永續氫能的未來及挑戰

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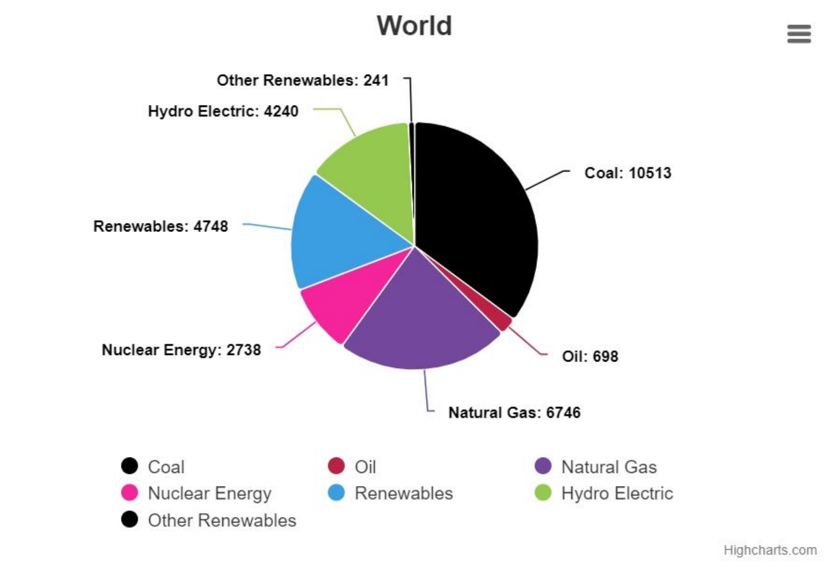
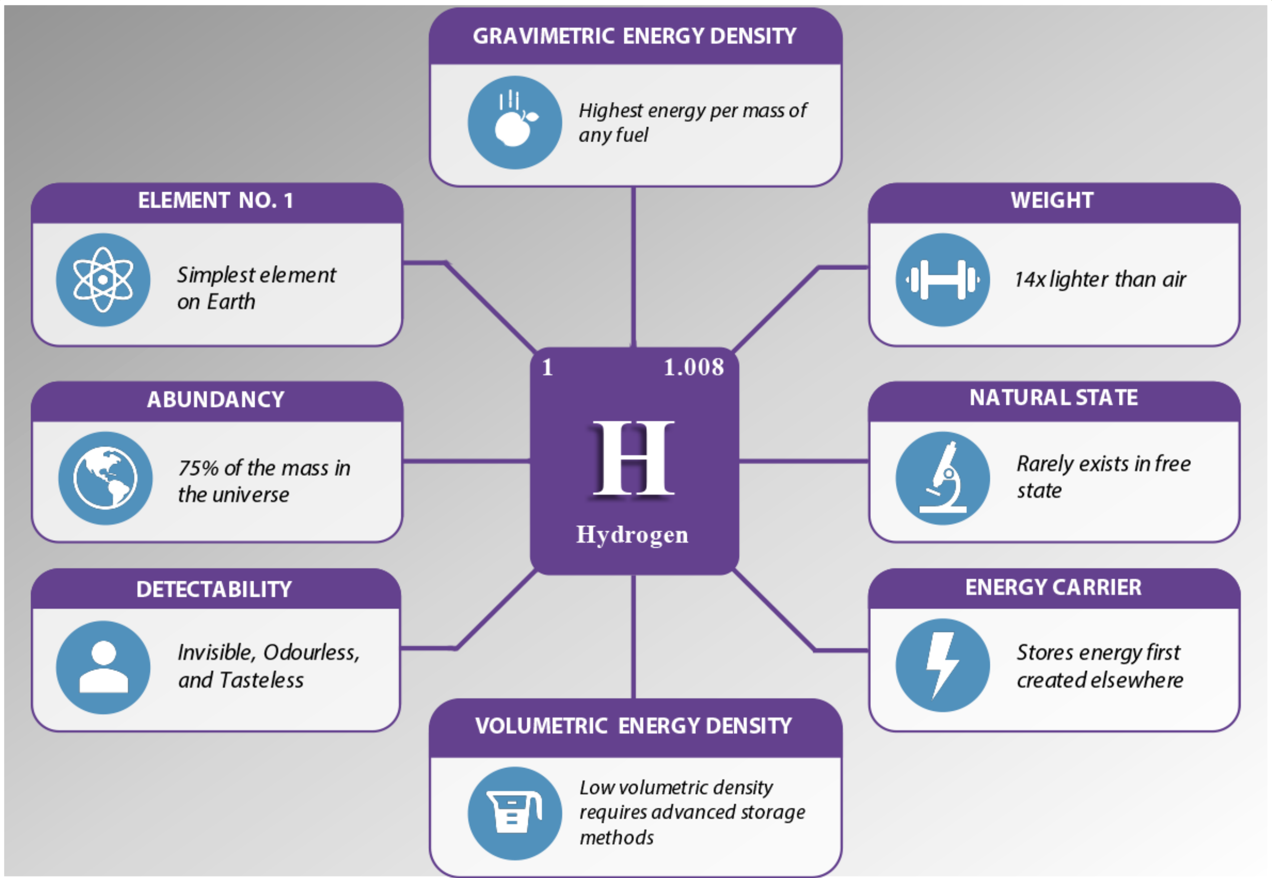
- PART I
- 整體氫氣能源角色及挑戰

前言

- 全球淨零碳排目標推動**能源轉型**
- 氫能被譽為「未來的**綠色燃料**」
- 燃燒後只產生**水**，是**潔淨能源**
- 台灣於2022年列為**淨零12項關鍵戰略**之一



What is hydrogen ?



What is Hydrogen Energy?

Most Abundant

Hydrogen is the most abundant element in the universe, making up 75% of all matter

Zero Emissions

Produces only water and heat as byproducts when used in fuel cells

High Energy

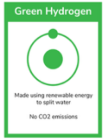
Contains 3x more energy per unit mass than gasoline

Key Advantage

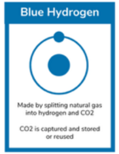
Hydrogen can be produced from diverse domestic resources with virtually zero greenhouse gas emissions

Types of Hydrogen energy

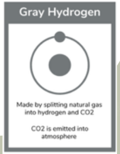
✓ **Green Hydrogen:** Produced via electrolysis powered by renewable energy, green hydrogen is the most sustainable form. It has zero carbon emissions, making it a top choice for eco-friendly energy solutions.



✓ **Blue Hydrogen:** Derived from natural gas through a process called steam methane reforming (SMR), blue hydrogen incorporates carbon capture and storage (CCS) technology to minimize emissions. It offers a relatively clean alternative, although not as eco-friendly as green hydrogen.



✓ **Grey Hydrogen:** Also produced from natural gas, grey hydrogen is identical to blue hydrogen in its extraction process but lacks carbon capture capabilities. This makes it the least environmentally friendly, as it emits substantial CO_2 during production.



氫能發展關鍵數字及目標

- 氫氣之高能量密度(每公斤~33.6 kWh(度);約化石燃料三倍)、可被儲存特性、以及在工業和交通運輸中能實現淨零排放的能力,使其成為各國低碳能源結構中不可或缺的一環。
- 2050年全球對氫能之需求將增長五倍以上(從2020年約1億噸→2050年5-6億噸)。
- 國際能源署(IEA)預估至2050年,低碳氫將達全球總能源消耗量的10-13%;全球已有44個個國家公布國家級氫能戰略圖。
- IEA預估由水電解及化石燃料重組/裂解(搭配碳捕捉/封存/再利用技術)所生產的低碳氫(綠氫、藍氫)占比從2020年的10%上升到2030年的70%,到2050年接近99%。

氫能發展關鍵數字及目標

- 2050年全球低碳氫產量中預估有60%來自水電解,因此電解槽裝置量必須逐年快速增加;目前僅約有1-2 GW(百萬瓩),而到2050年須達3,600 GW,才能達到淨零排放目標。
- 氫氣應用層面廣泛:能源應用(供電、供熱)之外,可作為生產工業的原料（如氨氣、半導體製程、以及煉鋼等）。各國氫能政策提案多以運輸轉型優先、工業應用其次。
- 氫經濟成長路徑與利潤尚待確定;機會因國家、地區、及產業而異,取決於市場承購潛力、供應條件、優勢應用、政府補助與碳稅政策、以及運輸與儲存基礎設施要求。
- 氫能推動催化劑:低成本再生能源(風能、太陽能)可降低電解綠氫之生產成本;預期碳捕捉/封存技術和電解槽建置將更便宜;碳稅徵收亦將進一步提高氫能之競爭力。

製氫成本比較

TABLE 1 | Different hydrogen production methods, their advantages, efficiency, and cost (Shiva Kumar and Himabindu, 2019).

Hydrogen production method	Advantages	Disadvantages	Efficiency [%]	Cost [$/kg]
Steam reforming	Developed technology & existing infrastructure	Produced CO, CO_2; unstable supply	74–85	2.27
Partial oxidation	Established technology	Along with H_2 production, produced heavy oils, and petroleum coke	60–75	1.48
Auto thermal reforming	Well-established technology & existing infrastructure	Produced CO_2 as a byproduct, use of fossil fuels	60–75	1.48
Bio photolysis	Consumed CO_2, produced O_2 as a byproduct, working under mild conditions	Low yields of H_2, sunlight needed, large reactor required, O_2 sensitivity, high cost of materials	10–11	2.13
Dark fermentation	Simple method, H_2 produced without light, no limitation O_2, CO_2-neutral, involves to waste recycling	Fatty acids elimination, low yields of H_2, low efficiency, necessity of huge volume of reactor	60–80	2.57
Photo fermentation	Involves to wastewater recycling, used different organic waste waters, CO_2-neutral	Low efficiency, low H_2 production rate, sunlight required, necessity of huge volume of reactor, O_2-sensitivity	0.1	2.83
Gasification	Abundant, cheap feedstock, and neutral CO_2	Fluctuating H_2 yields because of feedstock impurities, seasonal availability, and formation of tar	30–40	1.77–2.05
Pyrolysis	Abundant, cheap feedstock, and CO_2-neutral	Tar formation, fluctuating H_2 amount because of feedstock impurities and seasonal availability	35–50	1.59–1.70
Thermolysis	Clean and sustainable, O_2-byproduct, copious feedstock	High capital costs, elements toxicity, corrosion problems	20–45	7.98–8.40
Photolysis	O_2 as byproduct, abundant feedstock, no emission	Low efficiency, non-effective photocatalytic materials, requires sunlight	0.06	8–10
Electrolysis	Established technology, zero emission, existing infrastructure O_2 as byproduct	Storage and transportation problem	60–80	10.30

Current applications

Transportation
Fuel cell vehicles, buses, trains, ships

Industry
Steel production, ammonia synthesis, oil refining

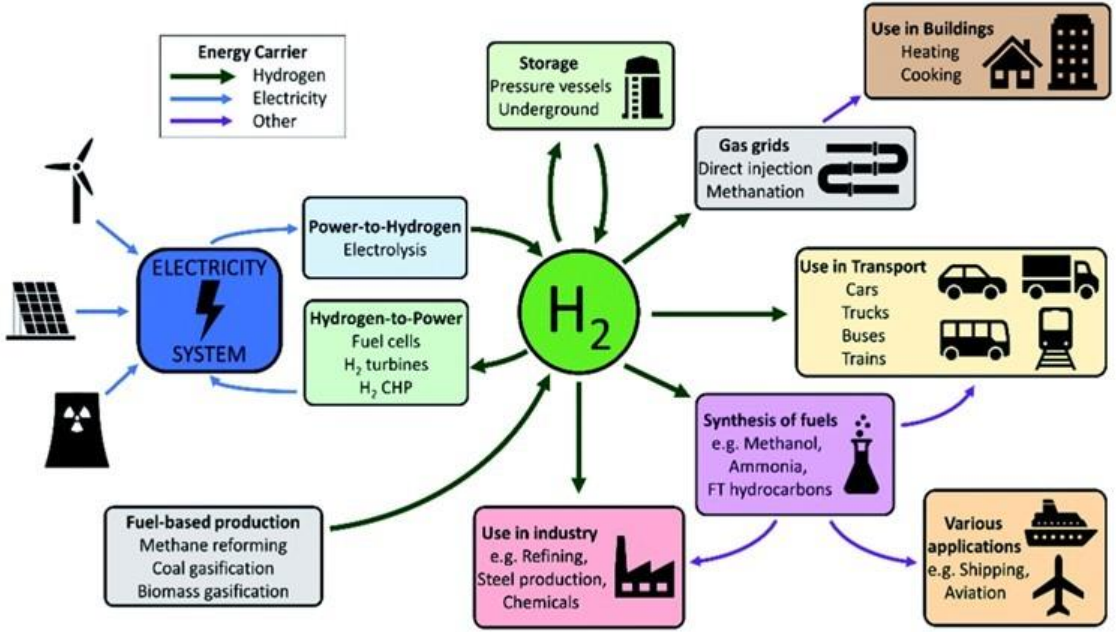
Energy Storage
Grid-scale storage for renewables

Buildings
Heating and power generation

Power Plants
Backup power and peak demand

Chemical
Fertilizers and plastics

Applications of hydrogen in various industries



⚠ Current Challenges

💰 High Production Costs

Green hydrogen is 2-3x more expensive than fossil fuels. Technology improvements needed.

🏠 Limited Infrastructure

Few refueling stations and distribution networks exist globally.

📦 Storage Challenges

Requires high pressure or cryogenic temperatures for efficient storage and transport

⚡ Energy Efficiency

Energy losses occur during production, storage, and conversion processes.

The Future : 2030 Targets

- ✓ **Cost Parity:** Green hydrogen competitive with fossil fuels
- ✓ **500+ GW** of global electrolyzer capacity installed
- ✓ Widespread hydrogen refueling infrastructure in major cities
- ✓ Hydrogen-powered commercial **aircraft prototypes**
- ✓ **Zero-emission** shipping vessels operating globally
- ✓ Major industrial sectors transitioning to hydrogen
- ✓ Integration with renewable energy grids

Vision 2050

22%
Of world's energy needs supplied by hydrogen

$2.5T
Global hydrogen economy market value

30M
Jobs created in hydrogen sector worldwide

Net-Zero Achievement

- ✓ Complete decarbonisation of heavy transport
- ✓ Net-zero carbon emissions in industrial sectors
- ✓ Renewable hydrogen backbone infrastructure
- ✓ Global hydrogen trade networks established

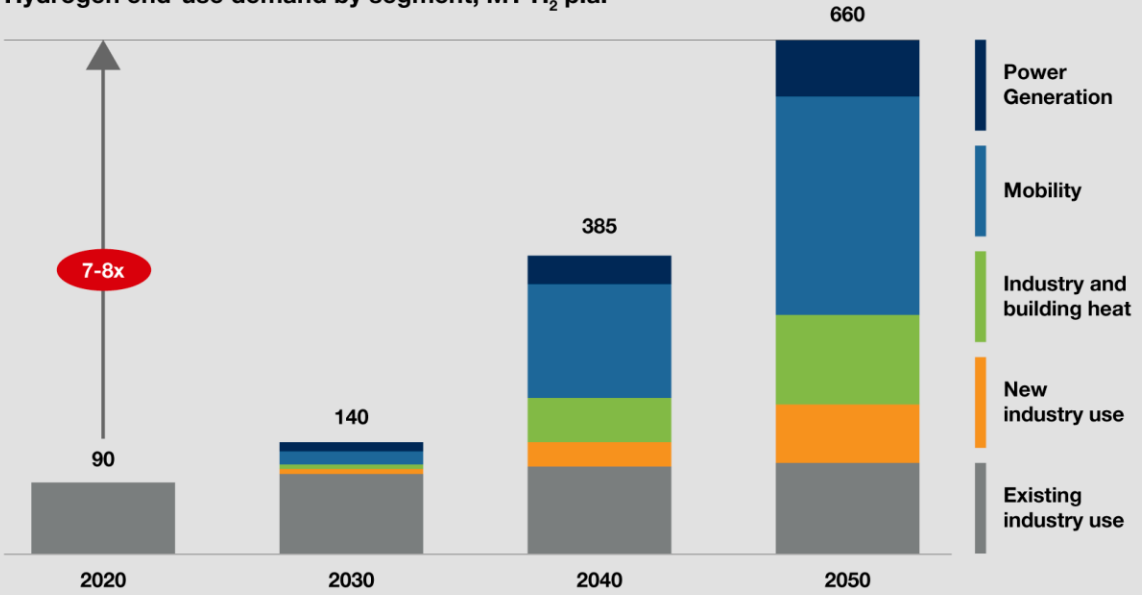
氫能的成長趨勢

NOMURA

GREEN HYDROGEN SET TO BE MAINSTREAM BY 2030

Hydrogen demand will grow by 7-8x until 2050

Hydrogen end-use demand by segment, MT H_2 p.a.



22%

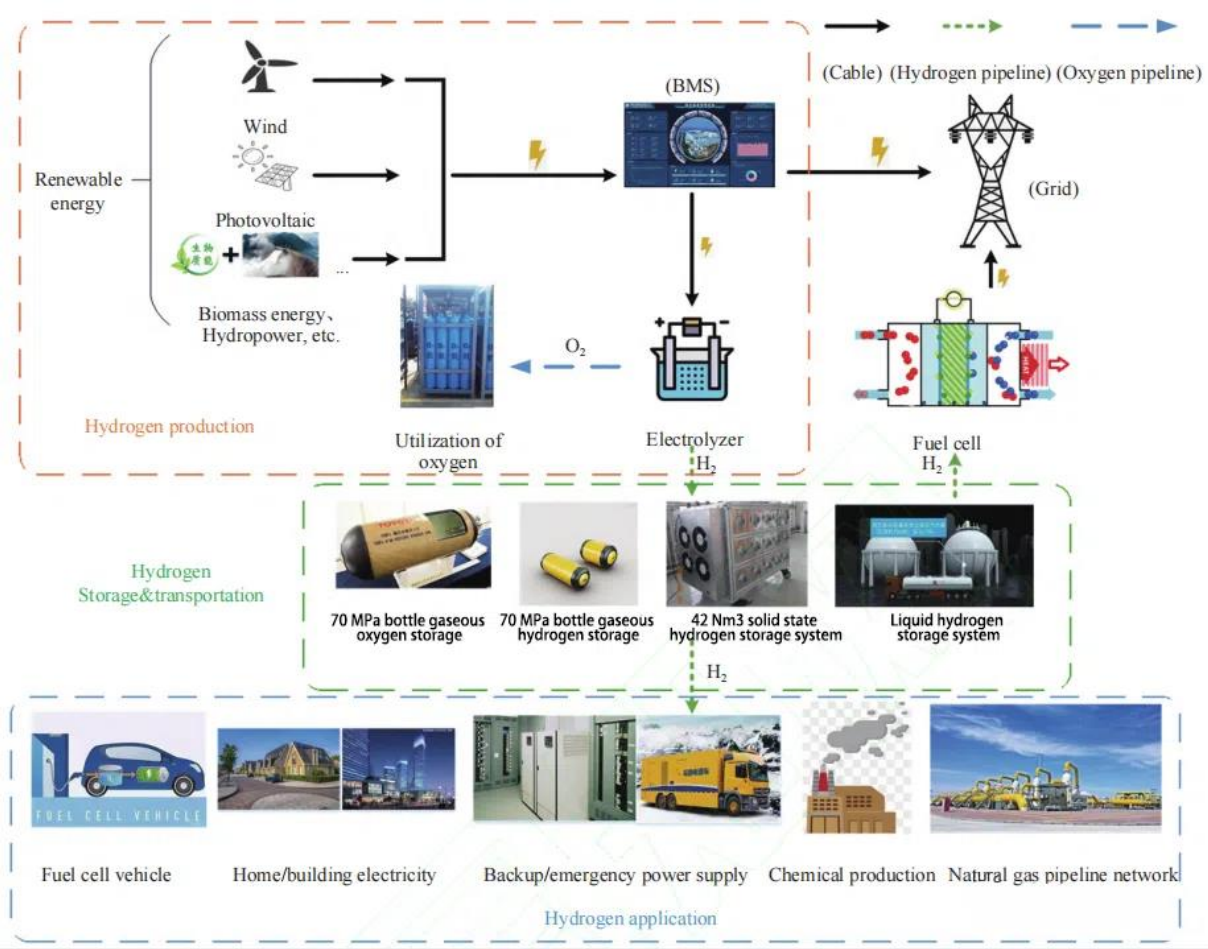
of global final energy demand[1]

660 MT

hydrogen required p.a. in 2050 for net-zero

Note: 1) IEA net-zero scenario with 340 EJ final energy demand in 2050. HHV assumed. Excluding power.
Source: IEA Net Zero by 2050.

綠氫的生產、儲存及應用


(Cable) (Hydrogen pipeline) (Oxygen pipeline)
Renewable energy
Wind
Photovoltaic
Biomass energy、Hydropower, etc.
(BMS)
(Grid)
O_2
Utilization of oxygen
Electrolyzer
Fuel cell
H_2
Hydrogen production
Hydrogen Storage&transportation
70 MPa bottle gaseous oxygen storage
70 MPa bottle gaseous hydrogen storage
42 Nm3 solid state hydrogen storage system
Liquid hydrogen storage system
FUEL CELL VEHICLE
Fuel cell vehicle
Home/building electricity
Backup/emergency power supply
Chemical production
Natural gas pipeline network
Hydrogen application

Emerging Technologies

Solar Hydrogen

Direct sunlight to hydrogen conversion using photo electrochemical cells

Bio-Production

Using algae and bacteria for natural hydrogen generation

Solid Storage

Metal hydrides for safer, efficient transport

Aviation

Zero-emission hydrogen aircraft development

Ocean Energy

Offshore production using wave and tidal power

Home Systems

Residential fuel cells for heat and electricity

Global Initiatives

EU European Union

€470 billion investment by 2050. Target: 40 GW electrolyzer capacity by 2030

JP Japan

Leading hydrogen society initiative. Massive infrastructure development

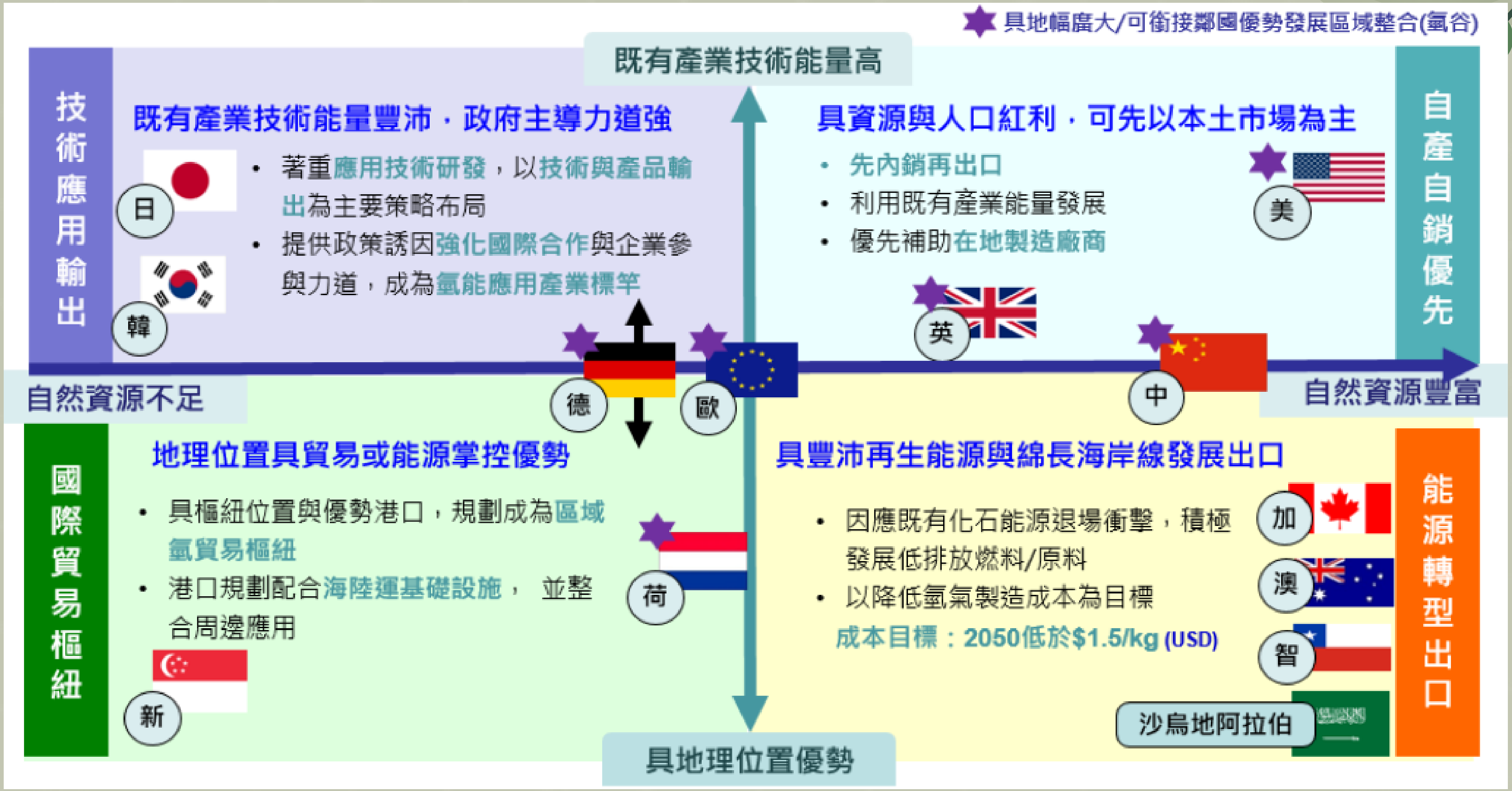
CN China

World's largest producer. Rapidly expanding green hydrogen capacity

US United States

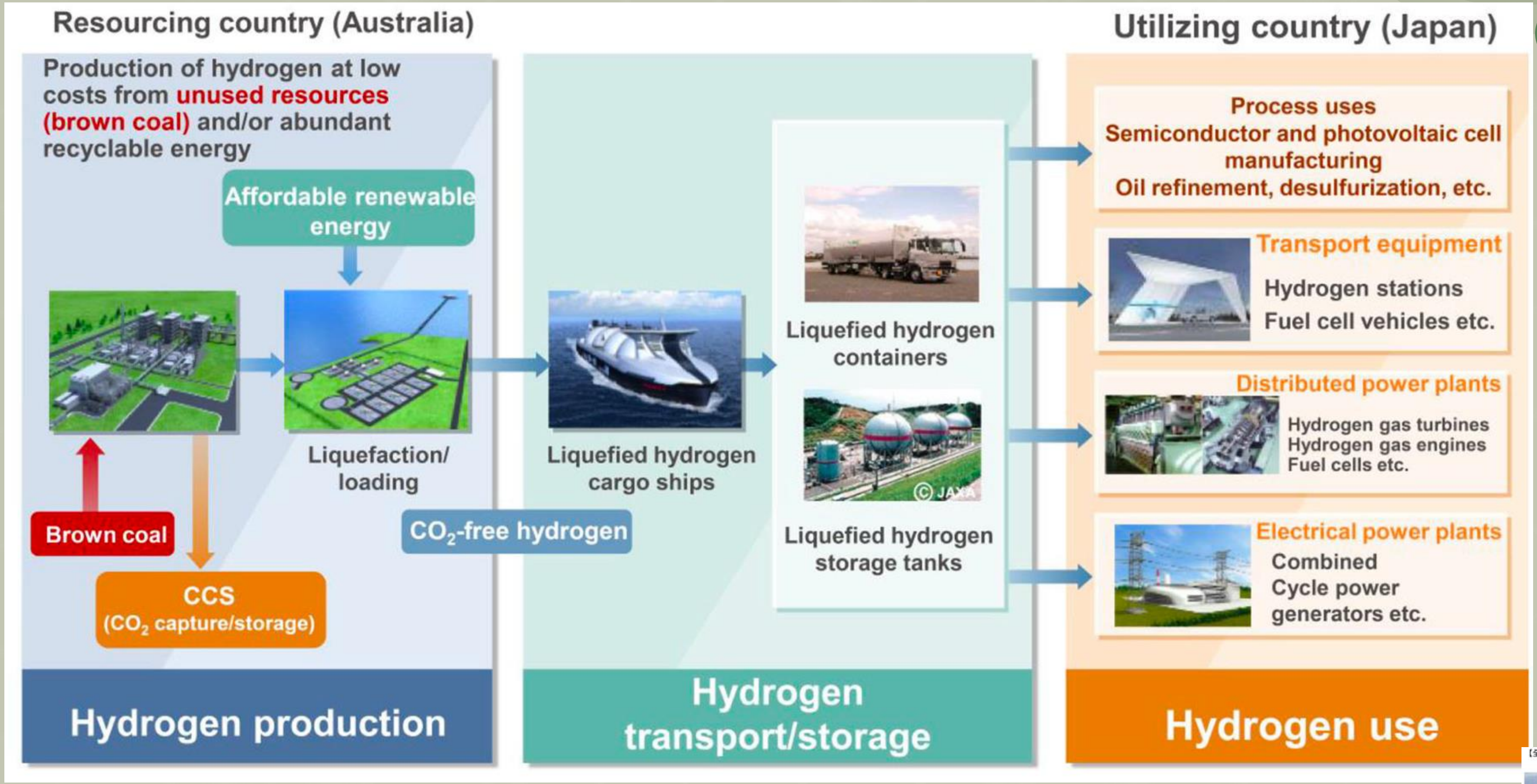
$8 billion Clean Hydrogen Strategy funding

世界氫能應用趨勢及合作



(參考資料:中技社<至2030年氫能技術發展>)

國際氫能合作及運送案例



F. Eljack and M.K. Kazi, Frontier in Sustainability, Vol.1, 612762, 2021

【全球大搜奇】日澳合作液態氫運輸船 完成全球首航

Key benefits

Environmental

- Zero GHG emissions at point of use
- Combats climate change
- Reduces air pollution

Energy Security

- Reduces fossil fuel dependence
- Domestic production possible
- Diverse energy sources

Economic Growth

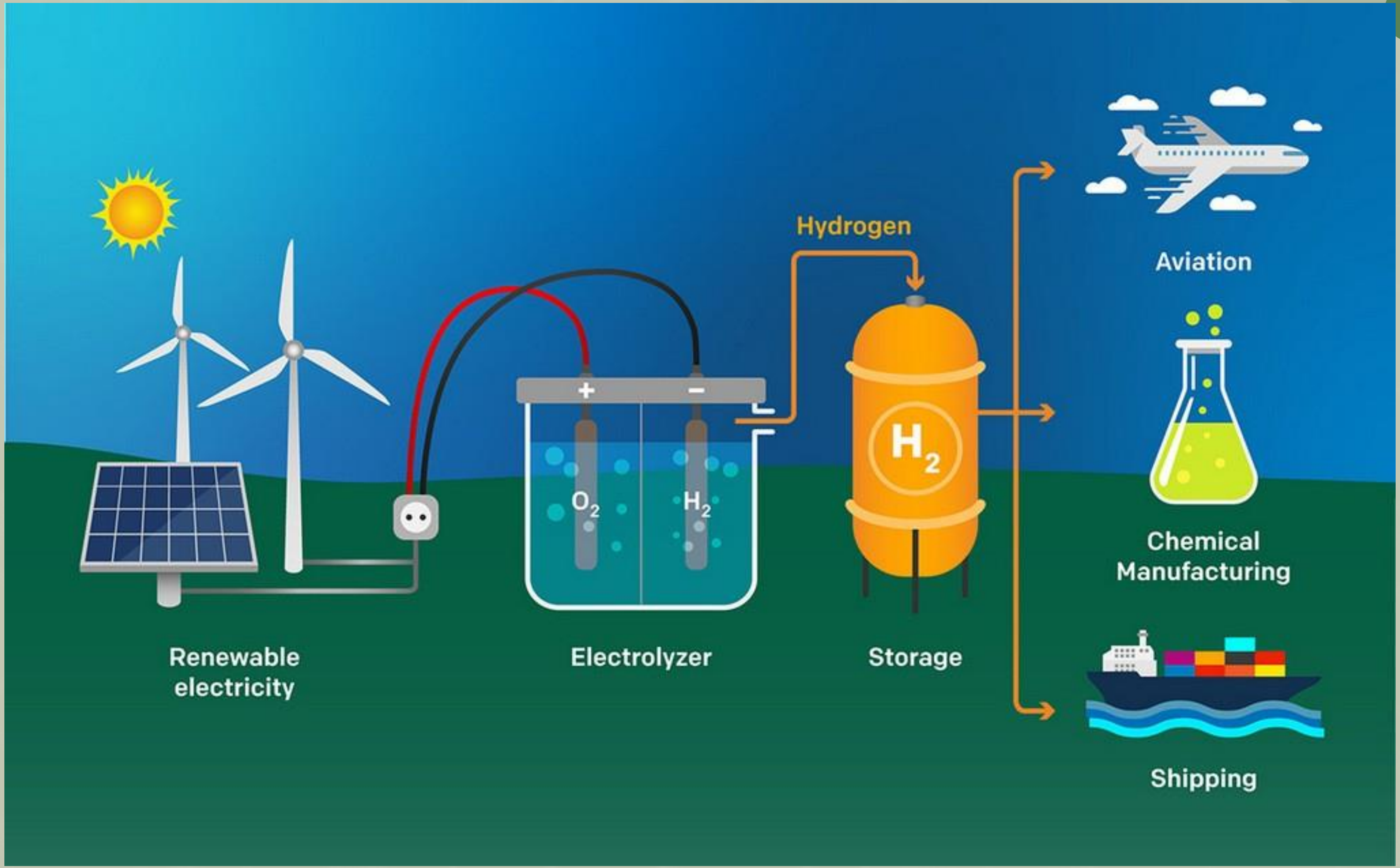
- Millions of new jobs
- Innovation driver
- New industries created

Versatility

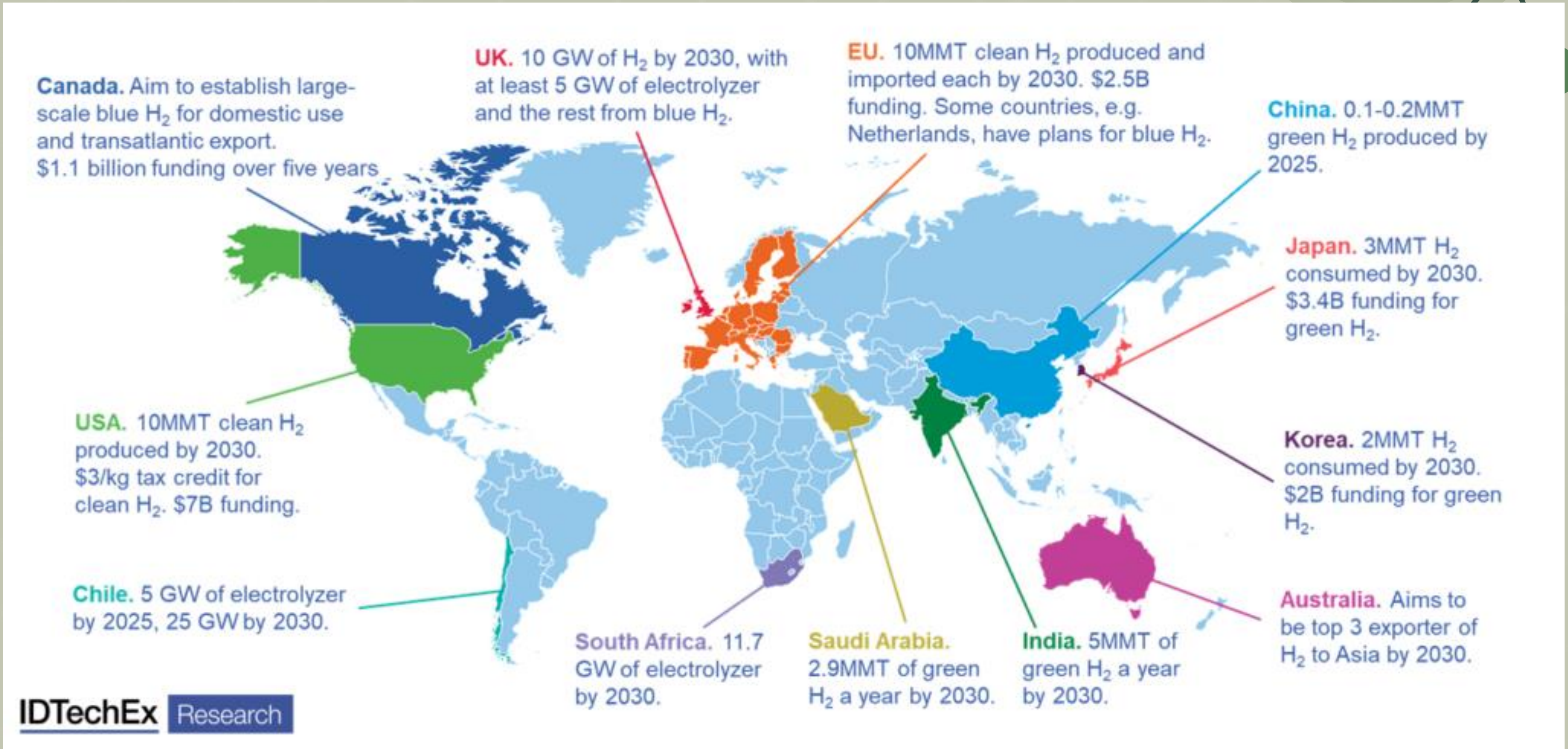
- Multiple applications
- Energy storage solution
- Transport & industry fuel

Green Hydrogen production pathyway for sustainable future with net zero emissions

How can we produce hydrogen with zero carbon emissions? This is a question that is important to answer to meet the global challenge of climate change mitigation. The electrolysis of water is a key component of any future energy systems aimed at achieving this goal.



2030年全球氫能生產及投資分佈



- **PART II**
- 氫能製造及挑戰

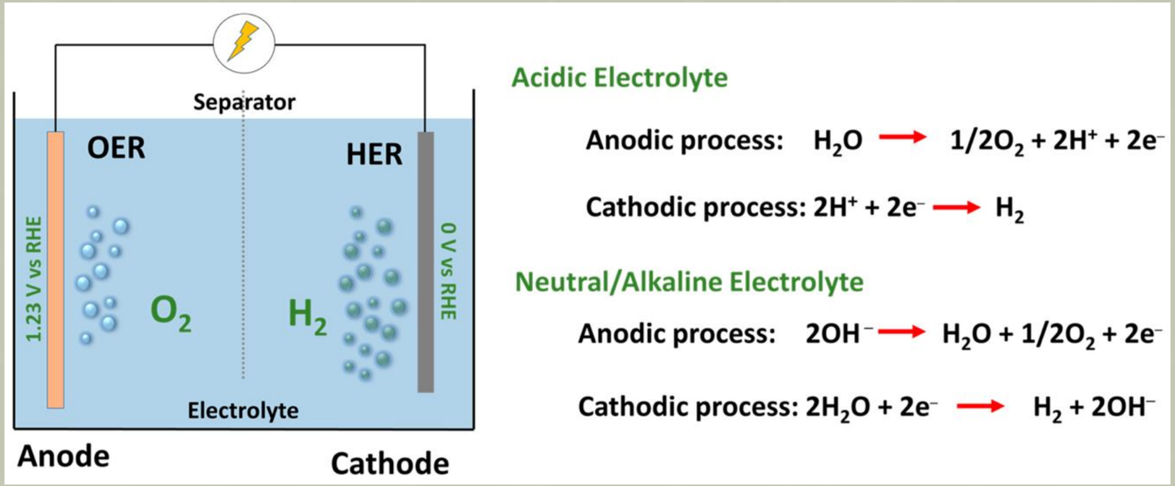
Conventional Water Splitting for H_2 Generation

Electrolysis Technologies and Applications

Clean Energy & Hydrogen Production

What is water splitting ?

Water electrolysis is an electrochemical process that splits water (H_2O) into hydrogen (H_2) and oxygen (O_2) using electrical energy.

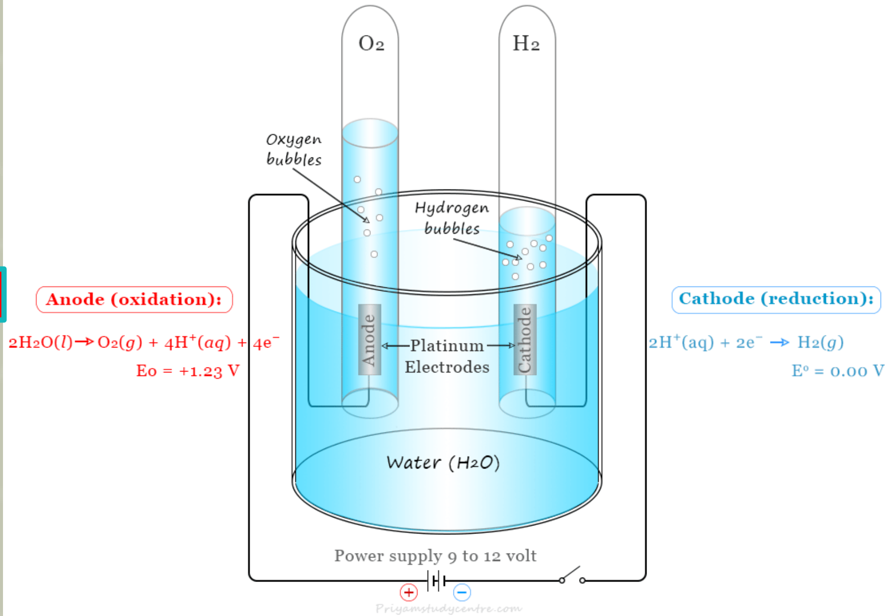


Key Advantages

- **Zero carbon emissions** when powered by renewables
- **High purity hydrogen** (99.9%+)
- **Scalable** from kW to MW systems
- **Mature technology** with commercial availability

Energy Requirements for water electrolysis

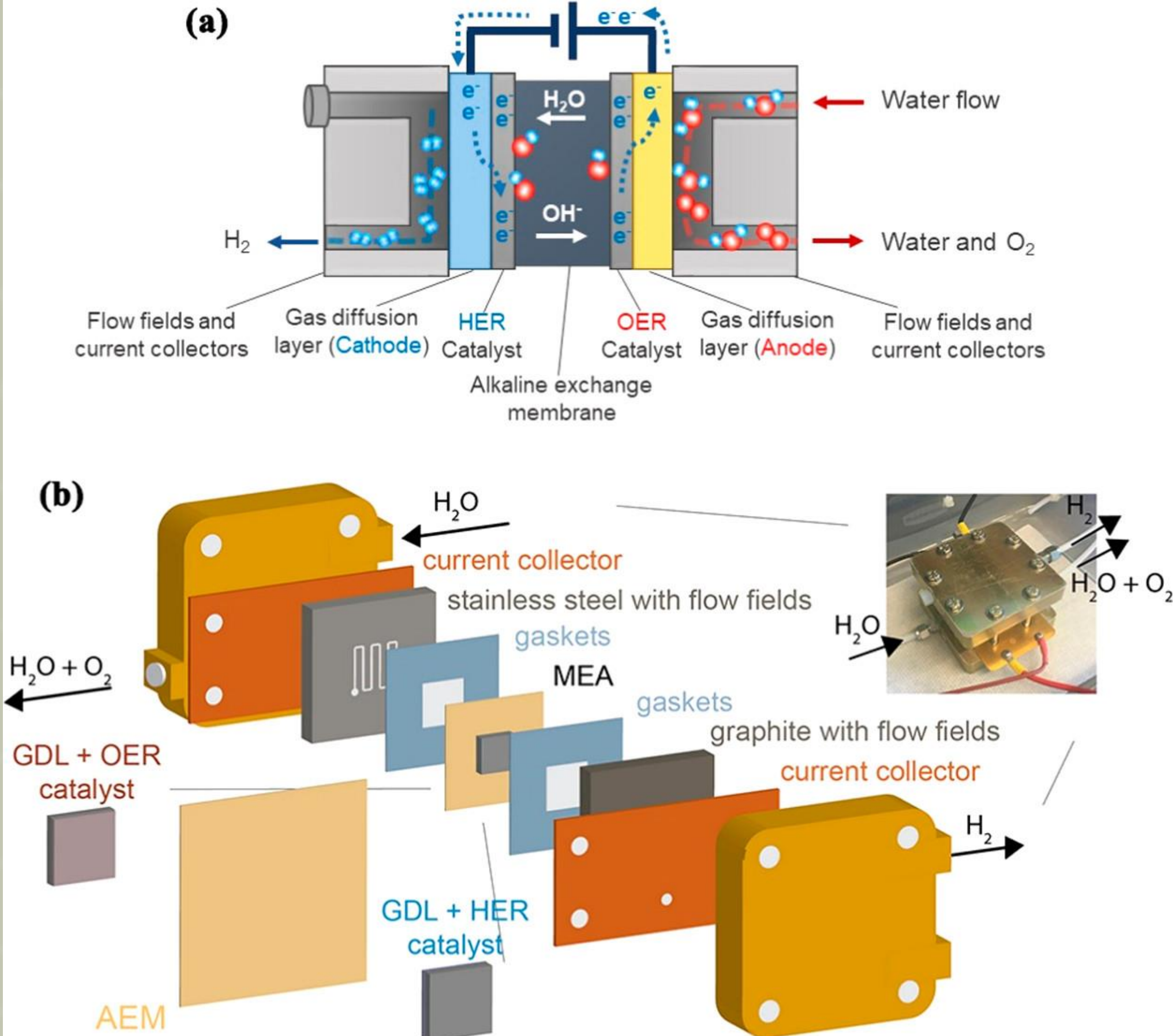
- ✓ **Theoretical minimum:** 1.23 V (237 kJ/mol)
- ✓ **Thermoneutral voltage:** 1.48 V (286 kJ/mol)
- ✓ **Practical operation:** 1.8-2.0 V
- ✓ **Energy consumption:** 50-55 kWh/kg H_2 (practical)



Types of Conventional Electrolyzers

Technology	Electrolyte	Temperature	Efficiency
Alkaline WE	KOH/NaOH (20-40%)	60-80 ^{0}C	62-70 %
Proton exchange membrane WE	Solid polymer membrane	50-80 ^{0}C	67-75 %
Solid oxide WE	Solid oxide ceramic	700-900 ^{0}C	85-90 %

Alkaline water electrolysis



Alkaline water electrolysis

Advantages

- ✓ Lowest capital cost
- ✓ Long operational lifetime (60,000-90,000 hrs)
- ✓ Non-precious metal catalysts
- ✓ Well-established technology
- ✓ Large stack sizes (up to MW)

Limitations ✗

- Lower current density
- Slower dynamic response
- Crossover issues
- Corrosive electrolyte
- Lower partial load efficiency

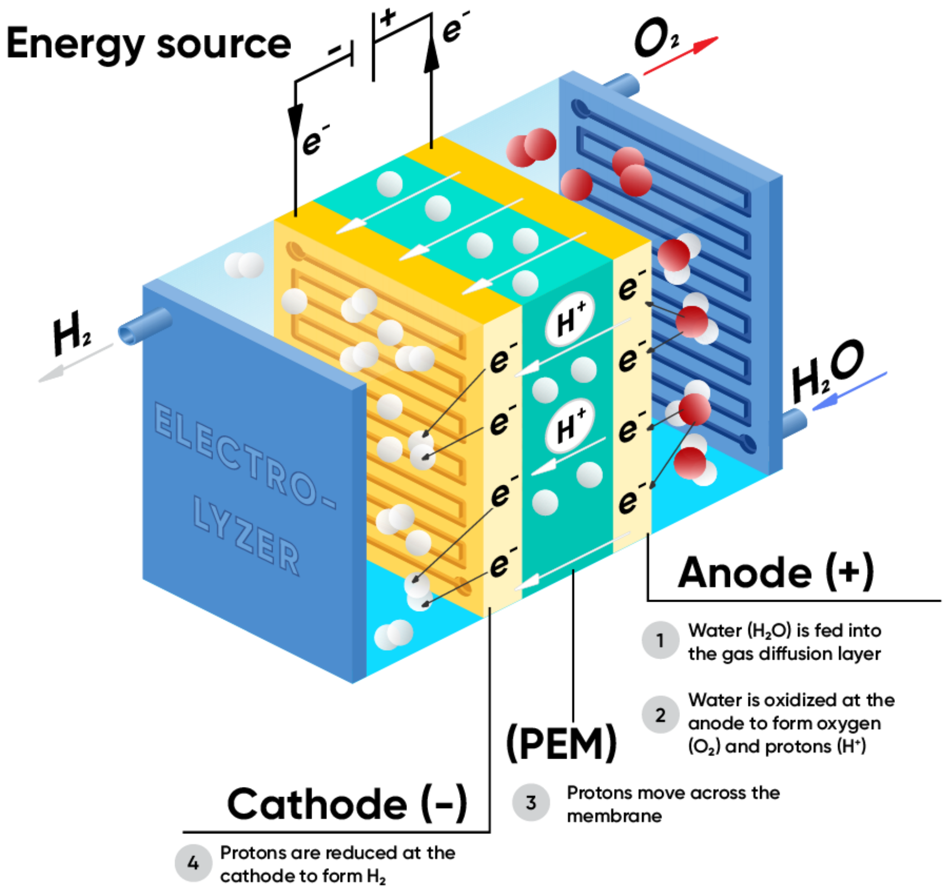
PEM water electrolysis

Advantages ✓

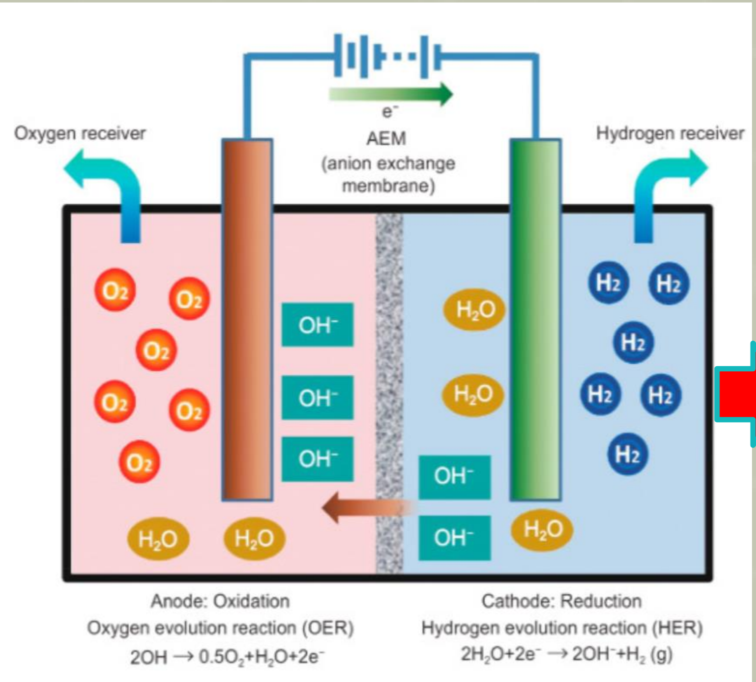
- High current density
- Fast dynamic response (seconds)
- Compact design
- High purity H_2 (99.999%)
- Excellent partial load operation
- High pressure capability

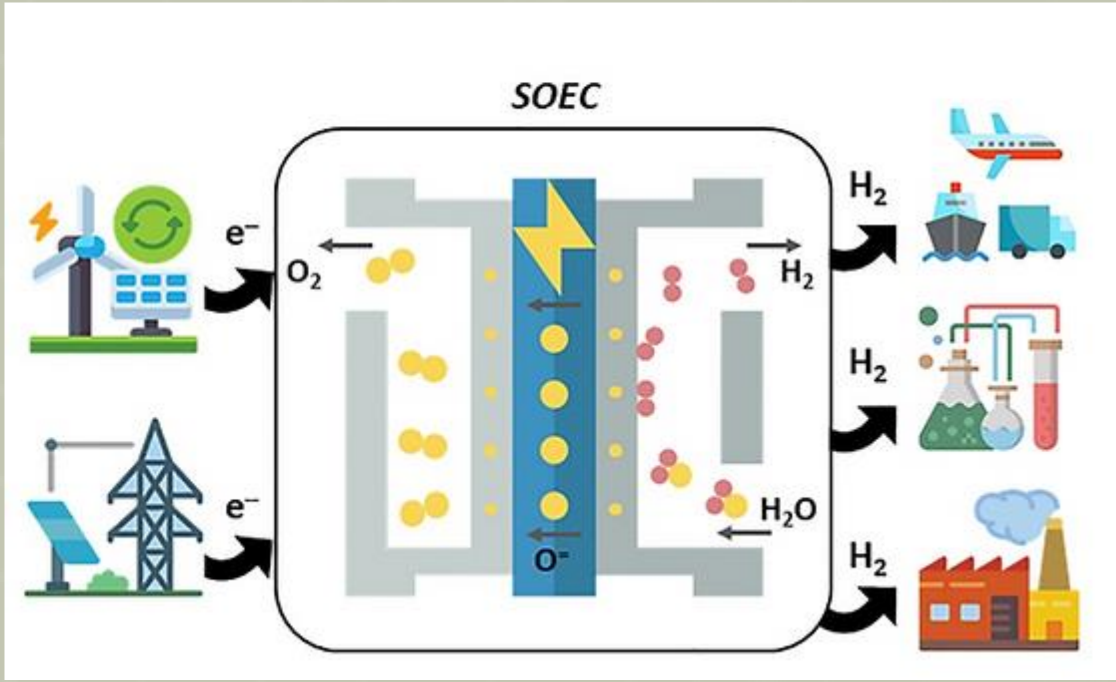
Limitations ✗

- Expensive precious metal catalysts
- Higher capital cost
- Membrane degradation
- Shorter lifetime (40,000-60,000 hrs)
- Acidic corrosive environment



Solid Oxide Electrolyzer Cells (SOEC)





Solid Oxide Electrolyzer Cells (SOEC)

Key Advantages

- ✓ **Highest efficiency** - thermally assisted electrolysis
- ✓ **Reversible operation** - can operate as fuel cell
- ✓ **Utilizes waste heat** from industrial processes
- ✓ **Lower electrical energy** requirement

Challenges

- ✓ Material degradation at high temperatures
- ✓ Thermal cycling issues
- ✓ Long startup times
- ✓ Currently at pilot/demonstration scale

Technology Comparison

Parameter	Alkaline	PEM	SOEC
Maturity	Commercial (mature)	Commercial	Pilot/Demo
System Efficiency	62-70%	67-75%	85-90%
Current Density	0.2-0.4 A/cm²	1-3 A/cm²	0.3-1 A/cm²
Load Range	20-100%	0-100%	50-100%
Response Time	Minutes	Seconds	Hours
CAPEX ($/kW)	500-1000	1100-1800	2000-3500
Stack Lifetime	60,000-90,000 hrs	40,000-60,000 hrs	20,000-40,000 hrs

Applications & Markets

Current Applications

Industrial:

- Ammonia production (fertilizers)
- Petroleum refining
- Methanol synthesis
- Electronics (semiconductor manufacturing)

Energy:

- Grid energy storage
- Renewable energy integration
- Power-to-gas systems
- Backup power systems

Emerging Applications

- **Transportation:** Fuel cell vehicles, aviation, maritime
- **Green steel production:** Direct reduction of iron ore
- **Synthetic fuels:** E-fuels, green methanol
- **Seasonal energy storage:** Long-duration storage solution

Economics

Capital costs:
$500-1000/kW installed

Operating costs:
Dominated by electricity (70-80%)

Levelized Cost of H_2

Present: \$4-6/kg H_2

Economics & Challenges

Reducing noble metal catalyst loading (PEM)

Improving durability and lifetime

Material degradation at high operating conditions

Challenges

Future Outlook & Conclusion

Market Projections

- ✓ **Global capacity:** Expected to grow from ~1 GW (2023) to 100+ GW by 2030
- ✓ **Cost reduction:** 50-70% decline expected by 2030 through manufacturing scale-up
- ✓ **Investment:** $300+ billion announced globally through 2030

Technology Trends

- ✓ **Alkaline:** Larger stack sizes, improved efficiency (targeting 70%+)
- ✓ **PEM:** Reduced catalyst loading, lower cost membranes
- ✓ **SOEC:** Commercial demonstration projects (5-10 MW scale)
- ✓ **AEM:** Emerging as low-cost alternative combining benefits of both

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Coupled Water Electrolysis for Energy-Saving Hydrogen Production

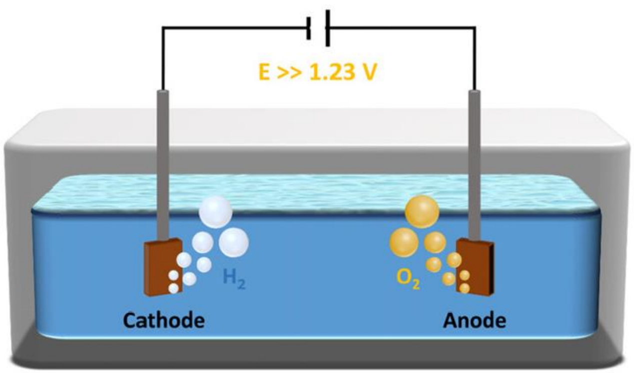
Next-Generation Electrolysis Technology

Combining H_2 Production with Valuable Co-Products

Sustainable Energy & Advanced Electrocatalysis

The Challenge with Conventional Electrolysis

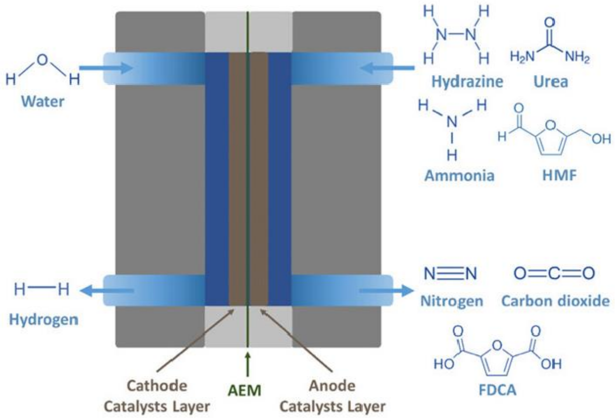
Conventional water electrolysis



Challenges of Conventional water electrolysis

- High thermodynamical potential with sluggish 4-eletrons transfer process
- Low-value anodic product
- Explosive gas mixture (H_2/O_2)

Hybrid water electrolysis (HWE)



Characteristics of HWE

- Lower Energy consumption due to thermodynamically favorable reaction
- Value-added product
- Non-reactive gas mixture
- Purifying wastewater

Coupled Electrolysis Concept

Conventional

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

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

Cell Voltage: 1.8-2.0 V

Byproduct: O_2 (low value)

Coupled

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

Anode: Organic/substrate oxidation

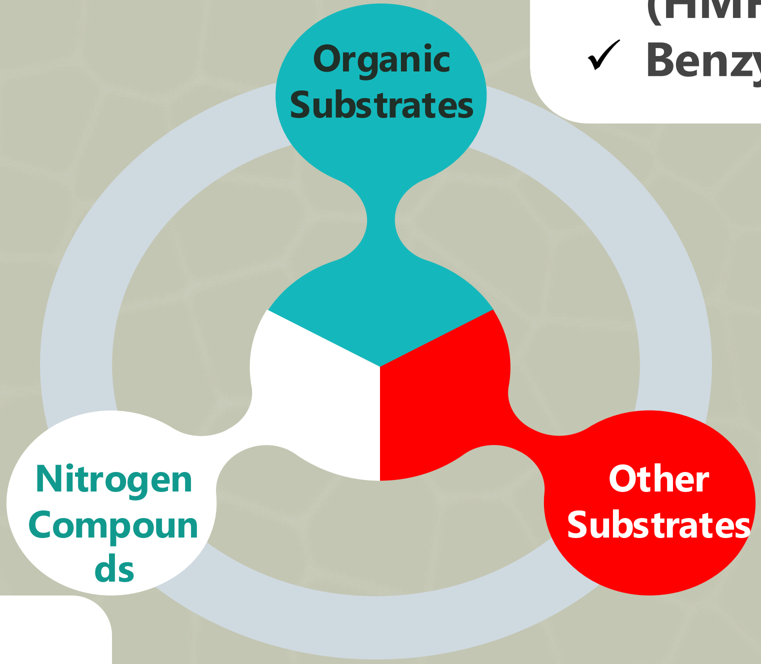
Cell Voltage: 1.3-1.6 V

Co-product: Valuable chemicals

20-40% Energy Savings!

Types of Coupled Electrolysis

- ✓ Alcohols (methanol, ethanol, glycerol)
- ✓ Biomass derivatives (HMF, furfural)
- ✓ Benzyl alcohol



- ✓ Sulfide/Sulfite
- ✓ Chloride
- ✓ Industrial waste streams

- ✓ Urea
- ✓ Ammonia
- ✓ Hydrazine

Urea-Assisted Electrolysis

Reaction Chemistry

Anode: $CO(NH_2)_2 + 6OH^- \rightarrow N_2 + 5H_2O + CO_2 + 6e^-$ (0.37 V vs RHE)

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

Energy Advantage

Potential reduction: ~0.86 V lower than OER
Cell voltage: 1.3-1.5 V (vs 1.8-2.0 V conventional)
Energy savings: 25-35%

Dual Benefits

✓ Clean H_2 production
✓ Nitrogen removal (N_2)
✓ Pollution remediation
✓ Reduced treatment costs

Applications

•Wastewater treatment (urine, agricultural runoff)
•Municipal wastewater streams
•Industrial effluents

Challenges

•Selectivity to N_2 (avoid NH_3, NO_3^-)
•Competing hydrolysis
•Catalyst stability

Alcohol-Assisted Electrolysis

Common Alcohol Substrates

Alcohol	Oxidation Potential	Products	Applications
Methanol	0.02 V vs RHE	Formate, CO_2	Wastewater, byproduct streams
Ethanol	0.08 V vs RHE	Acetate, acetaldehyde	Fermentation waste, biofuels
Glycerol	0.15 V vs RHE	Glycerate, formate, oxalate	Biodiesel byproduct (10% yield)
Benzyl alcohol	~0.3 V vs RHE	Benzaldehyde	Fine chemical production

Biomass Valorization Electrolysis

5-Hydroxymethylfurfural (HMF) Oxidation

Source & Reaction

- ✓ Derived from cellulose/lignocellulosic biomass
- ✓ Platform chemical for bio-based materials
- ✓ Oxidation potential: ~0.3 V vs RHE

$$HMF \rightarrow FDCA + H^{+} + e^{-}$$

FDCA: 2,5-Furandicarboxylic acid

Product Value

FDCA Applications:

- ✓ Bio-plastic precursor (PEF)
- ✓ Replacement for terephthalic acid
- ✓ Market value: $1000-3000/ton
- ✓ 100% bio-based polymer pathway

Other coupled electrolysis system

Hydrazine assisted electrolysis

$$N_2H_4 + 4OH^- \rightarrow N_2 + 4H_2O + 4e^- \quad (-0.33\ V\ vs\ RHE)$$

- **Extremely low potential:** Theoretically spontaneous!
- **Cell voltage:** < 0.5 V possible
- **Energy savings:** 70-80%
- **Limitation:** Hydrazine toxicity and cost

Energy Savings Comparison

Anode Reaction	Potential (V)	Cell Voltage (V)	Energy Savings	Co-Product Value
OER (Baseline)	1.23	1.8-2.0	—	Low (O_2)
Urea oxidation	0.37	1.3-1.5	25-35%	Medium
Methanol oxidation	0.02	1.2-1.4	30-40%	High
Glycerol oxidation	0.15	1.3-1.5	25-35%	High
HMF oxidation	~0.3	1.3-1.4	25-35%	Very High
Hydrazine oxidation	-0.33	0.3-0.5	70-80%	Medium
Sulfide oxidation	0.48	1.4-1.6	20-30%	Medium

Key Insight: Most coupled systems achieve 20-40% energy reduction, with some (like hydrazine) offering even greater savings. Combined with valuable co-products, overall economics improve significantly.

Electrocatalyst Design

Urea Oxidation

- $Ni(OH)_2$/NiOOH active phase
- NiFe-LDH (enhanced conductivity)
- Ni-Mo (synergistic effects)
- 3D Ni foam substrates

HMF/Biomass Oxidation

- NiFe-based materials
- Co_3O_4 (selective to FDCA)
- N-doped carbon with metal sites
- Bimetallic combinations

Alcohol Oxidation

- Pt-Ru alloys (methanol, acidic/alkaline)
- Pd-based (ethanol, glycerol)
- Ni-Co oxides (alkaline glycerol)
- Au nanoparticles (selective)

Ammonia Oxidation

- Pt-based (most active)
- Ni-based (cost-effective, alkaline)
- Cu-based materials

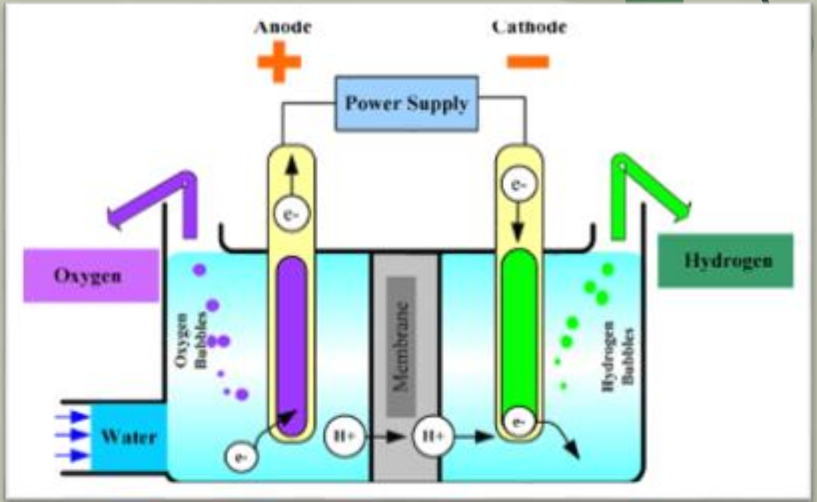
Electrocatalyst Design Principles

- ✓ **Selectivity:** Target specific products, minimize side reactions
- ✓ **Activity:** Low overpotential at practical current densities
- ✓ **Stability:** Resist fouling from organic substrates
- ✓ **Cost:** Earth-abundant materials preferred for scale-up

System configurations

1. H-Cell Configuration

- Separated anode/cathode compartments
- Ion-exchange membrane separator
- Prevents product crossover
- Different pH optimization possible



Best for:

- High-value products requiring purity
- Different electrolyte requirements

Industrial applications

Waste water treatment integration

Municipal & Agricultural Wastewater

- ✓ **Urea-rich streams:** Agricultural runoff, urine (1000 L/day → 40-50 g H_2/day)
- ✓ **Ammonia removal:** Municipal wastewater nitrogen treatment
- ✓ **Dual benefit:** Clean H_2 + pollution remediation
- ✓ **Cost offset:** Treatment cost reduced by H_2 value

Industrial applications

Biorefinery Integration

Biodiesel Industry

- ✓ Glycerol byproduct (10% yield)
- ✓ Convert to value chemicals + H_2
- ✓ Additional revenue stream
- ✓ Waste-to-value transformation

Lignocellulosic Biorefinery

- ✓ HMF from cellulose → FDCA + H_2
- ✓ Bio-plastic precursor production
- ✓ Integrated biorefinery concept
- ✓ Carbon-neutral H_2 pathway

Chemical Industry Synergies

- **Chlor-alkali integration:** Co-produce H_2, Cl_2, NaOH
- **Fine chemicals:** Selective oxidations (benzyl alcohol → benzaldehyde)
- **Pharmaceutical intermediates:** Electrochemical synthesis pathways

Techno-Economic Analysis

Cost of hydrogen production

System Type	Energy (kWh/kg H_2)	LCOH ($/kg H_2)	Cost Reduction
Conventional Alkaline	50-55	$4.50	Baseline
Urea-Coupled	35-40	$3.20	29%
Glycerol-Coupled	32-38	$3.00*	33%
HMF-Coupled (w/ FDCA credit)	35-40	$2.80*	38%

*Includes co-product value credits

Techno-Economic Analysis

Economic Drivers

Cost Reductions

- ✓ 20-40% lower electricity consumption
- ✓ Reduced CAPEX (lower voltage operation)
- ✓ Improved catalyst lifetime
- ✓ Lower cooling requirements

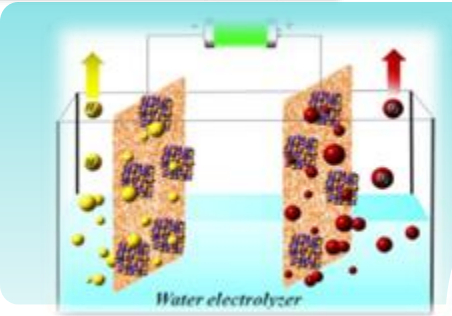
Revenue Enhancement

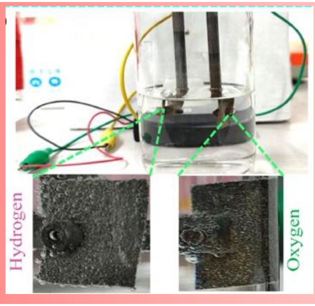
- ✓ Valuable co-products ($2-5/kg)
- ✓ Waste treatment credits
- ✓ Carbon credits (biomass-based)
- ✓ Circular economy incentives

Break-Even Analysis: With 25-35% energy savings + co-product value, coupled electrolysis can achieve $2-3/kg H_2, competitive with steam methane reforming (SMR) while being carbon-neutral.

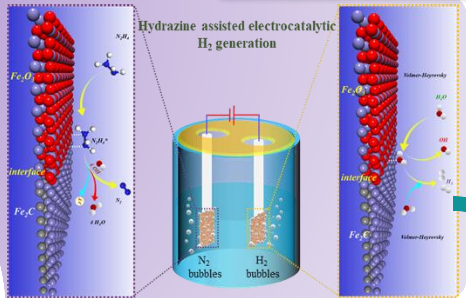
Traditional Water electrolysis

Coupled Water electrolysis





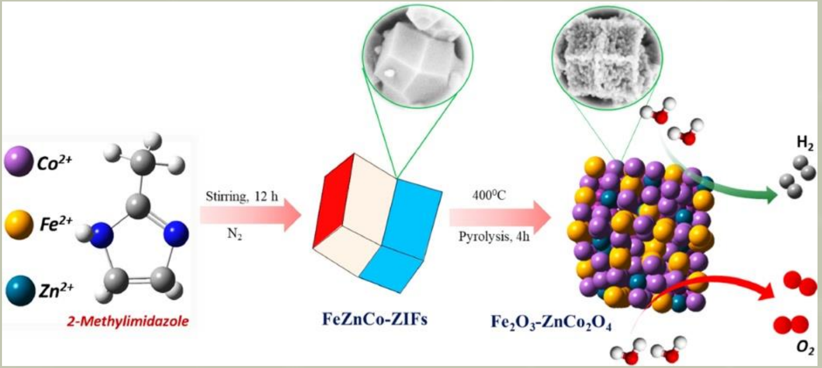
FCU LAB-WATER ELECTROLYSIS



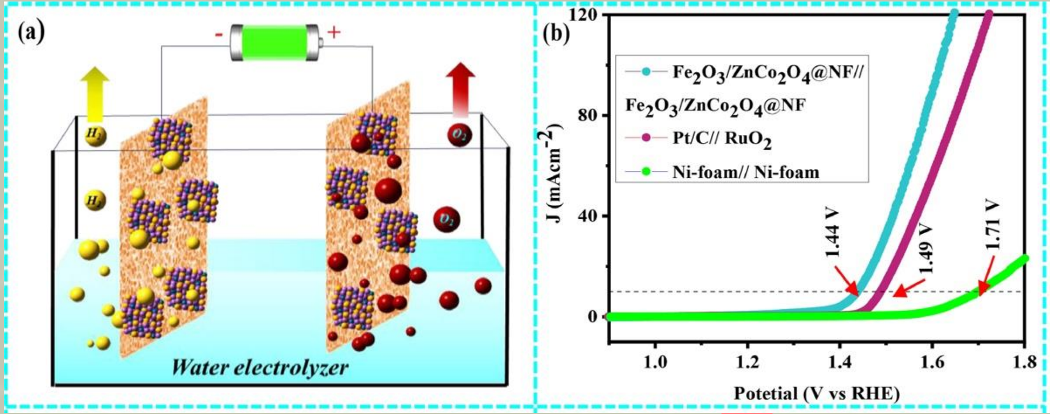
FCU LAB-WATER ELECTROLYSIS

Metal organic frameworks (MOFs) derived materials for overall water splitting

Electrocatalyst Design



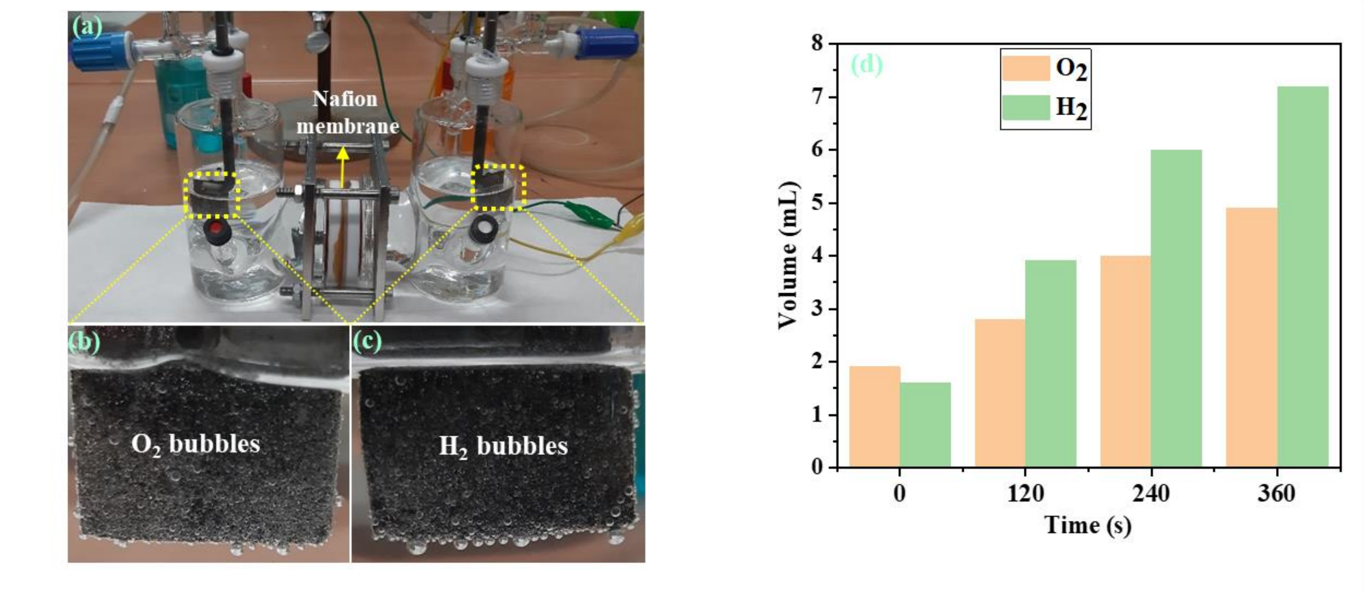
Traditional WE



Closer value to the theoretical voltage (1.3 V), its workable for commercial alkaline water electrolyzer

FCU LAB-WATER ELECTROLYSIS

Metal organic frameworks (MOFs) derived materials for overall water splitting

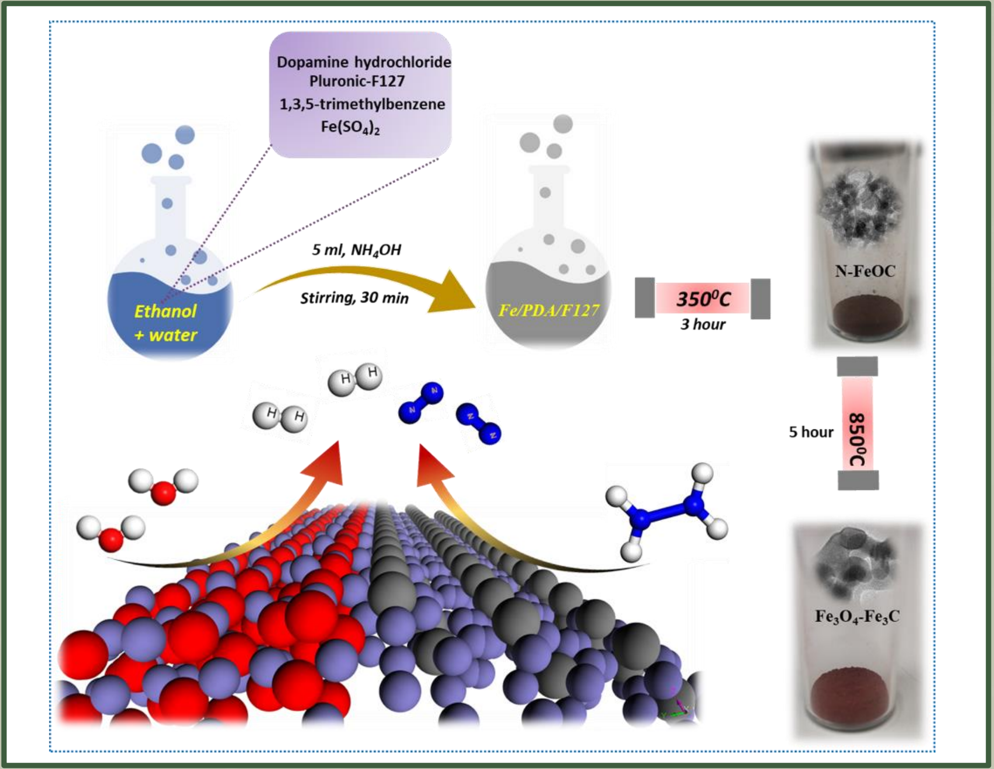


Digital image of (a) gas collecting water splitting device in 1 M KOH electrolyte solution, (b, c) generation of O_2 and H_2 bubbles on Ni-foam during the water splitting analysis, (d) the amount of H_2 and O_2 measured versus various time

FCU LAB-WATER ELECTROLYSIS

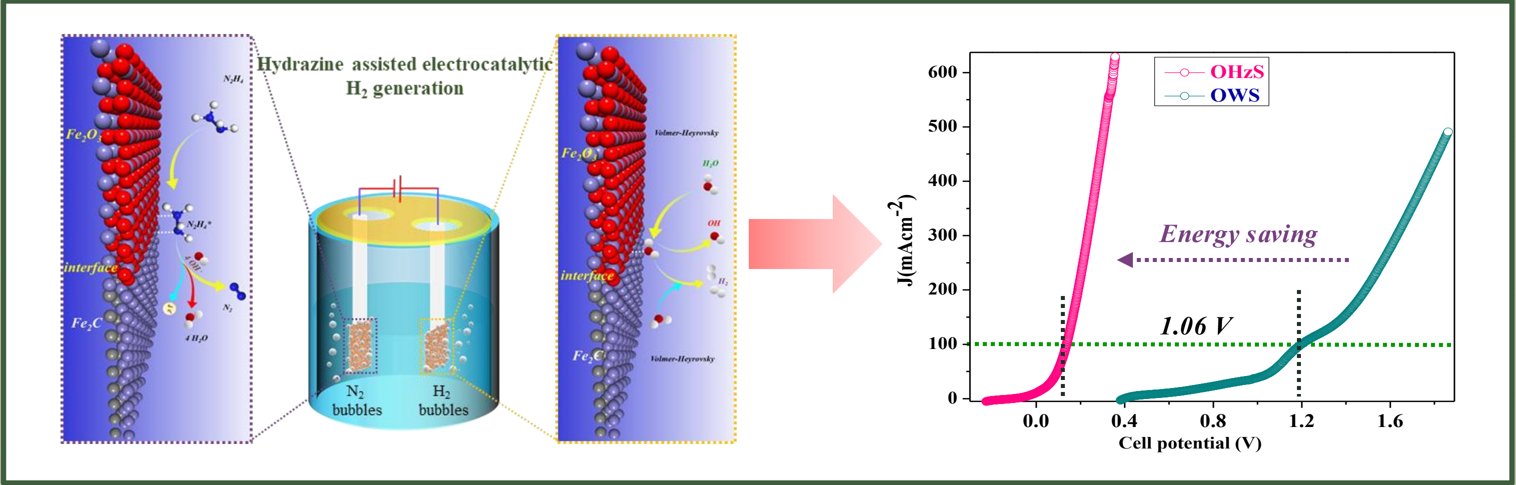
Recently we developed the coupled water electrolysis based on the "Interface Engineering and Dual Active Sites in Iron Oxycarbide Nanoclusters Enable Energy-Efficient H_2 Evolution via Electrocatalytic Hydrazine Oxidation"

Catalyst design



FCU LAB-WATER ELECTROLYSIS

Coupled water electrolysis



- ✓ **Extremely low potential:** Theoretically spontaneous!
- ✓ **Cell voltage:** < 0.5 V possible
- ✓ **Energy savings:** 70-80%
- ✓ **Limitation:** Hydrazine toxicity and cost

Challenges & Solutions

Technical Challenges

Challenge	Impact	Solutions
Catalyst Selectivity	Unwanted byproducts	Rational catalyst design, bimetallics, surface engineering
Organic Fouling	Catalyst deactivation	Self-cleaning surfaces, periodic regeneration, pulsed operation
Mass Transport	Substrate depletion	Flow systems, 3D electrodes, enhanced mixing
Product Separation	Mixed streams	Membrane separators, sequential processing
Faradaic Efficiency	Competing reactions	Potential control, selective catalysts, pH optimization

Challenges & Solutions

Scale-up considerations

- ✓ Substrate variability: Real wastewater composition varies
  - ✓ Solution: Adaptive catalysts, AI-controlled operation
- ✓ Long-term stability: 5000+ hour lifetime needed
  - ✓ Solution: Robust catalyst formulations, advanced characterization
- ✓ Co-product markets: Demand limitations for chemicals
  - ✓ Solution: Diversified product portfolio, market analysis

Recent Advances & Future Outlook

State-of-the-Art Developments (2023-2025)

High-Entropy Catalysts

NiCoFeMnCr for urea oxidation:

1.32 V at 100 mA/cm²

Atomic Layer Deposition

Precise Pt coating on Ni:

Enhanced methanol oxidation

In-Situ Spectroscopy

Real-time mechanism

understanding for better design

Commercial Pilots (2024-2025)

Multiple demonstrations coupling H_2 production with wastewater treatment at 10-100 kW scale. Technology transitioning from lab to early commercial deployment.

Recent Advances & Future Outlook

Emerging Directions

- **Multi-substrate systems:** Processing mixed waste streams (real wastewater)
  - AI-driven adaptive control for varying composition
- **Photo-assisted coupled electrolysis:** Solar + favorable anodic reactions
  - Further voltage reduction, daytime peak operation
- **CO_2 co-utilization:** Capture CO_2 from oxidation, reduce at cathode
  - Carbon-neutral syngas production (H_2 + CO)
- **Microbial electrolysis cells (MEC):** Biological catalysts
  - Very low voltage (<0.5 V), direct wastewater processing

Conclusions & Key Takeaways

Paradigm Shift in H_2 Production

Coupled water electrolysis transforms H_2 production from a single-product energy consumer to a multi-product value generator

Key advantages

Energy Efficiency ⚡

- 20-40% electrical energy savings
- Lower operating temperatures possible
- Reduced cooling requirements

Economics 💰

- \$2-3/kg H_2 achievable
- Valuable co-products offset costs
- Waste treatment credits

Conclusions & Key Takeaways

Key advantages

Sustainability ♻️

- Waste valorization (circular economy)
- Pollution remediation
- Carbon-neutral pathways

Versatility 🔄

- Multiple substrate options
- Industry integration opportunities
- Scalable (kW to MW)

Conclusions & Key Takeaways

Implementation pathway

1. Identify waste streams and available substrates
2. Match catalyst systems to specific applications
3. Pilot-scale demonstration (1-10 kW)
4. Economic validation with co-product markets
5. Scale-up to commercial deployment

Future Vision: Coupled electrolysis as standard practice for sustainable H_2 production integrated with waste treatment and chemical manufacturing by 2030-2035

Thank you for your attention