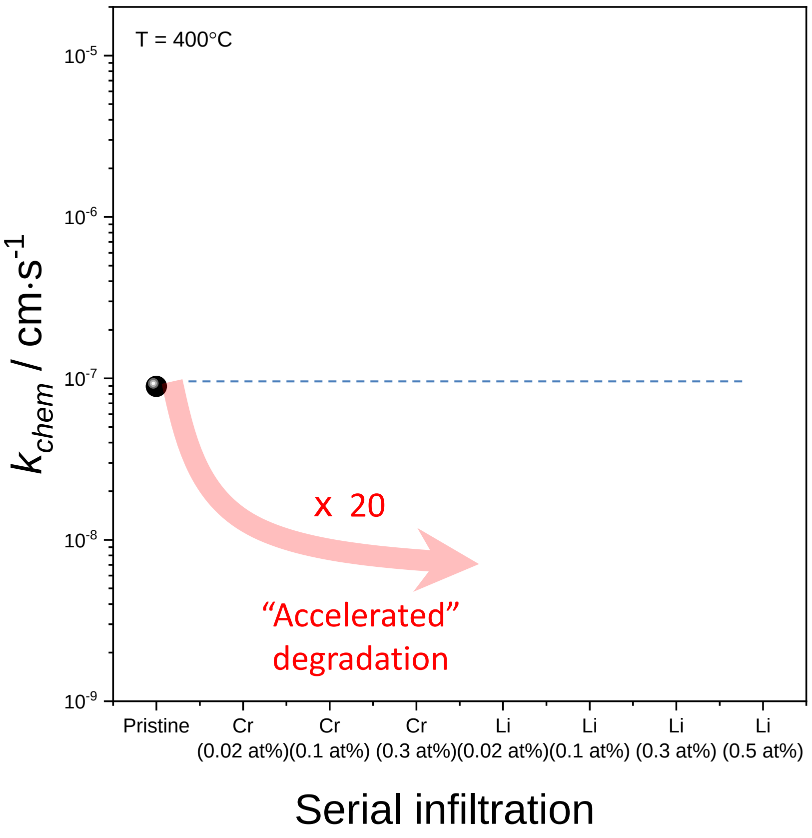
- Cr-containing interconnects
- Chemical degradation by Cr-impurities
- Largest source of degradation in SOFCs

> *To date, the main source of Cr-induced degradation remains controversial.*

Keep in mind: 1. initial performance, 2. rate of performance degradation, 3. critical materials

Cr-Poisoning & Recovery: Serial Infiltration with Li





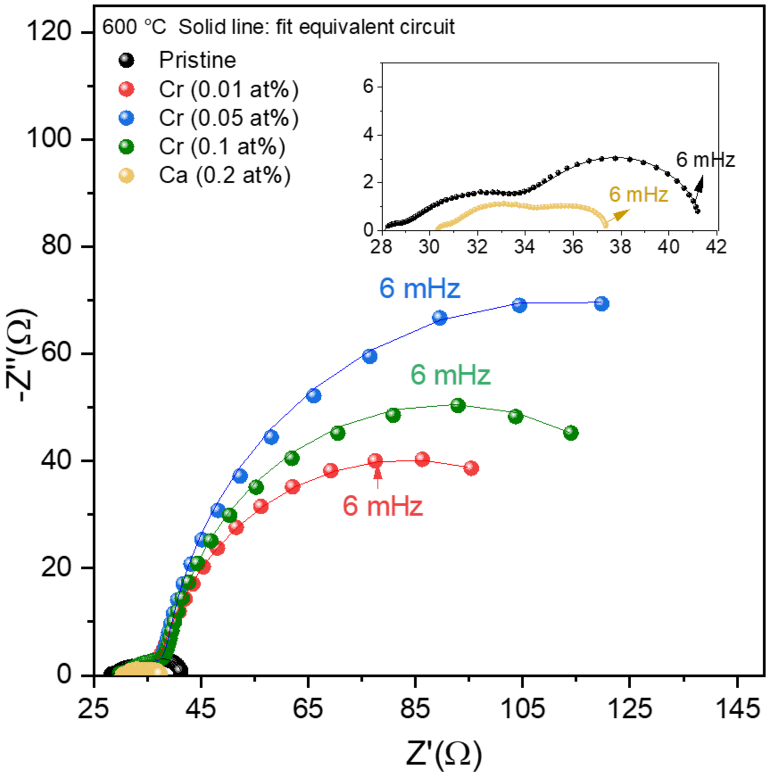
*__H. G. Seo, H.L. Tuller__ et al., Energy Environ. Sci., **2022**, 15, 4038*

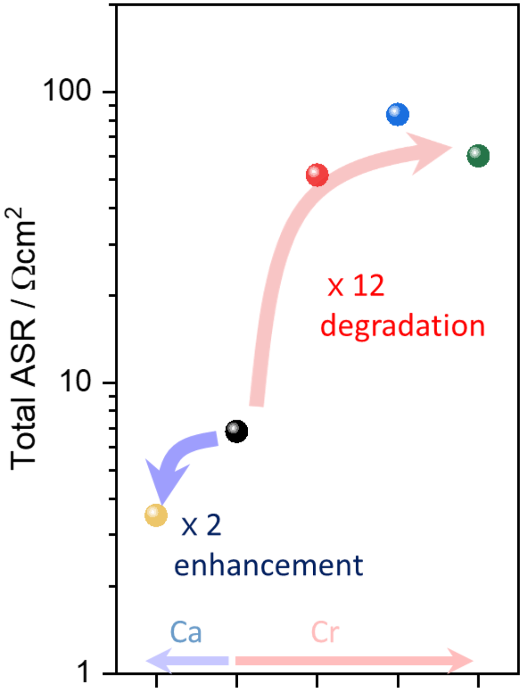
Patent Pending

Surface Additive-Induced ORR Activity

Basic additives can lead to enhanced performance!

Non-serial infiltration



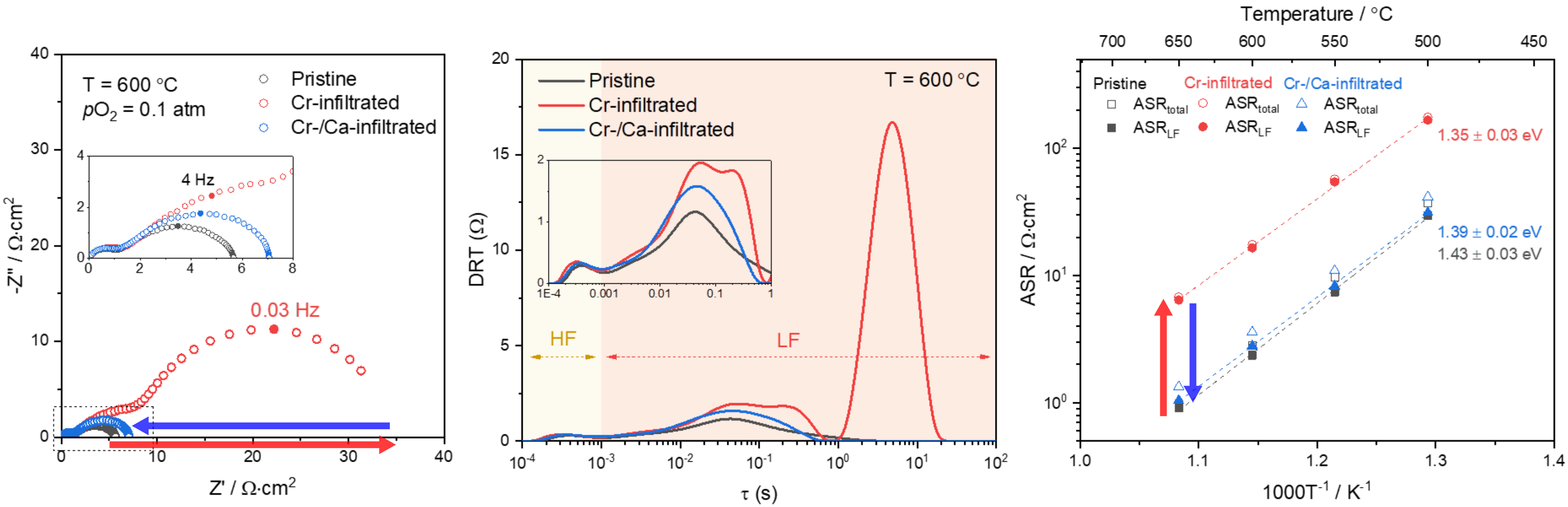


Massachusetts Institute of Technology

*A. Staerz, H. G. Seo, H.L. Tuller, et al., J. Electrochem. Soc., **2022**, 169, 044530*

Can Ca-Additives Reactivate Cr-Poisoned Surface?

Symmetric cells



Cr-additives significantly impeded rate of oxygen reduction, leading to increases in ASR.
Remarkedly, degraded ASR can be recovered by addition of Ca-additives.

H. G. Seo, H.L. Tuller, *et al., J. Power Sources.,* ***2022***

Conclusions

Demonstrated with controlled acidity:

- *Enhanced performance*
- *Extended life*
- *Reduced dependence on critical materials*

"IMPACT": Accelerate ability to bring wide range of technologies to market!