Workshop on Fuel Cells for Automotive Applications

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IRA A. FULTON SCHOOLS OF engineering
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Fuel Issues

and

Fuel reformers

Hydrogen

The Only Truly Clean Chemical Fuel

Hydrogen (Greek: water former) is an odorless, tasteless, colorless and very reactive element in group 1 of the periodic table.

H2 is the simplest element known

Hydrogen

- Hydrogen also can be found in many organic compounds, as well as water.
- It's the most abundant element on the Earth.
- But it doesn't occur naturally as a gas.
- It's always combined with other elements, such as with oxygen to make water.
- Once separated from another element, hydrogen can be burned as a fuel or converted into electricity.

Why H_2?

- **Can be derived from diverse domestic resources (fossil, nuclear, renewable).**
- **Is compatible with high-efficiency fuel cells, combustion turbines and reciprocating engines to produce power with near-zero emissions of criteria pollutants.**
- **Produces near-zero emissions of greenhouse gases from renewable and nuclear sources and from fossil fuel-based systems with carbon sequestration.**
- **Can serve all sectors of the economy (transportation, power, industrial, and buildings)**

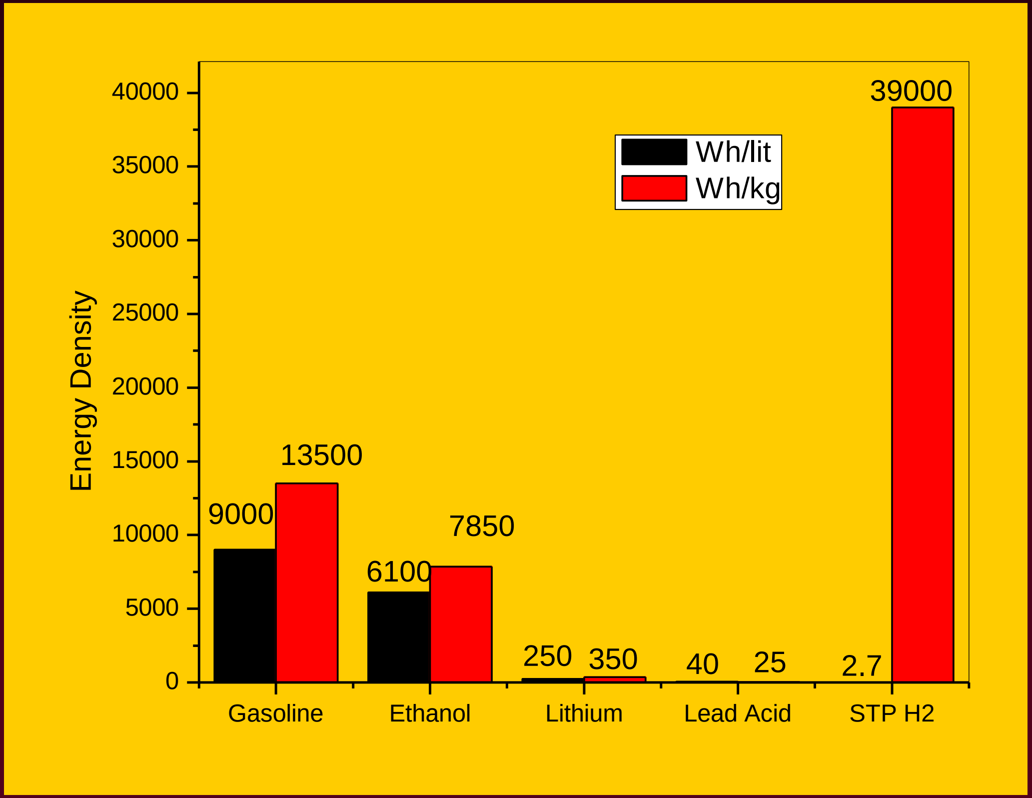
H_2 as a Fuel

- The transport of people, goods, and services is among the fastest growing sources of CO_2 emissions worldwide.
- Hydrogen fuel cell vehicles could help significantly to reduce CO_2 emissions, especially if the hydrogen is produced from renewable sources, nuclear energy, or fossil fuels in conjunction with carbon capture and storage.
- Mainstream use of H_2 as an energy carrier could also help expand the commercial feasibility of renewable energy sources by capturing the full amount of solar or wind generated power even when electric demand is low.

Energy Density: Comparison

- **Gasoline (and diesel and hydrocarbon equivalents) remains the standards of energy density comparisons at 9000 Wh/lit and 13,500 Wh/kg.**

H_2 gives the highest Gravimetric Energy Density



Energy Transformation

- The transition to a H2 economy - though it may sound implausible – is not unprecedented.
- Up until the last half of the 19th century, the United States had an energy system that relied upon draft animals for transportation, and wood for heating and cooking.
- Today, energy in the form of transportation fuels and electricity has become so ubiquitous it is difficult to separate it from the function of modern society.





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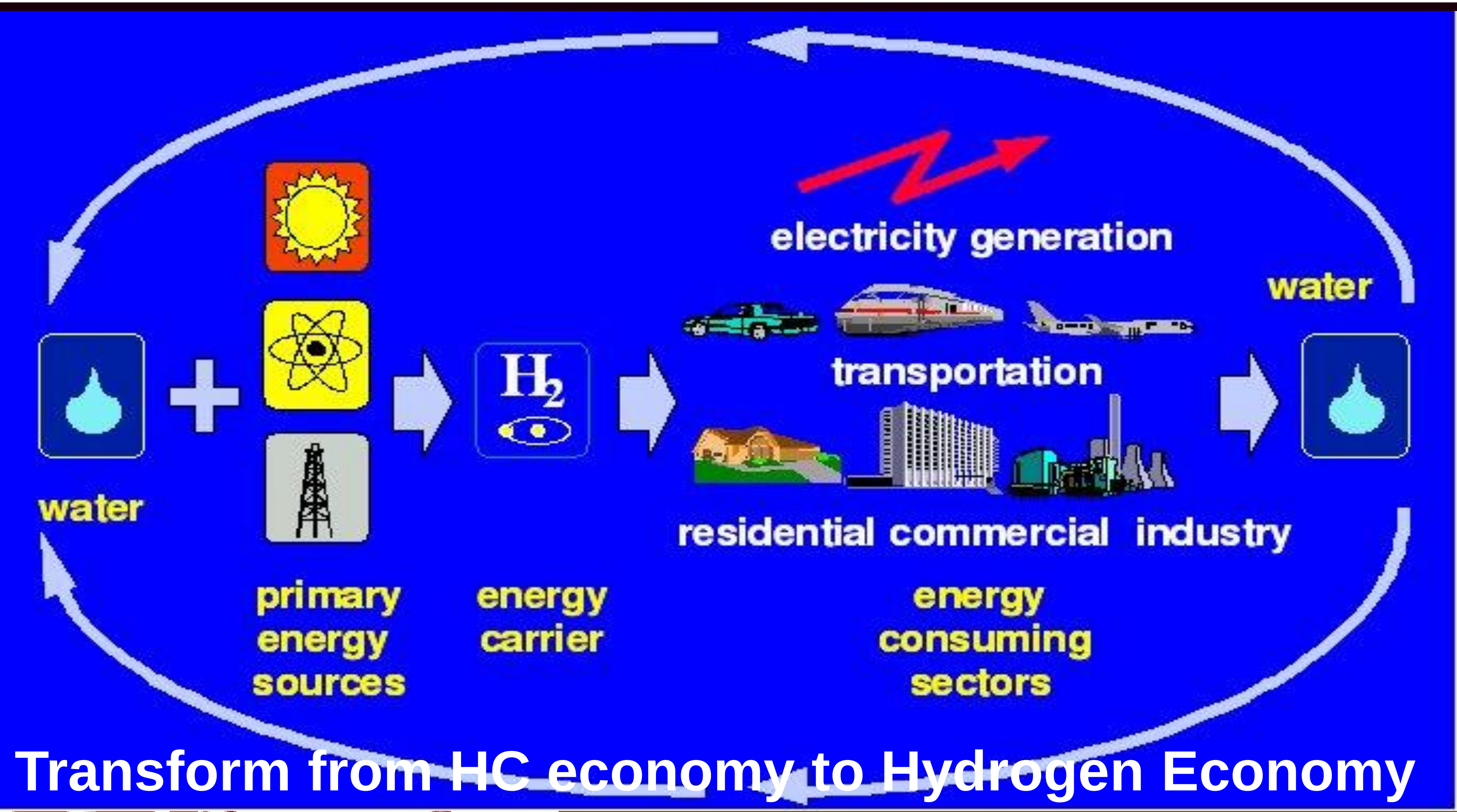
Clean Energy Drive

"The Stone Age did not end because we ran out of stones, and the Oil Age will not end because we run out of oil" - **Don Huberts, Shell Hydrogen**

H_2 ECONOMY

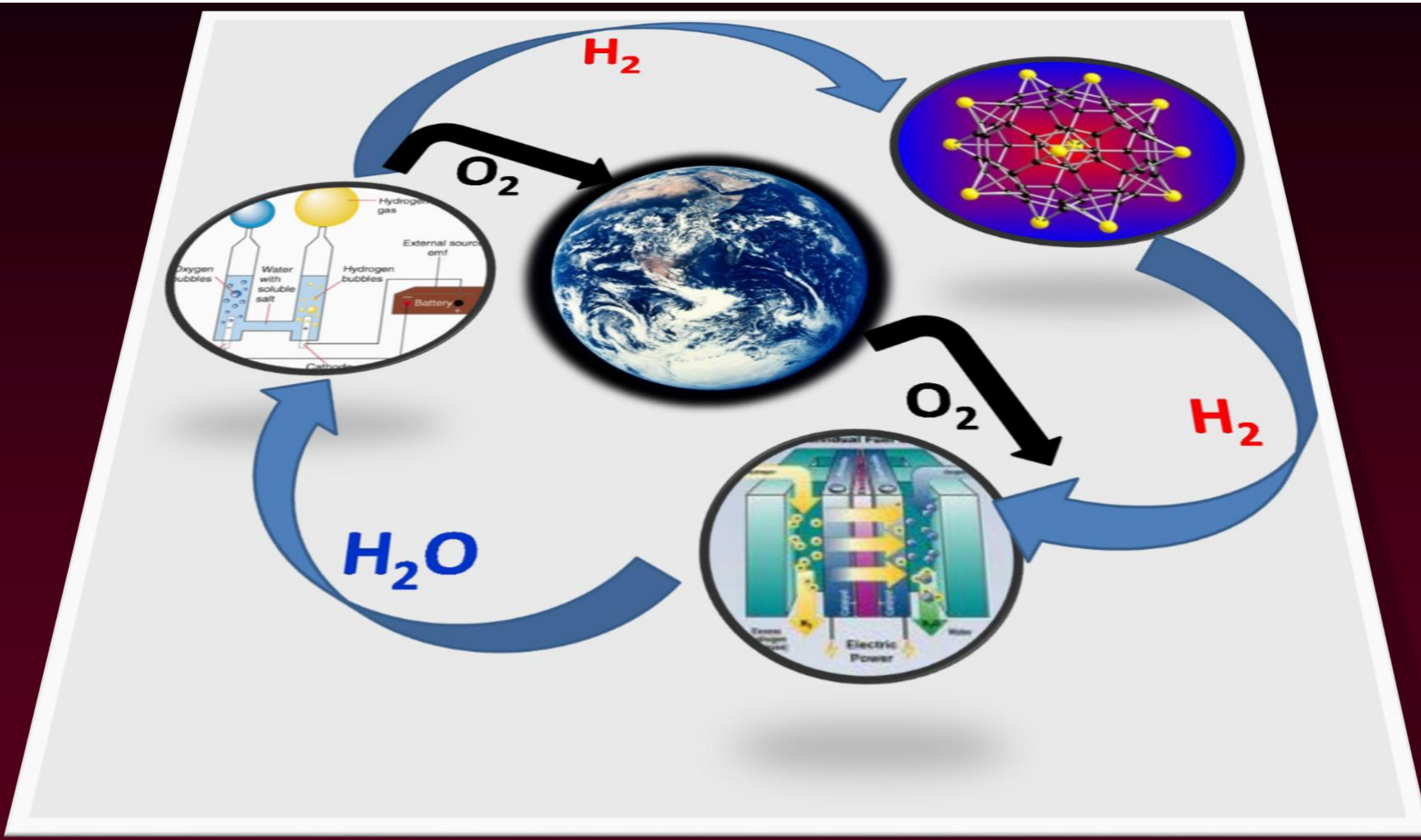
- The international community recognizes H2 as a key component in a clean, sustainable energy system, or H2 economy.
- The future H2 economy features hydrogen as an energy carrier in the stationary power, transportation, industrial, residential and commercial sectors.
- H2 as an energy carrier will be produced via water electrolysis using electricity from solar, wind etc and stored, transported by truck or pipeline, and used in a fuel cell, turbine, or engine to generate an electric current with water as the only by-product.

Energy of the Future World



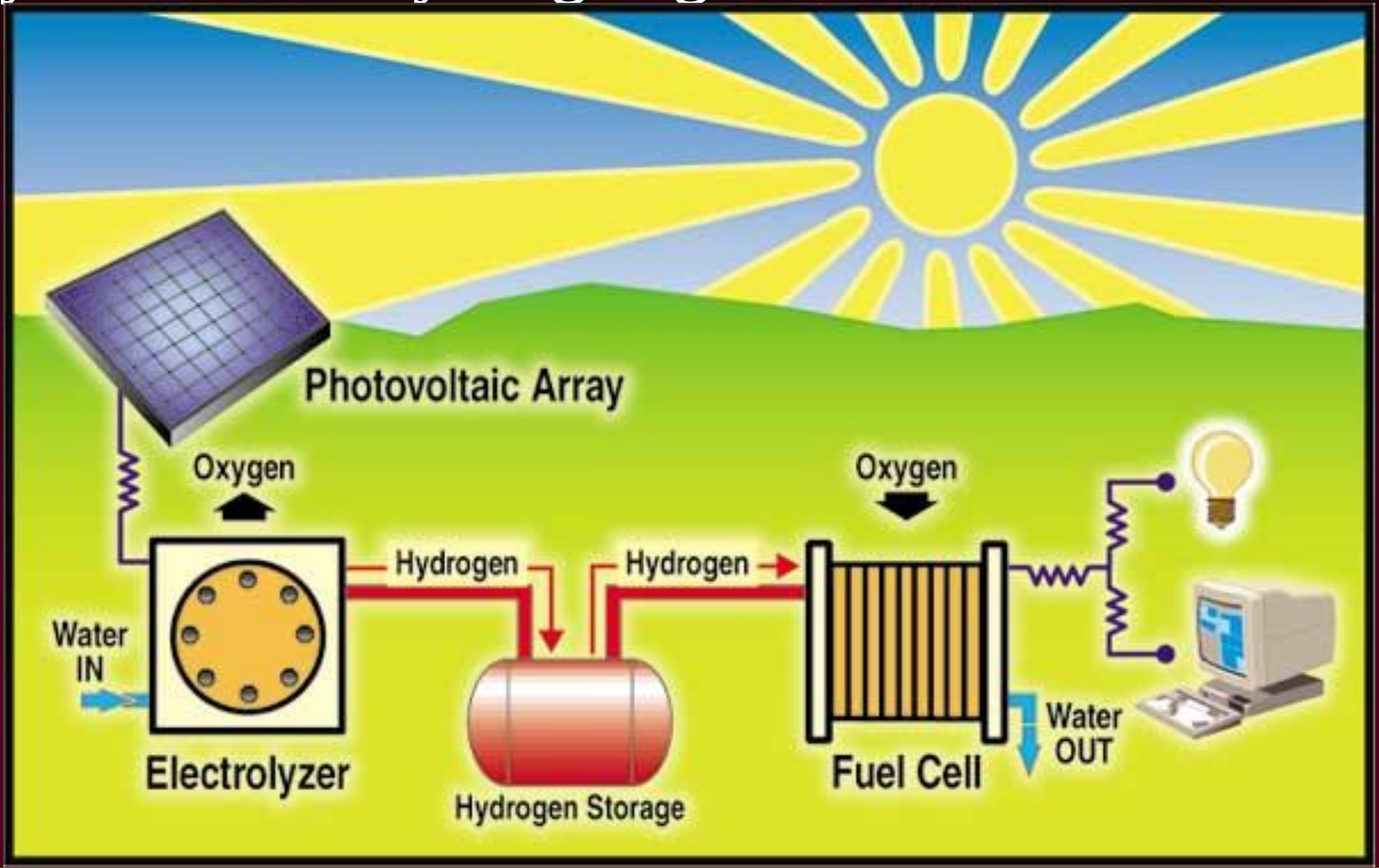
Transform from HC economy to Hydrogen Economy

Hydrogen As Energy Carrier

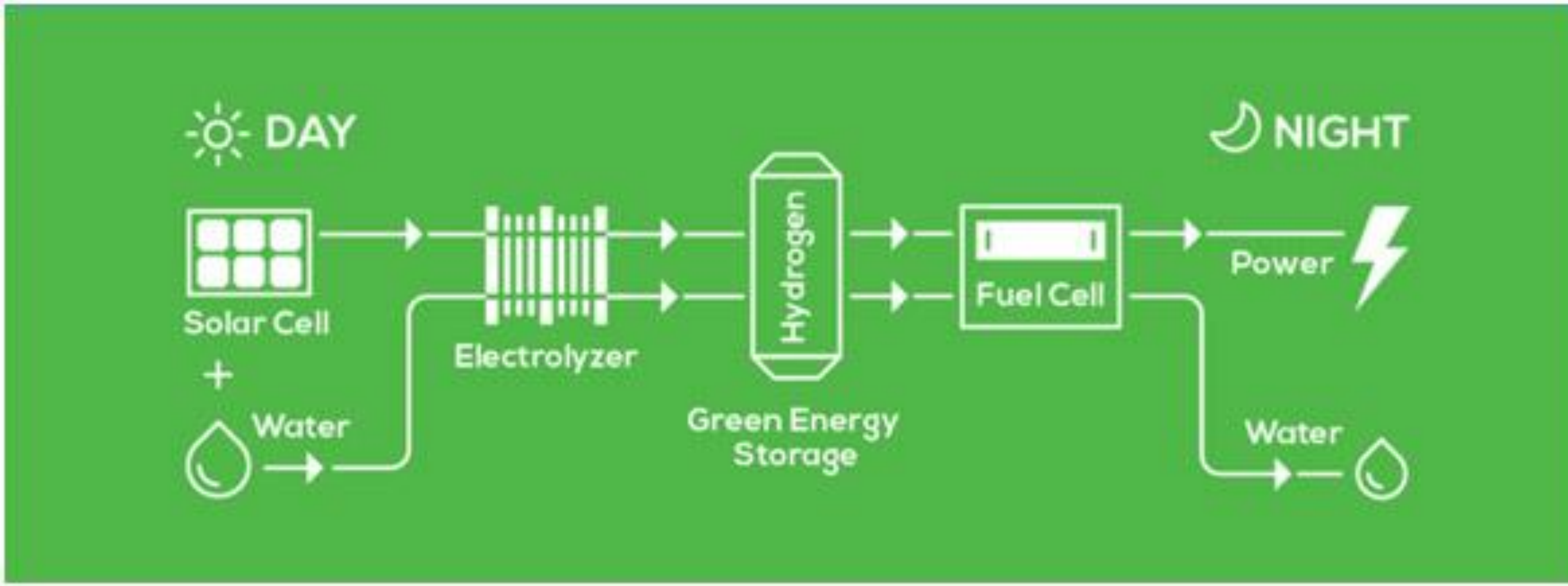


Solar H_2 Cycle

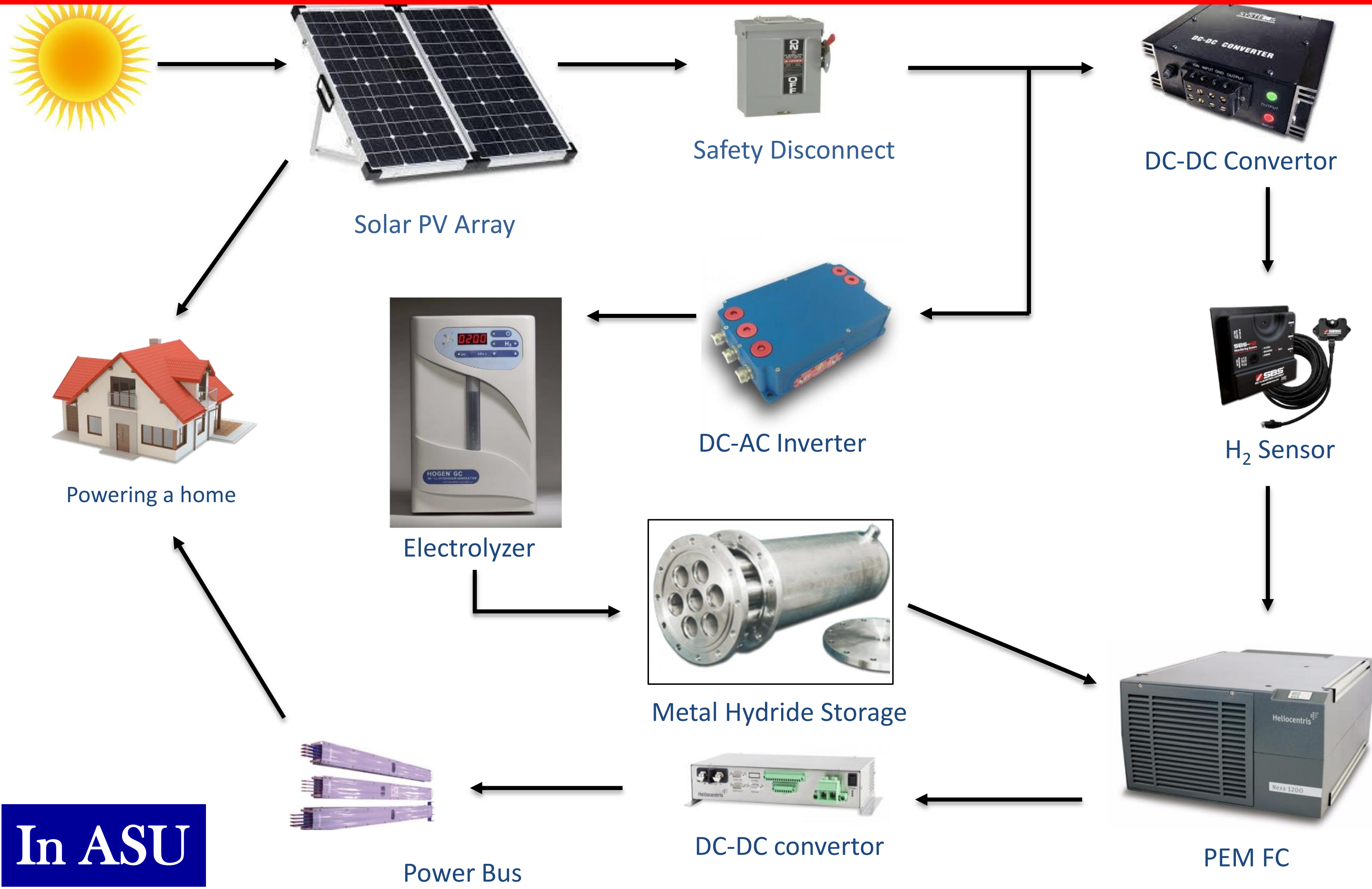
- Fully renewable hydrogen generation



Ref: IEE, Mexico


DAY
NIGHT
Solar Cell
+
Water
Electrolyzer
Hydrogen
Green Energy
Storage
Fuel Cell
Power
Water

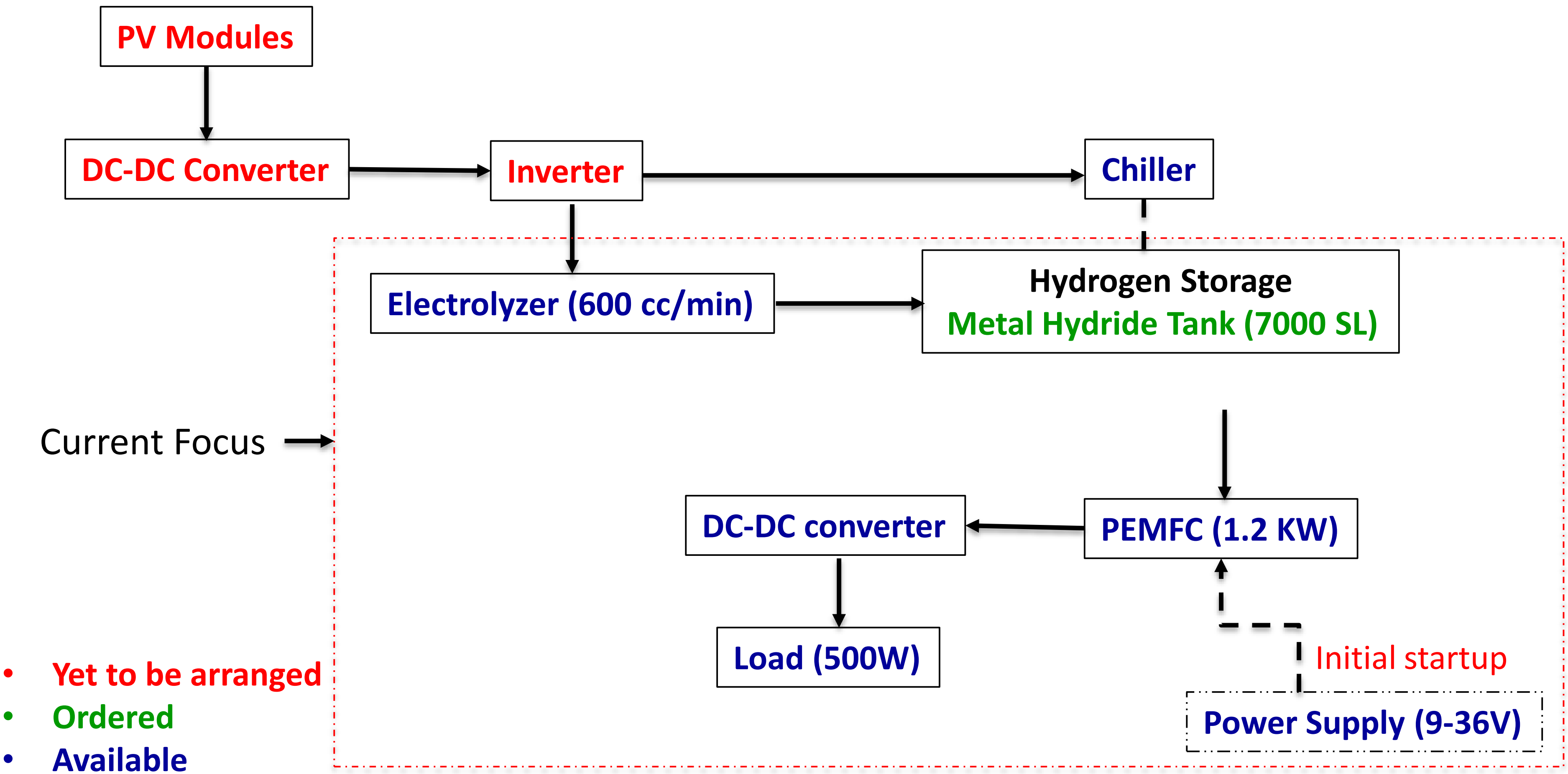
A system using compressed H_2 to store PV generated energy instead of batteries has the benefit of efficient and higher energy density storage than the traditional battery storage approach.



In ASU

Objective/Goal

Demonstration of the proposed system



Component Specifications

Nexa FC System

Power : 1200 W
DC Voltage range : 22 - 50 V
Hydrogen Flow rate : 15 L/min
Operational temp. : 5 – 40 °C

Electrolyzer

Delivery pressure : 3 - 13.8 bar
H_2 Flowrate : 0.5 L/ min

Metal Hydride Tank (Pragma Ind.)

Storage Capacity : 7000 L
Charging Pressure : 15 bar
Charging Temp. : 25 °C (max)
Discharge rate : 21 L/h (max)

DC- DC Convertor

Vin : 12 - 45 V
Vout : 24 V
Iout : 55 A

Hydrogen Generation and Consumption

Electrolyzer to MH Tank:

$$\frac{7000\ \text{L}}{0.5\ \text{L/min}} * \frac{1\ \text{hr}}{60\ \text{min}} * \frac{1\ \text{day}}{24\ \text{hr}} = 9.7\ \text{days}$$

MH Tank to Fuel Cell:

$$\frac{7000\ \text{L}}{15\ \text{L/min}} * \frac{1\ \text{hr}}{60\ \text{min}} = 7.7\ \text{hrs}$$

Why Metal Hydride Unit?

We need a system to store hydrogen to operate the PEM fuel cell during the off hours of the Solar PV Array.

- Compressed hydrogen cylinder
    - Requires Hydrogen compressor
        - High pressure required
        - Additional Air Compressor
    - Multiple Tanks Required (mass storage)
- Metal Hydride Storage Tank
    - Small Space Claim
    - Requires Cooling Tank

<u>Why?</u>

- Light weight and Compact
- Can store at ambient temp. and pressure
- Safe storage

Technological foresights

A fact: The hydrogen economy is at best an enormous, long-term challenge

- **Even if main drivers; technology, economic, security of supply, and environmental factors were *all* favourable.**

H_2 future depends on

1. **Development of new, efficient H_2 production system**
2. **H_2 Storage systems**
3. **Deployment rate of H_2 distribution systems**
4. **Expected Fuel cell market growth**

Hydrogen and Fuel Cells

- Hydrogen and fuel cells are clean options for future energy supply and vehicle propulsion systems.
- In the future, hydrogen could establish one of the important basis to save our mobility.
- The portable, mobile and stationary application of fuel cells enable uninterrupted power supply

H2Stations.org

H2Mobility.org

Number of H2 Filling Stations

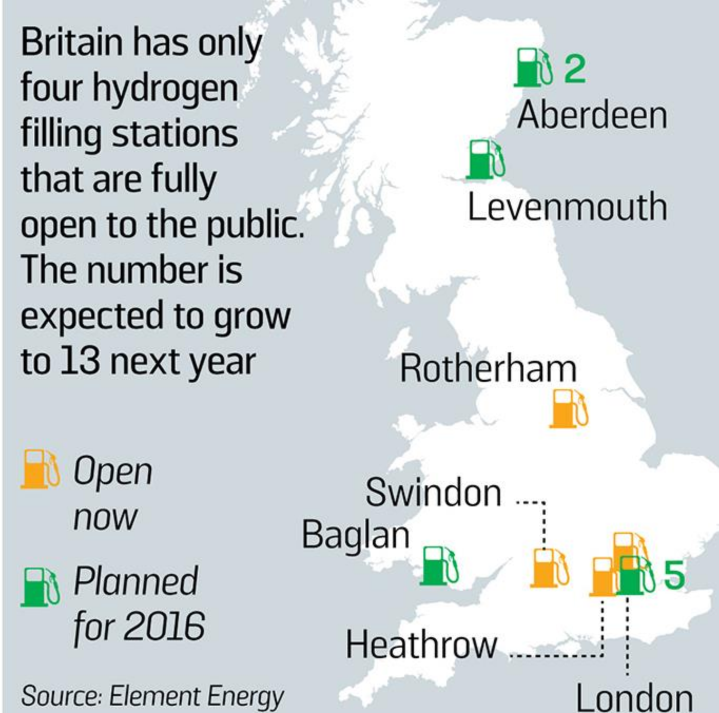
- **http://www.netinform.net/h2/H2Stations/Default.aspx**

Current number of database entries: 729

06.12.2016	Riviera Trasporti hydrogen station, San Remo (Italy)
06.12.2016	3Emotion, Cherbourg (France)
06.12.2016	Iwatani Shibakoen station, Tokyo (Japan)
06.12.2016	Nimohisu Mobile station Kudan, Tokyo (Japan)

H2 FILLING STATIONS IN LONDON

- £2.8m contract to supply three refueling stations in London
- ITM Power, the clean fuel company, is pleased to announce the successful award of a contract to supply three of its electrolyzer-based refueling stations to London under HyFive project announced by the Mayor of London's.



Hydrogen: Advantages

- H2 has a high energetic value, it is more fuel efficient than fossil fuels.
- It produces water during combustion.
- It is not toxic and does not contribute to the Greenhouse Effect, ozone depletion or acid rain.
- It can be used as an energy storage (instead of batteries or flywheels for example).
- It produces great heat.
- It is more expensive to move electrical energy across the continent than an equal amount of H2 as a compressed gas by pipeline.
- H_2, when combined with Oxygen, produces 9 times the amount in clean, potable water.

H2 is very Safe

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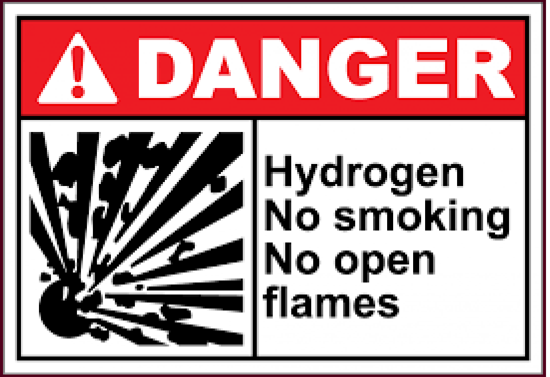
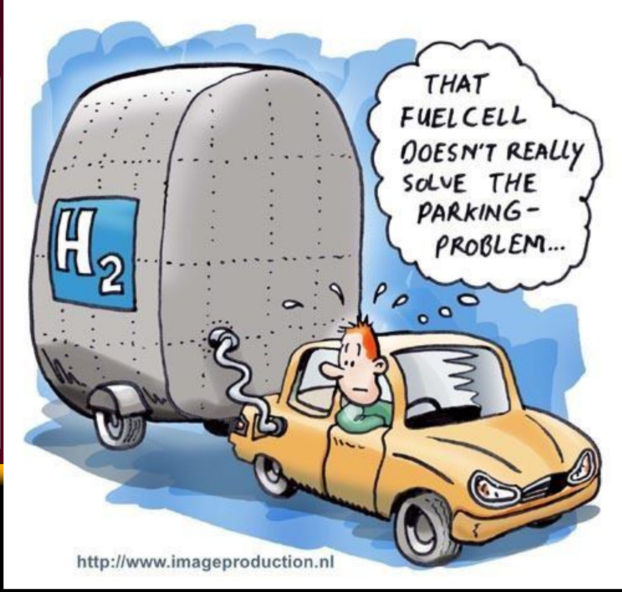
Safety of H_2 in vehicles

Hydrogen: Disadvantages

- It seldom comes alone.
- It can't be used as a primary energy source.
- More energy is used to produce H2 than what is obtained from combustion or FC.
- It is very flammable and volatile





IEA Report: 2014

http://www.iea.org/publications/freepublications/publication/2014_IEA_AnnualReport.pdf

- "The drive to clean up the world's energy system has stalled," IEA Executive Director Maria van der Hoeven told, at the meeting of ministers representing countries responsible for four-fifths of global greenhouse-gas emissions.
- **"Despite much talk by world leaders, and despite a boom in renewable energy over the last decade, the average unit of energy produced today is basically as dirty as it was 20 years ago."**

Elon Musk on H2 Car

http://www.digitaltrends.com/cars/elon-musk-says-fcvs-are-extremely-silly/

"If you get that hydrogen from water, so you're splitting H2O, the electrolysis is extremely inefficient as an energy process," he explained. "If you took a solar panel and used that energy from the solar panel to just charge the battery pack directly, compared to trying to split water, take the hydrogen, dump the oxygen, compress that hydrogen to an extremely high pressure or liquefy it, and then put it in a car and run a fuel cell, it is about half the efficiency. It's terrible."

"What would you do that?" he asked. "It makes no sense."

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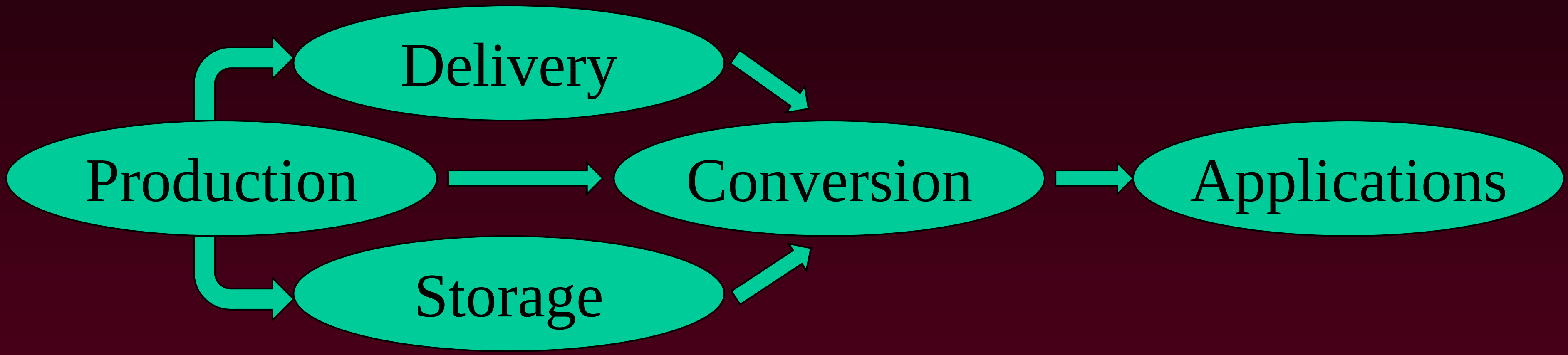
Hydrogen Roadmap



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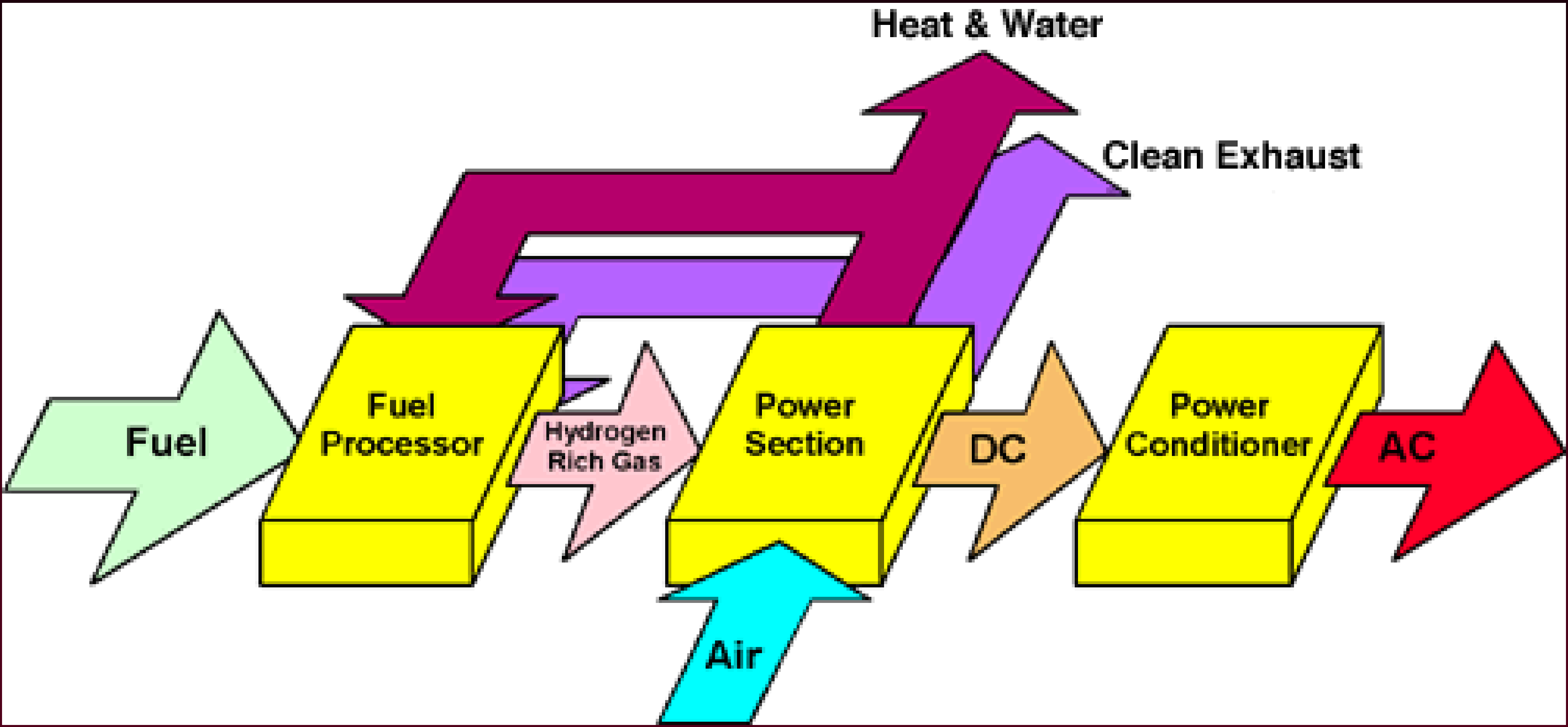
Fuel Reformers



THERMOCHEMICAL PROCESSES

- Some thermal processes use the energy in various resources, such as natural gas, coal, or biomass, to release H2 from their molecular structure.
- Following are various thermochemical processes:

1. Natural gas reforming (also called steam methane reforming or SMR)
2. Coal gasification
3. Biomass gasification
4. Biomass-derived liquid reforming
5. Solar thermochemical hydrogen (STCH)

NATURAL GAS REFORMING

- Natural gas reforming is an advanced and mature production process that builds upon the existing natural gas pipeline delivery infrastructure.
- Today, 95% of the hydrogen produced in the United States is made by natural gas reforming in large central plants.
- This is an important technology pathway for near-term hydrogen production.

Natural gas (CH_4) can be used to produce H2 by steam-methane reformation and partial oxidation.

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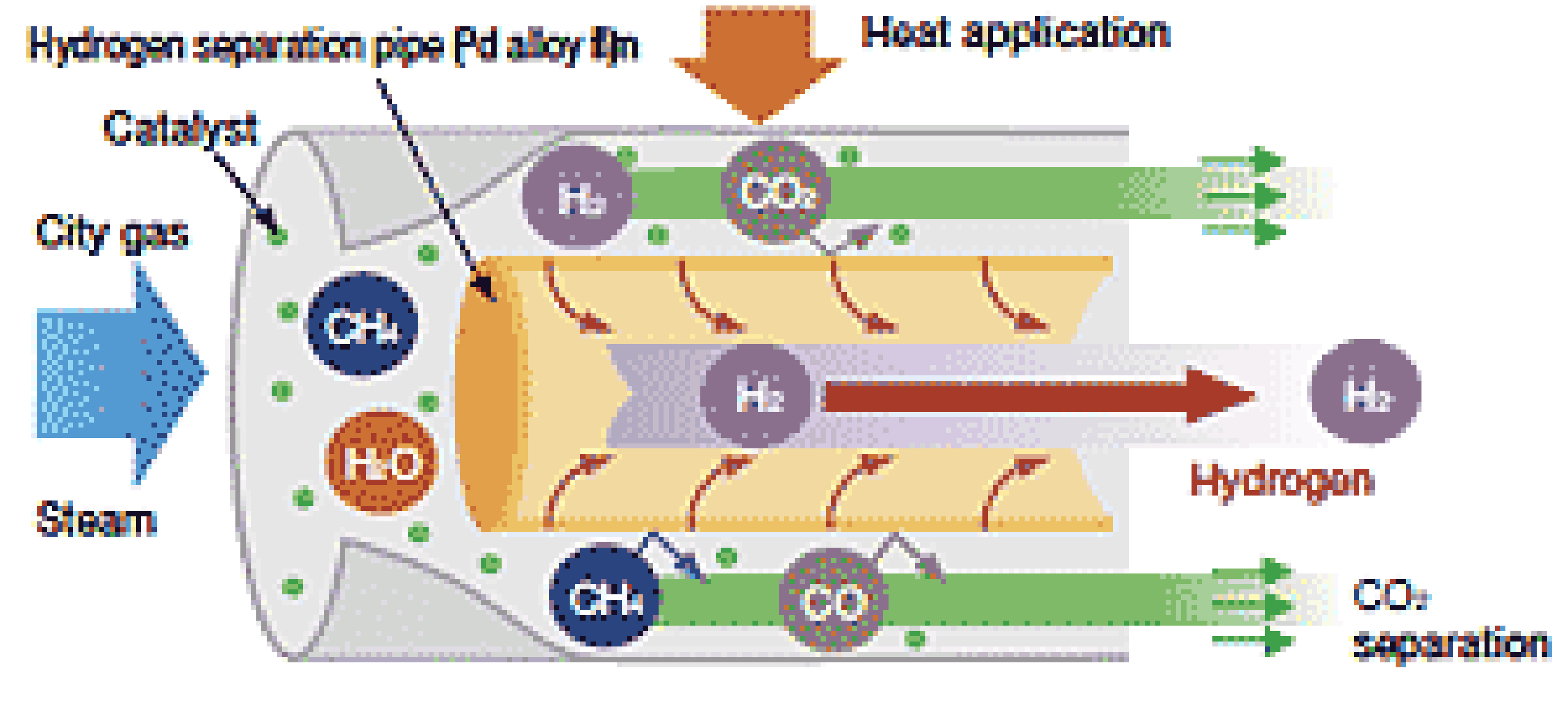
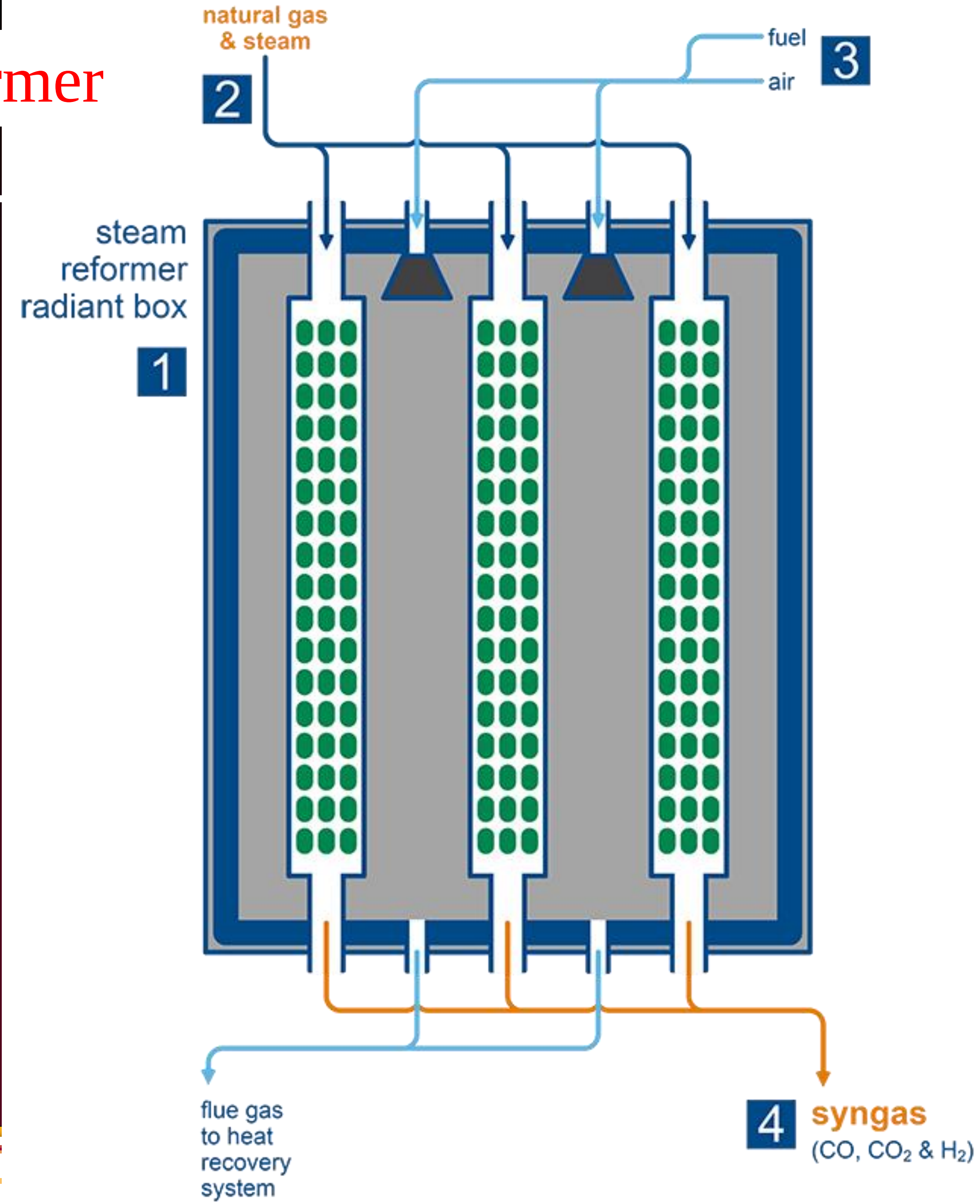
Steam Methane Reforming



Steam Methane Reformer

The reforming process takes place in a single radiant box.



Steam Methane Reforming

- In steam-methane reforming, methane reacts with steam under 3–25 bar pressure (1 bar = 14.5 psi) at 700 to 1000 oC, in the presence of a catalyst to H2, CO and a relatively small amount of CO2.
- Steam reforming is endothermic - that is, heat must be supplied to the process for the reaction to proceed.
- **In water-gas shift reaction the CO & steam are reacted using a catalyst to produce CO2 and H2**

Steam-methane reforming reaction

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

Water-gas shift reaction

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

Steam Methane Reforming

In a final process step called "pressure-swing adsorption“, CO_2 and other impurities (Flue gas) are removed from the gas stream, leaving essentially pure H_2.

Steam reforming can also be used to produce hydrogen from other fuels, such as ethanol, propane, or even gasoline.

PARTIAL OXIDATION

- In partial oxidation, the methane and other hydrocarbons in natural gas react with a limited amount of O_2 that is not enough to completely oxidize the hydrocarbons to CO_2 and water.
- With less than the stoichiometric amount of O_2 available, the reaction products contain primarily H_2 and CO and a relatively small amount of CO_2 and other compounds.
- Subsequently, in a water-gas shift reaction, the carbon monoxide reacts with water to form carbon dioxide and more hydrogen.

PARTIAL OXIDATION

- Partial oxidation is an exothermic process - it gives off heat.
- The process is, typically, much faster than steam reforming and requires a smaller reactor vessel.
- This process initially produces less H2 per unit of the input fuel than is obtained by steam reforming of the same fuel.

Partial oxidation of methane reaction

$$CH_4 + \frac{1}{2}O_2 \rightarrow CO + 2H_2 \text{ (+ heat)}$$

Water-gas shift reaction

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

ELECTROLYTIC PROCESSES

- Electrolyzers use electricity to split water into H_2 and O_2.
- This technology is well developed and available commercially, and systems that can efficiently use intermittent renewable power are being developed.

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SURF 'N' TURF (UK)

- An innovative new community project in Orkney that takes excess electricity generated from renewable energy sources and turns it into hydrogen for fuel on land and sea.

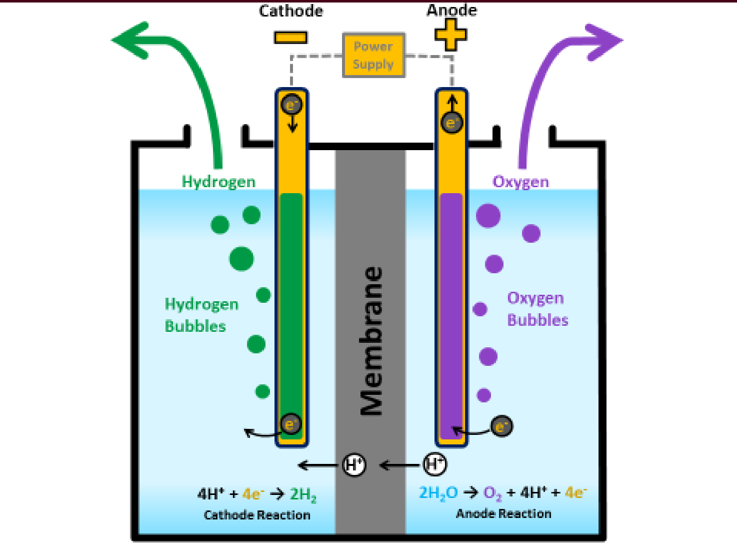
PEM ELECTROLYZERS

- In a PEM electrolyzer, water reacts at the anode to form oxygen and positively charged hydrogen ions (protons).
- The electrons flow through an external circuit and the H+ ions move across the PEM to the cathode.

At the cathode, hydrogen ions combine with electrons from the external circuit to form hydrogen gas.

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

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



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ALKALINE ELECTROLYZERS

- Alkaline electrolyzers operate via transport of hydroxide ions (OH^-) through the electrolyte from the cathode to the anode with hydrogen being generated on the cathode side.
- Electrolyzers using a liquid alkaline solution of sodium or potassium hydroxide as the electrolyte have been commercially available for many years.

Newer approaches using solid alkaline exchange membranes as the electrolyte are showing promise on the lab scale.

SOLID OXIDE ELECTROLYZERS

- Solid oxide electrolyzers, which use a solid ceramic material as the electrolyte that selectively conducts negatively charged oxygen ions (O^{2-}) at elevated temperatures, generate hydrogen in a slightly different way.
- Water at the cathode combines with electrons from the external circuit to form hydrogen gas and negatively charged oxygen ions.
- The oxygen ions pass through the solid ceramic membrane and react at the anode to form oxygen gas and generate electrons for the external circuit.

Solid Oxide Electrolyzers

- Solid oxide electrolyzers must operate at temperatures high enough for the solid oxide membranes to function properly (about 700°–800°C, compared to PEM electrolyzers, which operate at 70°–90°C, and commercial alkaline electrolyzers, which operate at 100°–150°C).

The solid oxide electrolyzers can effectively use heat available at these elevated temperatures (from various sources, including nuclear energy) to decrease the amount of electrical energy needed to produce hydrogen from water.

Why is this Pathway considered?

1. H2 produced via electrolysis can result in zero greenhouse gas emissions, depending on the source of the electricity.
2. **The source of the required electricity** - including its cost and efficiency, as well as emissions resulting from electricity generation - must be considered when evaluating the benefits and economic viability of hydrogen production via electrolysis.

H2 production via electrolysis with renewable (wind) and nuclear energy options will result in virtually zero greenhouse gas and criteria pollutant emissions.

RESEARCH FOCUSES ON OVERCOMING CHALLENGES

1. Reducing the capital cost of the electrolyzer unit and the balance of the system, and improving energy efficiency for converting electricity to hydrogen.
2. Integrating compression into the electrolyzer to avoid the cost of a separate hydrogen compressor needed to increase pressure for hydrogen storage.

Technical Targets: Distributed Forecourt Water Electrolysis Hydrogen Production

Characteristics	Units	2011 Status	2015 Target	2020 Target
Hydrogen levelized cost[d] (production only)	$/kg	4.20[d]	3.90[d]	2.30[d]
Electrolyzer system capital cost	$/kg	0.70	0.50	0.50
	$/kW	430[e,f]	300	300
System energy efficiency	% (LHV)	67	72	75
	kWh/kg	50	46	44
Stack energy efficiency	% (LHV	74	76	77
	kWh/kg	45	44	43
Electricity price	$/kWh	From AEO 2009	From AEO 2009	0.037

CENTRAL VERSUS DISTRIBUTED HYDROGEN PRODUCTION

- Central, semi-central, and distributed production facilities are expected to play a role in the evolution and long-term use of hydrogen as an energy carrier.
- The different **resources** and **processes** used to produce hydrogen may be suitable to one or more of these scales of production.

DISTRIBUTED PRODUCTION

- Hydrogen can be produced in small units where it is needed, such as vehicle refueling stations, in a manner known as "distributed production."
- Two distributed hydrogen production technologies that may offer potential for development and commercialization are
  - reforming natural gas or liquid fuels, including renewable liquids, such as ethanol and bio-oil, and
  - small-scale water electrolysis.

Distributed production may be the most viable approach for introducing hydrogen in the near term in part because the initial demand for hydrogen will be low.

CENTRALIZED PRODUCTION

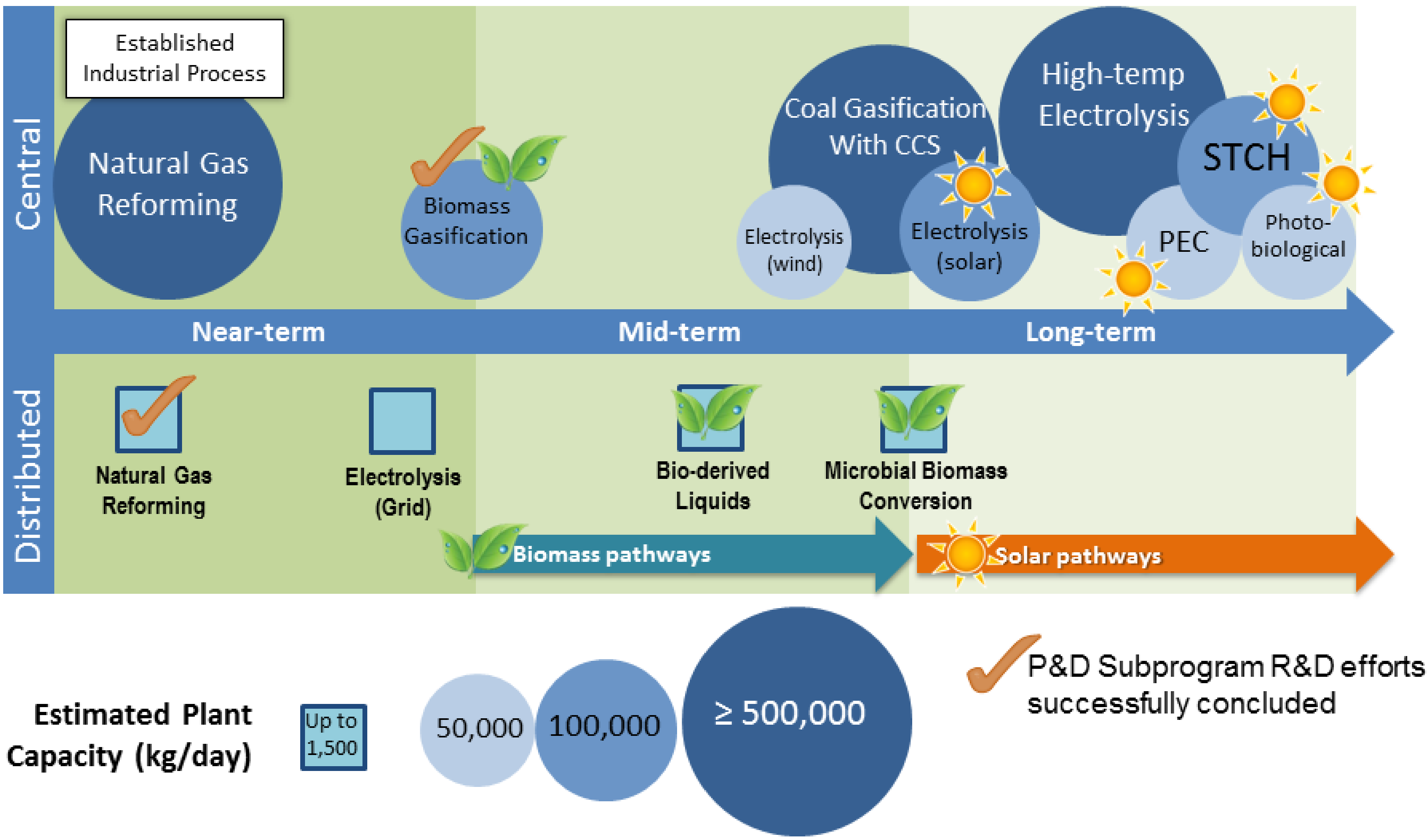
- Large central H2 production facilities (750,000 kg/day) that take advantage of economies of scale will be needed in the long term to meet the expected large demand.
- Compared with distributed production, centralized production will require more capital investment as well as a substantial hydrogen transport and delivery infrastructure

The new SMR, owned and operated by Air Liquide, has an annual production capacity of 22,000 tonnes of hydrogen

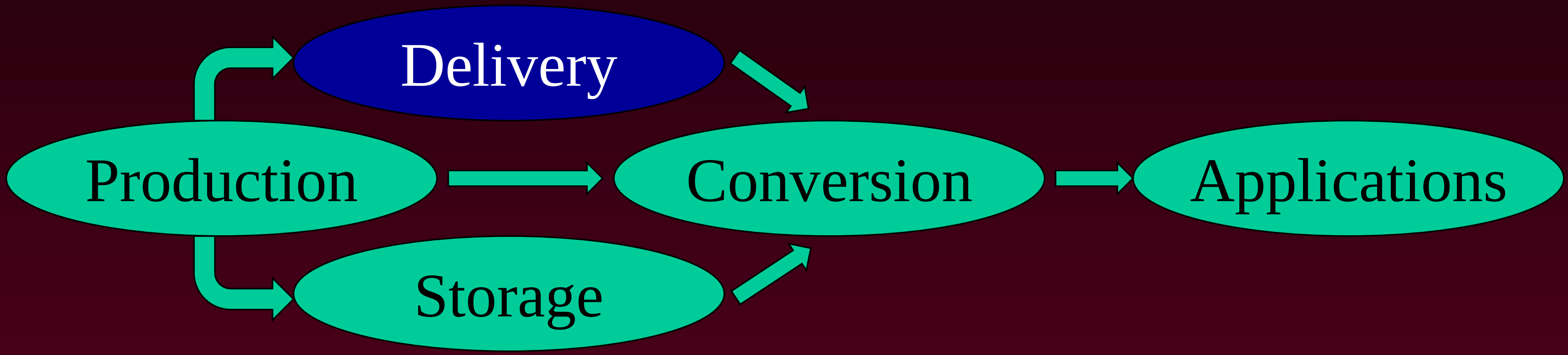
SEMI-CENTRAL PRODUCTION

- **Intermediate-size hydrogen production facilities (5,000–50,000 kg/day) located in close proximity (25–100 miles) to the point of use may play an important role in the long-term use of hydrogen as an energy carrier.**
- These facilities can provide not only a level of economy of scale but also minimize hydrogen transport costs and infrastructure.

H2 Production



Hydrogen Roadmap



H2 Delivery

- Hydrogen is not just the smallest element on earth, it is also the lightest—as a point of comparison, the mass one gallon of gasoline is approximately 2.75 kg where one gallon of hydrogen has a mass of only 0.00075 kg (at 1 atm pressure and 0°C).
- In order to transport large amounts of hydrogen it must be either pressurized and delivered as a compressed gas, or liquefied.

GASEOUS HYDROGEN DELIVERY

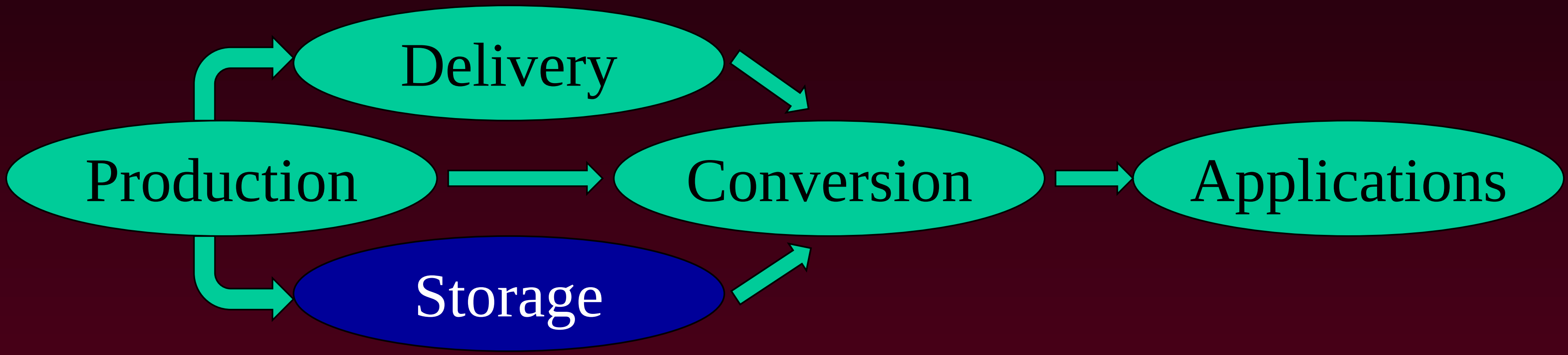
- Gaseous hydrogen is most commonly delivered either by trucks or through pipelines.
- Trucks that haul gaseous hydrogen are called tube trailers.
- Gaseous hydrogen is compressed to pressures of 180 bar (~2,600 psig) or higher into long cylinders which are stacked on the trailer that the truck hauls.

Gaseous hydrogen can also be transported through pipelines much the way natural gas is today. This is common for long distance and high volume transport.

Cost Targets for H2 Delivery

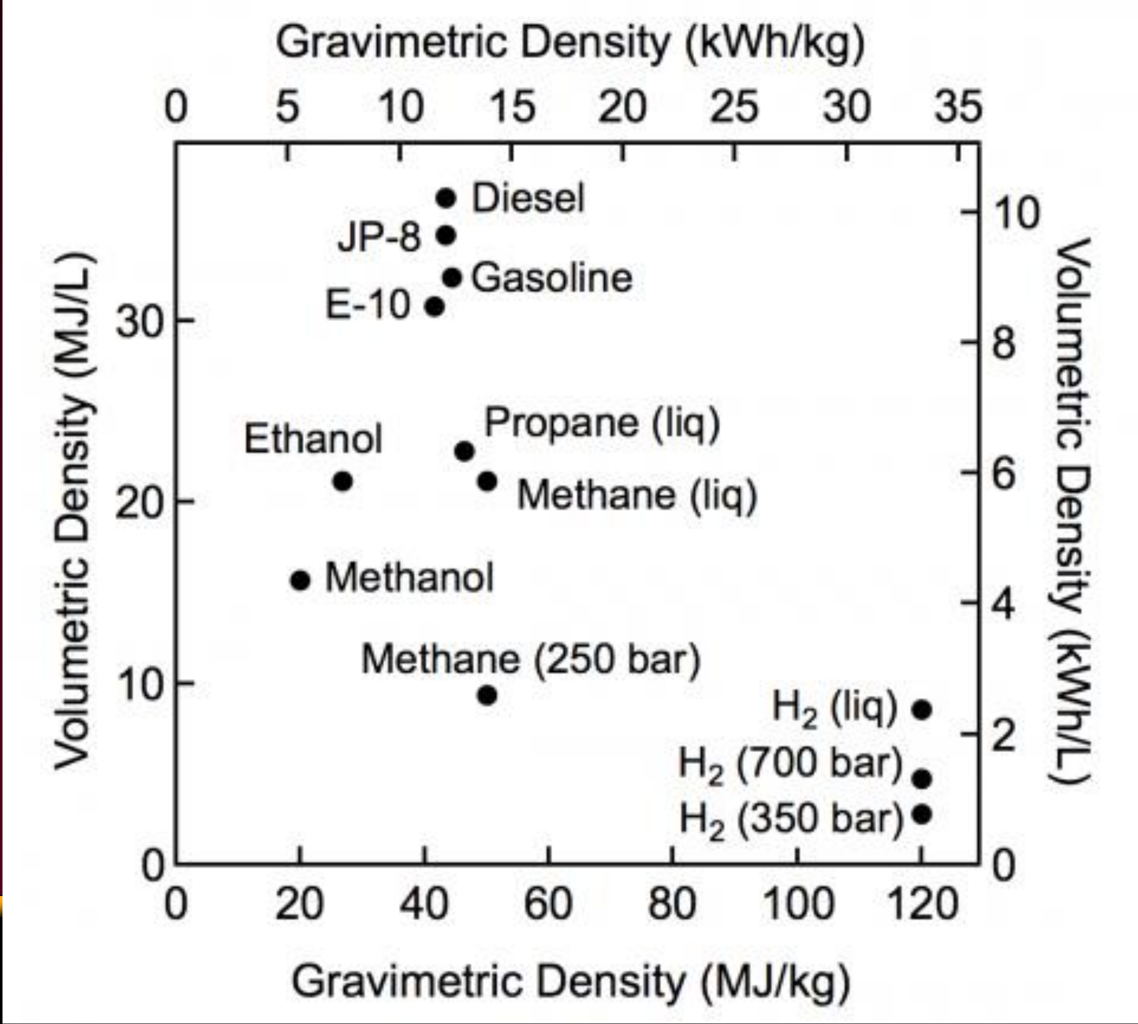
Category	FY 2011 Status[bb]	FY 2015 Status	FY 2020 Target	Ultimate Target[cc]
Delivery costs associated with distributed H_2 production[aa]				
Aggregate fueling station cost ($/gge)	2.50	2.19	2.15	<1.70
Delivery costs associated with centralized H_2 production[aa]				
Aggregate cost of transport, distribution, and fueling ($/gge)	3.60–4.40	3.35–4.35	2.00	<2.00

Hydrogen Roadmap



Various Fuels

- Comparison of gravimetric density and volumetric density for several fuels



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H2 STORAGE CHALLENGES

- High density H2 storage is a challenge for stationary and portable applications and remains a significant challenge for transportation applications.
- Presently available storage options typically require large-volume systems that store hydrogen in gaseous form.
- This is less of an issue for stationary applications, where the footprint of compressed gas tanks may be less critical.

Fuel-cell-powered vehicles require enough hydrogen to provide a driving range of more than 300 miles with the ability to quickly and easily refuel the vehicle.

H2 Storage Methodologies

- Hydrogen can be **stored physically** as either a gas or a liquid. Storage of hydrogen as a gas typically requires high-pressure tanks (350–700 bar [5,000–10,000 psi] tank pressure).
- Storage of hydrogen as a liquid requires cryogenic temperatures because the boiling point of hydrogen at one atmosphere pressure is −252.8°C.
- Hydrogen can also be stored on the surfaces of solids (by adsorption) or within solids (by absorption).

H2 storage is a key enabling technology for the advancement of H2 and FC technologies in applications including stationary power, portable power, and transportation.

How is hydrogen stored?

Physical-based

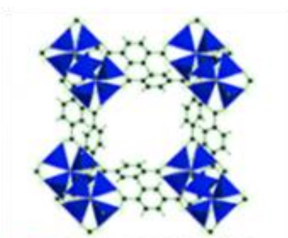
- Compressed Gas

- Cold/Cryo Compressed

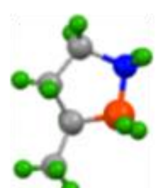
- Liquid H_2

Material-based

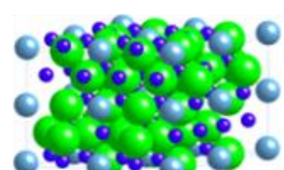
- Adsorbent
  Ex. MOF-5



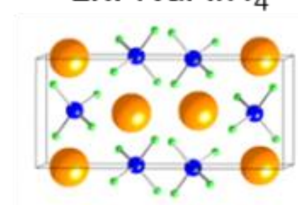
- Liquid organic
  Ex. BN-methyl cyclopentane



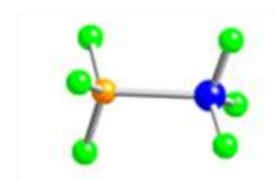
- Interstitial hydride
  Ex. $LaNi_5H_6$



- Complex hydride
  Ex. $NaAlH_4$



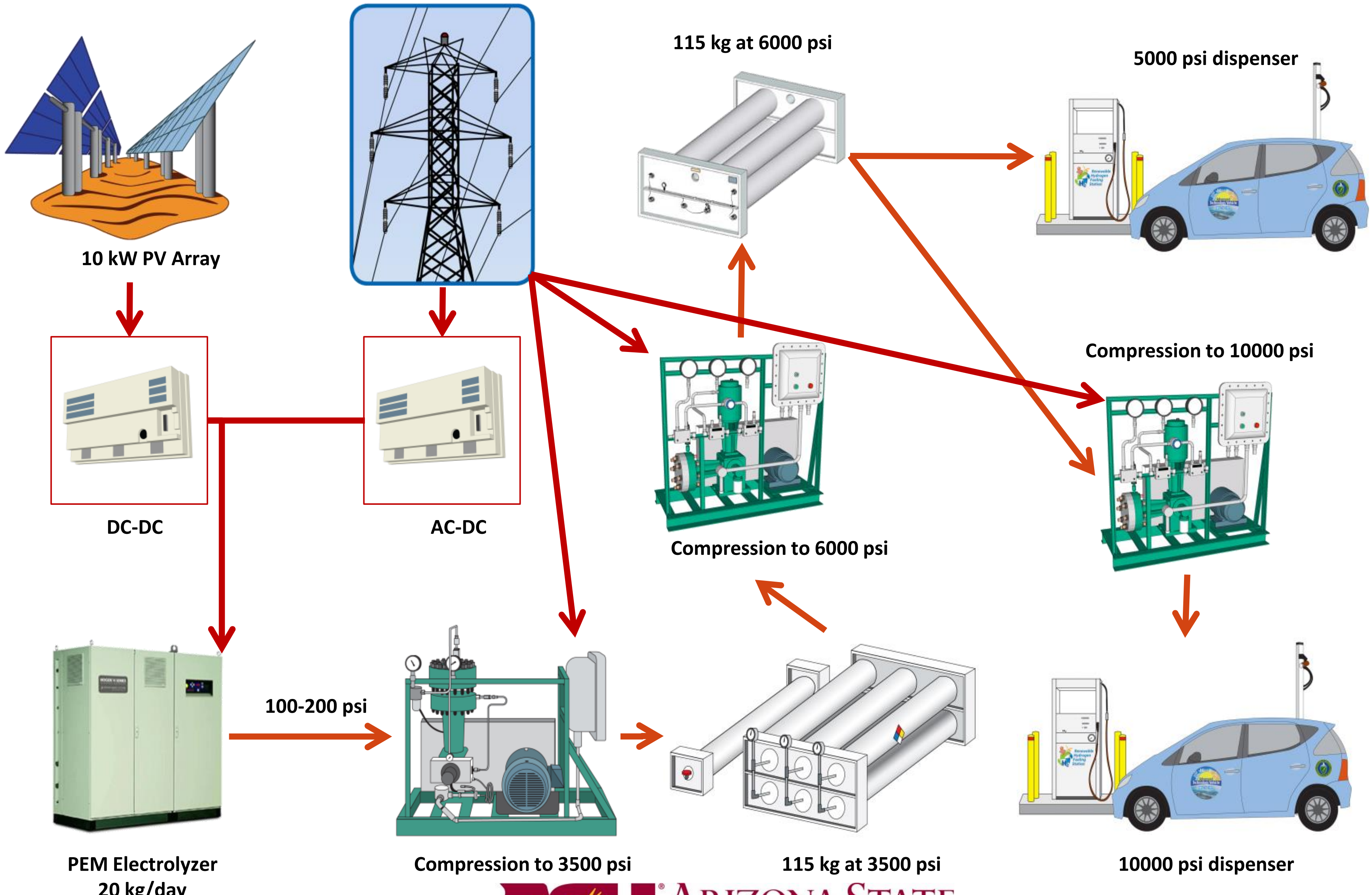
- Chemical hydrogen
  Ex. NH_3BH_3



Distributed Electrolysis H2A Example Cost Contributions

Characteristics		Units	2011 Status	2015	2020
Electrolysis system	Cost contribution	\$/kg H_2	0.70	0.50	0.50
	Production equipment availability	%	98	98	98
Electricity	Cost contribution	\$/kg H_2	3.00[i]	3.10[i]	1.60[j]
Production fixed O&M	Cost contribution	\$/kg H_2	0.30	0.20	0.20
Production other variable costs	Cost contribution	\$/kg H_2	0.10	0.10	<0.10
Hydrogen production	Cost contribution	\$/kg H_2	4.10	3.90	2.30
Compression, storage, and dispensing	Cost contribution	\$/kg H_2	2.50	1.70	1.70
Total H2 levelized cost (dispensed)		\$/kg H_2	6.60	5.60	4.00

H2 Refueling Trend



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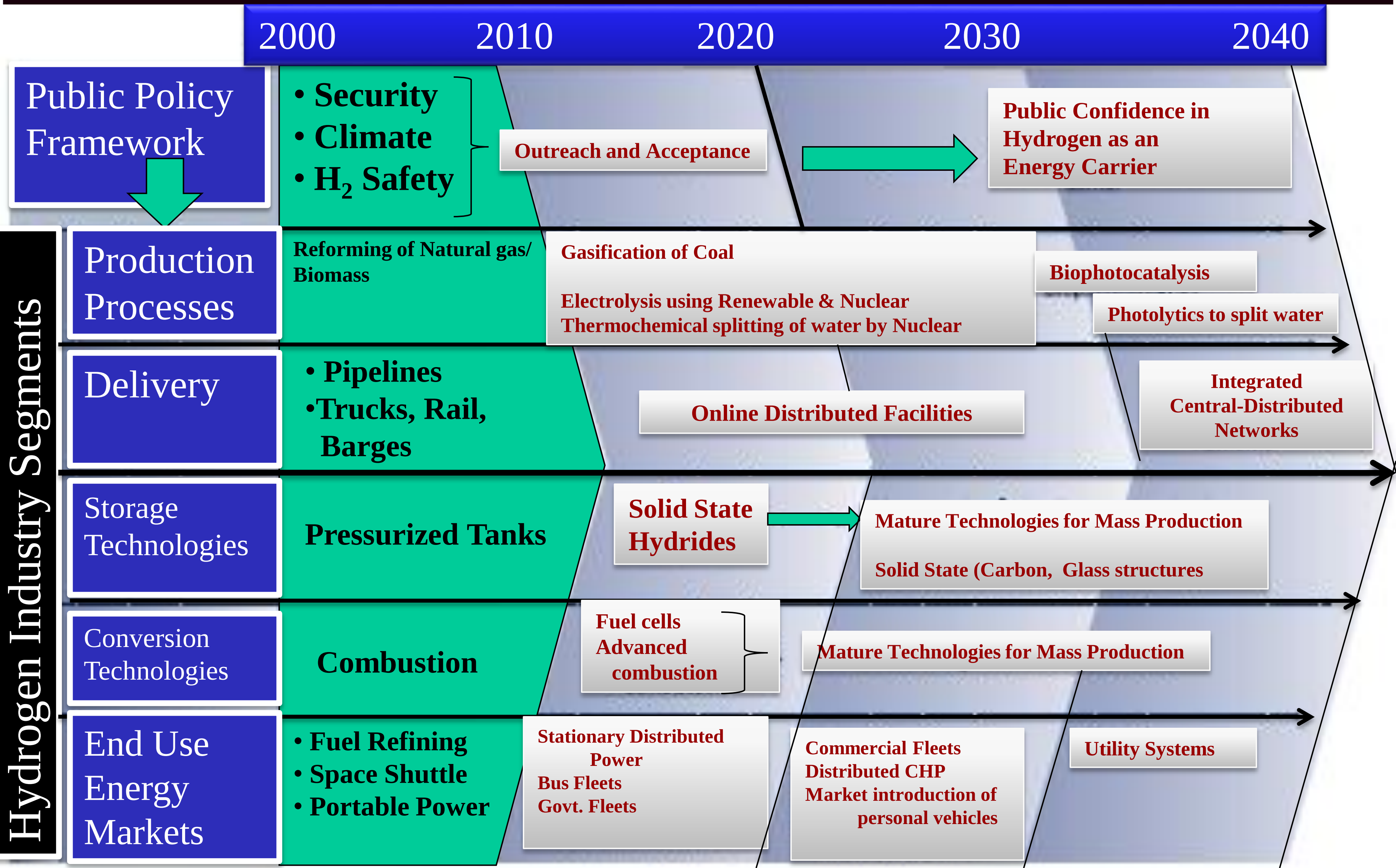
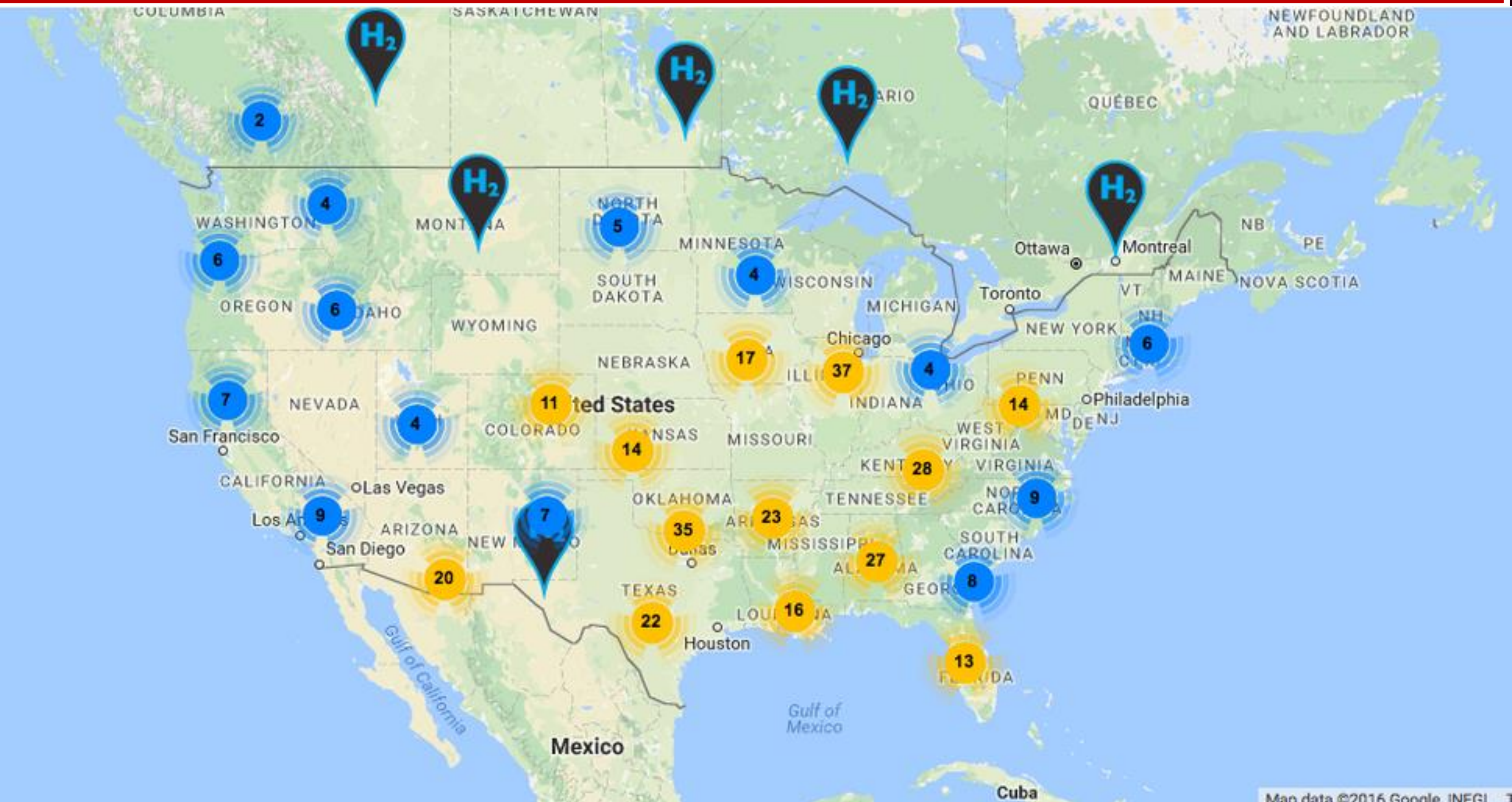
US Fuel Cell Seminar: H2 Stations

US Fuel Cell Seminar: FC Cars

Transition to the H_2 Economy



Nikola's biggest hurdle may be developing a national H2 fueling infrastructure



H2 Filling Stations

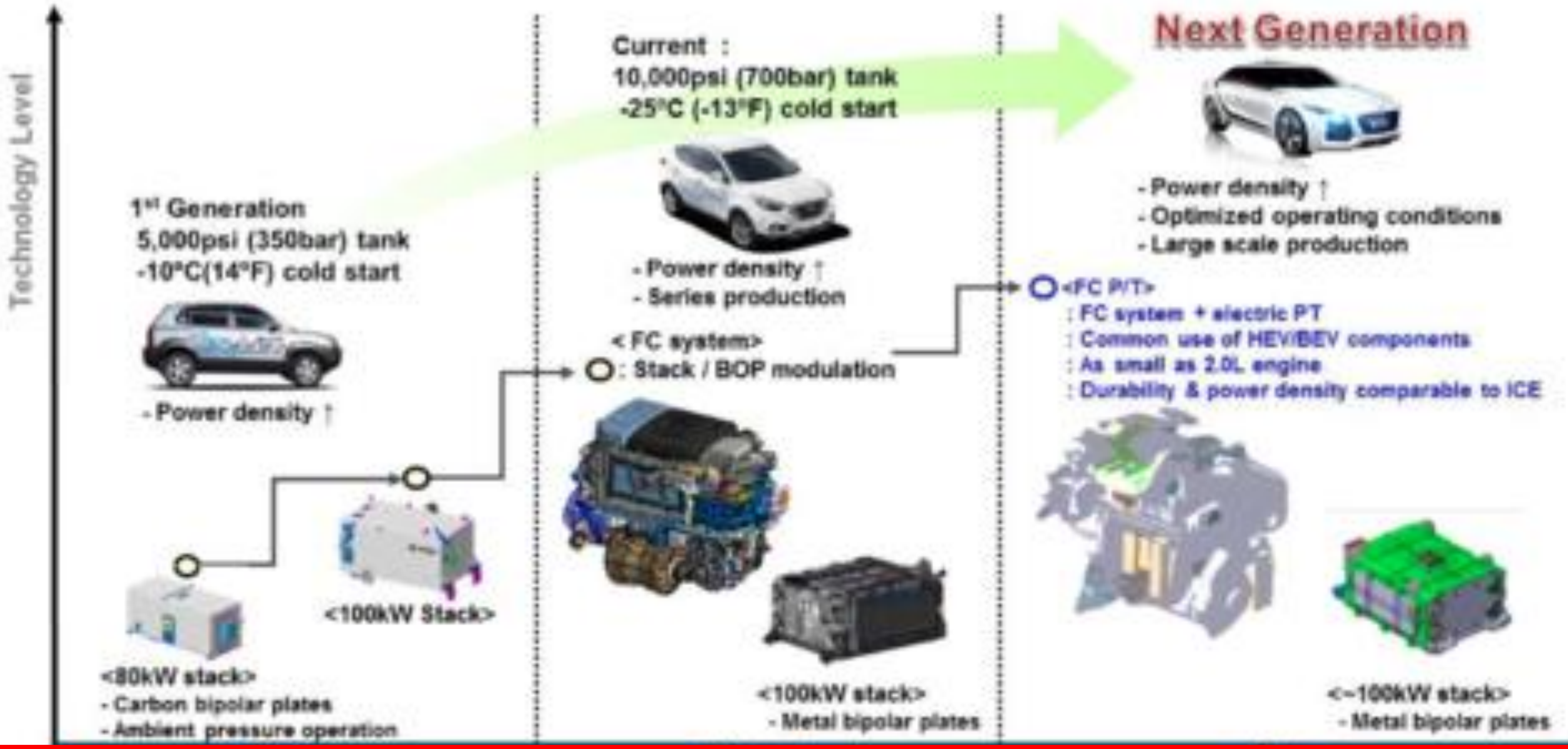
- Nikola is planning a string of hydrogen stations across the United States and Canada, with construction beginning in January, 2018.
- The 364 stations are slated to start coming online in late 2019.
- 5-20 minutes per fill-up
- H2-powered cars can use these stations as well.

CHALLENGES

- Technology validation addresses the following key challenges to pave the way for commercialization of fuel cell and hydrogen infrastructure technologies:
- Fuel Cell Cost and Durability
- Hydrogen Storage
- Hydrogen Production and Delivery
- Public Acceptance

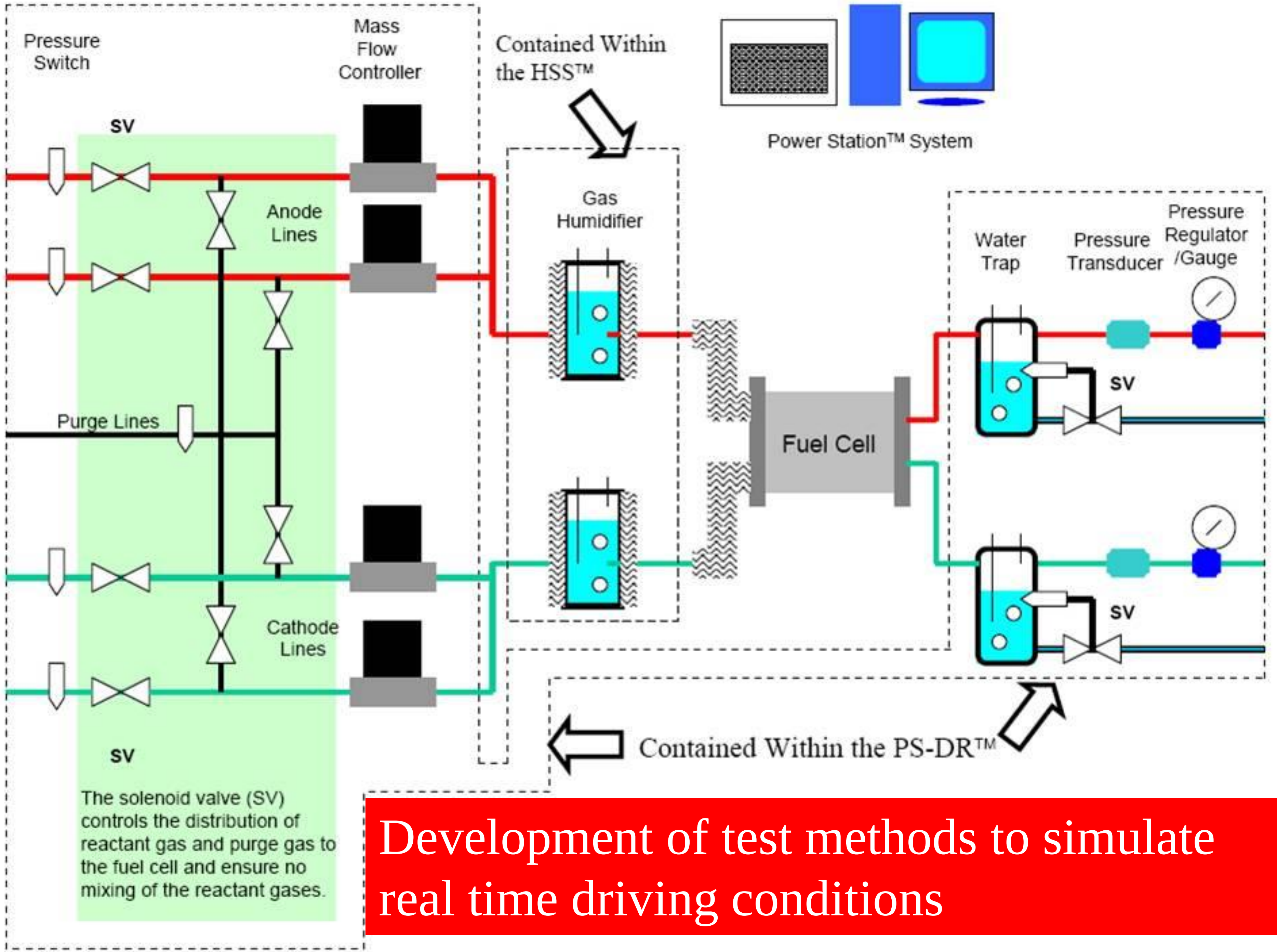
Development, Testing, and Life Cycle/Operational life Issues

FC Technology Development



Past Present Future

Unprecedented Growth by the Asian countries



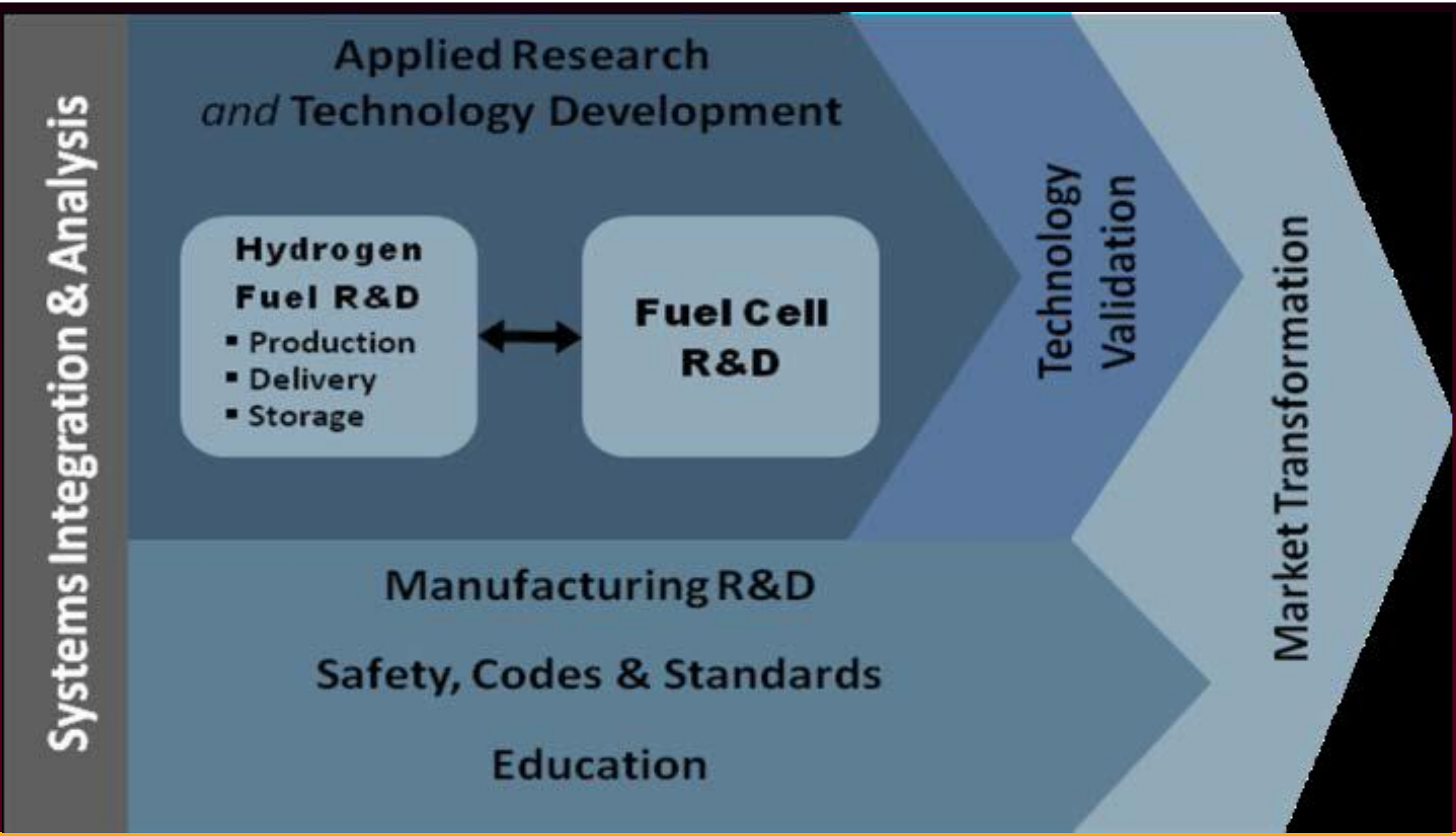
Development of test methods to simulate real time driving conditions

NREL researcher works in the gas manifold corridor for cell testing in the Fuel Cell Test and Development Laboratory

Ballard's state-of-the-art test lab sets the industry standard for proton exchange membrane fuel cell development and testing.

- Automated test stations able to run on O2, air, H2 and fuel blends
- Environmental chambers for freeze start high temperature testing
- Customizable accelerated stress test stations
- Custom diagnostic tests for systems, stacks and components such as anode and cathode half-cell potential measurements and current mapping

FC System Integration & Analysis



FC System Integration & Analysis

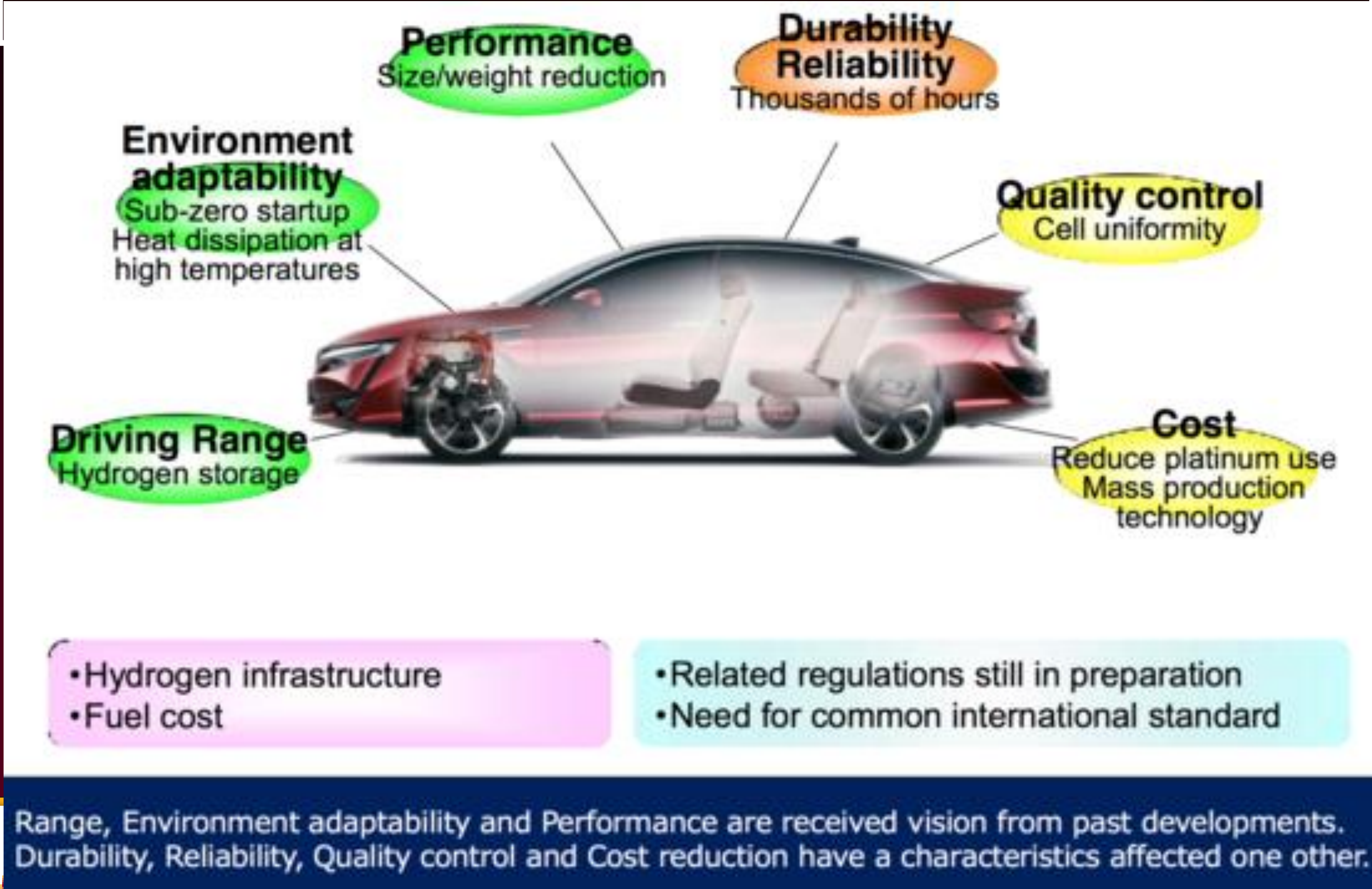
- **Activities include pathway analysis for**
  - H2 production
  - Evaluating impacts of **technology advancements on FC cost**
  - Analyzing impacts of **H2 quality on FC performance and infrastructure**, and
  - Complete "well-to-wheels" or life-cycle analysis of pathways to determine **reductions in greenhouse gas emissions** and petroleum use.

FC System Integration & Analysis

- **Risk analysis** is also performed to determine the effects of certain variables on the targets and to help identify risk mitigation strategies towards:

  - Performance
  - Durability and
  - Cost

FC Vehicles Issues and Strategies



FC System Integration & Analysis

- **Policy analyses** include
  - Investigating the effects of different policy options and scenarios,
  - Infrastructure and resource analysis,
  - Vehicle consumer choice analysis, and
  - Market penetration studies.

FC System Integration & Analysis

- **Analysis of employment** opportunities and needs,
  - manufacturing capability and growth potential, and
  - overall domestic competitiveness are also a critical part of the FC activities.

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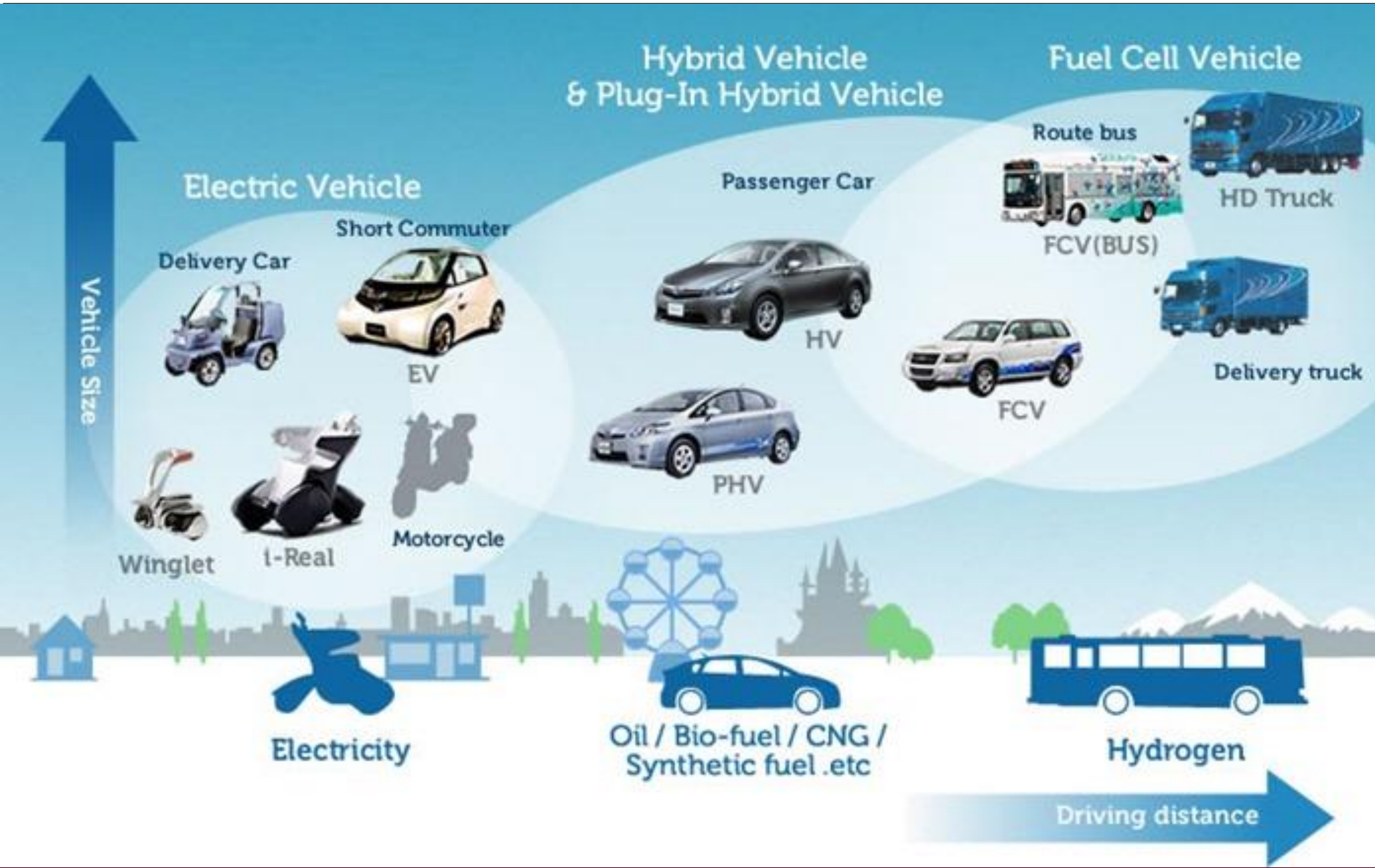

BEVs to FCVs - a natural progression

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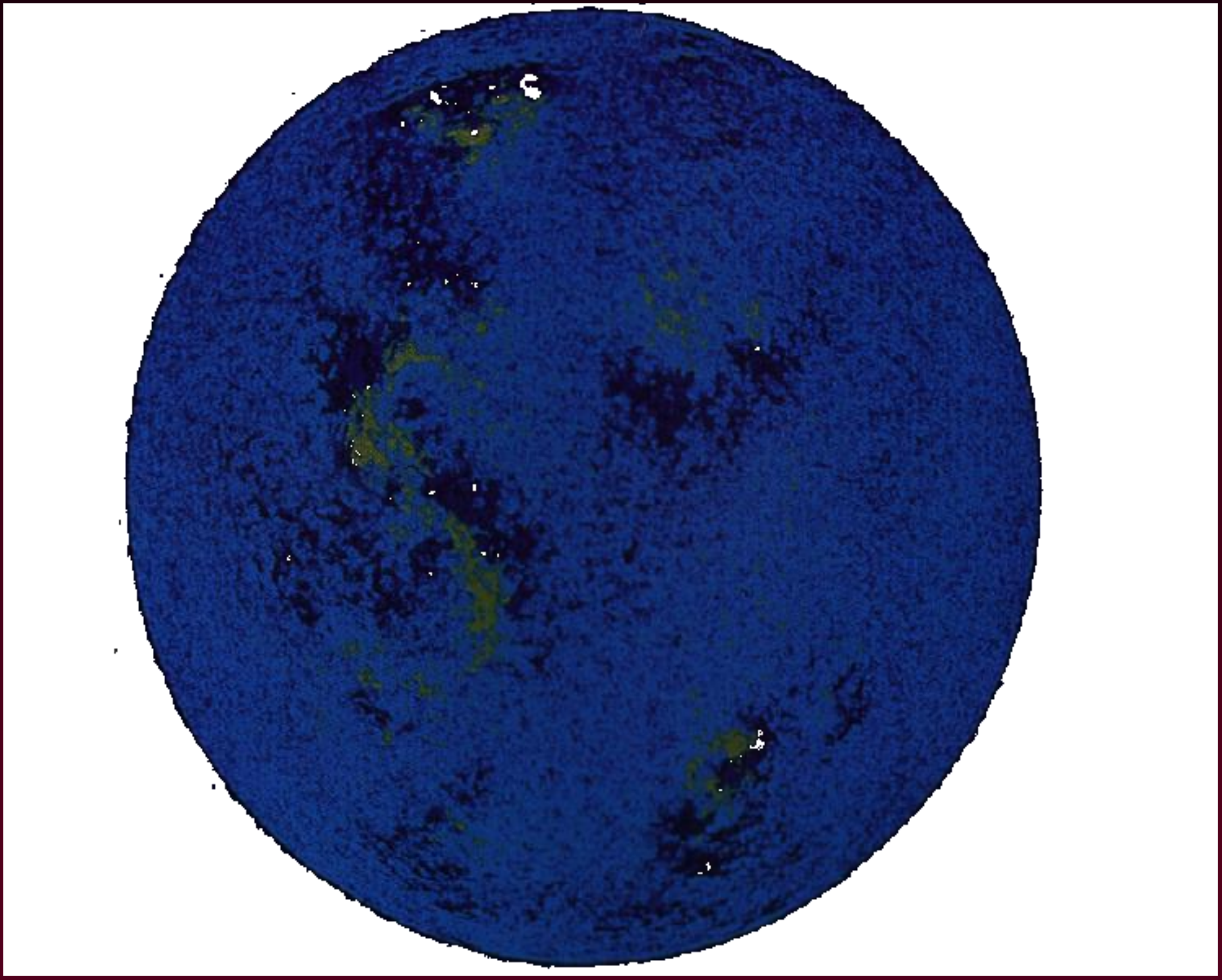
Where we are headed without using alternative energy sources...



This is what it should look like

Which one we need?

Decision is OURS

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