Living with a Hydrogen Fuel-Cell Automobile

Jim Harrison

K6OUE

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2004

- California Governor Arnold Schwarzenegger declares California will be a “Hydrogen Economy”
  - He converts one of his Hum-Vees to run on hydrogen
  - “Hydrogen Highway” initiated by executive order
  - Goal is more than 100 hydrogen stations in California by 2010

June 2004

- South Coast Air Quality Management District (AQMD) leases two hydrogen fuel cell cars from Honda
  - For evaluation
  - Reported cost to produce cars: $1 million apiece

2005 to 2015

- “Hydrogen Economy” didn’t materialize
- By 2010 there are <10 H_2 stations in California
- No fuel-cell cars available
- Is the hydrogen fuel-cell car dead?

2016

- The Toyota Mirai is offered for sale or lease

Oct. 25, 2016

- I lease a new Toyota Mirai fuel-cell car
  - $400/month lease, for 36 months
  - Free hydrogen for 3 years or $15,000
  - Free maintenance
  - Free roadside assistance
- You could buy the car for $57,500
- I return the car when lease is up on Oct. 25, 2019

New car at LB H_2 Station

Back of car, H_2Only

Front of car, ugly?

What I Liked

- Toyota Mirai is a luxury car
  - Mid-sized, heavy, very well-made, like a Lexus
  - Every electronic gadget you could think of
- Super quiet
  - It is all-electric, fuel-cell has no moving parts
  - No engine vibration or noise
- Fast
  - Super acceleration, like a Tesla
  - Electric motors have full torque at zero RPM

What I didn’t Like

- Not spacious inside
  - Somewhat cramped, small trunk
- Range should be a little longer
  - 300 miles. 350 would reduce range anxiety
- Too heavy
  - Weighs 4000 pounds (why?)
- Hydrogen availability
  - Not enough stations

What is a Fuel Cell?

- Converts a fuel directly to electricity without combustion
  - Utilizes chemical reactions to release electrons
  - More efficient
    - No waste heat generated
    - Almost all of the energy in the fuel is converted to electricity
- Can use a variety of fuels
  - Usually hydrogen, but also methanol, ethanol, etc.

Heat Engines

- External combustion (ECE): Steam engines
- Internal combustion (ICE): Gasoline engines
- Combustion releases heat
  - Heat causes gases to expand
  - Expanding gases move pistons or turbines
- Most of the heat is radiated away without producing useful work!

Efficiency

- Efficiency of an engine =
  - Percentage of energy that is translated to motion
- Inefficiencies:
  - Friction within engine
  - Friction in transmission
  - Radiated heat
  - Internal resistance of batteries, motors, etc.

Efficiency

- Internal Combustion Engine Car (ICE)
  - 20% efficient
    - 20% of the energy in the chemical bonds in the gasoline is converted to motion of the car
- Hydrogen Fuel Cell Electric Car (FCEV)
  - 60% efficient
    - Fuel cell and electric motor
- Battery Electric Car (BEV)
  - 80% efficient
    - Battery and electric motor

Fuel Cell vs. ICE

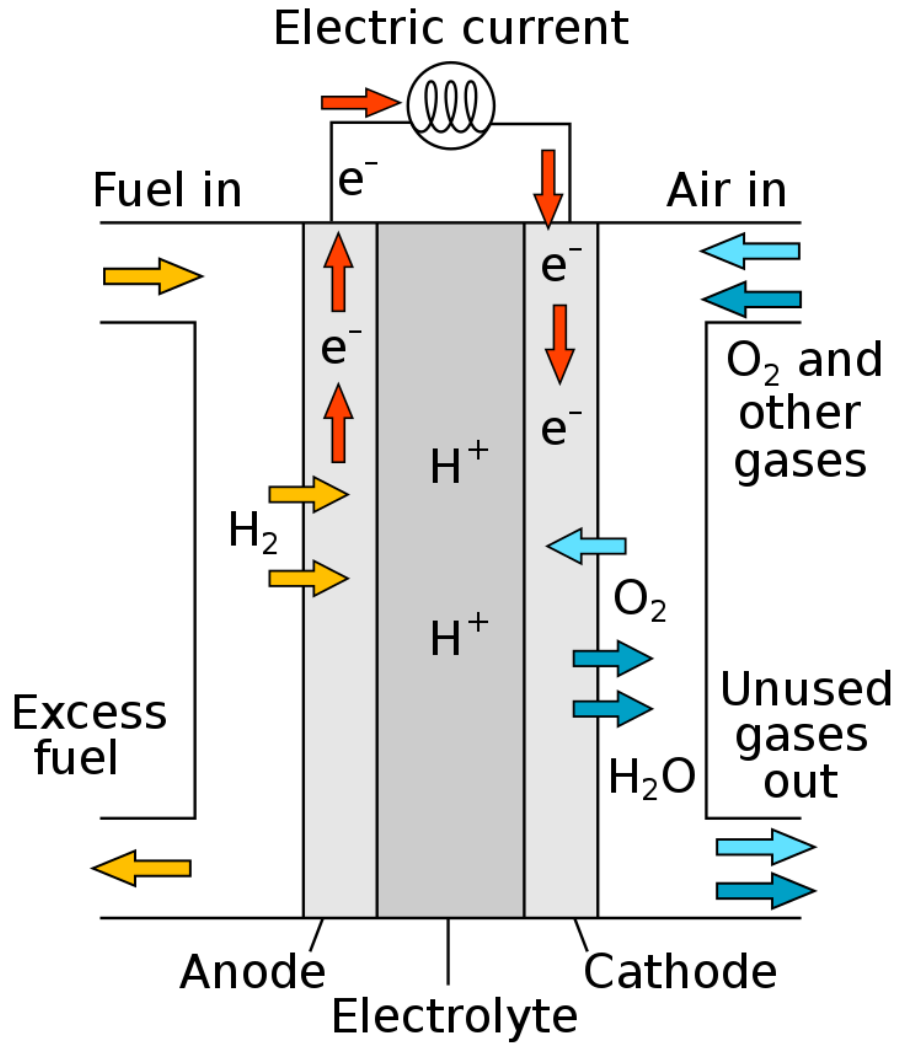
- More efficient
  - 60% vs. 20%
- No pollution
  - Only output is water (pure H_2O)

Fuel Cell vs. Battery

- Greater range
  - 300 to 350 miles
- Quick refueling
  - 4 minutes to fill up
    - Vs. hours to fully charge batteries
    - 30 minutes for fast charge to 75% charged
      - (Tesla Superchargers)
- Less weight than batteries

How does a fuel cell work?

- Anode catalyst
  - Platinum
- Cathode catalyst
  - Nickel
- PEMFC
  - Proton-Exchange Membrane Fuel Cell



History of Fuel Cells

- First demonstrated in 1838
- Modern fuel cell invented in 1932 in England
- Fuel cells first used by NASA in manned space programs, Gemini and Apollo
- Current uses:
  - Backup power for buildings
  - Fork lifts, buses, trucks
  - Submarines
  - Cars

Where does H_2 come from?

- There is almost no hydrogen in the atmosphere
  - It is lighter than air, so it floats away to space
  - There is no H_2 gas in the ground
- So it must be generated
  1. Electrolysis of water
  2. Hydrocarbons
  3. Industrial by-product

H_2 from Electrolysis

- Electricity can decompose water molecules into hydrogen and oxygen
  - $2H_2O = 2H_2 + O_2$
- The electricity can come from:
  - Burning fossil fuels
  - Nuclear power
  - Solar, wind, tidal power, etc.
    - “Green” hydrogen

H_2 from Hydrocarbons

- Most H_2 today is produced from natural gas
  - Approximately 95%
- Steam methane reforming
  - High pressure steam and methane in contact with a nickel catalyst
    - $CH_4 + H_2O = CO + 3H_2$
    - $CO + H_2O = CO_2 + H_2$
  - If the CO_2 is released to air, it is called “gray” H_2
  - If the CO_2 is captured and sequestered, it is called “blue” H_2

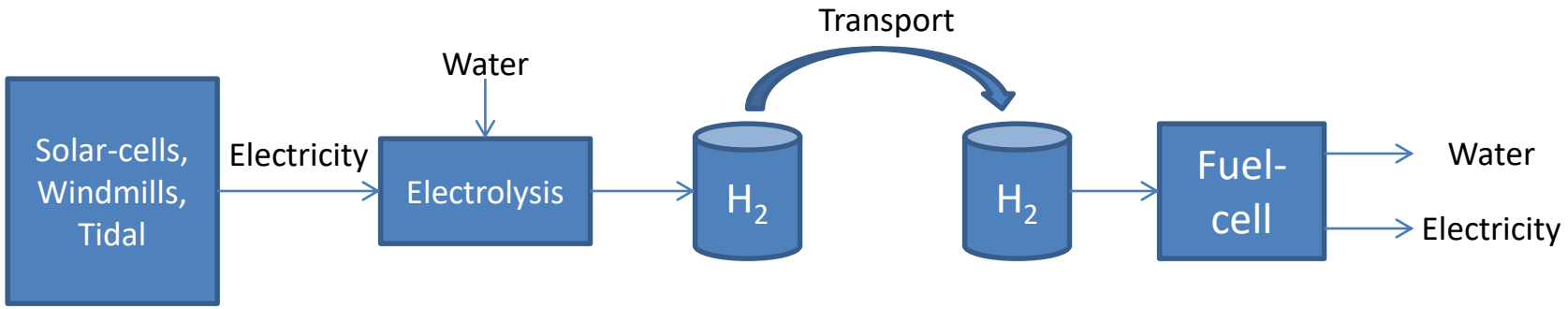
What's the Point?

- Why go to H_2 if it is just coming from fossil fuels anyway? Possible answers:

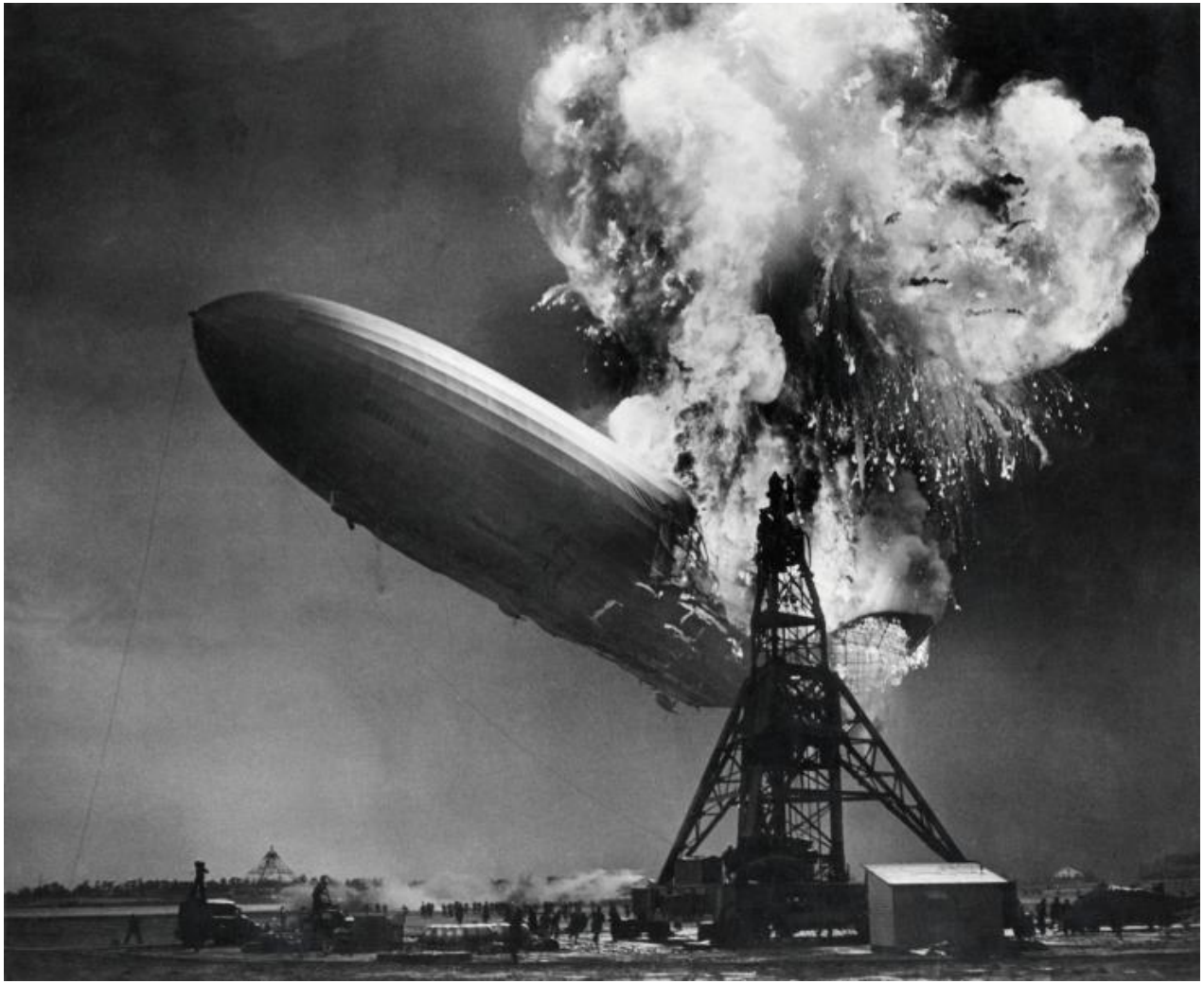
1. First need to get H_2 infrastructure in place, then eventually go to all "green" H_2
2. CO_2 capture and pollution controls are better and more economical at a large central plant than at each vehicle
3. Fuel cell vehicles are more efficient than ICE vehicles. "Well-to-wheels" more efficient

Change of Mindset

- Think of H_2, not as a fuel, but as an energy storage medium
  - Electrical energy is stored as H_2 for later use
  - Another application:
    - Excess solar-cell energy in day, stored as H_2
    - Use H_2 to generate electricity at night



Safety of Hydrogen



Safety - Fire

- Hindenburg
  - Hydrogen fire ball drifted up into the air
  - All of the hydrogen burned up in 90 seconds
  - Most of destruction from burning of aluminum lacquer skin
- Hydrogen is probably safer than gasoline
  - Hydrogen floats up and away
    - Fireball rises above people and vehicles
  - Gasoline pools on ground and burns everything
    - Flames burn people and vehicles
    - Your gasoline tank is a giant Molotov cocktail!

Safety – Hydrogen Leaks

- Car has sensors to detect H_2 leaks
  - Car will shut down if leak detected
  - Hydrogen will be shut off
- Hydrogen stations have sensors for leaks
  - H_2 pump will shut down if leak detected

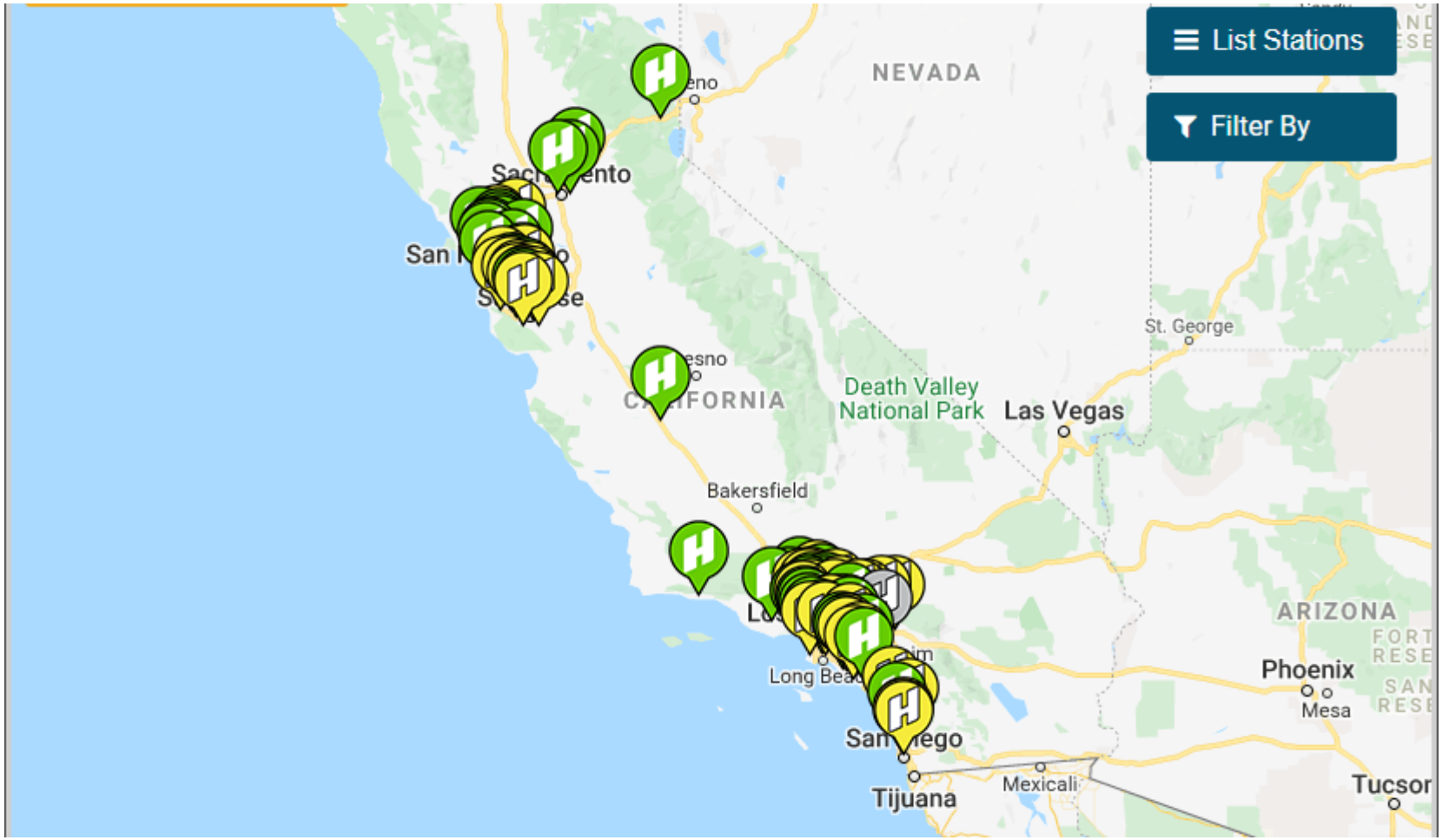
Safety - Pressure

- Tank contains H_2 at 10,000 PSI
  - Could it explode?
- Tank is wrapped in carbon fiber
  - Toyota put fully pressurized tanks thru crash tests
  - Fired bullets at tanks
  - Could only puncture tanks with armor piercing bullets
    - And then tanks only leaked
    - They did not explode

What was it like to own?

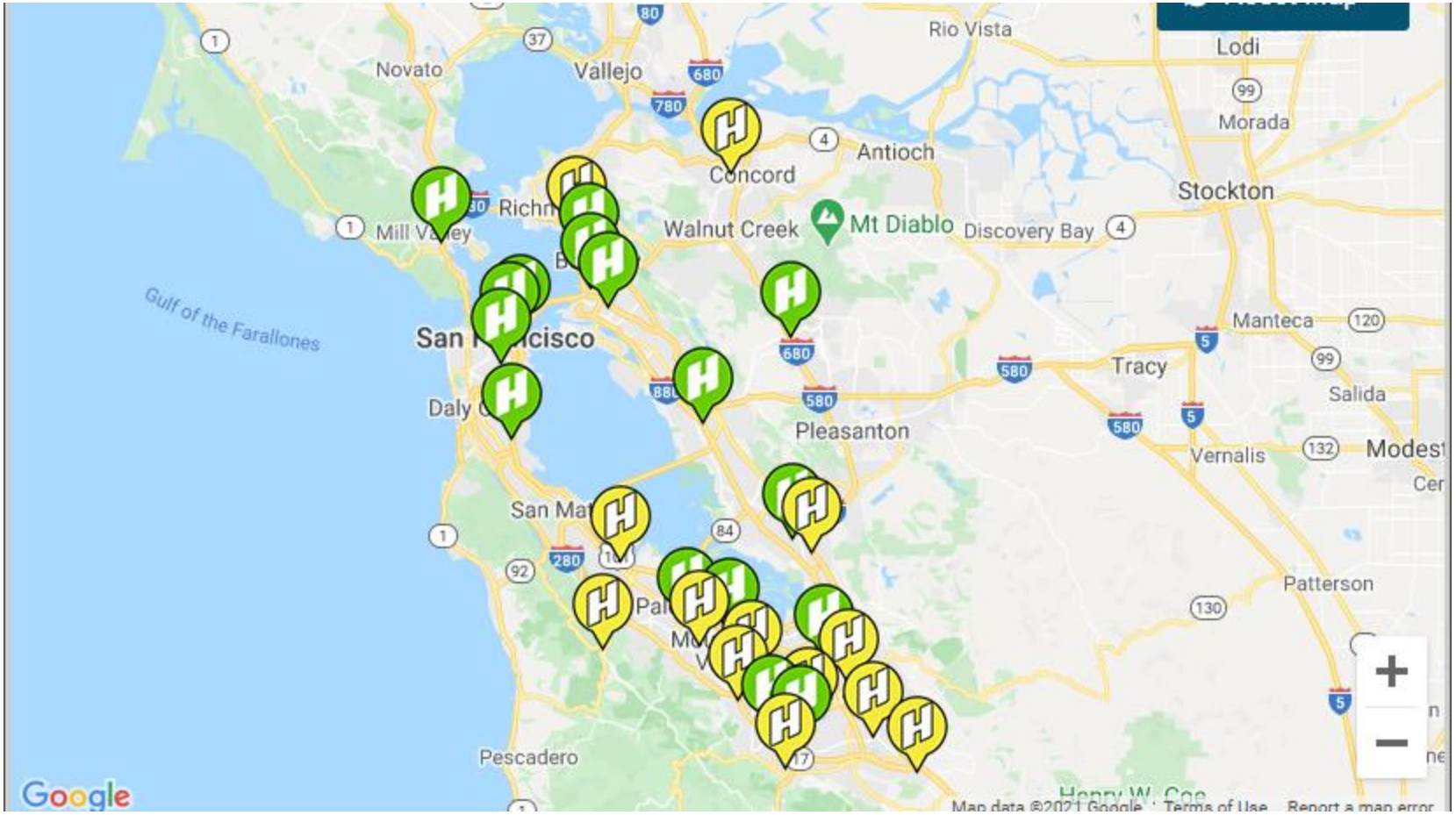
- Every trip had to be planned
  - Know where hydrogen stations are
  - Know how much range I have left
- Nearest hydrogen station to home is 10 miles
  - Had to make a special trip to fuel up
  - Used up 10 miles of range just re-fueling
- Accept fact I might be stranded
  - If hydrogen station is not working

44 H_2 Stations in California

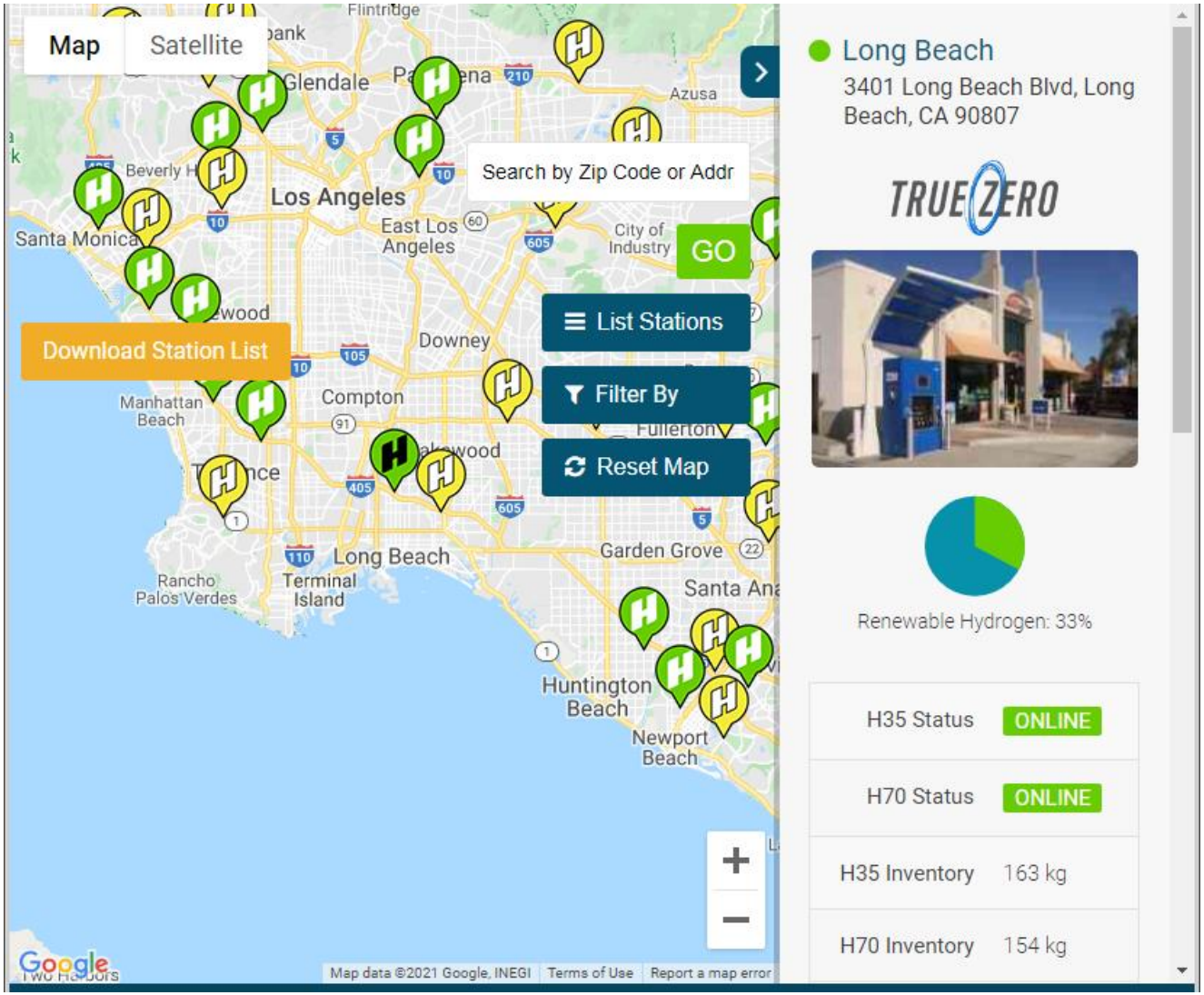


21 H_2 Stations in So Cal

16 H_2 Stations in Bay Area



Long Beach H_2 Station



Driving to Sacramento

- From home to Harris Ranch: 223 miles
  - Had to “baby” it over Tejon Pass
  - Usually had about 25 miles left at Harris Ranch
  - If station down, I would be stuck
    - It was never down!
- From Harris Ranch to W. Sacramento: 182 mi
  - This station was down twice
  - Had to go to Bay area to get fuel, and then home

Harris Ranch H2 Station

H35* Status: ONLINE

H35* Inventory: 47 KG

H70* Status: ONLINE

H70* Inventory: 38 KG

Last Updated: Monday, 2/8/2021, 1:16 PM

*H35 = 35 MPa or 5,000 PSI
*H70 = 70 MPa or 10,000 PSI

24505 West Dorris Avenue, Coalinga,

Re-fueling

- Similar to fueling a gasoline car
- Takes about 4 minutes
  - Connect hose to car
  - Put in credit card
  - Push start button
  - Fill is automatic, stops when reach 10,000psi
  - Disconnect hose (sometimes freezes on)
- Usually takes 3.5 to 4.5 kg to fill Mirai
  - Tank capacity is 5 kg

Fueling at H_2 Station

H_2 Nozzle

H_2 Pump


Sale $
KILOGRAMS
15.90
0.950
Bennett,
H70
TAKE RECEIPT
Price per Kg
Price per Kg
H70

Pressure

Unit of Pressure	Definition	Atmospheric Pressure	H70 Hydrogen
PSI	Pounds/sq. inch	14.7 PSI	10,000 PSI
Pascal	Newtons/sq. meter	101,325 Pa	70 MPa
Atmospheres	Air pressure at sea level	1 atm	690 atm
Bar	100,000 Pa	~1 bar	700 bar
Torr	1 millimeter of mercury	760	525,000 Torr

“What mileage does it get?”

- There is no way to directly compare mileage
  - Fuel is completely different
  - A gas instead of a liquid
  - Measured in kilograms vs. gallons
- What people really want to know is how much does it cost to go a certain distance

Mirai Cost per mile

- Range is 312 miles, tank holds 5 kg
- Mileage is 60 miles/kg
- Hydrogen is $16/kg
- It costs 5 X $16 = $80 to go 300 miles
- This is $80/300 = 27 cents/mile

Cost per mile comparison

Vehicle	Miles/unit	Cost/unit	Cost/mile	Cost/ 100 miles	Cost/ 300 miles
Mirai (rated)	60 m/kg	$16.81/kg	$0.28	$28	$84
Mirai (best)	65 m/kg	$14.99/kg	$0.23	$23	$69
Prius	50 mpg	$3.80/gal	$0.076	$7.60	$22.80
Lexus	30 mpg	$3.80/gal	$0.127	$12.66	$38
BMW	25 mpg	$4.20/gal	$0.168	$14	$42

Compared to Prius, 3.68 times more per mile, = gasoline $14/gal
Compared to Lexus, 2.2 times more per mile, = gasoline $8.36/gal
Compared to BMW, 1.6 times more per mile, = gasoline at $6/gal

Fuel Cell Cars Available

Mfr.	Model	Type	Years	Range (miles)
Toyota	Mirai	Sedan	2016 - 2020	312
Toyota	Mirai II	Sedan	2021 -	402
Honda	Clarity	Sedan	2017 -	366
Hyundai	Tucson	SUV	2013 - 2018	369
Hyundai	Nexo	SUV Crossover	2019 -	380

Conclusions

- It is really cool technology
- Reliable, low maintenance, fun to drive
- Refuels almost instantly (compared to charging batteries)
- Good range (> 300 miles)
- Could be a success if:
  - Can make cheaper and lighter weight than batteries
  - Can get cost of hydrogen down
  - Can get more H_2 stations operational!