



IAEA

International Atomic Energy Agency

Atoms for Peace and Development

26th INPRO Dialogue Forum on the Deployment of Nuclear Energy Systems for Applications Beyond Electricity

Bangkok, Thailand, 24–28 August 2026

Recent developments in Nuclear Hydrogen Production

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Outline

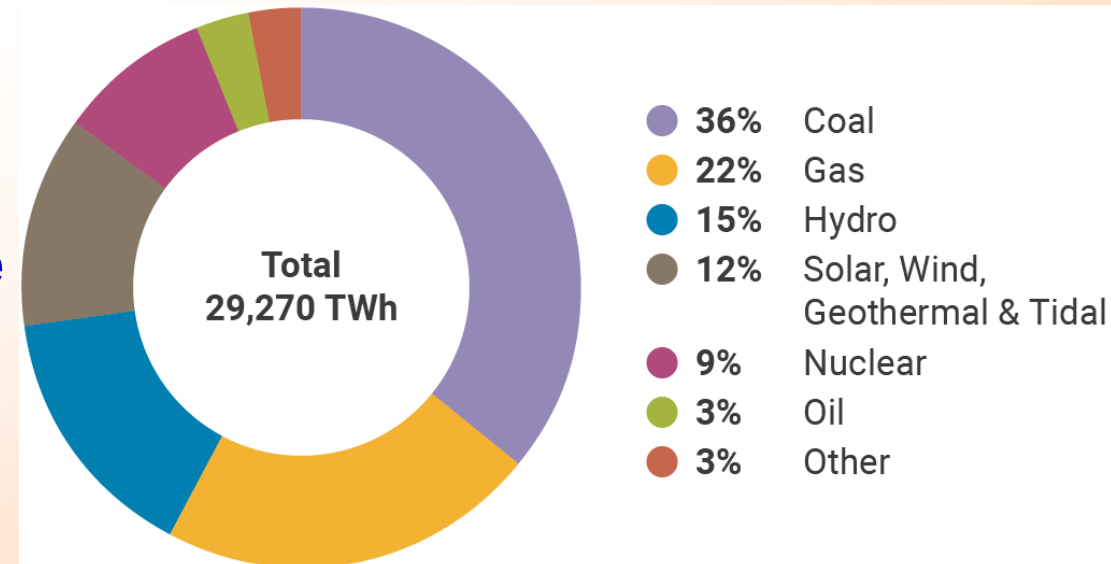
- The World Energy Picture and Issues
- Hydrogen as Green Fuel –as an Energy Carrier
- Nuclear Hydrogen Production- Technology and Efforts
 - ❖ Electrolysis- PEM and Alkaline Eelctrolyzers
 - ❖ High Temperature Solid Oxide Electrolyzer
 - ❖ Thermochemical Water Splitting
- High Temperature Reactor
- US DOE Initiates on Hydrogen

World Energy Use a day (June 14, 2025)

- **426,358, 428 MWh** -Energy used today of which
- **352,568,138 MWh**- From non-renewable sources
- **62,234,562 MWh**- From renewable sources
- **2,627,459 MWh** - From Nuclear Energy
- **2,589,456,690,517 MWh** -Solar energy striking Earth today
- **Nuclear energy now provides about 9% of the world's electricity from about 439 power reactors.**

➤ **Operable Reactors 439, Power 397,742 MWe**
Reactors Under Construction 69, 70,804, MWe
Reactors Shutdown 213, 105,334 MWe

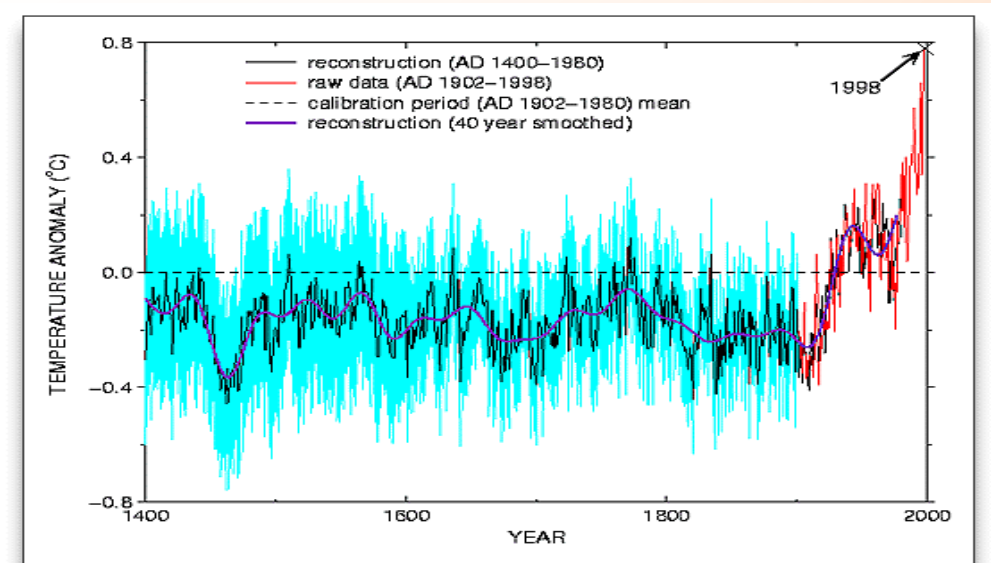
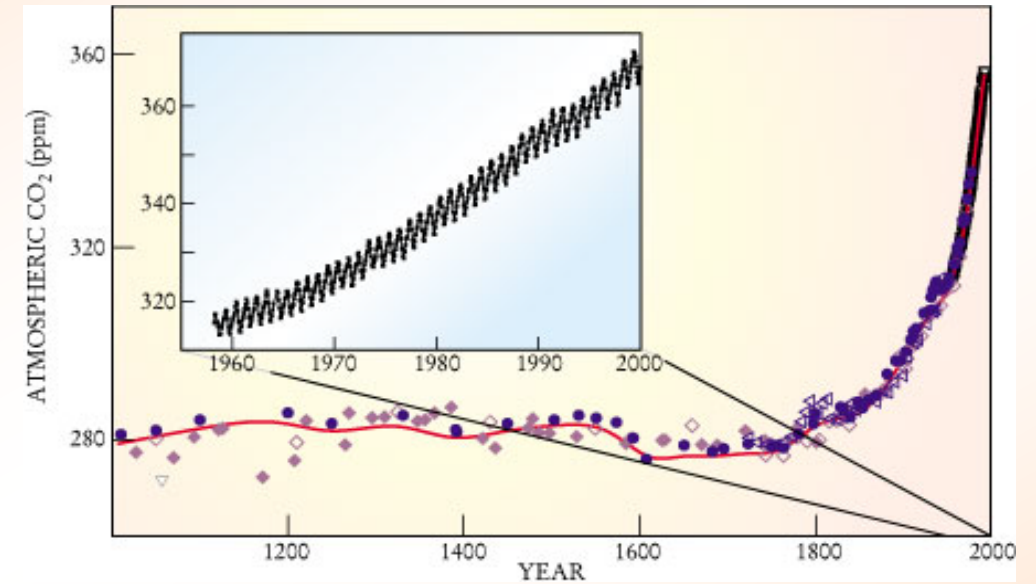
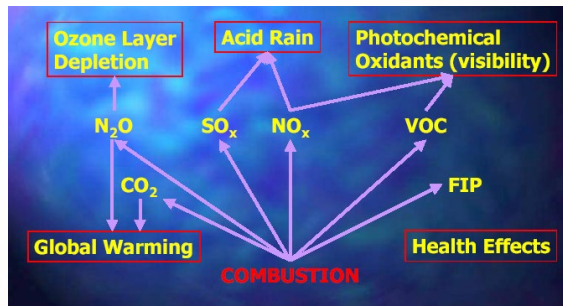
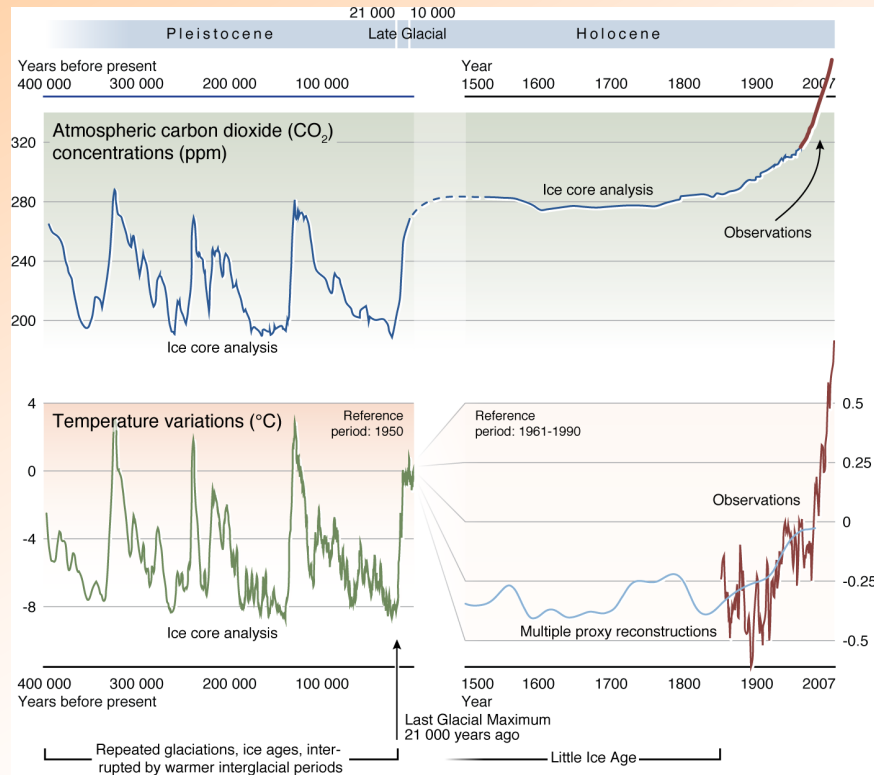
<https://world-nuclear.org/nuclear-reactor-database/summary>
<https://www.worldometers.info/>



Source: IEA

Environmental Issues

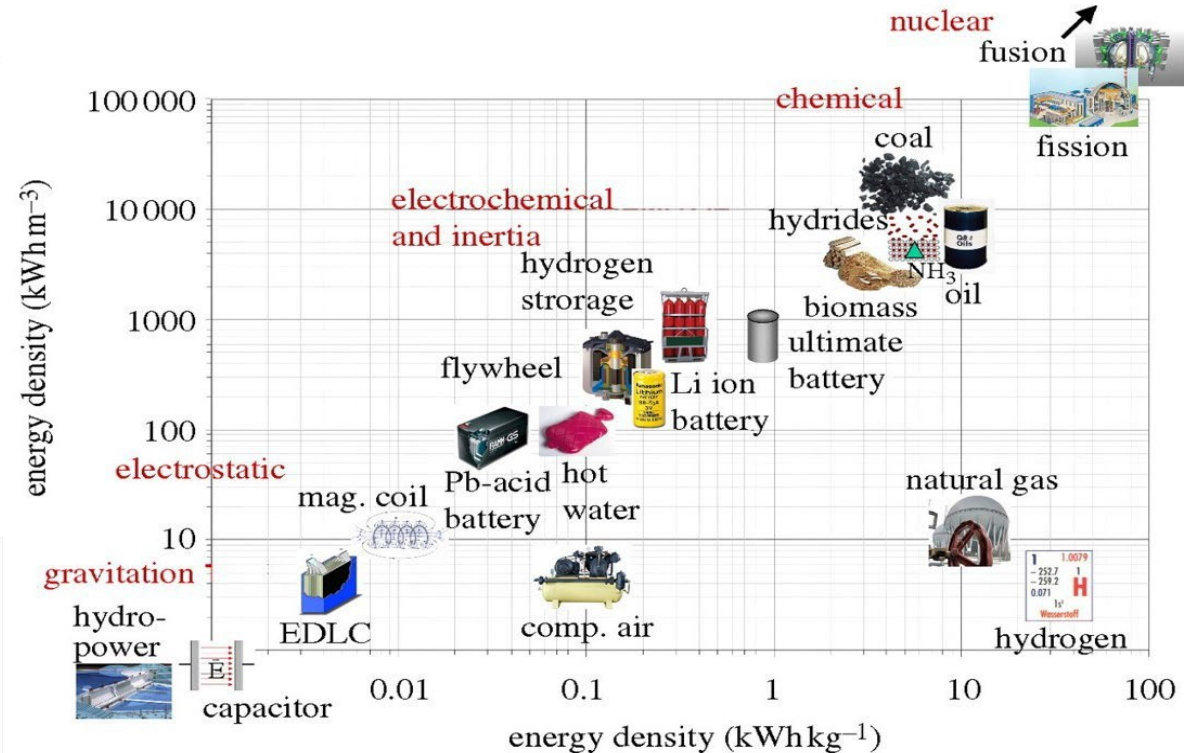
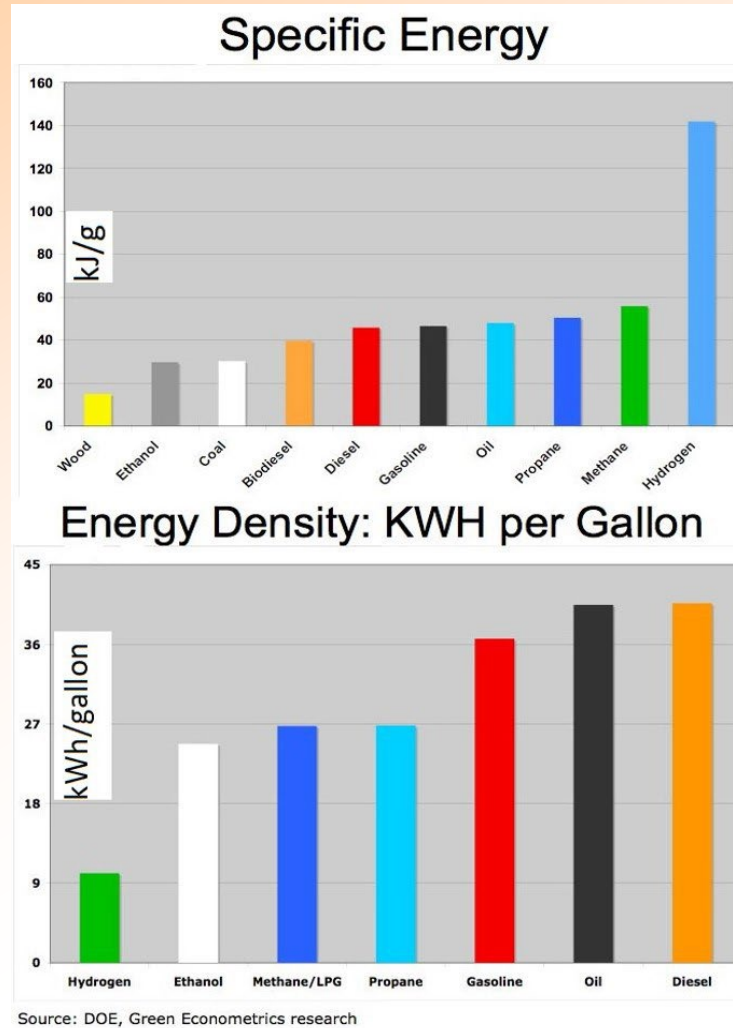
- CO₂ Buildup
- Global Temperature
- Pollution



Hydrogen as Energy Carrier

- ✓ **Why do we need it as an alternative fuel?**
 - **Environment**
Global warming, local urban air quality
 - **Energy reserves**
Increasing consumption vs. decreasing reserves
 - **Global political**
Energy security and energy access, independency
 - **Hydrogen value proposition**
New technology for car industry
- ✓ **H₂ Can be produced from**
 - **Renewables** –solar, wind, biomass, wave 
 - Any fossil fuel
 - **Nuclear energy** 

Hydrogen – A Critical Energy Carrier For Future



A. Zuttel et.al., Phil. Trans. R. Soc. A(2010), 368, 3329-3342

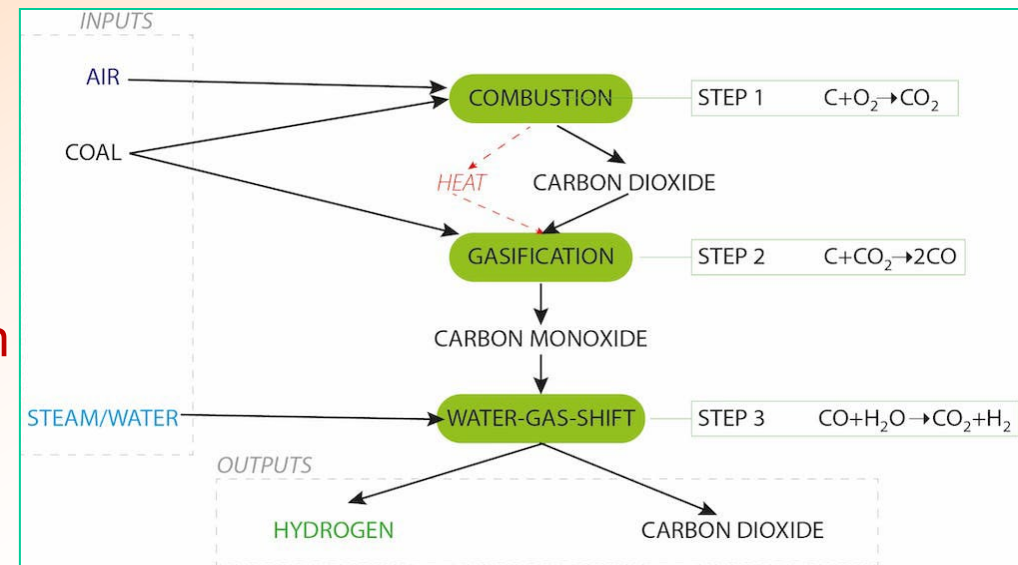
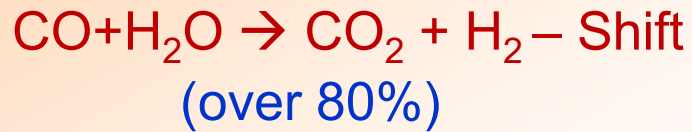
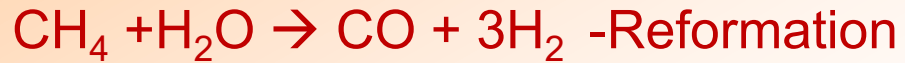
Hydrogen Demand and Use

- World Production 75 Million Tons/year, pure hydrogen, additional 45 Mt/yr as part of mix gases
- Equivalent to 2.5 % of current world energy demand
- 11 Mt/yr of hydrogen produced in US each year
 - 55% Oil Refining,
 - 35% Ammonia and Methanol,
 - 2% : Metal,
 - 8% Other
- 6 Mt/yr consumed by India 2023, Projected demand 12 Mt in 2030.
 - Oil refineries 3.0 Mt
 - Fertilizer (Ammonia) 2.4 Mt
 - Steel and chemical industries 0.6 Mt.

Hydrogen Production

Established Technology

- **Natural Gas Reforming/ Gasification:**



- **Electrolysis:** An electric current splits water into hydrogen and oxygen.
- **Renewable Liquid Reforming:** Renewable liquid fuels, such as **ethanol**, are reacted with high-temperature steam to produce hydrogen near the point of end use.
- **Fermentation:** Biomass is converted into sugar-rich feedstocks that can be fermented to produce hydrogen.
- ✓ **Biomass Gasification example reaction:** $\text{C}_6\text{H}_{12}\text{O}_6 + \text{O}_2 + \text{H}_2\text{O} \rightarrow \text{CO} + \text{CO}_2 + \text{H}_2 + \text{other}$

Technology Under Development

- **High-Temperature Water Splitting:** High temperatures generated by solar concentrators or nuclear reactors drive chemical reactions that split water to produce hydrogen.
- **Photobiological Water Splitting:** Microbes, such as green algae, consume water in the presence of sunlight and produce hydrogen as a byproduct.
- **Photoelectrochemical Water Splitting:** Photoelectrochemical systems produce hydrogen from water using special semiconductors and energy from sunlight.

The Hydrogen Rainbow

THE COLORS OF HYDROGEN

GREEN

Hydrogen produced by electrolysis of water, using electricity from renewable sources like wind or solar. Zero CO₂ emissions are produced.

BLUE

Hydrogen produced from fossil fuels (i.e., grey, black, or brown hydrogen) where CO₂ is captured and either stored or repurposed.

GREY

Hydrogen extracted from natural gas using steam-methane reforming. This is the most common form of hydrogen production in the world today.

PURPLE/PINK

Hydrogen produced by electrolysis using nuclear power.

TURQUOISE

Hydrogen produced by thermal splitting of methane (methane pyrolysis). Instead of CO₂, solid carbon is produced.

BROWN/BLACK

Hydrogen extracted from coal using gasification.

GOLD

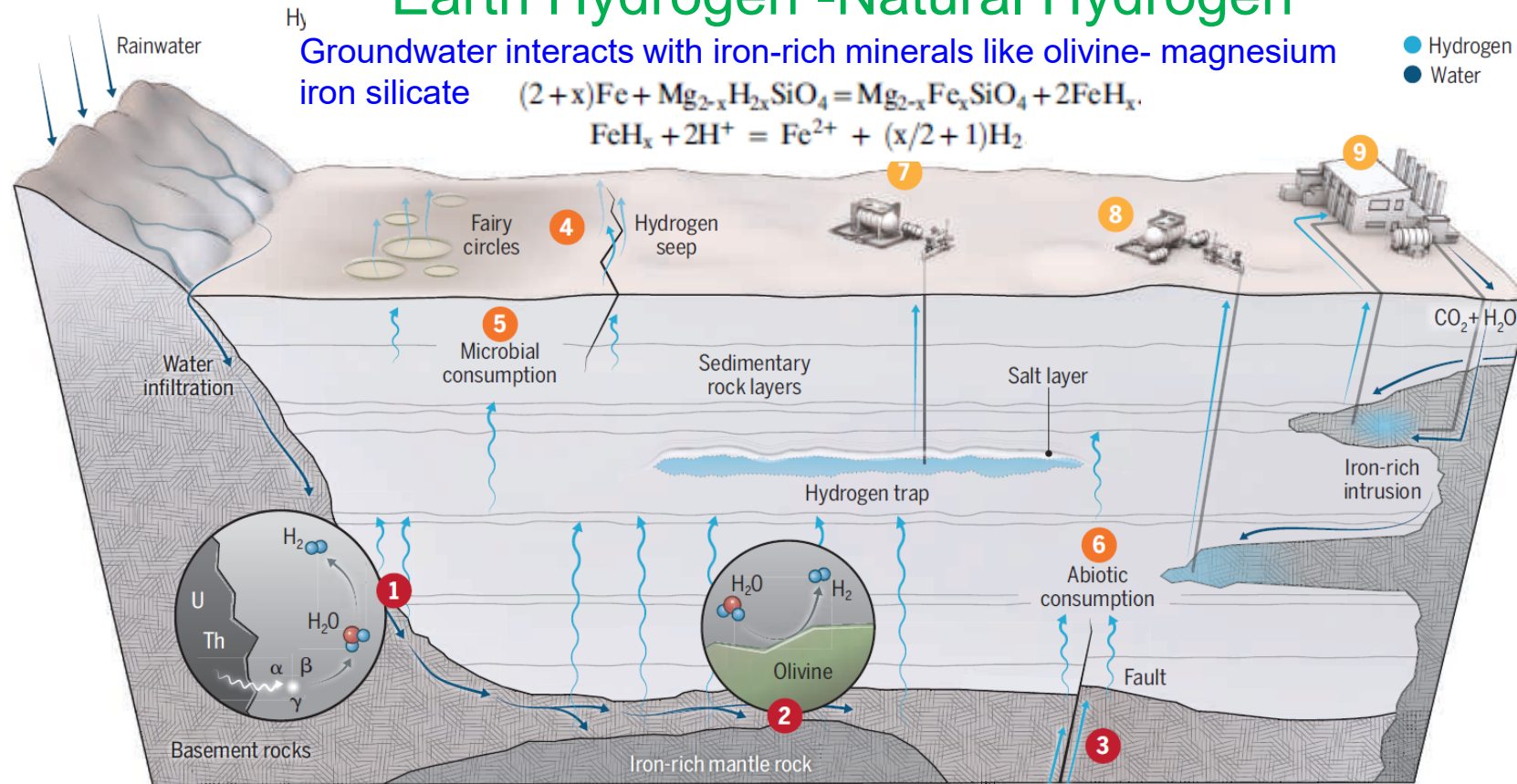
Tapped from natural subsurface accumulations.

ORANGE

Stimulated by pumping water into deep source rocks.



Earth Hydrogen -Natural Hydrogen



Science, Vol 379, Issue 6633.

Generation

1 Radiolysis

Trace radioactive elements in rocks emit radiation that can split water. The process is slow, so ancient rocks are most likely to generate hydrogen.

2 Serpentinization

At high temperatures, water reacts with iron-rich rocks to make hydrogen. The fast and renewable reactions, called serpentinization, may drive most production.

3 Deep-seated

Streams of hydrogen from Earth's core or mantle may rise along tectonic plate boundaries and faults. But the theory of these vast, deep stores is controversial.

Loss mechanisms

4 Seeps

Hydrogen travels quickly through faults and fractures. It can also diffuse through rocks. Weak seeps might explain shallow depressions sometimes called fairy circles.

5 Microbes

In shallower layers of soil and rock, microbes consume hydrogen for energy, often producing methane.

6 Abiotic reactions

At deeper levels, hydrogen reacts with rocks and gases to form water, methane, and mineral compounds.

Extraction

7 Traps

Hydrogen might be tapped like oil and gas—by drilling into reservoirs trapped in porous rocks below salt deposits or other impermeable rock layers.

8 Direct

It might also be possible to tap the iron-rich source rocks directly, if they're shallow and fractured enough to allow hydrogen to be collected.

9 Enhanced

Hydrogen production might be stimulated by pumping water into iron-rich rocks. Adding carbon dioxide would sequester it from the atmosphere, slowing climate change.

Nuclear Hydrogen Production

Hydrogen can be produced with Nuclear Energy

- **Electric power generation → Electrolysis**
 - Proven technology
 - Overall efficiency ~24% (LWR), ~36% (Hi T Reactors)
(efficiency of electric power generation x efficiency of electrolysis)
- **Heat → Thermochemical water-splitting**
 - Net plant efficiencies of up to ~50%
 - Developing technology
- **Electricity + Heat → High temperature electrolysis or Hybrid cycles**
 - Low-temperature electrolysis (<200°C).
 - High-temperature steam electrolysis (550 – 850°C)
 - Thermochemical process (550 – 950°C)
 - Nuclear SMR process can reduce natural gas consumption and CO₂ emissions by 30%

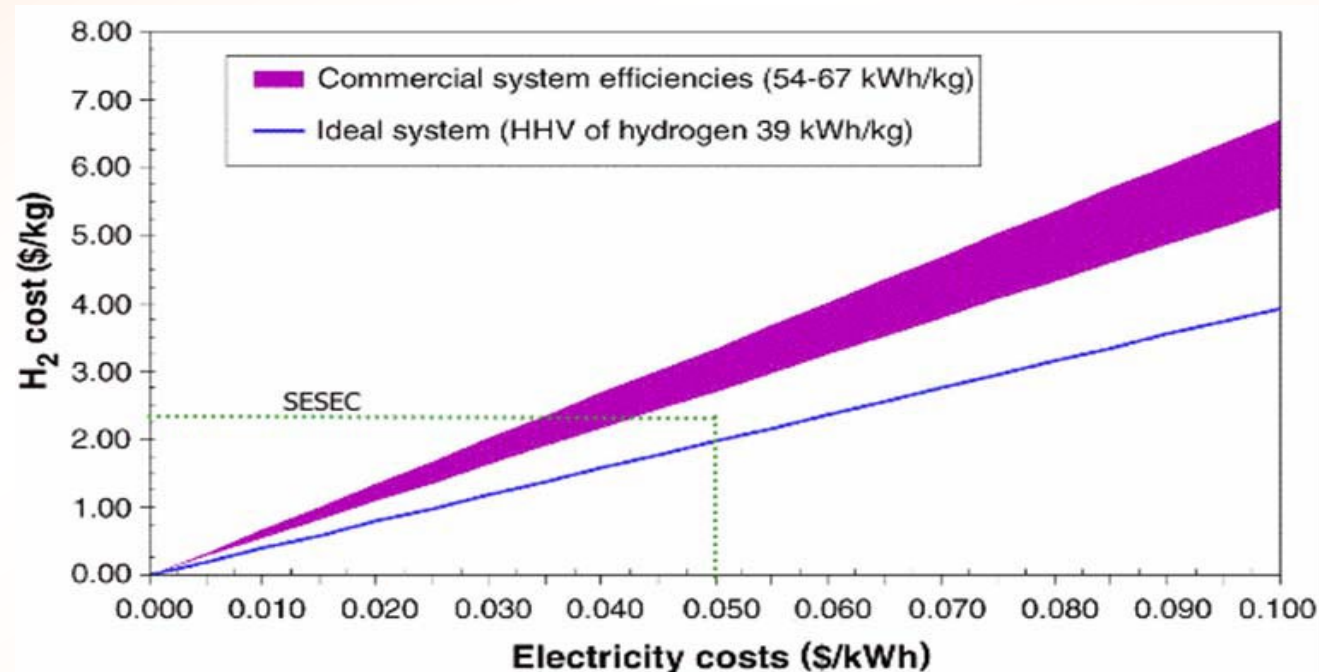
Electrolysis

Quantity`	H ₂ O	H ₂	0.5O ₂	Change
Enthalpy	-285.83kJ	0	0	$\Delta H = -285.83\text{kJ}$
Entropy	69.91 J/K	130.68J/K	0.5x205.14J/K	$T\Delta S = 48.7 \text{ kJ}$

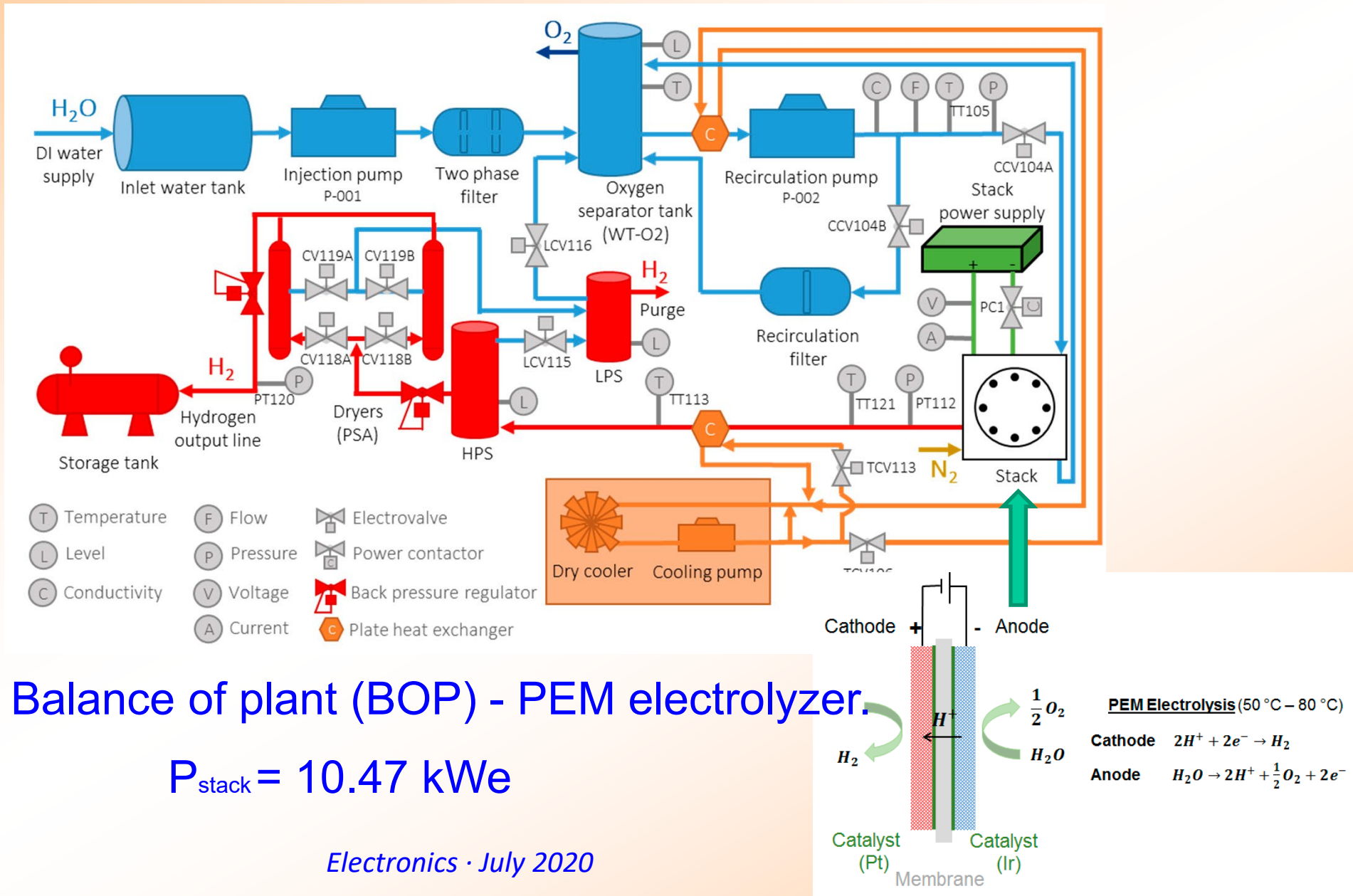
$$W = P\Delta V = (101.3 \text{ kPa})(1.5 \text{ moles})(22.4 \times 10^{-3} \text{ m}^3/\text{mol})(298\text{K}/273\text{K}) = 3715 \text{ J}$$

$$\Delta U = \Delta H - P \Delta V = 285.83\text{kJ} - 3.72 \text{ kJ} = 282.1 \text{ kJ}$$

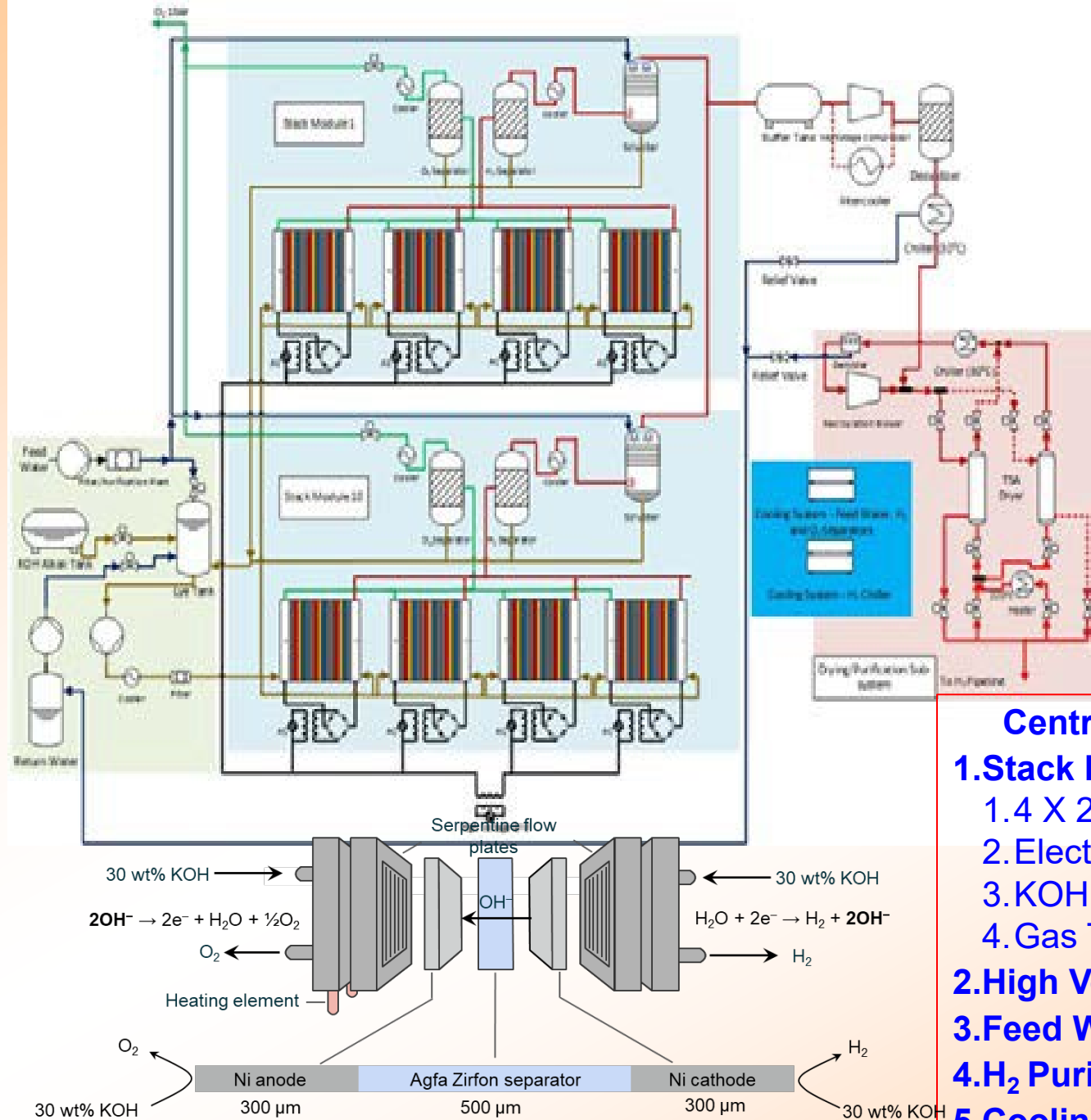
$$\Delta G = \Delta H - T \Delta S = 285.83 \text{ kJ} - 48.7 \text{ kJ} = 237.1 \text{ kJ}$$



PEM Electrolyzer



Alkaline Electrolyzer



NREL/PR-5900-86490

- Centralized Alkaline EZ**
- 1.Stack Modules**
 - 1.4 X 2.5 MW stacks
- 2.Electrical BOP Subsystem**
- 3.KOH Subsystem**
- 4.Gas Treatment Subsystem**
- 2.High Voltage Transformer**
- 3.Feed Water System**
- 4.H₂ Purification System**
- 5.Cooling Water System**

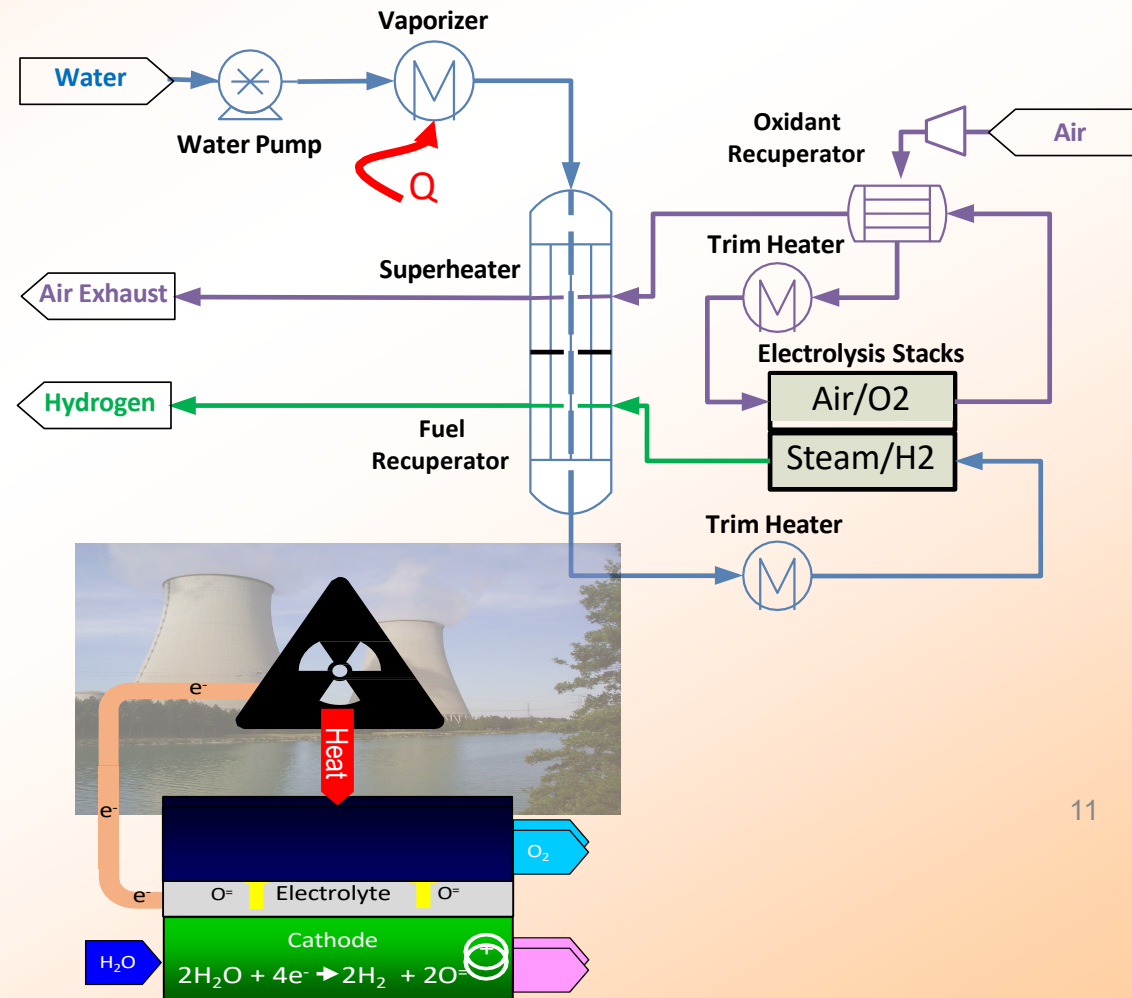
Solid Oxide Electrolyzer

System Characteristics

Parameter	Value	Units
Inputs		
Water	0.25	gpm
Energy		
Heat Recovery/Thermal Input (Q)	30	kW
Total Electrical Input	247	kW
Total Energy Input	277	kW
Output		
Hydrogen Production	150	kg/day
System Efficiencies (HHV)		
Stack Electrical Efficiency (HHV)	126%	
System Electrical Efficiency (HHV)	100%	
System Total Efficiency (HHV)	89%	
Consumption		
Total Electrical Consumption	39.6	kWh/kg H ₂
Total Energy Consumption	44.3	kWh/kg H ₂

System process design for production of 150kg H₂/day

System Process Flow Diagram



1.1 MW SOEC Product



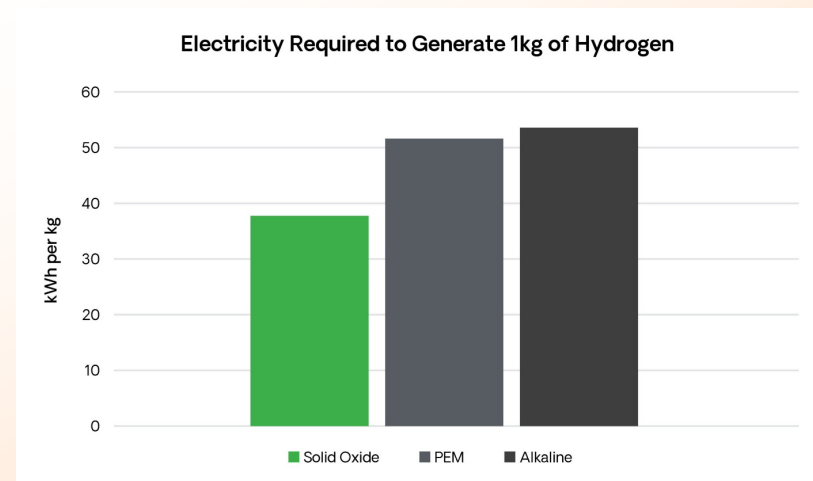
Solid Oxide Electrolysis Platform

- 1.1MW Rated Input
- 600 kg/day hydrogen production
- Power input reduced to 1.0 MW with supplied waste heat
- Two modules – stack/mechanical BOP and electrical BOP
- Stack/Mechanical BOP is repeating unit in larger systems

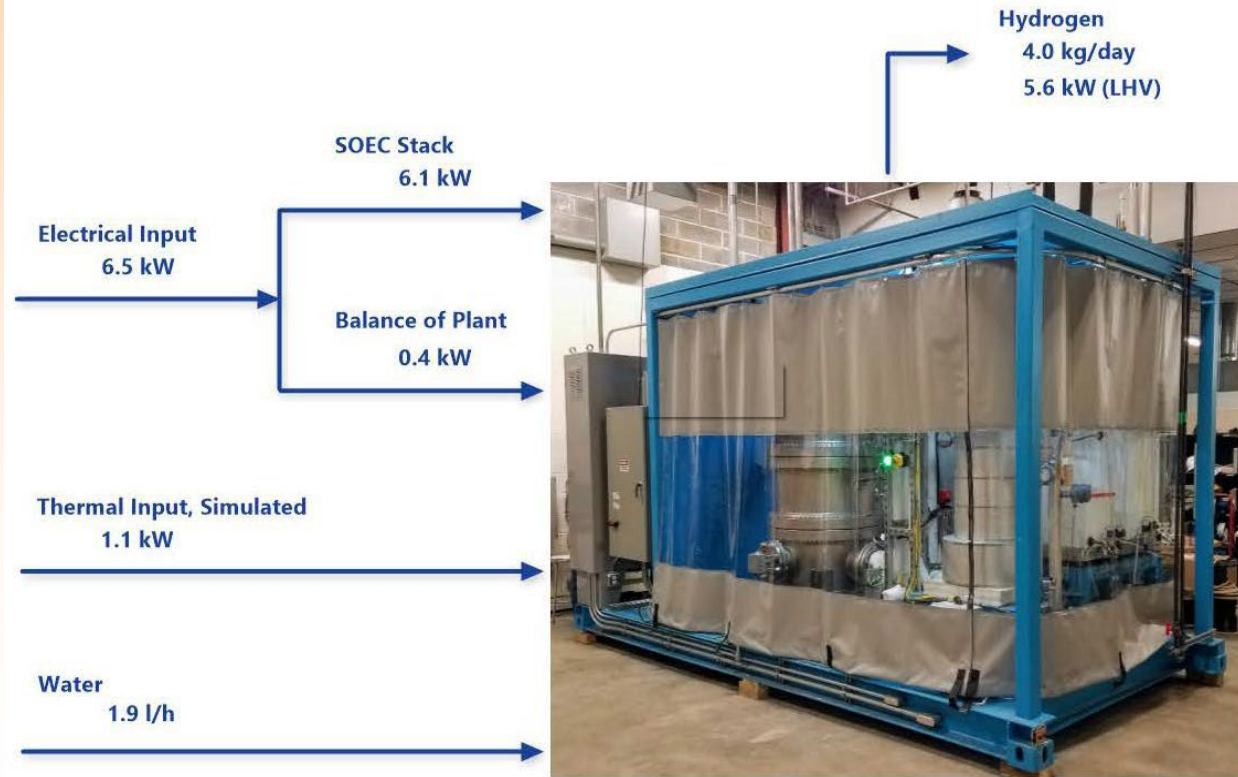
Specifications subject to change without notice. All specifications quoted at initial operation.

Hydrogen Production Rate _____ ~600 kg/day Pressure _____ 14.7 psia (1 bar(a))*	Module Dimensions (W x L x H) Width: 8' Length: 40' Height: 10' Width: 2.43m Length: 12.19m Height: 3.04m <i>There are two modules in a standard configuration.</i>
Performance (With and Without Heat Input) Efficiency (HHV) With Heat _____ 100% Electricity Consumption With Heat _____ 39.4 kWh/kg Efficiency (HHV) No Heat _____ 90% Electricity Consumption No Heat _____ 43.8 kWh/kg <i>Efficiency levels are +/- 2%.</i>	Electrical Input Plant Power Input _____ 1.1 MW Voltage (3-phase) _____ 480 V (400 V Option) Frequency _____ 60 Hz (50 Hz Option)
Product Composition H ₂ _____ 99% dry basis, by volume <i>Purification and compression options available.</i> N ₂ _____ ~1% dry basis, by volume	Water Water Conductivity _____ < 1 µS/cm <i>Treatment options available for lower quality water.</i> Nominal Consumption _____ 1 gpm (5,451 SLPD) Drainage for Maintenance _____ 46 gallons (174 L)
Ramping (Increasing or Decreasing) 0% - 100% load _____ 10% per minute	Sound Levels Standard _____ < 72 db(A) @ 10 Feet (Option < 65)
Optional Customer Steam Supply for Higher Efficiency (Saturated or Superheated) Recommended Temperature Range _____ 259 - 295 °F (126 - 146 °C) Recommended Pressure Range _____ 20.0 - 47.1 psig (1,379 - 3,254 mbar) Recommended Flow Rate Range _____ 340 - 570 lb/hr (154 - 258 kg/hr)	

*Optional compression is available and will add 2 to 4 kWh/kg power consumption depending on pressure level.



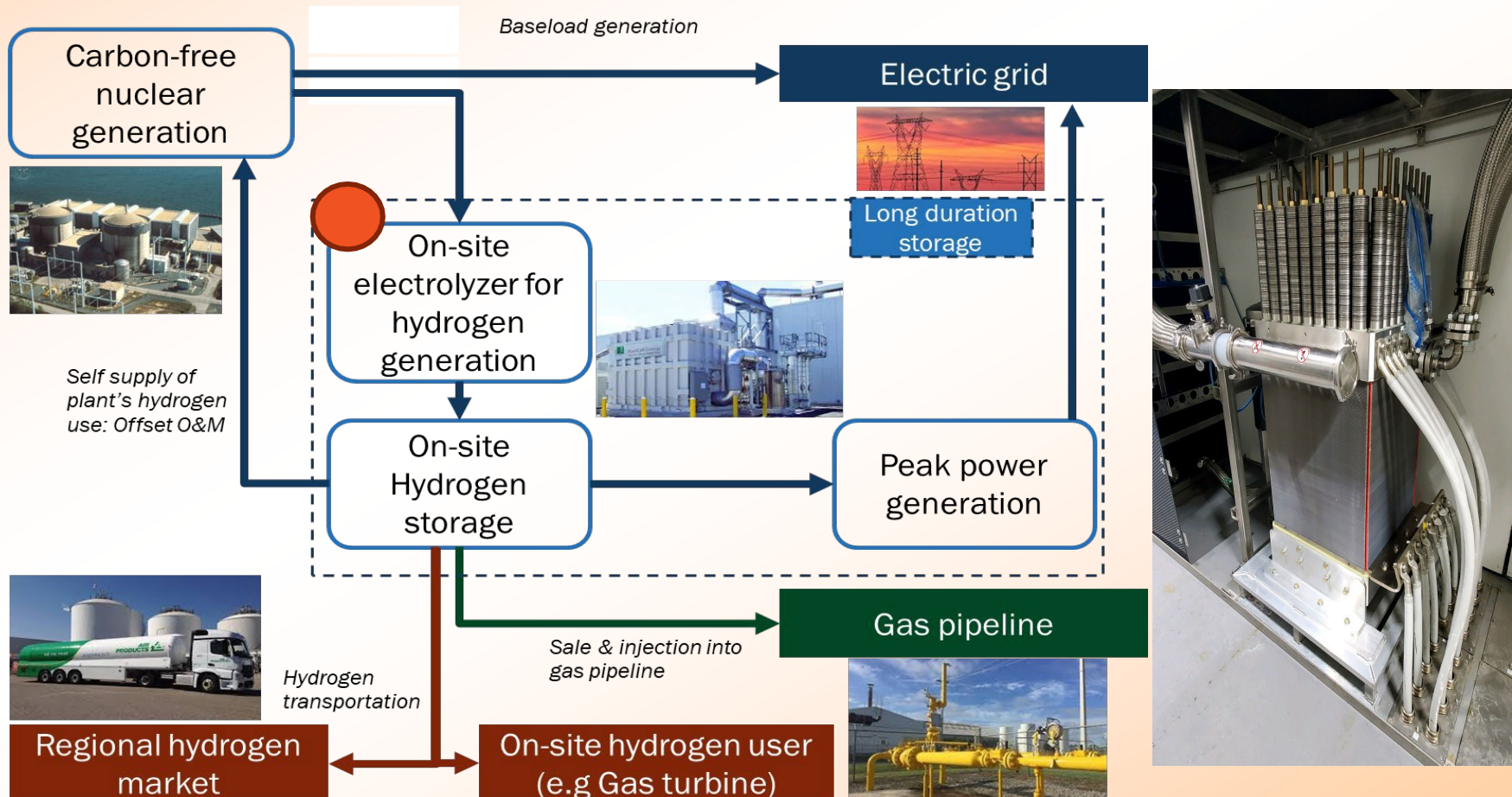
4kg H₂/day Pilot System Performance



System Performance Parameter	Value
Stack Electrical Efficiency (LHV)	93.1 %
System Electrical Efficiency (LHV)	85.1 %
System Total Efficiency (LHV)	73.0 %
Electricity Consumption	39.2 kWh/kg
Thermal Consumption, Simulated	6.5 kWh/kg
Total Energy Consumption	45.7 kWh/kg

Nuclear Utility Hydrogen Production Demonstrations

- Constellation's Nine Mile Point NPP, in Oswego, New York. - USA's first-of-its-kind 1 MW PEM Electrolyzer, H₂ Production, Feb 2023



Nuclear Utility Hydrogen Production Demonstrations

- Energy Harbor -Davis–Besse Nuclear Power Station (Oak Harbor, OH) Alkaline Electrolyzer, H₂ Production, 2024.
- Xcel Energy and Bloom Energy -Prairie Island Nuclear Generating Plant, Red Wing, MN), 240 kW, HTE , 2024
- Arizona Public Service and Pacific North West Hydrogen (PNW) Hydrogen -The Palo Verde Generating Station in Arizona – Alkaline Electrolyzer 2024.

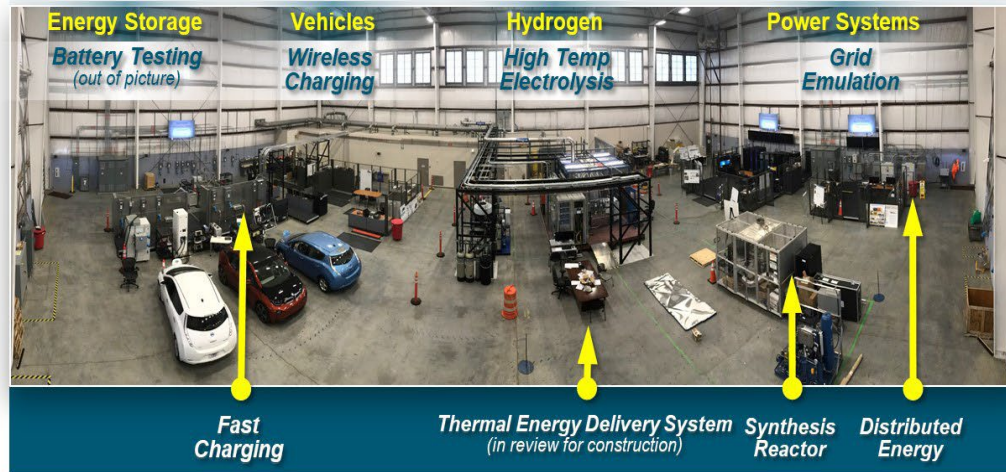
HTE Tech provider demonstrations (“supply-driven”)

- FuelCell Energy: Solid oxide electrolysis (HTE) system demonstration
- Bloom Energy: HTE hydrogen production using nuclear power
- OxEon Energy: Performance validation of a 30 kW reversible HTE system

US Advanced Hydrogen Production Research & Current Efforts

Energy Systems Laboratory

Systems Integration Lab

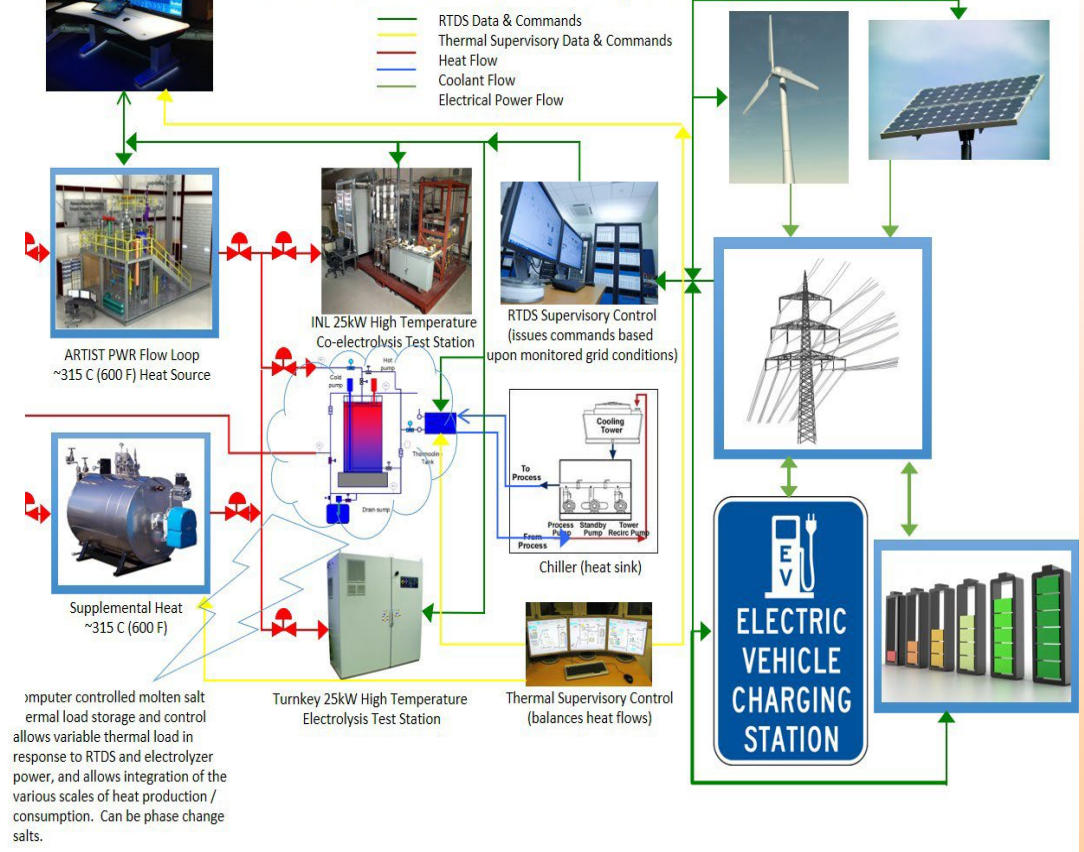


Overall DETAIL Facility Display & Data Collection



INL DETAIL Thermal, Electrical, Control, & Data Integration

- RTDS Data & Commands
- Thermal Supervisory Data & Commands
- Heat Flow
- Coolant Flow
- Electrical Power Flow



Focused on Nuclear Hybrid Energy Systems Concept & Dynamic Energy Transport & Integration Laboratory, at INL

High Temperature Electrolysis (HTE) Technology Progress- INL

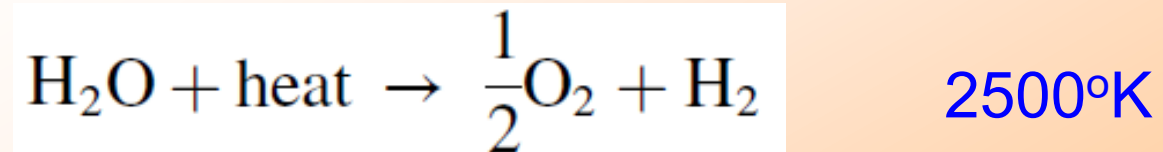
- **Completed Design and Installation of Facility Support Infrastructure**
 - Power, DI water system, drain lift station, enclosure, ventilation system, H2 vent, gas monitoring, safety interlocks, fire protection, structural support systems
- **25 KW HTE Test Facility**
 - Steam generation and supply system
 - High-temperature furnace
 - High-temperature air supply for sweep gas
 - N2 purge systems
 - Hydrogen recycle and gas dryer system
 - Gas monitoring system with interlocks
 - Instrumentation
- Facility has been commissioned for HTE hydrogen production up to the 25 kW scale-under way



Thermochemical Water Splitting

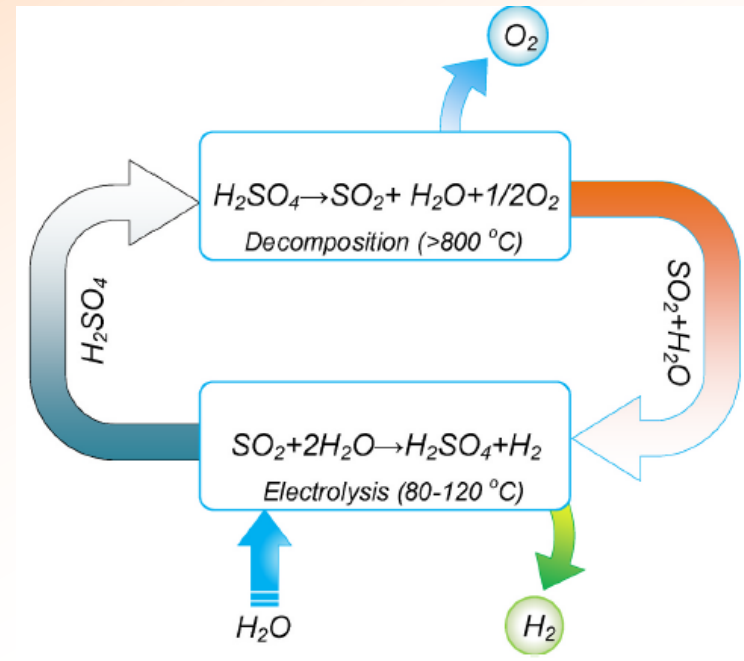
- Explored since 1970s several efforts at different scale.
- A set of coupled, thermally-driven chemical reactions that sum to the decomposition of water in H₂ and O₂.
 - All reagents returned within the cycle and recycled
 - Input water and high temperature heat, output H₂ and O₂ and low heat.
- Numerous possible cycles identified and explored:

- ❖ Single Step

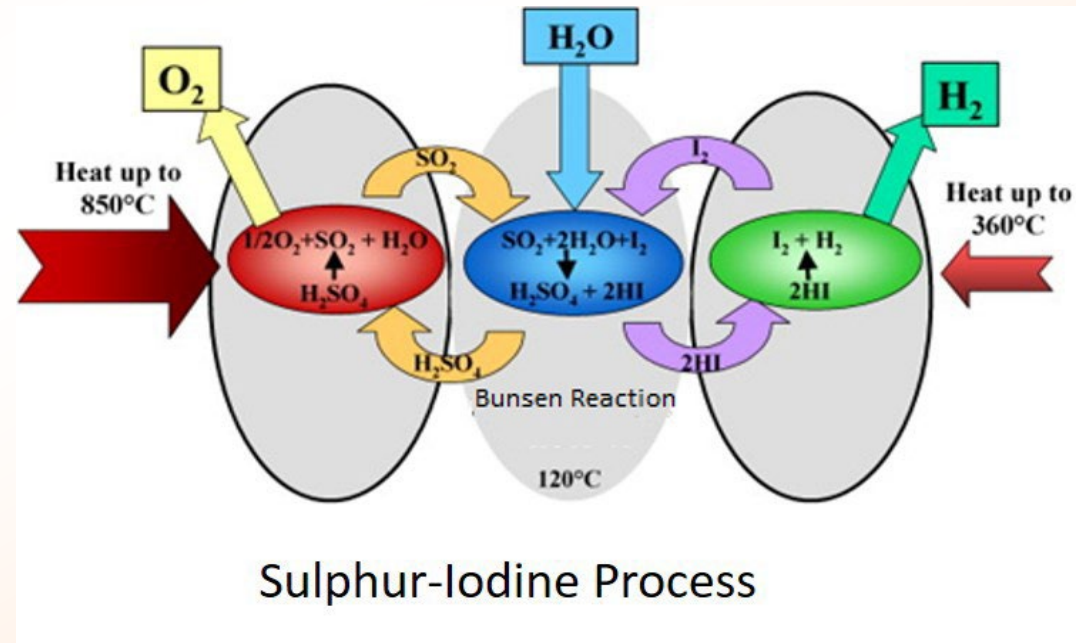


Thermochemical Water Splitting

❖ Two Step

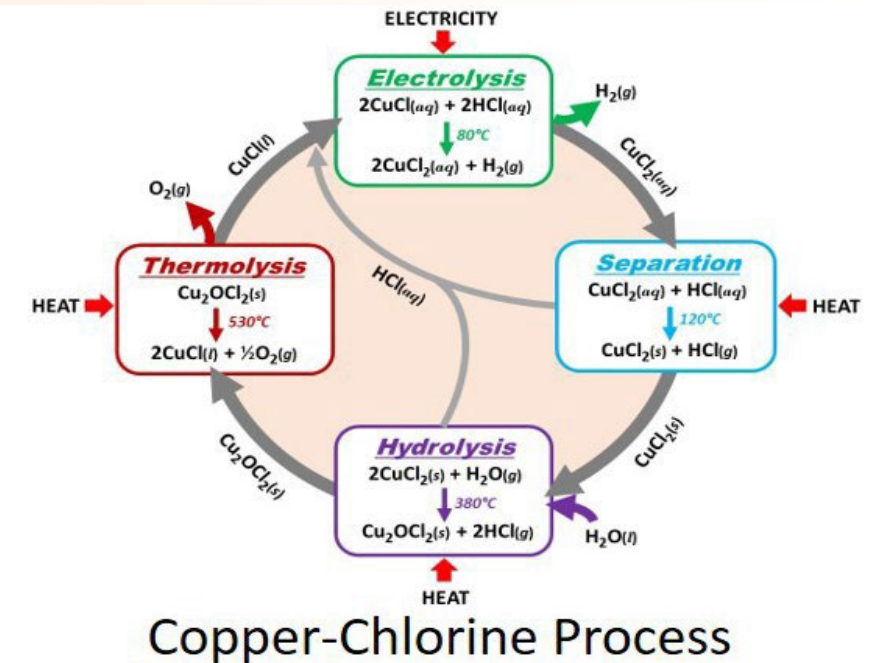


❖ Three Step

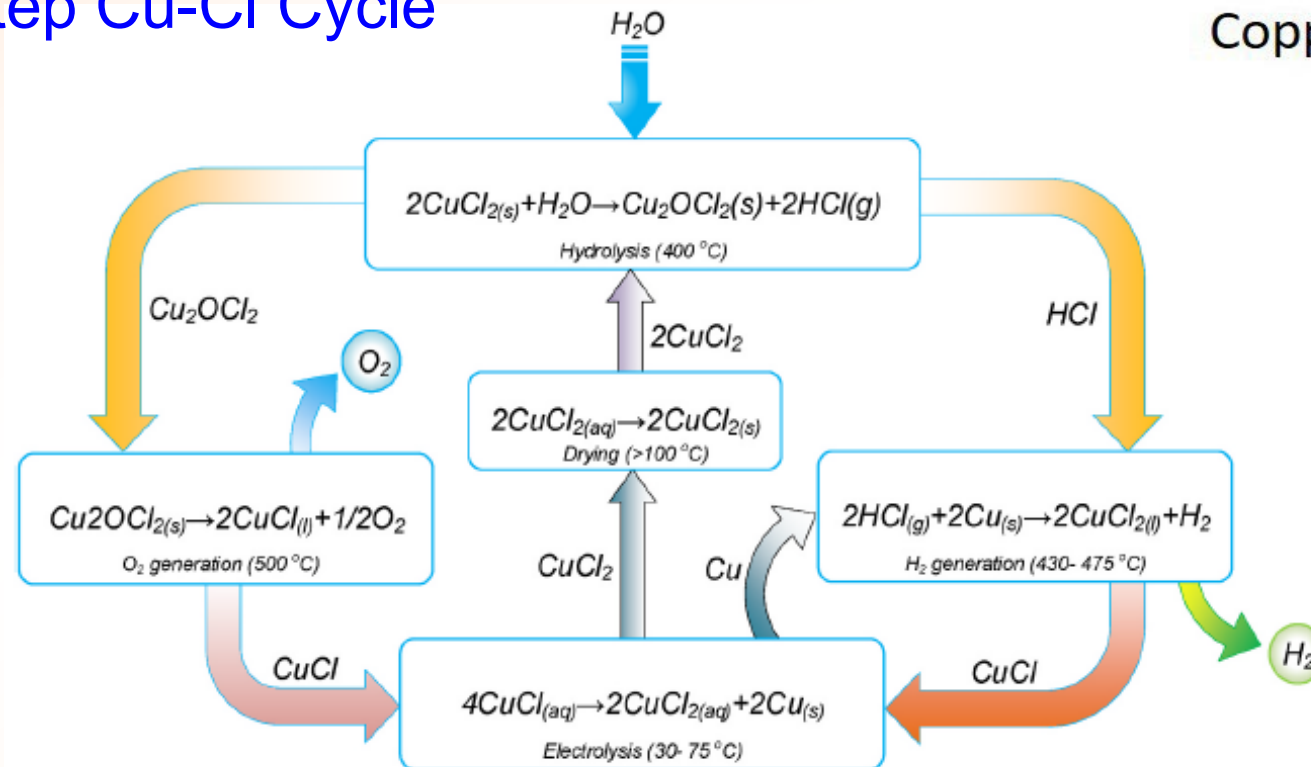


Thermochemical Water Splitting

❖ Four Step, Cu-Cl Cycle

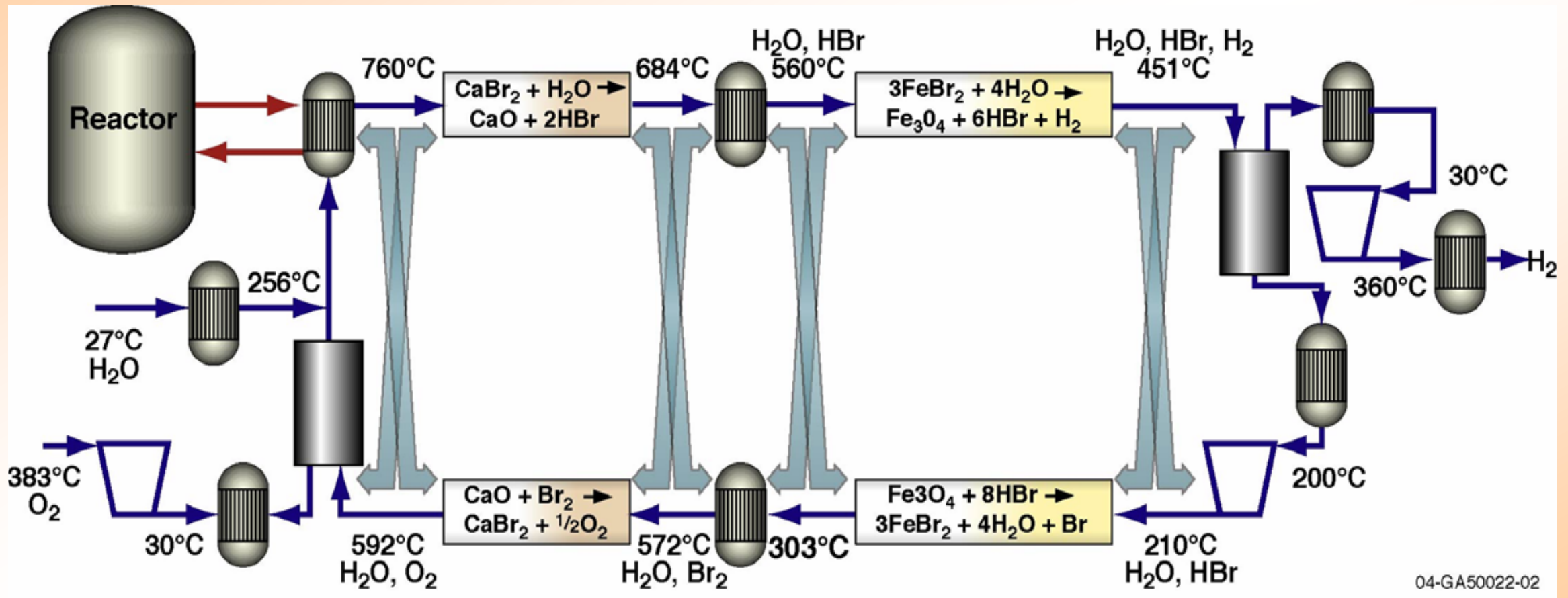


❖ Five Step Cu-Cl Cycle



Thermochemical Water Splitting

❖ Multistep CYCLE : Calcium -Bromine cycle (UT-3 -Japan, modified UT-3).



SI-Thermochemical cycle

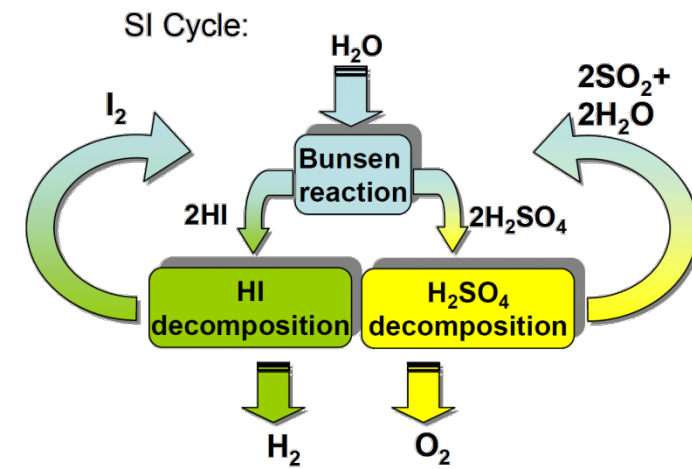
- ✓ SI cycle was developed and flow-sheeted by General Atomics in the 1970s

Integrated SI loops:

- 1980s GA, (US)
- 2004 JAERI, (Japan)
- 2009 INERI (DOE/CEA), (France)
- 2010 Tshingua (China)
- 2011 KAERI-KIER-RIST-POSTECH
- 2020~ INET, JAEA

Separate Effects Tests

GA, SNL, CEA, JAERI, KAIST, POSTECH



India -Copper-Chlorine Demonstration Plant using FBBR (June 2026)

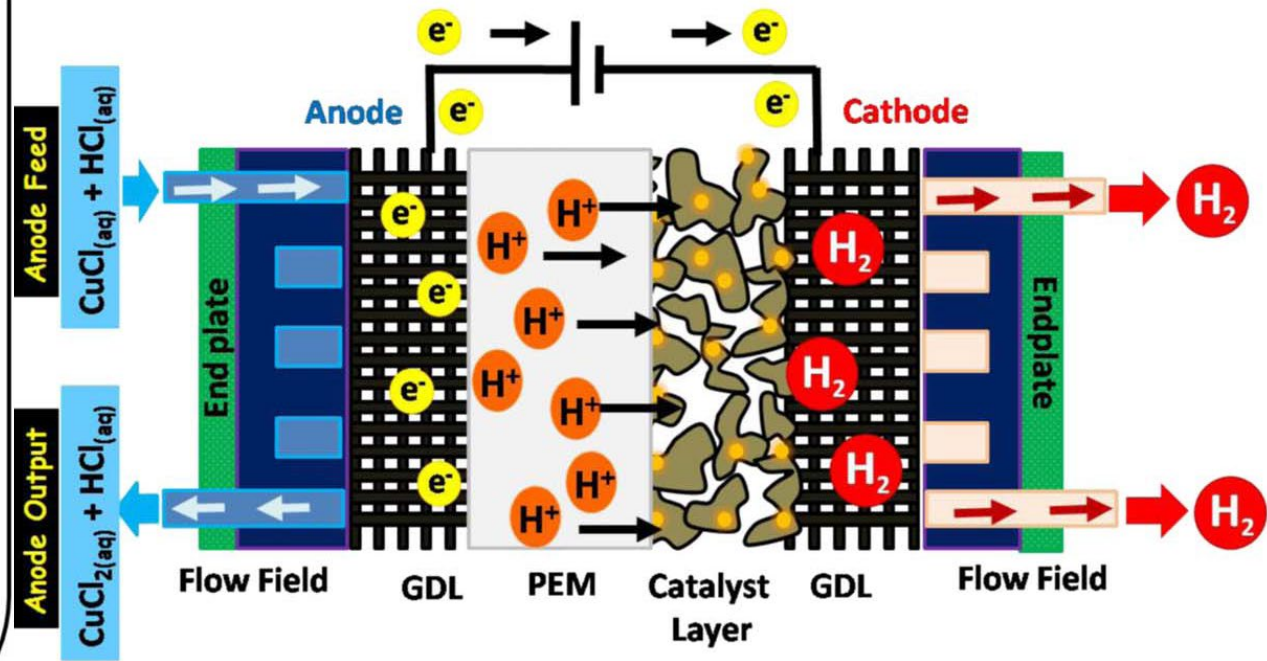
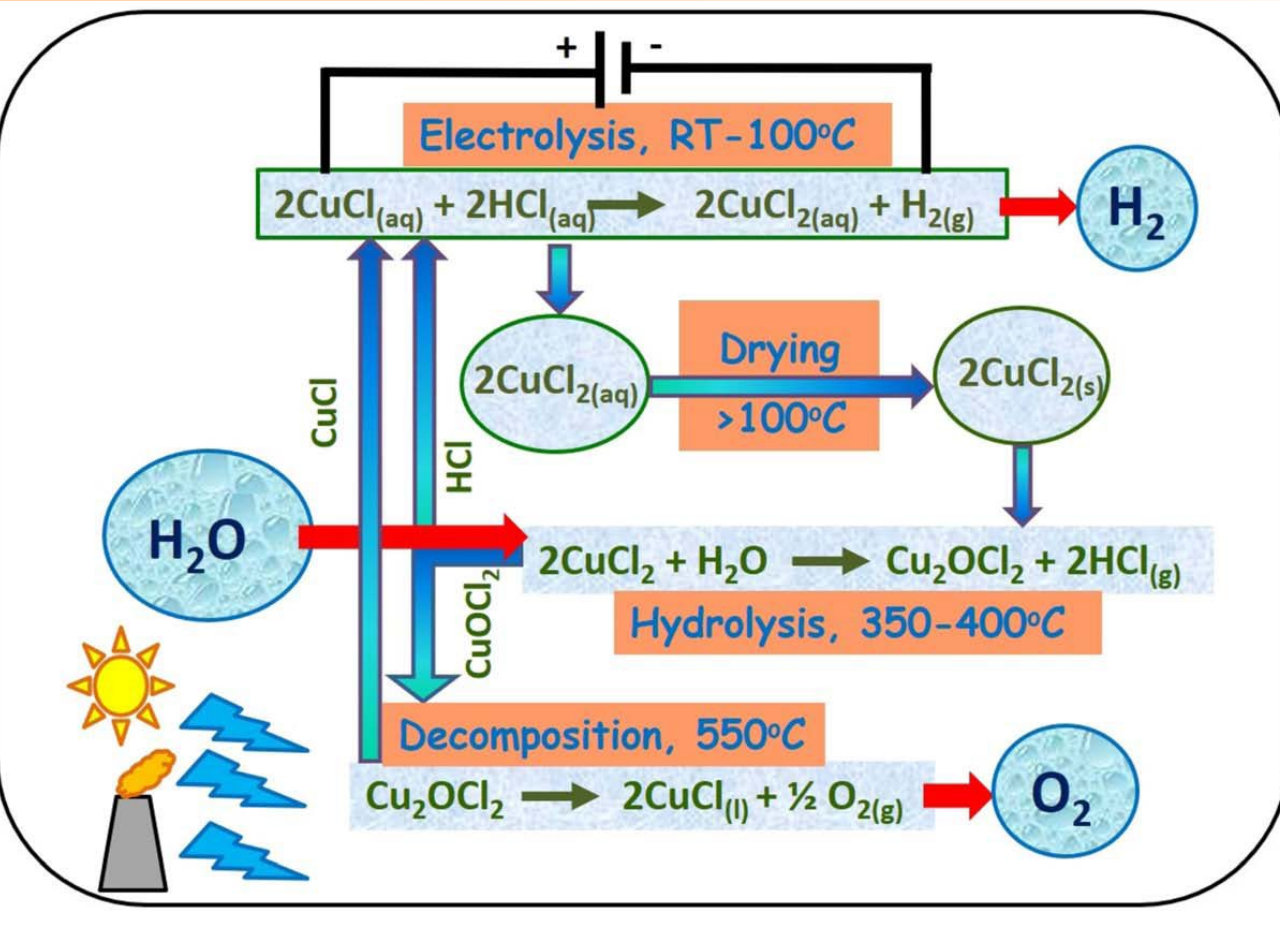


Steps:

1. Electrolysis Step Development
2. $\text{CuCl}/\text{CuCl}_2/\text{H}_2\text{O}/\text{HCl}$ Separation System
3. Experimental Study of CuCl_2 Hydrolysis
4. Cu_2OCl_2 Decomposition

- Low temperature requirement for heat source $<530^\circ\text{C}$
- Ideally suited for Small Modular Reactors
- Inexpensive raw materials as recycle agents (for example, compared to iodine for S-I cycles)
- No requirement for catalyst in thermal reactions

CuCl/HCl Electrolysis Using a Pt/C Electrocatalyst-based Membrane Electrode Assembly



Thermochemical hydrogen production cycles – High Temperature Reactors

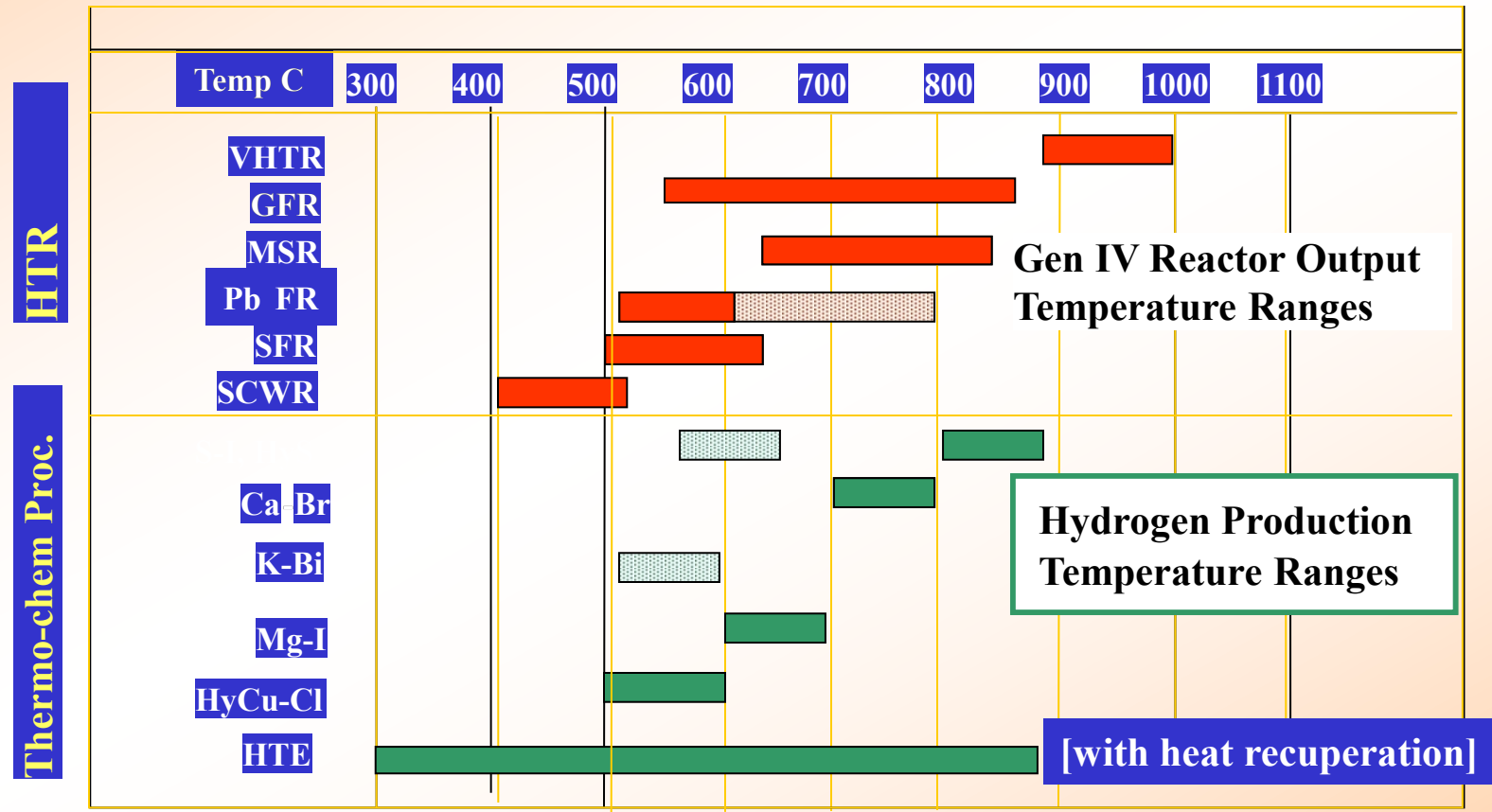
				Thermochemical hydrogen production cycles							
		Eff. range (%)	Temp. range	Cu-Cl	Mg-Cl	S-I	HYS	Fe-Cl	Ca-Br	V-Cl	ZnO/Zn
Advanced nuclear reactor types	SCWR	44-48	500-625 °C	✓	✓	X	X	X	X	✓	X
	VHTR	40-50	750- 950 °C	✓	✓	✓	✓	✓	✓	✓	X
	SFR	38-42	450-550 °C	✓	✓	X	X	X	X	✓	X
	GFR	45-48	750-850 °C	✓	✓	✓	X	✓	✓	✓	X
	MSR	45-55	650- 850 °C	✓	✓	✓	X	✓	✓	✓	X
	LFR	42-45	450-800 °C	✓	✓	X	X	✓	✓	✓	X

- *SCWR: Super Critical Water Reactor*
- *VHTR: Very High Temperature Reactor*
- *SFR: Sodium cooled Fast Reactor*

- *GFR: Gas cooled Fast Reactor*
- *MSR: Molten Salt Reactor*
- *LFR: Lead cooled Fast Reactor*

HTR Energy Conversion

- Electrical generation - *Gen IV Energy Conversion Program*
- Hydrogen production - *Nuclear Hydrogen Initiative (NHI)*



High Temperature Gas-cooled Reactor (HTGR)

Superior inherent safety

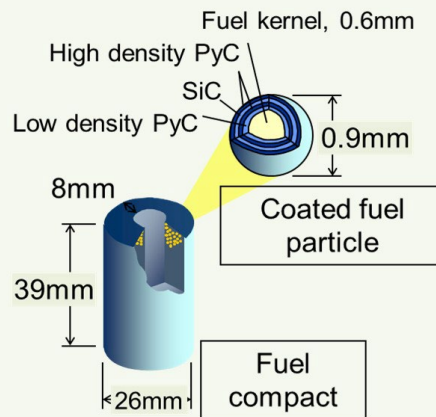
- Accidents that cause release of a large amount of radioactive materials to environment do not occur.
- A nuclear accident similar to that in the Fukushima-Daiichi Nuclear Power Station does not happen.

A wide range of heat applications

- Helium gas cooled reactor with outlet coolant temperature as high as 950°C
- A wide range of heat applications, such as hydrogen production, electric power generation, desalination, etc.

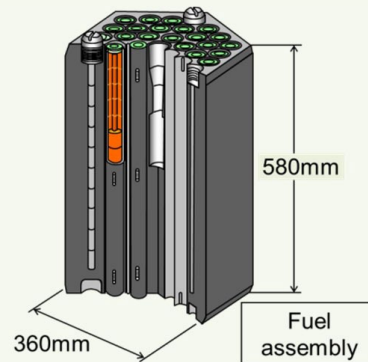
Ceramic fuel coating

Retain radioactive material at **1600°C**



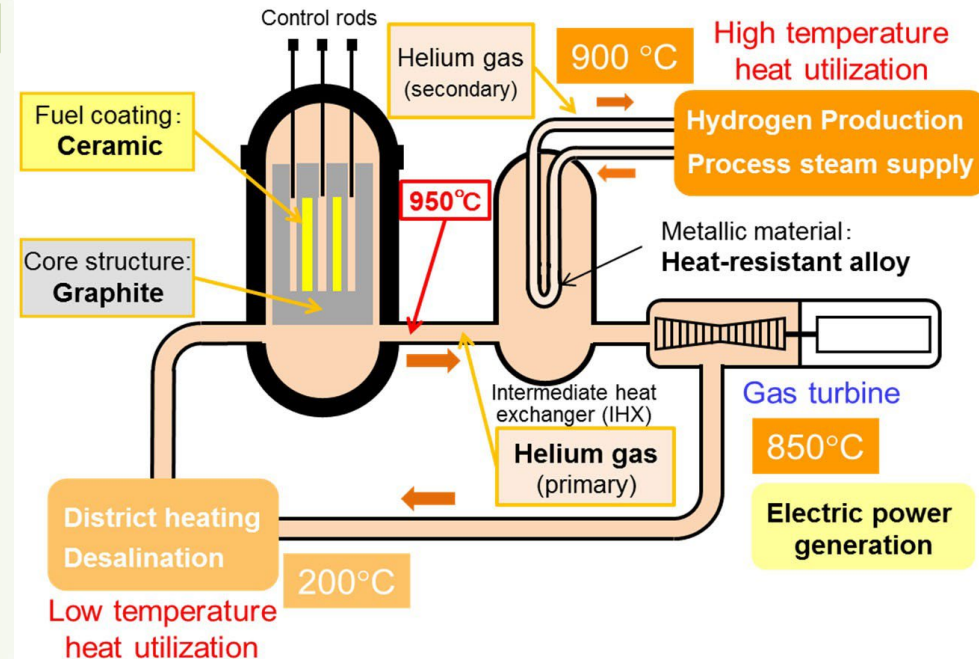
Graphite core structure

Temperature limit **2500°C**

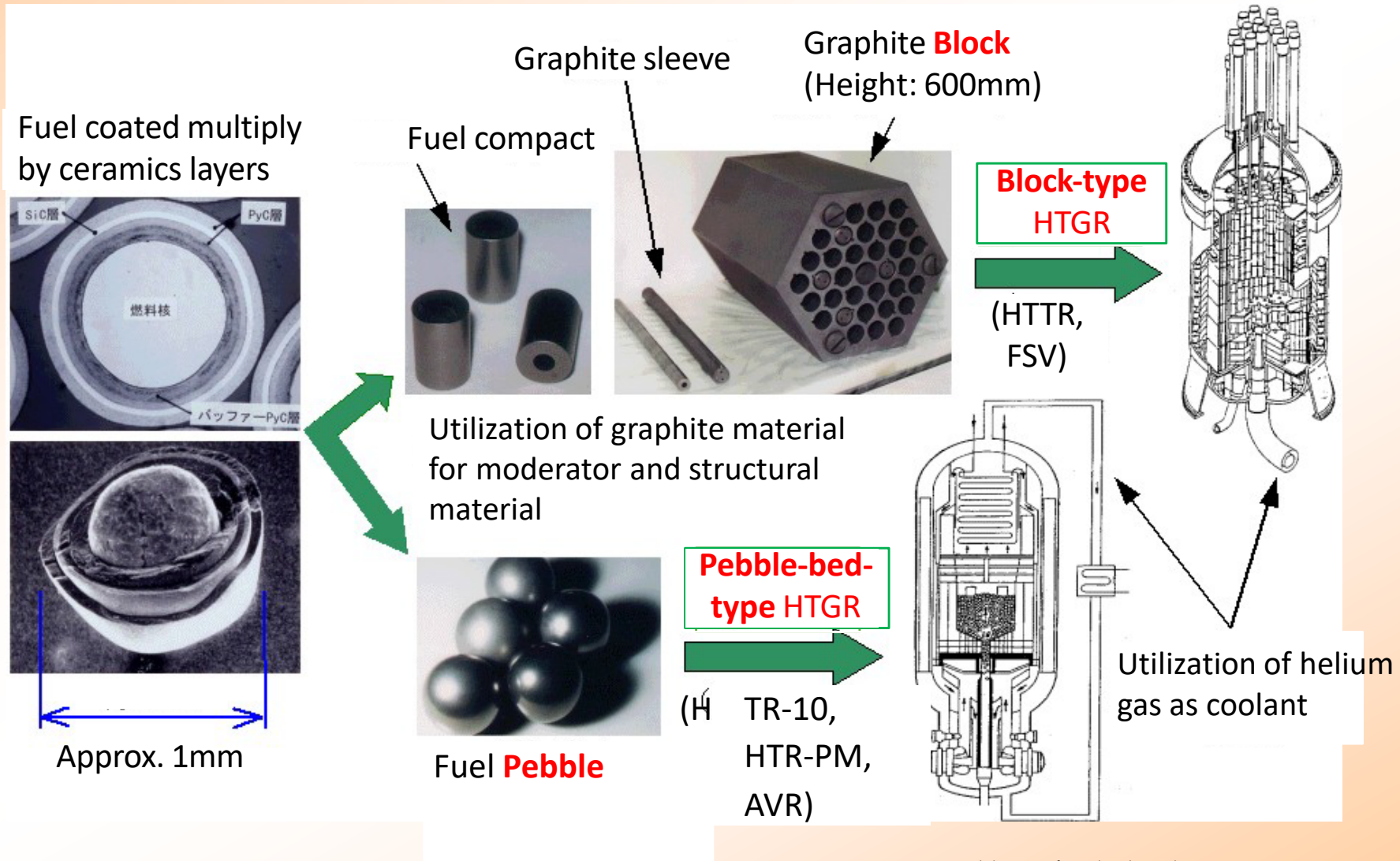


Helium coolant Stable

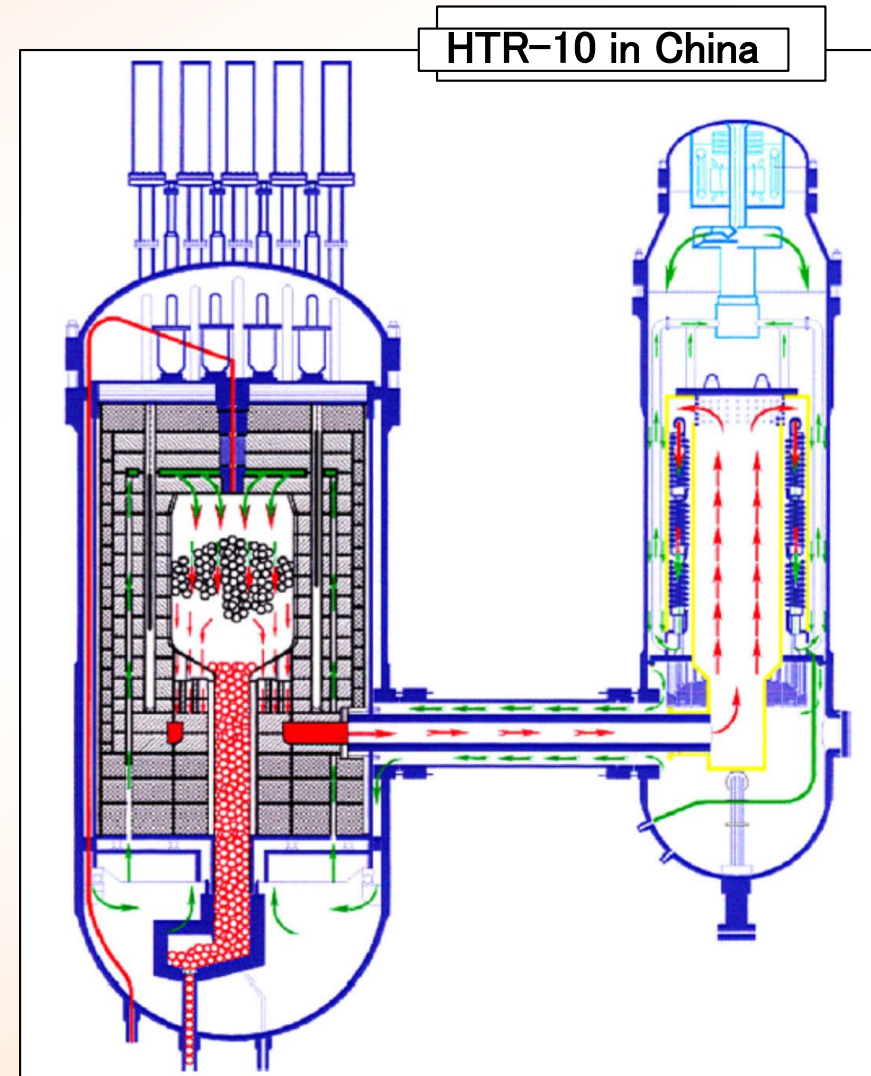
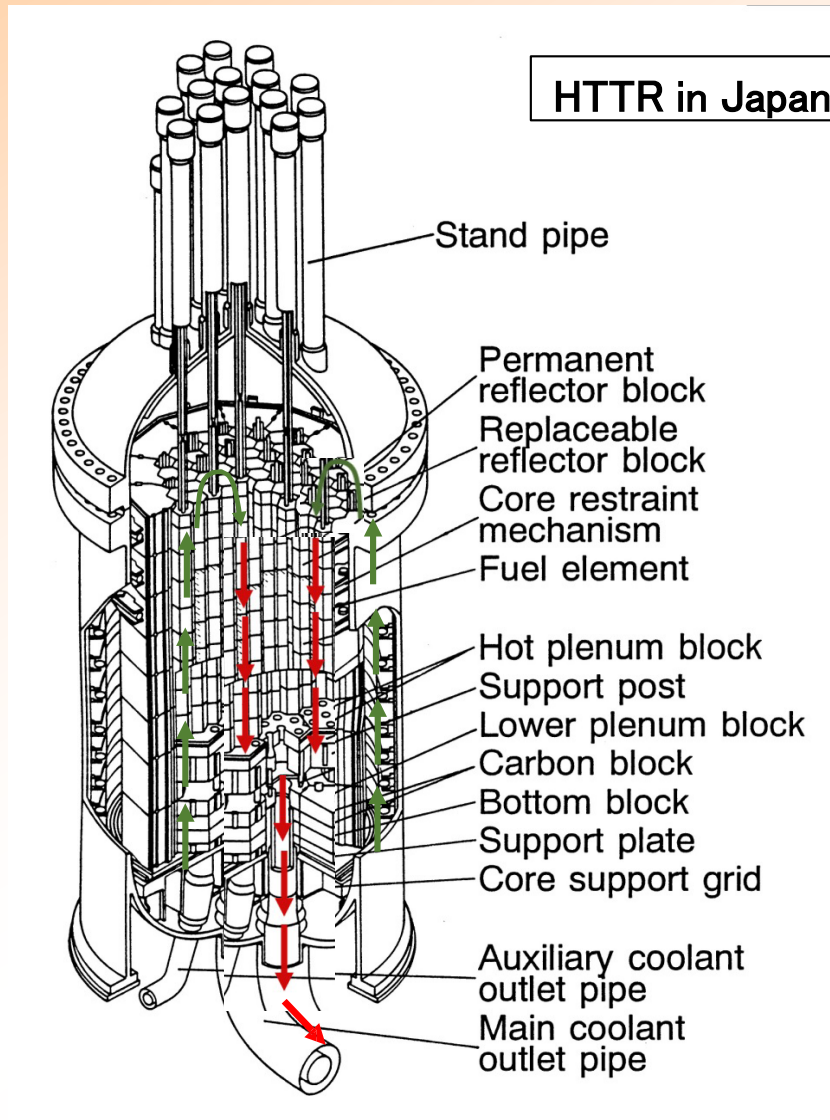
at high temperature
(No temperature limit)



Block-type HTGR and Pebble-bed-type HTGR



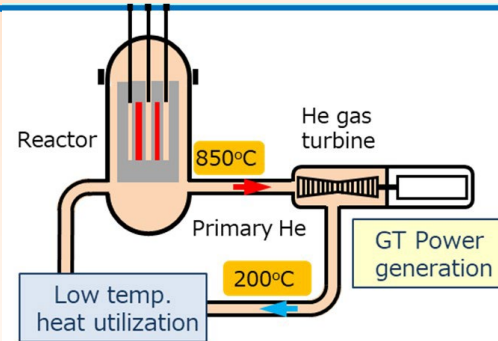
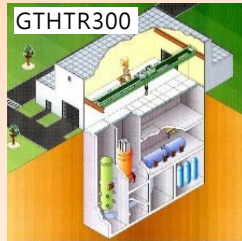
Block-type HTGR and Pebble-bed-type HTGR



IAEA-TECDOC-1694 Evaluation of High Temperature Gas Cooled Reactor Performance: Benchmark Analysis Related to the PBMR-400, PBMM, GT-MHR, HTR-10 and the ASTRA Critical Facility

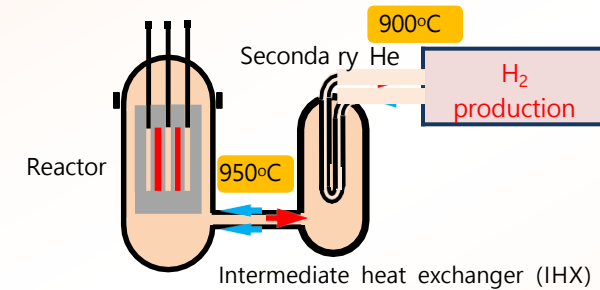
HTGR Systems Applications

HTGR Gas Turbine (GT) System



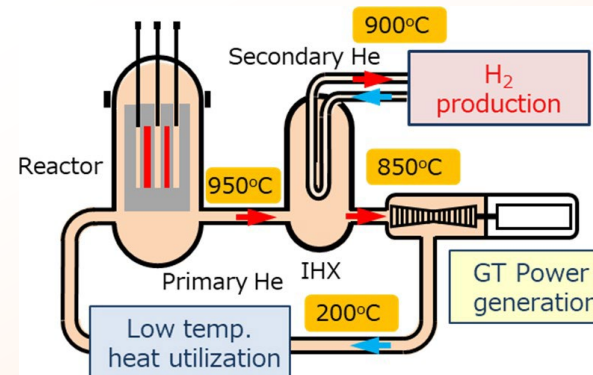
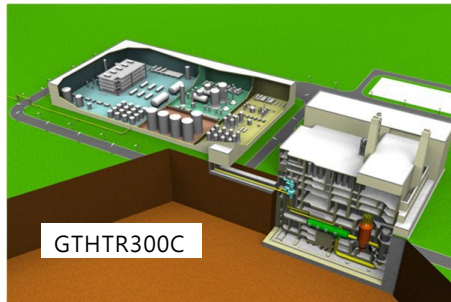
- Reactor: ~ 600 MWt (~ 300 MWe, 850°C)
- Helium gas turbine (Generation efficiency ~ 50%)
- High economy
- Deployment in 2030s

HTGR Hydrogen Production System



- Reactor: ~ 600 MWt, 950°C
- Hydrogen production 85,000 Nm³/h
- Deployment in 2040s

HTGR Cogeneration System (hydrogen production & power generation by GT)



- Reactor : ~ 600 MWt, 950°C
- Cogeneration of hydrogen and electricity
- Hydrogen production ~ 50,000 Nm³/h
- Heat utilization rate is about 80%
- Deployment in 2040s

Impact of Deployment of HTGR Hydrogen System

H₂ requirements, numbers of HTGRs, CO₂ reduction in 2050s

Sectors		H ₂ requirements (Mt/y)	Number of units, installed capacity	Contribution ratio of HTGR H ₂ supply (%)	HTGR H ₂ supply (Mt/y)	Number of HTGRs	CO ₂ reduction (Mt/y)
H ₂ steelmaking		2.2	Shaft furnace 18 units ^{※2}	80 ^{※4}	1.8	34 ^{※5}	56.0 ^{※2}
FCV	Car	1.8 ^{※1}	20 million units ^{※3}	30 ^{※4}	0.5	17 ^{※5}	4.2 ^{※2}
	Truck	1.0 ^{※1}	3.4 million units ^{※3}		0.3		7.0 ^{※2}
	Bus	0.1 ^{※1}	0.1 million units ^{※3}		0.0		0.4 ^{※2}
Stationary FC	At-home	1.8 ¹⁾	15.3 million units ^{※3}	30 ^{※4}	0.5	22 ^{※5}	4.7 ^{※2}
	Business	2.0 ¹⁾	17.8 GW ^{※3}		0.6		5.2 ^{※2}
Total		9.0			3.8	73	77.6 (5.9%) ^{※6}

H₂ requirements for H₂ steelmaking (2.2 Mt/y)

= Total in Japan (85.7 Mt-steel/y)²⁾ × Contribution ratio of H₂ steelmaking (40%)^{※4}

× H₂ requirement for H₂ steelmaking (0.065 kg-H₂/t-steel)^{※2}

HTGR hydrogen production system has the potential to supply about 40% of H₂ needed for H₂ steelmaking, FCVs, and FCs

※1 : Estimated using ref. 1)

1) Y. Matsuo et al., Position and introduction prospects of hydrogen energy toward a low-carbon society in 2050, The Institute of Energy Economics, Japan, 2013.

2) Steel statistical yearbook 2017, World Steel Association, 2018.

3) Japan's National Greenhouse Gas Emissions (1990~2016) , National Institute for Environmental Studies, Japan.

※2 : Estimated value by JAEA

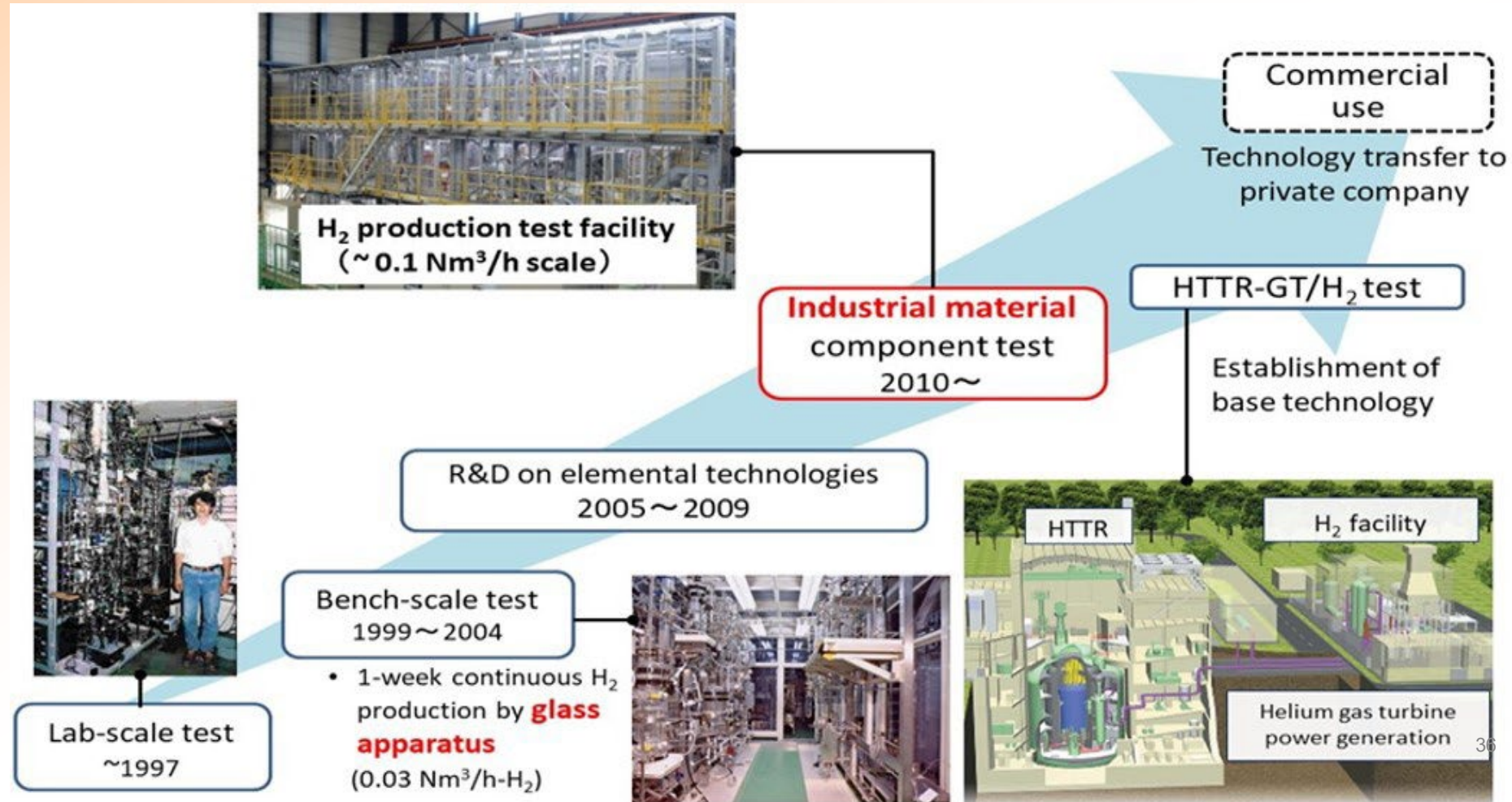
※3 : Value from ref. 1)

※4 : Assumed by JAEA

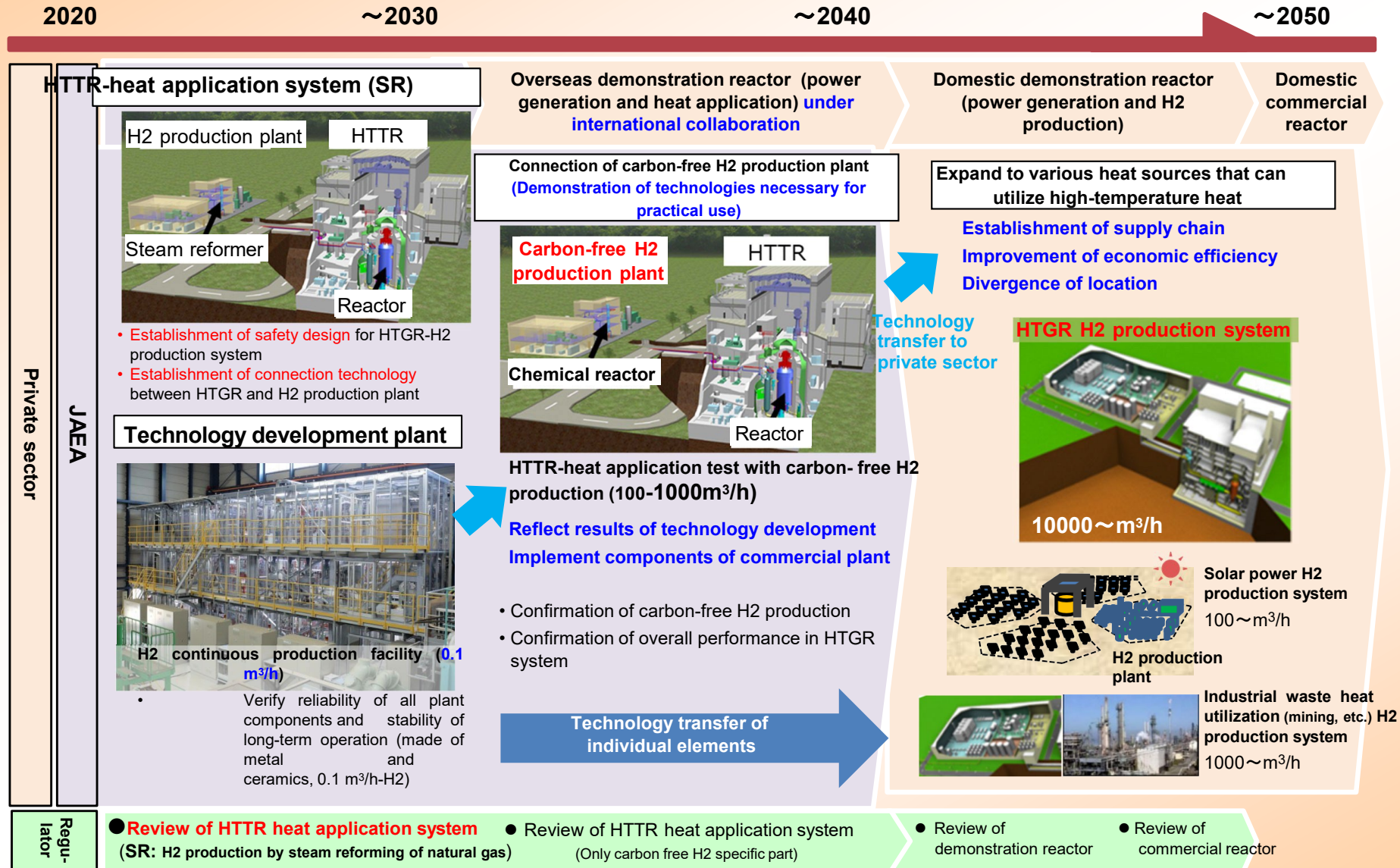
※5 : Thermal power of reactor : 600MWt, H₂ production : 85,000 Nm³/h

※6 : Reduction ratio to 2013 CO₂ emission³⁾

JAEA Progress on Sulfur-Iodine Process R&D

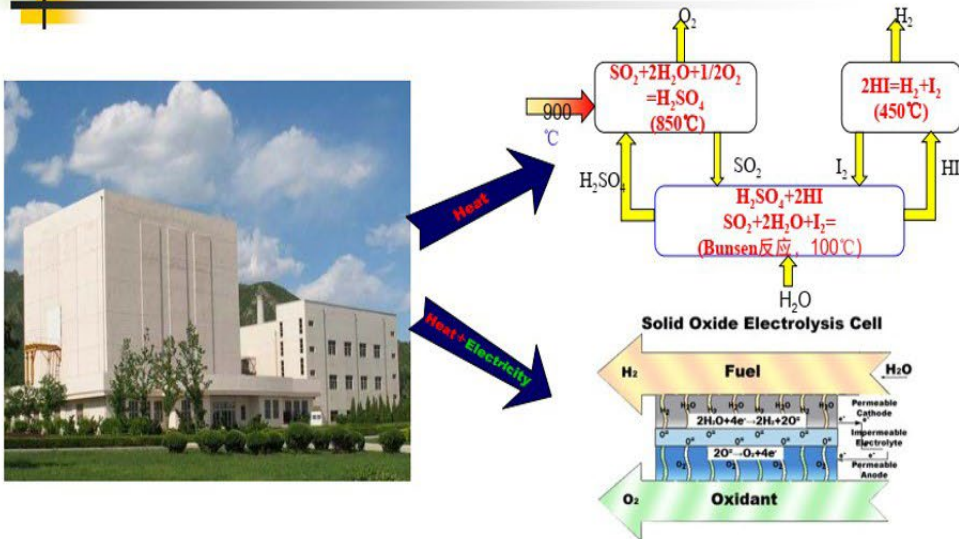


JAEA Roadmap for HTGR Hydrogen System



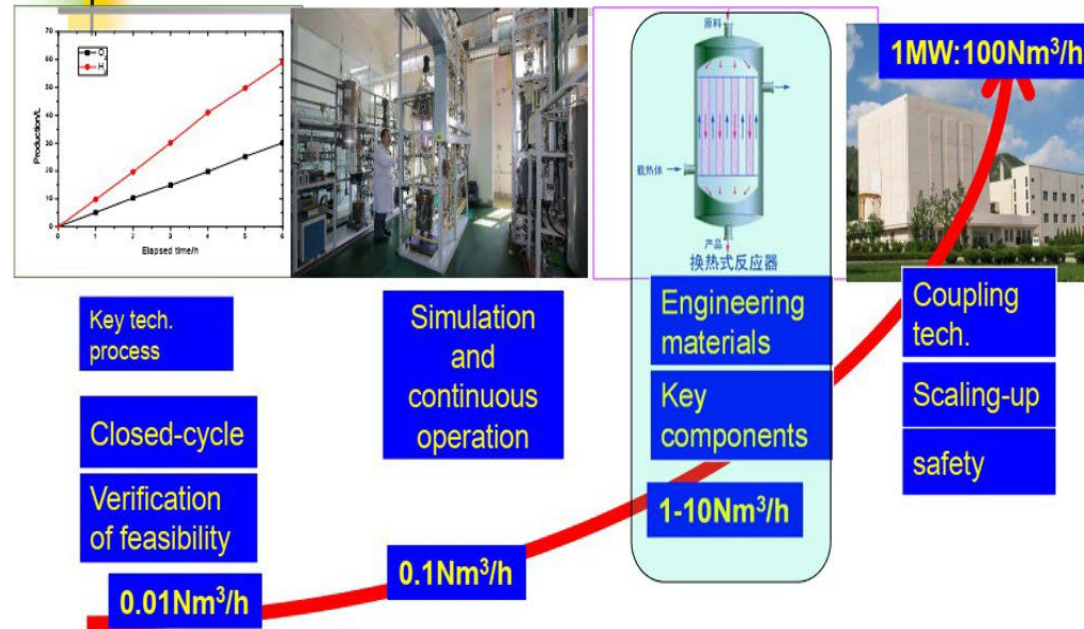
China INET's Efforts on Nuclear Hydrogen Production

Nuclear hydrogen program at INET



- ◆ **Iodine sulfur (IS) process:** high efficiency, CO₂ free, large-scale hydrogen production technology
- ◆ **High temperature steam electrolysis (HTSE):** high efficiency, modular design, flexible and suitable to various scale H₂ production.
- ◆ R&D on the two processes were conducted in parallel since 2005, and IS process was selected for scaling up and potential coupling to HTR-10.

R&D route of NH through IS process



Key tech.
process

Closed-cycle

Verification
of feasibility

0.01Nm³/h

Simulation
and
continuous
operation

0.1Nm³/h

Engineering
materials
Key
components

1-10Nm³/h

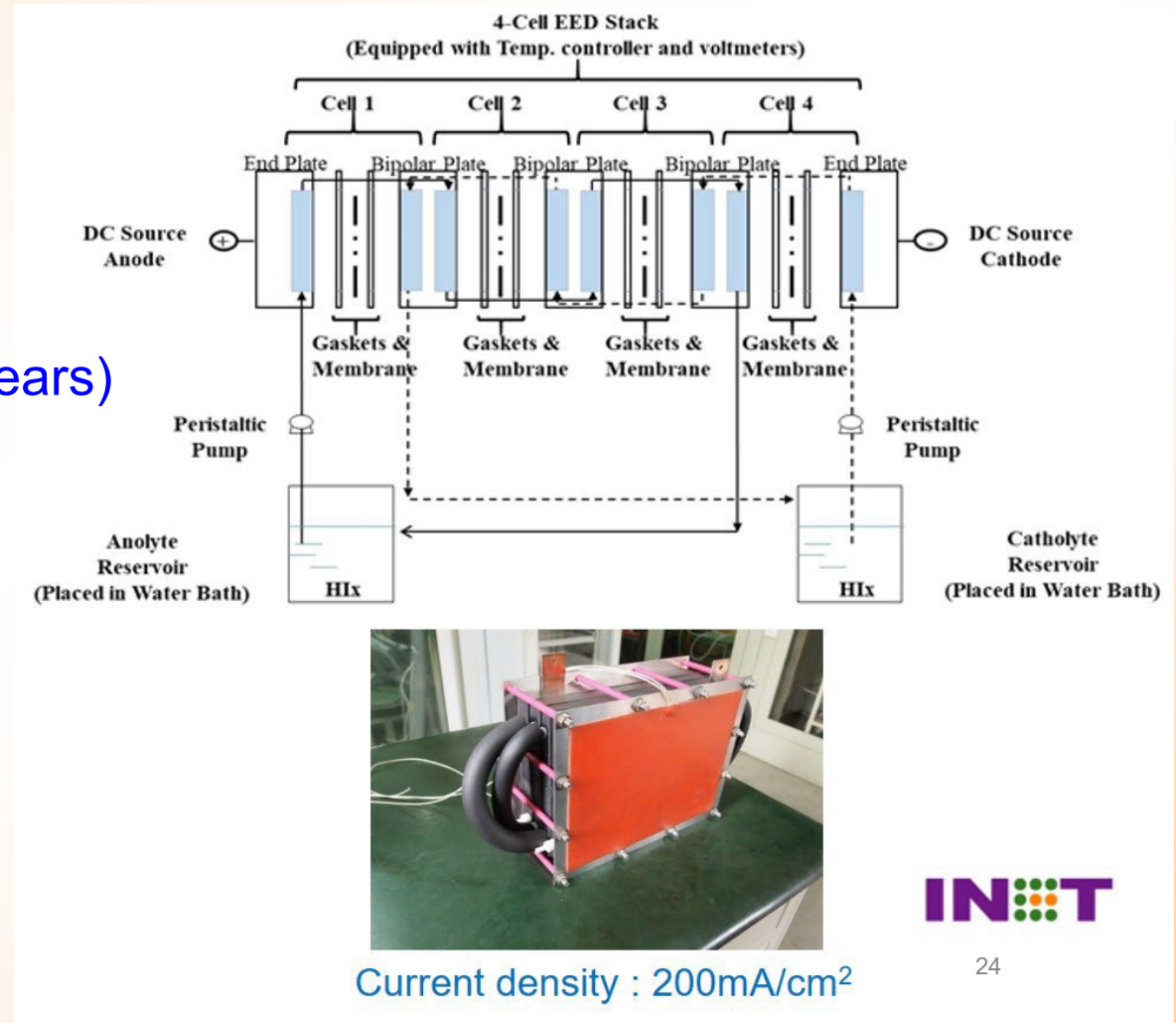
Coupling
tech.
Scaling-up
safety

Fundamental study	System integration	Key components	Pilot demo
2005-2010	2010-2015	2016-2020	2021-2025

INET P Zhang, et al. *Renewable & Sustainable Energy Reviews*, <https://doi.org/10.1016/j.rser.2017.05.235>

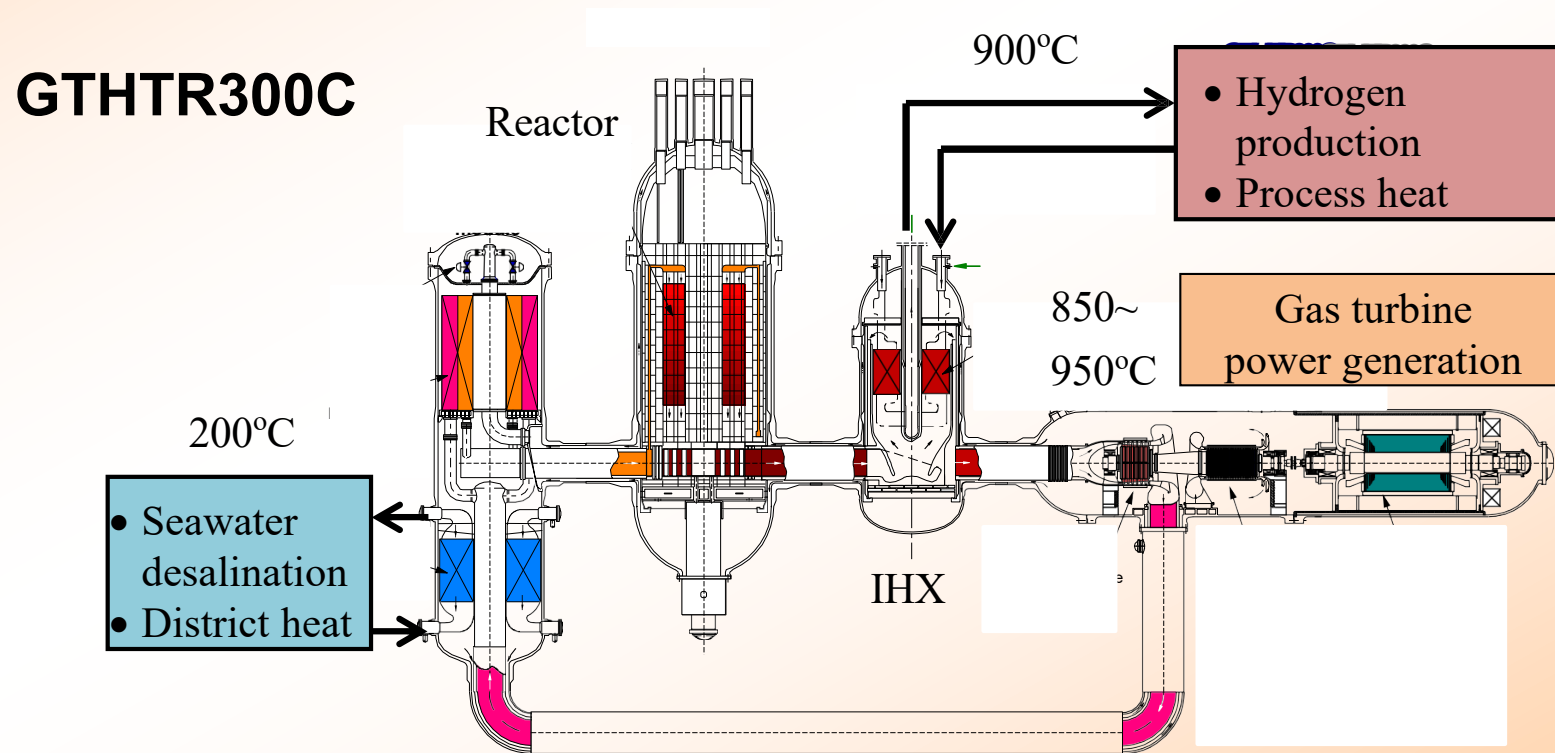
Current & Future R&D Activities in SI-Cycle in China

- Development of the key reactor components
 - Sulfuric acid decomposer
 - HI decomposer
 - Bunsen reactor
 - Electro-electrodialysis (EED).
- Dynamic simulation
- Pilot scale IS development (two phases, ~ 10years)
 - Safety issues on nuclear hydrogen
 - Key technologies of pilot scale
- Engineering materials
- Reactors, components, loops.....
 - HTR-IS coupling technology(2021-2025)
 - Scale-up of components
 - Coupling technology
- HTR technology for H₂ production and heat application
 - VHTR (950-1000°C)
 - IHX

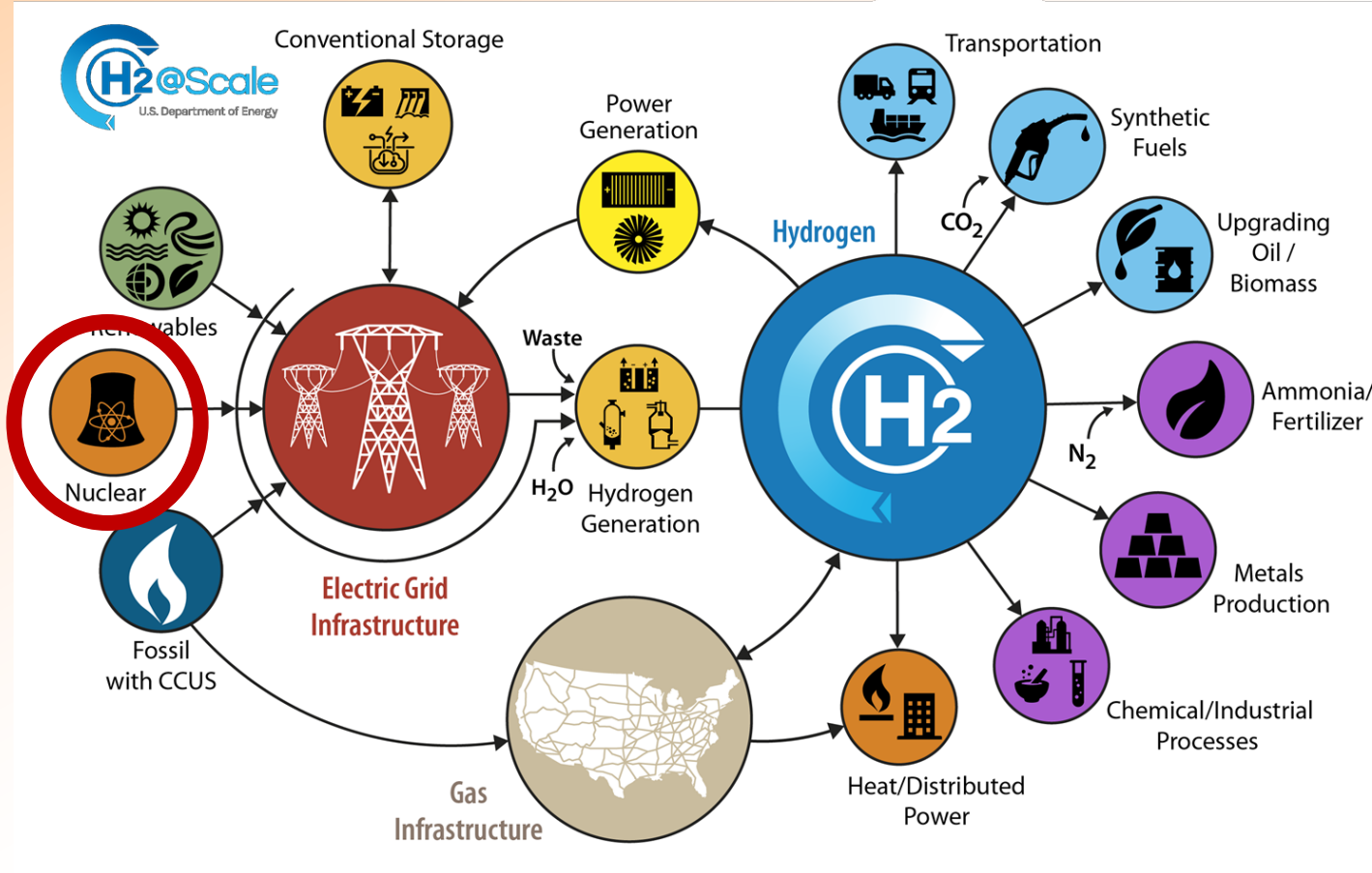


GTHTR300C: HTGR Hybrid Energy System

- HTGR system for power generation and cogeneration of hydrogen, desalination, steelmaking, etc.
- Designed by JAEA in collaboration with Mitsubishi Heavy Industries, Fuji Electric, Kawasaki Heavy Industries, Nuclear Fuel Industries, Toshiba, IHI, others.
- Development status: Pre-licensing basic design completed.



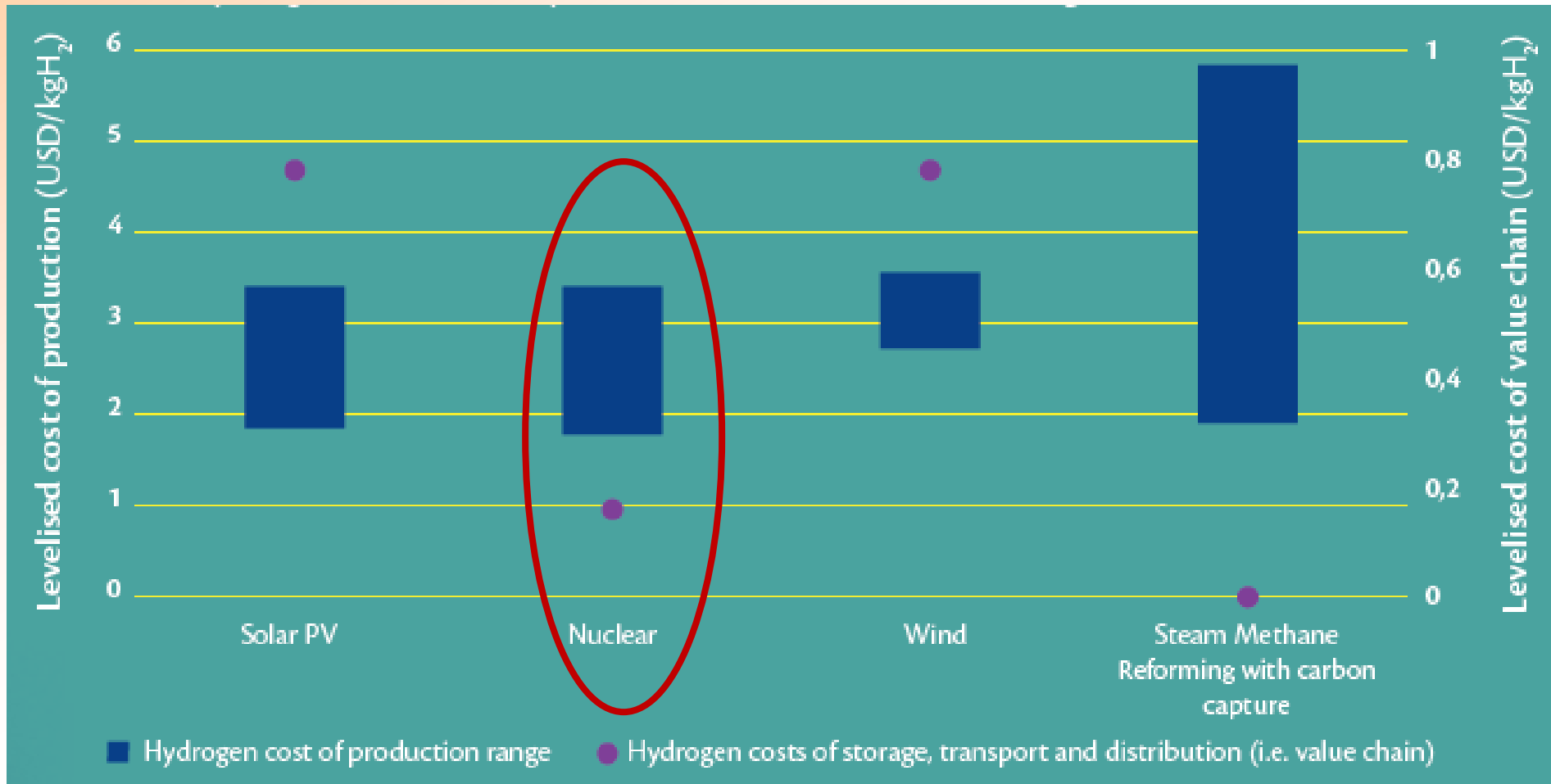
US DOE Initiates H2@Scale: Enabler for Deep Decarbonization



Key Opportunities

- **Industry and Chemicals** Steel, ammonia, cement, syn fuels (e.g., aviation), exports
- **Transportation** Trucks, marine, buses, etc.
- **Power and Energy Storage** Long duration storage, NG blending, turbines, fuel cells

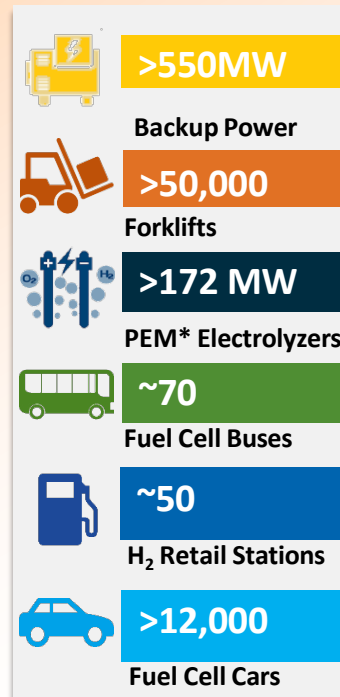
Hydrogen Costs, H2 form Electrolysis and Methane Reforming- 2035 timeframe



Nuclear Energy Agency: Nuclear-Hydrogen Digest: Nuclear Energy in the Hydrogen Economy,

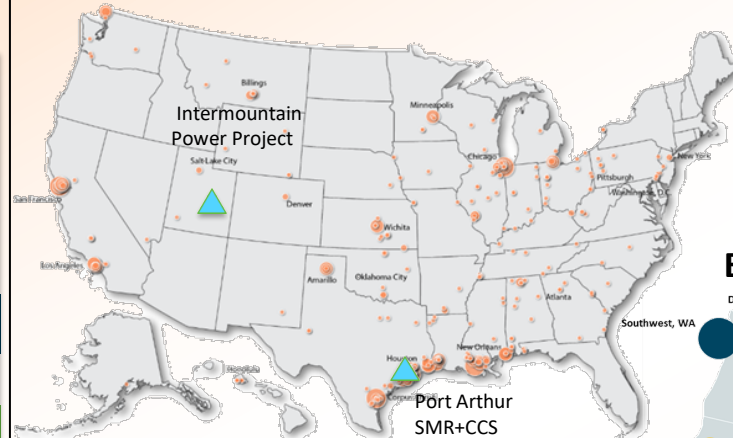
Snapshot of Hydrogen and Fuel Cells in the U.S.

Deployment Examples



* PEM: Polymer electrolyte membrane

Examples of Hydrogen Production Locations



Examples of Hydrogen Station Plans

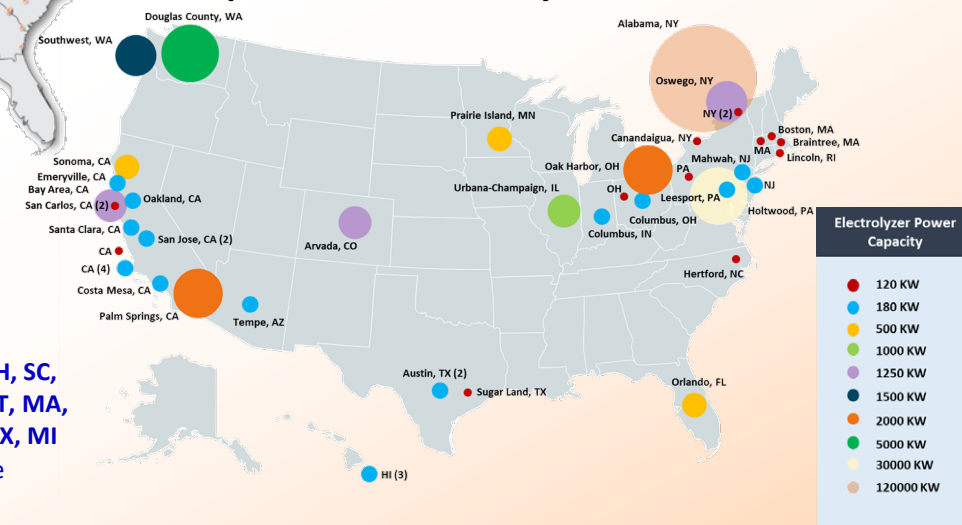
California
200 Stations Planned
California Fuel Cell Partnership Goal

Northeast
12 – 20
Stations
Planned

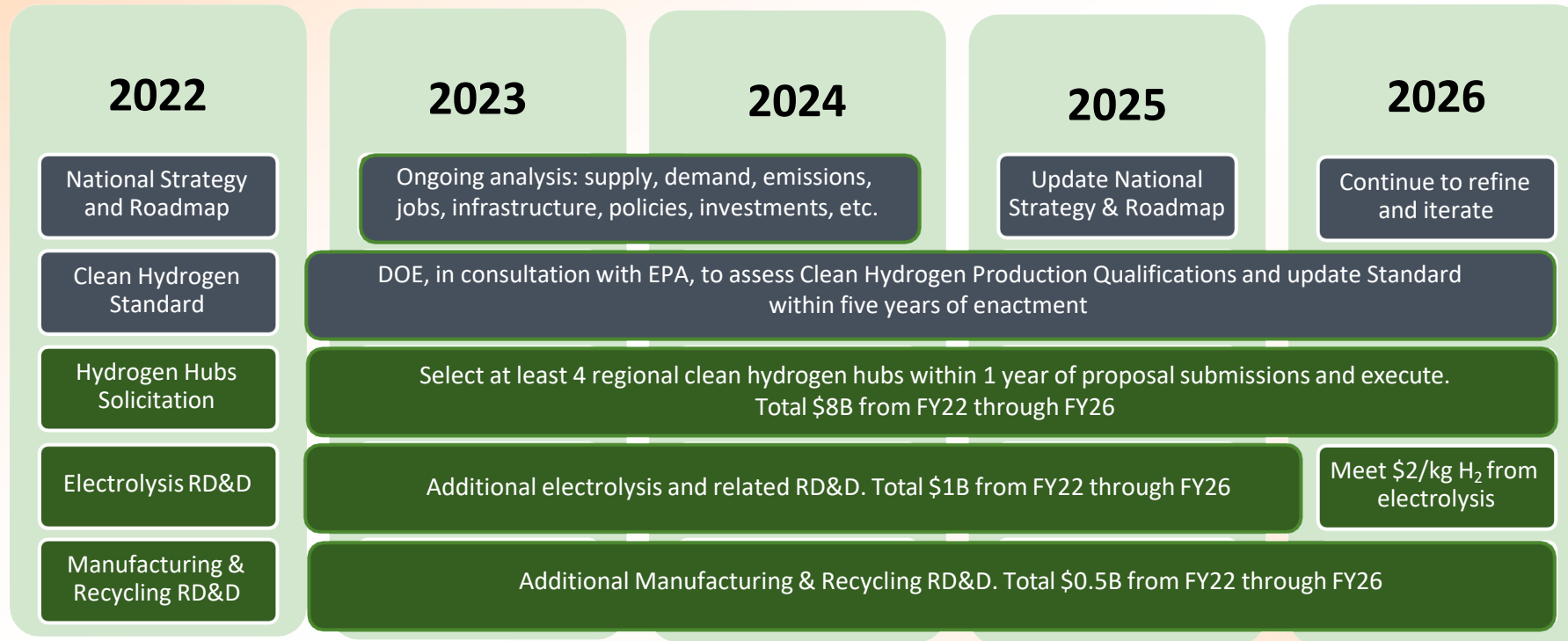
**AZ, HI, OH, SC,
NJ, NY, CT, MA,
CO, UT, TX, MI
And more**

- 11 million metric tons (MMT) H₂/yr
- Over 1,600 miles of H₂ pipelines
- World's largest H₂ storage cavern

Examples of PEM Electrolyzer Installations



Timeline for Key Hydrogen Provisions



7 Regional Clean Hydrogen Hubs (October 2023)

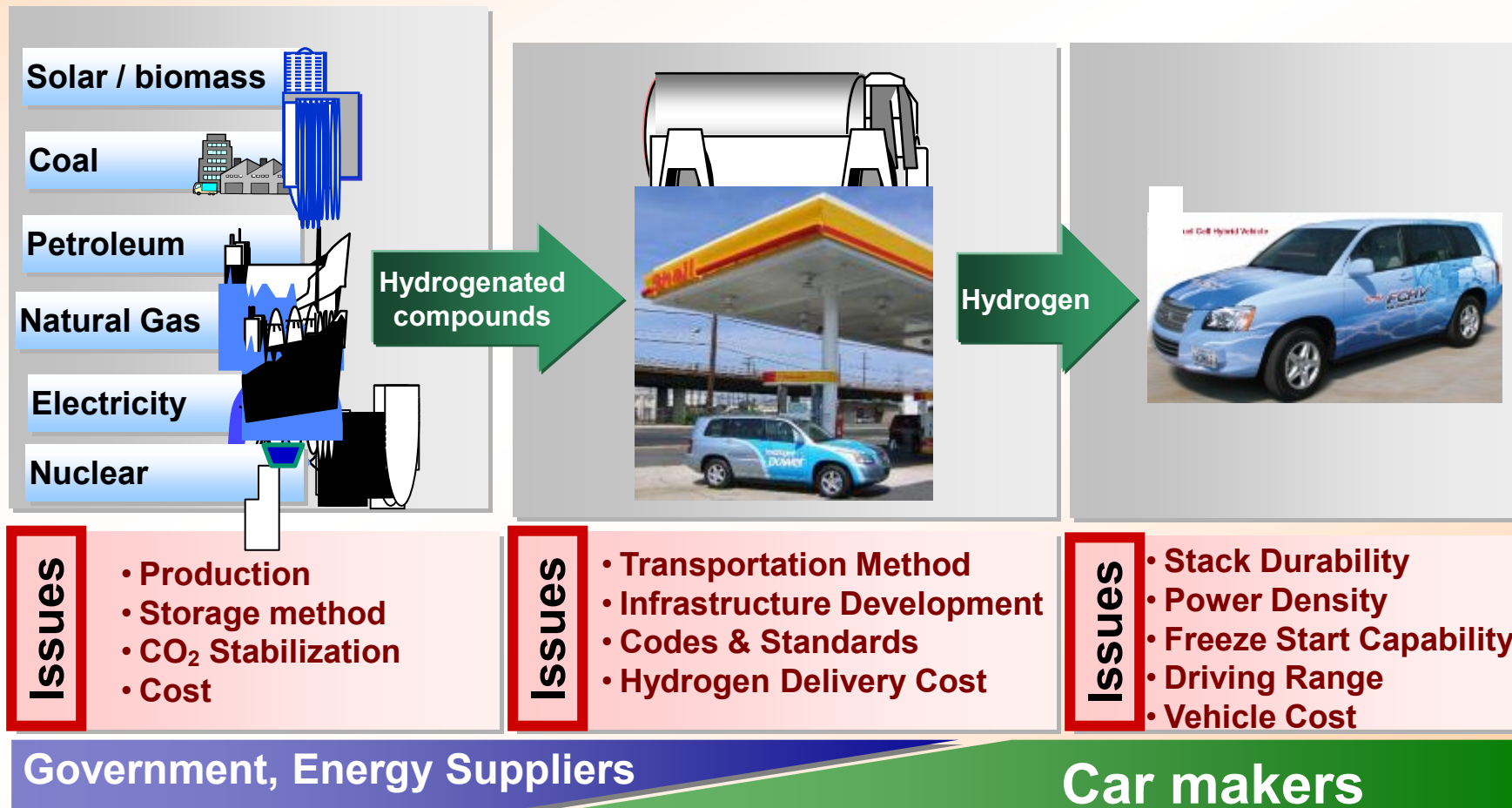
- Mid-Atlantic Hydrogen Hub (**Mid-Atlantic Clean Hydrogen Hub (MACH2); Pennsylvania, Delaware, New Jersey**)- H2 from renewable **and nuclear electricity**
- Midwest Hydrogen Hub (**Midwest Alliance for Clean Hydrogen (MachH2); Illinois, Indiana, Michigan**) — H2 from renewable energy, natural gas, and **low-cost nuclear energy**.
- Appalachian Hydrogen Hub (**Appalachian Regional Clean Hydrogen Hub (ARCH2); West Virginia, Ohio, Pennsylvania**)
- California Hydrogen Hub (**Alliance for Renewable Clean Hydrogen Energy Systems (ARCHES); California**)
- Gulf Coast Hydrogen Hub (**HyVelocity Hydrogen Hub; Texas**)
- Heartland Hydrogen Hub (**Minnesota, North Dakota, South Dakota**)
- Pacific Northwest Hydrogen Hub (**PNW H2; Washington, Oregon, Montana**)

Challenges and Opportunities

Production

Delivery, Supply

Usage/Application





Production: Challenges

- Hydrogen production costs are high relative to conventional fuels
- Current technologies produce large quantities of carbon dioxide and are not optimized for making hydrogen as an energy carrier.
- Low carbon advanced hydrogen production methods need development.
- Public-private production demonstrations are essential.

Production: Nuclear – Electrolysis and Thermochemical Methods

Scientific Challenges and Opportunities

- ✓ New materials for cost/efficiency (duty cycle) for thermo-chemical (TC)
- ✓ Separations and materials performance
- ✓ Thermodynamic data and modeling for TC
- ✓ High temperature materials in oxidizing environments at $\sim 900^{\circ}\text{C}$
 - Solid oxide materials and membranes
 - TC heat exchanger materials
- ✓ High temperature gas separation
- ✓ Improved catalysts for reactions

Recent Research Trends (2023–2026)

- ✓ AI-assisted plant optimization
- ✓ Advanced SOEC materials
- ✓ Digital twin technology
- ✓ High-temperature alloys
- ✓ Nuclear-renewable hybrid systems
- ✓ Hydrogen storage integration
- ✓ Autonomous plant operation

R &D Opportunities in Nuclear hydrogen Systems

GEN-IV Reactor Systems Analysis and Demonstration :

Reactor Design, Advanced Fuel Development , (Advanced Fuel Cycle Initiative),
Moderator, Instrumentation, Energy Conversion Systems

High-temperature, corrosion resistant materials - R&D will be required to develop, test, and verify materials capable of performing at high temperatures (400-950°C) in the presence of caustic chemicals to ensure the safety and economics of the facility.

High-temperature heat exchangers – Research is needed to design heat exchangers to transfer heat from an intermediate heat loop to the process at high temperatures, high pressures, and in harsh chemical environments

Chemical reaction data - Research is needed on basic chemical reaction data (equilibrium constants, reaction rates, etc.) to better determine the operating parameters of the thermochemical system

System design – Studies are needed to study the hydrogen plant and its relationship to the reactor, including configuration options and operating conditions, scaling, control, system isolation issues, and intermediate heat transfer loop design.

Future Outlook

- ✓ Expected developments
 - Commercial SOEC plants
 - SMR-based hydrogen hubs
 - Green steel production
 - Synthetic aviation fuel
 - Nuclear-powered ammonia production
 - Net-zero industrial parks

Conclusions

- ✓ Nuclear Hydrogen (NH) provides reliable low-carbon hydrogen and is solution to energy challenges and security
- ✓ NH development may lead to commercial-scale production of hydrogen
- ✓ NH is strongly supported by the GEN IV Reactor development
- ✓ SMRs offer flexible hydrogen production near industrial users.
- ✓ Continued advances in materials, economics, and regulations will accelerate commercialization.
- ✓ Nuclear hydrogen is expected to play a significant role in achieving global net-zero emissions.
- ✓ Several Challenges exist and so new R & D opportunities exist in the NH program

Thank you