Clean Hydrogen

Renewable Thermal Technology

RENEWABLE THERMAL COLLABORATIVE

Technology Overview

Description of technology

- Hydrogen is a combustible gas that can substitute for natural gas in nearly all industrial heating applications
- Green hydrogen production has no CO_2 emissions, and hydrogen combustion produces only water vapor and heat
- This analysis only considers hydrogen produced using renewable energy (green hydrogen via electrolysis), since other hydrogen production methods emit CO_2 and are non-renewable (i.e., blue and grey H_2).
- Currently, hydrogen is primarily used as feedstock in the chemicals and petroleum refining industries (e.g., ammonia production, hydrocracking)

Types of equipment

- Most gas combustion equipment can switch to hydrogen as a fuel with relatively minor equipment modifications. Hydrogen catalyzed equipment are new technologies that provide lower temperature heat via flameless combustion at high efficiencies.

Hydrogen furnaces[1]

Hydrogen combustion boilers[2]

Hydrogen catalyzed boilers[3]

Note: Example equipment not exhaustive

1. Thermal Technology LLC Hydrogen Furnace; 2. Bosch Hydrogen-ready Boiler; 3. Giacomini hydrogen-powered catalytic boiler

Technical characteristics

- **Temperature range:** Up to 2,100 ºC
  - Meets the highest temperature industrial heating applications
  - Likely applicable but not ideal heat source for lower temperature applications due to availability of alternatives heating technologies
- **Heat flux:** High
  - Similar heat transfer characteristics to natural gas combustion except for lower radiative heat transfer due to lack of soot particulate production
- **Heated materials:** Most materials are applicable
  - Hydrogen combustion eliminates potential contamination of heated materials with fuel particulates or combustion flue gases
- **Emissions:** Near zero emissions relative to natural gas combustion if hydrogen is produced using renewable electricity
  - If hydrogen is produced by electrolysis using grid electricity, hydrogen combustion will decrease emissions in only a handful of states today, and increases to around half of states by 2030
- **Technical maturity:** Low to medium maturity
  - Combustion of hydrogen as a minor constituent within fuel gas blends is widespread in refineries and chemical plants today
  - Pure hydrogen combustion is not deployed commercially beyond pilot and demonstration projects
  - Hydrogen catalyzed heating is a nascent technology

Hydrogen can provide industrial heating for all sectors and applications except for steelmaking

Key properties of RNG combustion heating include:

- 2,100 ºC max. temp.
- High heat flux
- Heats all materials

These properties align with requirements for several process heating applications.

Industry Sector	Process Heating Applications						Relevant Equipment
Refineries	Distillation	Reactors					Boiler, process heater
Chemicals	Distillation	Drying	Reactors				Boiler, process heater, furnace, air heater
Iron & steel	Pelletization	Hot rolling	Basic oxygen furnace	Blast furnace			Boiler, furnace
Food	Drying	Pasteurizing	Boiling	Sterilizing	Washing	Cooking	Air heater, boiler, oven
Paper	Stock steaming	Drying	Wood processing	Evap. & chem. prep.	Lime calcination		Air heater, boiler, oven, furnace
Cement	Pre-heating & treating	Melting furnace	Forming	Annealing	Kiln combustion		Furnace

Not applicable | Potentially applicable | Currently deployed

Currently, H_2 combustion heating is not widely deployed in the US

- Hydrogen combustion heating, particularly using pure hydrogen, is not used today and has significantly higher cost relative to natural gas.
- However, hydrogen combustion may have enormous industrial thermal decarbonization potential. A combination of factors may make it attractive, including:
  - **Government incentives – primarily from the Inflation Reduction Act**
    - Hydrogen production tax credit (PTC) and investment tax credits (ITC) has the potential to reduce costs by 50-70% and cost competitive with natural gas
  - **Broad applicability for industrial heating**
    - Able to reach highest required temperatures (e.g., chemical reactors, cement kilns)
    - Meets stringent particulate emissions standards
  - **Long-term sustainable net-zero fuel**
    - Only supply constraint is quantity of available renewable electricity
    - Low supply potential of other zero emissions fuels (e.g., RNG)

Practically applicable sectors & locations

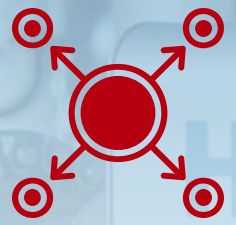
- Potentially viable and applicable deployment of hydrogen combustion industrial heating include:
  - **Industry sectors**
    - Cement,
    - Iron and steel making,
    - Refining and chemicals
  - **Regions**
    - **Future H_2 hubs**
  - **Other potential application (partial decarbonization)**
    - Blending (up to 15% H_2) into natural gas network

There are two primary methods of green hydrogen procurement

Onsite production and usage

- Nearby renewable electricity or grid electricity used to power hydrogen electrolyzers
- Likely not economically viable in the short and medium term

Central production hub



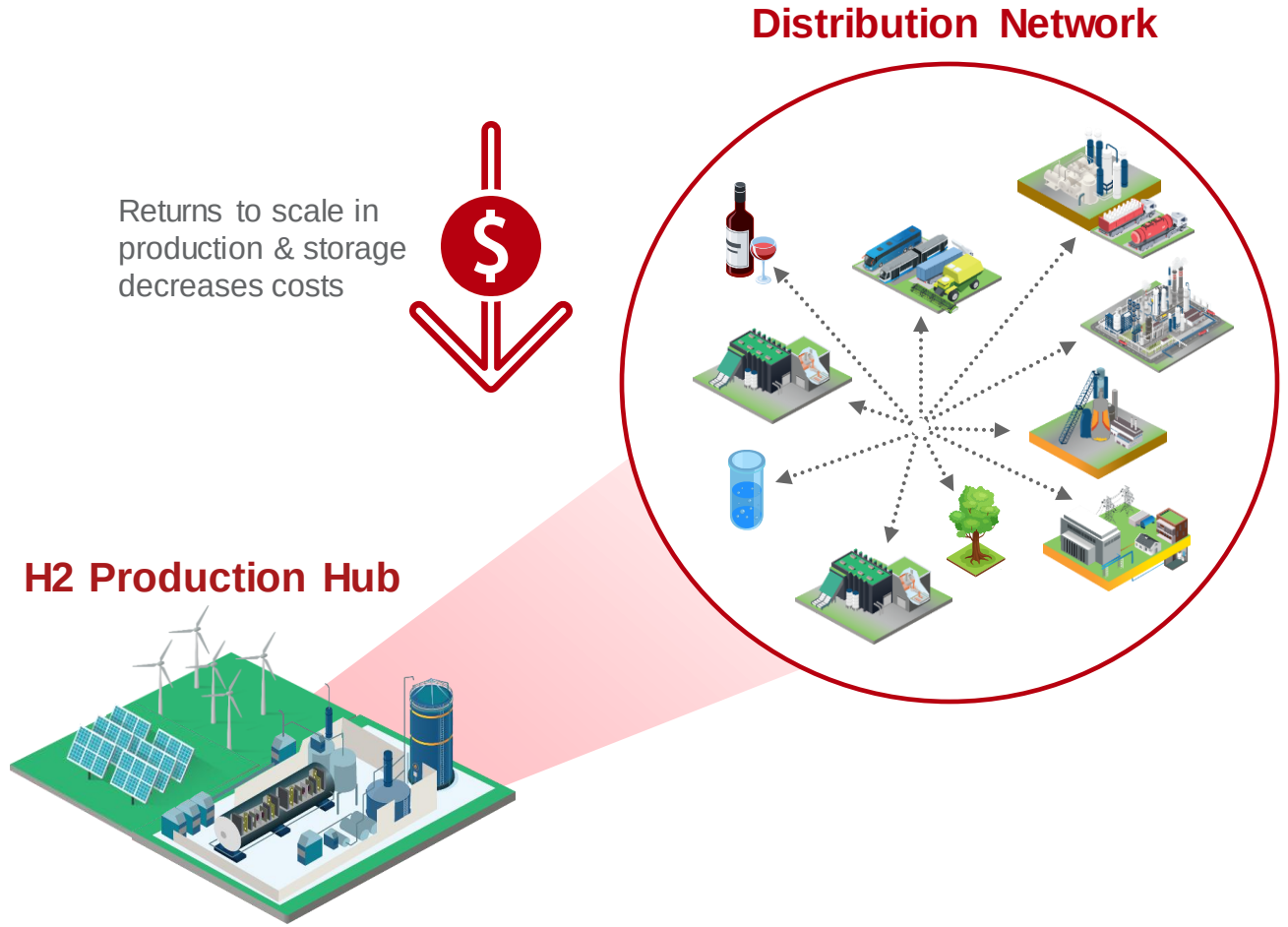
- Electrolyzers located near renewable energy resources produce hydrogen to be distributed to a network of local or regional consumers
- Hubs in planning or development stages across US and Europe

Examined in this fact base

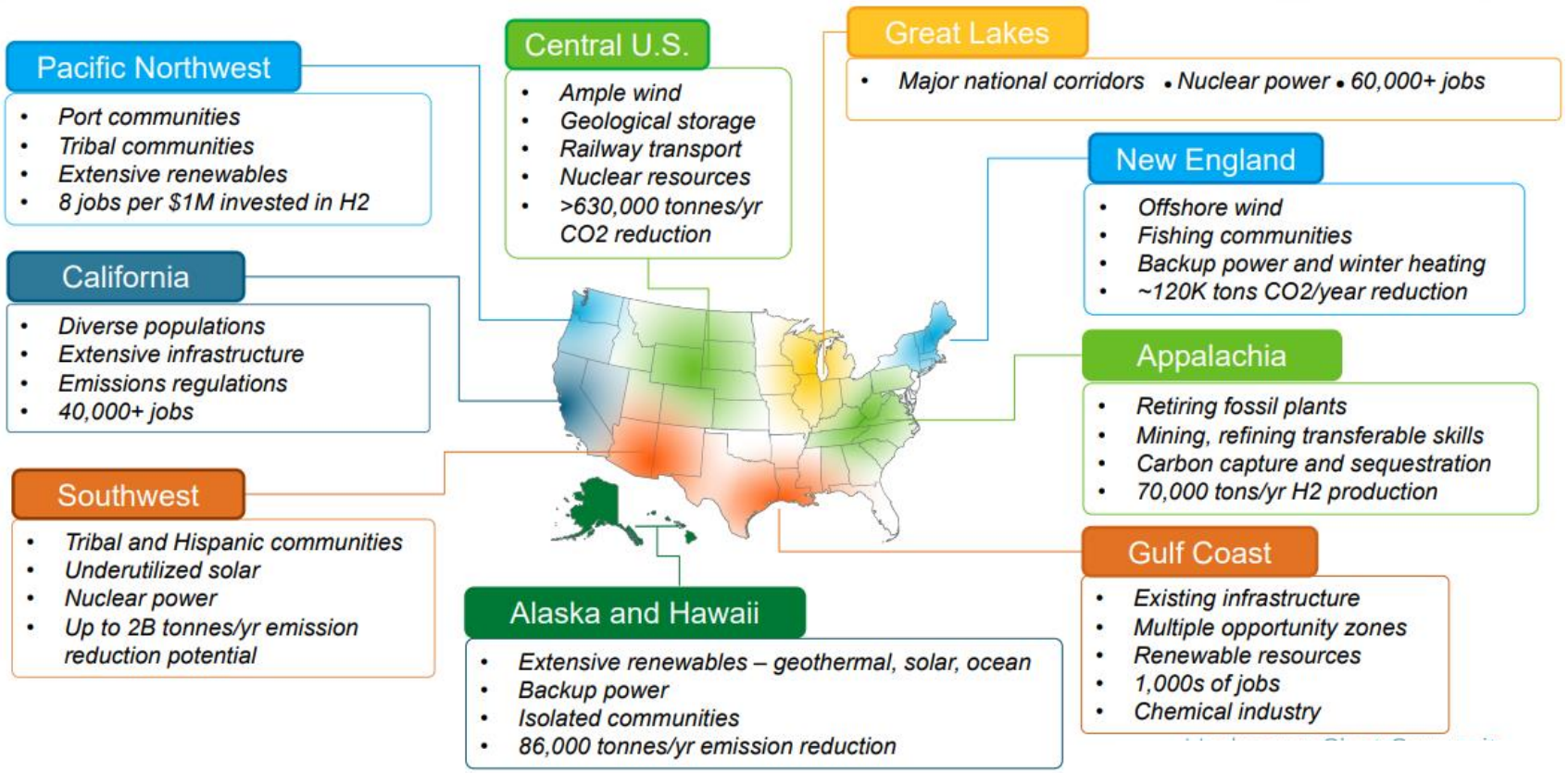
Central hubs are cost advantaged compared to onsite hydrogen production

Adding additional demand sites to the hub decreases cost through returns to scale

Hubs can tap into off-grid or wholesale electricity, which is much cheaper relative to retail industrial electricity. This can potentially lead to lower costs of from green hydrogen combustion heating compared with electric resistance heating.



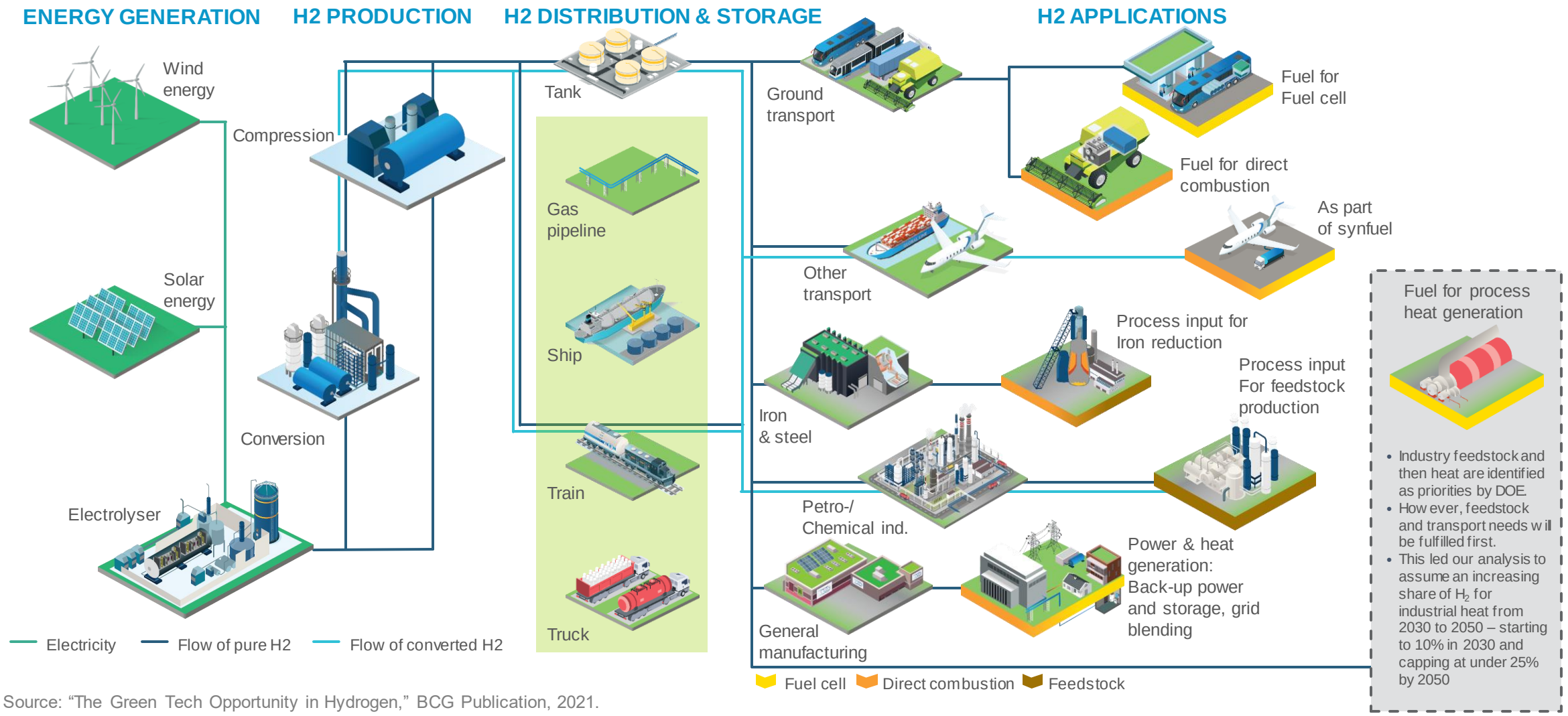
DOE identified 9 potential regional hubs for clean hydrogen production to accelerate decarbonization across sectors and geographies



The Infrastructure Investment and Jobs Act (IIJA) passed in late 2021 appropriated $8 billion for the development of at least four Regional Clean Hydrogen Hubs (H2Hubs) across the country

Source: DOE Dec 2021 Update on Hydrogen Shot, RFI Results, and Summary of Hydrogen Provisions

Hubs centralize the production, storage & distribution of hydrogen to supply various current and emerging consumers of hydrogen



Source: "The Green Tech Opportunity in Hydrogen," BCG Publication, 2021.

Hydrogen for industrial heating is likely deprioritized vs. other applications, which may lead to strong competition for supply and increased prices

Chemicals feedstock	Refining	Power generation	Transport	Steel
NH_3 Ammonia	Hydrotreating	Power storage	Heavy road	Reducing agent
CH_3OH Methanol	Hydrocracking	Supply balancing	Shipping	
			Aviation	

Uncertain deployment of limited clean H_2 in refining given supply constraints (for details, see refinery sector perspective)

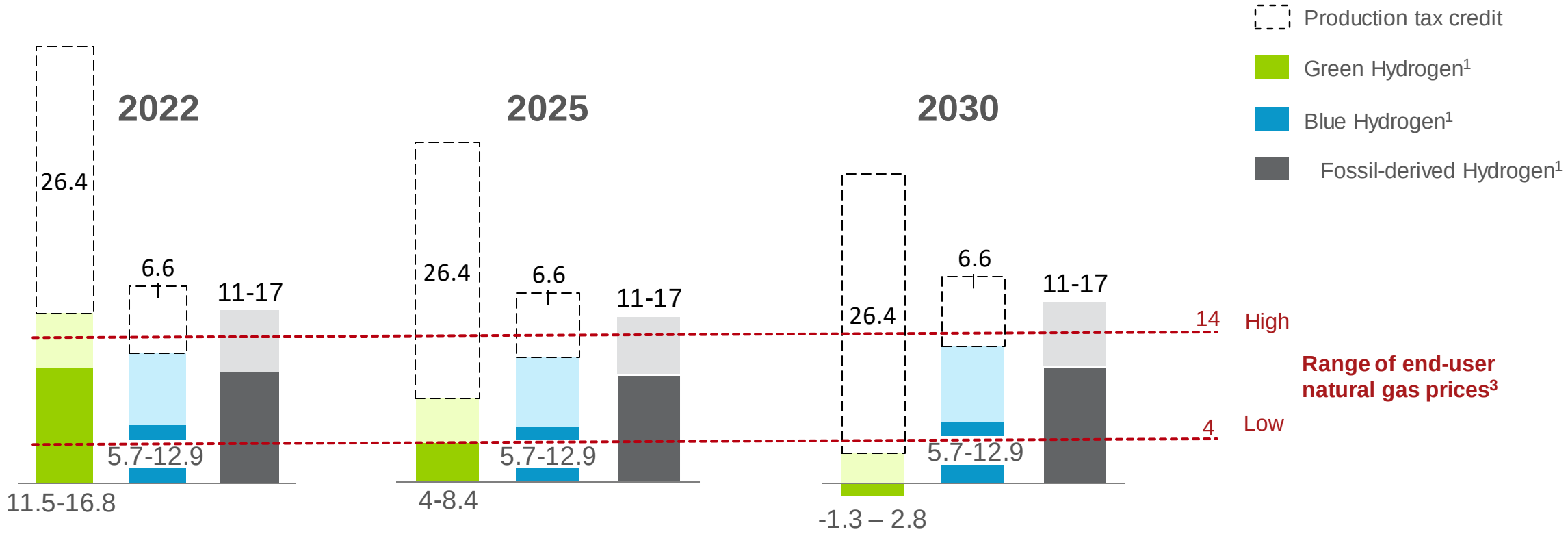
Mature applications → *Emerging applications*

With Inflation Reduction Act subsidies, hydrogen prices are expected to be competitive relative to natural gas prices today

United States Levelized Cost of Hydrogen

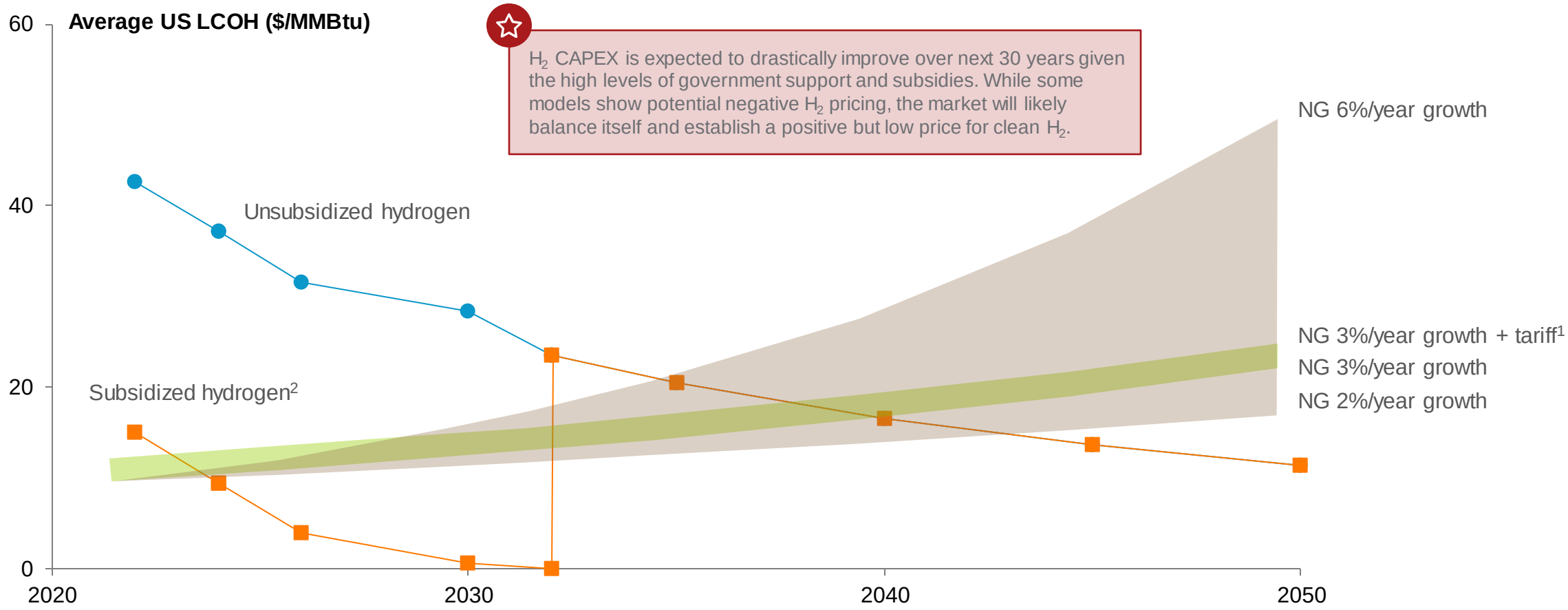
($/MMBtu, production cost plus T&D costs)[1]

Lighter shades reflects range of cost uncertainty[2]



1. Lighter shade reflects pricing uncertainty regarding natural gas (lower limit $2/MMBTU, upper limit $5/MMBTU) and electricity; 2. Starts at $0.4/kg H2 for 60-75% greenhouse gas reduction vs fossil-derived hydrogen, goes up to $0.75/kg H2 for 75-85% greenhouse gas reduction; 3. US EIA May 2022
Source: BCG North America H2 Supply Model

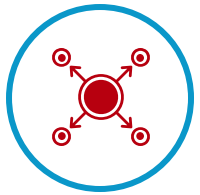
Hydrogen prices will be reduced by government subsidies, additionally CAPEX of hydrogen equipment is also expected to fall over the next 30 years



1. Based on $51/tonne CO2 social cost of carbon; 2. Inflation Reduction Act hydrogen production tax credit and investment tax credits

Significant advancements will be required for green H_2 to become competitive for decarbonization of industrial thermal applications

Key advancements needed to achieve green H_2 feasibility



Develop H_2 hubs

Industrial players should support and invest in H_2 hubs now to secure future H_2 supplies

Reduced power price

Resulting in OPEX reduction (e.g., from wind / solar reduced costs, cost exemptions1)

Matured technology

Increased electrolyzer and fuel cell efficiency and scale of production, reducing CAPEX

Regulatory support

Aggressive emissions targets and the legislation to support them (e.g., higher CO_2 price)

High levels of VRE

More variable renewable energy disrupting the grid & requiring new solutions (e.g., storage)

1. E.g., Exemptions from grid fees, taxes and levies for large scale setups

Industrial heating using H2 combustion has potential for displacing many fossil fuels if price declines are actualized, but face several high barriers to adoption

Advantages

Able to reach highest industrial temperature requirements

Potential cost savings with subsidies and CAPEX declines

Relatively simple retrofit of gas combustion equipment

Eliminates hazardous combustion particulates or emissions

Barriers

Likely higher fuel costs compared to natural gas systems in the short term

Difficult to store and transport hydrogen

Competitive supply environment (i.e., chemicals feedstock, transportation)

Combustion system full redesign needed for certain sectors

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