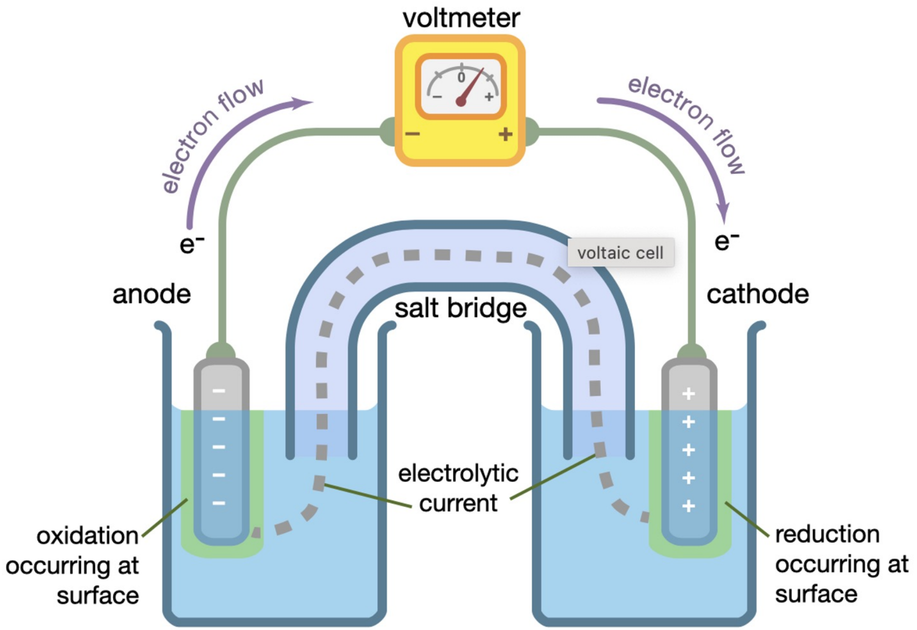
# $H_2$ fuel cell slides

# Basic Components of an Electrochemical Cell

- Anode- Site of oxidation
- Cathode- Site of reduction
- Salt Bridge- Pathway for ion transport

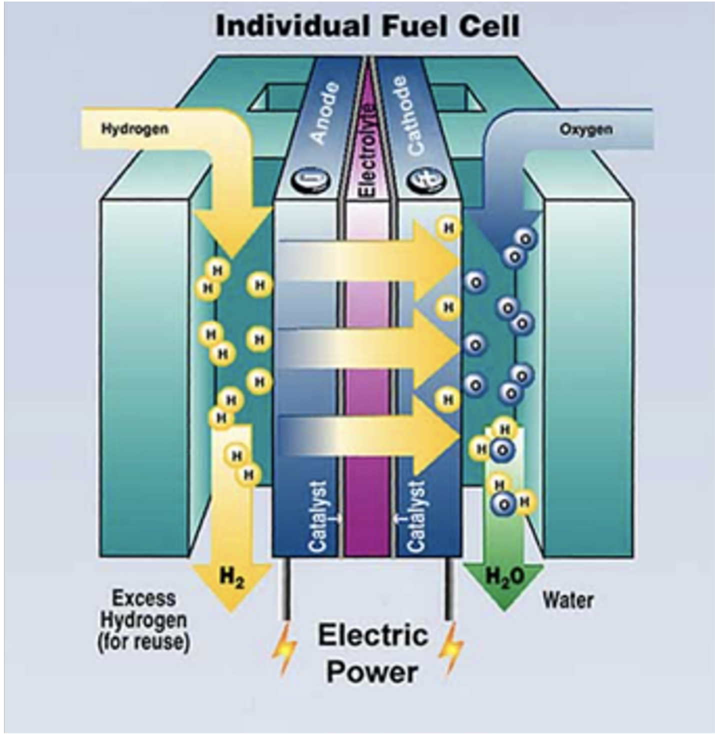
- Electrochemical Potential:
  - Energy per change
  - Varies with position in cell
  - Cell potential: $E_{cathode}$- $E_{anode}$

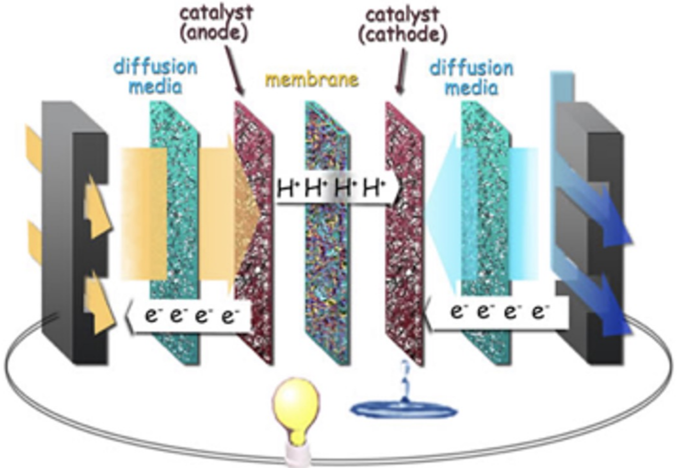


# Hydrogen Fuel Cell Overview

https://www.youtube.com/watch?v=08ZH7vwzzEg

# Hydrogen Fuel Cells




Anode – oxidation

$2H_2 \rightarrow 4H^+ + 4e^-$ $E^\circ = 0$ V

Cathode – reduction

$O_2 + 4H^+ + 4e^- \rightarrow 2H_2O$ $E^\circ = 1.2$ V

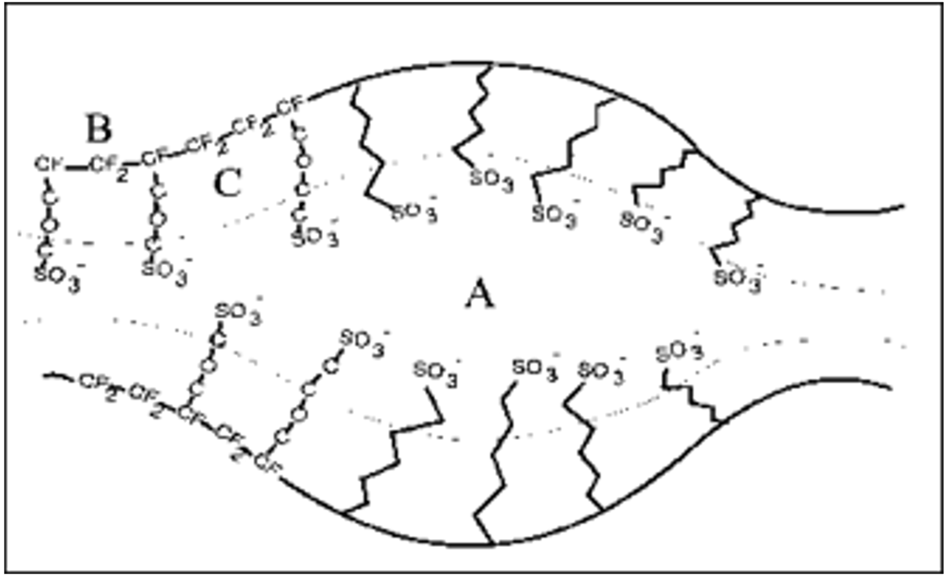
Overall:

$$O_2 + 2H_2 \leftrightarrow 2H_2O \quad E^0_{cell} = 1.2V$$

# HFC Proton-Exchange Membrane (PEM)

Nafion

- The membrane is a fluoropolymer between the anode and cathode so hydrogen ions can pass through, but not $H_2$ or $O_2$



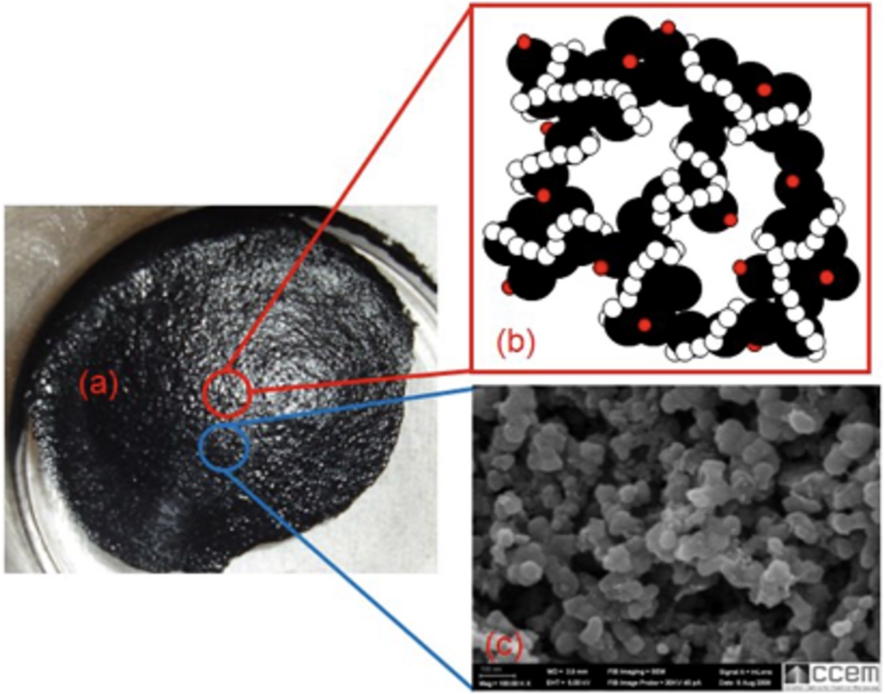
# Electrode-Catalyst Design

- Platinum electrode-catalyst with nanoparticles dispersed with carbon

- Polymer wrapped around to transport hydrogen

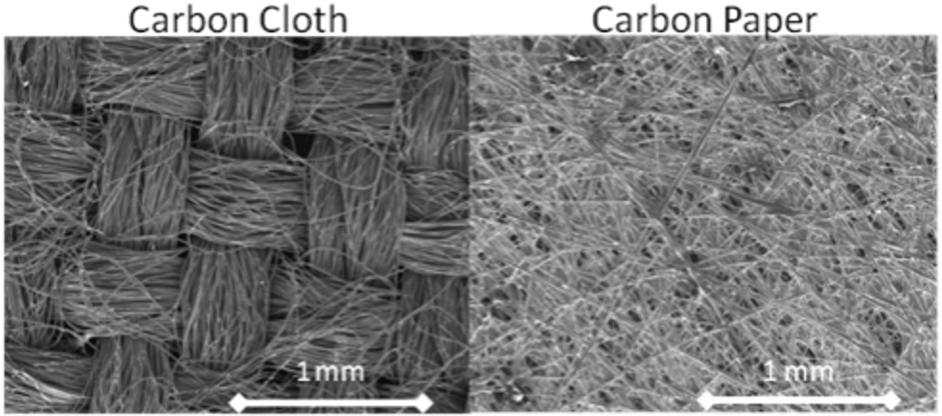
- Platinum serves as the catalyst

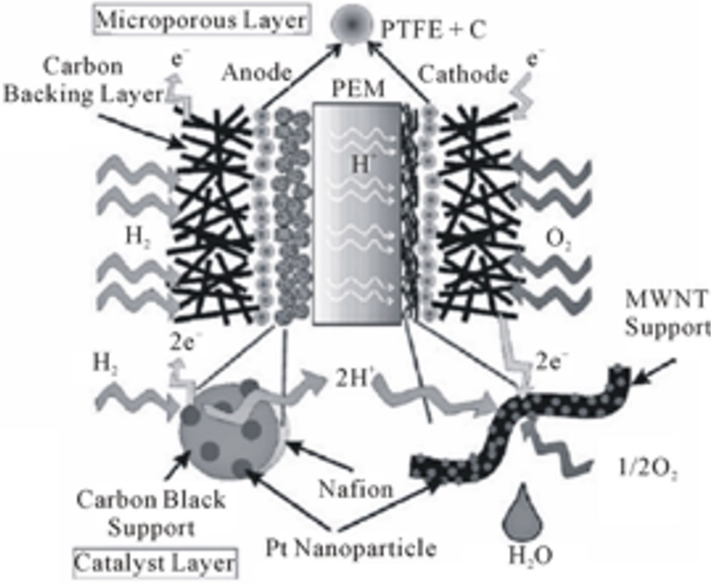
- Nanoparticles maximizes surface area and decrease weight



# Gas Diffusion Layer

- Facilitates transport of reactants and removes the product, water
- Fabricated from carbon fiber sheets coated with PTFE (Teflon)

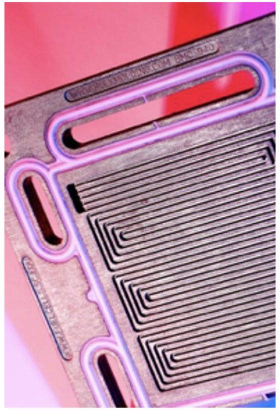


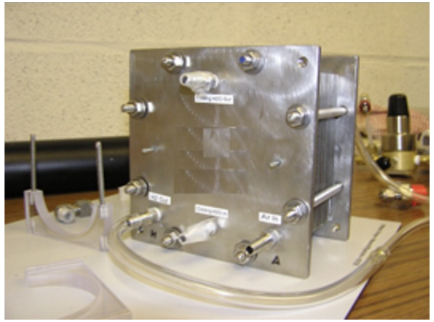



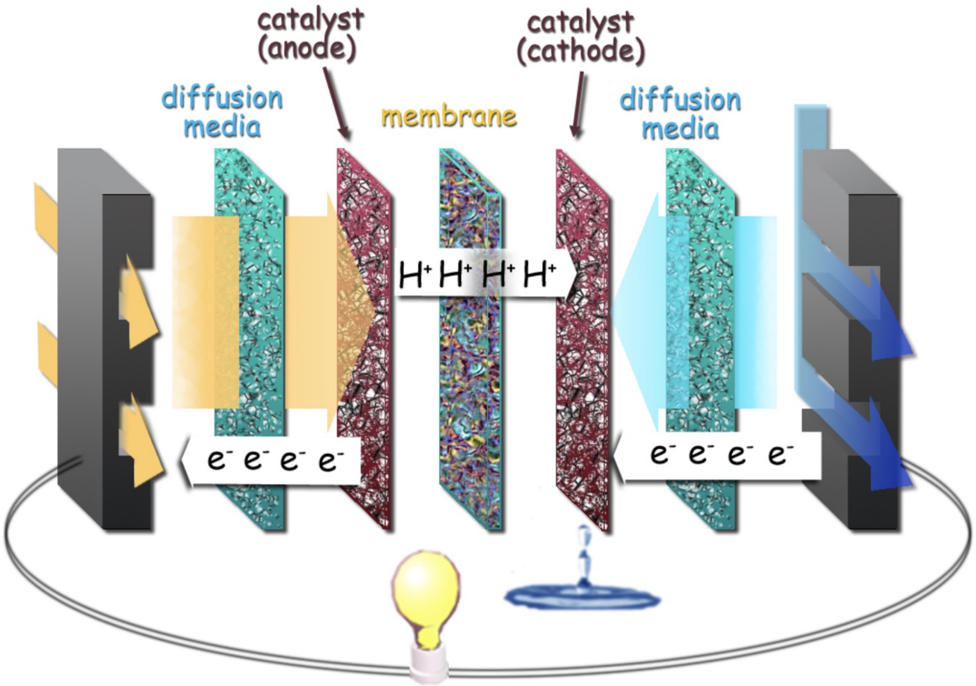
# Structure of a Hydrogen Fuel Cell

- Grooved plate design allows flow of gas

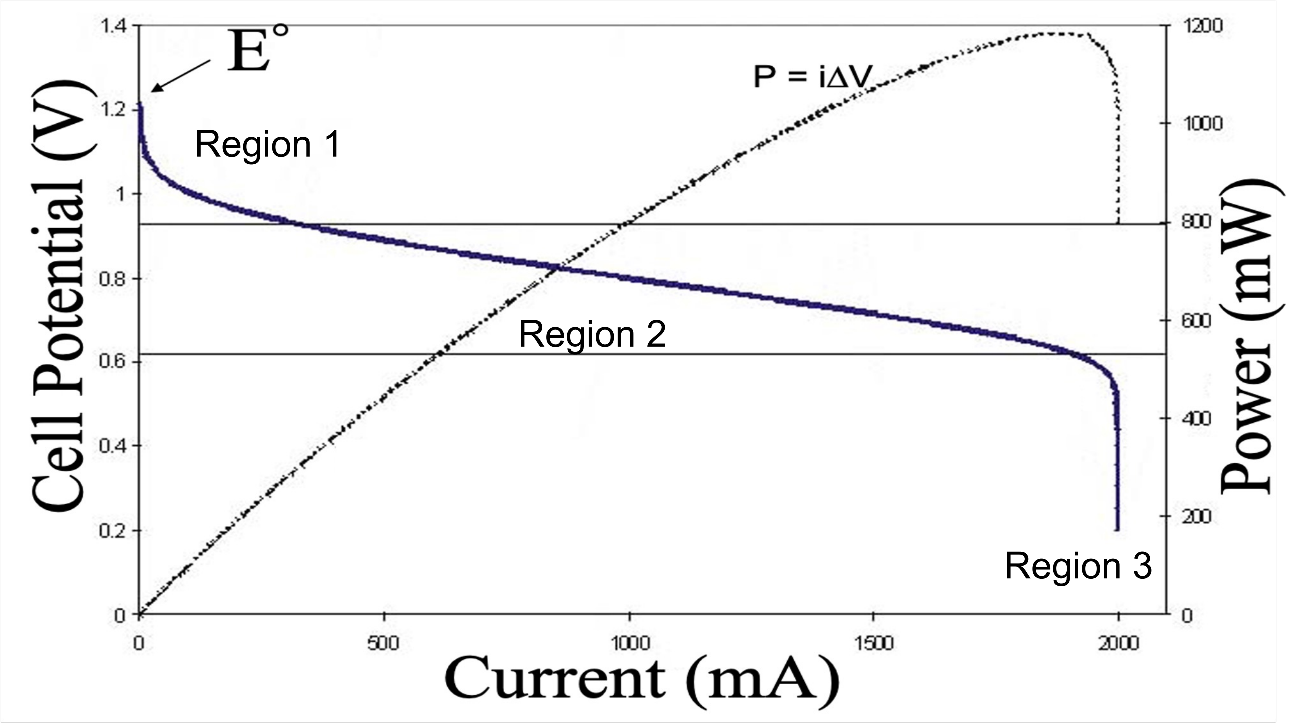
- Size can range from the size of a hand to the size of a laptop







# Hydrogen Fuel Cell Polarization curve




Hydrogen Fuel Cell Performance can be separated into 3 regions:

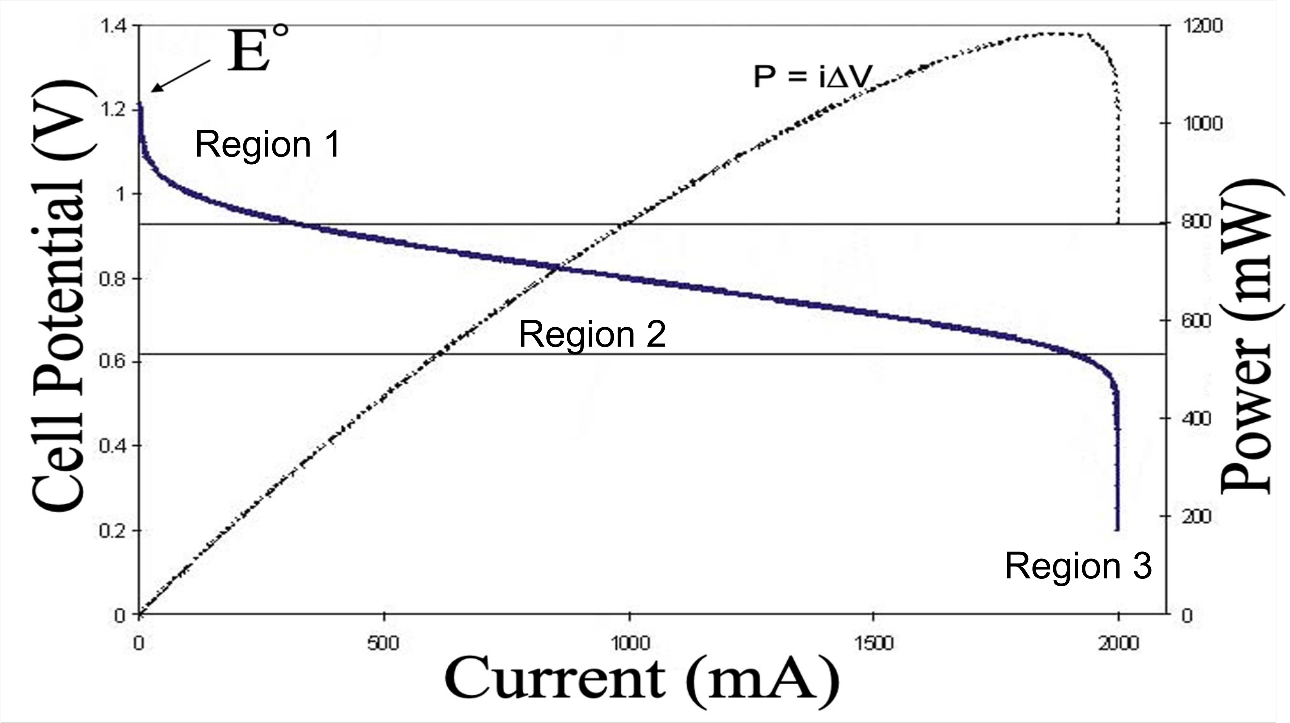
**Region 1**: Electrode Kinetics Driven Exponential Decay

k=k0 exp [(E0-E)nF/RT]

**Region 2**: Linear Decay Driven by H+ Transport (Steady State Diffusion)

**Region 3**: Reactant Limited Decay Vertical Asymptote due to independence of reactant transport and E

# Hydrogen Fuel Cell Polarization curve




- At maximum power, the efficiency of the hydrogen fuel cell is 50%
- Where Fuel Cell efficiency is given by:

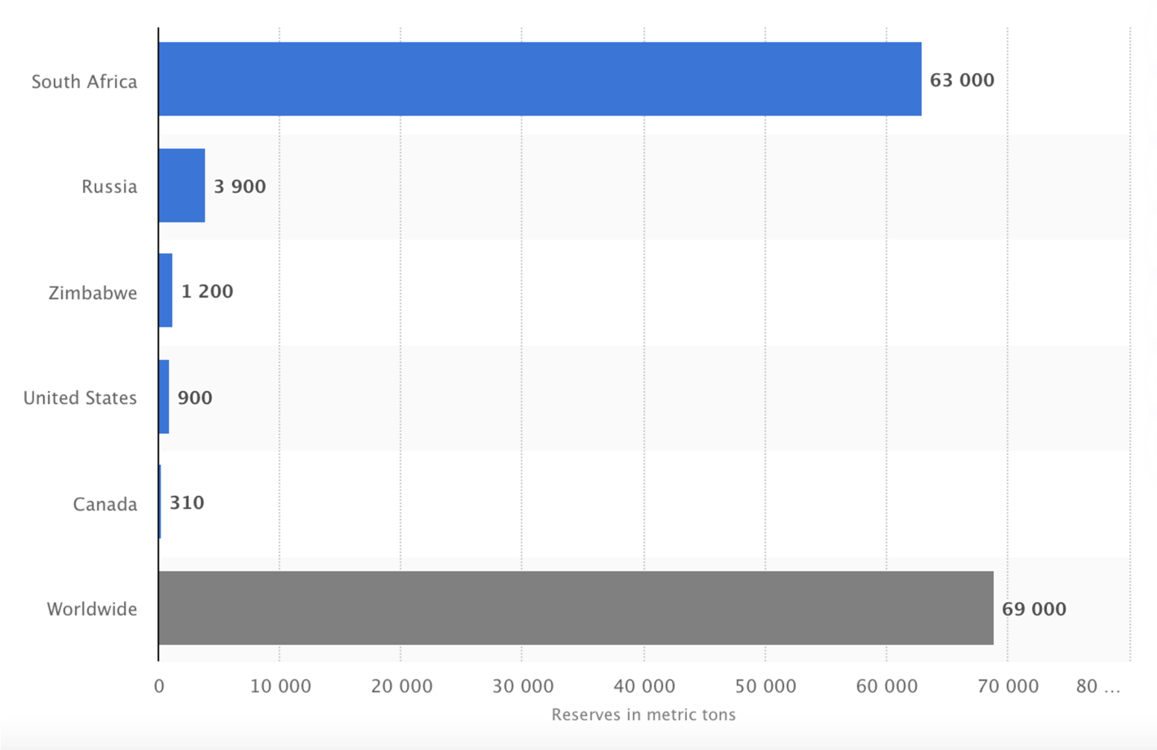
$$\eta = \Delta V / E0$$

- There exists a tradeoff between power and efficiency
- How often does one really need maximum power?

# Platinum is the most common catalyst in PEM Fuel Cells

- Platinum is used at both the anode and cathode
- Small particles exist on the electrode surrounded by larger carbon particles
- It currently costs about $38/gram
- 0.2 grams are required to make a single cell sandwich
- The current world reserves are estimated to be 69,000 tons

# Platinum metal reserves worldwide as of 2020, by country




- Most of the world's platinum exists in South Africa
- United States does not have much
- We either need to import it, or find a cheaper, more abundant catalyst

# Class Activity #1

Assuming a typical 240V AC Induction Motor (Requires 300V DC Input), what is the minimum number of hydrogen fuel cells would you need connected in series to reach the desired voltage output (Assume an ideal voltage source at all range of power outputs: i.e. $\Delta V_{cell} = E^0_{cell}$) and what is the cost incurred by using 0.20g of platinum as the electrodes for each cell?

Useful Information:

Anode : oxidation

$H_2 \rightarrow 2H^+ + 2e^-$   $E^\circ = 0$ V

Cathode : reduction

$O_2 + 4H^+ + 4e^- \rightarrow 2H_2O$   $E^\circ = 1.2$ V

Overall:

$O_2 + 2H_2 \leftrightarrow 2H_2O \quad E^0_{cell} = 1.2V$

Price of Platinum:
$32.50/gram

# Class Activity #1

$$Number\ of\ Cells = \frac{\Delta V_{need}}{\Delta V_{cell}} = \frac{300V}{1.2V} = 250\ Cells$$

$$Cost = Number\ of\ Cells * \frac{Platinum}{Cell} * \frac{Cost\ of\ Platinum}{Gram}$$

$$Cost = (250cells)\left(\frac{0.20g}{cell}\right)\left(\frac{\$32.50}{g}\right) = \$1625$$

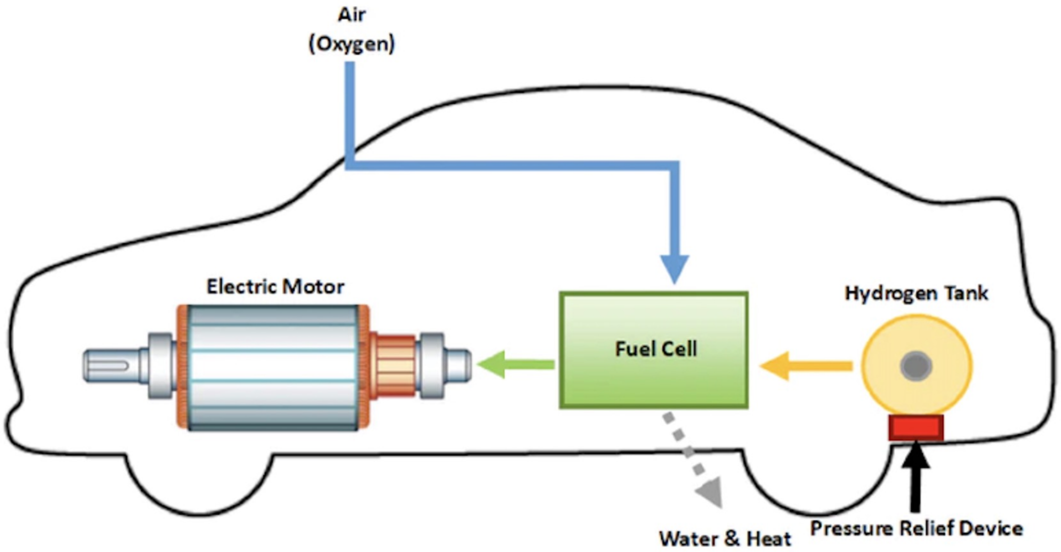
# How Many Vehicles Can The World Reserves of Platinum Produce?

- Assume from previous problem that a car requires roughly 250 fuel cells
- World’s reserves of platinum (6.26*10^10 grams)
- Number of cars on the road in the USA is about 285 million

$$Number\ of\ Cars = \frac{\frac{Platinum\ Reserves}{Platinum\ per\ Cell}}{\text{Cells Per Car}} = \frac{\frac{6.26*10^{10}\text{g}}{\frac{0.2\text{g}}{\text{Cell}}}}{250\frac{\text{Cells}}{\text{Car}}}$$

$Number\ of\ Cars = 1.252$ Billion Cars or 4.38 times the number of cars in the USA in 2020

# How Hydrogen Fuel Cells are Used in Transportation




1. Hydrogen and oxygen are supplied to fuel cell stack
2. Fuel cell produces electricity, heat, and water
3. Electricity is used to power electric motor

- Light-duty fuel cell vehicles can travel for an average of 300 miles before refueling
- ~3-5 min fueling time
- 50% theoretical efficiency at maximum power

# Hydrogen Production- Steam Methane Reforming Process (SMR)

1. high-temperature steam (**700°C–1,000°C**) is used to produce hydrogen from a methane source
2. methane reacts with steam under **3–25 bar pressure** in the presence of a catalyst to produce hydrogen, carbon monoxide, and a relatively small amount of carbon dioxide
3. Subsequently, in what is called the "water-gas shift reaction," the carbon monoxide and steam are reacted using a catalyst to produce carbon dioxide and more hydrogen.
4. In a final process step called "pressure-swing adsorption," carbon dioxide and other impurities are removed from the gas stream

**Steam-methane reforming reaction**

$CH_4 + H_2O$ (+ heat) $\rightarrow CO + 3H_2$

**Water-gas shift reaction**

$CO + H_2O \rightarrow CO_2 + H_2$ (+ small amount of heat)

**Currently, the cost to produce Hydrogen via SMR varies between $1.5/kg H2 to $3.5/kg H2**

- **95% of hydrogen fuel is produced via SMR**

# Pros and Cons of Steam Methane Reforming

Pros:

Cons:

# Pros and Cons of Steam Methane Reforming

Pros:

- Abundance/Cost of Natural Gas
- Existing infrastructure
- Can provide enough hydrogen for transportation purposes
- Creation of jobs

Cons:

- Does produce greenhouse gases
- Limited stores of methane

Is it any better than just producing electricity from Methane to charge a Lithium ion battery? Maybe?

# Hydrogen Production- Biomass and Coal Gasification

- **Biomass and coal Gasification and follow a very similar pathway as Natural Gas Reforming Biomass**

**Biomass Gasification (Simplified example reaction)***

$C_6H_{12}O_6 + O_2 + H_2O \rightarrow CO + CO_2 + H_2$ + other species

**Water-gas shift reaction**

$CO + H_2O \rightarrow CO_2 + H_2$ (+ small amount of heat)

**Coal gasification reaction (unbalanced): Production of Syngas**

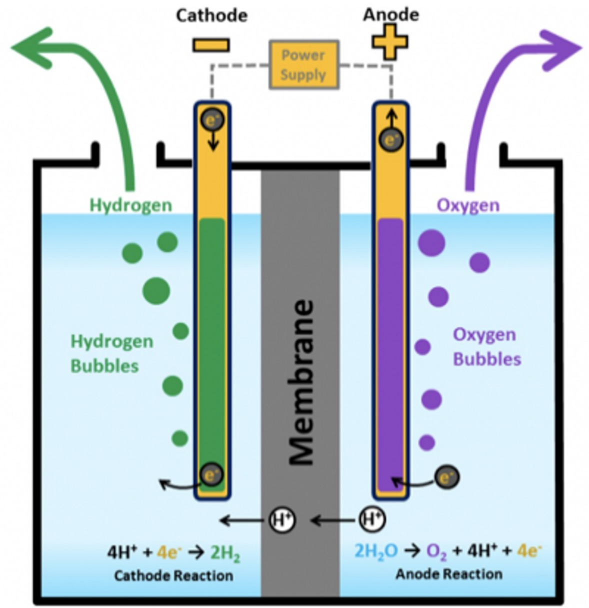
$CH_{0.8} + O_2 + H_2O \rightarrow CO + CO_2 + H_2$ + other species

# Hydrogen Production- Electrolysis

1. Electrical current is supplied by electrodes
2. Water reacts at the anode to form oxygen and positively charged hydrogen ions (protons).
3. The electrons flow through an external circuit and the hydrogen ions selectively move across the PEM to the cathode.
4. At the cathode, hydrogen ions combine with electrons from the external circuit to form hydrogen gas.

Anode Reaction: $2H_2O \rightarrow O_2 + 4H^+ + 4e^-$

Cathode Reaction: $4H^+ + 4e^- \rightarrow 2H_2$




**Currently, the energy value of Hydrogen gas produced is about 80% of the electricity that was used to split the water molecule. Also, the electrolyzers are expensive to manufacture.**

Question: Why would we use electrolysis if we lose energy value and it is expensive?

# Distribution- Centralized Production of Hydrogen

- Large, centralized production facilities where hydrogen is produced via electrolysis,  SMR with sequestration, or coal gasification with sequestration
- Ideal for long-term

# Transportation from large, centralized facilities

<u>Gaseous Hydrogen Transportation</u>:

- Hydrogen Tube Trailers (Pressures of up to 250 bar)
- Pipelines (Similar to natural gas pipelines; but with a higher tendency for leakages due to the small size of hydrogen)

<u>Liquid Hydrogen Transportation</u>:

- Super-insulated tanker trucks certified for cryogenic transport
- More dense than gaseous hydrogen (uses 30% of energy density of hydrogen)

# Benefits/Drawbacks of Centralized Hydrogen Production

Benefits:

- Can be produced cheaply after high capital cost
- Supply enough hydrogen for high fuel cell vehicle density
- Potential to have zero emissions if produced via electrolysis or if sequestration is used

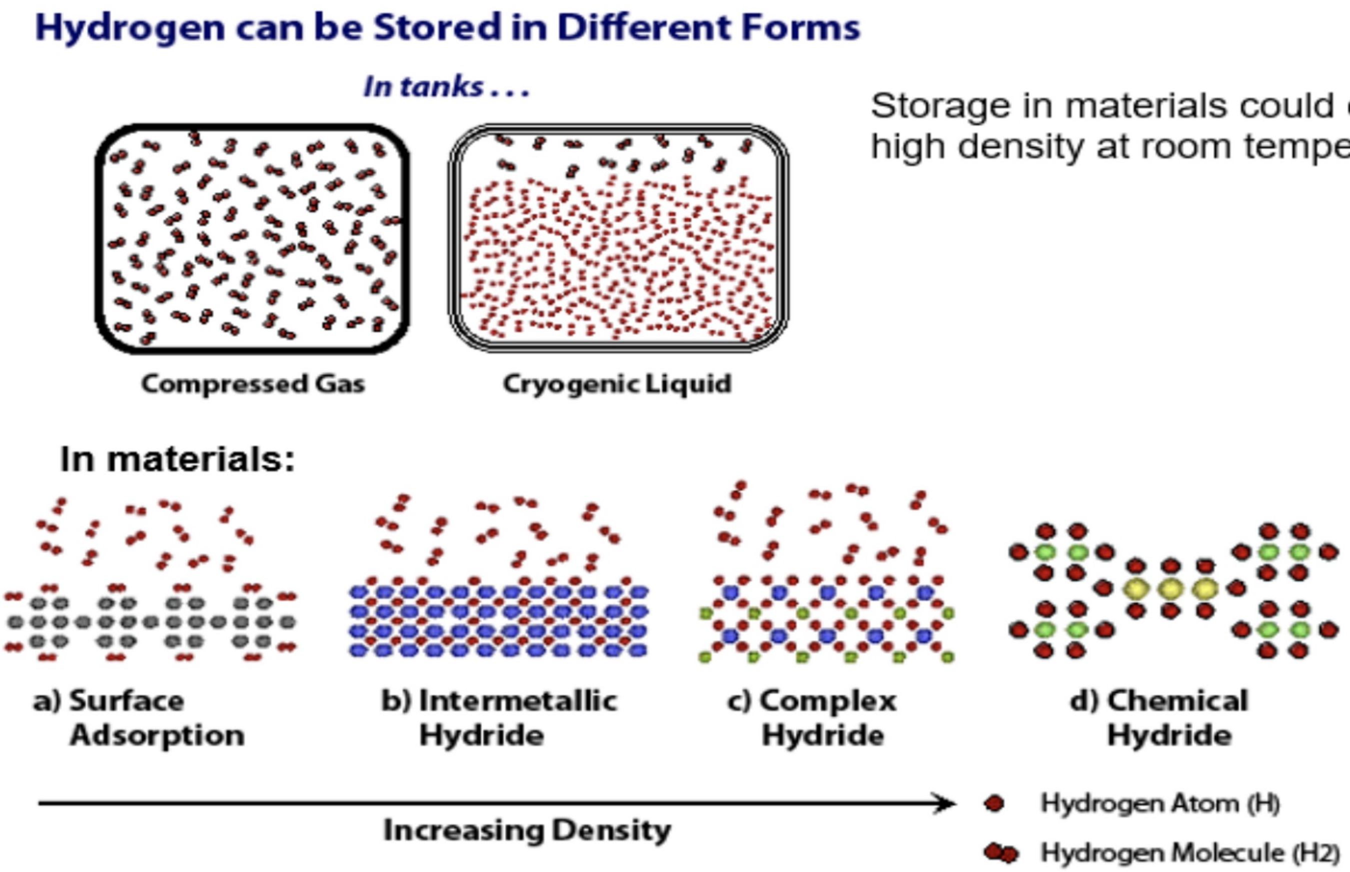
Drawbacks:

- Massive capital cost
- Chicken egg dilemma, which came first?
- Could be dangerous to transport high pressure vessels

# Distributed Manufacture of Hydrogen

- local distributed generation with small-scale natural gas reformers or by electrolysis of water
- Much lower capital cost
- Can be built slowly as demand increases until the need for a centralized production facility arises
- Much more likely case for near future

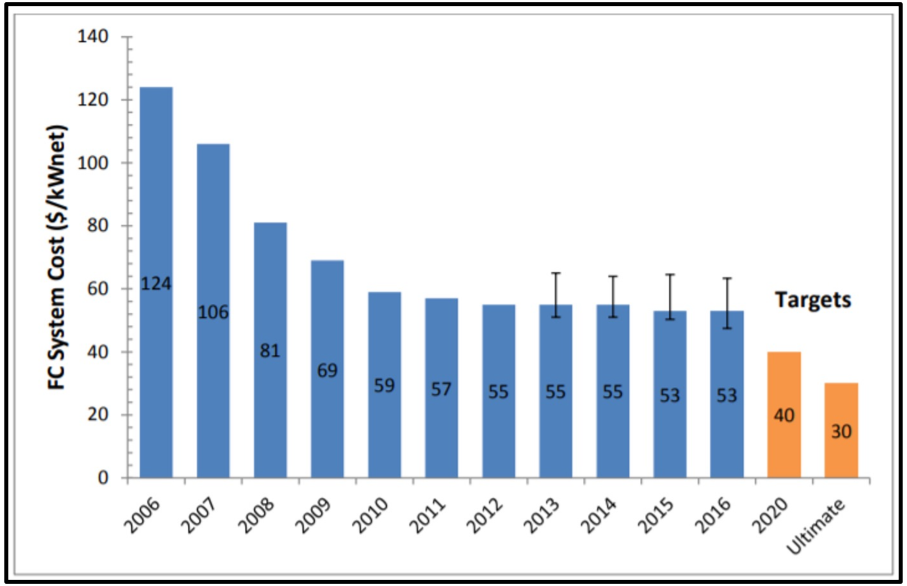
# Storage of Hydrogen



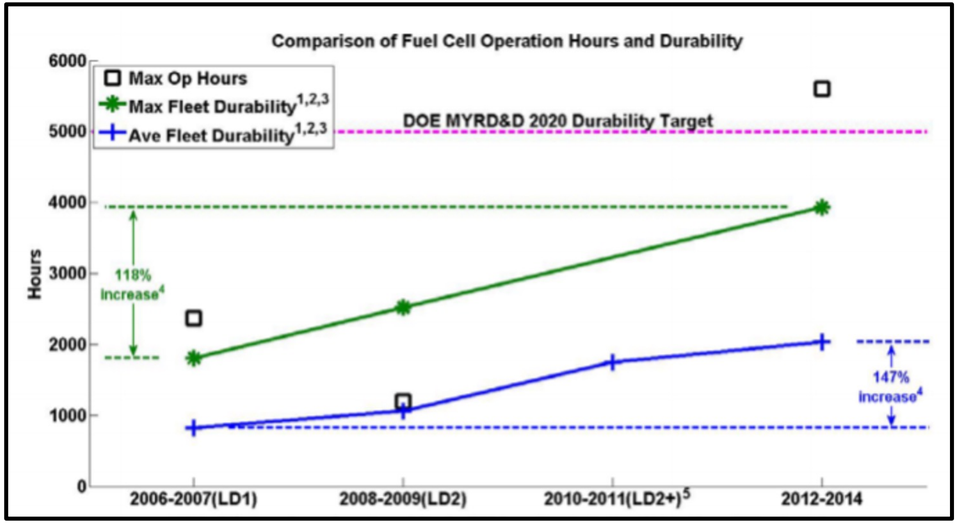

Storage in materials could enable a high density at room temperature

# The Need to Create Cheaper Fuel Cells

- <u>Advancements already made:</u>
  - Cost of fuel cells decreased 60% from 2006-2016
    - 5x reduction in platinum content
- <u>Advancements that need to be made:</u>
  - Cheaper alternative to platinum catalyst (~$30,000/kg)
  - Reduce the cost of hydrogen fuel ($16/kg)
    - Gasoline Gallon Equivalent (GGE) average price of hydrogen fuel in California: $5-$6
    - Average price of gasoline in California: $3.88

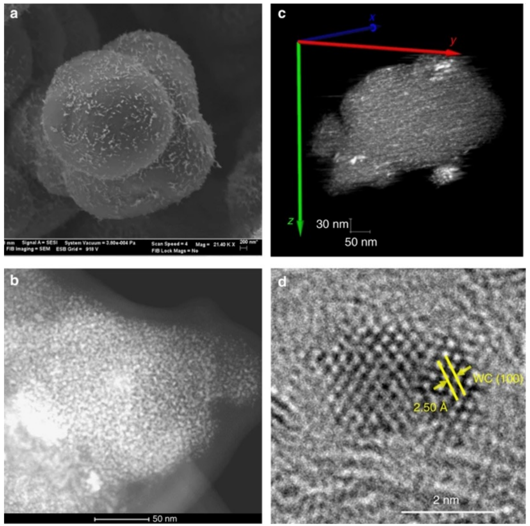


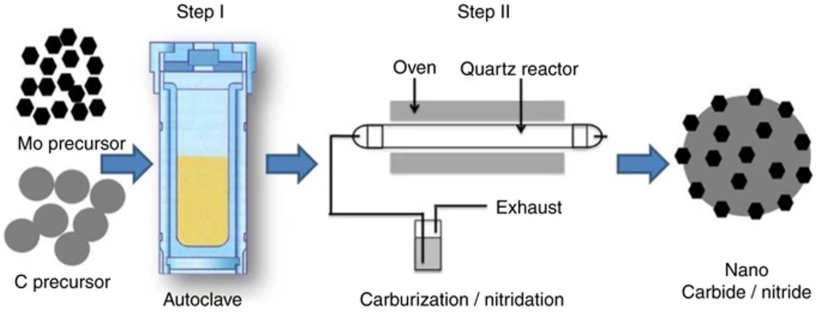
# The Need to Create More Durable




- <u>Advancements already made:</u>
  - Quadrupled fuel cell durability from 2006-2016
    - Achieved durability of 4100 hours (or 120,000 miles)
- <u>Advancements that need to be made:</u>
  - Fuel cells need to be durable enough to last at least 5,000 hours (150,000 miles)
    - Required for realistic operating conditions that stress chemical and mechanical stability of fuel cell system

# University of Delaware Study - 2017




- Cost
  - Tungsten Carbide Catalyst Cost: $150 per kilogram
  - Platinum Catalyst Cost: $30,000 per kilogram
- Membrane of Hydrogen Fuel Cell can easily wear down but:
  - Tungsten carbide catalyst found to optimize performance
  - Tungsten carbide catalyst captures damaging free radicals before they degrade the membrane
  - Membrane lasts longer when use tungsten carbide catalyst

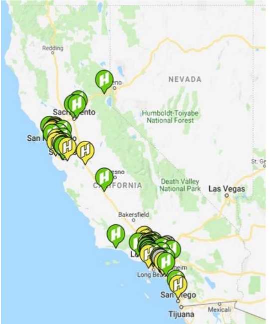
# Advantages & Disadvantages compared to Electric Vehicles

**Advantages:**

- Time it takes to Refuel: shorter refueling time (3-4 mins vs. 0.5-12 hrs)
- Equipment: Hydrogen Fuel Cells are lighter than batteries used in EVs
- Use of Lithium Ion Batteries: only used in EVs & produce a lot of toxic waste


**Disadvantages:**

- Cost: Start at $71.5K (per FCV) vs. $25K (per EV)
- Cost per mile: 25¢ per mile (FCV) vs. 3-4¢ per mile (EV)
- Convenience of Refueling: more refueling stations for EVs
- Cost of building Refueling Stations: cheaper to build EV refueling stations
- Hydrogen Extraction: expensive and not very efficient
- Environmental Impact: $CO_2$ emissions from EVs over their lifetime is lower than emissions from FCV




Hydrogen Fueling Stations in California

# Advantages & Disadvantages compared to Internal Combustion Vehicles

**Advantages:**

- Noise: FCV produce almost no noise compared to ICV
- Environmental Impacts: FCV produce way less harmful gas emissions
- Production of Hydrogen vs. Gasoline: Producing hydrogen emits 34-50% less GHG than producing gasoline
- Chemical Exposure: when fueling Hydrogen Vehicles, we are exposed to less harmful chemicals
- Efficiency: Hydrogen fuel cells are 40-60% efficient in generating electricity & IC engines are 30-35% efficient
    - HFCV get double the mile range

**Disadvantages:**

- Initial Cost: FCV are 7.5x more expensive
- Cost of Fuel: hydrogen fuel is much more expensive than gasoline
- Cost of Storage and Transportation: more expensive to store and transport hydrogen than gasoline
- Refueling Stations: more readily available for ICV

# Fuel Cell Vehicles Currently Being Used


2015 Toyota Mirai


Honda Clarity Fuel Cell Vehicle


Hyundai Nexo

- Since 2012, 8,931 HCV have been sold in the US
  - Can mainly operate in Cali (43 out of 45 of hydrogen refueling stations are located there)
- Progress in HCV
  - Toyota Mirai (2015) - first to build HCVs in volumes of 1,000+
    - >6,500 have been leased or sold (2015-2020)
  - Followed by Honda Clarity and Hyundai Nexo
    - Only 3 types of HCV currently

# The Future of Hydrogen Fuel Cell Vehicles

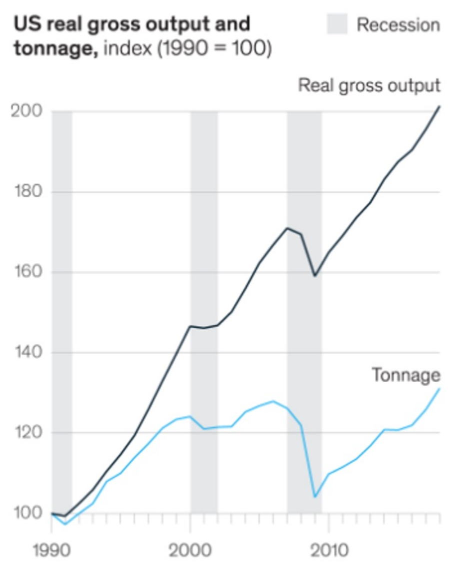

2021 Hyundai Nexo

- **Toyota Mirai:** 402 mile range
- **Hyundai Nexo:** 380 mile range
- **Nikola FCEV:** 300-900 mile range
    - <u>Metro/Regional:</u> Nikola Tre BEV (300 mile range)
    - <u>Regional:</u> Nikola Tre FCEV (500 mile range)
    - <u>Long-Haul:</u> Nikola Two FCEV (900 mile range)

2021 Toyota Mirai


Nikola FC Truck

# Potential for use in heavy duty vehicles

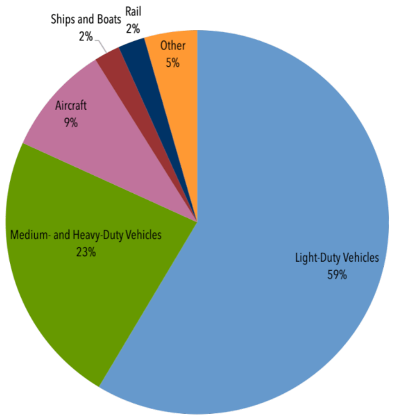



Growth of the U.S. Freight Industry

- <u>Why Change Needs to Happen:</u>
    - US Department of Transportation predicts that freight volume in the US will increase by 45% or 29 billion tons by 2040
    - Heavy-duty vehicles account for 2% of vehicles on the road, but 23% of $CO_2$ emissions
    - Truck industry of US, EU, and China combined consumes ⅕ of global demand of oil

- <u>Why Hydrogen Fuel Cells vs. Electric</u>
    - Refueling time
    - Range
    - Battery Life Requirements
    - Higher Specific Energy

CO2 Emissions




# Summary

- Polarization Curve displays the trade-off between power and cell efficiency
- There is an abundance of Platinum in the world reserves but it is very expensive to obtain
- Natural Gas Reforming is where most Hydrogen comes from, but it still emits CO2
- Electrolysis could have zero emissions if renewable electricity is used to produce Hydrogen
- Centralized production of Hydrogen is ideal for long term, but capital cost is too high for the lack of current demand
- Storage of Hydrogen in high pressure gas cylinders seems to be winning
- In order to successfully use Hydrogen Fuel Cells for Transportation, we need to find ways to make them cheaper and more durable.
- There are currently some Hydrogen Fuel Cell vehicles available for purchase & there are companies working to make new models of HFCV that have a longer range.
- It would be most beneficial and profitable to make heavy-duty vehicles out of Hydrogen Fuel Cells.