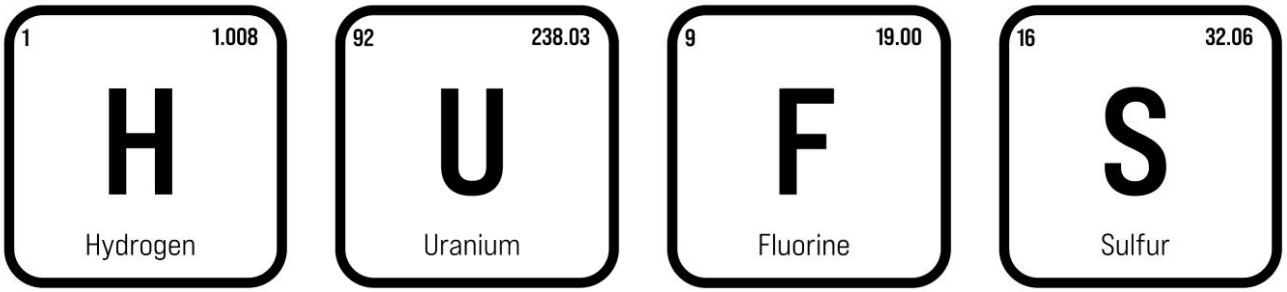
01st Sep 2026



수소경제와 에너지저장 시스템

(Hydrogen Economy and Energy Storage Systems)

Haewon Seo, Ph. D

Hydrogen **E**nerg**Y** Lab **ON E**arth

Assistant Professor

Division of Climate Change

Hankuk University of Foreign Studies (HUFS)

Course Introduction

- **Lecture: Hydrogen Economy and Energy Storage Systems (L01212101)**
  - Class time: Tuesday, 15:00–17:50

- **Professor**: Haewon Seo
  - Office: Prof Res Bldg , Rm 202
  - E–mail: heyone@hufs.ac.kr
  - Office hour: Wednesday (till 17:00)

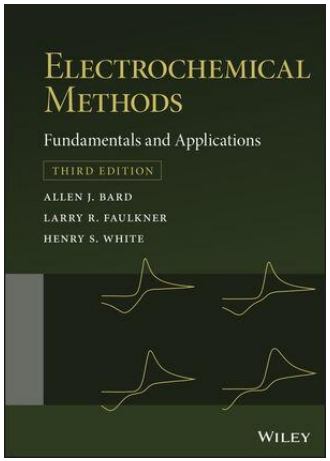
- **Scope**
  - This course introduces hydrogen energy and its associated devices for a clean and sustainable future. Based on fundamental electrochemistry, it examines the operating principles of energy conversion systems for hydrogen production and utilization. Furthermore, it reviews the latest technological trends and explores the development of next-generation energy conversion technologies.

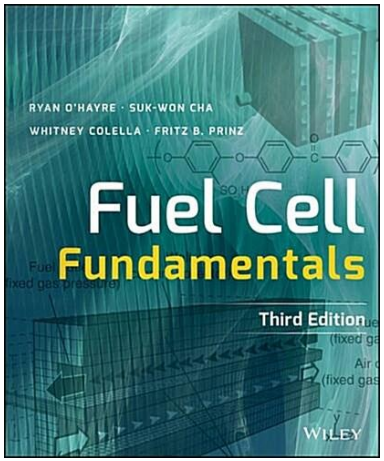
Course Introduction

❑ Textbook

– Main

- Electrochemical Methods (A.J. Bard et al.), 3rd Ed., Wiley (2022)
- Thermodynamics (Y.A. Cengel et al.), 9th Ed., McGraw-Hill (2018)
- Fuel Cell Fundamentals (R. O'Hayer et al.), 3rd Ed., Wiley (2016)





– Reference

- Scientific articles
- IRENA, IEA, World Energy Council, DOE, etc.

Course Introduction

- **Schedule**; to be flexibly operated

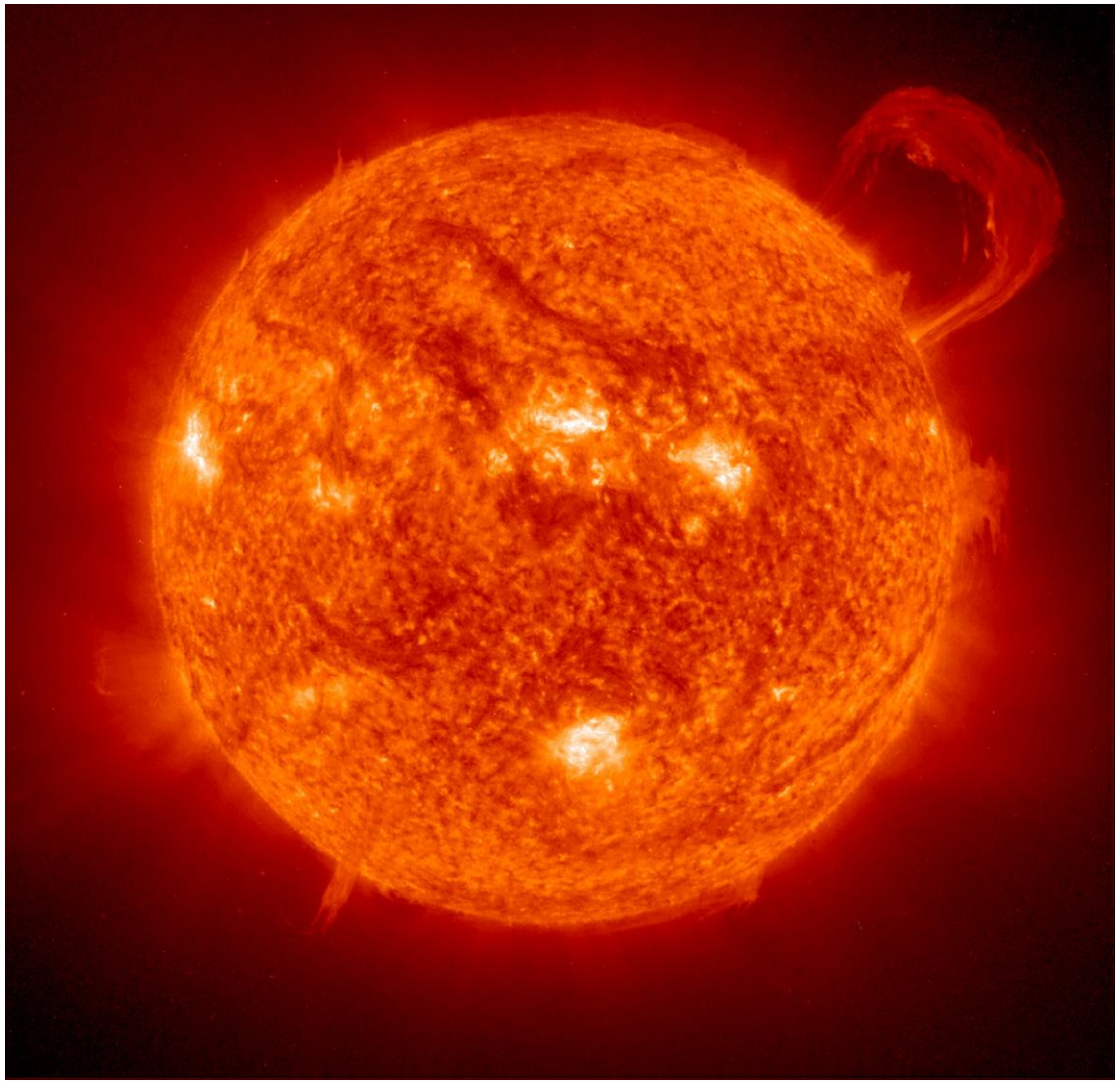
Week	Date	Contents
01st	**Sep 01st 2026**	**Introduction to Hydrogen (1)**
02nd	Sep 08th 2026	Introduction to Hydrogen (2)
03rd	Sep 15th 2026	Laws of Thermodynamics (1)
04th	Sep 22nd 2026	Laws of Thermodynamics (2)
05th	Sep 29th 2026	Thermodynamics of Reacting Systems
06th	Oct 06th 2026	Electrochemical Cells & Potentials
07th	Oct 13th 2026	Reference Electrodes & Practical Cells
08th	Oct 20th 2026	Midterm exam
09th	Oct 27th 2026	Cell Polarization & Overpotentials
10th	Nov 03rd 2026	Electrode Kinetics & Interface (EDL)
11th	Nov 10th 2026	Mass Transport & Chronoamperometry
12th	Nov 17th 2026	Voltammetry & Reaction Mechanisms
13th	Nov 24th 2026	Electrochemical Impedance
14th	Dec 01st 2026	Applications
15th	Dec 15th 2026	Final exam

Course Introduction

- **Evaluation**
  - Attendance (10%)
  - Assignment (20%)
  - Midterm Exam (30%)
  - Final Exam (40%)

1. Introduction to Hydrogen

Overview of Hydrogen

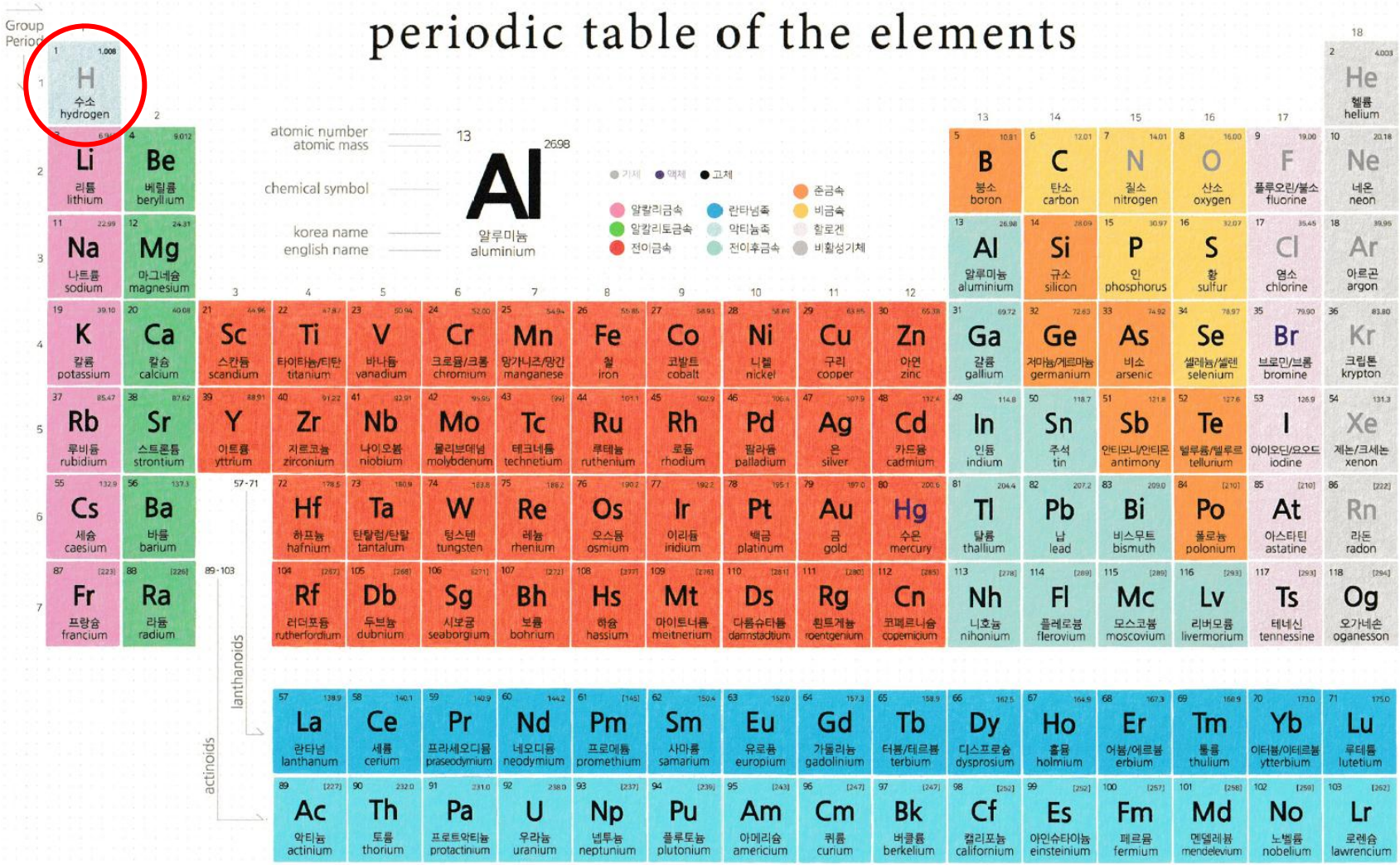


<Source: NASA>

Overview of Hydrogen

❑ Hydrogen

The simplest element in the universe (one proton, one electron, and no neutron)

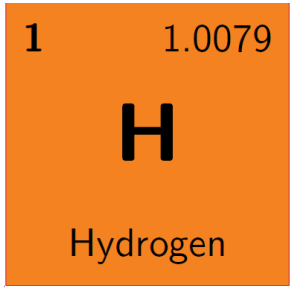


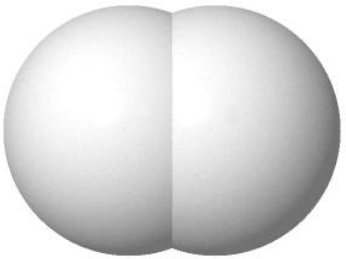
Overview of Hydrogen

❑ Hydrogen

The simplest (one proton & one electron) and abundant (~75%) element in the universe

- Symbol: H
- Atomic Number: 1
- Atomic Weight: 1.0079 u
- Melting Point: –259.2 °C
- Boiling Point: –252.9 °C
- Density: 0.090 g L^{-1} (at STP (0 °C, 1 atm))





–Typically, hydrogen refers to *hydrogen gas* (H_2), which is a colorless, odorless, and nontoxic gas

Table Physical properties of gases at standard temperature and pressure (STP) (0 °C, 1 atm)

Gas	Density, ρ (g L^{-1})	Specific heat capacity, C_p (J g^{-1} K^{-1})	Thermal cond., k (W m^{-1} K^{-1})	Viscosity, μ (μPa s)
H_2	**0.090**	**14.28**	**0.168**	**8.4**
He	0.179	5.19	0.142	18.6
CH_4	0.717	2.22	0.030	10.3
Air	1.292	1.005	0.024	17.2
O_2	1.429	0.915	0.024	19.2
CO_2	1.977	0.823	0.015	13.7

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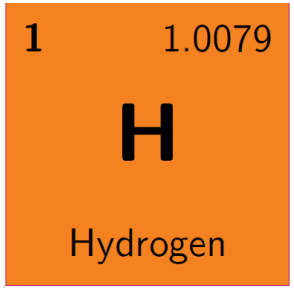

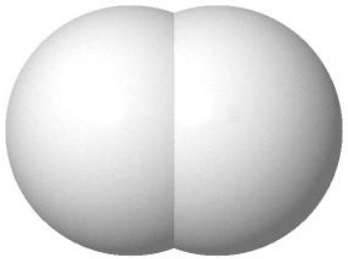

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Table Physical properties of liquids

Liquid	Density, ρ (g L^{-1})	Boiling point (°C)	Remarks
H_2	**70.85**	**–252.9**	**~1/6 of CH4's density**
He	125.0	–268.9	
CH_4	422.8	–161.5	
Air	874.0	–194.3	
O_2	1141	–183.0	
CO_2	1178	–78.5	At triple–point

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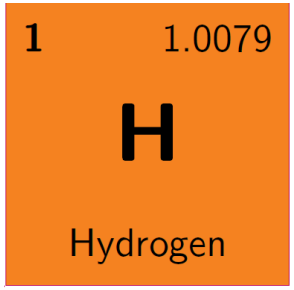

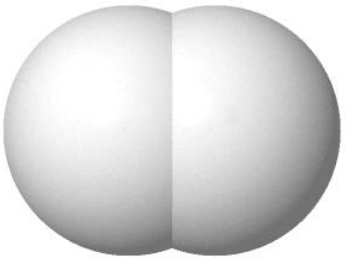

–H_2 makes up ~0.5–0.6 ppm of the Earth's atmosphere, whereas H is ubiquitous in water (H_2O), organic compounds (CHONPS), and other matter.

Table Major constituents of the atmosphere of Earth in parts–per million (ppm)

Gas	Volume fraction (ppm)	Gas	Volume fraction (ppm)	Gas	Volume fraction (ppm)
N_2	780,840	CH_4	1.92	O_3	0.07
O_2	209,460	Kr	1.14	NO_2	0.02
Ar	9,340	**H_2**	**0.55**	H_2O	Up to 40,000
CO_2	420	N_2O	0.33		
Ne	18.182	CO	0.10		
He	5.24	Xe	0.09		

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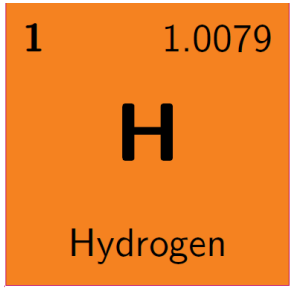
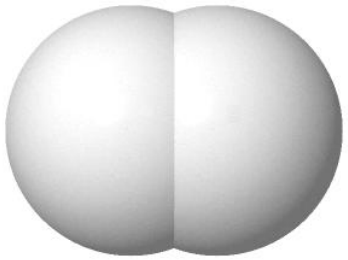
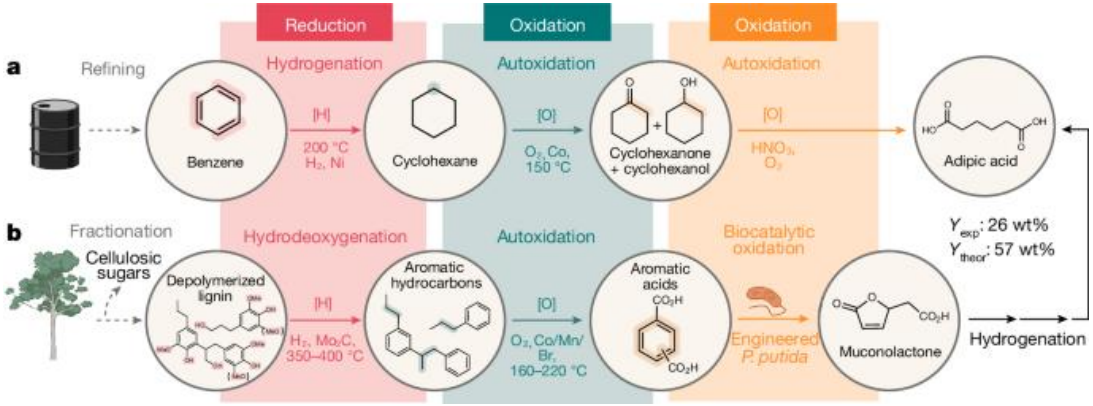




*$H_2 \rightarrow 2H$ ($\Delta H° = 435.14$ kJ mol^{-1})

–Low reactivity at room temperature, but reacts with most elements and compounds at high temperatures or in the presence of catalysts

–Involved in biological redox (oxidation–reduction) reactions



Nature, **654** (2026) 668–675

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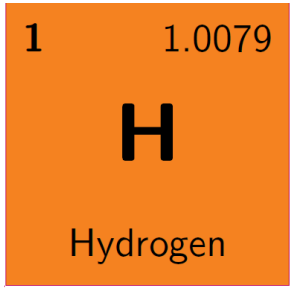
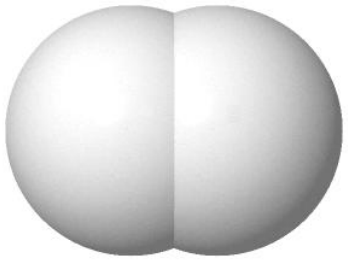




–Reacts with halogens to form hydrogen halides, and with CO to produce hydrocarbons and alcohols

*$H_2 + X_2 \rightarrow 2HX$ (X = F, Cl, Br, I)

**$nCO + (2n+1)H_2 \rightarrow C_nH_{2n+2} + nH_2O$

***$nCO + 2nH_2 \rightarrow C_nH_{2n+1}OH + (n-1)H_2O$

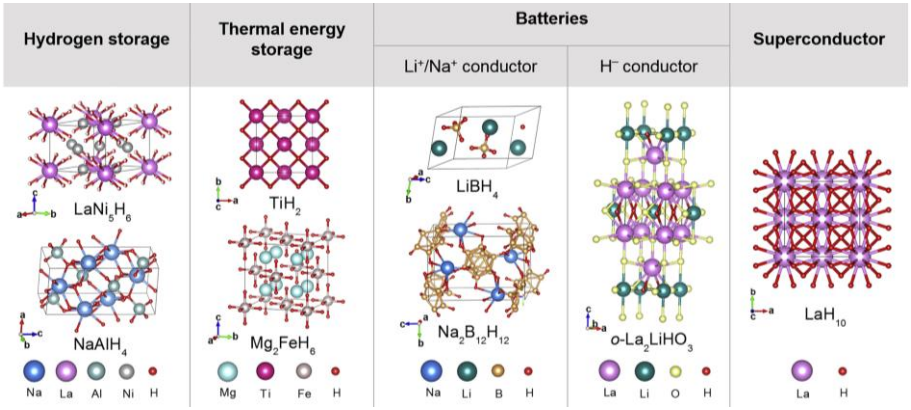
–Combines with numerous elements to form various hydrides

*Ionic hydride (groups 1, 2 except for Be, Mg) (e.g., LiH, NaH, CaH_2, etc.)

**Covalent hydride (groups 13–17) (e.g., B_2H_6, CH_4, NH_3, H_2O, HF, etc.)

***Metallic hydride (typically transition metals) (e.g., TiH_2, PdH_x, etc.)

***Complex hydride (e.g., $NaBH_4$, $LiAlH_4$, $NaAlH_4$, etc.)



Joule, **4**(4) (2020) 705–709

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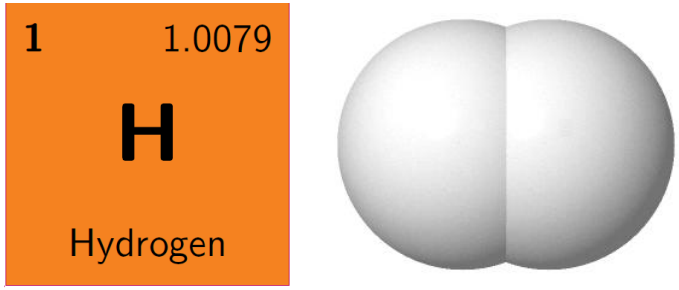
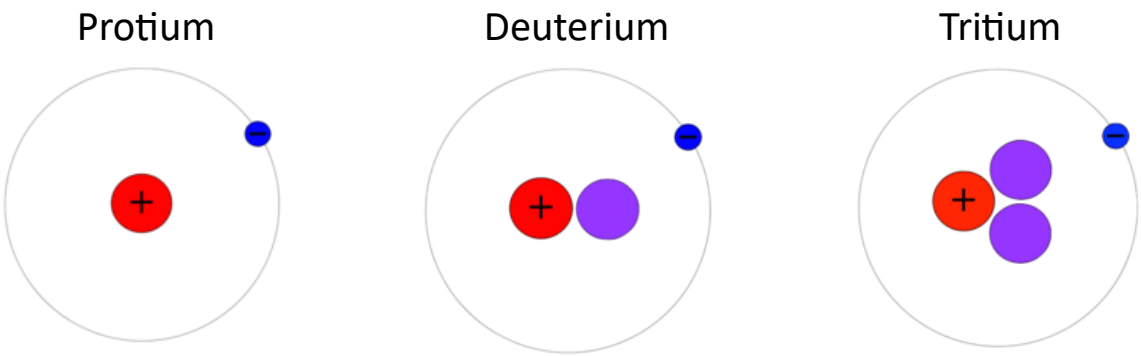


–Hydrogen has three main naturally occurring isotopes: ^{1}H (protium), ^{2}H (D) (deuterium), ^{3}H (T) (tritium)



	Protium	Deuterium	Tritium
Atomic Weight	1.0079 u	2.0141 u	3.0160 u
Half-Year	Stable	Stable	12.32 yr
Abundance	99.9855%	0.0115%	trace

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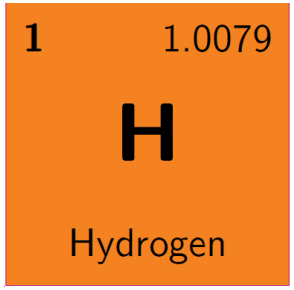
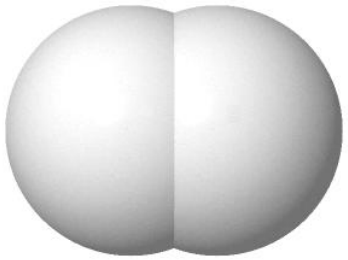
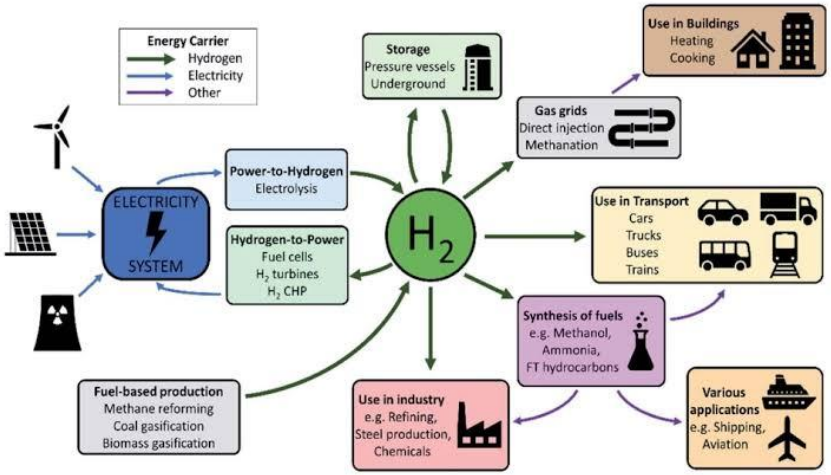




–H_2 is *an energy carrier* that is converted from primary energy sources into a secondary form, making it **storable** and **transportable**.



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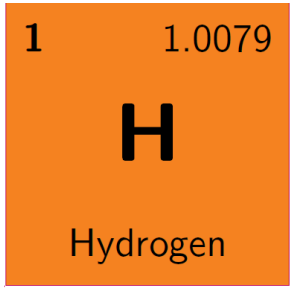
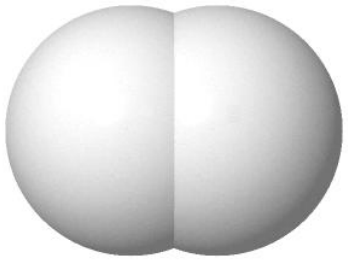
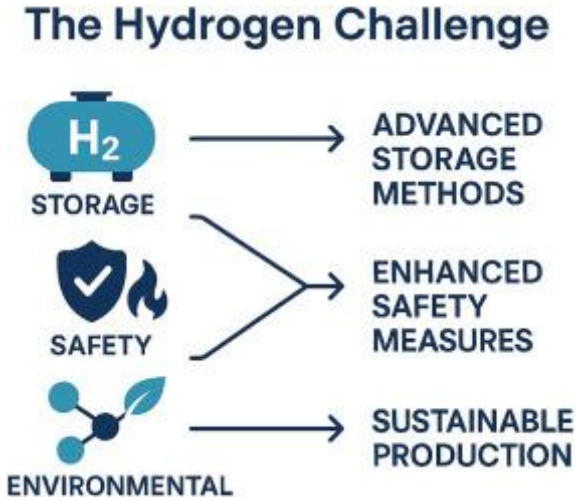
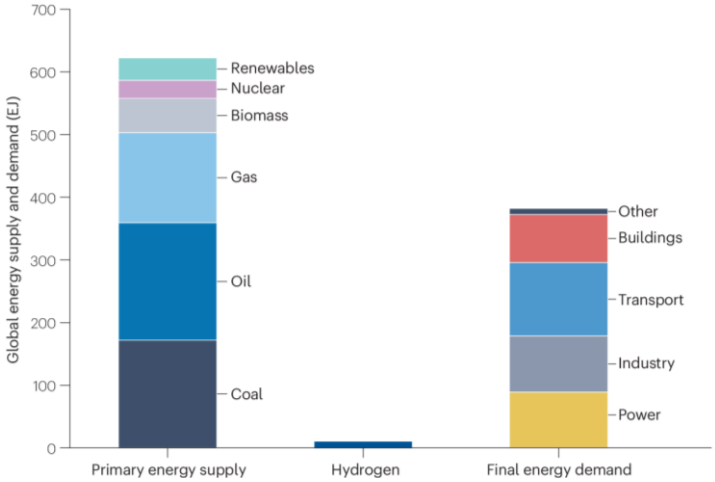


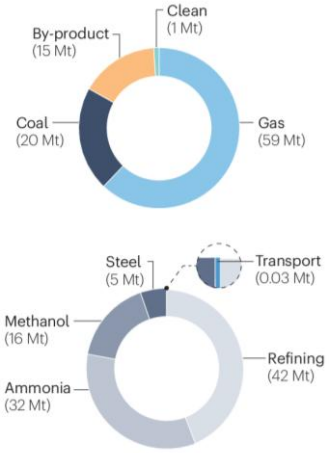


–Major challenges include production costs, storage limitations, the development of highly efficient combustion engines, and safety; **the economic viability needs be improved**.



Int. J. Hydrogen Energy, **167** (2025) 150952



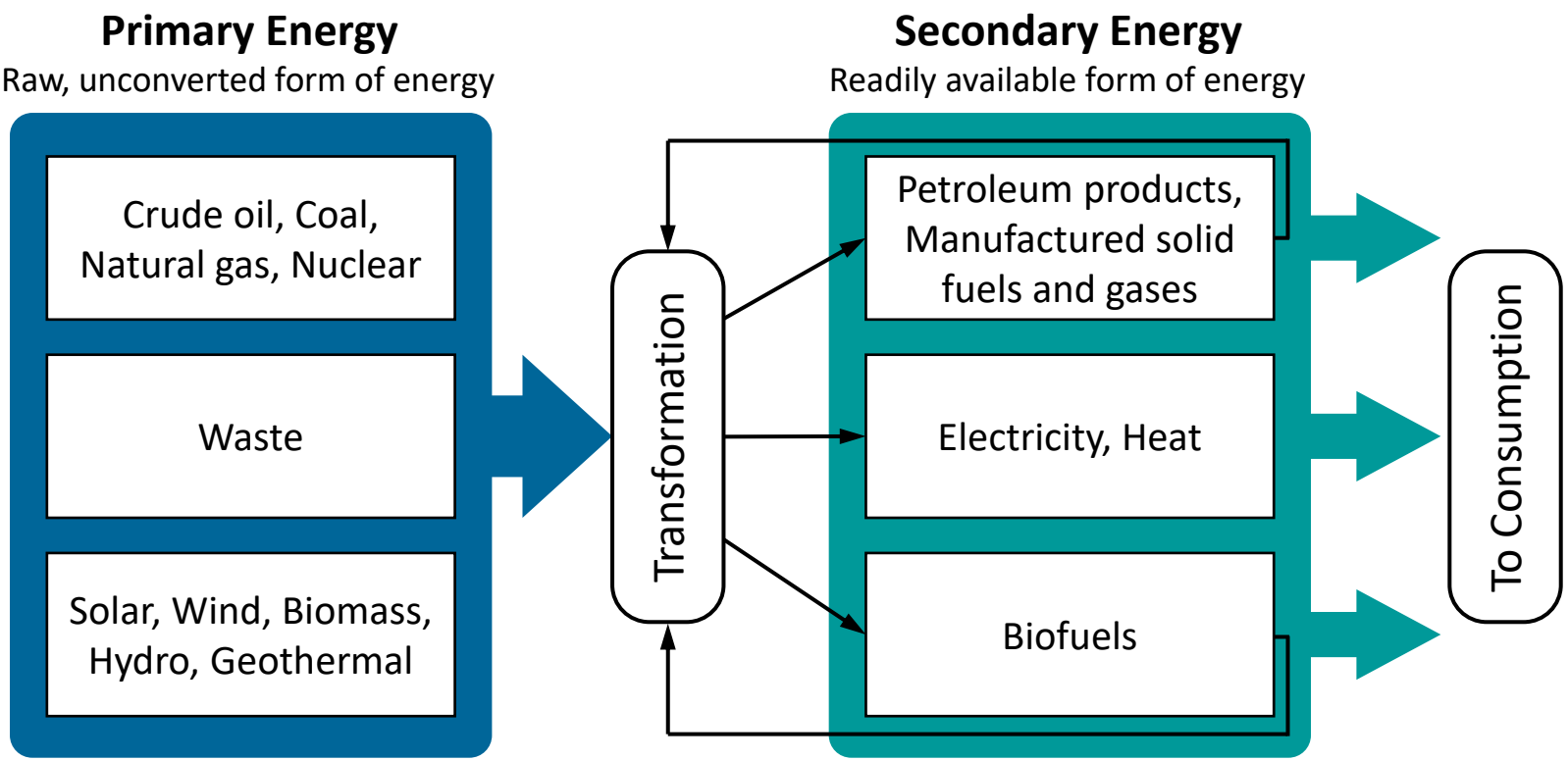


Nat. Rev. Clean Technol., **1** (2025) 351–371

Types of Energy

❑ Primary and Secondary Energy

Energy is indeed abundant, but *usable* energy is strictly limited, making *tools* essential



– *Usable* energy must be transformed from primary energy sources

– Every energy conversion process must entail *losses*

Renewable Energy

❑ Renewable Energy

Energy derived from natural resources that are replenished on a human timescale

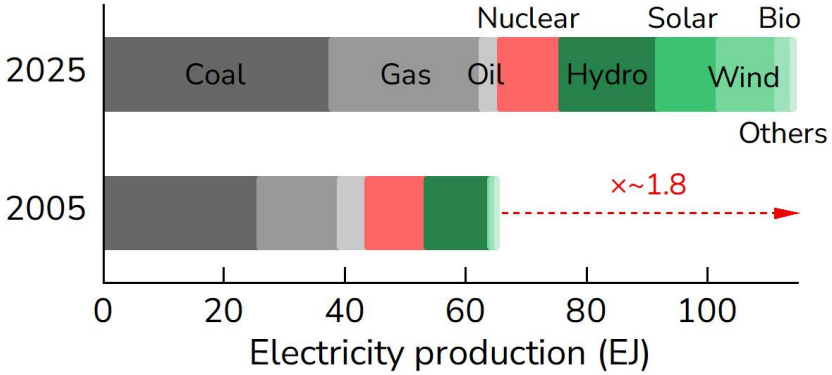
*Inexhaustible, Ubiquitous, Zero–CO_2 Emission

Solar Wind Hydropower Biomass Geothermal Heat

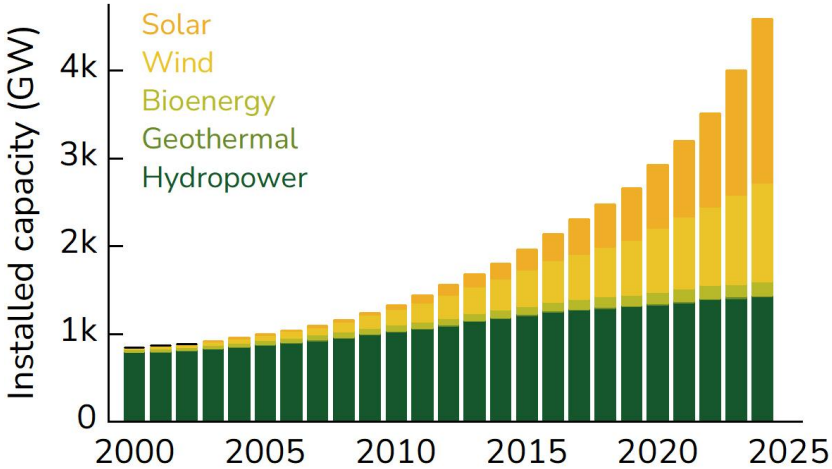
❑ Global Electricity Production

RE accounts for 34% in 2025 (18% in 2005)

*Others: geothermal, biomass, waste, wave and tidal



<Source: Statistical Review of World Energy (2025)>



<Source: IRENA (2025)>

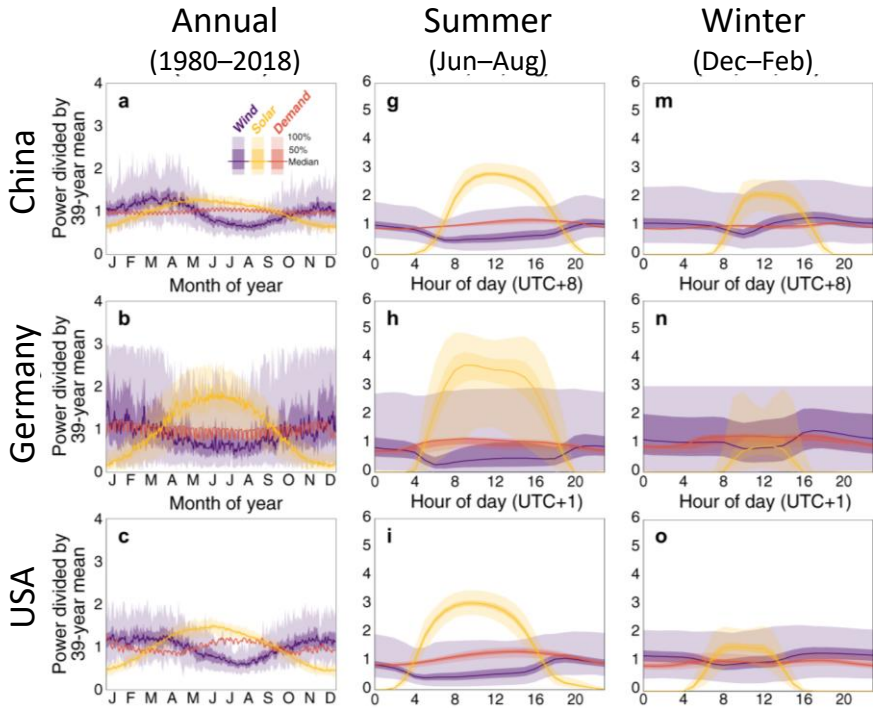
Challenges for Renewables

❑ Transport Issues

RE power generation sites are geographically distant from major urban consumption centers. Long–distance bulk power transmission suffers severe grid losses and infrastructure bottlenecks

❑ Storage Issues

RE power generation fluctuates based on weather and diurnal cycles. Electricity is difficult to store directly on a massive, long–term seasonal scale without loss.

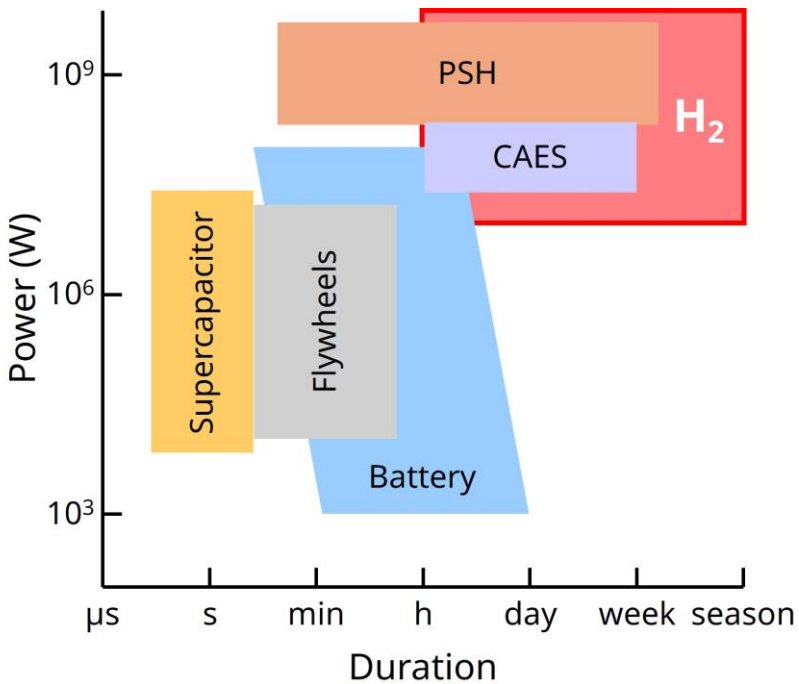


Nat. Comm., **12** (2021) 6146

Energy Storage System

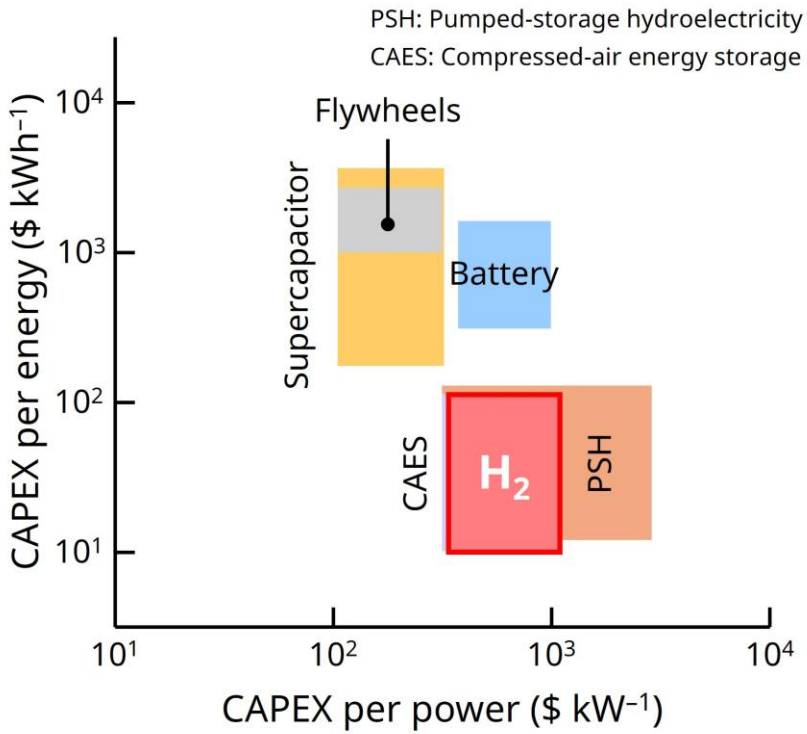
❑ Storage Capacity & Duration

- Long-duration storage
- High energy density in mass (120 MJ kg^{-1})



❑ Cost Effectiveness

- Low CAPEX per energy & power



<Source: IEA Technology Roadmap Hydrogen and Fuel Cells>

– H_2 has very high energy density in mass (120 (LHV) & 141.8 (HHV) MJ kg^{-1})

– H_2 can be transported in bulk and stored for long periods w/o degradation

Hydrogen Energy

❑ Renewable Energy

Energy derived from natural resources that are replenished on a human timescale

*Inexhaustible, Ubiquitous, Zero–CO_2 Emission

Solar | Wind | Hydropower | Biomass | Geothermal Heat

❑ Hydrogen Energy

Energy obtained as heat or power by combusting compounds that contain H or processing them through energy conversion systems

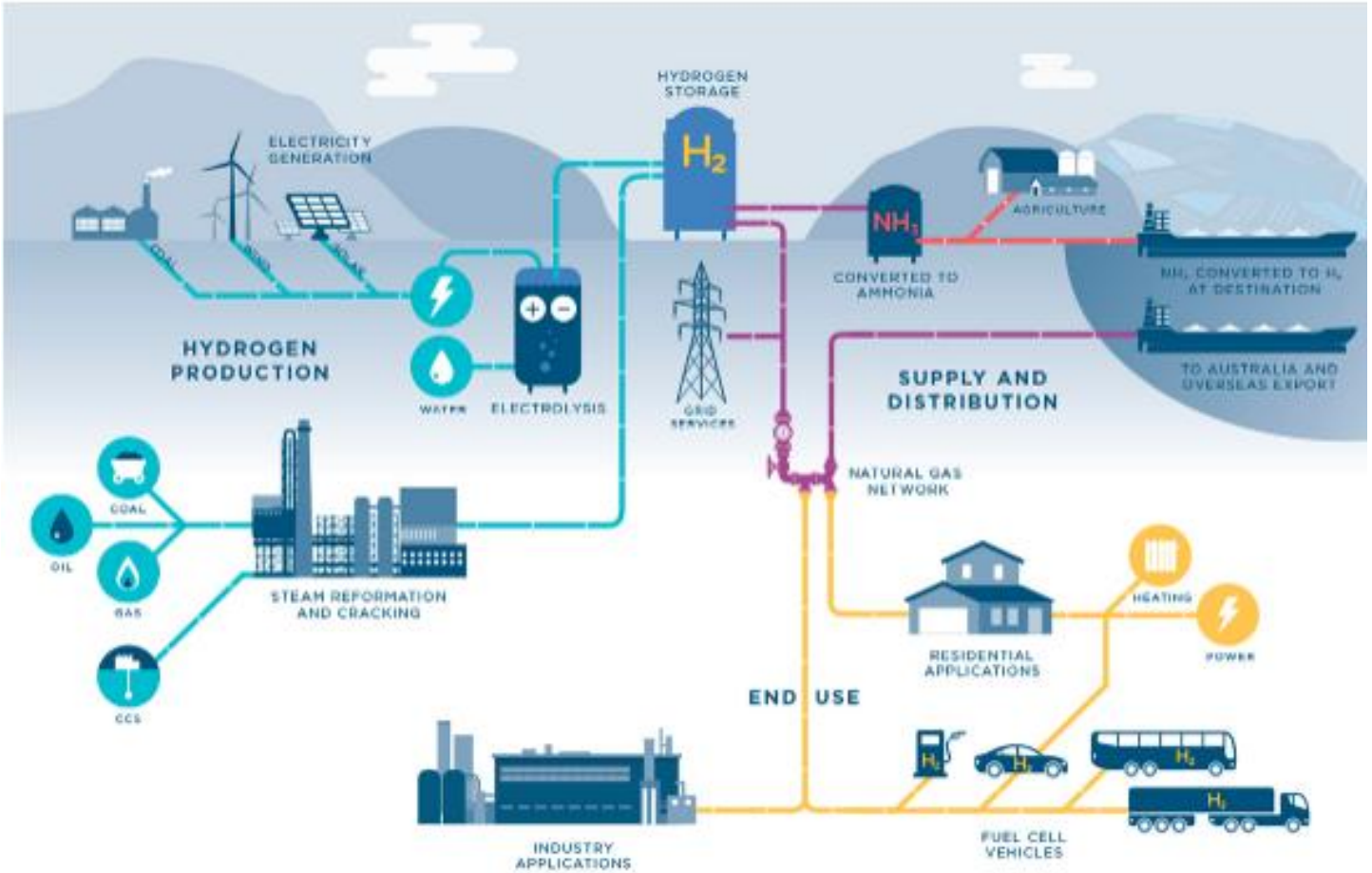
- Interoperability with Electricity
- Capability to Coupling with Renewable Energy

H_2 is highly interchangeable with electricity via fuel cells and electrolyzers. Thus, it enables full utilization and balancing of intermittent renewables.

Hydrogen Supply Chain

❑ Produce, store/transport, and use

Establishing, standardizing, and commercializing secure, low–cost technologies across these *three primary pillars* is essential for introducing a full hydrogen society



<Source: https://snurecl.com/>

Key Technological Objectives

❑ Produce, store/transport, and use

Establishing, standardizing, and commercializing secure, low–cost technologies across these *three primary pillars* is essential for introducing a full hydrogen society

PRODUCE

- Low cost
- Large scale
- Carbon-free production

STORE & TRANSPORT

- High density
- Loss free
- Safe contaminant

USE

- High efficiency
- Clean energy
- Safe energy

Key Technological Objectives

❑ Produce, store/transport, and use

Establishing, standardizing, and commercializing secure, low–cost technologies across these *three primary pillars* is essential for introducing a full hydrogen society

PRODUCE

- Low cost
- Large scale
- Carbon-free production

STORE & TRANSPORT

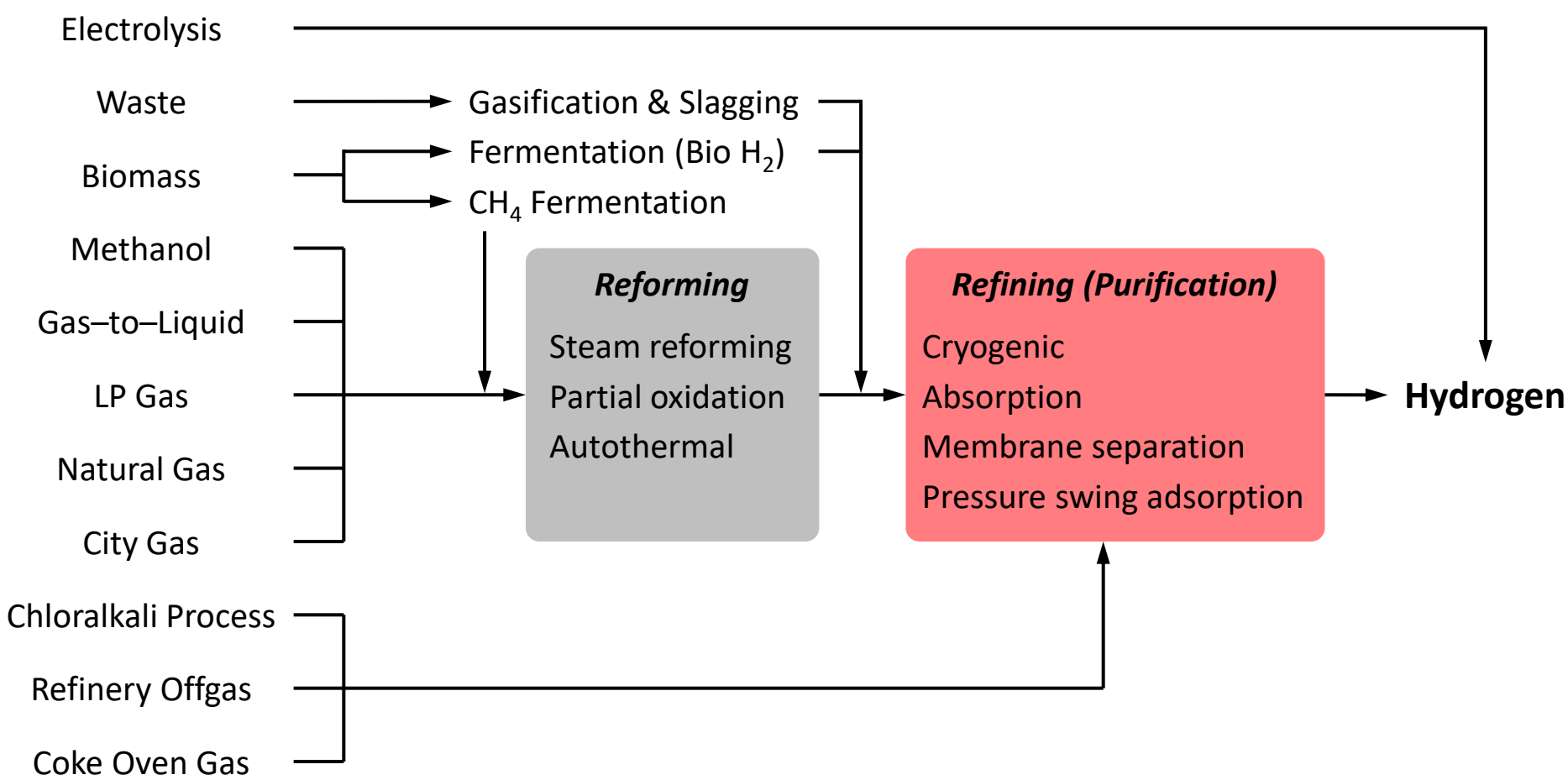
- High density
- Loss free
- Safe contaminant

USE

- Highly efficient device
- Clean energy

Hydrogen Production

❑ Various Production Methods



Global Hydrogen Production

❑ Grey, Blue, and Green Hydrogen

The world relies on fossil fuels (grey hydrogen), which account for ~98% of hydrogen production

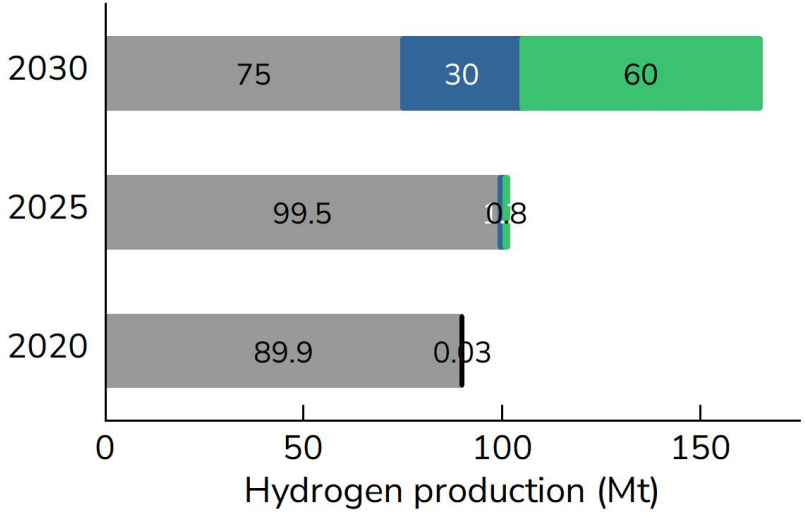
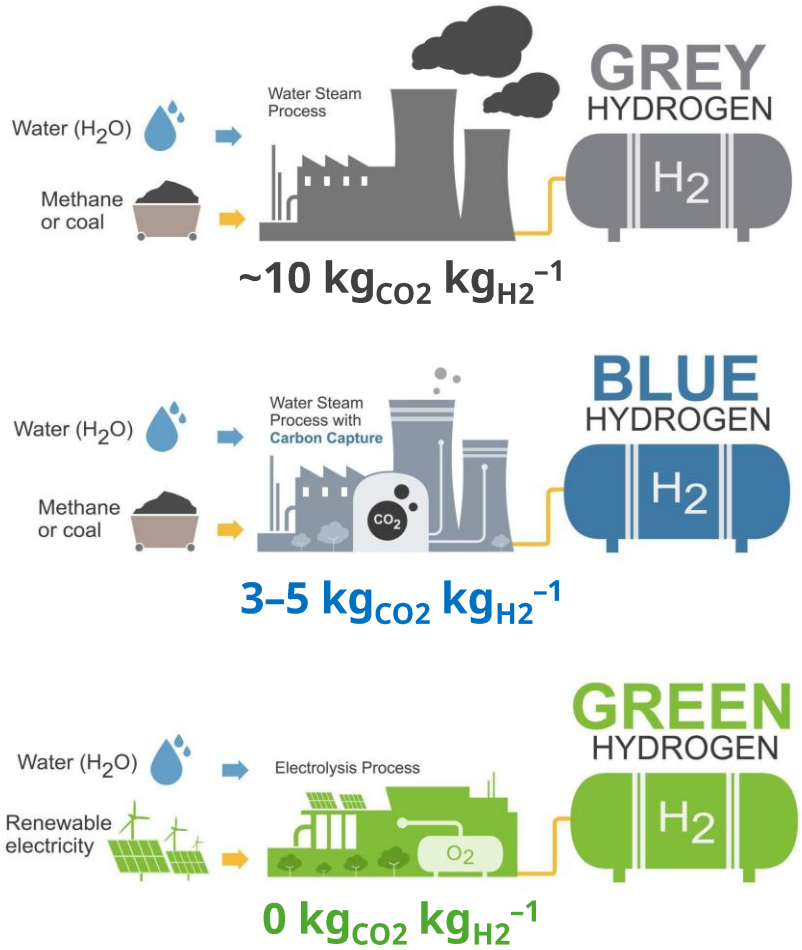


Table Levelized cost of hydrogen (USD kg^{-1})

	2020	**2025**	2030
Grey	1.0–2.5	**1.5–3.0**	1.5–3.2
Blue	1.5–3.0	**2.0–3.8**	1.8–3.5
Green	3.5–7.5	**4.5–8.5**	1.5–4.5

<Source: IEA (2025)>



Global Hydrogen Production

❑ Grey, Blue, and Green Hydrogen (2025)

The world relies on fossil fuels (grey hydrogen), which account for ~98% of hydrogen production

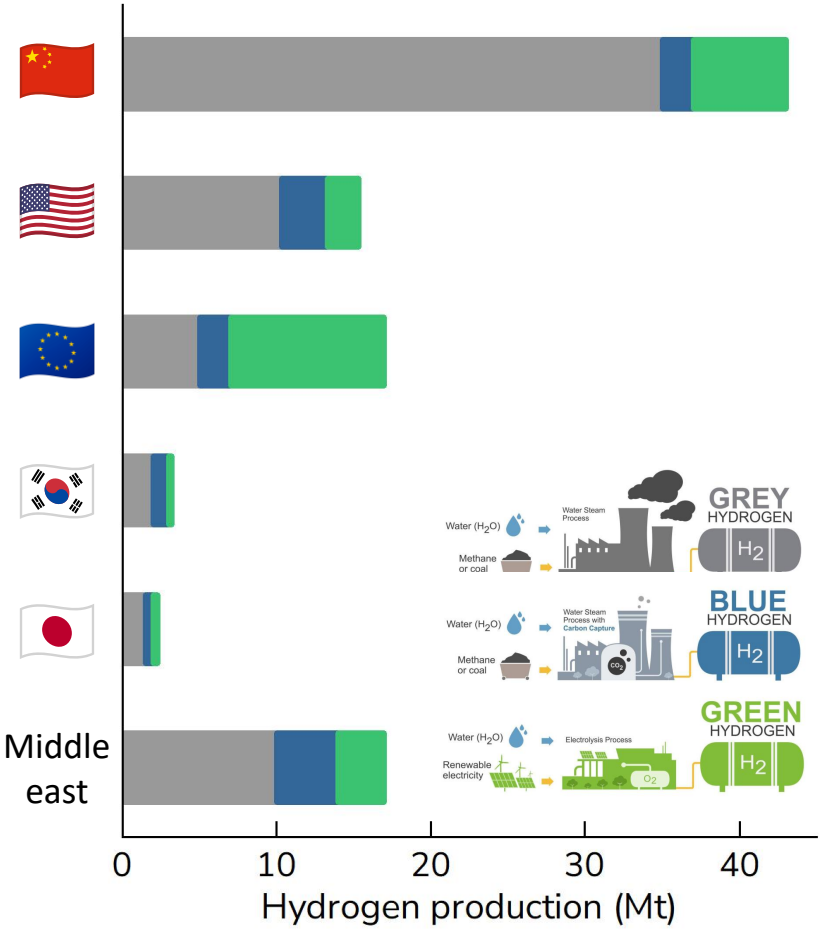
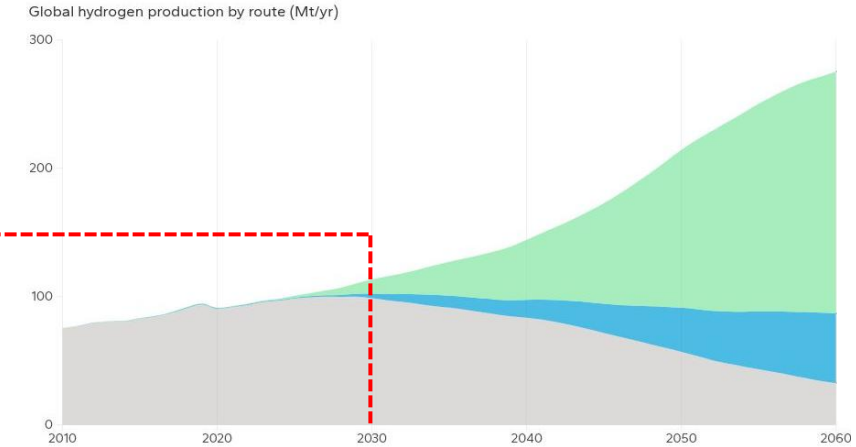
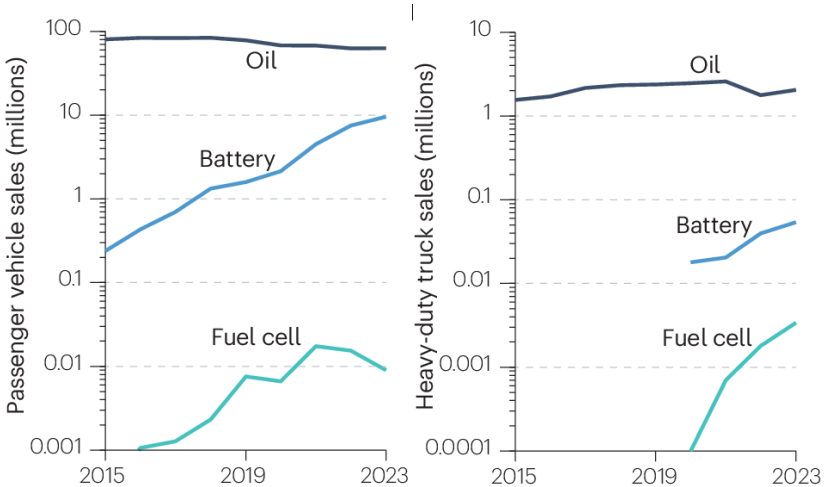


Fig. Hydrogen production prospects to 2030

<Source: IEA (2025)>



<Source: Energy Transition Outlook (2026)>



Nat. Rev. Clean Technol., **1** (2025) 351–371

Domestic Hydrogen Production

❑ Annual H_2 Production (2025)

Annual H_2 production in S. Korea reached ~2.2 Mt in 2025, >99% of which is grey hydrogen

기업		내용
HYUNDAI	현대차	수소전기차, 수소연료전지시스템 생산·판매
SK	SK	수소 밸류체인(생산·유통·소비) 구축, 수소충전소 운영
POSCO	포스코	수소 생산·판매
HYOSUNG	효성	수소 생산·유통, 수소충전소 운영
Hanwha	한화	수소 밸류체인 구축
DOOSAN	두산	수소연료전지 사업, 수소 생산·유통, 수소드론 판매
현대중공업	현대중공업	수소 밸류체인 구축
LOTTE	롯데	수소 생산·판매, 수소충전소 설치, 수소저장탱크 사업
GS	GS	수소 공급, 수소연료전지발전 구축
KOLON	코오롱	수소차 연료전지부품 생산·판매

- Byproduct (62.3%, ~1.4 Mt)
- Steam reforming (36.4%, ~0.80 Mt)
- Low- and/or zero-carbon (0.91%, ~0.020 Mt)

Domestic Hydrogen Production

❑ Byproduct Hydrogen

Oil Refinery in Ulsan

- 3rd largest in the world
- Ownership: SK Energy
- Capacity: 40.2 Mt yr^{-1} & 850,000 bpd
  *1 barrel = 159 L
- Products: LPG, Gasoline, Diesel, Jet fuel, Asphalt

Oil Refinery in Yeosu

- 5th largest in the world
- Ownership: GS Caltex (50% GS Holdings + 50% Chevron)
- Capacity: 730,000 bpd
- Products: Heavy Oil Upgrade (Gasoline, Kerosene, Naphtha)

– Large-scale refining & reforming processes generate abundant byproduct hydrogen

Domestic Hydrogen Production

❑ Steam Methane Reforming (SMR)

SMR Plant in Pyeongtaek

- Largest scale in Korea
- Ownership: KOGAS, HyNet, etc.
- Capacity: 2,550 t yr^{-1} (7 t day^{-1})
- Products: High-purity compressed H_2 for mobility, Tube trailers

SMR Plant in Changwon

- 1st commercial liquefied hydrogen plant
- Ownership: Doosan Enerbility, etc.
- Capacity: 1,800 t yr^{-1} (5 t day^{-1})
- Products: Liquefied Hydrogen, High-purity gas for buses, power generation

– NG-based SMR plants supply dedicated reformed H_2 for urban and regional mobility

Domestic Hydrogen Production

❑ Water Electrolysis

Water Electrolysis Plant in Jeju

- Largest facility in Korea (12.5 MW)
- Ownership: Korea Southern Power, etc.
- Capacity: 1,176 t yr^{-1} (up to ~250 kg h^{-1})
- Products: High-purity H_2 for FCVs, buses, and tube trailers

Water Electrolysis Plant in Buan

- Commercial MW-scale water electrolysis demonstration plant (2.5 MW)
- Ownership: Hyundai E&C, etc.
- Capacity: 365 t yr^{-1} (1 t day^{-1})
- Products: Green H_2 for local mobility, regional storage & distribution

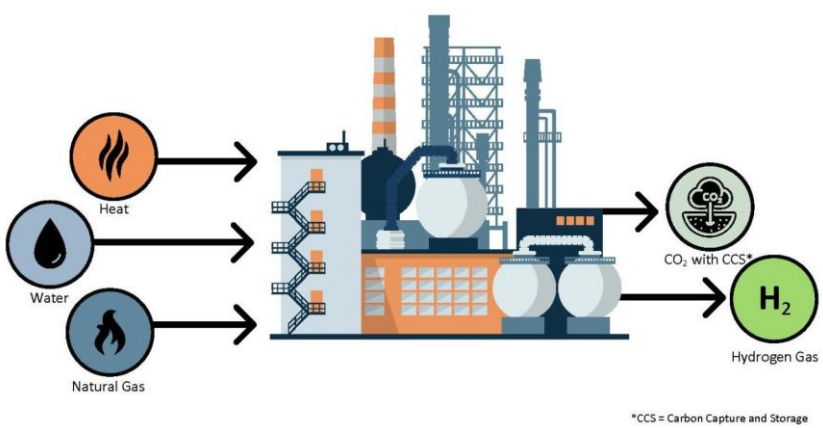
– Renewable-based water electrolysis plants supply zero-carbon green H_2 for public transport and carbon neutrality demonstration

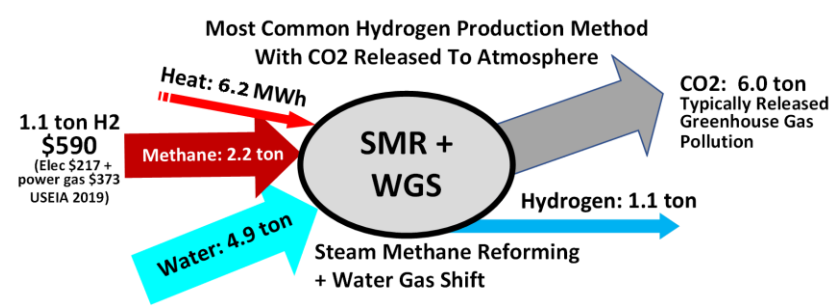
Reformed Hydrogen

❑ Steam Methane Reforming (SMR)

A method for producing syngas (H_2+CO) by reaction of hydrocarbon (e.g., NG) and water

- SMR is dominant method and accounts for ~60–75% of global hydrogen production
- $CH_4 + H_2O \rightarrow CO + 3H_2$ ($\Delta H° = 206.1$ kJ mol^{-1})
- CH_4 reacts with H_2O at high temperatures (700–1000 °C) & high pressures (3–25 bar)
- Then, water–gas shift reaction occurs (WGS) ($CO + H_2O \rightarrow CO_2 + H_2$ ($\Delta H° = -41.2$ kJ mol^{-1}))
- **Direct steam reforming** $CH_4 + 2H_2O \rightarrow CO_2 + 4H_2$ ($\Delta H° = 164.9$ kJ mol^{-1})





<Source: https://www.energy.gov/media/292851>

<Source: https://en.wikipedia.org/wiki/Steam_reforming>

Reformed Hydrogen

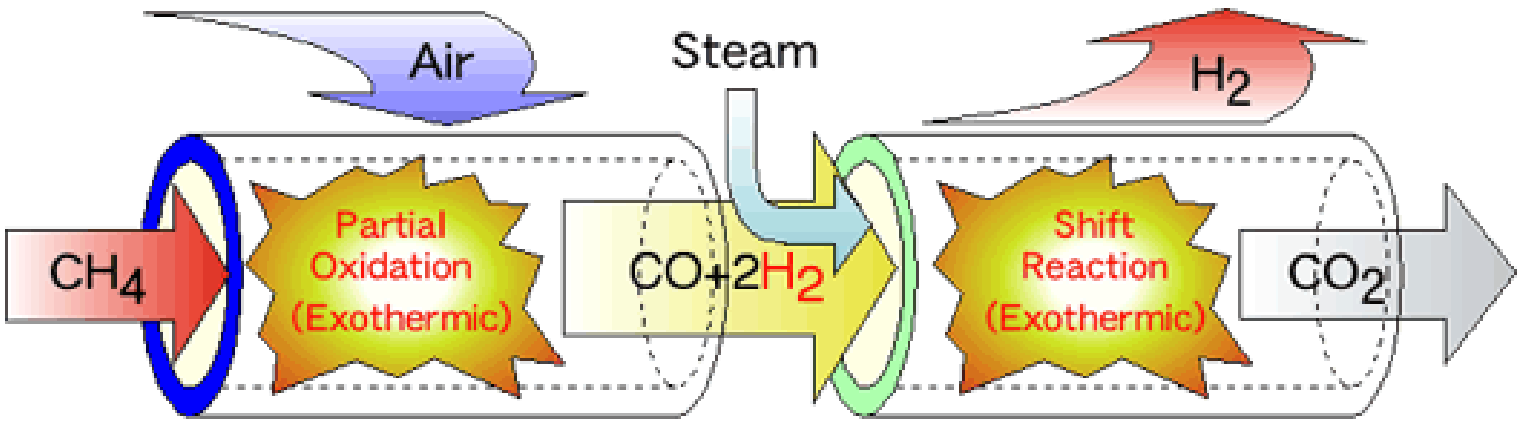
❑ Partial Oxidation (POX)

POX occurs when a substoichiometric fuel–air mixture is partially combusted in a reformer

- $C_nH_m + 0.5nO_2 \rightarrow nCO + 0.5mH_2$ ($\Delta H°_{POX} < 0$)

  (e.g., partial oxidation of methane: $CH_4 + 0.5O_2 \rightarrow CO + 2H_2$ ($\Delta H°_{POX} = -35.7$ kJ mol^{-1}))

  (cf., complete oxidation of methane: $CH_4 + 2O_2 \rightarrow CO_2 + H_2O$ ($\Delta H°_{COX} = -891$ kJ mol^{-1}))
- Subsequently, water–gas shift reaction occurs ($CO + H_2O \rightarrow CO_2 + H_2$ ($\Delta H°_{WGS} = -41.2$ kJ mol^{-1}))
- POX is much faster than SMR and requires a smaller reactor vessel



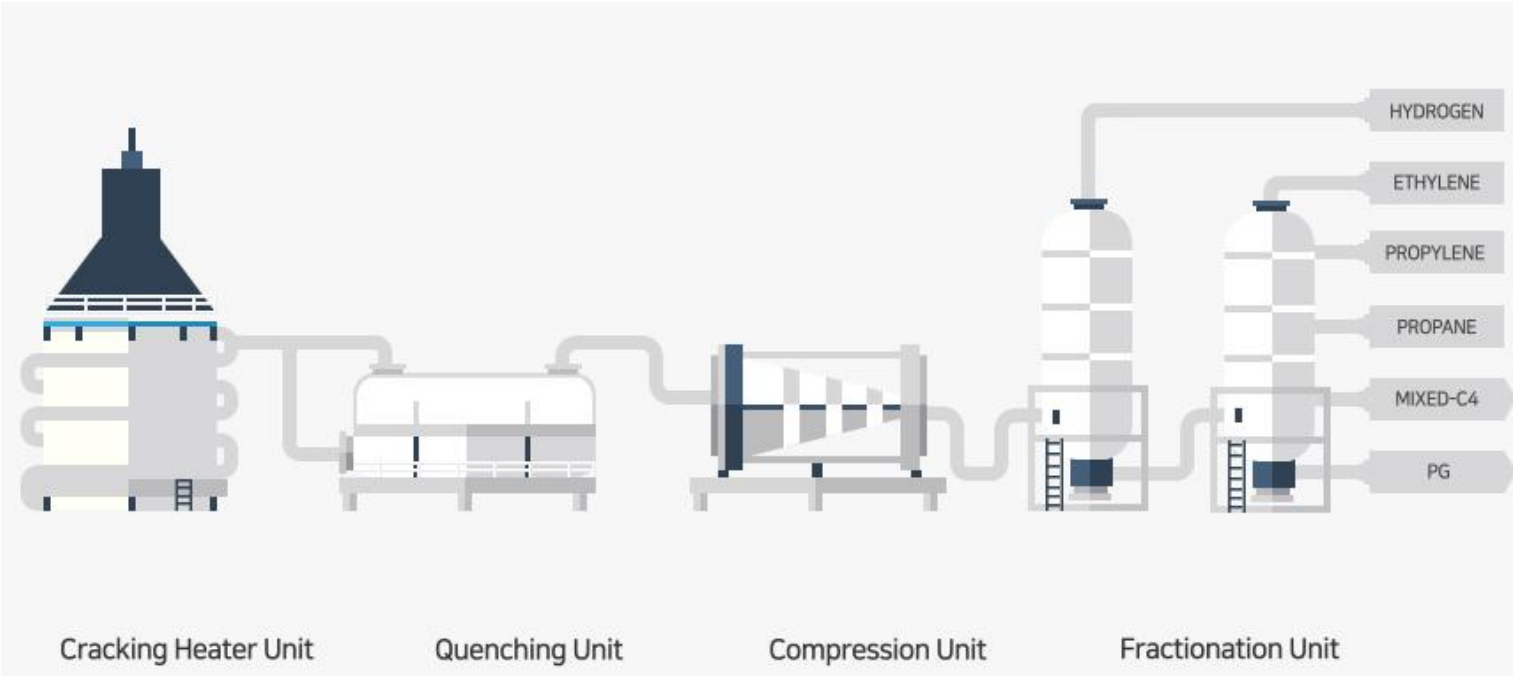
<Source: https://ceram.material.tohoku.ac.jp/~takamura/research_opm_e.html>

Byproduct Hydrogen

❑ Hydrocarbon Steam Cracking

Pyrolysis of hydrocarbons (naphtha, ethane, LPG, gas oil, etc.) produces byproduct hydrogen along with basic petrochemicals (ethylene, propylene, propane, etc.), followed by purification using deep cryogenic distillation (boiling point differences).

- **Internal**: Fuel for cracking furnaces, selective hydrogenation of alkynes
  *$C_2H_2 + H_2 \rightarrow C_2H_4$ (Ethylene)
- **External**: Hydrodesulfurization in oil refineries, industrial fuel, or chemical reduction processes
  **$Fe_2O_3 + 3H_2 \rightarrow 2Fe + 3H_2O$



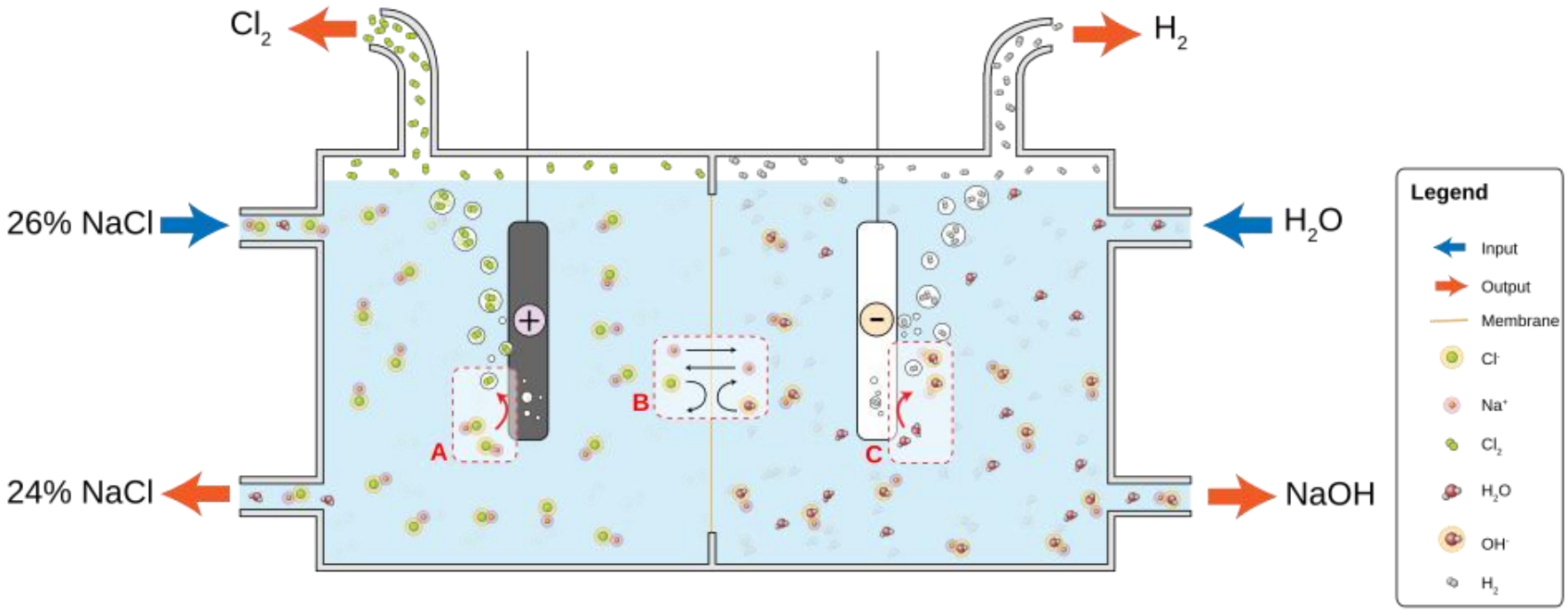
<Source: https://www.yncc.co.kr/en/product/factory/3/ethylene.do>

Byproduct Hydrogen

❑ Chloralkali Process

Electrolysis of sodium chloride (NaCl) solutions (e.g., brine (high-conc. solution of salt in water))

- $2NaCl + H_2O \rightarrow Cl_2 + H_2 + 2NaOH$
- 97 Mt of Cl_2 were prepared in 2022 (35 Mt in 1987)
- To produce 1 t of NaOH, 2500 kWh of electricity is used with ~25 kg of H_2 as a byproduct



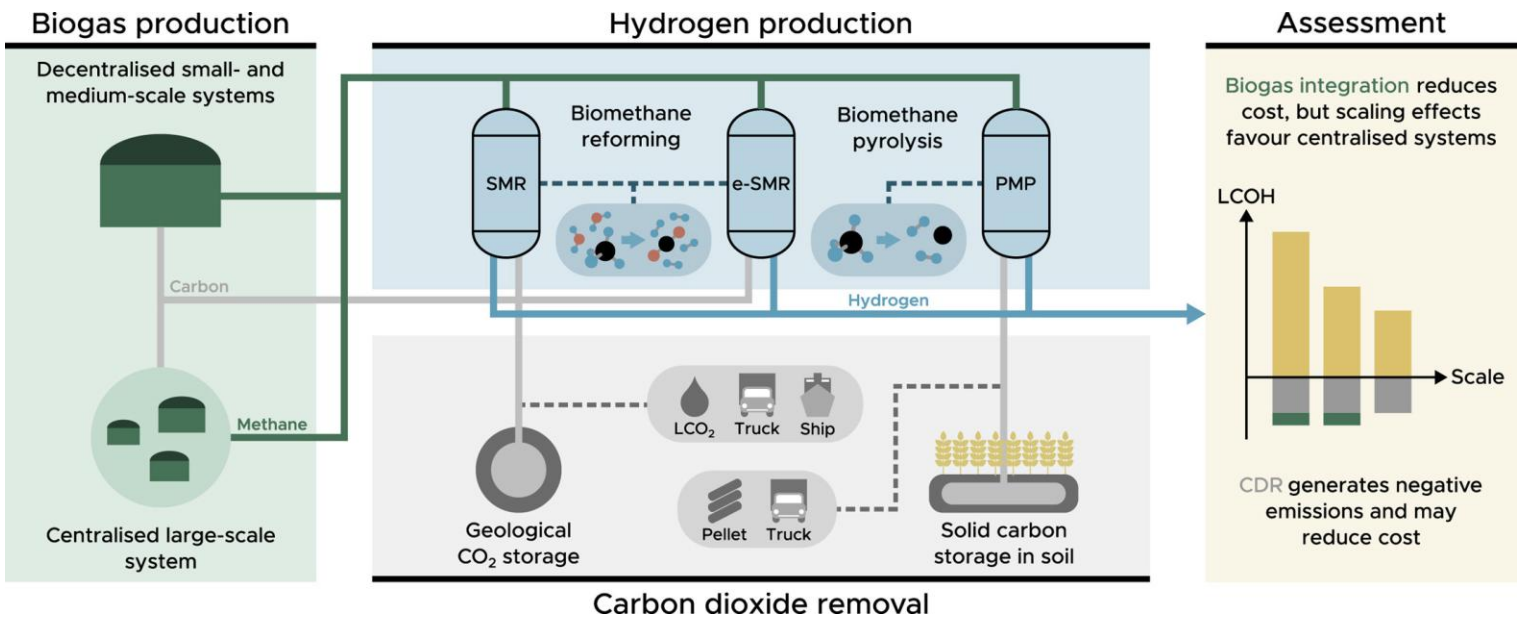
<Source: https://en.wikipedia.org/wiki/Chloralkali_process>

Biohydrogen

❑ Thermochemical Process (Biogas Reforming)

Obtained by reforming biogas, which is a mixture produced by microorganisms decomposing organic waste under anaerobic conditions (oxygen-free conditions)

- Upgrades raw biogas to high-purity CH_4 first by removing CO_2 and impurities, followed by SMR
- Emits CO_2 during the reforming step, requiring CCUS integration for zero-carbon certification
- e.g., Hyundai Motor, Hanwha E&C



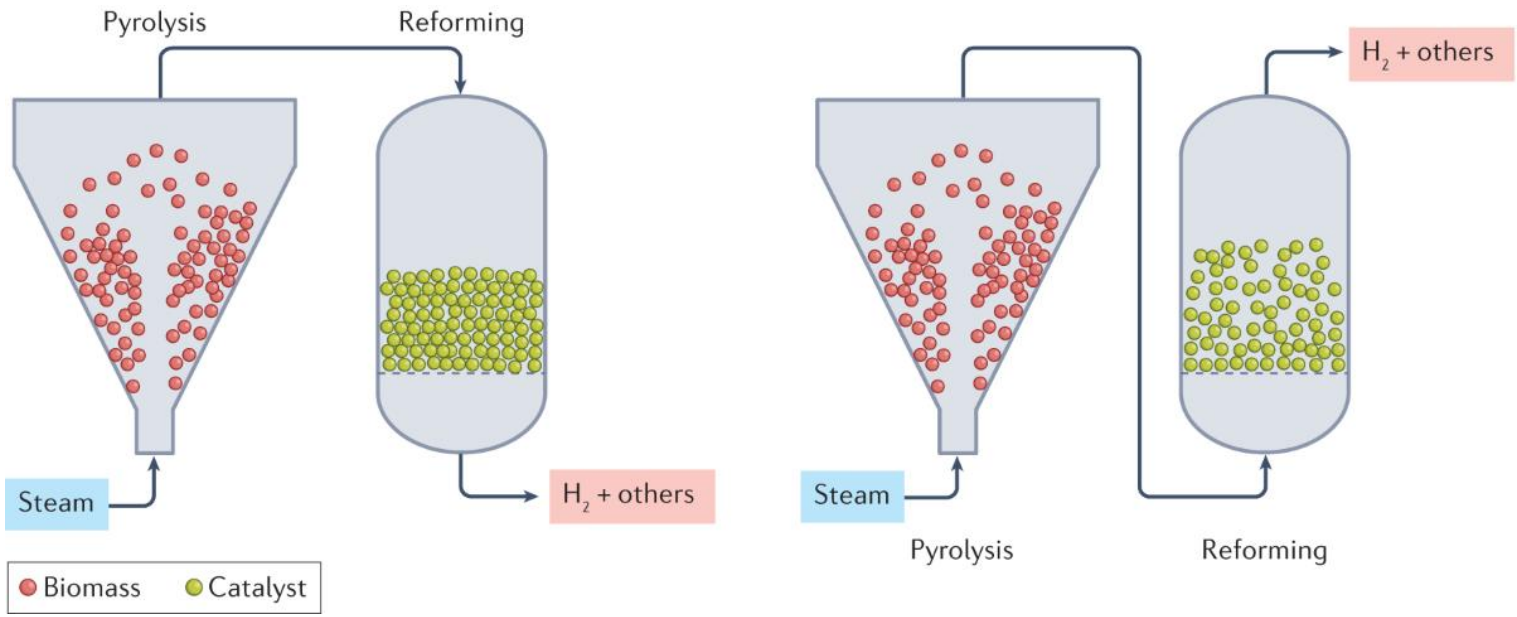
Int. J. Hydrogen Energy, **258** (2026) 156625

Biohydrogen

❑ Thermochemical Process (Biomass Gasification)

A technology pathway that uses a controlled process involving heat, steam, and oxygen to convert biomass to hydrogen and other products at high temperature (>700 °C), without combustion

- (Step 1) Pyrolysis of biomass to volatiles
- (Step 2) $C_nH_mO_k + (n–k)H_2O \rightarrow nCO + (n+0.5m–k)H_2$
- Subsequently, water–gas shift reaction occurs ($CO + H_2O \rightarrow CO_2 + H_2$ ($\Delta H° = –41.2$ kJ mol^{-1}))



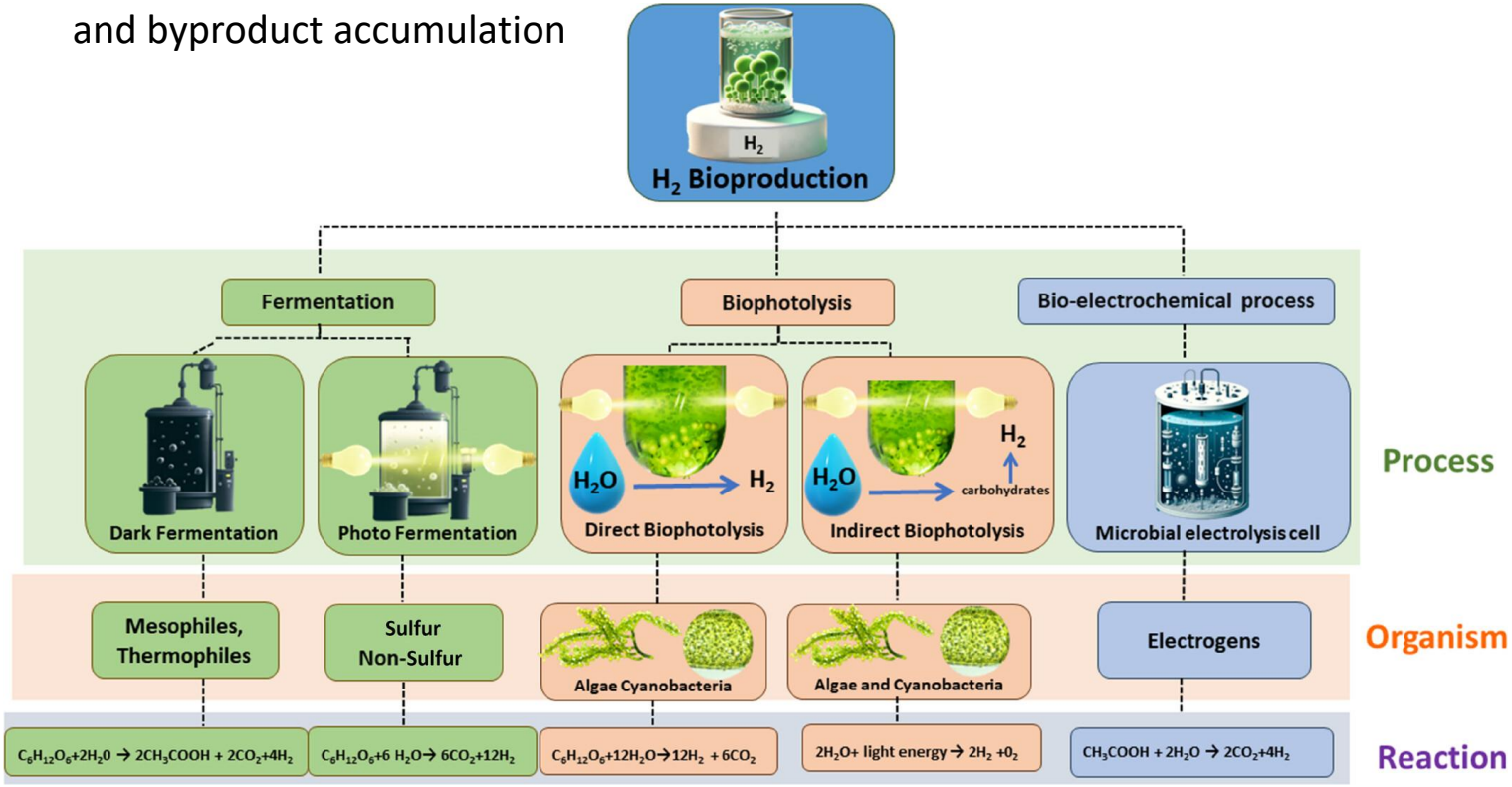
Nat. Rev. Methods Primers, **2** (2022) 20

Biohydrogen

❑ Biological Process

Biologically produced H_2 using microorganisms or biological catalysts (bacteria, microalgae, enzymes)

- Utilizes renewable organic waste and biomass at low temperatures/pressures, enabling a zero/carbon-negative footprint
- Low conversion eff. and slow production speeds due to limited thermodynamic boundaries and byproduct accumulation



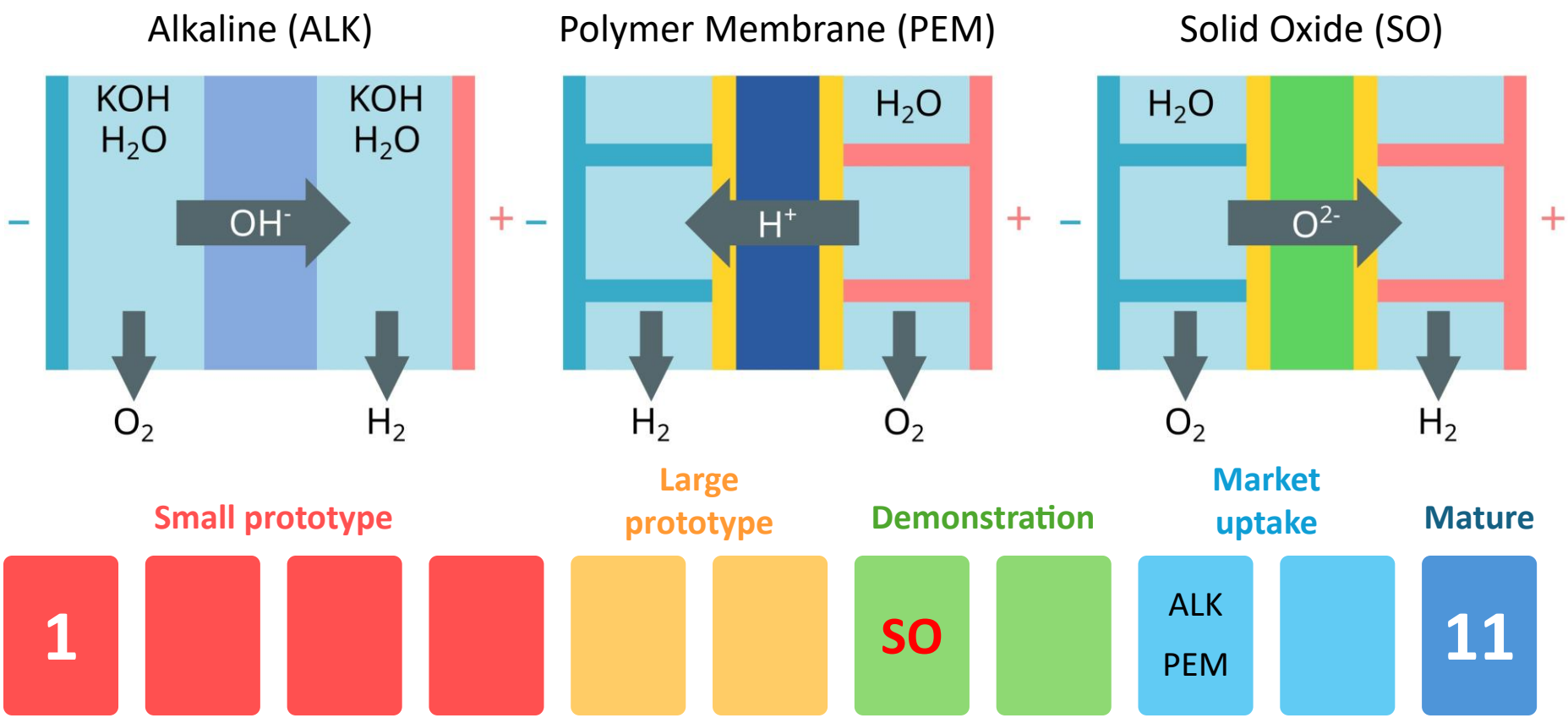
Wiley Interdiscip. Rev.: Energy Environ., **13**(3) (2024) e526

Electrolysis Hydrogen

❑ Water (Steam) Electrolysis

A process of using direct electric current to split water into hydrogen and oxygen

- H_2O(l or g) → H_2(g) + 0.5O_2(g)



<Source: IEA Electrolyser>

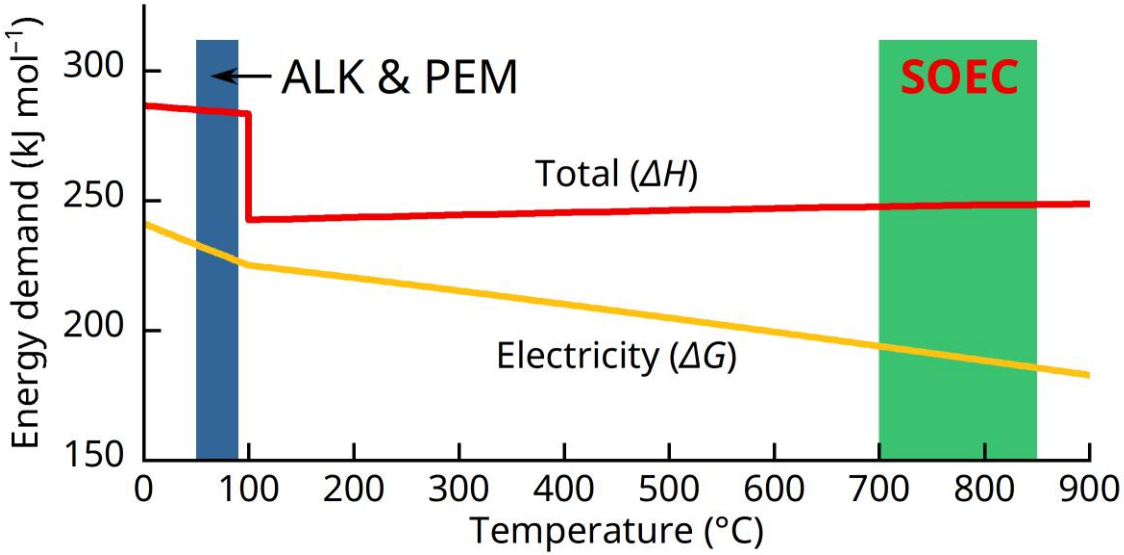
Electrolysis Hydrogen

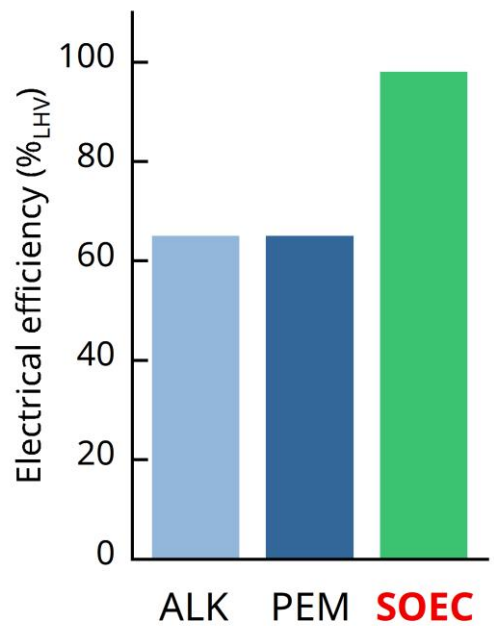
❑ Water (Steam) Electrolysis

A process of using direct electric current to split water into hydrogen and oxygen

Efficiency Low ⟷ High

Kinetics Slow ⟷ Fast





Small prototype				Large prototype		Demonstration		Market uptake		Mature
1						SO		ALK PEM		11

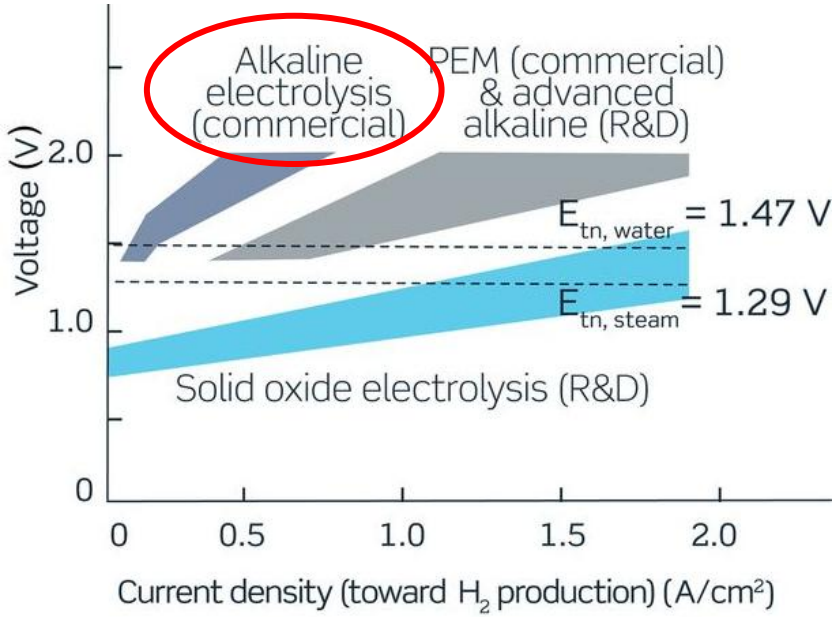
<Source: IEA Electrolyser>

Electrolysis Hydrogen

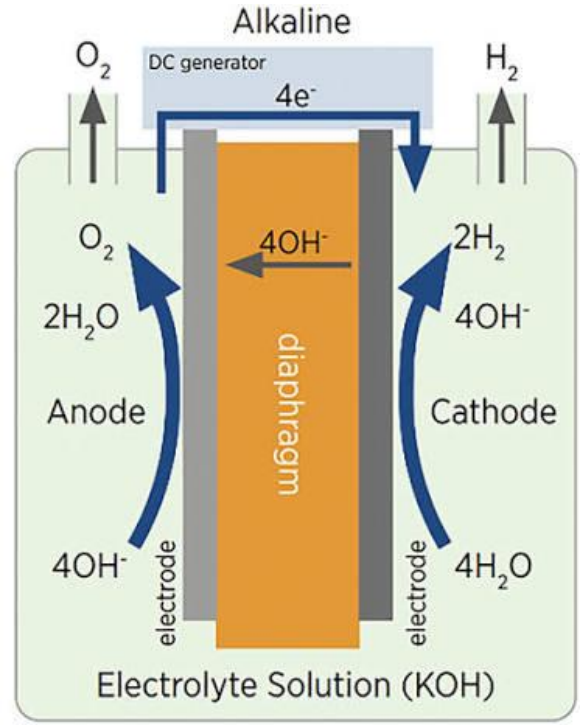
❑ Alkaline Water Electrolysis

Characterized by having two electrodes operating in *a liquid alkaline electrolyte*, where a 25–40 wt% KOH or NaOH solution is used

- A highly reliable, mature electrolysis technology with a technology readiness level (TRL) of 9
- High power consumption
- Necessity of corrosion-resistant electrodes (e.g., Ni-based alloy)
- Periodic replenishment of electrolyte



Science, **370**(6513) (2020) aba6118



Anode: $4OH^- \leftrightarrow 2H_2O+O_2+4e^-$

Cathode: $4H_2O+4e^- \leftrightarrow 2H_2+4OH^-$

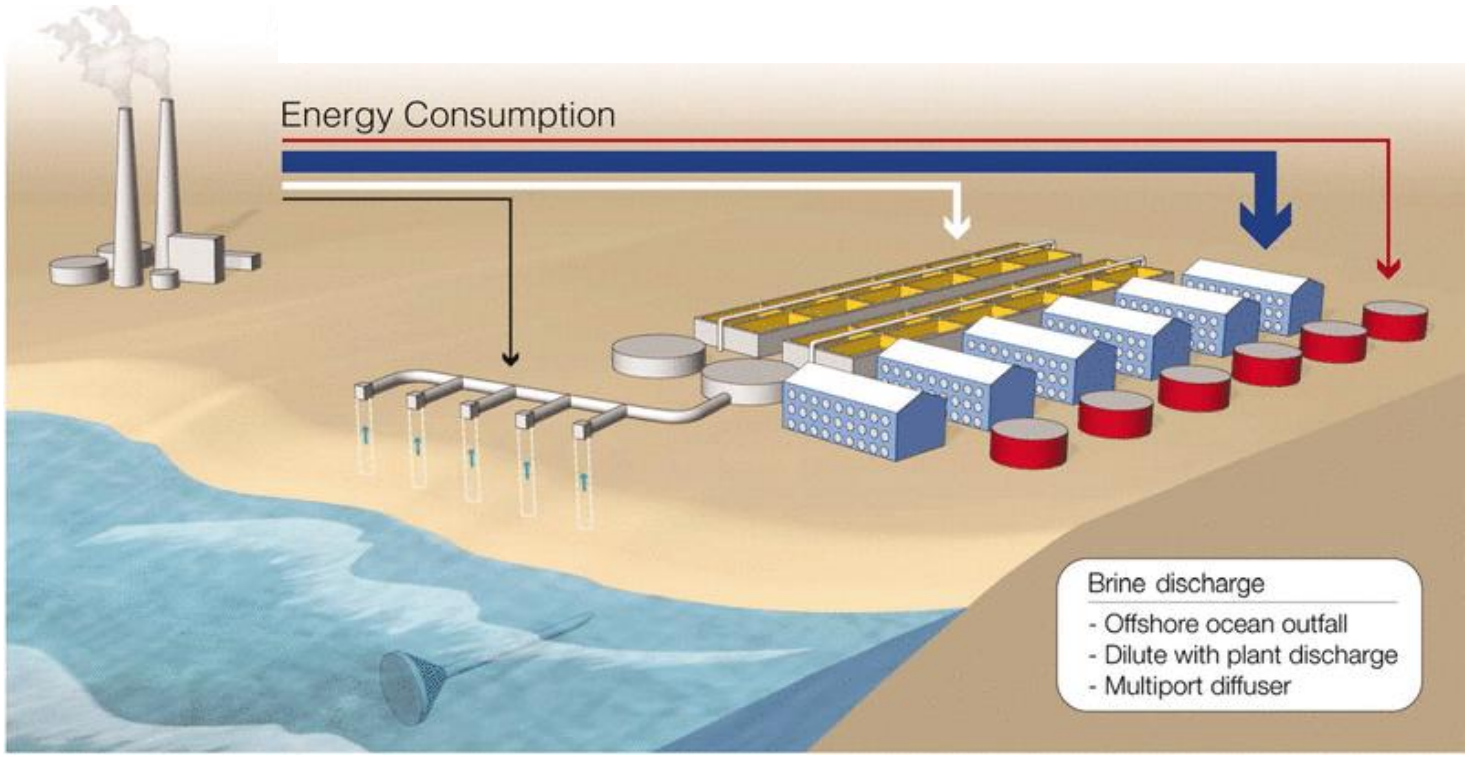
<Source: IRENA>

Electrolysis Hydrogen

❑ Alkaline Water Electrolysis

Significant interest in direct seawater electrolysis (saline water electrolysis) using ALKs

- Annually 4.43 Gt (=~12 Mt per day) of H_2O is required to produce 492 Mt of H_2 (2050 target)
- Abundant seawater (~97%) vs. extremely scarce high-purity freshwater (<1% of total 13.9 Gt)



Science., **333**(6043) (2011) 712–717

Electrolysis Hydrogen

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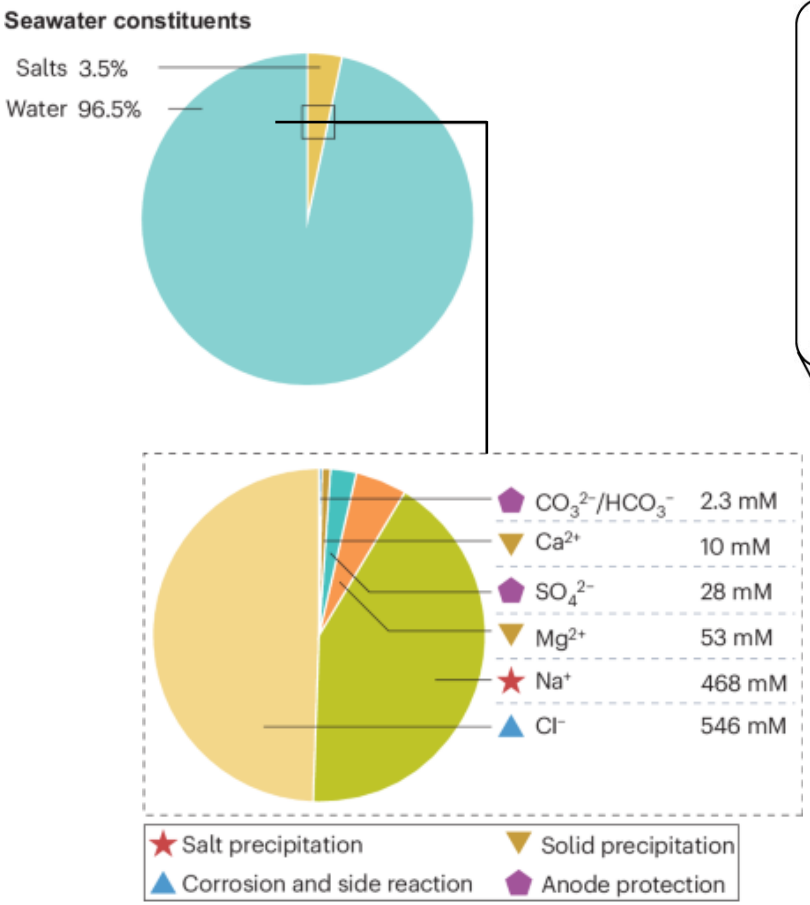
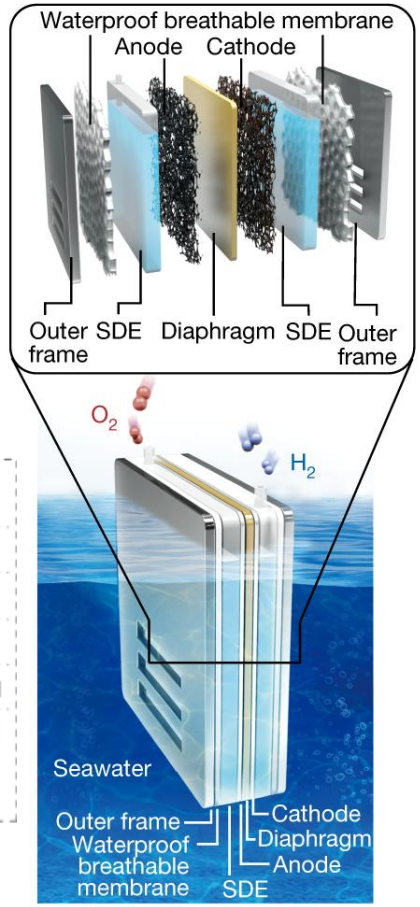
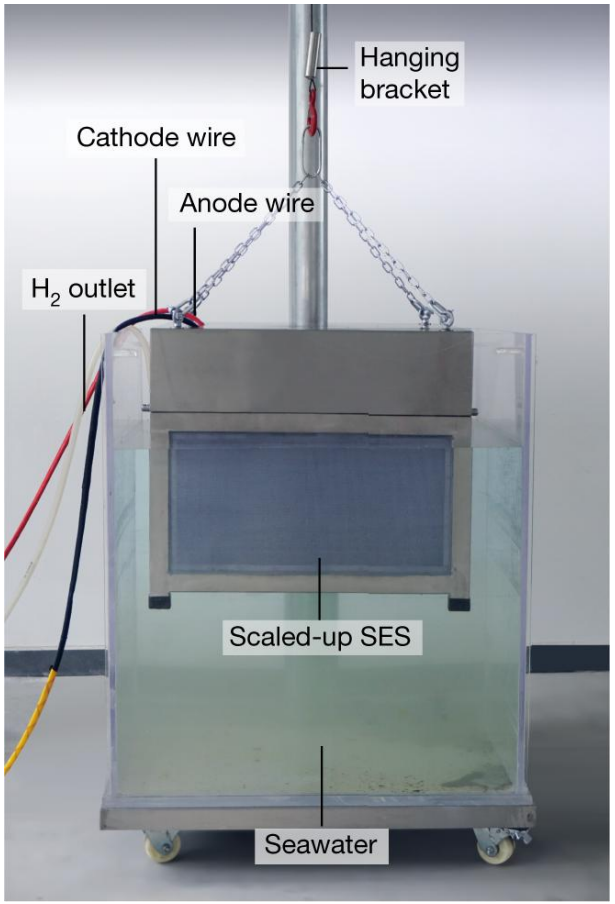


Nat. Rev. Mater., **10** (2025) 857–873



Nature, **612** (2022) 673–678

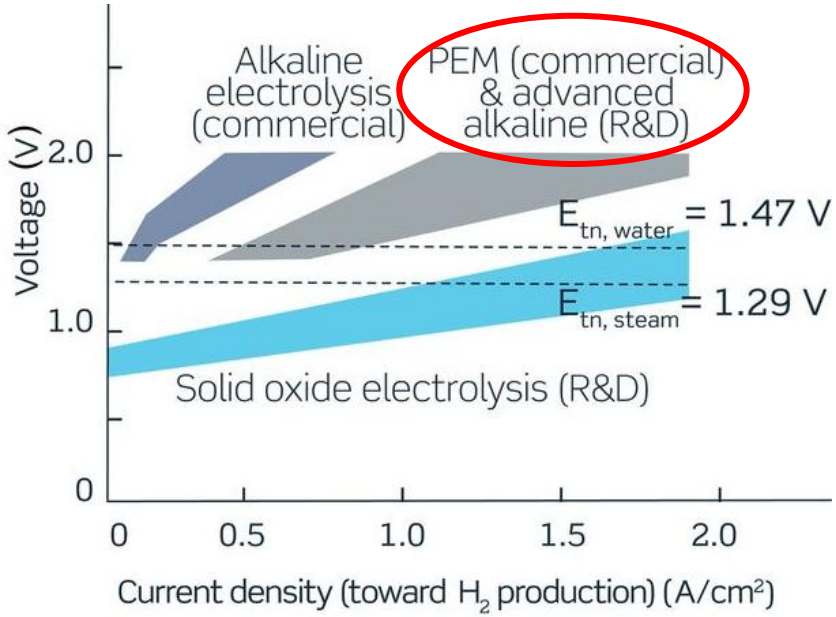


Electrolysis Hydrogen

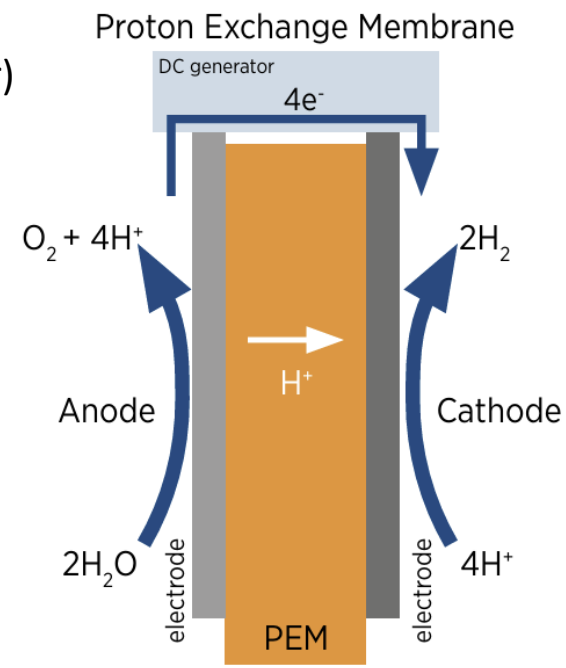
❑ Proton Exchange Membrane Water Electrolysis

Uses *a solid polymer electrolyte* to split pure H_2O into H_2 and O_2 using electricity

- A highly reliable, mature electrolysis technology with a technology readiness level (TRL) of 9
- Polymer membrane serving for ion exchange and stable electrolyte
- Simple, noncorrosive cell structure
- Highly dependent on a noble metal catalyst (e.g., Ir)



Science, **370**(6513) (2020) aba6118



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

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

<Source: IRENA>

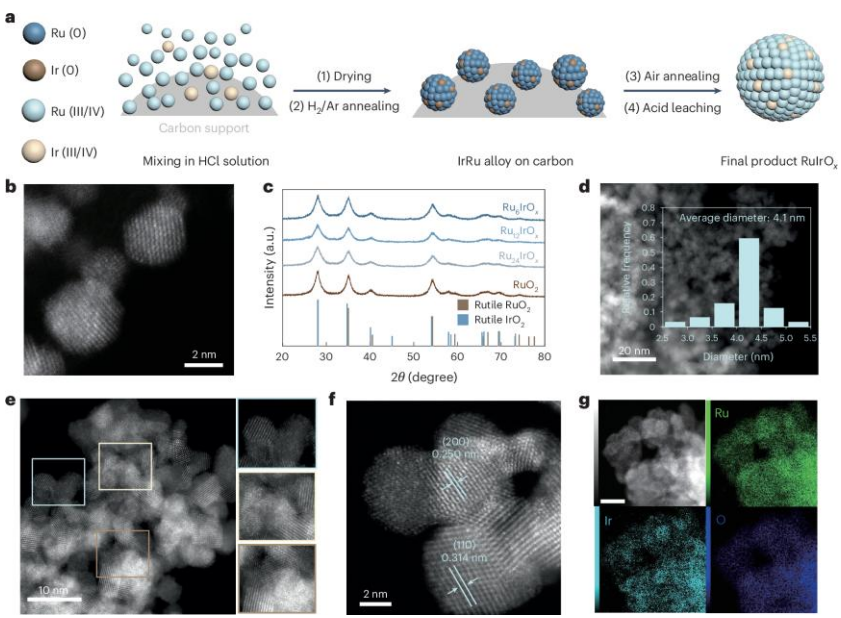
Electrolysis Hydrogen

❑ Proton Exchange Membrane Water Electrolysis

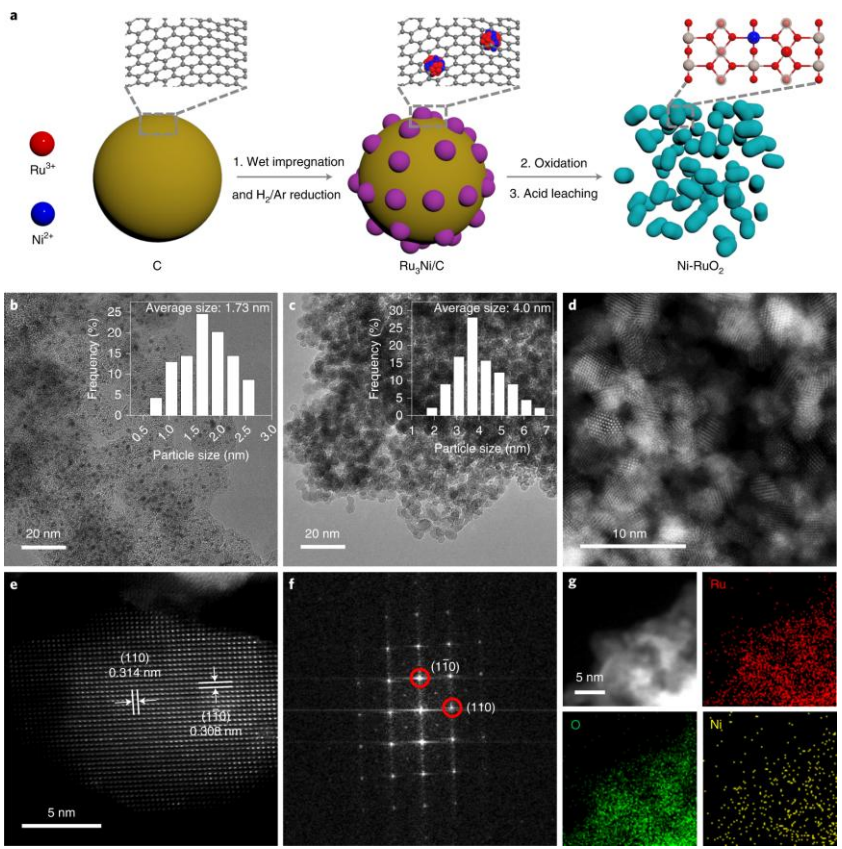
Significant interest in reducing dependence on expensive *iridium catalysts*

Table Prices of noble metals as of 2025 ($ kg^{-1})

Ir	**144,000**	Ru	10,400
Au	75,430	Rh	147,000
Pt	27,800	Pd	49,500



Nat. Nanotechnol., **20** (2025) 1787–1795



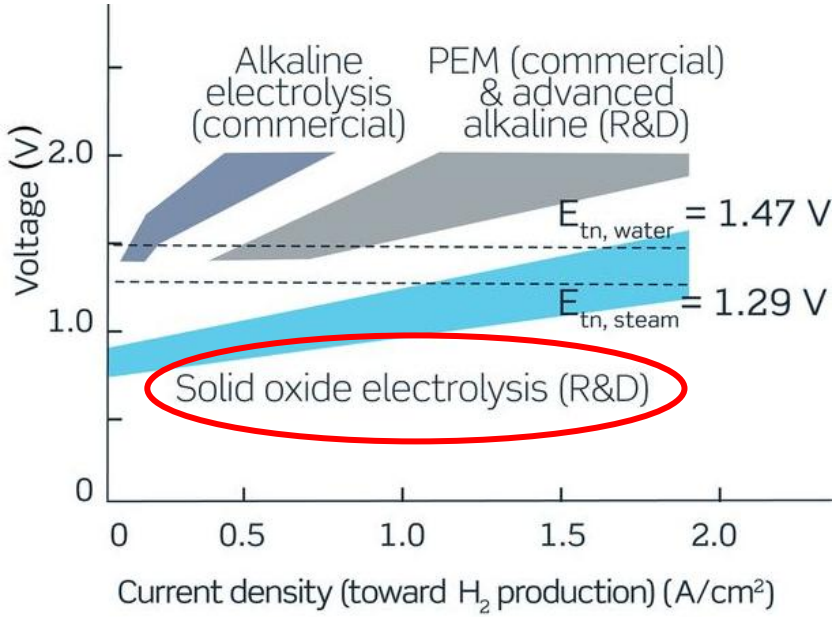
Nat. Mater., **22** (2023) 100–108

Electrolysis Hydrogen

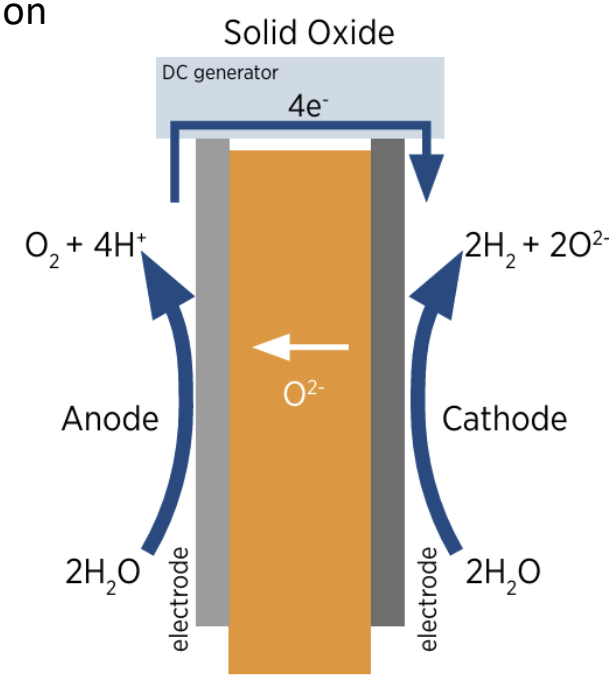
❑ Solid Oxide Electrolysis

Uses *a solid oxide, or ceramic, electrolyte* to produce H_2 gas (and/or CO) and O_2

- Highly efficient device due to high-temperature operation (>600 °C)
- Enables producing high-purity hydrogen
- Low competitiveness due to massive H_2 consumption



Science, **370**(6513) (2020) aba6118



Anode: $2O^{2-} \leftrightarrow O_2 + 4e^-$

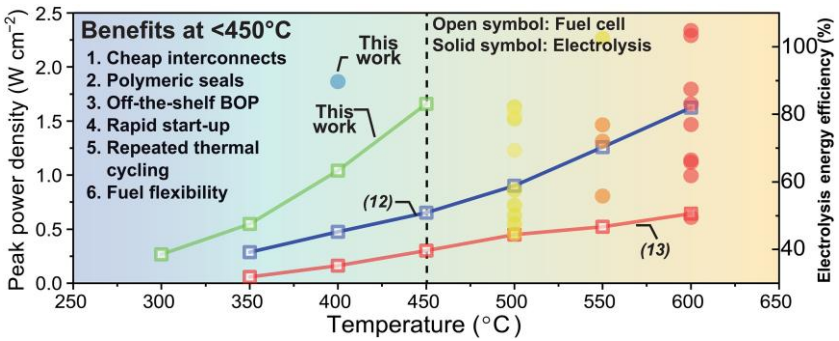
Cathode: $2H_2O + 4e^- \leftrightarrow 2H_2 + 2O^{2-}$

<Source: IRENA>

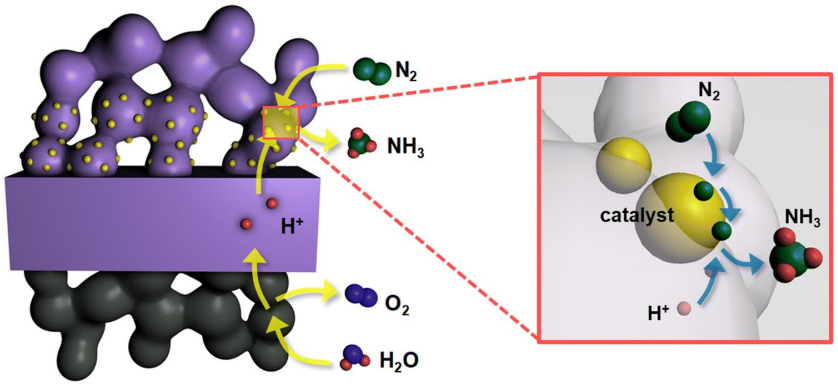
Electrolysis Hydrogen

❑ Solid Oxide Electrolysis

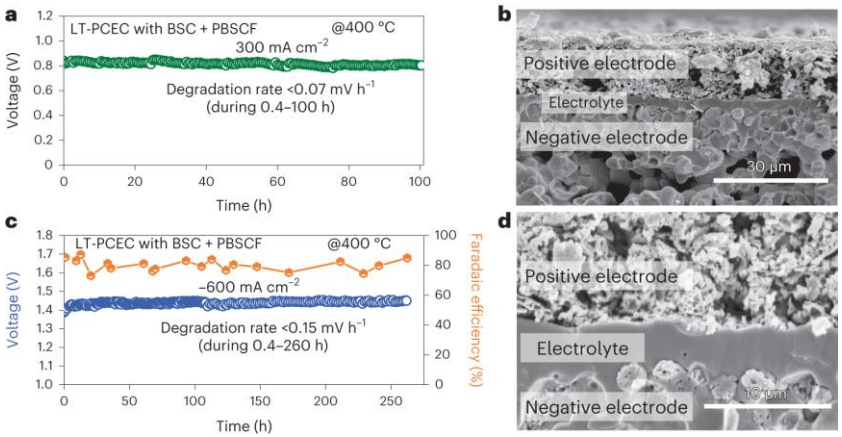
Significant focus on *lowering operating temp.* and *producing value-added chemicals* (CH_4, NH_3, etc.)



Sci. Adv., **11**(2) (2025) adq2507

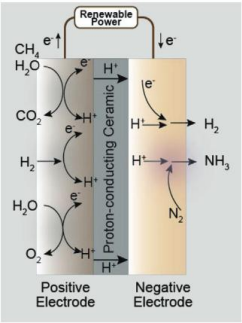


J. Korean Ceram. Soc., **57** (2020) 480–494

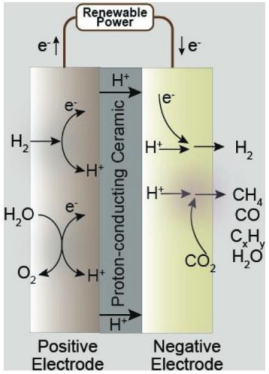


Nat. Energy, **8** (2023) 1145–1157

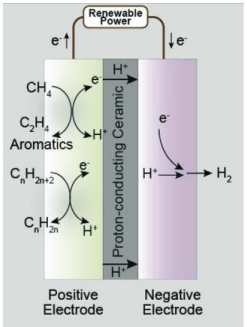
NH_3 synthesis



CO_2 reduction



C_mH_n conversion



Adv. Sci., **10** (2023) 2206478

Electrolysis Hydrogen

❑ Comparison of Electrolysis Technology

	ALK	PEM	SO
Operating temp. (°C)	70–90	50–80	**700–850**
Operating pressure (bar)	1–30	<70	**1**
Electrolyte	5–7 mol L^{-1} KOH	PFSA membrane	**Y_2O_3-stabilized ZrO_2 (YSZ)**
Separator	ZrO_2 stabilized with PPS mesh	Solid electrolyte (above)	**Solid electrolyte (above)**
Oxygen electrode	Ni-coated perforated stainless steel	IrO_2	**Perovskite oxide (e.g., LSCF, LSM)**
Hydrogen electrode	(above)	Pt/C	**Ni–YSZ**
Porous transport layer (Anode)	Ni mesh	Pt-coated sintered porous Ti	**Ni mesh**
Porous transport layer (Cathode)	Ni mesh	Sintered porous Ti or C cloth	**–**
Bipolar plate (Anode)	Ni-coated stainless steel	Pt-coated Ti	**–**
Bipolar plate (Cathode)	Ni-coated stainless steel	Au-coated Ti	**Co-coated stainless steel**
Frames and Sealing	PSU, PTFE, EPDM	PTFE, PSU, ETFE	**Ceramic glass**

<Source: IRENA>

Electrolysis Hydrogen

❑ Comparison of Electrolysis Technology (Today vs. 2050)

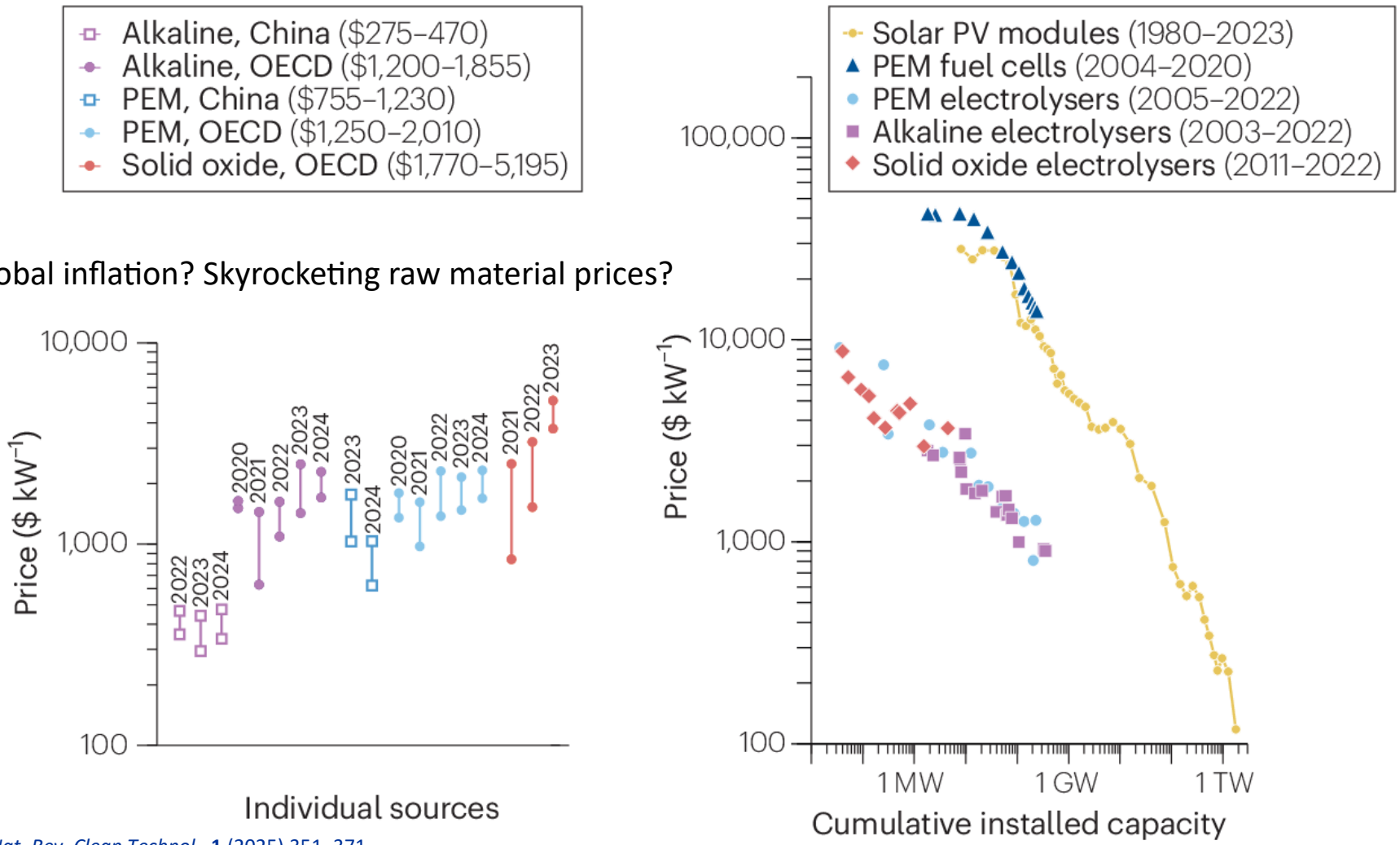
	2020			2050		
	ALK	PEM	**SOEC**	ALK	PEM	**SOEC**
Nominal current density (A cm^{-2})	0.2–0.8	1–2	**0.3–1**	>2	4–6	**>2**
Voltage range (V)	1.4–3.0	1.4–2.5	**1.0–1.5**	<1.7	<1.7	**<1.48**
Operating temp. (°C)	70–90	50–80	**700–850**	>90	80	**<600**
Cell pressure (bar)	<30	<30	**1**	>70	>70	**>20**
H_2 purity (%)	>99.9	>99.9	**99.9**	>99.9999	Same	**>99.9999**
Voltage eff. (LHV) (%)	50–68	50–68	**75–85**	70	>80	**85**
Electrical eff. (stack) (kWh kg^{-1})	47–66	47–66	**35–50**	<42	<42	**<35**
Electrical eff. (system) (kWh kg^{-1})	50–78	50–83	**40–50**	<45	<45	**<40**
Lifetime (system) (kh)	60	50–80	**<20**	100	100–120	**80**
Stack unit size (MW)	1	1	**0.005**	10	10	**0.2**
Electrode area (cm^2)	>10000	1500	**200**	30000	>10000	**500**
Startup (to nominal load) (min)	<50	<20	**>600**	<30	< 5	**<300**
CAPEX (stack) (>1 MW) ($ kW^{-1})	270	400	**>2000**	<100	<100	**<200**
CAPEX (system) (>10 MW) ($ kW^{-1})	500–1000	700–1400	**N/A**	<200	<200	**<300**

<Source: IRENA>

Electrolysis Hydrogen

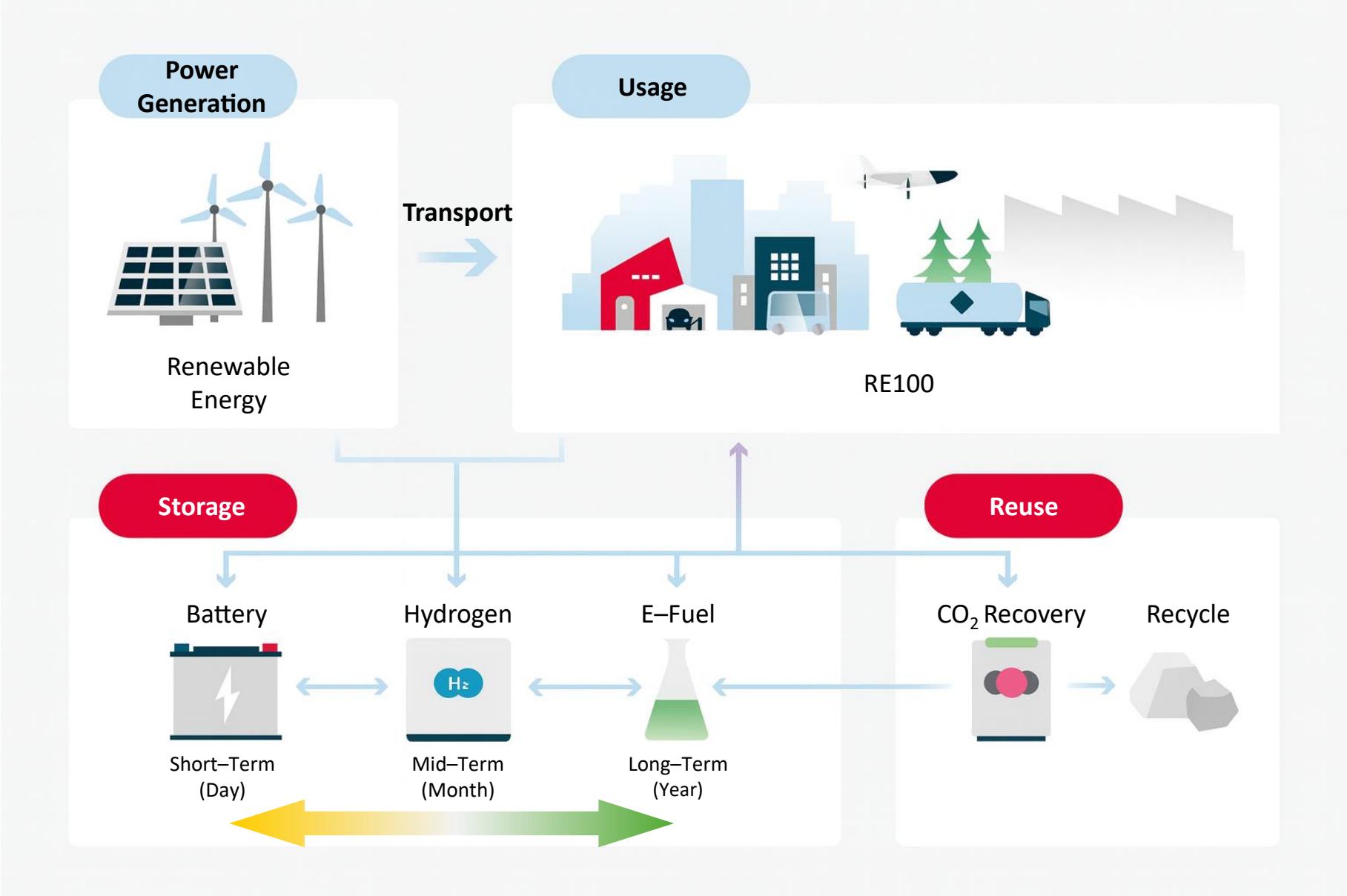
❑ Levelized Cost of Hydrogen (LCOH) & Capital Cost (CAPEX)

Global inflation? Skyrocketing raw material prices?



Nat. Rev. Clean Technol., **1** (2025) 351–371

Surplus RE Hydrogen Utilization



Assignment (~08th Sep)

❑ Why Is Hydrogen So Scarce in Earth's Atmosphere?

H_2 makes up only about 0.55 ppm of Earth's atmosphere (See Slide #11). Even though Earth is known as the "water planet," atmospheric H_2 is extremely scarce. A common explanation often states:
"Because H_2 is the lightest molecule, it continually rises through the atmosphere due to buoyancy and eventually escapes into outer space."
Is this explanation physically accurate? If not, what is the correct scientific mechanism behind the low concentration and escape of H_2 from Earth's atmosphere?

(Hint 1)
A helium balloon floats because surrounding air pushes it up. But what happens to a balloon when there is no air left to push it? Can "buoyancy" kick something entirely out into space?

(Hint 2)
Below 100 km, the Earth's atmosphere is constantly stirred by strong winds and turbulence. Does H_2 really rise to the top by itself?

(Hint 3)
Consider the Maxwell–Boltzmann distribution for root-mean-square speed ($v_{rms} = 3k_bT/m)^{0.5}$ vs. Earth's escape velocity v_{esc} = 11.2 km s^{-1} (k_b: Boltzmann constant, T: Temperature, m: mass)

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