WRI INDIA

INTRODUCTION TO GREEN HYDROGEN ECONOMY

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ABOUT WRI INDIA

WRI India is a research organization that turns big ideas into action at the nexus of environment, economic opportunity and human well-being

We work with governments, businesses, multilateral institutions and civil society to improve people's lives and protect nature.

AGENDA

1. Introduction to Hydrogen
2. What & Why of Green Hydrogen
3. Green Hydrogen Technologies
4. Policy and Regulations for Green Hydrogen
5. Q & A

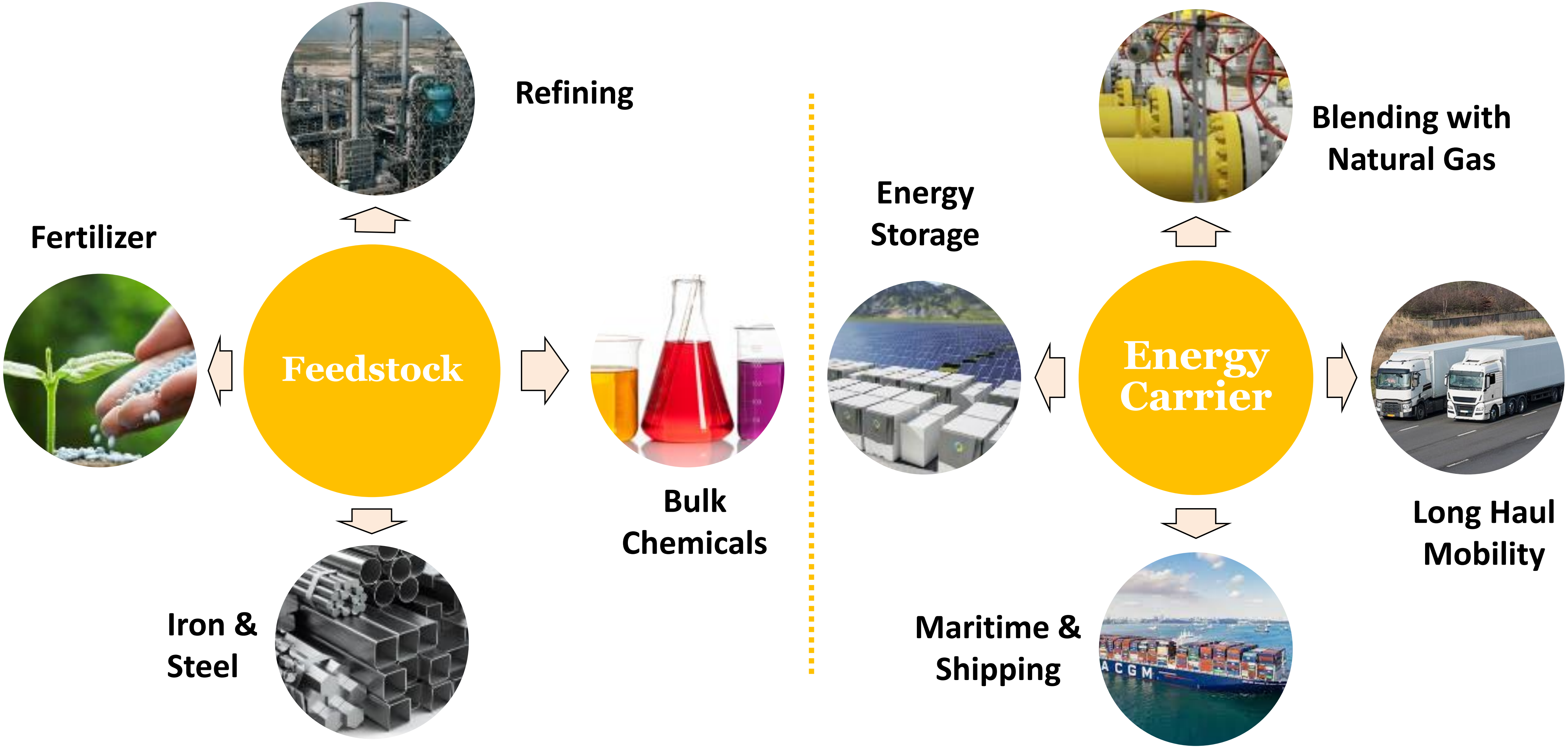
INTRODUCTION TO HYDROGEN

INTRODUCTION TO HYDROGEN

- Hydrogen is the lightest and the most abundant element in the universe
- Hydrogen is colourless and odourless
- Lowest density among all gases, atomic weight of 1
- Hydrogen is only found in compound form with other elements eg: water (H_2O), ammonia (NH_3), methane (CH_4)
- Despite its sheer abundance, hydrogen does not occur naturally as a gas

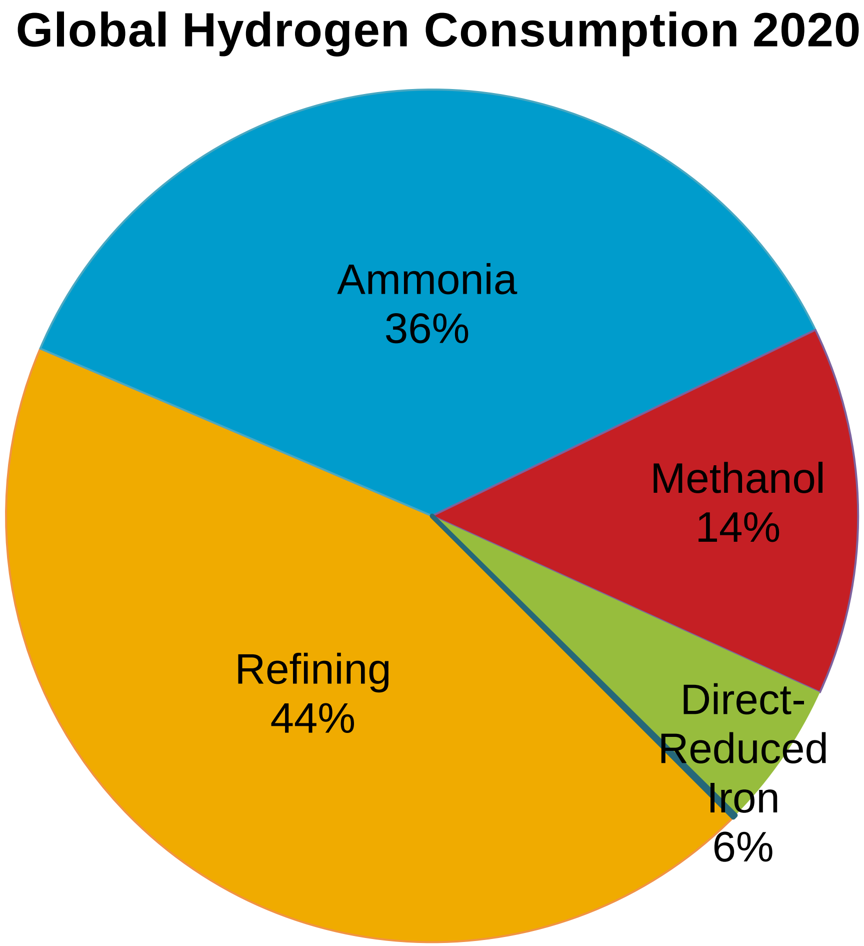
Property	Hydrogen	Comparison
Density (gaseous)	0.089 kg/m^3 (0°C, 1 bar)	1/10 of natural gas
Density (liquid)	70.79 kg/m^3 (-253°C, 1 bar)	1/6 of natural gas
Boiling point	-252.76°C (1 bar)	90°C below LNG
Energy per unit of mass (LHV)	120.1 MJ/kg	3x that of gasoline
Energy density (ambient cond., LHV)	0.01 MJ/L	1/3 of natural gas
Specific energy (liquefied, LHV)	8.5 MJ/L	1/3 of LNG
Flame velocity	346 cm/s	8x methane

HYDROGEN: FEEDSTOCK & ENERGY CARRIER



SECTORAL APPLICATIONS OF HYDROGEN

INDUSTRY SECTOR	KEY APPLICATIONS
CHEMICAL	• Ammonia • Polymers • Resins
REFINING	• Hydrocracking • Hydrotreating
IRON & STEEL	• Annealing • Blanketing gas • Forming gas
GENERAL INDUSTRY	• Semiconductor • Propellant fuel • Glass production • Hydrogenation of fats • Cooling of generators



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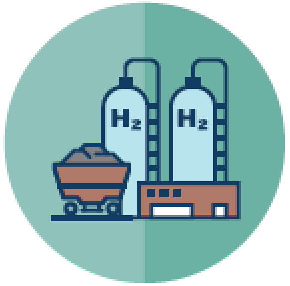
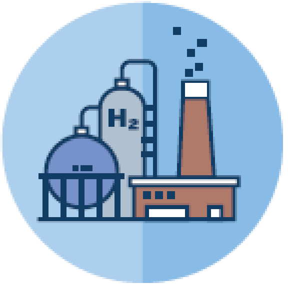
WHAT & WHY OF GREEN HYDROGEN

COLOUR CODES OF HYDROGEN



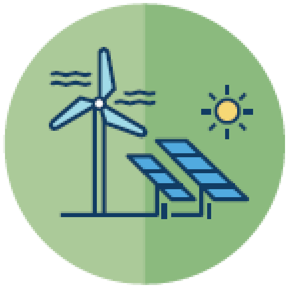
Grey/Brown Hydrogen

- ❑ Produced via Steam methane reformation (natural gas) or coal gasification
- ❑ High carbon intensity of around 9-12 kg of CO_2/ kg of hydrogen.



Blue Hydrogen:

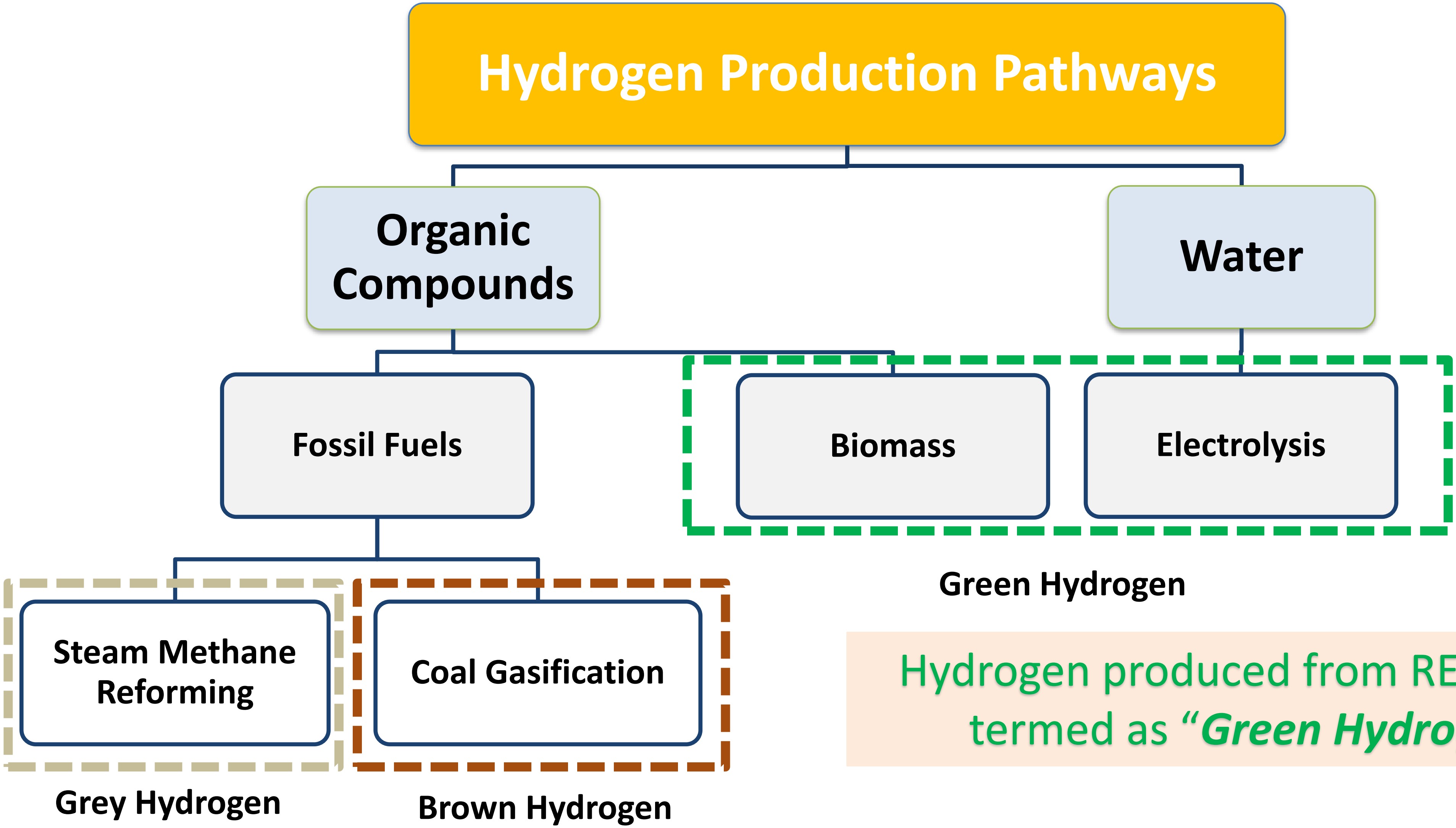
- ❑ Produced via Steam methane reformation or coal gasification with carbon capture & storage technologies to reduce carbon emissions.
- ❑ The carbon intensity is around 1-4 kg of CO_2/ kg of hydrogen.



Green Hydrogen

- ❑ Produced using electrolysis of water with electricity generated by renewable energy. This is the least carbon intensive process.
- ❑ The carbon intensity is around 0-0.6 kg of CO_2/ kg of hydrogen.

HYDROGEN PRODUCTION PATHWAYS

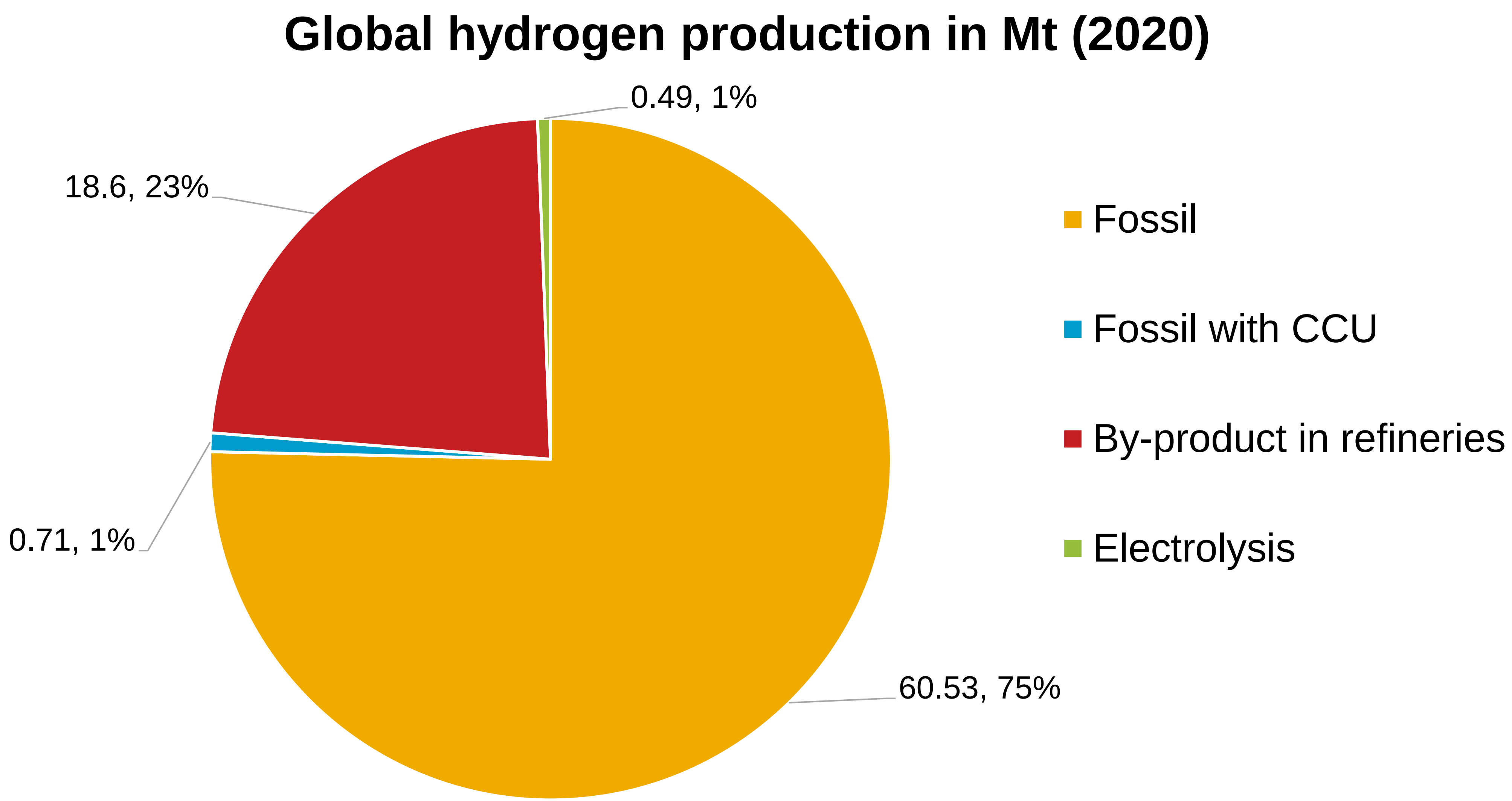


Hydrogen produced from RE sources termed as ***"Green Hydrogen"***

EMISSION INTENSITY OF HYDROGEN PRODUCTION

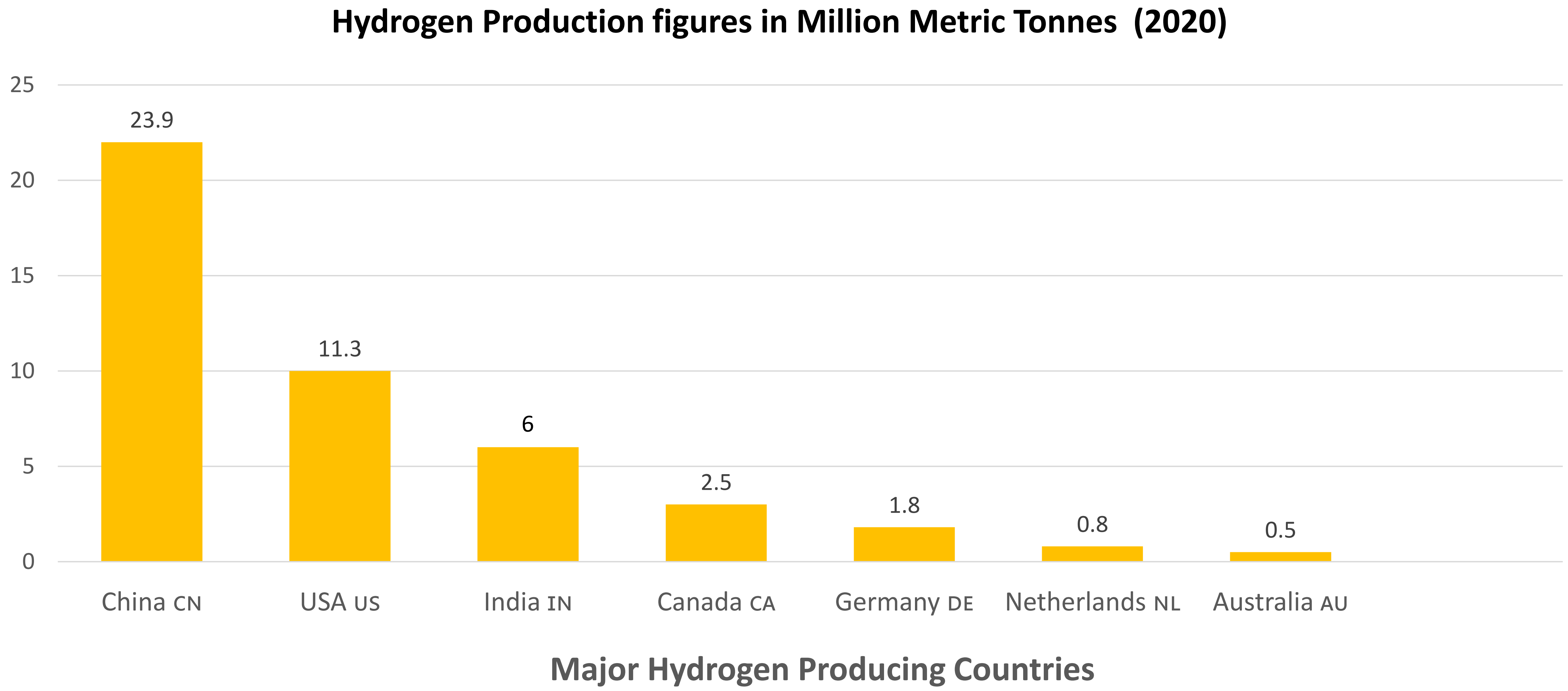
Technology	Colour Code	CO_2 footprint (kg of CO_{2e}/kg of H_2)
Coal Gasification		14.7 - 26.1
Steam Methane Reforming		10.1 - 17.2
Methane Pyrolysis		4.2 - 9.1
Steam Methane Reforming with CCUS		2.8 - 9.1
Electrolysis using Solar Electricity		1.3 - 2.5
Electrolysis using Wind Electricity		0.5 - 1.1
Electrolysis using Nuclear Electricity		0.5 - 1.0

HYDROGEN PRODUCTION TECHNOLOGY



Source: IEA 2021 Report

GLOBAL HYDROGEN CONSUMPTION



Source: Statista

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WHY GREEN HYDROGEN NOW

Climate Goals: Hydrogen can decarbonize Hard-to-abate sectors. (Northern Horizons Project, UK: 10 GW off-shore wind for GH_2 at CoP26)

Technology development: Increased efficiency, reliability and lower consumption of raw materials

Cost Trends: Economies of scale, automation, cheaper raw materials, are expected to drive cost reduction similar to solar & batteries

Global Momentum for Hydrogen

19 countries have released hydrogen strategies, **20 countries** publicly announced development of hydrogen strategies

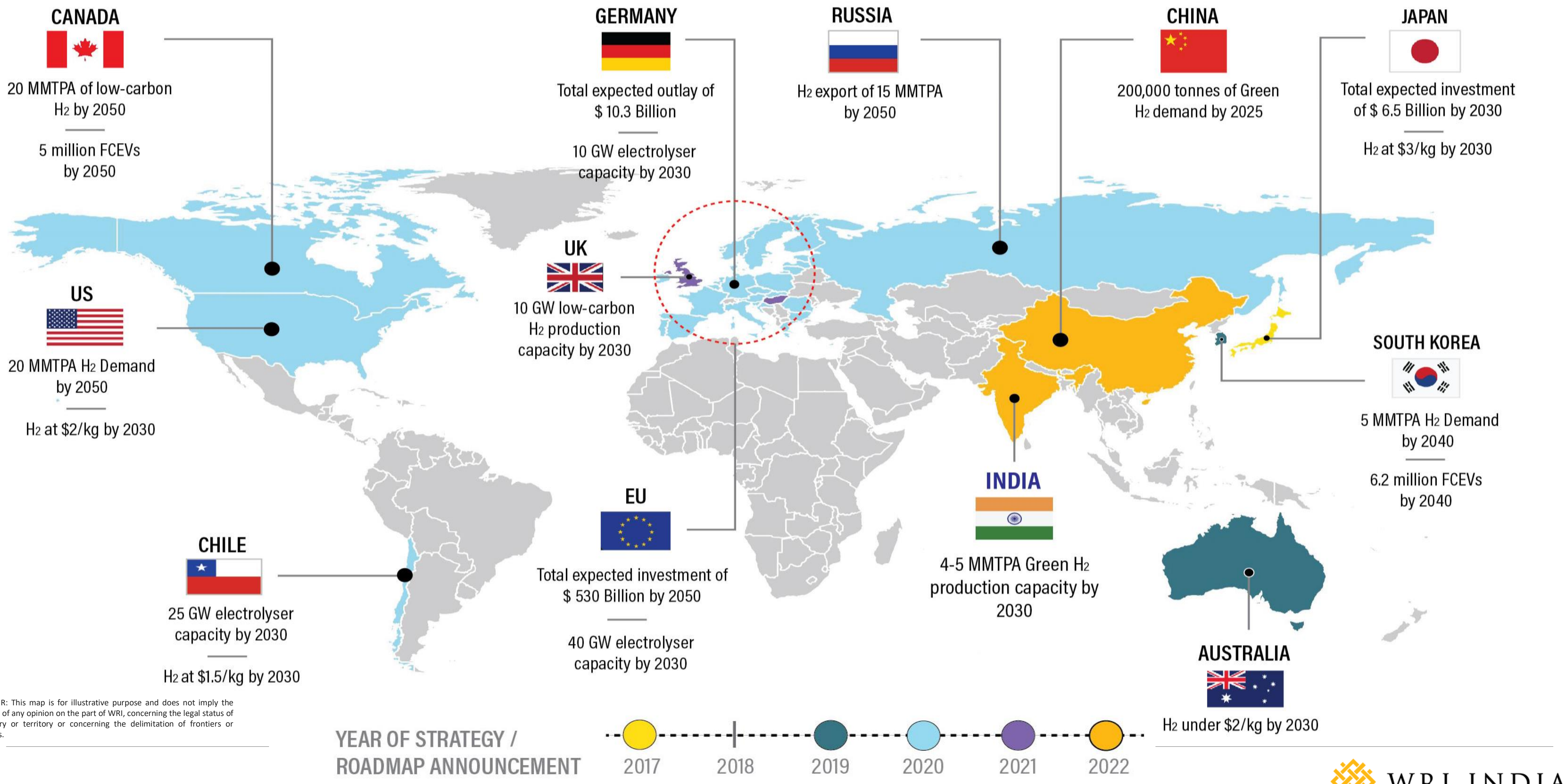
EU: 40 GW Electrolyser (2040), EUR 470 b investment (2050)

USA: 20 MMT Demand (2030), $2/kg in 10 yrs

China: 100 GW Electrolyser (2030), 5 MMT demand by 2030

Japan: 1 GW Electrolyser (2030), $20 b investment outlay

GREEN HYDROGEN- GLOBAL STRATEGY OUTLOOK



DISCLAIMER: This map is for illustrative purpose and does not imply the expression of any opinion on the part of WRI, concerning the legal status of any country or territory or concerning the delimitation of frontiers or boundaries.

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WHY SHOULD NATIONS INVEST IN GREEN HYDROGEN

Energy Security

Self-reliance in hydrogen production can **reduce India's energy and ammonia imports**

Decarbonisation

Green hydrogen can **catalyse >20% emission reduction**, primarily through industrial decarbonisation

Hydrogen Export

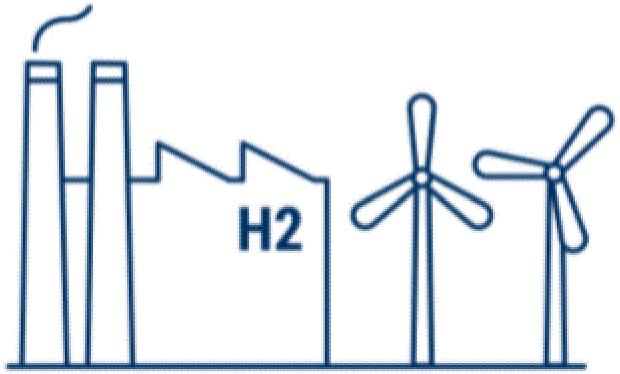
Driven by the **abundant availability of RE**, India can tap into significant **green H2 export market**

Import of crude, LNG, and petroleum products for 2020 valued at **₹7.8 lakh crores ($104 billion)**

Hydrogen adoption to support **India's commitments at the COP26**

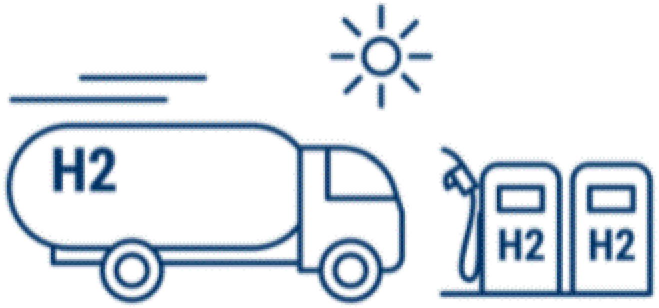
GREEN HYDROGEN TECHNOLOGIES

HYDROGEN TECHNOLOGIES



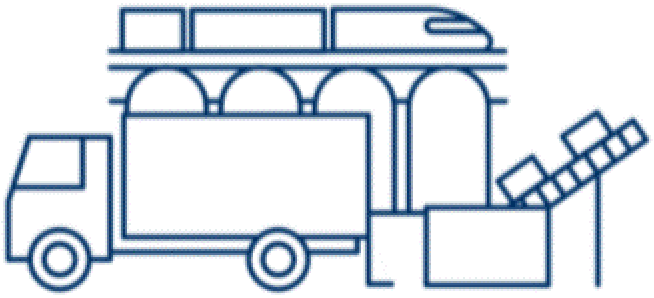
Production & Manufacturing

- ❑ Electrolysers
- ❑ Fuel Cells
- ❑ Bio-Hydrogen



Transport & Storage

- ❑ Pipelines & Bunkers
- ❑ Bulk Transport
- ❑ Transformation

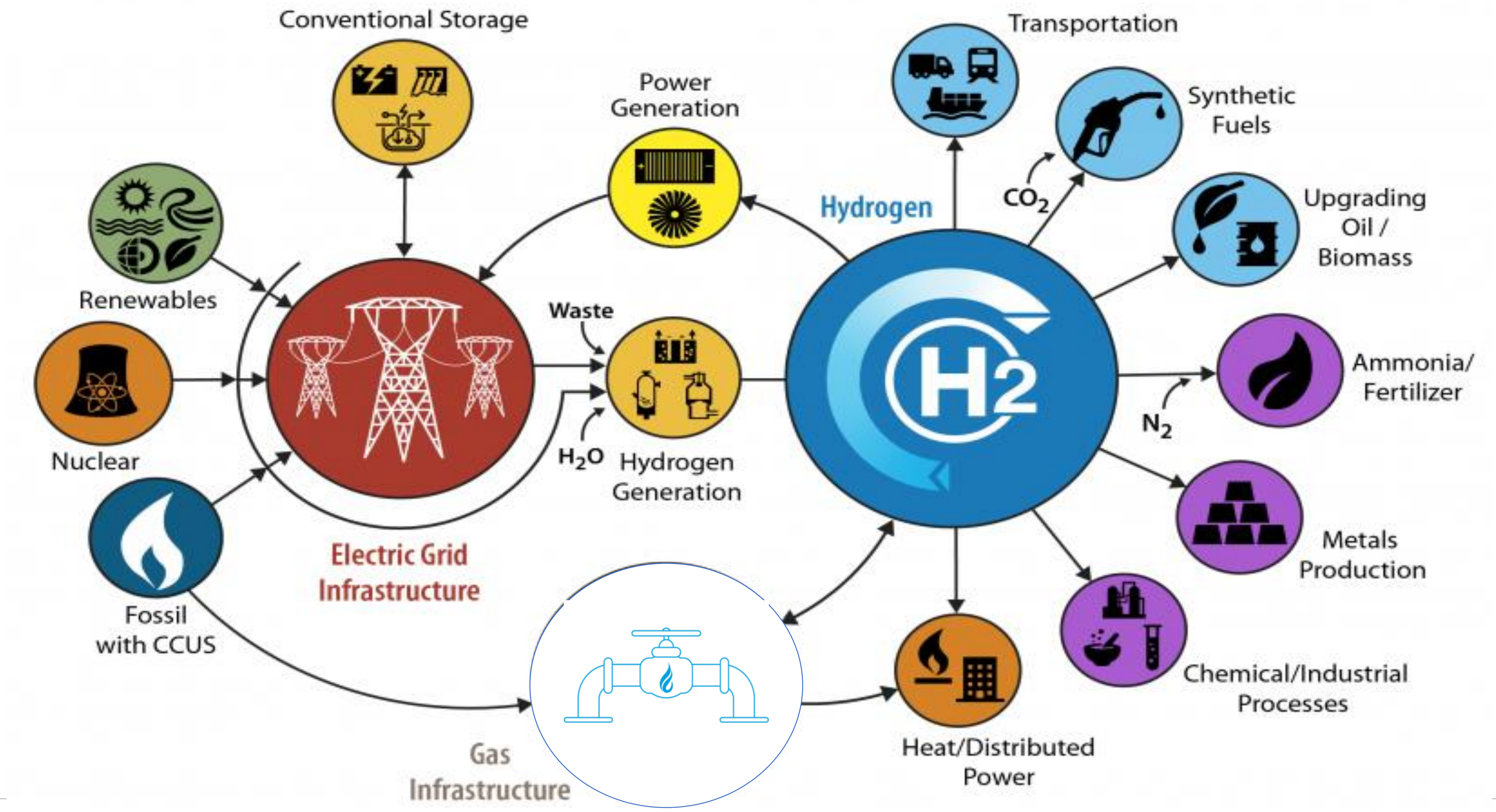


Utilization & Applications

- ❑ Hydrogen Derivatives
- ❑ Fuel for Energy
- ❑ Industrial Feedstock

IRENA

HYDROGEN VALUE CHAIN



US DOE

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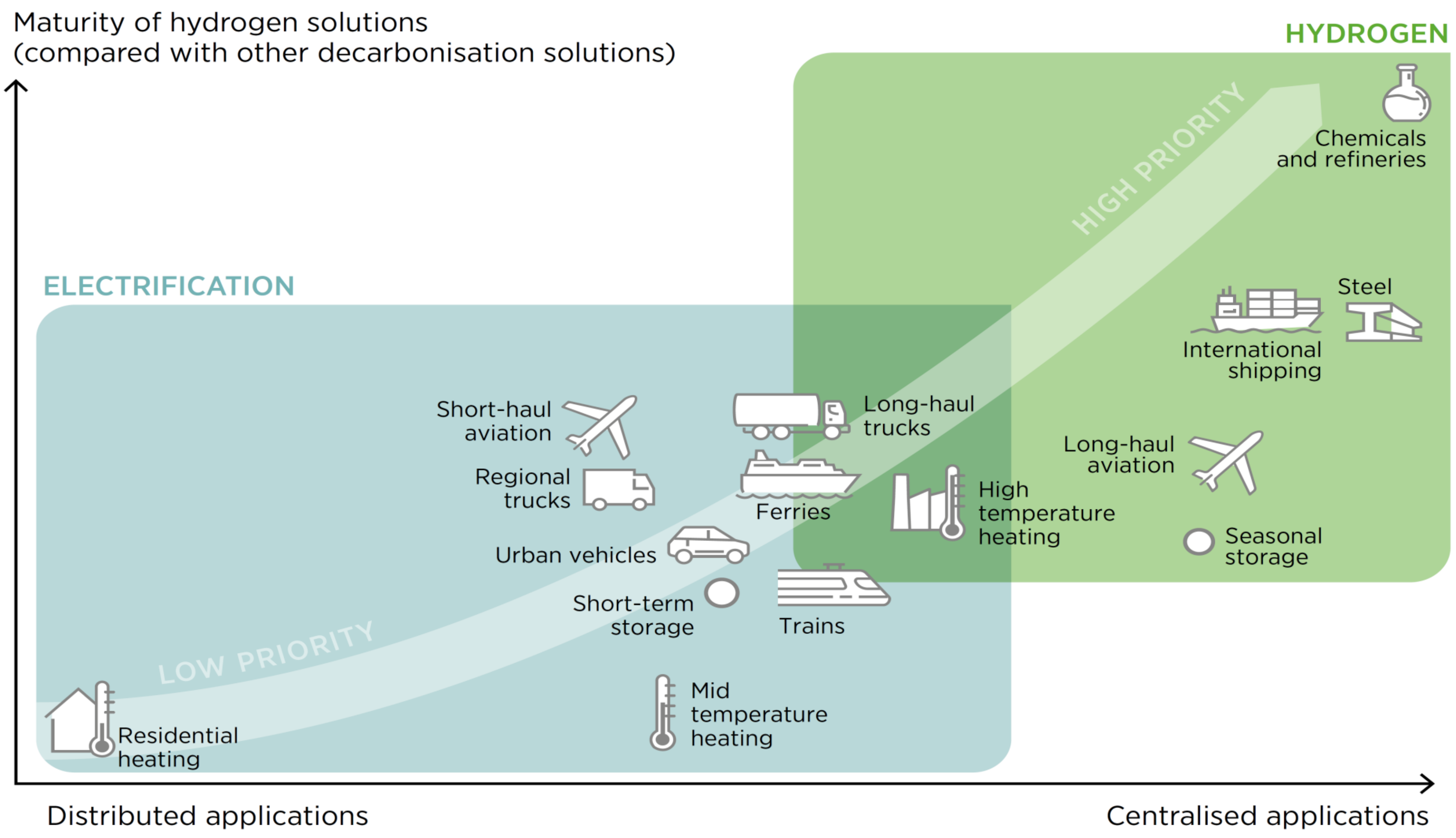
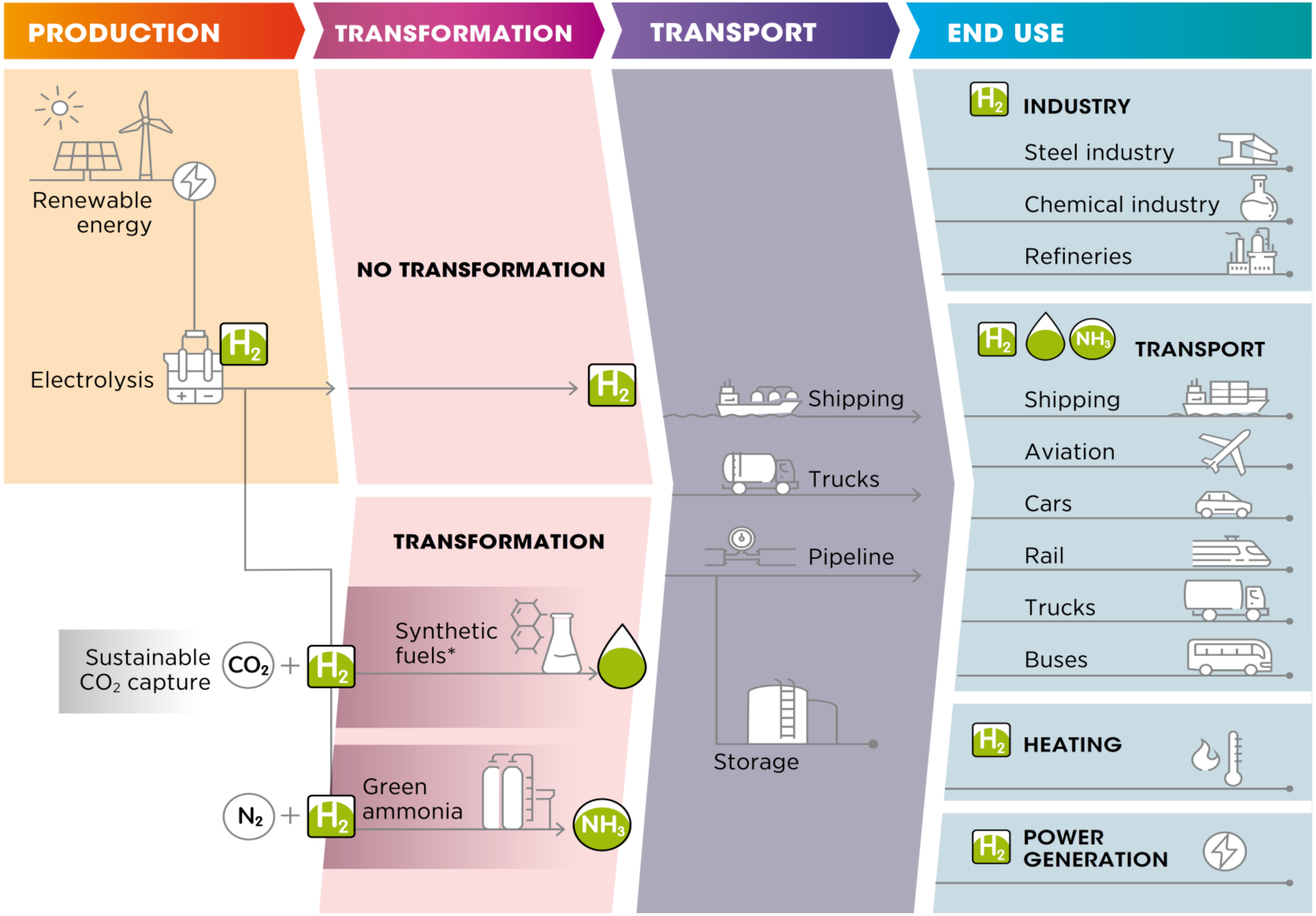
GREEN HYDROGEN- APPLICATIONS



IRENA

GREEN HYDROGEN- A POTENTIAL PATHWAY FOR DECARBONIZATION

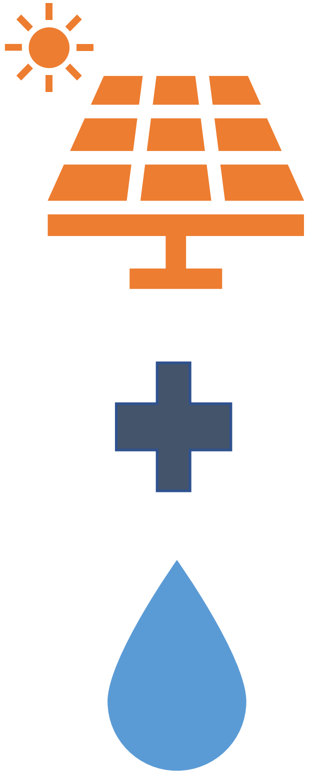


IRENA

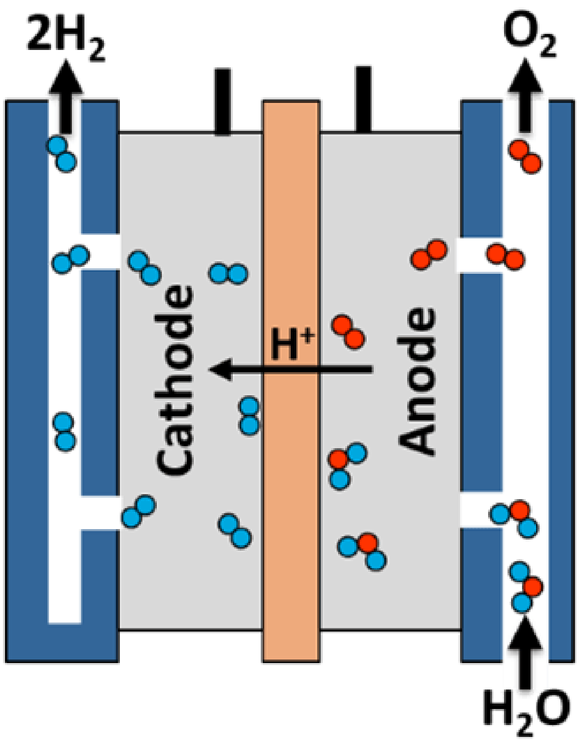
GREEN HYDROGEN PRODUCTION

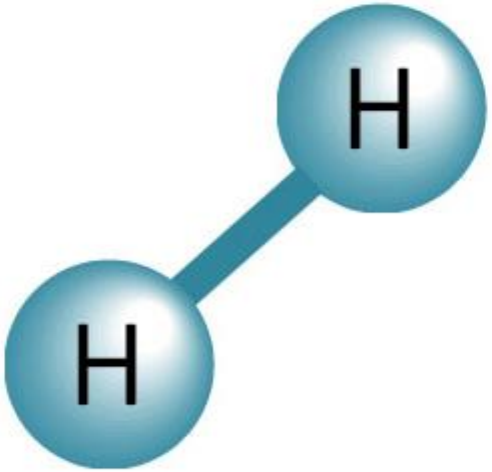
Renewable Energy

Water



Electrolyser





An electrolyser uses electricity to **split water (H_2O)** into its constituent molecules (ie: **H_2 and O_2**)

ELECTROLYSER REQUIREMENTS

Electrodes

Electrode in an electric conductor which provides the physical interface between the electric circuit providing the energy and the electrolyte

Electrolyte

A substance containing free ions which are the carrier of electric current in the electrolyte

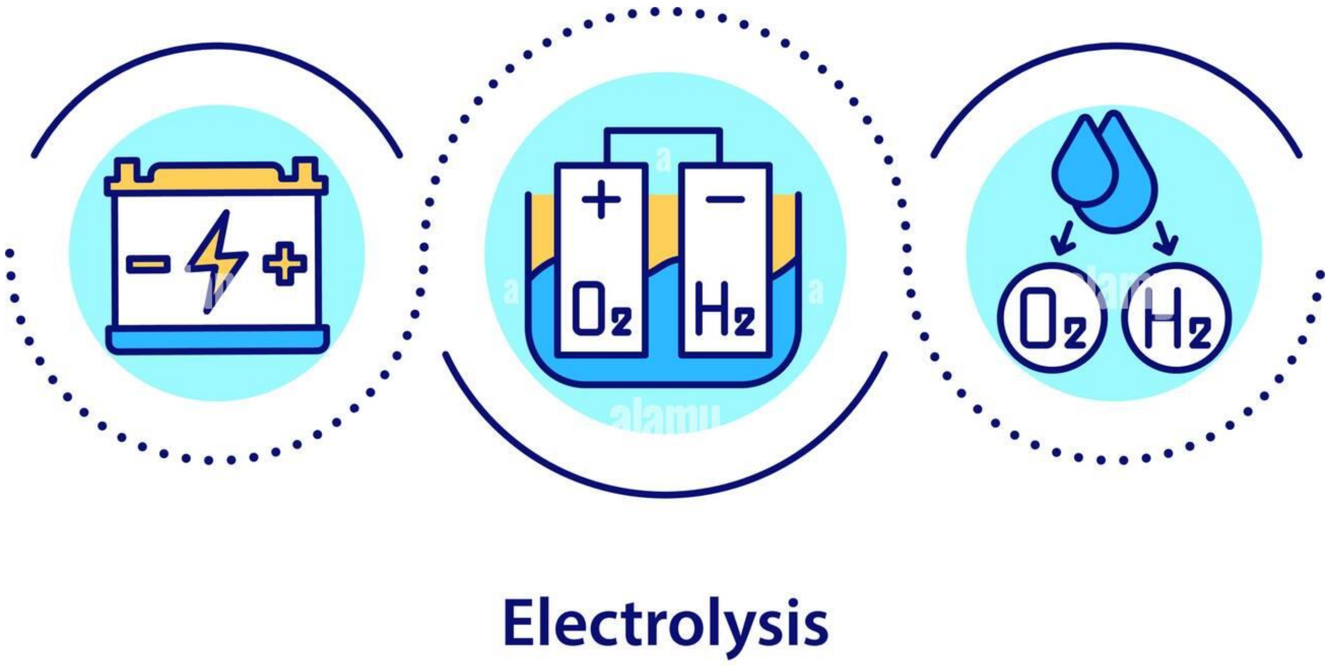
Key Requirements

- ❑ DI Water
- ❑ Renewable Energy

ELECTROLYSER TECHNOLOGIES

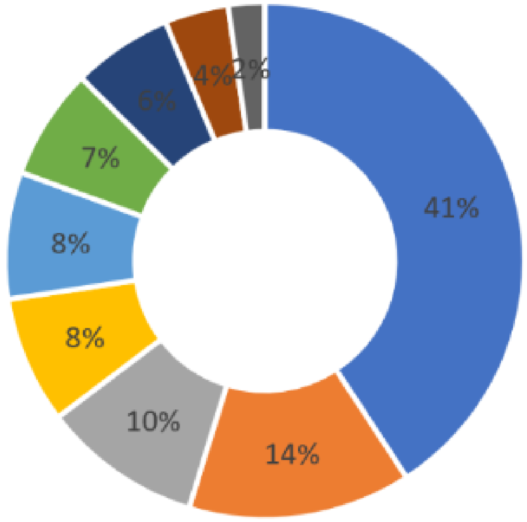
Technologies

- ❑ Alkaline Water Electrolysis
- ❑ PEM Electrolysis
- ❑ Solid Oxide Electrolysis
- ❑ Anion Exchange Membrane Electrolysis



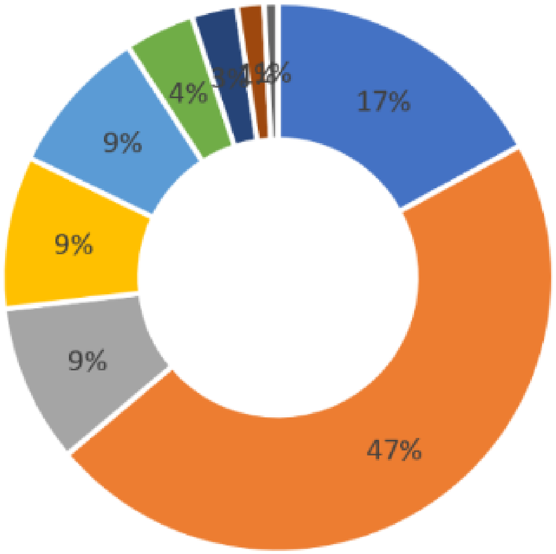
COMPONENT LEVEL BREAK-UP FOR ELECTROLYSER

Alkaline electrolyser



~ 84% of the cost can be domestically sourced

PEM electrolyser



~ 23% of the cost can be domestically sourced

COMPARISION OF DIFFERENT TECHNOLOGIES

Sr. No.	Characteristics	Alkaline	PEM	SOEC
1	Electrical efficiency (%LHV)	63-70	56-60	74-81
2	Operating pressure (bar)	1-30	30-80	1
3	Operating temperature (^{0}C)	60-80	50-80	650-1000
4	Stack life (operating hours)	60,000-90,000	30,000-90,000	10,000-30,000
5	Load range (%, relative to nominal load)	10-110	0-160	20-100
6	Plant footprint (m^2/kWe)	0.095	0.048	-
7	CAPEX (USD/kWe)	500-1400	1100-1800	2800-5600

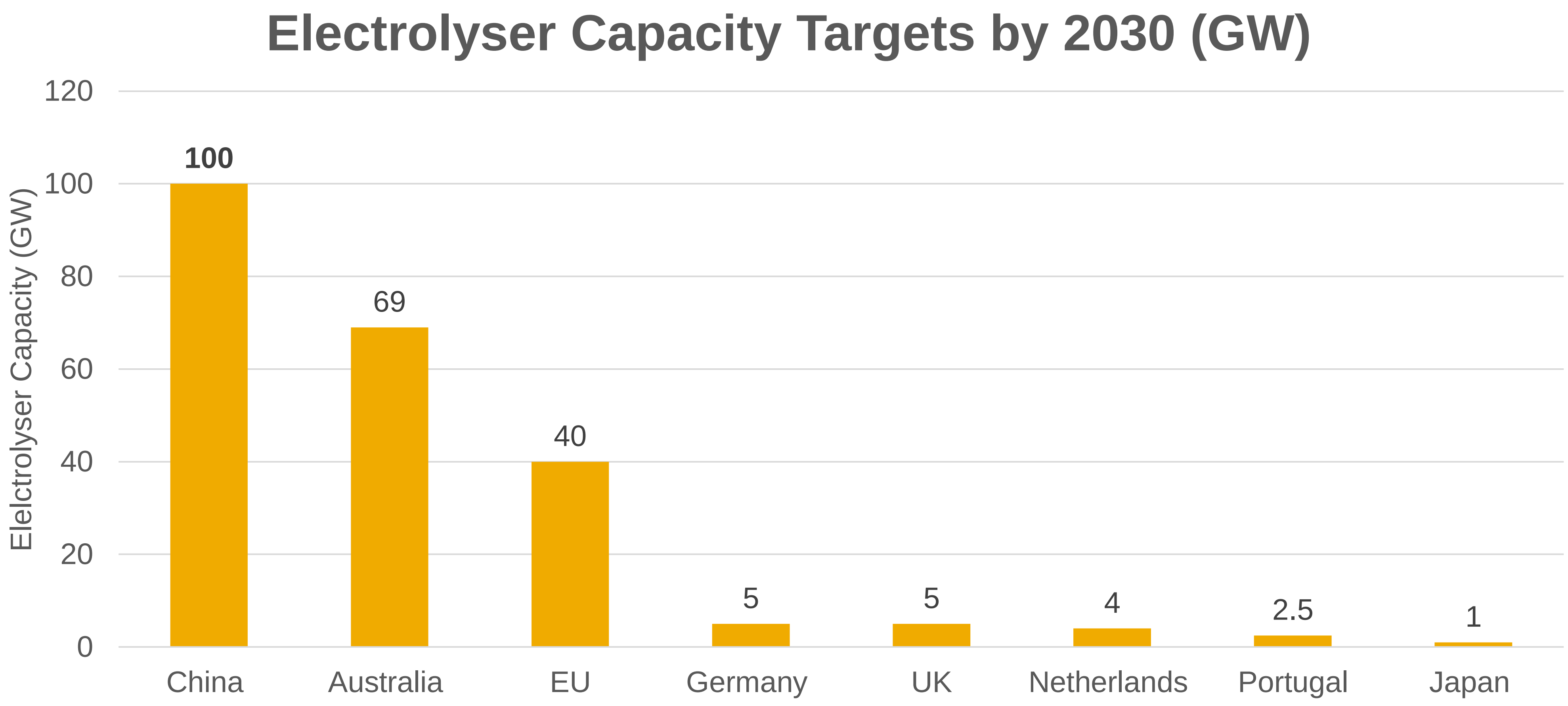
IEA Report, 2019

SUMMARY OF DIFFERENT TECHNOLOGIES

Electrolyser Technology	
Alkaline	○ Alkaline water electrolysis is mature and most widely used technology. ○ Alkaline water electrolyser lifetime is higher and the annual maintenance costs are lower compared to PEM.
PEM	○ High current density and compact & can achieve high pressures. ○ Preferred where dynamic operation is required, due to short start-up time and it provides a broad load flexibility range.
SOEC	○ Solid oxide electrolysis is high temperature electrolysis and having high efficiency and interchangeable operation.
AEM	○ Cost effective materials for construction of system ○ Chemical and mechanical stability of membrane, unstable operation and reduced lifetime.

IEA Report, 2019

ANNOUNCED ELECTROLYSER CAPACITY TARGETS



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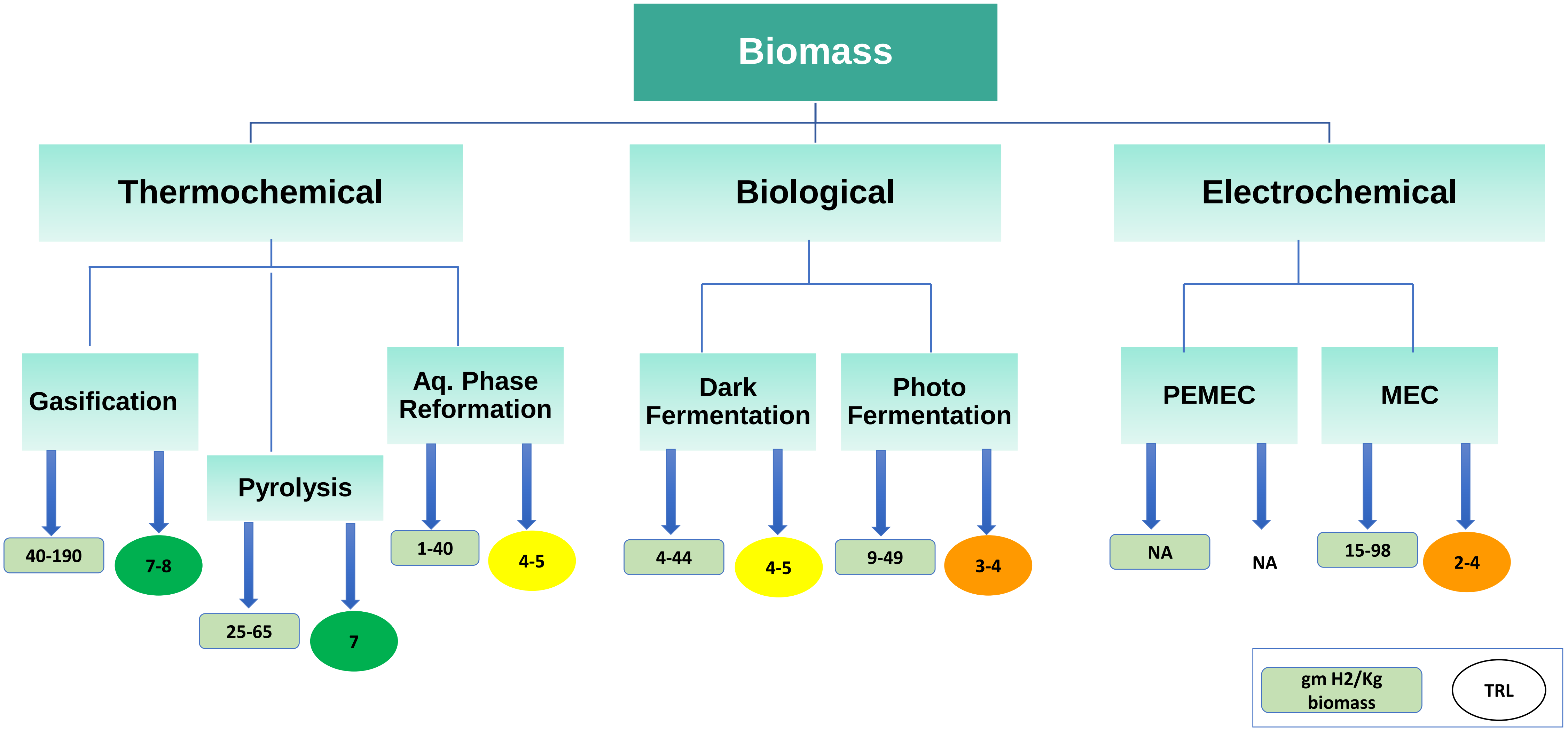
BIOMASS TECHNOLOGIES



[Biomass-to-hydrogen: A review of main routes production, processes evaluation and techno-economical assessment - ScienceDirect]

BIOMASS GASIFICATION

Air Gasification

- Max. 60 g/ kg of biomass achievable
- Typical yield of 35-40 g/ kg of biomass
- Typical composition of producer gas (H2-20%, CO – 20%, CO2- 12%, CH4 – 3%, N2 – 45% by volume)

Oxygen Gasification

- Using oxygen to increase H2 volume fraction by eliminating N2

Steam Gasification

- Using steam to increase H2 yield using C & CO through water gas reaction and water shift reaction

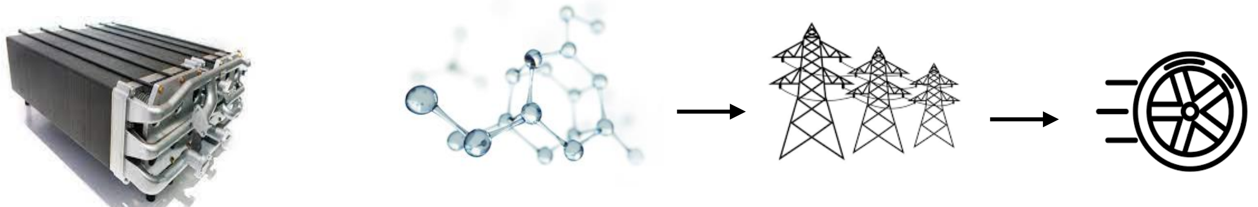
Oxy- steam Gasification

- Using steam & oxygen to increase H2 yield
- This yields 66 - 104 g / kg of biomass using excess steam as a reactant which depends on the H_2O/Biomass ratio.

Water gas : $C + H_2O \longrightarrow H_2 + CO - 131{,}400$ kJ

Water shift : $CO + H_2O \longrightarrow H_2 + CO_2 + 41{,}200$ kJ

FUEL CELL BASICS

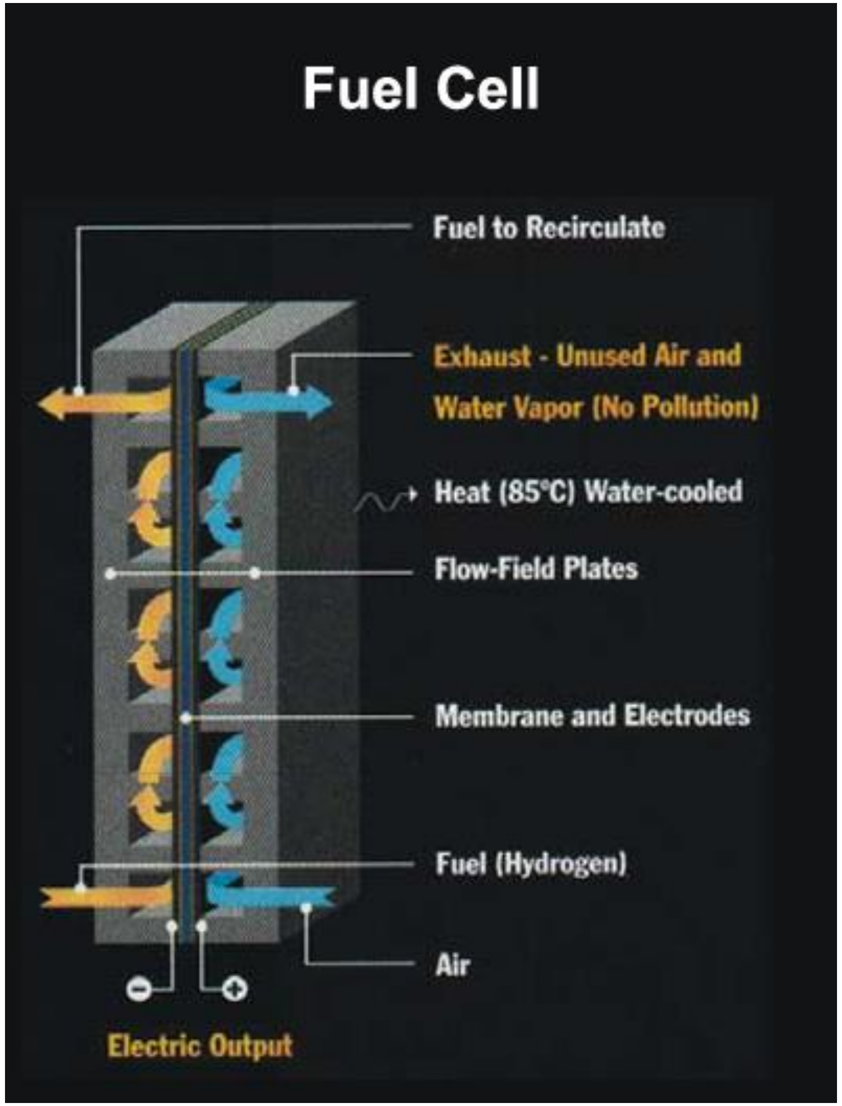


Fuel Cell | Chemical | Electrical | Mechanical

Energy conversion in fuel cell for mechanical output

Fuel Cell | Chemical | Electrical

Energy conversion in fuel cell for electrical output



General structure of a fuel cell

https://www.sciencedirect.com/science/article/pii/S1364032114000227

FUEL CELL HIGHLIGHT

Principles	Features
Electrochemical energy conversion	✓ High efficiency and energy density ✓ Elimination of noise
Fewer energy transformation	✓ High and consistent efficiency ✓ Prompt load-following
Operates best on Pure Hydrogen	✓ Emissions elimination ✓ Integration with renewables possible
Runs as long as fuel is supplied	✓ Long operational cycles ✓ High energy density
Expansion by addition of stacks	✓ Modularity ✓ Favourable integration with renewables
Static operation and no dynamic parts	✓ Reduced noise ✓ Modularity

https://www.sciencedirect.com/science/article/pii/S1364032114000227?

FUEL CELL APPLICATIONS

Portable Application

- Portable Power Generator
- Consumer Electronics
- Portable Military Equipment
- Battery Chargers
- Miniature Gadgets

Transportation Application

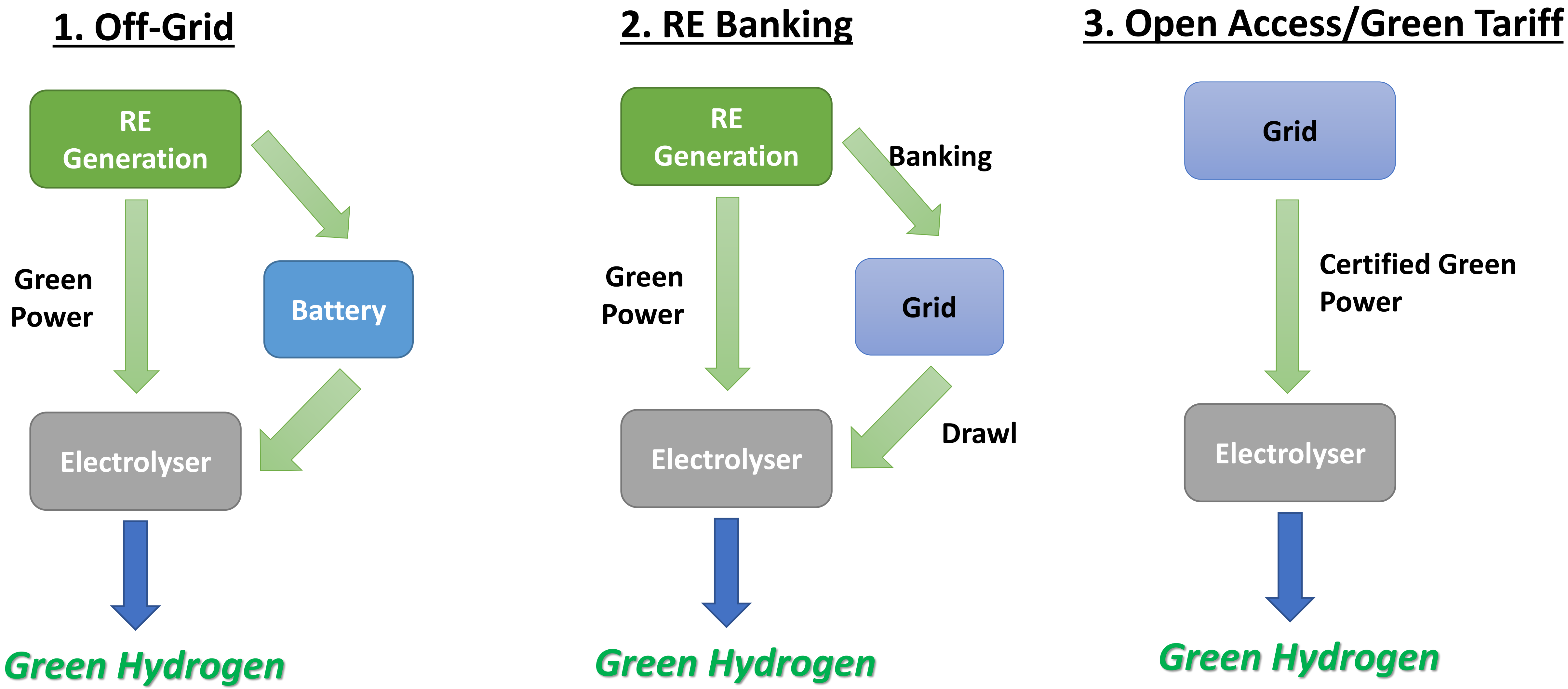
- Light traction vehicles
- Heavy Fuel Cell Vehicles
- Buses and trains
- Propulsion systems
- Military Submarines
- Boats and plane

Stationary Application

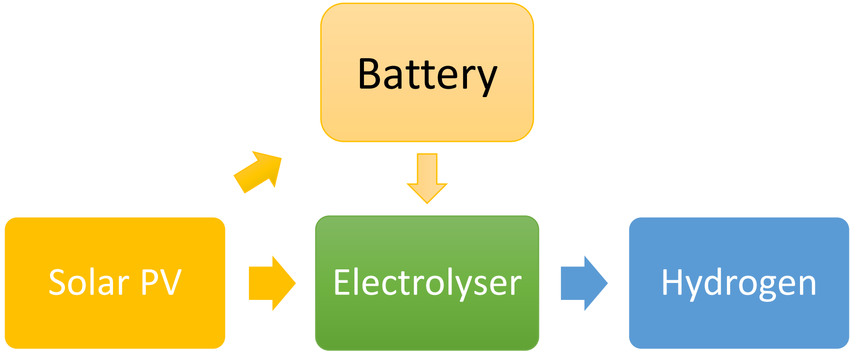
- Distributed Power Generation
- Combined Heat and Power
- Combined cooling and heat
- Back-up supply
- Distributed Generation

GREEN HYDROGEN PRODUCTION MODES

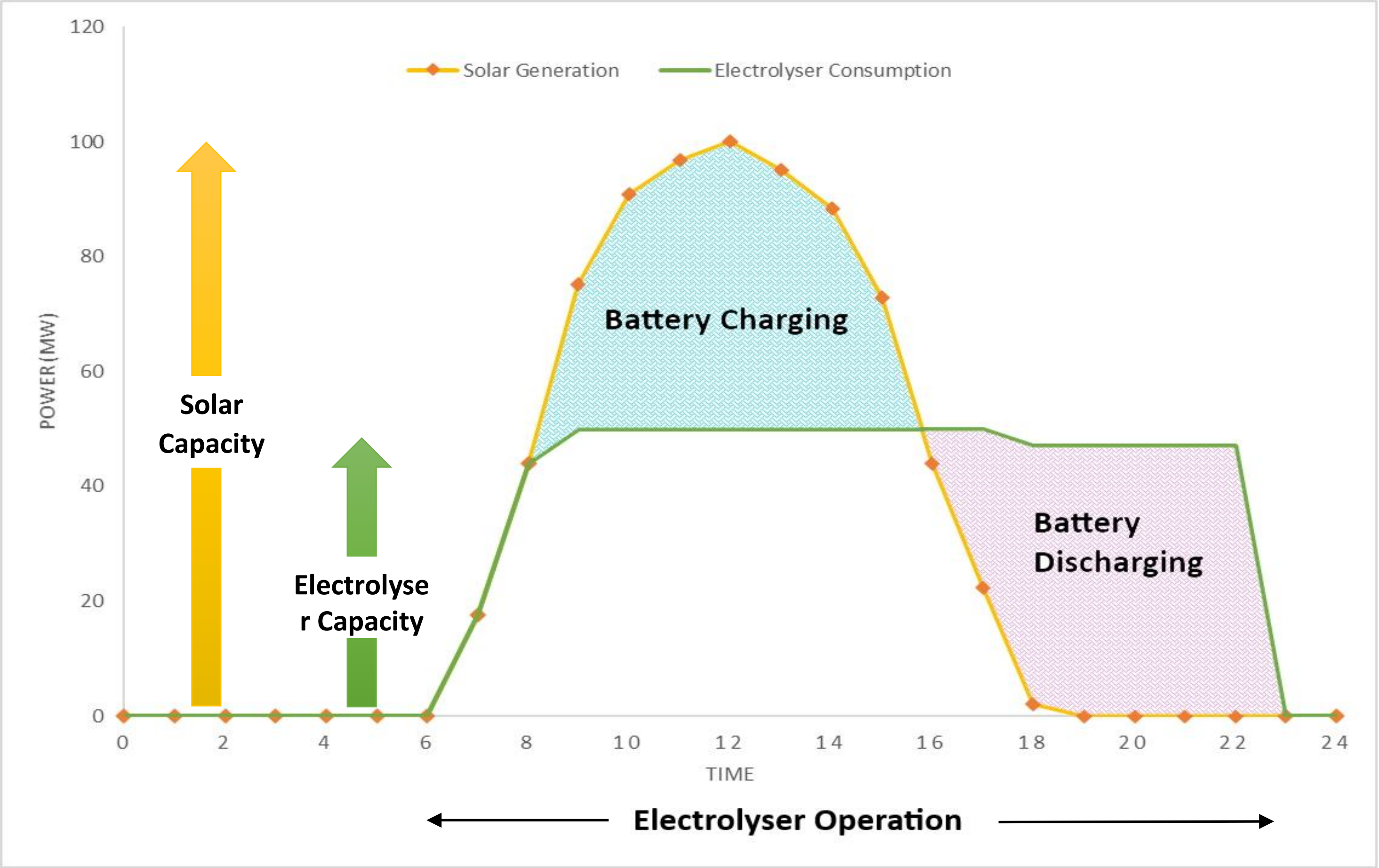
GREEN HYDROGEN PRODUCTION MODES



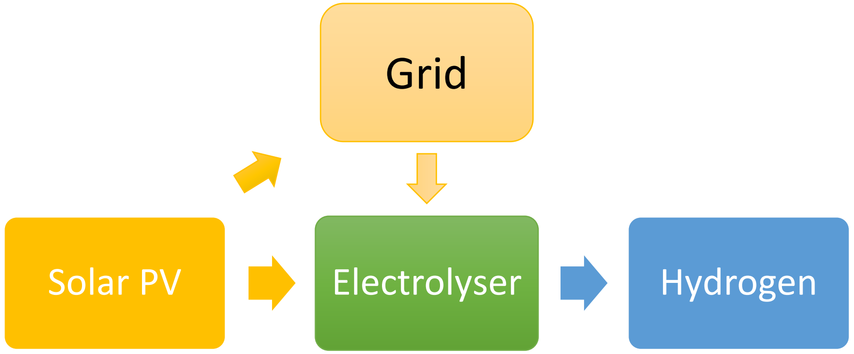
ELECTROLYSIS: OFF-GRID MODE



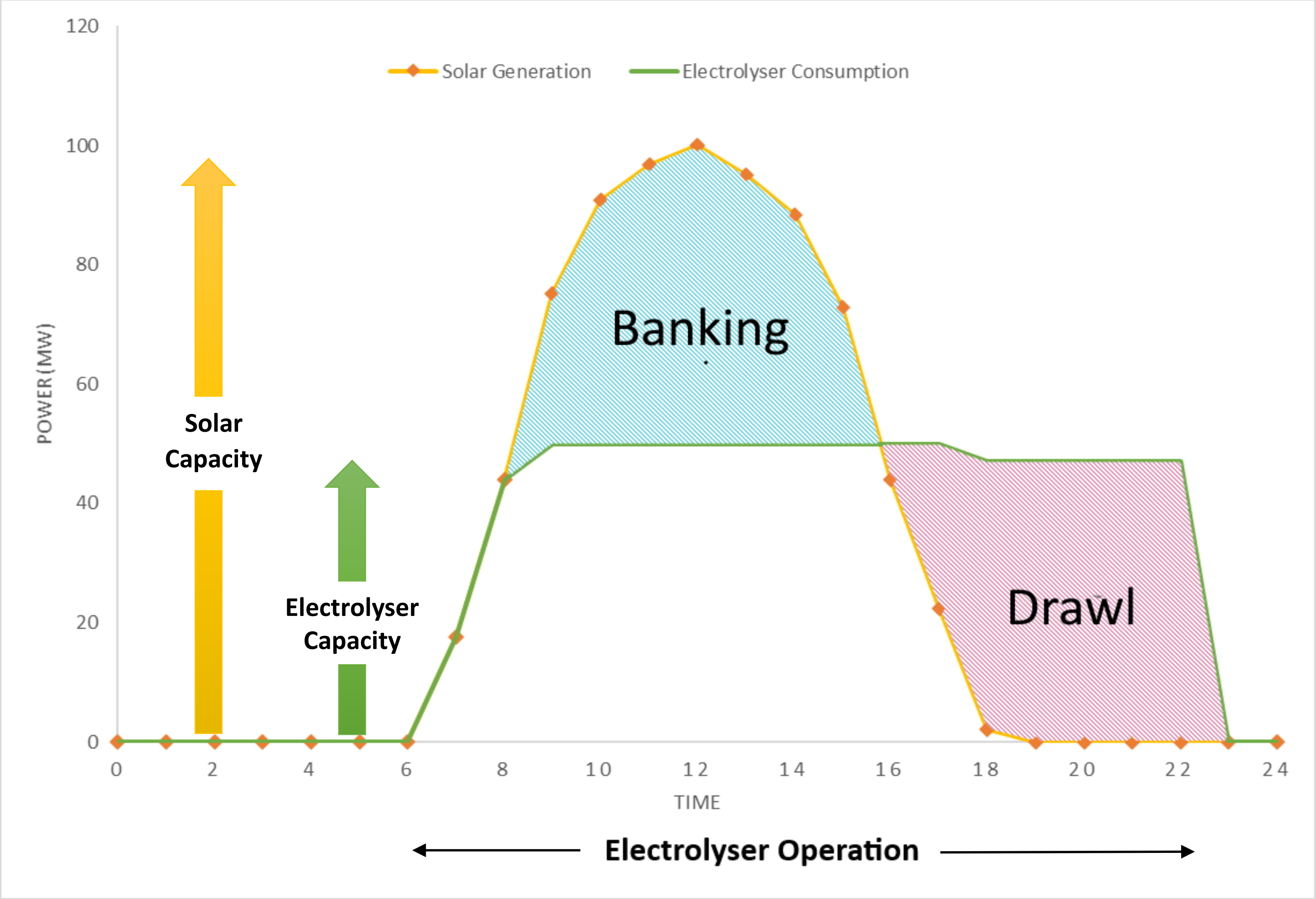
- ❑ **Cost of Battery Storage will increase cost of green Hydrogen production.**
- ❑ **Optimal balance would be needed between Electrolyser CUF and Battery Storage Capacity**



ELECTROLYSIS: GRID WITH BANKING

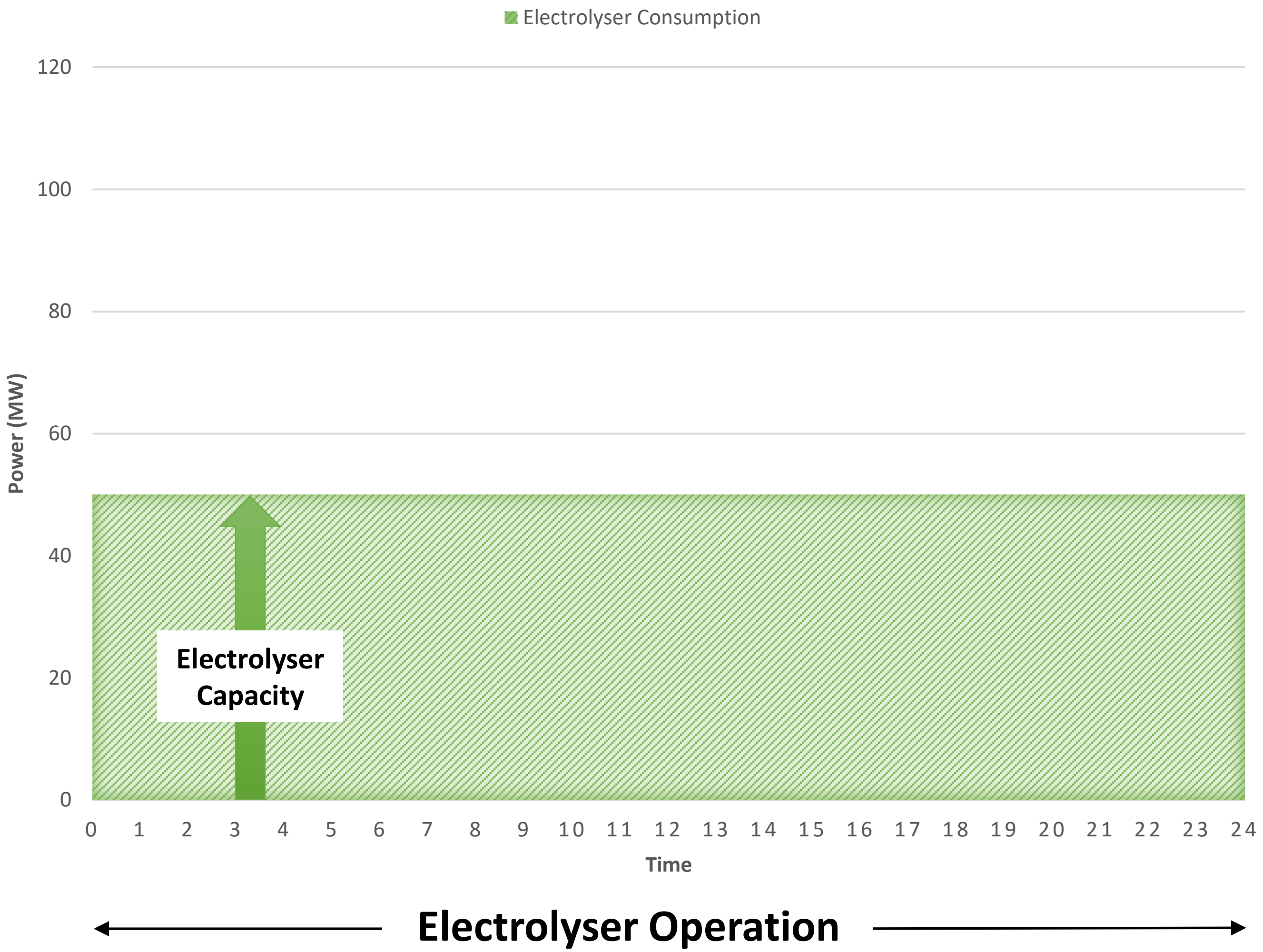


- RE banking is becoming more restrictive across states and also prohibited in many states
- Power generation assets on stand-by for off-peak generation



ELECTROLYSIS: 24X7 GREEN POWER

- Accounting for green power might not be accepted across all nations
- Regulations on definition of green power need to be standardized



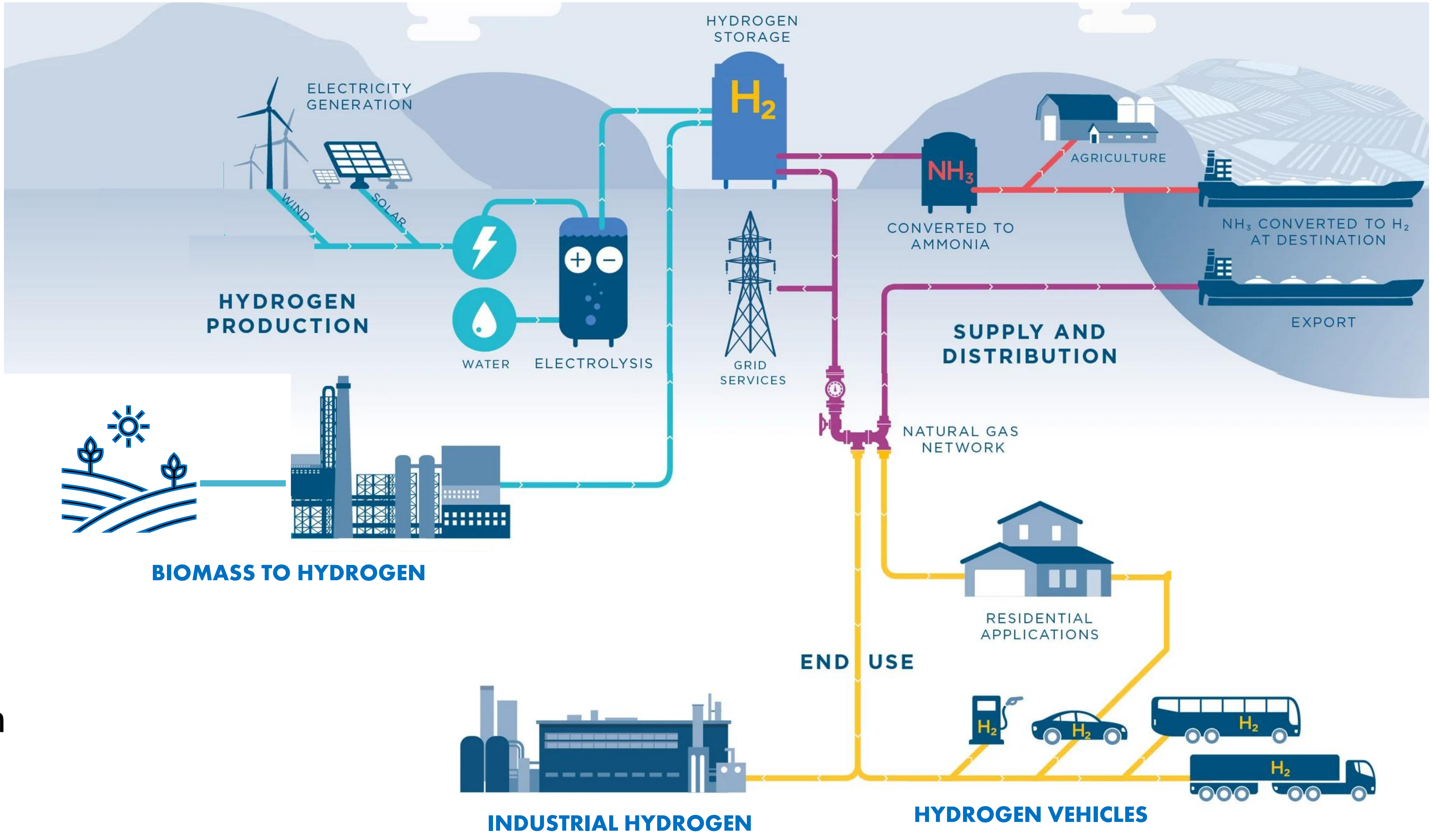
CHALLENGES WITH HYDROGEN

Transport, Storage & Handling

- **Weight and Volume**
  - Weight and volume of hydrogen storage systems are presently too high. Cylinder type rating are complex, hence costs are also high
- **Efficiency (round trip conversion, compression)**
  - Life-cycle energy efficiency is a challenge for chemical hydride storage in which the byproduct is regenerated off-board
  - Compression for achieving desired energy density can add upto 10%-30% additional energy costs
- **Material Durability**
  - Materials and components need to withstand the highly corrosive nature of hydrogen over repeated cycles
- **Codes and Standards**
  - Standardized hardware and operating procedures, and applicable codes and standards, are required

POTENTIAL HYDROGEN HUB

- Co-located production and consumption of GH_2
- Potential Hub Locations include Hazira, Gujarat & Vishakhapatnam, Andhra Pradesh
- Trunk Infrastructure to be supported which can inc.
  - ✓ Access to RE Power
  - ✓ Hydrogen Storage
  - ✓ Supply and Distribution Network

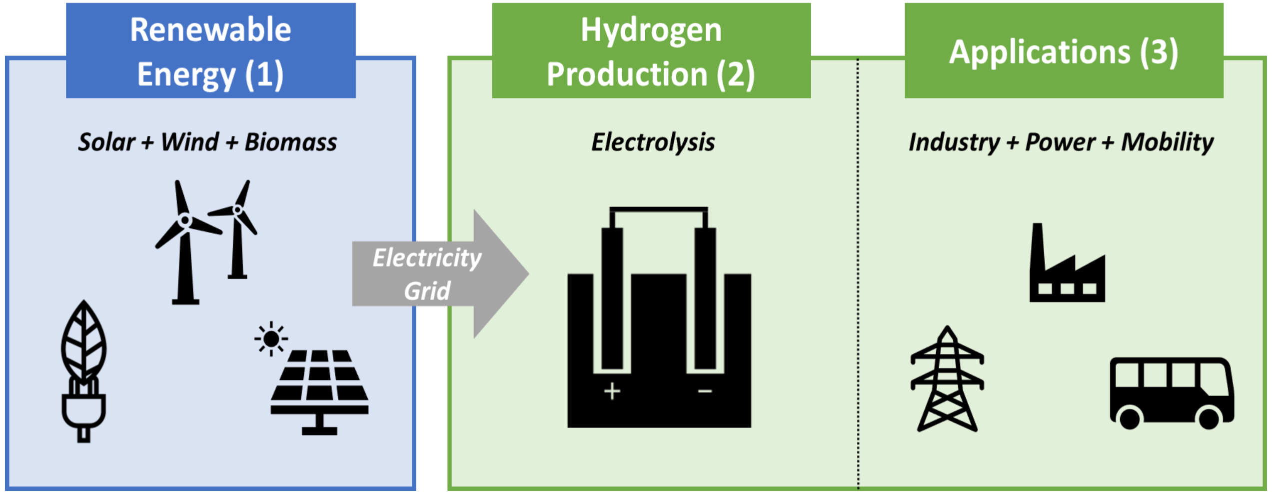


CO-LOCATING HYDROGEN SUPPLY WITH DEMAND

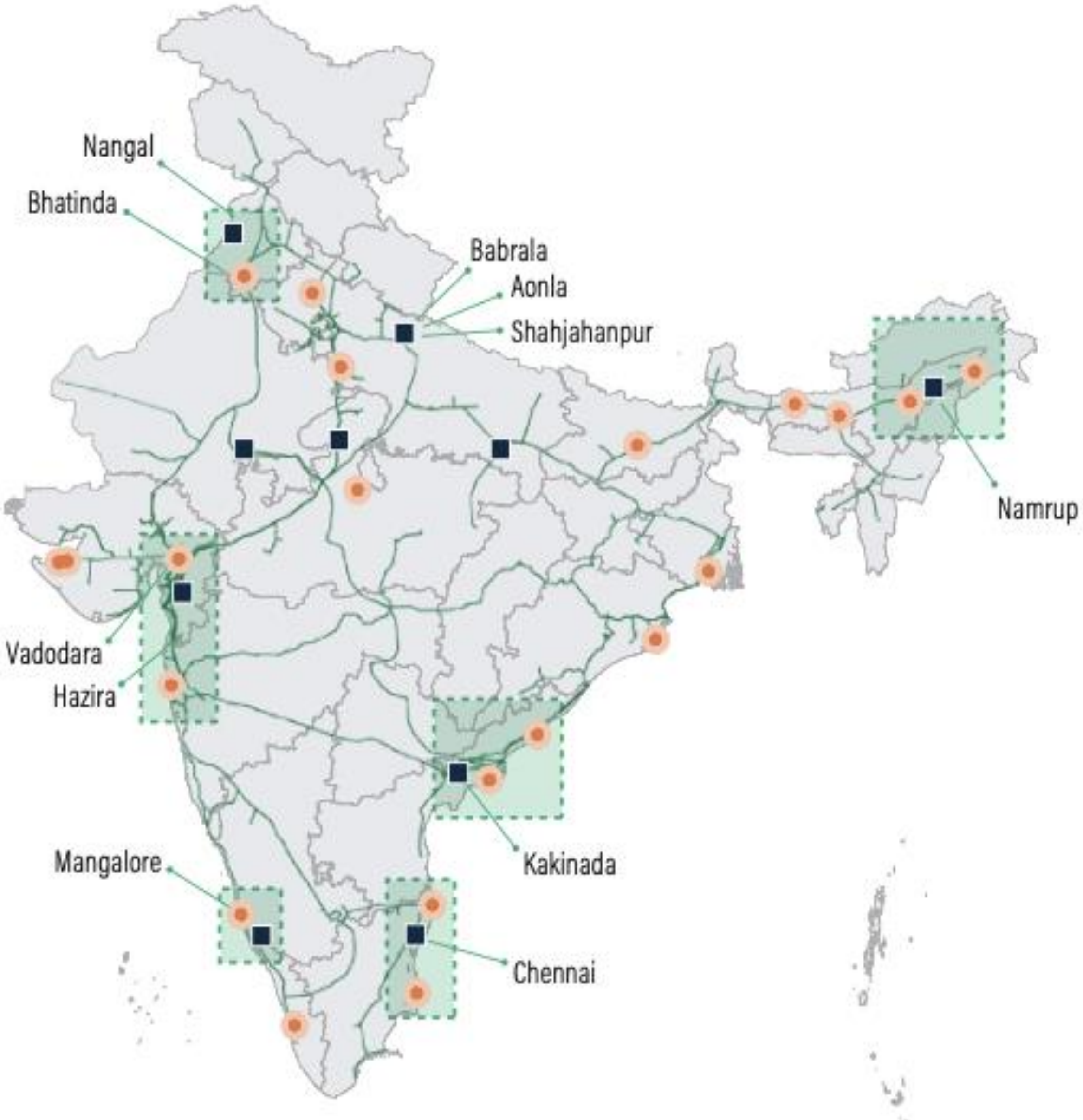
A. RE + Electrolysers + Demand

B. Grid Based RE + (Electrolysers + Demand)

C. (RE + Electrolysers) + H2 Transport + Demand



Hydrogen produced through electrolysis must be co-located with demand centres to eliminate high transport costs



GLOBAL POLICY PERSPECTIVE

GLOBAL SECTORAL FOCUS

Country	Power Generation	Heating Application	Industry			Transport					
			Iron & Steel	Chemical Feedstock	Refining	Cars	Trucks	Buses	Rail	Maritime	Aviation
European Union	Slow	Slow	Long-term	Aggressive	Aggressive	Slow	Aggressive	Aggressive	Aggressive	Long-term	Long-term
Australia	Aggressive	Slow	Long-term	Aggressive	Absent	Slow	Aggressive	Aggressive	Aggressive	Long-term	Slow
Germany	Slow	Absent	Aggressive	Aggressive	Aggressive	Slow	Aggressive	Aggressive	Slow	Long-term	Long-term
Japan	Aggressive	Aggressive	Slow	Slow	Slow	Aggressive	Aggressive	Long-term	Slow	Slow	Slow
South Korea	Slow	Aggressive	Slow	Absent	Absent	Aggressive	Aggressive	Aggressive	Slow	Slow	Absent
Canada	Aggressive	Slow	Aggressive	Aggressive	Aggressive	Long-term	Aggressive	Aggressive	Long-term	Long-term	Long-term
Norway	Slow	Absent	Slow	Aggressive	Slow	Slow	Slow	Slow	Absent	Aggressive	Slow
Portugal	Aggressive	Slow	Aggressive	Aggressive	Aggressive	Long-term	Aggressive	Aggressive	Aggressive	Long-term	Long-term
Netherlands	Aggressive	Slow	Aggressive	Aggressive	Aggressive	Long-term	Aggressive	Aggressive	Aggressive	Slow	Slow
Chile	Aggressive	Absent	Absent	Aggressive	Aggressive	Absent	Aggressive	Aggressive	Absent	Long-term	Long-term
France	Slow	Absent	Aggressive	Aggressive	Aggressive	Long-term	Aggressive	Aggressive	Slow	Slow	Slow

Absent Aggressive Long - term Slow

Factors Affecting Sectoral Preferences

- RE integration,
- Cost and ease of adoption,
- Need for diversification of energy systems,
- Ensuring geopolitical dominance,
- Sectoral decarbonisation targets

Focus on heavy mobility. Cost reduction from other demand will drive adoption of hydrogen powered mobility solutions. Current focus on industrial decarbonation.

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Legislative commitments and relevance

Countries	Strategy in Discussion	Roadmap Present	Strategy Present	Strategy + Legislative Framework	Legislative support
USA		■		■	Energy Policy Act 2005 & Hydrogen for Ports Act of 2021
China		■			14th Five Year Plan (2021-2025) to embedd hydorgen industry
EU			■	■	Fit for 55 Hydrogen Directive (2021) and Renewable Energy Directive (RED II)
Australia			■	■	Energy Legislation Amendment Bill 2021
Germany			■	■	Energy Act (2021 amd.), Climate Change Act (2021 amd.) and Federal Immission Control Act (2000)
Japan			■	■	Gas Business Act (1954) and High-Pressure Gas Safety Law (1996 amd.)
Canada			■		-
South Korea			■	■	Hydorgen Law (2021) and Renewable Energy Act (2017 amd.)
New Zealand			■		Gas Act (1992) and Resource Management Act (Review expected)
Norway			■		-
Portugal			■		Energy Bill
Netherlands			■		Gas Act and Electricity Act 1998
UK			■	■	Gas Act 1986, Electricity Act 1989 and Energy Act 2013
Chile			■		Define hydrogen in Law DFL 1 1979 and Law DL 2.224
France			■		Law-Decree No 2021-167 in Journal Officiel
Spain			■		-
Italy	■				-
India	■				Oilfields (Regulation & Development) Act, 1948, Energy Convervatiion Act, 2001
Finland	■				-
Russia	■				Federal Law on Gas Supply No. 69-FZ (1999) and Gas Exports No. 117-FZ (2006)
Saudi Arabia	■				Federal Law No 14 (2017) and The Basic Law of Saudi Arabia (1992)

Strategies in Discussion	(yellow)
Hydrogen Roadmaps and Programmes Present	(red)
National Hydrogen Strategy Present	(green)
Strategies Supported with legislative frameworks	(blue)

COLOR CODE TRANSITION ANALYSIS

GEOGRAPHY	HYDROGEN PRODUCTION PATHWAYS
Japan	Grey → Brown, Blue, Green
South Korea	Grey → Blue, Green
Australia	Grey → Brown, Blue, Green
New Zealand	Grey → Blue, Green
Norway	Grey → Brown, Blue, Green
Germany	Grey → Green
Portugal	Grey → Green
Netherlands	Grey → Blue, Green

GEOGRAPHY	HYDROGEN PRODUCTION PATHWAYS
Canada	Grey → Blue, Green
India	Grey → Green
China	Grey → Brown, Blue, Green
UK	Grey → Blue, Green
USA	Grey → Brown, Blue, Green
France	Grey → Green
EU	Grey → Blue, Green
Chile	Grey → Green

Color	Feedstock
	Grey: Natural gas reforming without CCUS
	Green: Electrolysis powered through renewable electricity
	Blue: Natural gas reforming with CCUS
*	**Brown:** Brown coal (lignite) as feedstock

* Adoption of brown hydrogen is being considered to meet the additional projected demand

SECTORAL FOCUS

Country	Power Generation	Heating Application	Industry			Transport					
			Iron & Steel	Chemical Feedstock	Refining	Cars	Trucks	Buses	Rail	Maritime	Aviation
European Union	Slow	Slow	Long-term	Aggressive	Aggressive	Slow	Aggressive	Aggressive	Aggressive	Long-term	Long-term
Australia	Aggressive	Slow	Long-term	Aggressive	Absent	Slow	Aggressive	Aggressive	Aggressive	Long-term	Slow
Germany	Slow	Absent	Aggressive	Aggressive	Aggressive	Slow	Aggressive	Aggressive	Slow	Long-term	Long-term
Japan	Aggressive	Aggressive	Slow	Slow	Slow	Aggressive	Aggressive	Long-term	Slow	Slow	Slow
South Korea	Slow	Aggressive	Slow	Absent	Absent	Aggressive	Aggressive	Aggressive	Slow	Slow	Absent
Canada	Aggressive	Slow	Aggressive	Aggressive	Aggressive	Long-term	Aggressive	Aggressive	Long-term	Long-term	Long-term
Norway	Slow	Absent	Slow	Aggressive	Slow	Slow	Slow	Slow	Absent	Aggressive	Slow
Portugal	Aggressive	Slow	Aggressive	Aggressive	Aggressive	Long-term	Aggressive	Aggressive	Aggressive	Long-term	Long-term
Netherlands	Aggressive	Slow	Aggressive	Aggressive	Aggressive	Long-term	Aggressive	Aggressive	Aggressive	Slow	Slow
Chile	Aggressive	Absent	Absent	Aggressive	Aggressive	Absent	Aggressive	Aggressive	Absent	Long-term	Long-term
France	Slow	Absent	Aggressive	Aggressive	Aggressive	Long-term	Aggressive	Aggressive	Slow	Slow	Slow

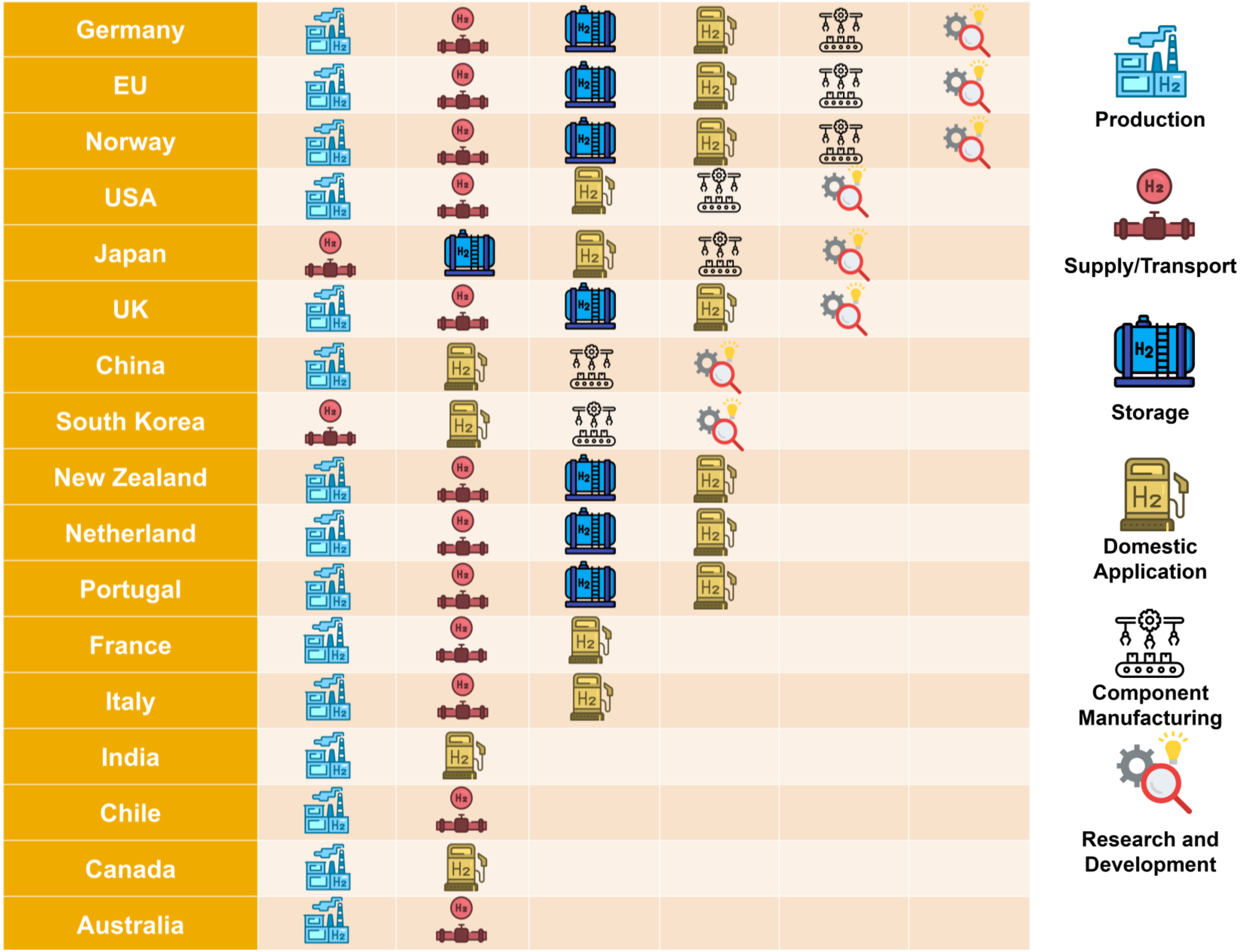
Absent Aggressive Long - term Slow

Factors Affecting Sectoral Preferences

- RE integration,
- Cost and ease of adoption,
- Need for diversification of energy systems,
- Ensuring geopolitical dominance,
- Sectoral decarbonisation targets

Focus on heavy mobility. Cost reduction from other demand will drive adoption of hydrogen powered mobility solutions. Current focus on industrial decarbonation.

VALUE CHAIN FOCUS

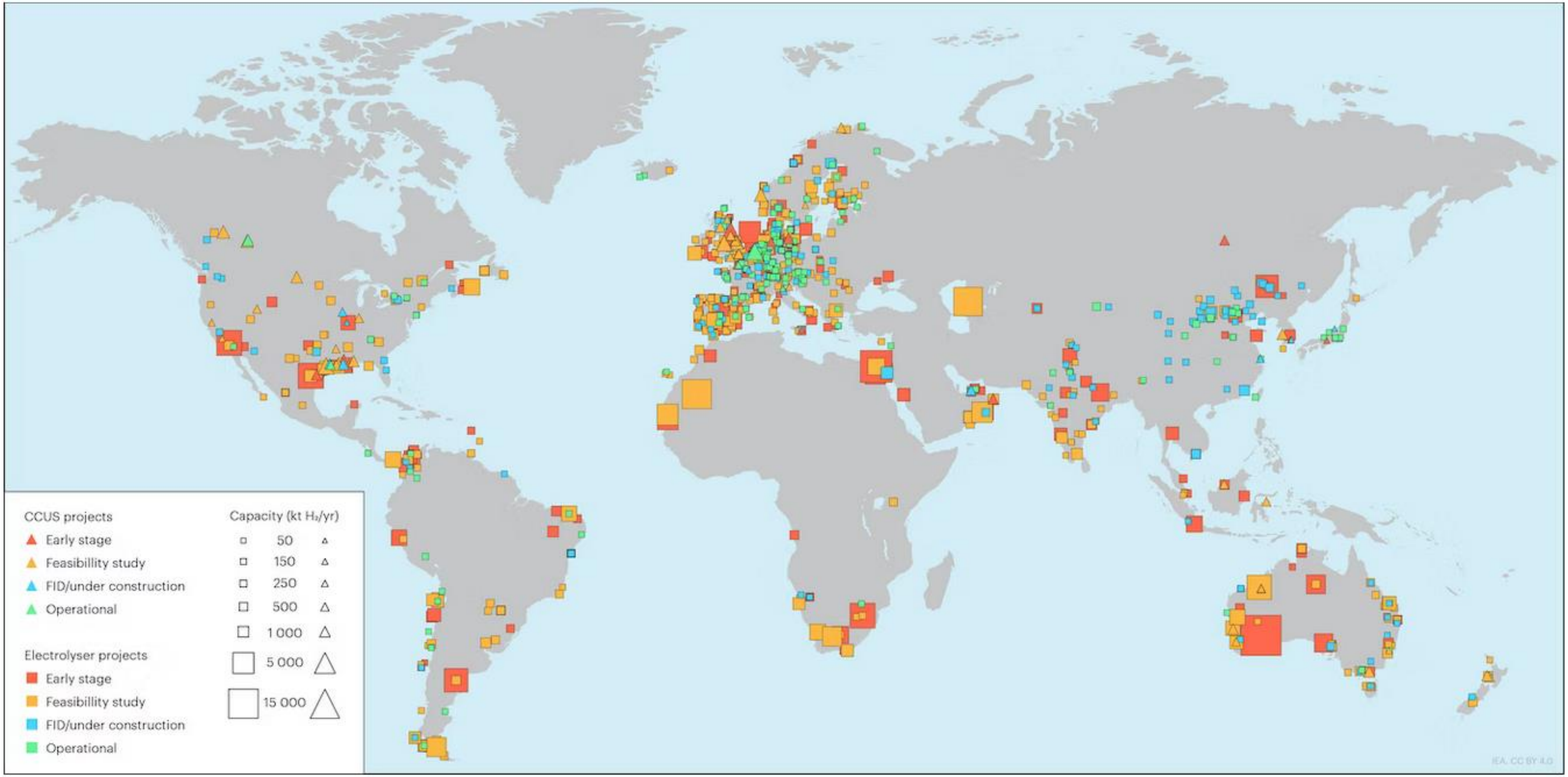


- Value chain focus looks from a **supply side perspective** as opposed to demand
- Almost all countries focussing on **production and supply of hydrogen**
- Countries with a focus on **R&D and component manufacturing** the most active in the global hydrogen ecosystem development.

Importance of R&D to be discussed and how R&D facilitates entire value chain development

WRI INDIA

ANNOUNCED GREEN HYDROGEN PROJECTS



Source: IEA (2023); https://www.iea.org/reports/global-hydrogen-review-2023/executive-summary

WRI INDIA

NATIONAL GREEN HYDROGEN MISSION (1/2)

Demand Creation

Export Markets

Capturing Global Demand

Substituting imports

Fossil Fuels and Fertilizers

Domestic Demand

Multiple Sectors

Incentivising Supply

Strategic Interventions for GH2 Transition

Direct Financial Incentives for:

- ❑ Electrolyser Manufacturing
- ❑ Green Hydrogen Production

NATIONAL GREEN HYDROGEN MISSION (2/2)

Key Enablers

Resources

Renewable energy - banking & storage, transmission, finance, land, water

R&D

Result oriented, time-bound, including through PPP, grand challenges

Ease of doing business

Simpler procedures, taxation, SEZ, commercial issues, single window

Infrastructure & Supply Chain

Ports, Re-fueling, Hydrogen Hubs, pipelines

Regulations & Standards

Testing facilities, standards, regulations, safety & certification

Skill Development, Public awareness

Coordinated skilling programme, online portal

KEY OUTCOMES OF MISSION

At least **5 MMT GH_2** annual Production	**60-100 GW** Electrolyser capacity	**125 GW** RE Capacity for GH_2 Generation & associated Transmission network

₹ 1 lakh crore Import Savings	**50 MMT CO_2** Annual Emissions Averted	**6 lakh** Jobs	**₹ 8 lakh cr** Investment

GREEN HYDROGEN PILOT PROJECTS

- **Pilot project design and objectives** based on sector
- **Technology validation** and identification of **regulatory requirements**
- **Estimation of CFA based** on additional costs related to Green hydrogen adoption

Industry

Mobility

Maritime

Infrastructure

Green H_2 from biomass

GREEN HYDROGEN- BARRIERS TO IMPLEMENTATIONS

TECHNOLOGY

- Promoting Development of Domestic Value Chains
- Promoting Innovation and R&D
- Technology Licensing and Transfer

REGULATORY

- Supply- Demand Incentivisation Frameworks
- Establishing Critical Hydrogen Infrastructure
- Modification of Existing Regulations and Legislations

THANK YOU