BCS LLC
A SUBSIDIARY OF MWI

www.bcs-hq.com

Coal and Carbon Management Guidebook

Coal-to-Hydrogen Opportunities and Challenges

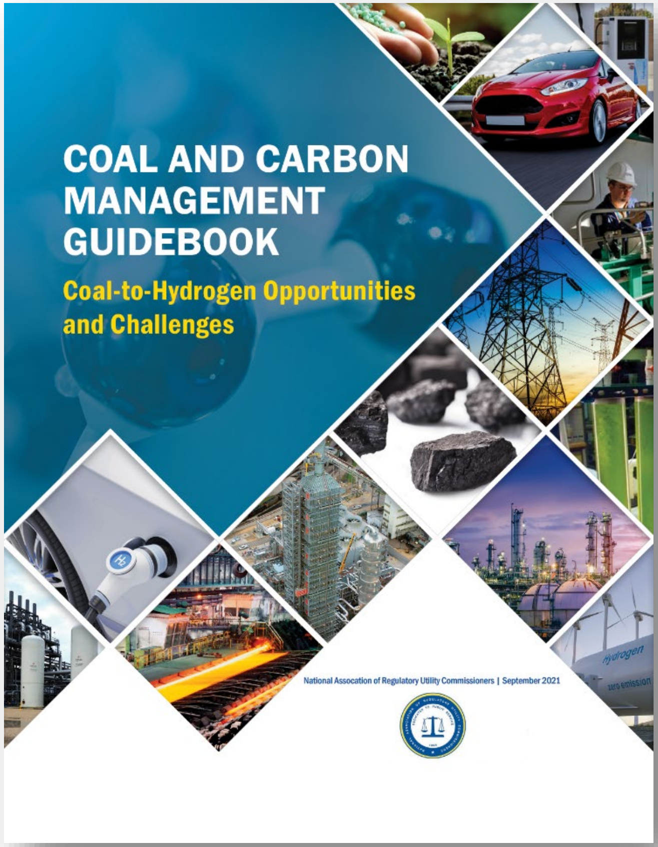
September 28, 2021






Acknowledgements

- Prepared by BCS, LLC as subcontractor to NARUC, for use by State Utility Regulators.
- BCS Project Team includes Feridun Albayrak, Michael Mudd, Jay Lenker, Colleen Newman, Raj Gupta, Samantha Ruiz, Jeff Hood.
- NARUC project oversight and guidance by Kiera Zitelman and Jasmine McAdams.
- We thank the U.S. Department of Energy, Office of Fossil Energy and Carbon Management (FECM), and the National Energy Technology Laboratory (NETL) for their support.

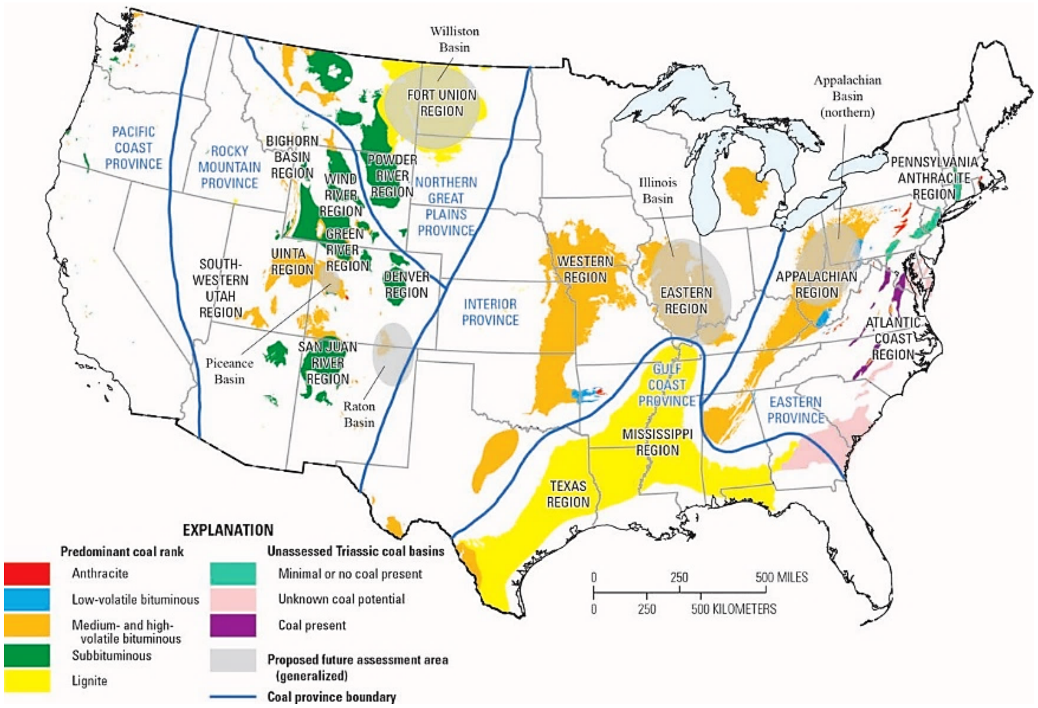


Guidebook Contents

- Executive Summary
- Introduction, Overview and Definitions
- Hydrogen Demand, and Decarbonization Potential in the United States
- Suitability of Various U.S. Coal Types for Hydrogen Production
- Prospect of Using Waste Coal-to-Hydrogen and Biomass with CCUS
- Maturity of Coal-to-Hydrogen Production Methods, Including CCUS
- Environmental Impacts Including GHG Emissions and Other Pollutants Generated from Coal-to-Hydrogen Production
- Challenges, Barriers, and Current Efforts
- How DOE's Hydrogen Program Strategy and Research Portfolio is Addressing Challenges; Gaps Remaining
- Regulatory Oversight of New Technologies: Coal-to-Hydrogen Fit within a Utility Regulator's Portfolio
- Economic Impacts on Coal-Producing Communities, Environmental Justice Considerations, and Implications on Clean Energy Jobs *
- Concluding Remarks
- Appendix A – Carbon Capture, Utilization, and Storage
- Appendix B – Coal Combustion Residuals

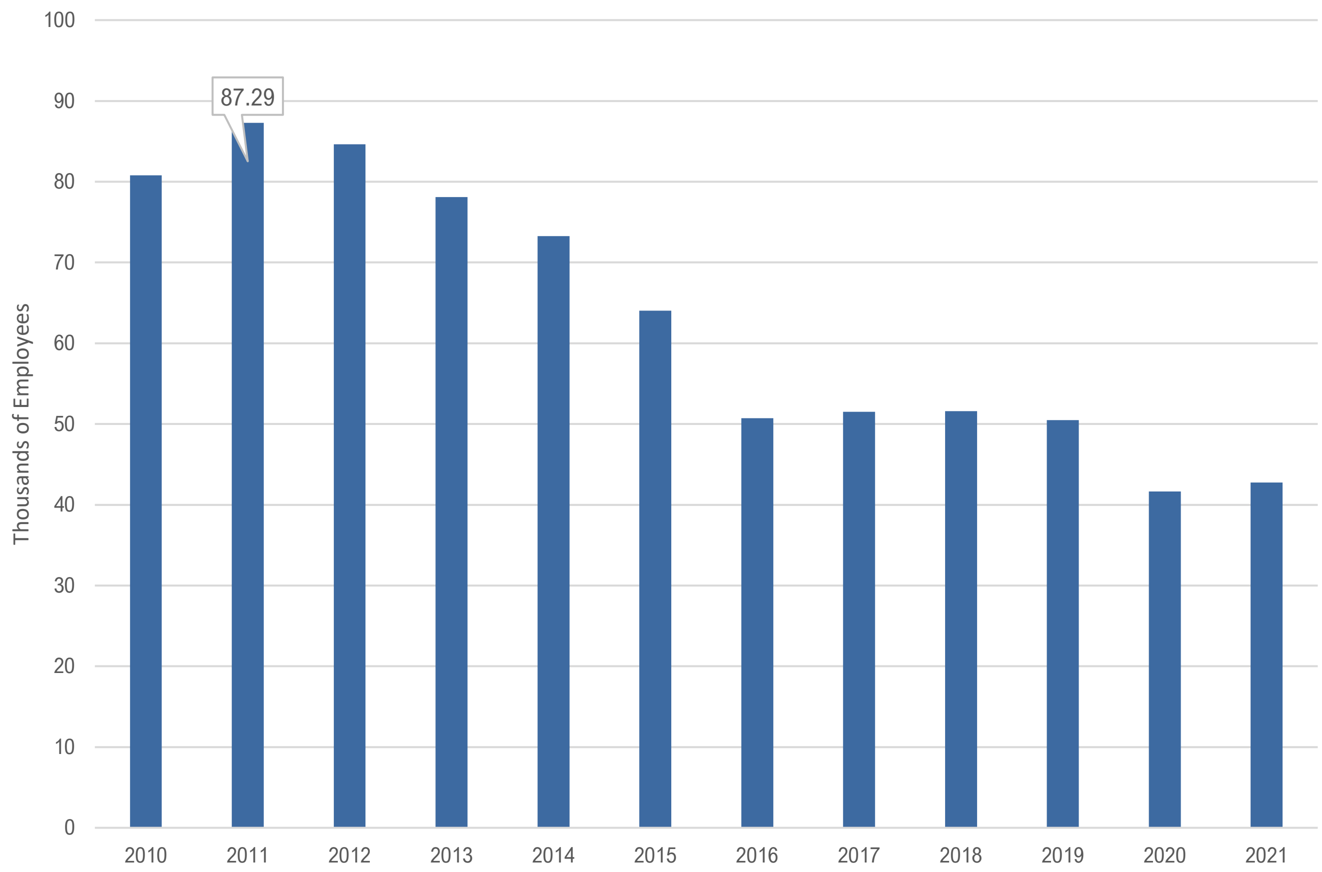
* Will be published separately

U.S. Coal Reserves



- 260 billion tons of recoverable reserves
- 28% of total global reserves
- 48% decline in production during past 12 years

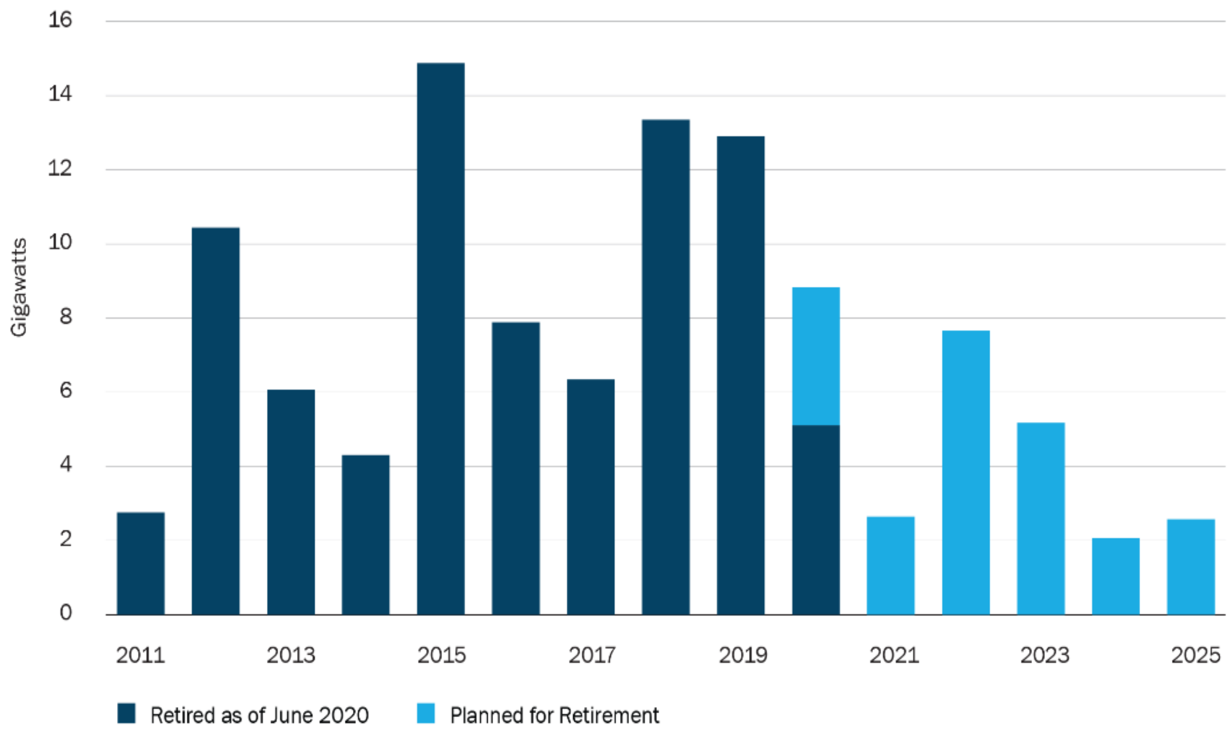
Coal Industry Jobs Have Declined



130,000 coal jobs have disappeared since 1985

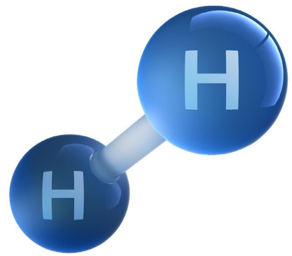
Coal Plants Have Been Retiring

More than 100 coal-fired plants have been replaced or converted to natural gas since 2011



From 2011 to mid-2020, 95 GW of coal capacity was closed or switched to another fuel and another 25 GW is slated to shut down by 2025

Hydrogen

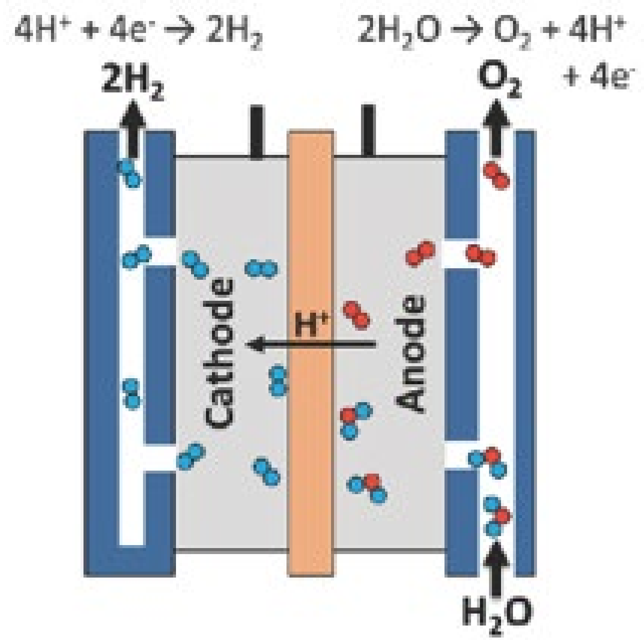


- The most abundant element in the universe
- Highest energy content per unit weight and lowest density of all fuels
- Natural form is as a molecular compound
  - Must be converted from a compound to be useable for combustion

Hydrogen Advantages

- Versatile fuel that offers a path to sustainable long-term economic growth.
  - Potential to meet 14% of U.S. total energy demand by 2050.
- Sustainable fuel for transportation, production of electricity, and heat for homes.
- Enables zero or near-zero emissions in transportation, stationary or remote power, and portable power applications.
- An integrated approach from all energy sectors (fossil, nuclear, and renewable energy systems) is required to realize the full potential and benefits of hydrogen.

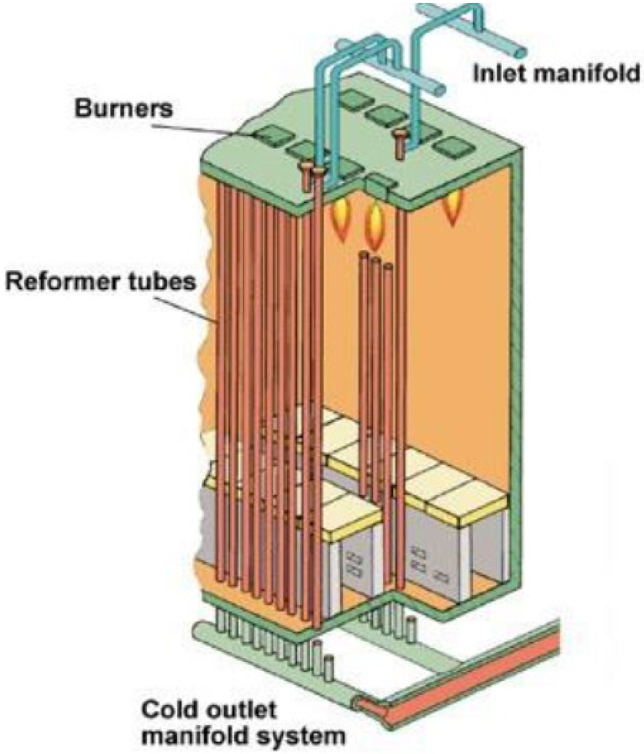
How Hydrogen is Produced: Electrolysis

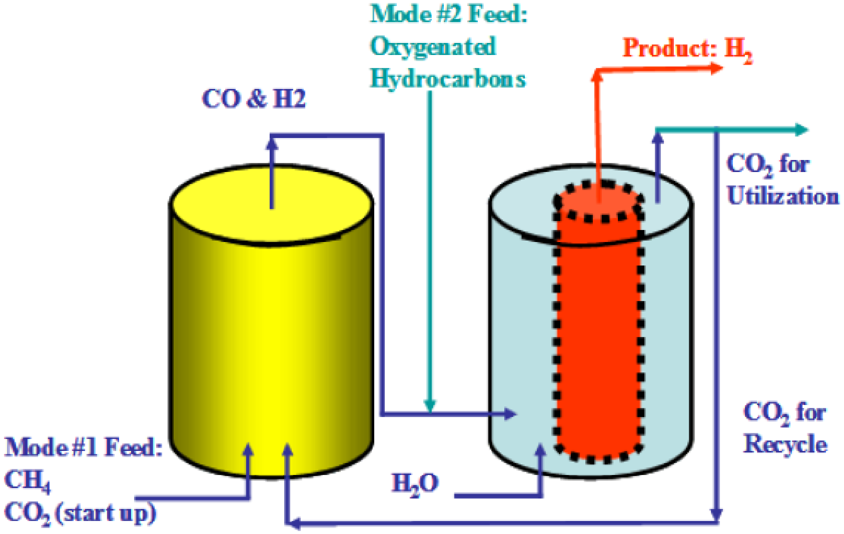


$$H_2O \xrightarrow{\text{Electricity}} H_2 + \tfrac{1}{2} O_2$$

Currently the most expensive process for producing hydrogen

How Hydrogen is Produced: Methane Reforming





Dry Reforming Reaction

WGS or Biomass Reactions

Steam-Methane Reforming Reaction

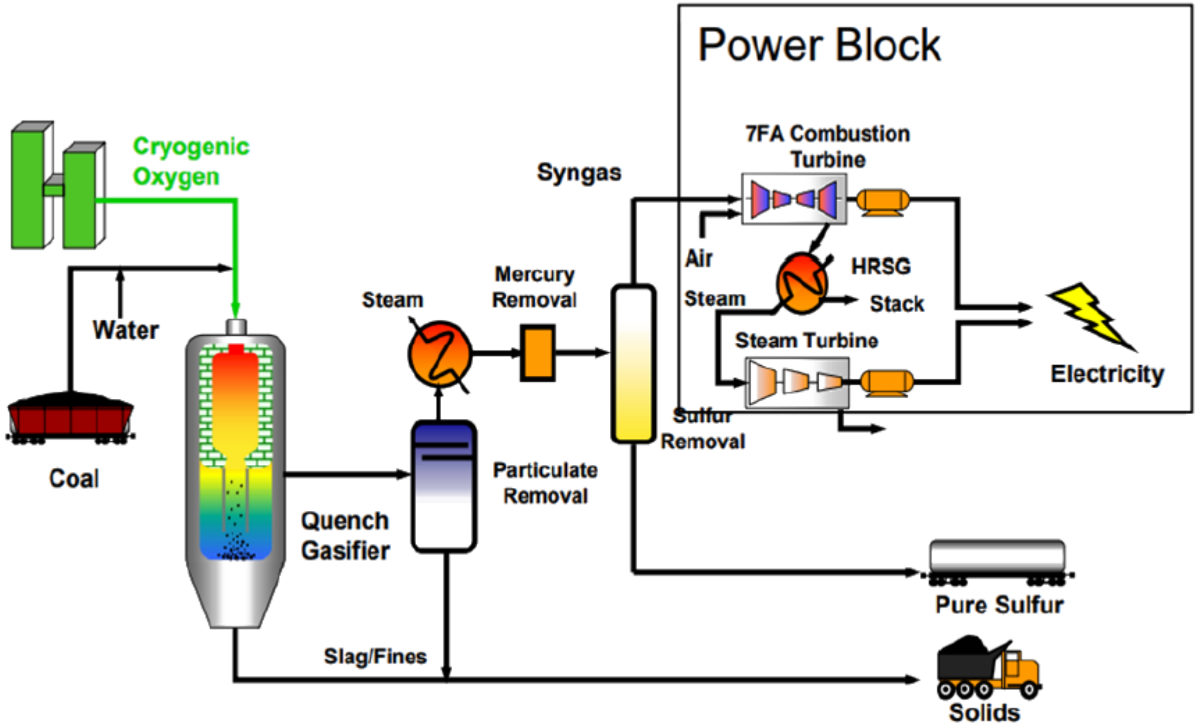
$CH_4 + H_2O$ **(+ heat) →** $CO + 3H_2$

Water-Gas Shift Reaction

$CO + H_2O \rightarrow CO_2 + H_2$ **(+ small amount of heat)**

Currently the most common process for producing hydrogen

How Hydrogen is Produced: Gasification



Gasification

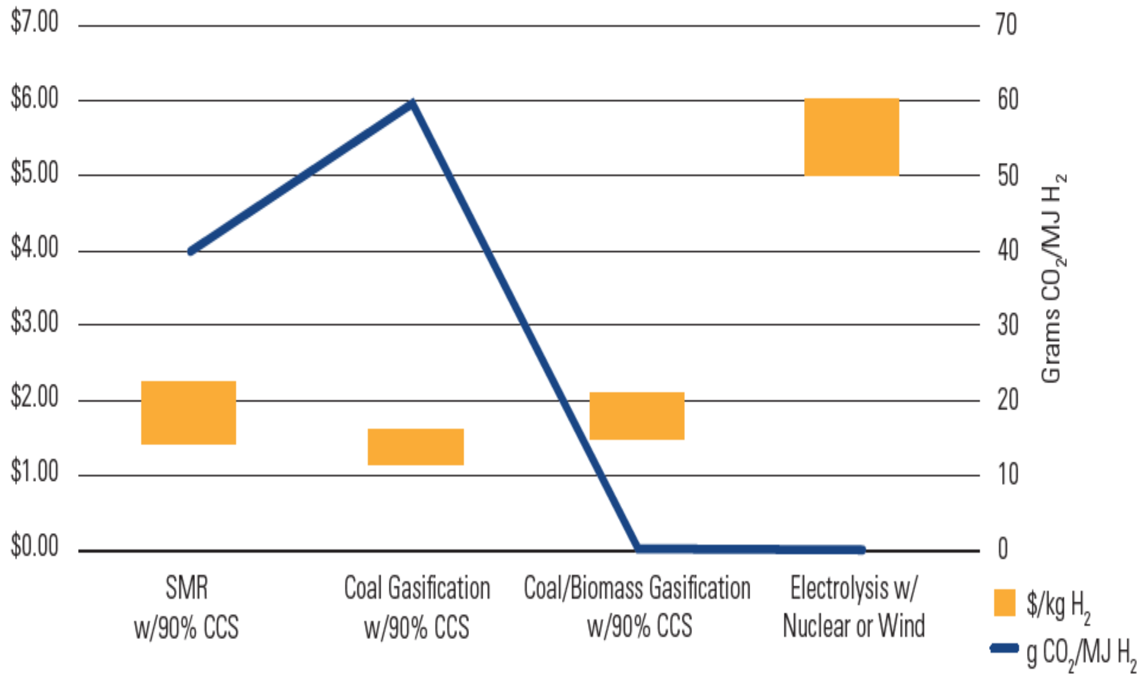
$C + H_2O + O_2 = CO + H_2$

Water-Gas Shift

$CO + H_2O = CO_2 + H_2$

Potential to be the least expensive process for producing hydrogen

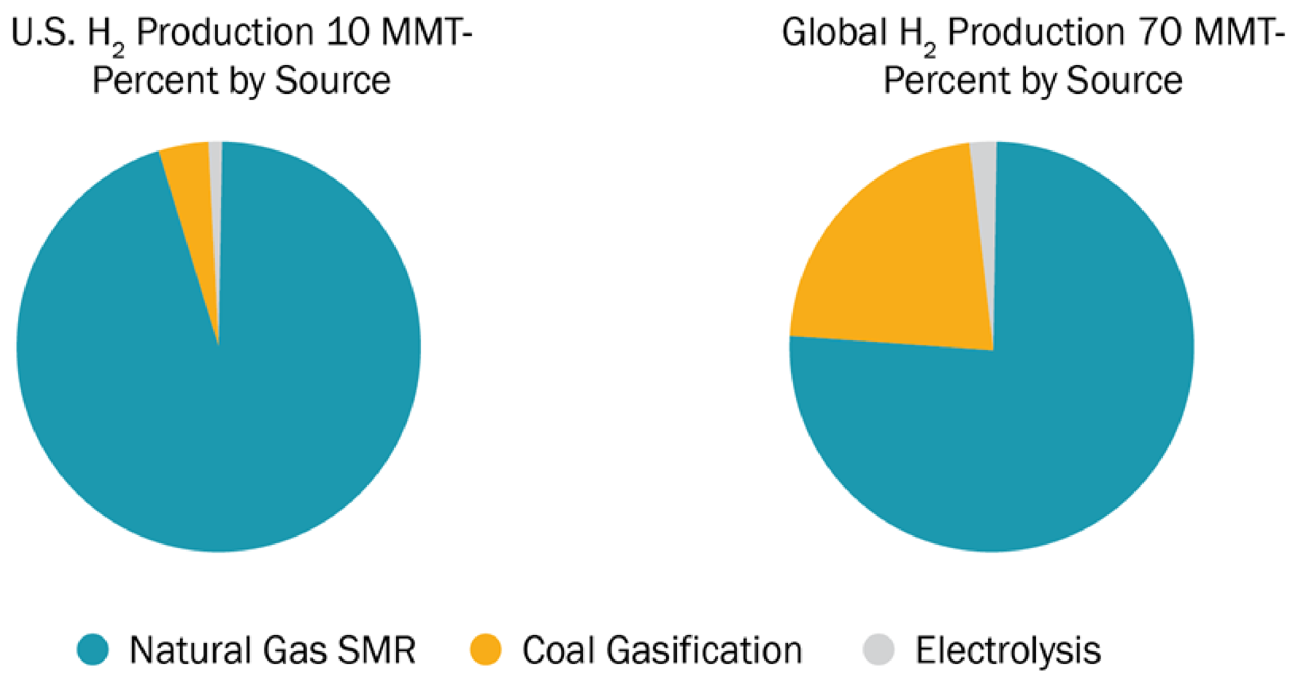
Comparative Cost of Hydrogen Production



Currently hydrogen production from fossil fuels is the least expensive source, even with CCUS

Current Hydrogen Production

United States | **Global**



United States:

- 96% by SMR
- 3% by Gasification
- 1% by Electrolysis

Global:

- 76% by SMR
- 22% by Gasification
- 2% by Electrolysis

Coal Combustion

CO_2 H_2O

Carbon Hydrogen Oxygen

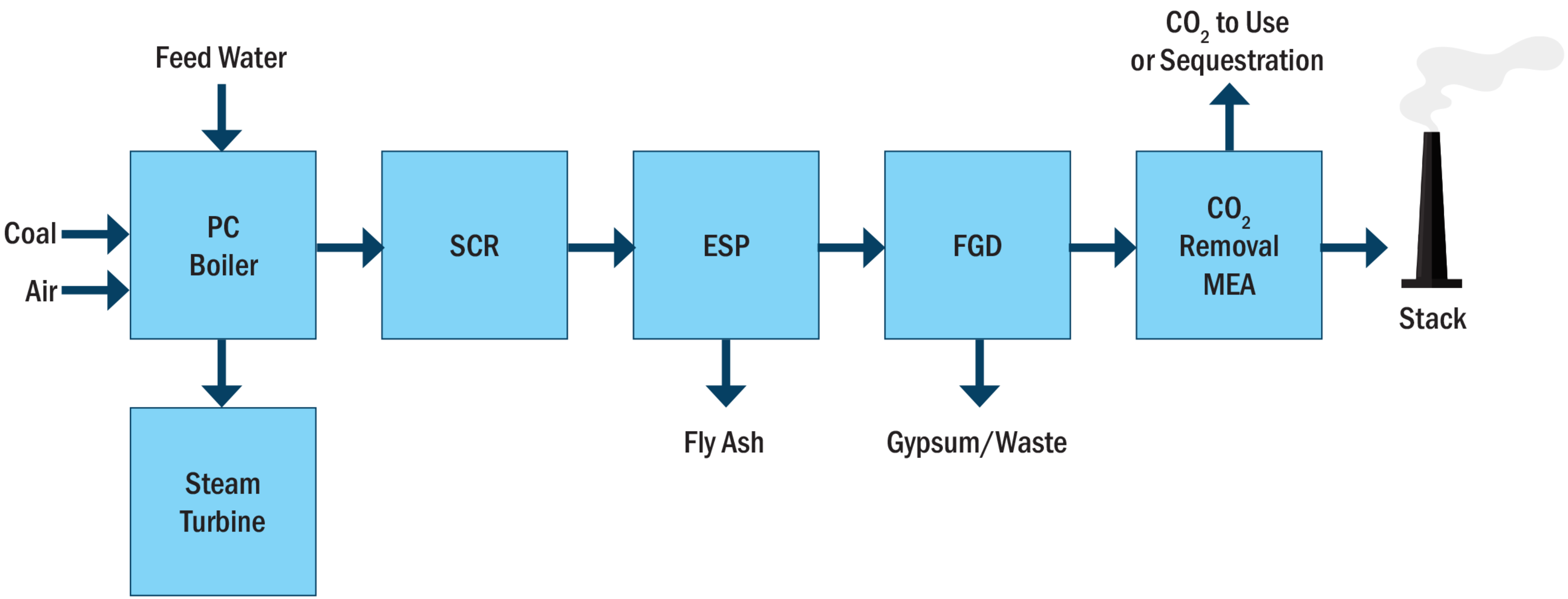
Oxygen
Nitrogen

Heat

Nitrogen Sulfur Ash

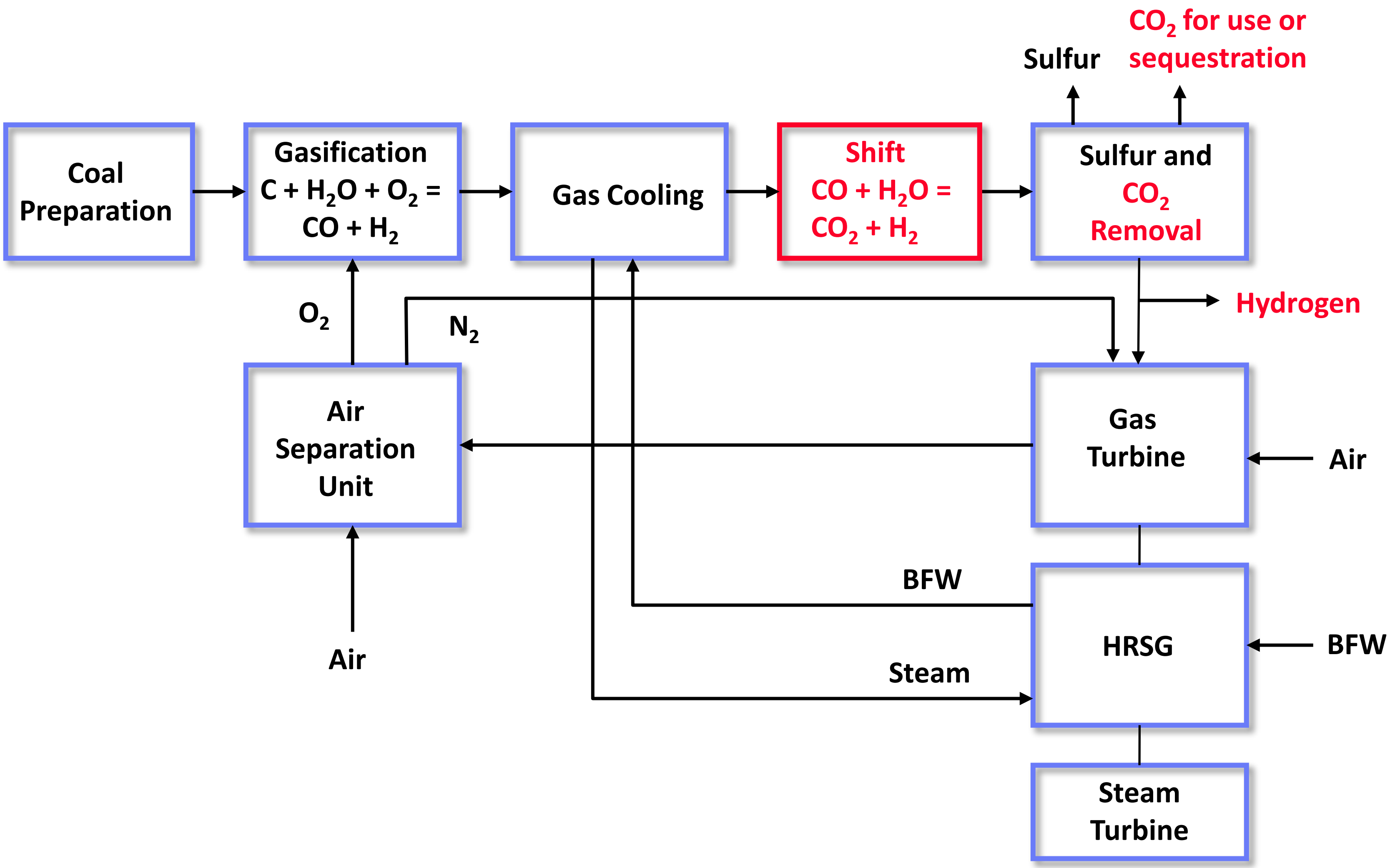
NO_x SO_x Fly Ash
Bottom Ash

Pulverized Coal with CO_2 Removal



PC with CO_2 removal does not produce hydrogen in the process

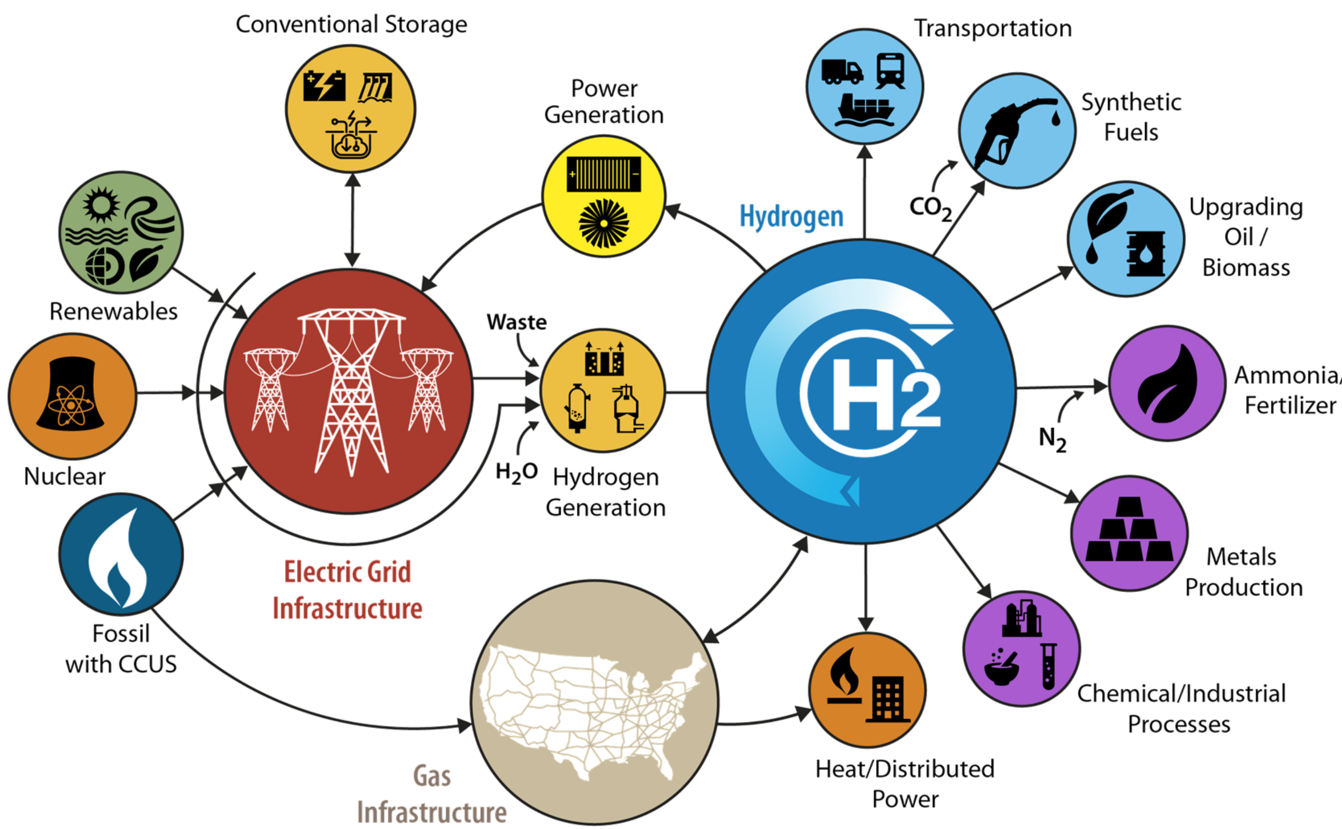
IGCC With CO_2 Separation and Hydrogen Production



Combustion vs. Gasification Byproducts

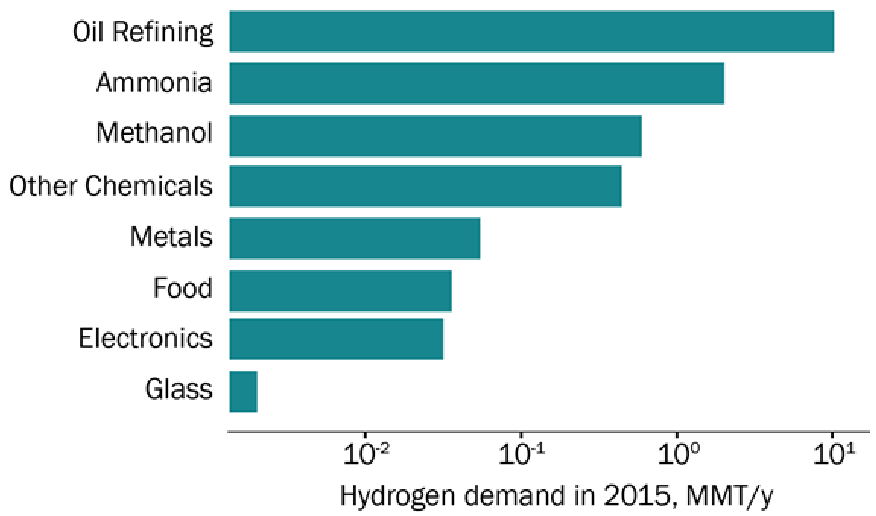
Byproduct	Combustion	Gasification
Carbon	CO_2	CO
Hydrogen	H_2O	H_2
Nitrogen	NO, NO_2	NH_3 or N_2
Sulfur	SO_2 or SO_3	H_2S or COS
Water	H_2O	H_2

Hydrogen Economy



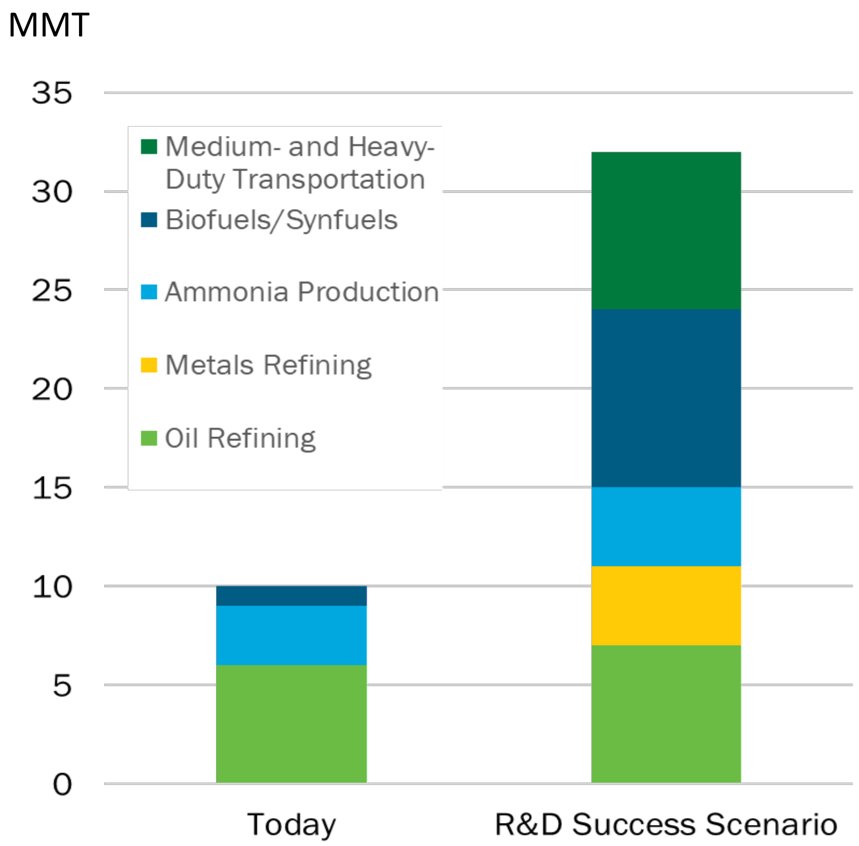
DOE's H2@Scale initiative provides an overarching vision for how hydrogen can enable energy pathways across applications and sectors in an increasingly interconnected energy system

U.S. Hydrogen Demand



- Current demand is about 10 MMT, mostly for oil refining and chemical production.
- Metals, electronics and glass production are main industrial sources of demand.
- Food production is main consumer source of demand.
- Transportation, building heating and electricity generation are areas of demand growth for a decarbonized economy.

U.S. Hydrogen Demand – Cont'd



These estimates can be achieved, provided R&D targets are met and market and transition barriers are overcome.

Conservative estimates show clean, low-cost hydrogen can enable >30 MMT hydrogen demand in industry, chemicals and transport in the United States

Relative Technology Costs

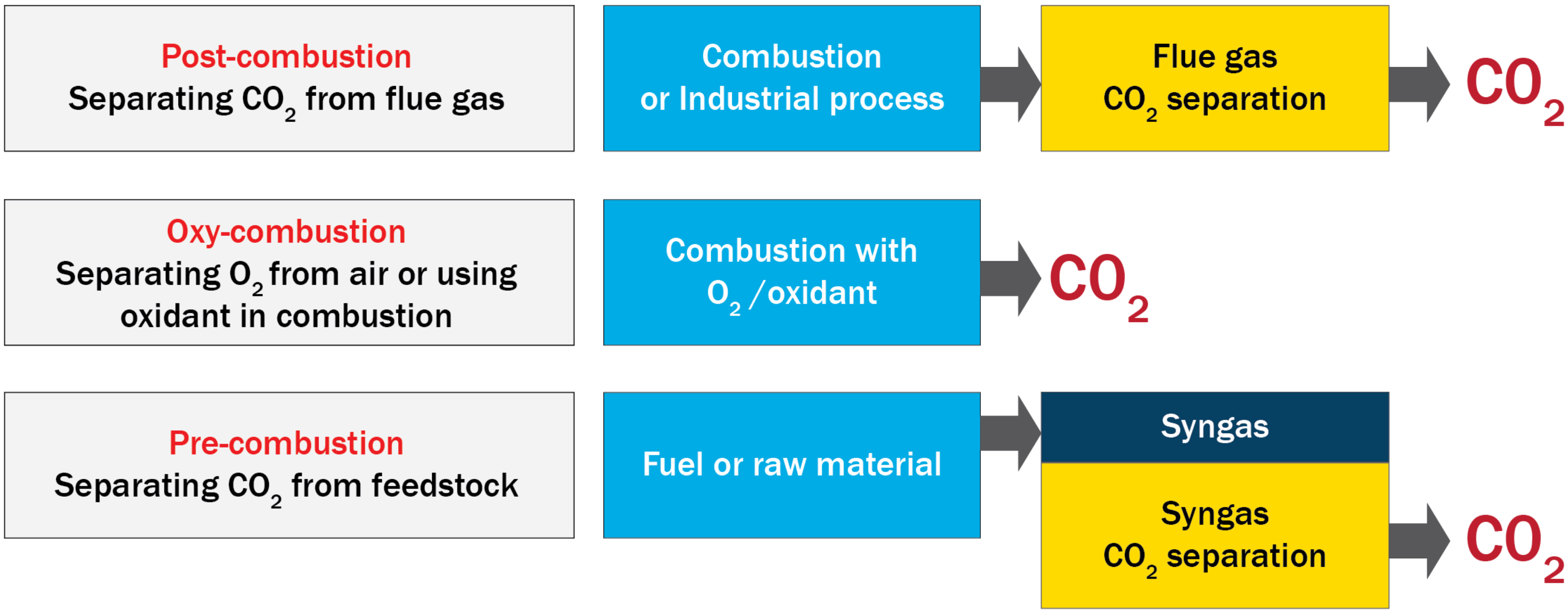
Technology	Nominal Plant Capacity (MW)	Net HHV Heat Rate (Btu/kWh)	Total Plant Cost* ($/kW)
Pulverized Coal with Carbon Capture	650	10,834 – 11,393	3,756 – 3,800
IGCC with Carbon Capture	519 – 557	10,101 – 10,497	5,177 – 6,209
NGCC with Carbon Capture	646	7,159	1,984
Biomass	50 –100	12,900 – 14,000	4,266 – 6,035**

* Based on 2016 EPRI data, cost in constant December 2018 Dollars

**Cost escalated from 2016 to 2018 Dollars

Costs for plants using new technology are subject to significant uncertainty

Carbon Capture

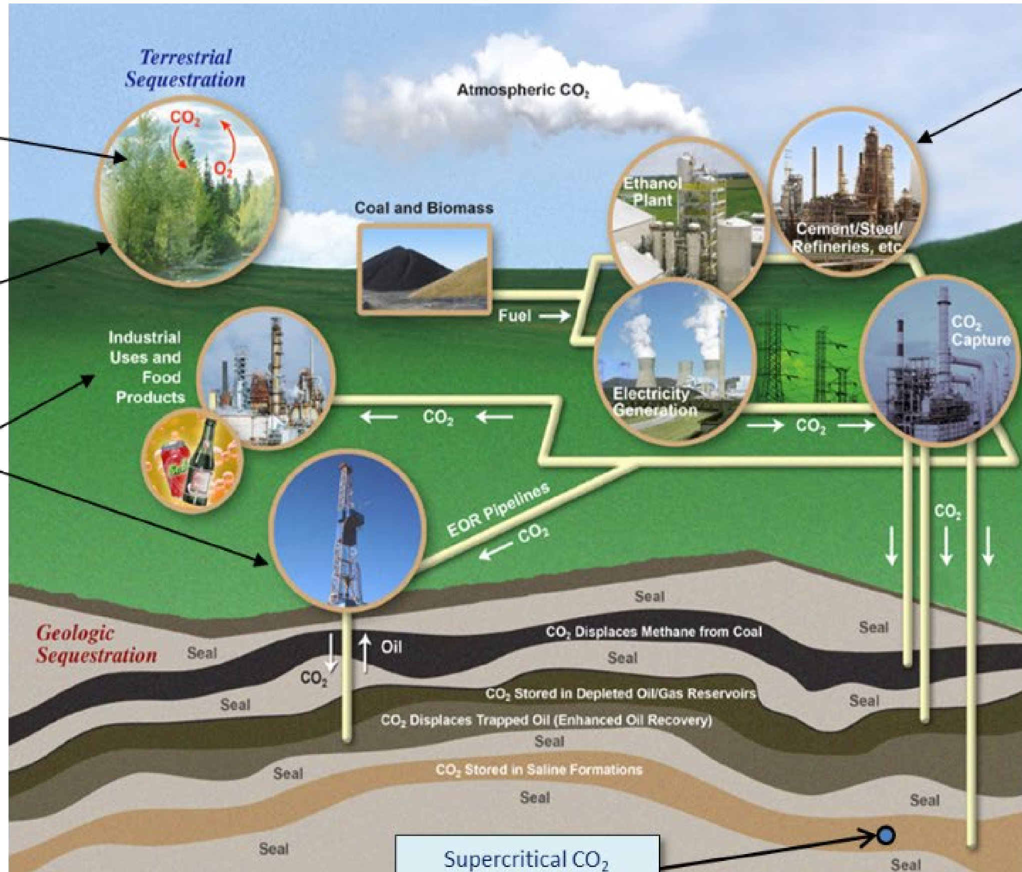


Carbon Capture, Utilization, and Storage (CCUS)

Terrestrial Capture
- CO_2 absorbed from air

Terrestrial Storage
- Trees, grasses, soils

Utilization
- EOR
- Beneficial reuse

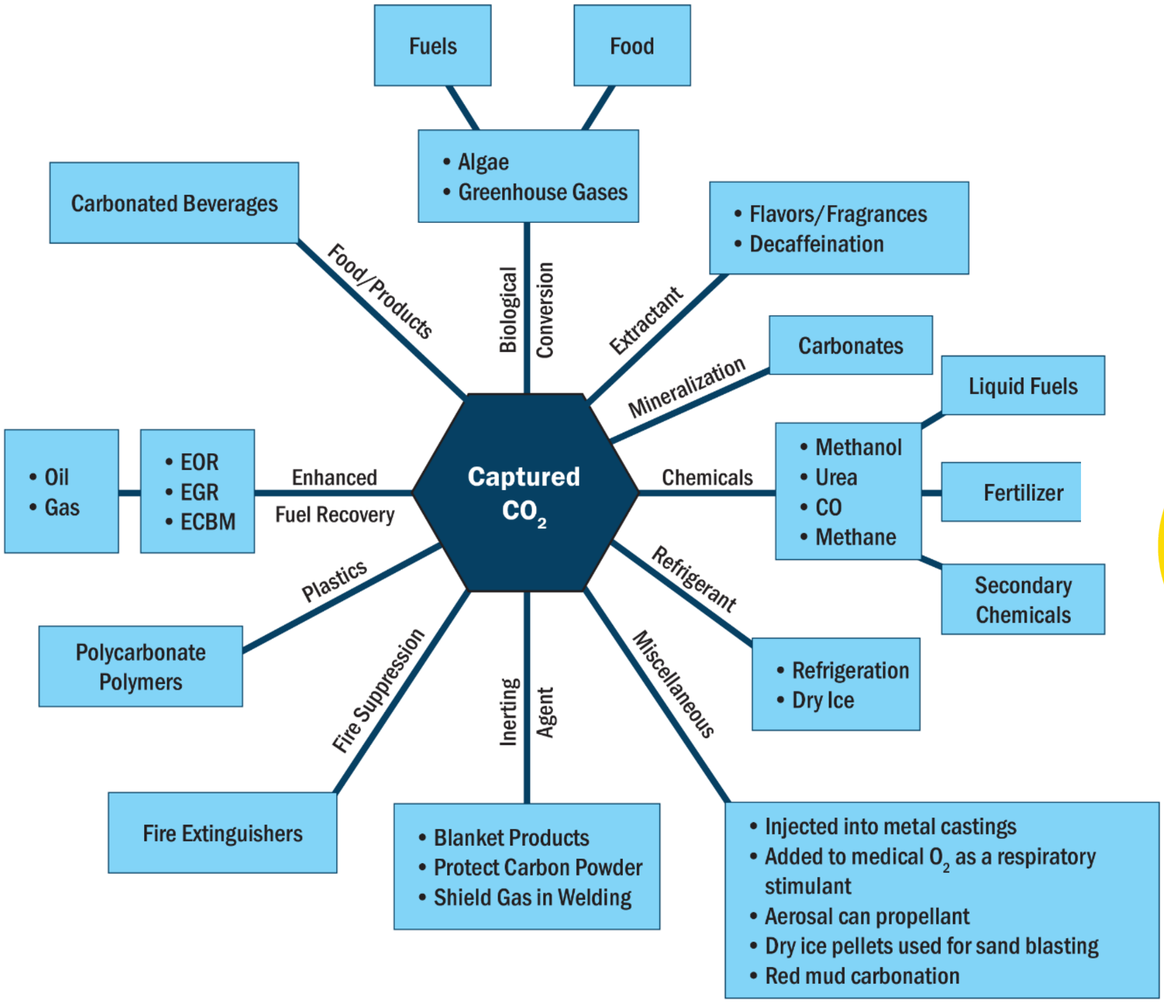


Supercritical CO_2
1/300th of Atm. CO_2

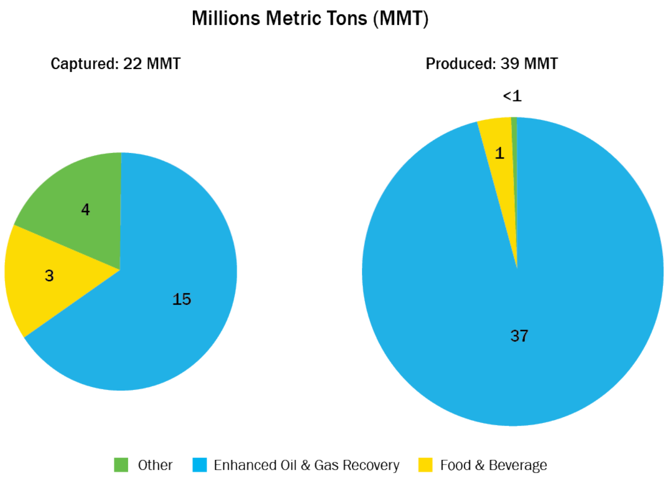
Point Source Capture
- Power plants
- Ethanol plants
- Cement
- Steel
- Refineries
- Natural gas processing

Geologic Storage
- Saline formations
- Depleted oil/gas
- Unmineable coal
- Other: basalts, shales

Potential Utilization Streams for CO_2



Primary End Uses for CO_2 Captured and Produced



CCUS Technology Challenges

- Capital intensive
- High parasitic load
- Higher operating costs
- Technology and operational risks
- Legislative uncertainty
- Uncertainty in CO_2 revenue stream value
- Liability of potential CO_2 leaks in storage sites

Quandary for Regulators

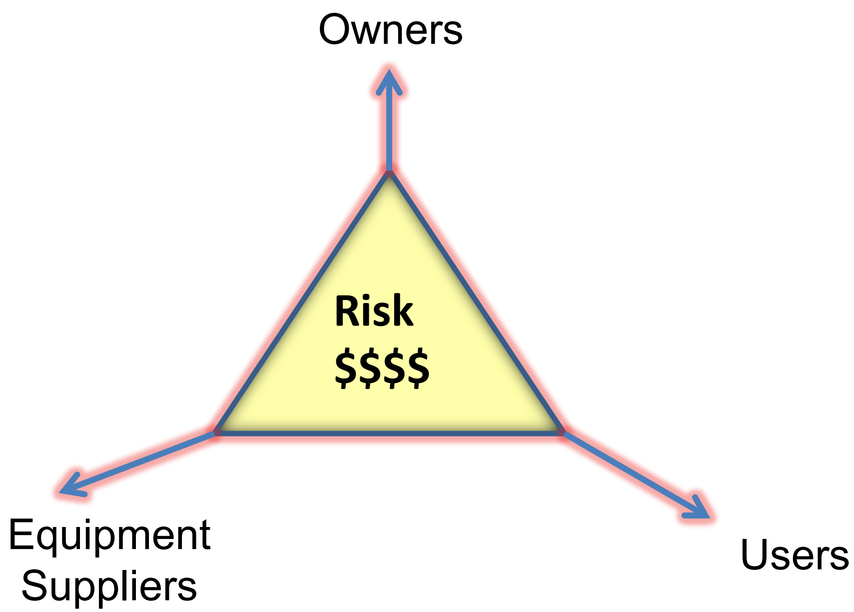
- Protection of ratepayers
- Risk / reward allocation
- Need for new technologies
- Long lead time for major capital projects

Challenges with FOAK Technologies

Technical Risk
- Performance
- Guarantees
- Availability
- Schedule

Cost Risk
- Cost uncertainty
- Escalation
- Redesign costs
- Market prices

Regulatory Risk
- Time for approval
- Interveners
- Policy changes
- Changes in law



Who will take on the risks?

Lessons Learned from Pioneering Projects

Petra Nova Plant, Texas - $1B Project

- 240-MW slip stream
- Operated 2017-2020
- Successful technical demonstration of CCUS
- Became uneconomical when CO_2 prices (for EOR) plummeted

Edwardsport Station, Indiana - $3.4B Project

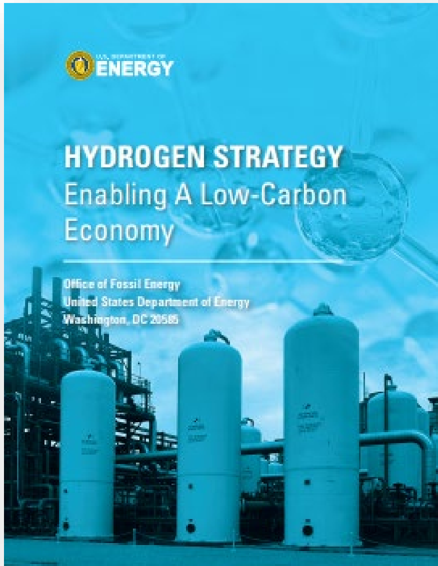
- 618-MW IGCC plant
- Construction start 2008
- Commercial operation 2013
- Beset by cost overruns and schedule delays
- Still in successful operation today

Kemper Plant, Alabama - $7.5B Project

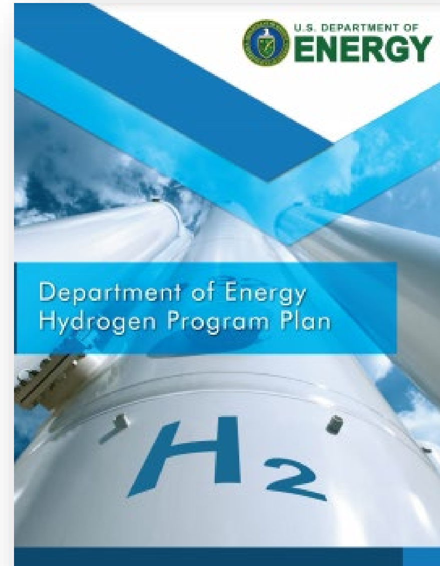
- 582-MW IGCC Plant
- Construction start 2010
- Switched to natural gas only in 2017
- Ambitious FOAK plant in many facets
- Cancelled due to overwhelming design risks, schedule delays, and cost overruns

FOAK demonstration plants entail risks for all stakeholders

FECM H2 Strategy and DOE H2 Program



July 2020



November 2020

Hydrogen Shot

The first of Energy Earthtshots, launched in June 2021.
Seeks to reduce the cost of clean hydrogen by 80% ("1, 1, 1")

BCS LLC

DOE Sponsored Projects

Steam Methane Reforming with CO_2 Capture

Air Products & Chemicals, Inc. (Port Arthur, TX)

- Largest and only hydrogen production facility with CO_2 capture in the world (90%+ capture).
- Built and operated by Air Products and Chemicals, Inc. and located at Valero Oil Refinery in Port Arthur, TX.
- CO_2 capture added to two existing Steam-Methane Reformers (SMRs) used for Hydrogen Production
- Capturing ~925,000 tonnes CO_2 / year.
- ~30 MWe cogeneration unit makeup steam to SMRs and power to VSA and Compressors.
- CO_2 to Denbury "Green" pipeline for EOR in Texas at the West Hastings oil field.

DOE Sponsored Projects – Cont'd

Hydrogen Production From Gasification FEED Studies

Electric Power Research Institute (Palo Alto, CA)

- Gasification of Coal and Biomass: The Route to Net-Negative-Carbon Power and Hydrogen – Integrated design study on an oxygen-blown gasification system coupled with water-gas shift, pre-combustion CO_2 capture, and pressure-swing adsorption working off a waste coal/biomass mix to yield high-purity hydrogen and a fuel off-gas that can generate power.
- Nebraska Public Power District
- CO_2 storage: enhanced oil recovery and saline sequestration
- Co-feed corn stover and possibly other biomass and waste plastics

Wabash Valley Resources, LLC (West Terre Haute, IN)

- Wabash Hydrogen Negative Emissions Technology – Complete system integrated design study for redeveloping the existing Wabash Valley Resources coal gasification site in West Terre Haute, Indiana, into a 21st century power plant for flexible fuel gasification-based carbon-negative power and carbon-free hydrogen co-production.
- Facility: Wabash Gasification Facility
- CO_2 Storage: Saline sequestration
- Co-feed woody biomass and/or agricultural residue and waste plastics

Moving New Technology Forward

Federal Government

- Continue to fund the development of new technologies through the basic research, development, and demonstration phases.
- Implement policies that address and overcome impediments to the deployment of new technologies.

Industry

- Allocate an appropriate percentage of their corporate budgets towards RD&D efforts.

Regulators

- Provide sufficient incentives that reward successful deployment of new technologies, yet protect ratepayers from cost overruns and other risks.

Project Contacts

BCS, LLC

Feridun Albayrak
Vice President
falbayrak@bcs-hq.com
202-410-9200, ext. 466
www.bcs-hq.com

Michael Mudd
Advanced Technology Consultant
Mmudd@bcs-hq.com

NARUC

Kiera Zitelman
Technical / Senior Manager
kzitelman@naruc.org
(202) 898-2200
www.naruc.org

Jasmine McAdams
Program Officer
jmcadams@naruc.org

References

- Slide 4: U.S. Geological Survey, “Coalfields of the Conterminous United States Map,” https://www.usgs.gov/media/images/usgs-coalfields-conterminous-united-states
- Slide 5: FRED Economic Data, “All Employees, Coal Mining, https://fred.stlouisfed.org/series/CES1021210001
- Slide 6: U.S. Energy Information Administration, “More than 100 Coal-fired Plants Have Been Replaced or Converted to Natural Gas Since 2011*,” Today in Energy*, August 5, 2020, https://www.eia.gov/todayinenergy/detail.php?id=44636
- Slide 9: U.S. Department of Energy, “Hydrogen Production: Electrolysis,” Hydrogen and Fuel Cell technologies Office, https://www.energy.gov/eere/fuelcells/hydrogen-production-electrolysis
- Slide 10: Kevin Bakey, The Production of Hydrogen Gas: Steam Methane Reforming, March 23, 2015, https://sites.psu.edu/kevinbakey/wp-content/uploads/sites/26382/2015/04/Process-Description.pdf
- Slide 11: James Katzer, “The Future of Coal-Based Power Generation with CCUS, MIT Energy Initiative, *MIT Future of Coal*, UN CCS Summit, https://sustainabledevelopment.un.org/content/documents/3290katzer_presentation.pdf
- Slide 12: U.S. Department of Energy, “Hydrogen Strategy: Enabling A Low Carbon Economy,” Office of Fossil Energy, July 2020, https://www.energy.gov/sites/prod/files/2020/07/f76/USDOE_FE_Hydrogen_Strategy_July2020.pdf
- Slide 16: Source: Electric Power Research Institute (EPRI)
- Slide 18: U.S. Department of Energy, “Department of Energy Hydrogen Program Plan,” November 2020, https://www.hydrogen.energy.gov/pdfs/hydrogen-program-plan-2020.pdf
- Slide 20: National Renewable Energy Laboratory, “The Technical and Economic Potential of the H2@Scale Concept within the United States,” October 2020, https://www.nrel.gov/docs/fy21osti/77610.pdf
- Slide 22: U.S. Department of Energy, “Accelerating Breakthrough Innovation in Carbon Capture, Utilization and Storage: Report of the Mission Innovation Carbon, Capture Utilization, and Storage Experts’ Workshop,” September 2017, https://www.energy.gov/sites/prod/files/2018/05/f51/AcceleratingBreakthroughInnovationinCarbonCaptureUtilizationandStorage_0.pdf
- Slide 23: Modified image, courtesy of the Rocky Mountain Coal Mining Institute
- Slide 24: Same as Slide 22.

Disclaimer

The *Coal and Carbon Management Guidebook* was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.