R&D efforts to develop suitable nuclear-powered water-splitting technologies for carbon-free sustainable H2 production

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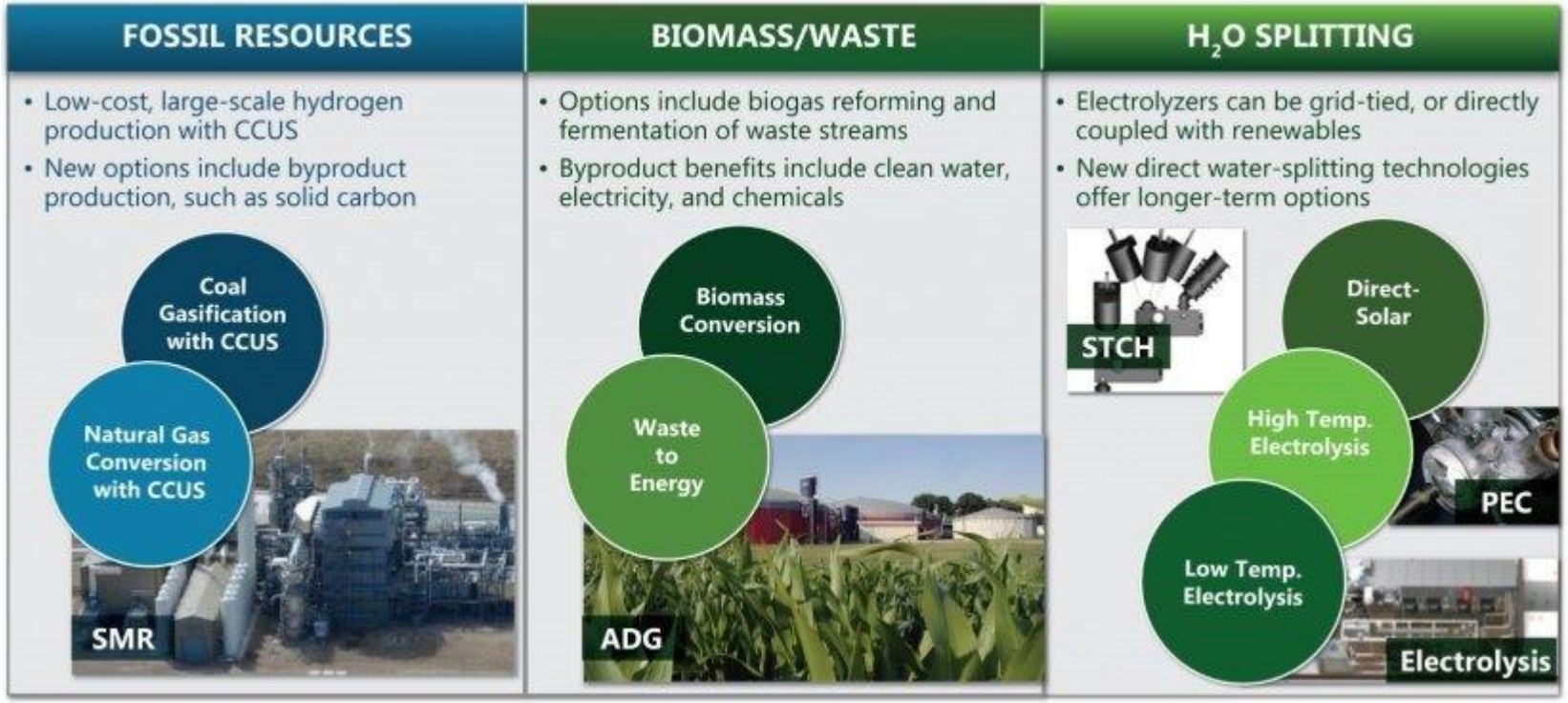
HYDROGEN PRODUCTION IN US

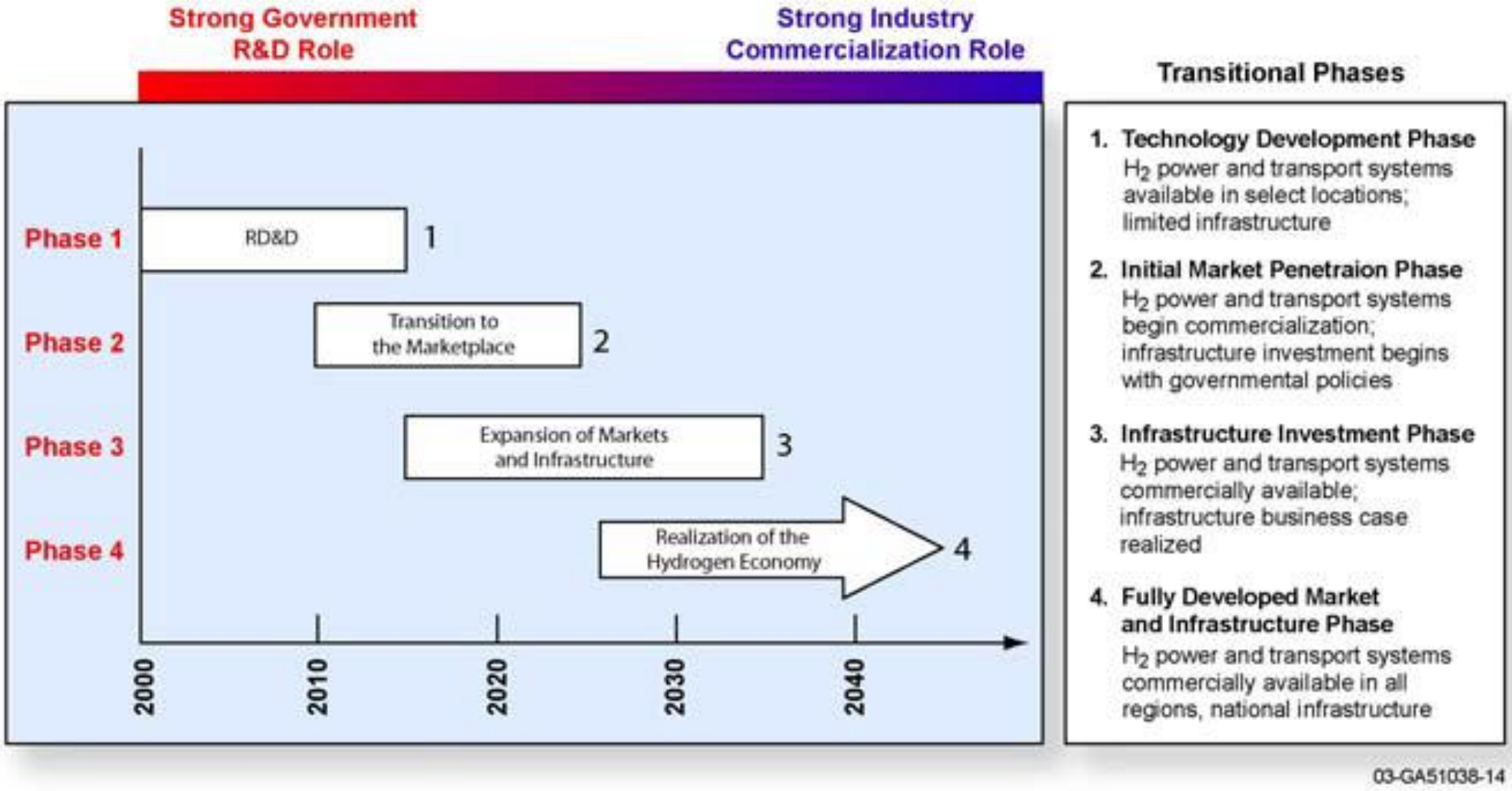
- **November 2002**, the U.S. Department of Energy (DOE) issued its National Hydrogen Energy Roadmap;
- **March 2004**, Department Of Energy Office of Nuclear Energy, Science and Technology - Nuclear Hydrogen R&D Plan;



CCUS: carbon capture, utilization, and storage; SMR: steam methane reforming; ADG: anaerobic digester gas; STCH: solar thermochemical hydrogen; PEC: photoelectrochemical

Hydrogen Production Pathways | Department of Energy

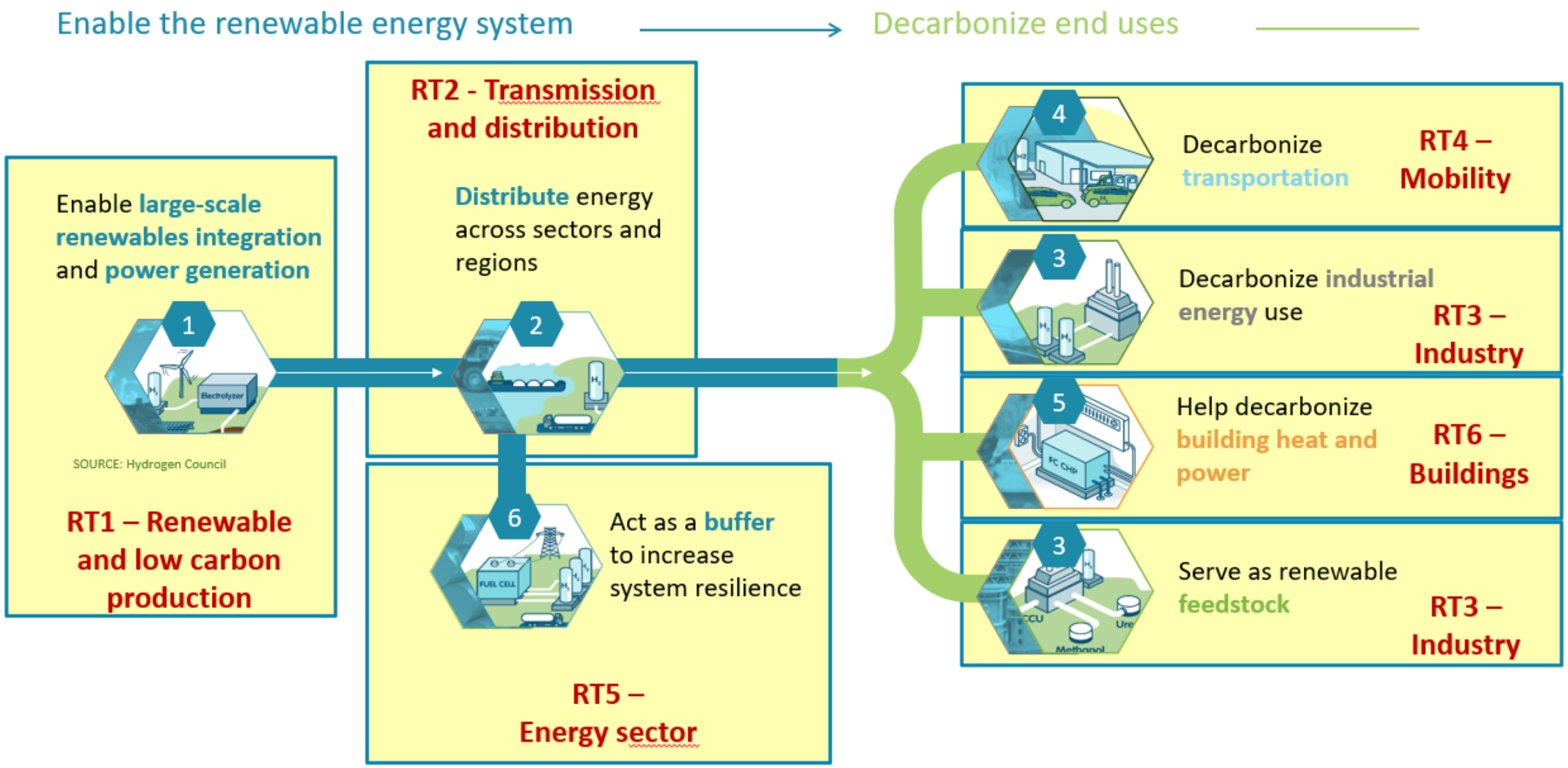
Phases in the development of the hydrogen economy - US



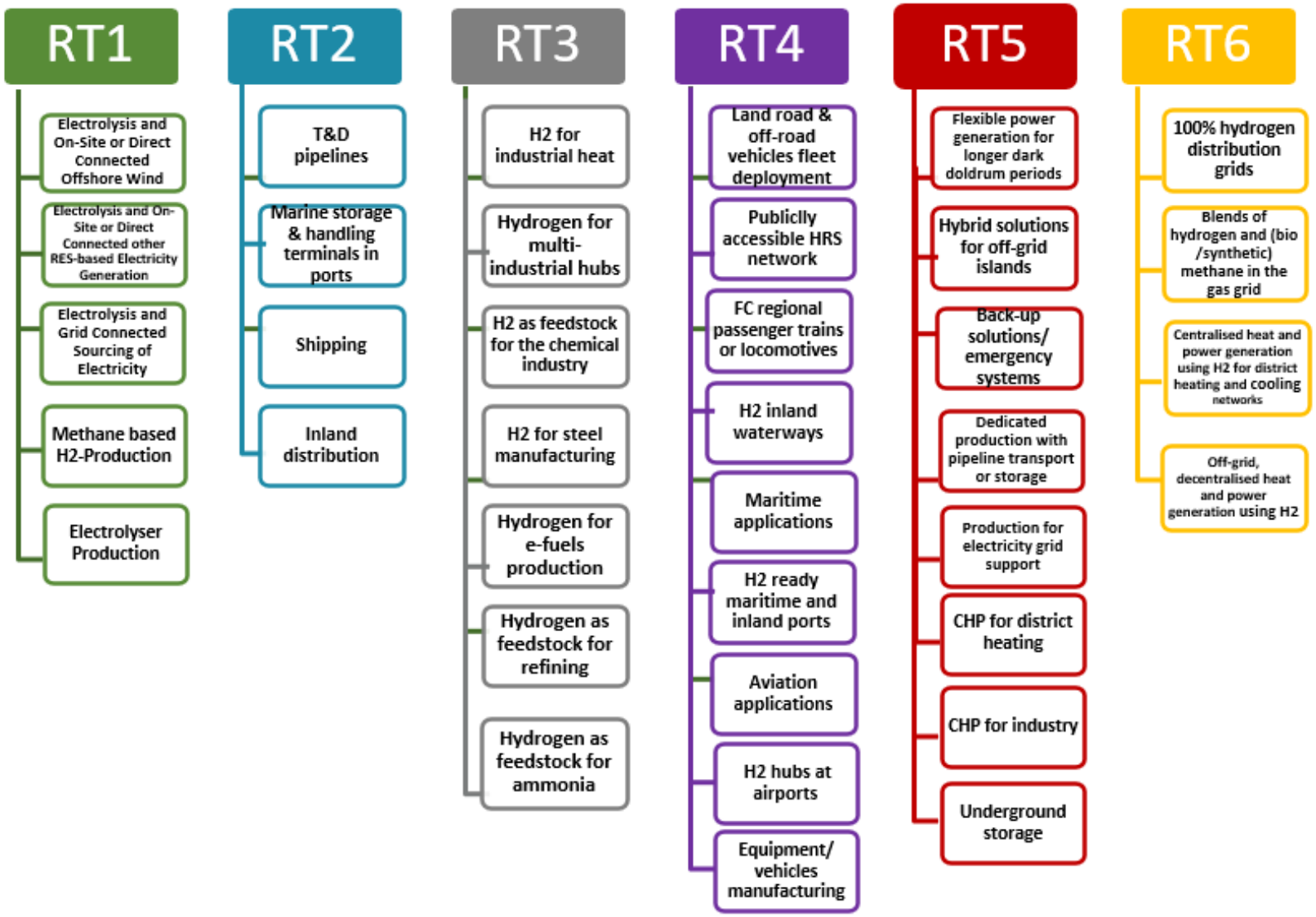
HYDROGEN PRODUCTION IN EU

- The **European Clean Hydrogen Alliance** was launched in **July 2020**, as one of the key initiatives of the new European Industrial Strategy and of the new EU Hydrogen Strategy for a climate neutral Europe, to support its important hydrogen production and deployment ambitions and ensure the emergence of a European Hydrogen economy by 2030;
  - The **priority for the EU is to develop renewable hydrogen**, produced using mainly wind and solar energy;
  - The **hydrogen ecosystem in Europe** is likely to **develop through a gradual trajectory**, at different speeds across sectors and possibly across regions and requiring different policy solutions;
  - In **the first phase**, from **2020 up to 2024**, the strategic objective is to install at least **6 GW** of **renewable hydrogen electrolysers** in the EU and the production of up to 1 million tonnes of renewable hydrogen;
  - In a **second phase**, from **2025 to 2030**, hydrogen needs to become an intrinsic part of an integrated energy system with a strategic objective to install at least **40 GW** of **renewable hydrogen electrolysers by 2030** and the production of up to 10 million tonnes of renewable hydrogen in the EU;
  - In a **third phase**, from **2030 onwards and towards 2050**, **renewable hydrogen technologies should reach maturity** and be deployed at large scale to reach all hard-to decarbonise sectors.

Roundtables (RT) activities of the entire hydrogen value chain - EU



Roundtables (RT) project models - EU



Hydrogen Value Chain

- Hydrogen Production
- Hydrogen Delivery
- Hydrogen Storage
- Fuel Cells
- Technology Validation
- Manufacturing Research and Development
- Safety, Codes and Standards
- Education
- Market Transformation
- Systems Analysis

Hydrogen Production

- Hydrogen is the simplest element on earth—it consists of only one proton and one electron—and **it is an energy carrier, not an energy source**. Hydrogen can store and deliver usable energy, but it doesn't typically exist by itself in nature and must be produced from compounds that contain it;
- Hydrogen can be produced using several different processes:
  - **Thermochemical processes** use heat and chemical reactions to release hydrogen from organic materials, such as fossil fuels and biomass, or from materials like water.
  - **Water (H_2O) can also be split** into hydrogen (H_2) and oxygen (O_2) using **electrolysis or solar energy**.
  - Microorganisms such as bacteria and algae can produce **hydrogen through biological processes**.

Hydrogen Production (cont.)

Thermochemical Processes

Some thermal processes use the energy in various resources, such as natural gas, coal, or biomass, to release hydrogen from their molecular structure. In other processes, **heat, in combination with closed-chemical cycles, produces hydrogen from feedstocks such as water**.

- Natural gas reforming (also called steam methane reforming or SMR)
- Biomass gasification
- Biomass-derived liquid reforming
- **Solar thermochemical hydrogen (STCH).**

Thermochemical water splitting processes use high-temperature heat (500°–2,000°C) to drive a series of chemical reactions that produce hydrogen. The chemicals used in the process are reused within each cycle, creating a closed loop that consumes only water and produces hydrogen and oxygen.

Hydrogen Production (cont.)

Thermochemical Processes

Volatile Metal Oxide:

$CdO(s) \rightarrow Cd(g) + \frac{1}{2}\ O2(g)$ (1450°C)

$Cd(l,s) + H2O \rightarrow CdO(s) + H2(g)$ (25-450°C)

Non-Volatile Metal Oxide:

Ferrite:

$NiMnFe4O8(s) \rightarrow NiMnFe4O6(s) + O2(g)$ (~1800°C)

$NiMnFe4O6(s) + H2O(g) \rightarrow NiMnFe4O8(s) + H2(g)$ (~800°C)

Multi-step cycle:

$2a\text{-}NaMnO2(s) + H2O(l) \rightarrow Mn2O3(s) + 2NaOH(a)$ (~100°C)

$2Mn2O3(s) \rightarrow 4MnO(s) + O2(g)$ (~1560°C)

$2MnO(s) + 2NaOH \rightarrow 2a\text{-}NaMnO2(s) + H2(g)$ (~630°C)

Sulfuric Acid:

$2H2SO4(g) \rightarrow 2SO2(g) + 2H2O(g) + O2(g)$ (~850°C)

$I2 + SO2(a) + 2H2O \rightarrow 2HI(a) + H2SO4(a)$ (~100°C)

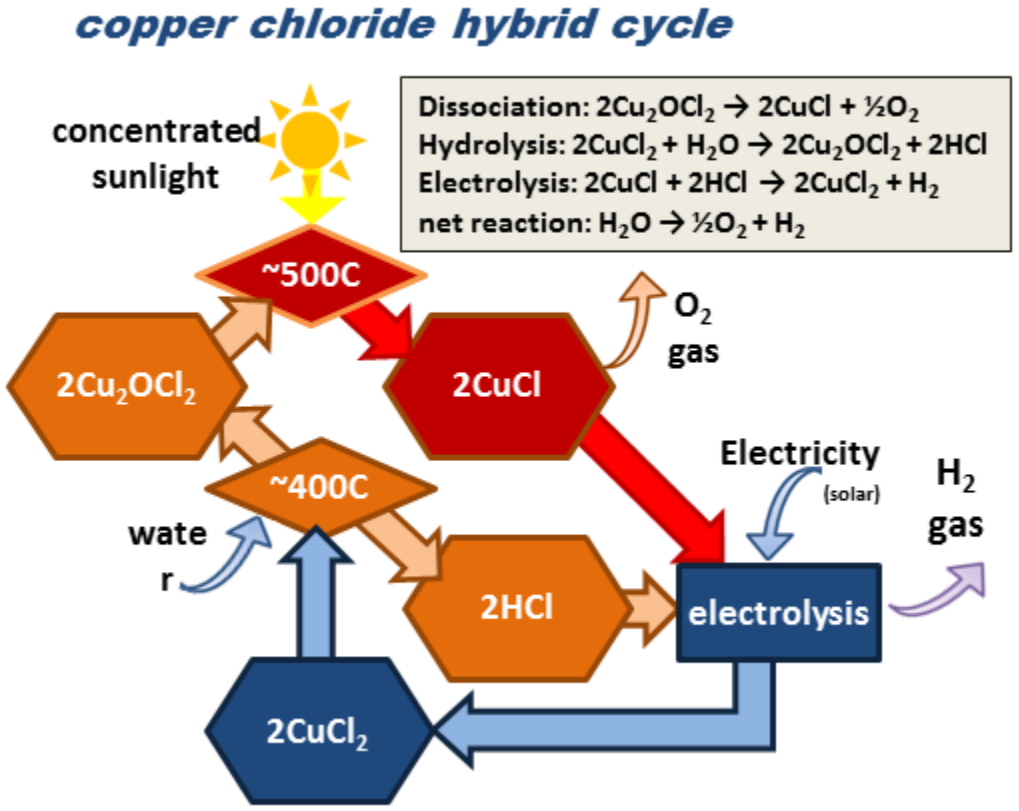
$2HI \rightarrow I2(g) + H2(g)$ (~300°C)

Hybrid Copper Chloride:

$2CuCl2 + H2O \rightarrow Cu2OCl2 + 2HCl$ (~400°C)

$2Cu2OCl2 \rightarrow O2 + 4CuCl$ (~500°C)

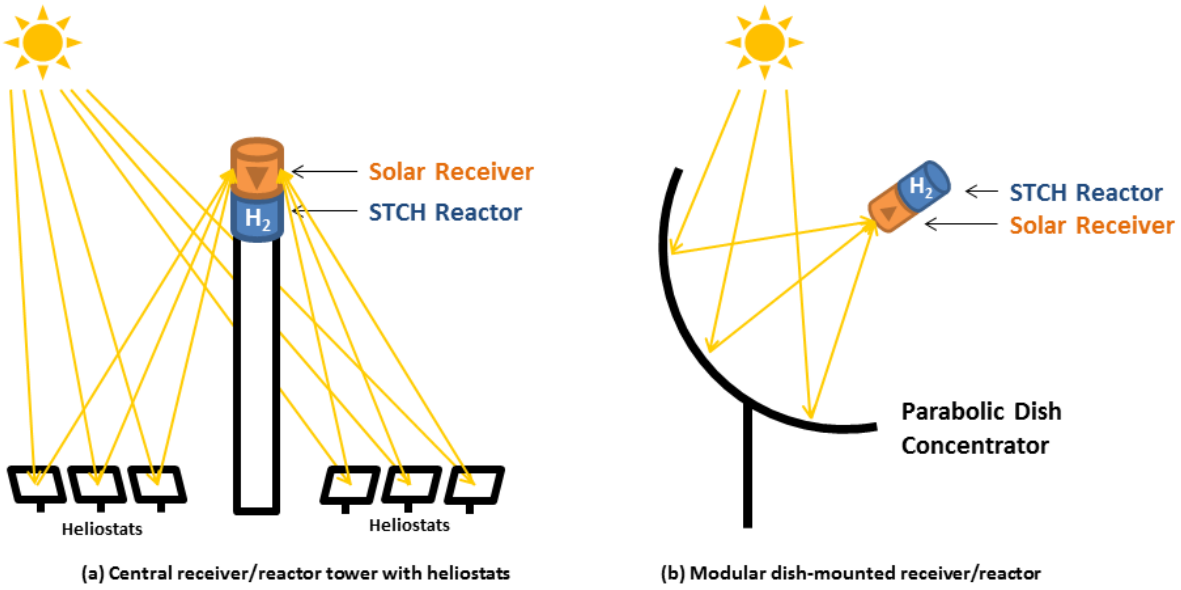
$2CuCl + 2HCl\ e^- \rightarrow 2CuCl2 + H2$ (~100°C)



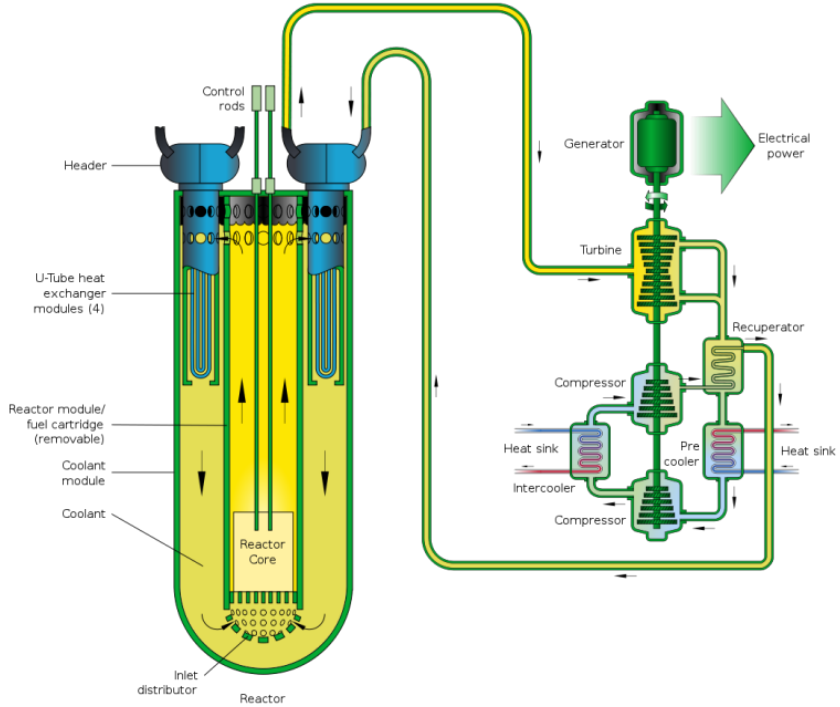
Hydrogen Production (cont.)

Thermochemical Processes

The necessary high temperatures can be generated in the following ways:



1. Concentrating sunlight onto a reactor tower using a field of mirror "heliostats“;



2. Using waste heat from advanced nuclear reactors.

Hydrogen Production (cont.)

Why Is This Pathway Being Considered?

Solar- and nuclear-driven high-temperature thermochemical water-splitting cycles ***produce hydrogen with near-zero greenhouse gas emissions using water and either sunlight or nuclear energy.***

Research Focuses On Overcoming Challenges

Challenges remain, however, in the research, development, and demonstration of commercially viable thermochemical cycles and reactors:

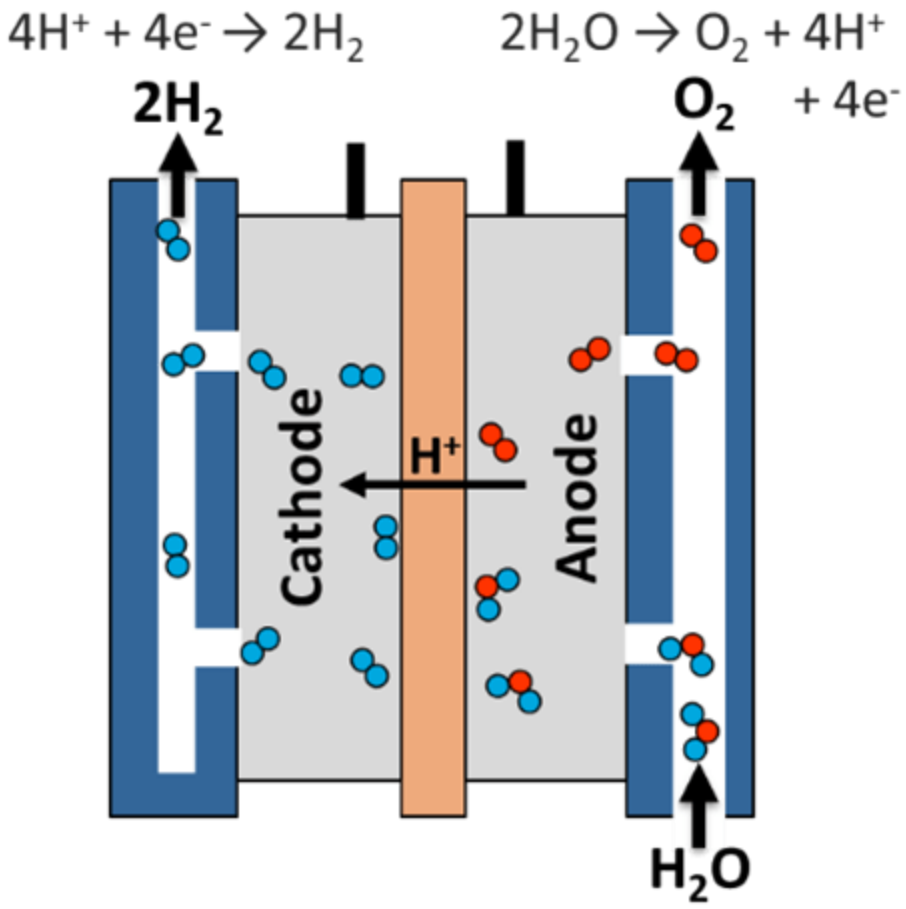
- The efficiency and durability of reactant materials for thermochemical cycling need to be improved.
- Efficient and robust reactor designs compatible with high temperatures and heat cycling need to be developed.
- For solar thermochemical systems, the cost of the concentrating mirror systems needs to be reduced.

Hydrogen Production (cont.)

Electrolytic Processes

Electrolysis is a promising option for carbon-free hydrogen production from **renewable and nuclear resources.** Electrolysis is the process of using electricity to split water into hydrogen and oxygen. This reaction takes place in a unit called an electrolyser. Electrolysers can range in size from small, appliance-size equipment that is well-suited for small-scale distributed hydrogen production to large-scale, central production facilities that could be tied directly to renewable or other non-greenhouse-gas-emitting forms of electricity production.

Like fuel cells, electrolysers consist of an anode and a cathode separated by an electrolyte. Different electrolysers function in different ways, mainly due to the different type of electrolyte material involved and the ionic species it conducts.



Hydrogen Production (cont.)

Electrolytic Processes (waste heat from advanced nuclear reactors)

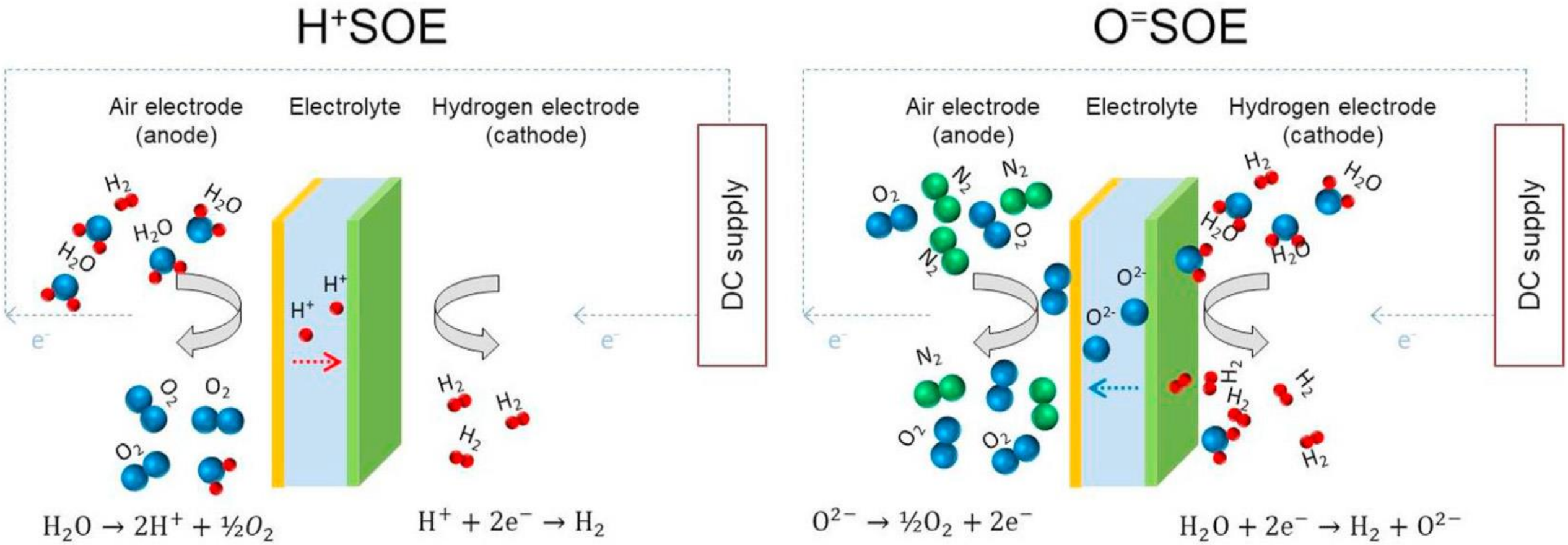
Solid Oxide Electrolysers or High Temperature Electrolysers

Solid oxide electrolysers, which use a solid ceramic material as the electrolyte that selectively conducts negatively charged oxygen ions (O^{2-}) at elevated temperatures, generate hydrogen in a slightly different way.

- Steam at the cathode combines with electrons from the external circuit to form hydrogen gas and negatively charged oxygen ions.
- The oxygen ions pass through the solid ceramic membrane and react at the anode to form oxygen gas and generate electrons for the external circuit.

Solid oxide electrolysers must operate at temperatures high enough for the solid oxide membranes to function properly (about 700°–800°C, compared to PEM electrolysers, which operate at 70°–90°C, and commercial alkaline electrolysers, which typically operate at less than 100°C). Advanced lab-scale solid oxide electrolysers based on proton-conducting ceramic electrolytes are showing promise for lowering the operating temperature to 500°–600°C. The solid oxide electrolysers can effectively use heat available at these elevated temperatures (from various sources, including nuclear energy) to decrease the amount of electrical energy needed to produce hydrogen from water.

Hydrogen Production (cont.)



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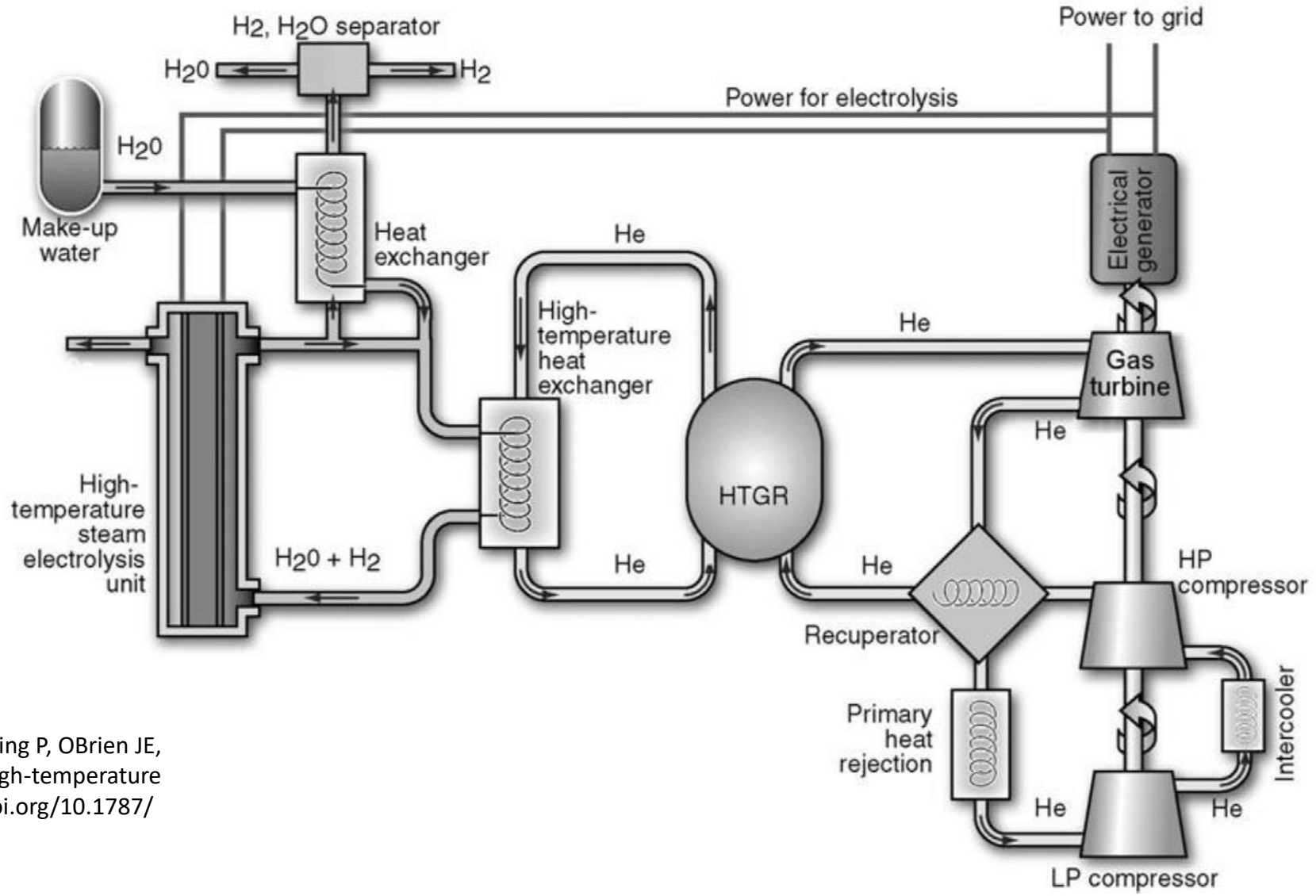
Hydrogen Production (cont.)



Elangovan S, Hartvigsen J, Herring JS, Lessing P, OBrien JE, Stoots C. Hydrogen production through high-temperature electrolysis in a solid oxide cell. https://doi.org/10.1787/9789264107717-15-en; 2004

Hydrogen Production (cont.)

Why Is This Pathway Being Considered?

Electrolysis is a leading hydrogen production pathway to achieve the **Hydrogen Energy Earthshot** goal of **reducing the cost of clean hydrogen by 80% to $1 per 1 kilogram in 1 decade ("1 1 1").** Hydrogen produced via electrolysis can result in zero greenhouse gas emissions, depending on the source of the electricity used. The production cost needs to be decreased significantly to be competitive with more mature carbon-based pathways such as natural gas reforming.

Research Focuses On Overcoming Challenges

- Meeting the Hydrogen Shot clean hydrogen cost target of $1/kg H_2 by 2030 (and interim target of $2/kg H_2 by 2025) through improved understanding of performance, cost, and durability trade-offs of electrolyser systems under predicted future dynamic operating modes using CO_2-free electricity.
- Reducing the capital cost of the electrolyser unit and the balance of the system.
- Improving energy efficiency for converting electricity to hydrogen over a wide range of operating conditions.
- Increasing understanding of electrolyser cell and stack degradation processes and developing mitigation strategies to increase operational life.

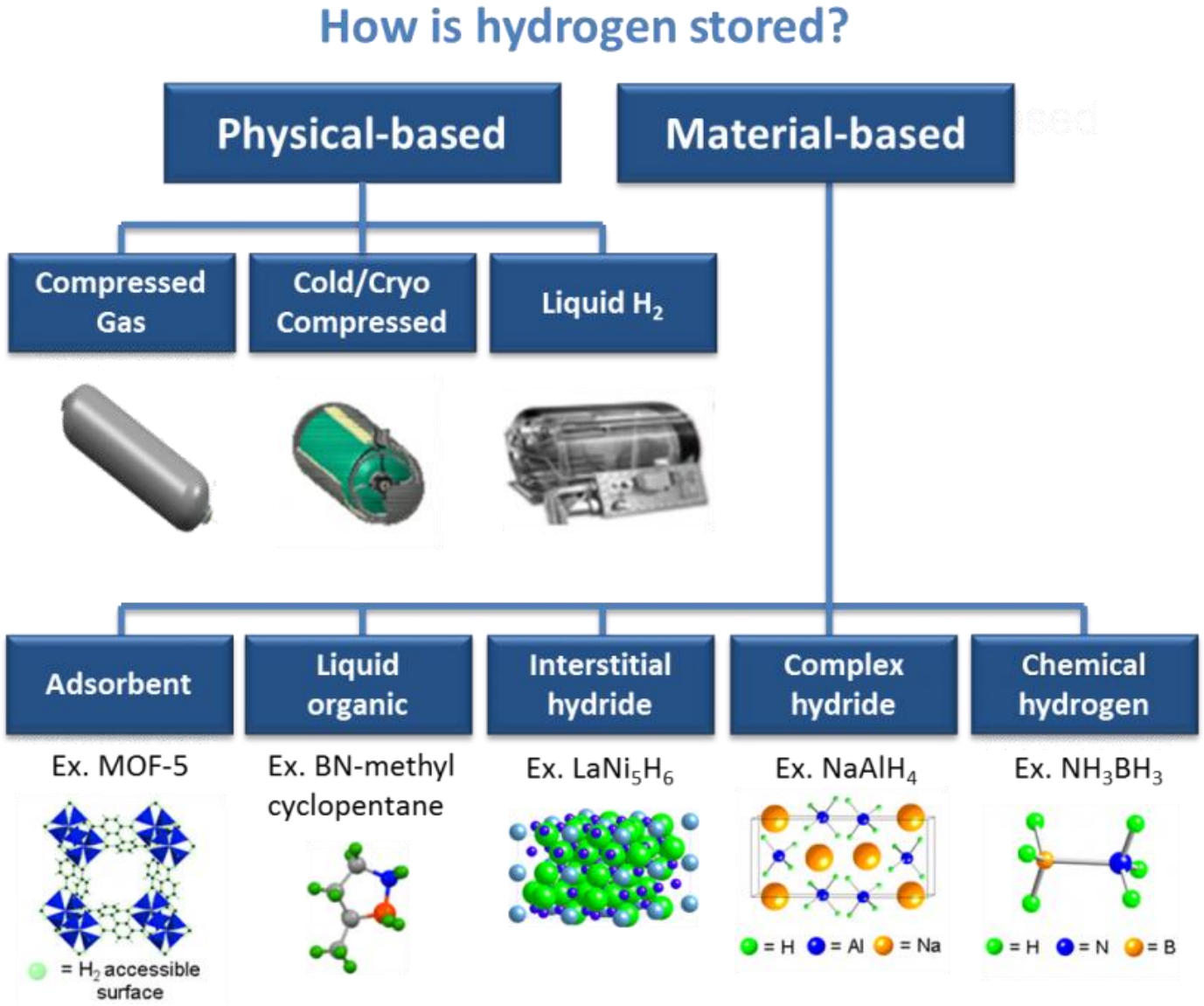
Hydrogen Storage

Why Study Hydrogen Storage

Hydrogen storage is a key enabling technology for the advancement of hydrogen and fuel cell technologies in **applications including stationary power, portable power, and transportation**. Hydrogen has the highest energy per mass of any fuel; however, its low ambient temperature density results in a low energy per unit volume, therefore requiring the development of **advanced storage methods that have potential for higher energy density**.

Hydrogen Storage (cont.)

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



Hydrogen Storage (cont.)

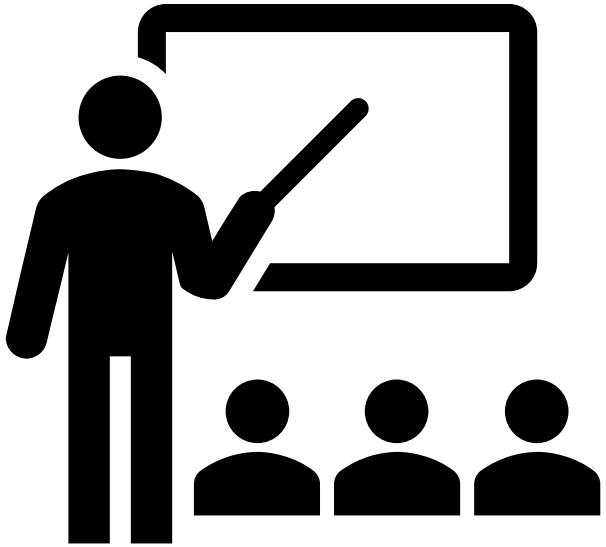
Research and Development Goals

- research and development activities to advance hydrogen storage systems technology and develop novel **hydrogen storage materials**. The goal is to provide adequate hydrogen storage to meet the hydrogen storage targets for **onboard light-duty vehicle**, **material-handling equipment**, and **portable power** applications.
- to develop and verify onboard automotive hydrogen storage systems achieving targets that will allow hydrogen-fueled vehicle platforms to meet customer performance expectations for range, passenger and cargo space, refueling time, and overall vehicle performance. Specific system targets include the following:

•1.5 kWh/kg system (4.5 wt.% hydrogen)
•1.0 kWh/L system (0.030 kg hydrogen/L)
•$10/kWh ($333/kg stored hydrogen capacity).

DOE Technical Targets for Onboard Hydrogen Storage for Light-Duty Vehicles | Department of Energy

Education



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THANK YOU!

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