KIAT Seminar, Aug 23rd, 2023

탄소중립을 위한 수소 생산 및 활용 기술개발 전망

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Overview

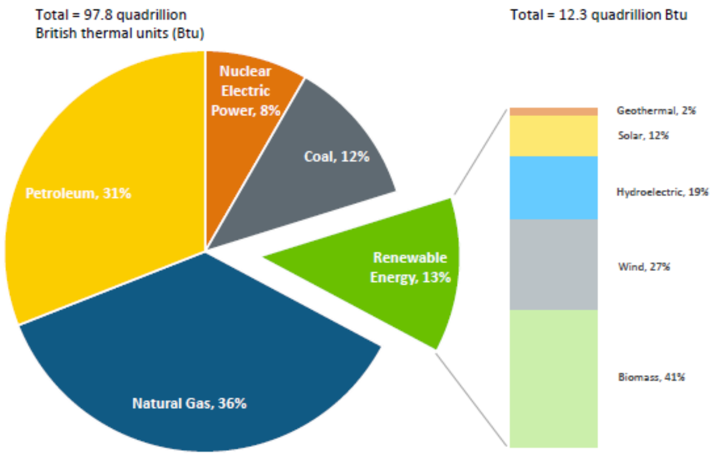
- Perspectives of Hydrogen to Power Industries in the United States
- Research Topics on Hydrogen Production/Utilization and Energy Recovery for Steelmaking Industry

Contents

- Perspectives of Hydrogen to Power Industries in the United States
  - Trends and Perspectives of Overall and Renewable Energy in US and Korea
  - Trends and Perspectives of Hydrogen Turbine and Fuel Cell in US
  - Impacts on Grids: Reliability and Potential Issues
  - Feasibility of Hydrogen to Electricity Business

Energy Key Goals in US

U.S. primary energy consumption by energy source, 2021



Note: Sum of components may not equal 100% because of independent rounding
Source: Data collected from U.S. Energy Information Administration, April 2022, *Monthly Energy Review*, preliminary data

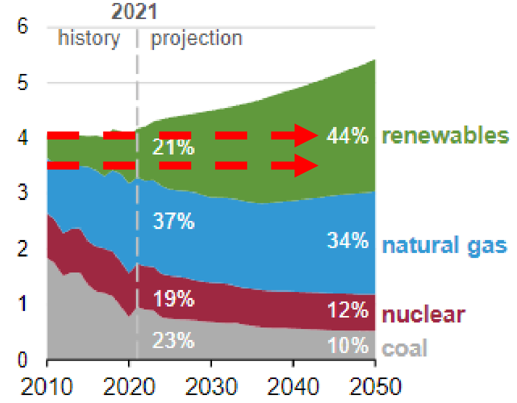
Administration Goals include:

- Net-zero emissions economy by 2050 and 50–52% reduction by 2030
- 100% carbon-pollution-free electric sector by 2035

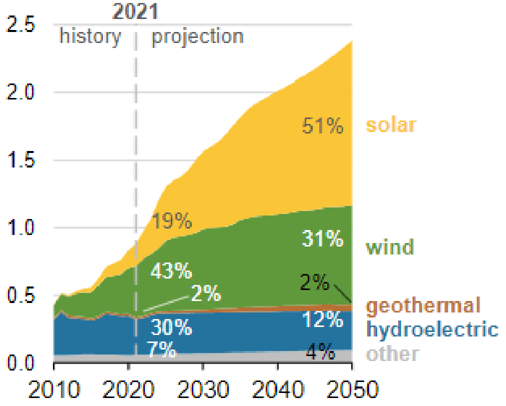
Priorities: Ensure benefits to all Americans, focus on jobs, EJ40: 40% of benefits in disadvantaged communities

EJ: Environmental Justice

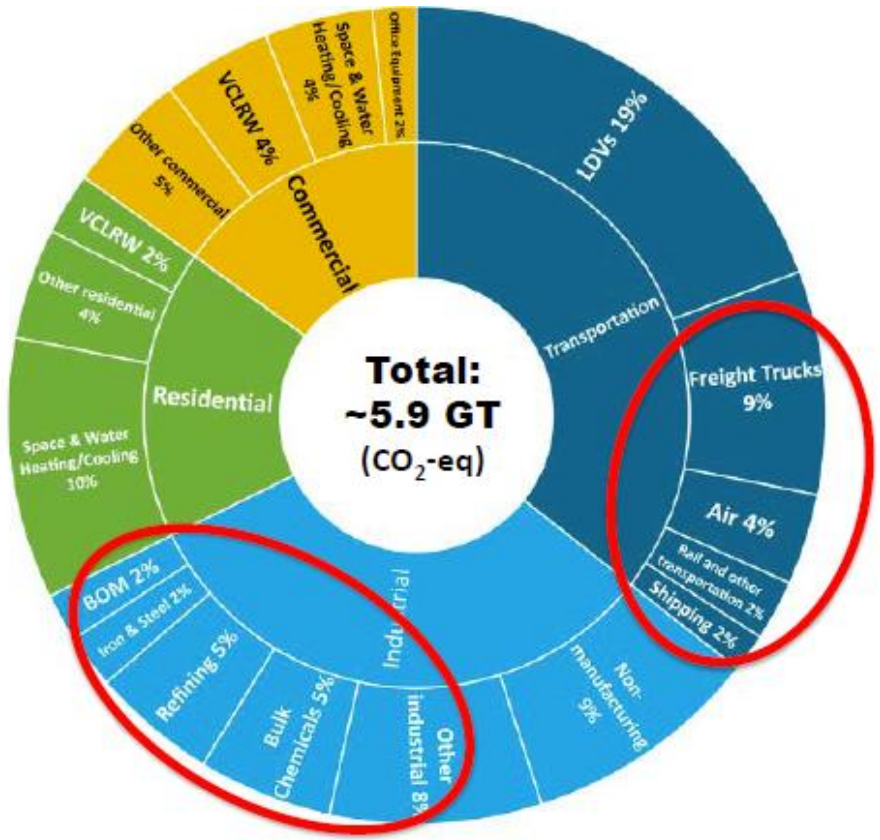
U.S. electricity generation
AEO2022 Reference case
trillion kilowatthours



U.S. renewable electricity generation including end use
trillion kilowatthours



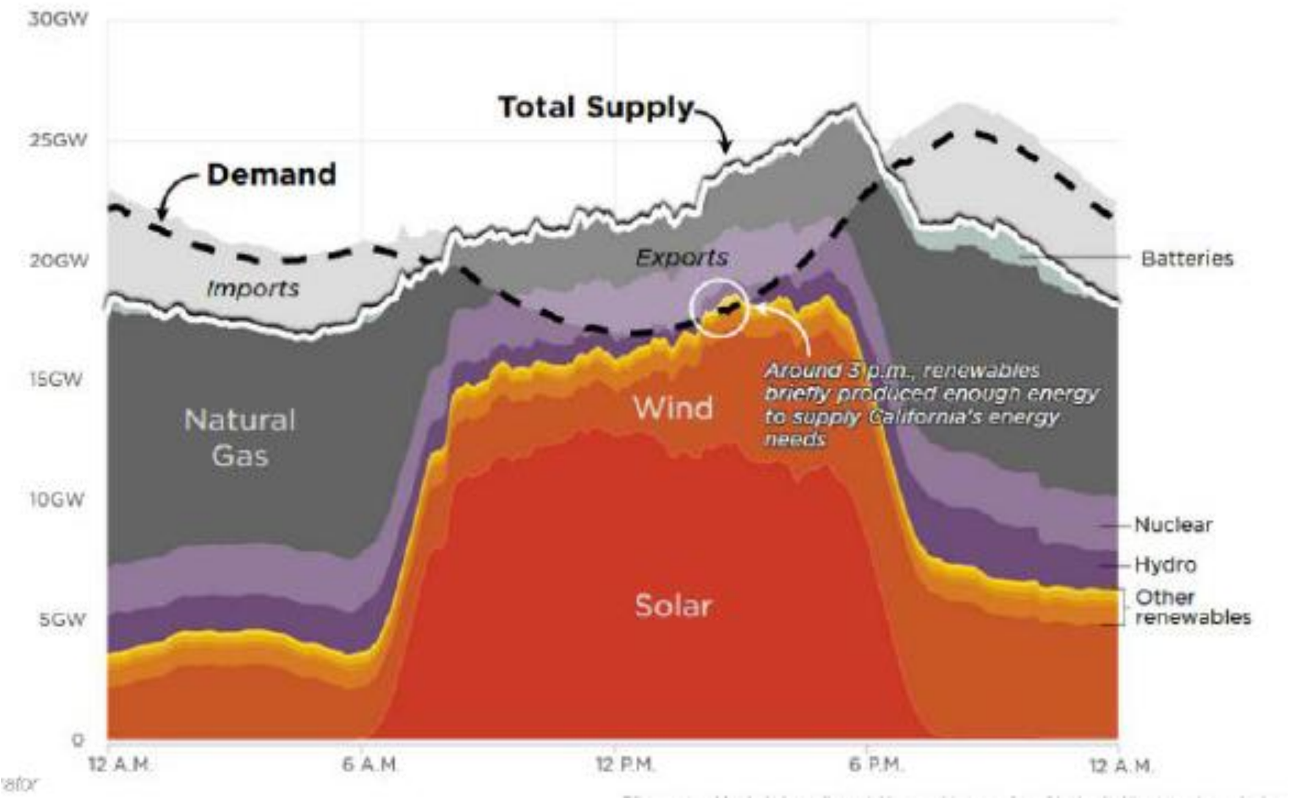
Source: U.S. Energy Information Administration, *Annual Energy Outlook 2022* (AEO2022)
Note: Biofuels are both shown separately and are included in petroleum and other liquids.



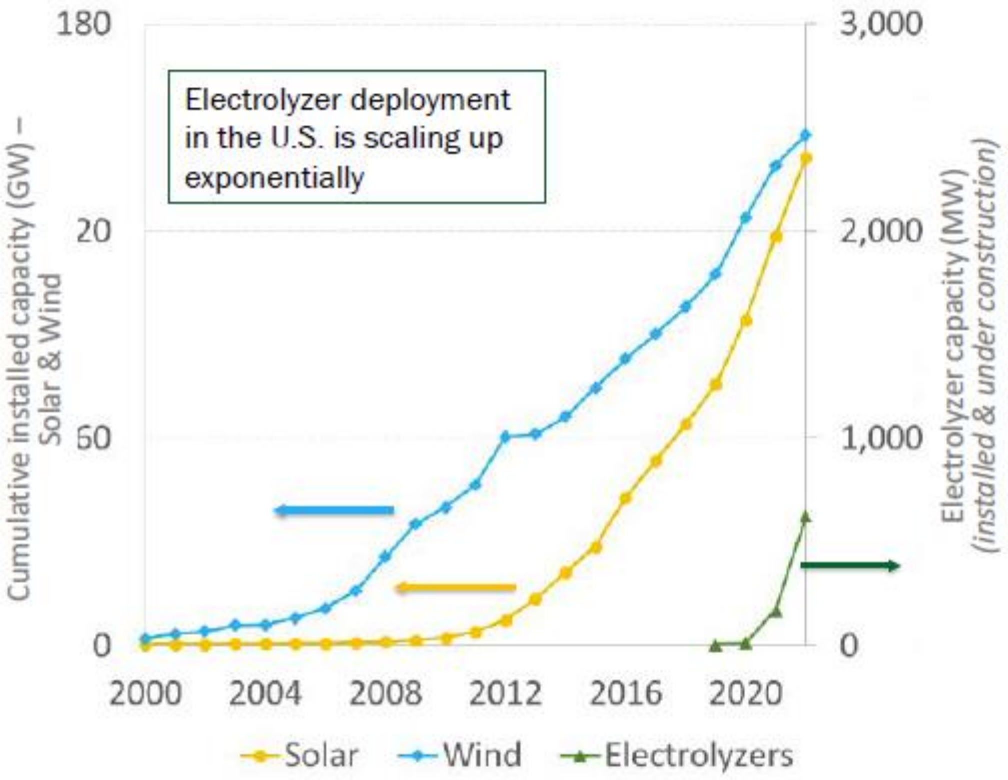
H2 can provide benefits particularly in hard to decarbonize sectors: industry, heavy duty transport, and to enable energy storage.

https://www.energy.gov/sites/default/files/2022-06/hfto-amr-plenary-satyapal-2022-1.pdf
https://www.eia.gov/outlooks/aeo/pdf/AEO2022_ChartLibrary_Electricity.pdf

Renewables Driving Energy Storage



For the first time in history, in May 2022, renewable power in California exceeded demand.



Status and Perspective of PEM Electrolyzer Capacity

- ***172 MW in 2021***
- ***More than 620 MW in 2022***
- ***60 GW by 2030***

https://www.energy.gov/sites/default/files/2022-06/hfto-amr-plenary-satyapal-2022-1.pdf

Bipartisan Infrastructure Law – H2 Highlights

- Includes $9.5B for clean hydrogen:
    - $1B for electrolysis research, development, and demonstration
    - $500M for clean hydrogen technology manufacturing and recycling R&D
    - $8B for at least four regional clean hydrogen hubs
- Aligns with Hydrogen Shot priorities by directing work to reduce the cost of clean hydrogen to $2 per kg by 2026
- H2 production from ALL resources: renewables, nuclear, and fossil + CCS

“Clean H_2 Electrolysis Program”: BIL Includes research, development, demonstration and deployment (RDD&D) across multiple electrolysis technologies, compression, storage, drying, integrated systems, etc. Directly supports Hydrogen Shot

Sec. 40314 (EPACT Sec 816): Clean Hydrogen Electrolysis Program; **$1 Billion over 5 years. Goal $2/kg by 2026**

“Clean Hydrogen Manufacturing and Recycling”

Raw Materials → **Processed Materials** → **Subcomponents** → **End Product**

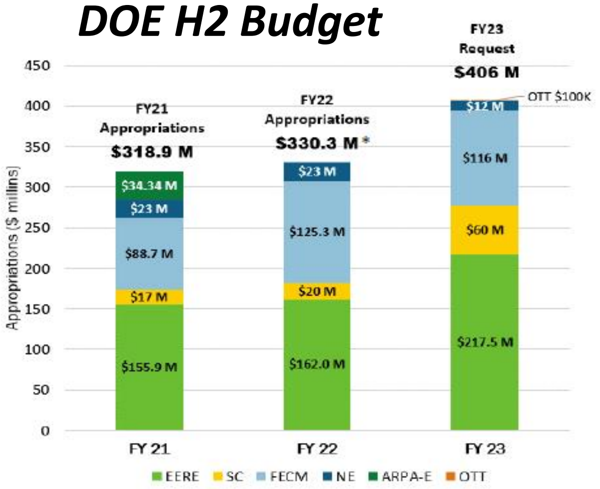
Focus on manufacturing and end of life/recycling RD&D

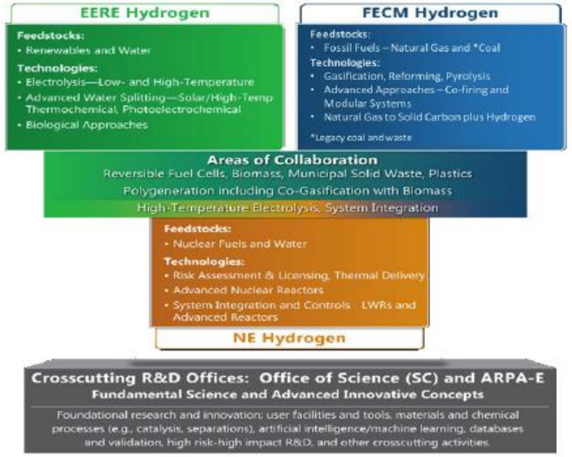
Sec. 40314 (EPACT Sec 815): Clean Hydrogen Manufacturing & Recycling **$0.5 Billion over 5 years**

Regional Clean H_2 Hubs: At least 4 Hubs, geographic diversity, includes renewables, fossil + CCS, nuclear, for clean hydrogen production, multiple end use applications.

Sec. 40314 (EPACT Sec 813): Regional Clean Hydrogen Hubs; **$8 Billion over 5 years**

DOE H2 Budget





EERE Hydrogen

Feedstocks:
- Renewables and Water

Technologies:
- Electrolysis—Low- and High-Temperature
- Advanced Water Splitting—Solar/High-Temp Thermochemical, Photoelectrochemical
- Biological Approaches

FECM Hydrogen

Feedstocks:
- Fossil Fuels – Natural Gas and *Coal

Technologies:
- Gasification, Reforming, Pyrolysis
- Advanced Approaches – Co-firing and Modular Systems
- Natural Gas to Solid Carbon plus Hydrogen

*Legacy coal and waste

Areas of Collaboration

Reversible Fuel Cells, Biomass, Municipal Solid Waste, Plastics

Polygeneration including Co-Gasification with Biomass

High-Temperature Electrolysis, System Integration

Feedstocks:
- Nuclear Fuels and Water

Technologies:
- Risk Assessment & Licensing, Thermal Delivery
- Advanced Nuclear Reactors
- System Integration and Controls – LWRs and Advanced Reactors

NE Hydrogen

Crosscutting R&D Offices: Office of Science (SC) and ARPA-E

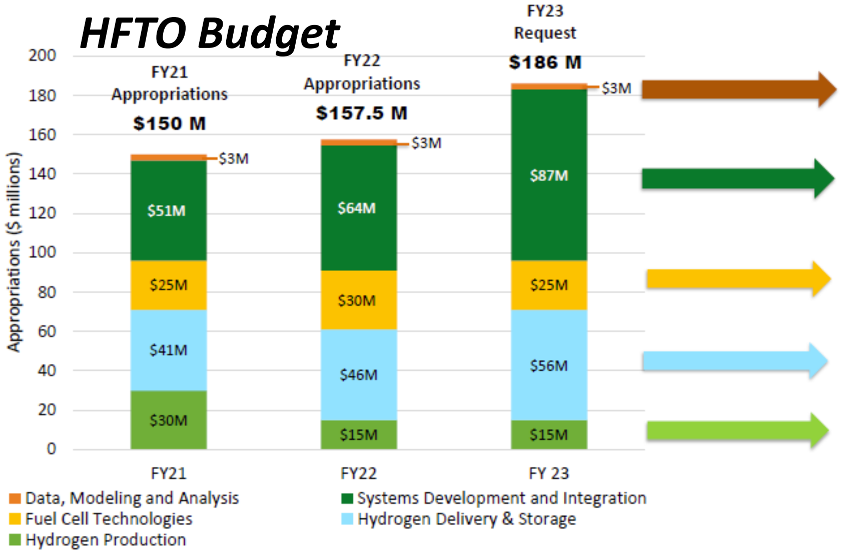
Fundamental Science and Advanced Innovative Concepts

Foundational research and innovation: user facilities and tools, materials and chemical processes (e.g., catalysis, separations), artificial intelligence/machine learning, databases and validation, high risk-high impact R&D, and other crosscutting activities.

See: .www.energy.gov/sites/default/files/2022-05/doe-fy2023-budget-volume-2-crosscutting.pdf

*Final to be updated EOY; pending SC, ARPA-E, and other final allocations by end of year. ARPA-E funding is determined annually based on programs. Annual funding only, excludes BIL funding and new offices (e.g., OCED) developed through office and stakeholder priorities. FY funding 2023 is TBD.

HFTO Budget

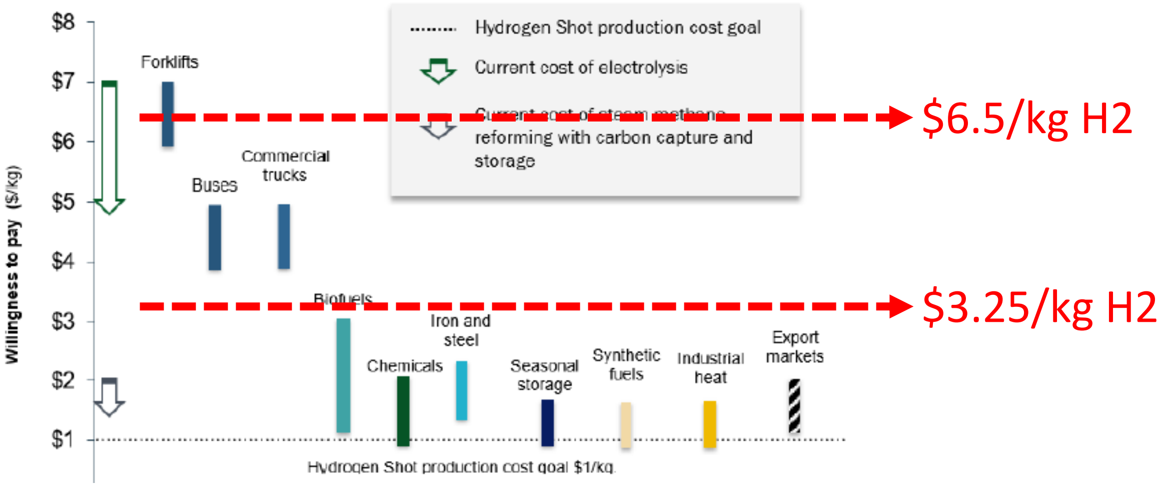


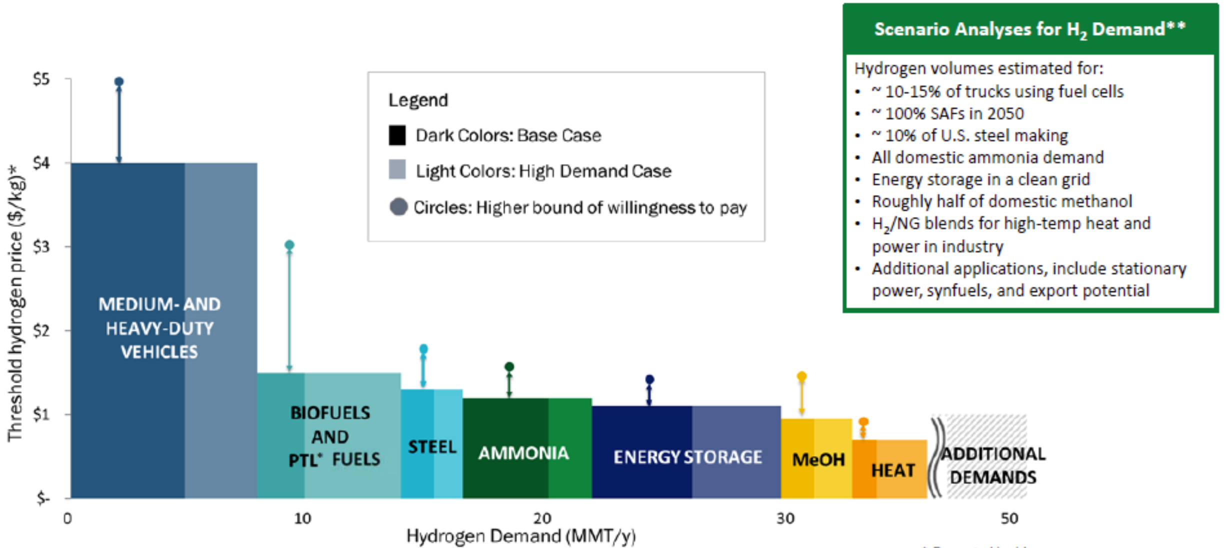
Activities

- **Guide and strengthen portfolio through rigorous analysis**
- **Validate first-of-a-kind systems across applications, de-risk technologies. Includes safety, codes, standards, workforce development**
- **Continue heavy-duty fuel cell R&D, including supply chain**
- **Increase bulk storage, liquid, and delivery focus (e.g., carriers)**
- **Supplement production RD&D with BIL funding (including $1B)**

https://www.energy.gov/sites/default/files/2022-06/hfto-amr-plenary-satyapal-2022-1.pdf

Threshold Costs for H2 to be Competitive Across Sectors



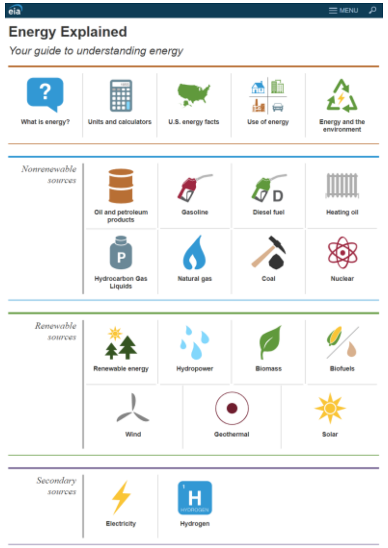


Scenario Analyses for H_2 Demand**

Hydrogen volumes estimated for:
- ~ 10-15% of trucks using fuel cells
- ~ 100% SAFs in 2050
- ~ 10% of U.S. steel making
- All domestic ammonia demand
- Energy storage in a clean grid
- Roughly half of domestic methanol
- H_2/NG blends for high-temp heat and power in industry
- Additional applications, include stationary power, synfuels, and export potential

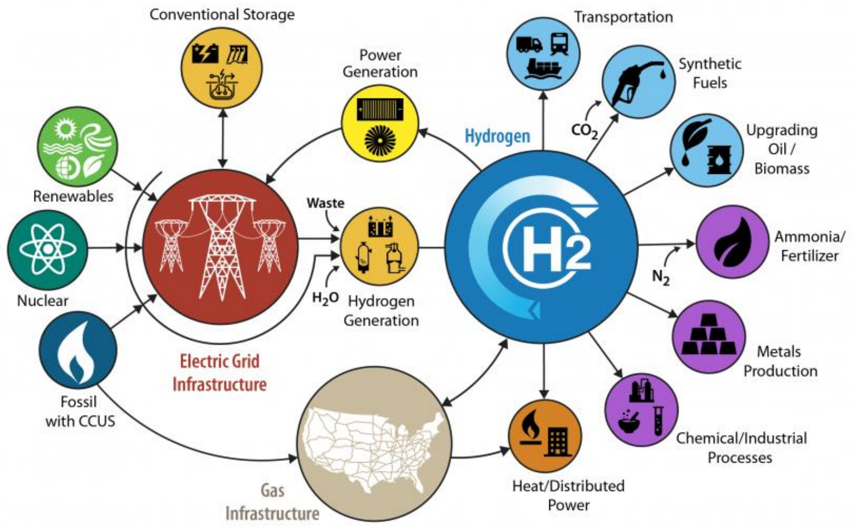
Costs include production, delivery, dispensing to the point of use (e.g., high-pressure fueling for vehicle applications)

* Power to Liquid
** Volumes dependent on multiple variables



Energy Explained

Your guide to understanding energy

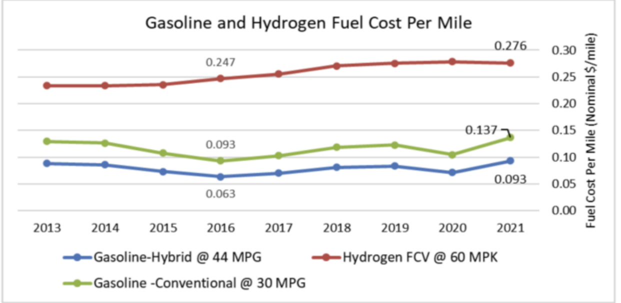


The annual average retail electricity prices by major types of utility customers in 2021 were:

residential	commercial	industrial	transportation
13.72¢ per kWh	11.27¢ per kWh	7.26¢ per kWh	10.21¢ per kWh

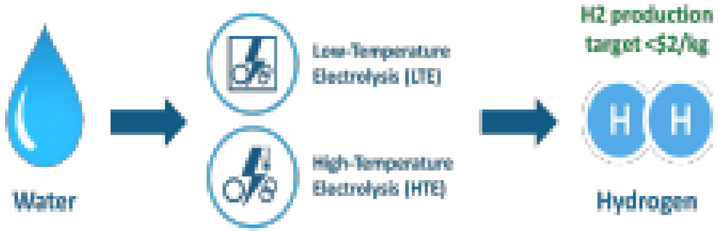

Front-month hydrogen prices hit record highs over 2021

Source: ICIS


Gasoline and Hydrogen Fuel Cost Per Mile

https://www.energy.gov/sites/default/files/2022-06/hfto-amr-plenary-satyapal-2022-1.pdf
https://www.eia.gov/energyexplained/
https://www.eia.gov/energyexplained/electricity/prices-and-factors-affecting-prices.php
https://www.powermag.com/blog/hydrogen-prices-skyrocket-over-2021-amid-tight-power-and-gas-supply/

H2 from the Next-generation of Electrolyzers of Water (H2NEW)



Electrolyzer technology focus areas:

- Low-Temperature -
  - PEM
  - Liquid Alkaline (*new expansion*)
- High-temperature -
  - O-SOEC

The emphasis is on addressing components, materials integration, and manufacturing R&D

Electrolyzer Stack Goals by 2026		
	LTE PEM	HTE
Capital Cost	$100/kW	$100/kW
Elect. Efficiency (LHV)	70% at 3 A/cm²	98% at 1.5 A/cm²
Lifetime	80,000 hr	60,000 hr

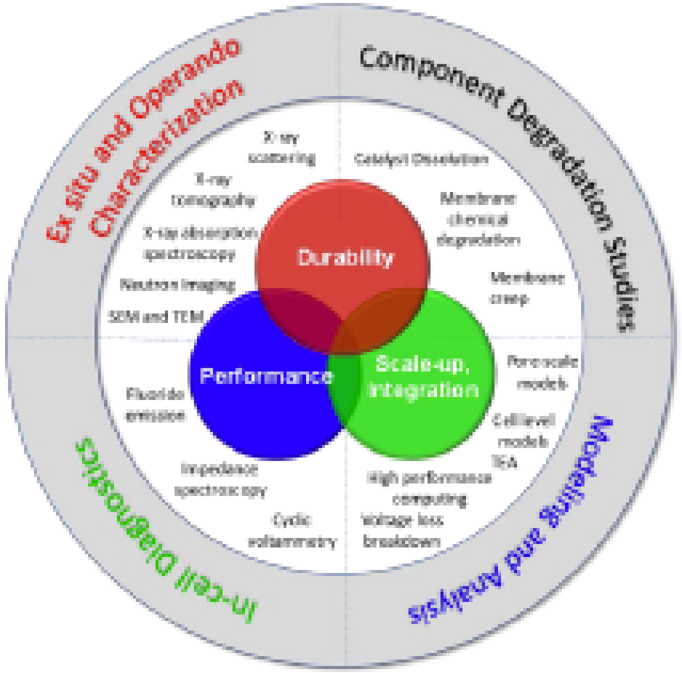
Consortium Team*

NREL
INL
Pacific Northwest
Argonne
Oak Ridge National Laboratory
NETL
Los Alamos
Berkeley Lab
Lawrence Livermore National Laboratory
NIST
UC Irvine
Carnegie Mellon University
Colorado School of Mines MINES

Durability/lifetime is initial focus:

- Develop fundamental knowledge of degradation mechanisms including under future operating modes
- Develop understanding to effectively accelerate degradation processes
- Develop and validate accelerated degradation processes to evaluate durability

Combines world-class experimental, analytical, and modeling tools



https://www.hydrogen.energy.gov/pdfs/review22/plenary6_stetson_2022_o.pdf

Million Mile Fuel Cell Truck Consortium (M2FCT)

MISSION

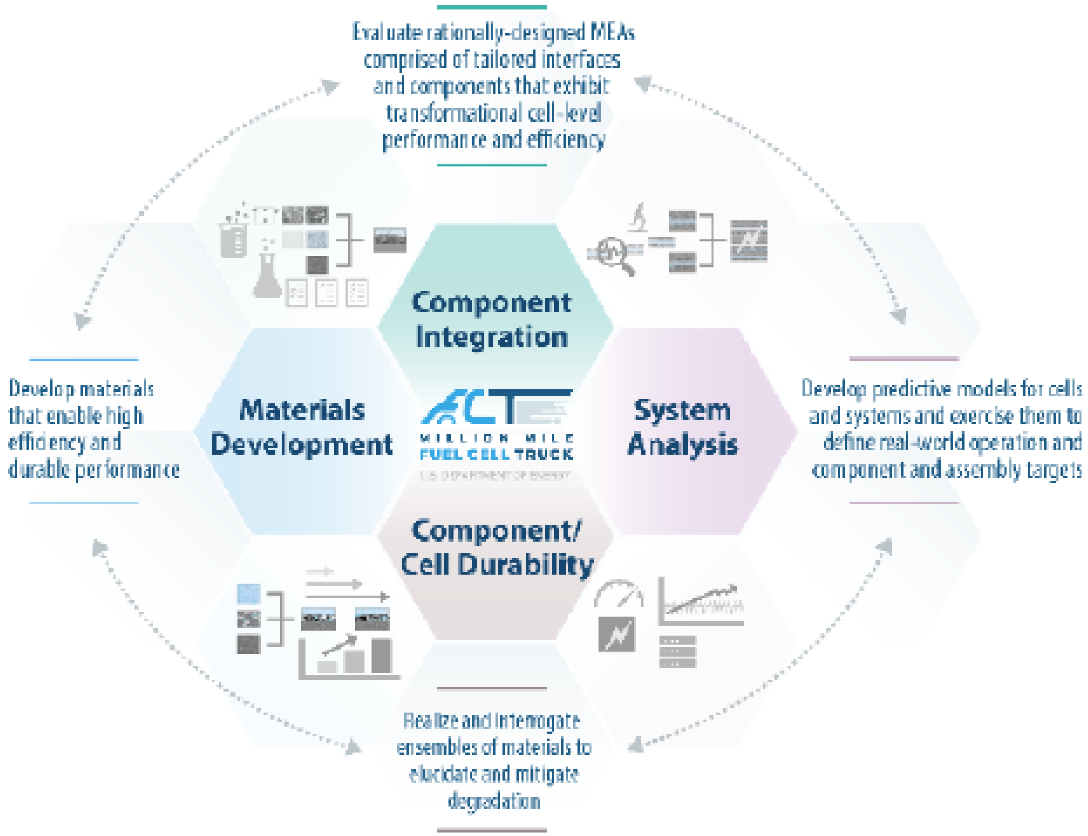
Advance efficiency and durability, and lower cost, of PEMFCs for heavy-duty vehicle applications

APPROACH

Pursue a “team-of-teams” approach with teams in analysis, durability, integration, and materials development

OBJECTIVE

Achieve MEA target : $2.5\ kW/g_{PGM}$ power ($1.07\ A/cm^2$ current density) at 0.7 V after 25,000 hour-equivalent AST



Evaluate rationally-designed MEAs comprised of tailored interfaces and components that exhibit transformational cell-level performance and efficiency

Develop materials that enable high efficiency and durable performance

Develop predictive models for cells and systems and exercise them to define real-world operation and component and assembly targets

Realize and interrogate ensembles of materials to elucidate and mitigate degradation

MEAs

gm, Carnegie Mellon University, NIKOLA

Membranes

T, Lubrizol, 3M, NIKOLA

Stacks

plug

Bipolar Plates

Raytheon Technologies, NEOGRAF SOLUTIONS, TreadStone Technologies, Inc., gm, plug

Air Management

CATERPILLAR, EATON, R&D Dynamics Corporation, MAHLE Driven by performance

Main Laboratories

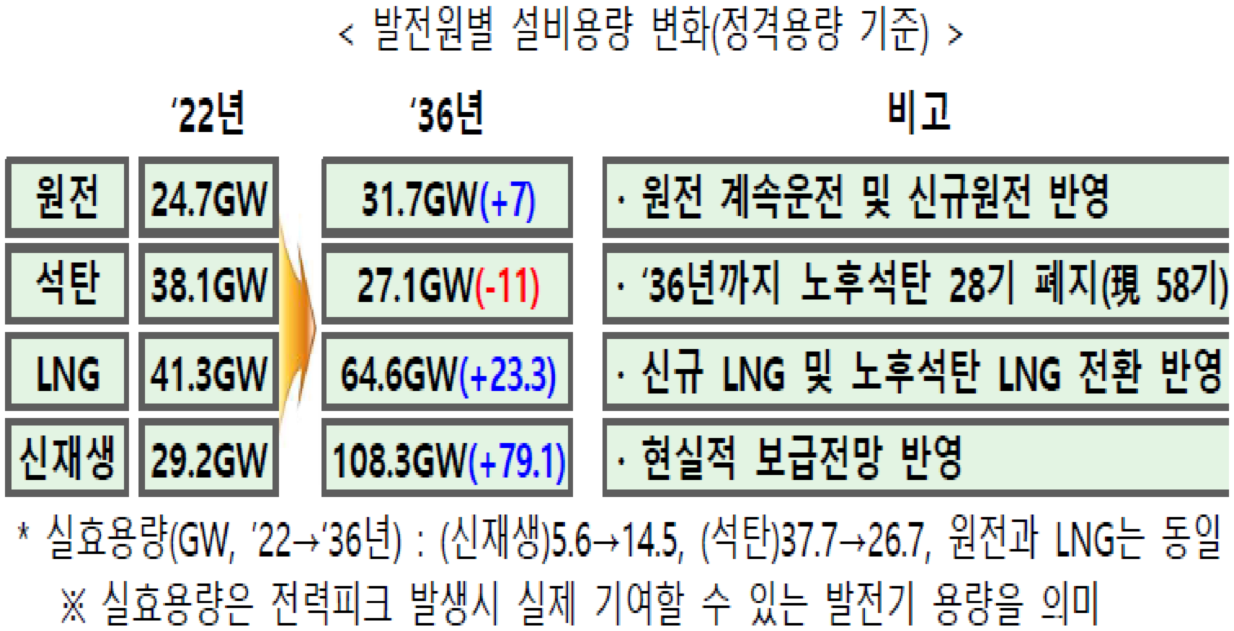
Los Alamos NATIONAL LABORATORY, OAK RIDGE National Laboratory, Argonne NATIONAL LABORATORY, BERKELEY LAB, NREL

Affiliate Laboratories

Pacific Northwest NATIONAL LABORATORY, NIST National Institute of Standards and Technology, BROOKHAVEN NATIONAL LABORATORY

https://www.energy.gov/sites/default/files/2022-06/hfto-amr-plenary-satyapal-2022-1.pdf

Trends and Perspectives of Overall and Renewable Energy in Korea

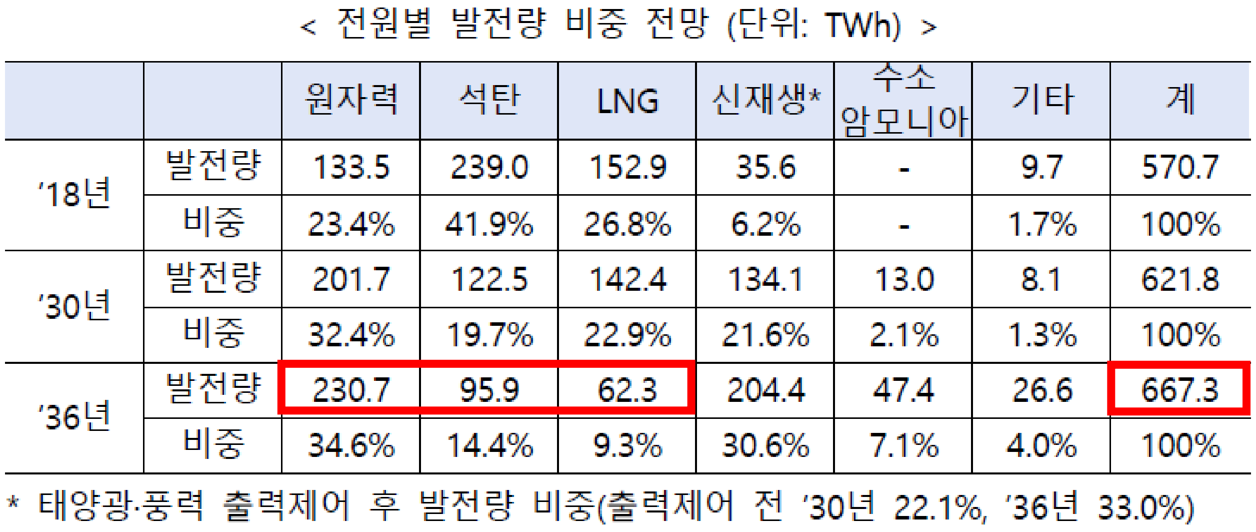


< 발전원별 설비용량 변화(정격용량 기준) >

	'22년	'36년	비고
원전	24.7GW	31.7GW(+7)	· 원전 계속운전 및 신규원전 반영
석탄	38.1GW	27.1GW(-11)	· '36년까지 노후석탄 28기 폐지(現 58기)
LNG	41.3GW	64.6GW(+23.3)	· 신규 LNG 및 노후석탄 LNG 전환 반영
신재생	29.2GW	108.3GW(+79.1)	· 현실적 보급전망 반영

* 실효용량(GW, '22→'36년) : (신재생)5.6→14.5, (석탄)37.7→26.7, 원전과 LNG는 동일

※ 실효용량은 전력피크 발생시 실제 기여할 수 있는 발전기 용량을 의미



< 전원별 발전량 비중 전망 (단위: TWh) >

		원자력	석탄	LNG	신재생*	수소 암모니아	기타	계
'18년	발전량	133.5	239.0	152.9	35.6	-	9.7	570.7
	비중	23.4%	41.9%	26.8%	6.2%	-	1.7%	100%
'30년	발전량	201.7	122.5	142.4	134.1	13.0	8.1	621.8
	비중	32.4%	19.7%	22.9%	21.6%	2.1%	1.3%	100%
'36년	발전량	230.7	95.9	62.3	204.4	47.4	26.6	667.3
	비중	34.6%	14.4%	9.3%	30.6%	7.1%	4.0%	100%

* 태양광·풍력 출력제어 후 발전량 비중(출력제어 전 '30년 22.1%, '36년 33.0%)

	2022 [TWh]	2036 [TWh]	E. Independence in 2022	Renewable in Electricity in 2022	Renewable in Electricity in 2050
KO	568	667	19.8%	8%	61-71%
US	4,200	4,700	100%	21%	44%

https://www.korea.kr/briefing/pressReleaseView.do?newsId=156547521

2050 탄소중립 시나리오안, 관계부처 합동, 2021.10. 18.

https://www.enerdata.net/publications/executive-briefing/co2-emissions-south-korea.html

https://www.eia.gov/outlooks/aeo/pdf/AEO2022_ChartLibrary_Electricity.pdf

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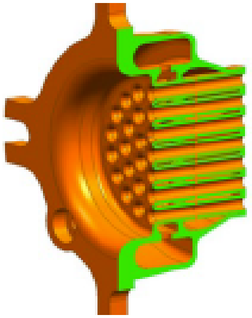
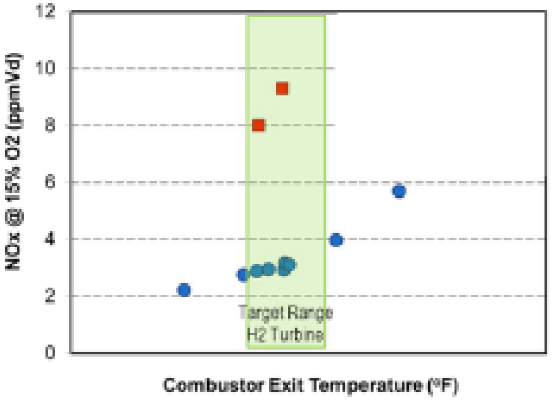
DOE FECM Funding and Key H2 Activities

Advanced Turbines Program

Representative-Scale H_2 Combustion Testing

- Tested at full F-class & advanced gas turbine conditions.
- 100+ hours full can combustor operation with > 90% H_2.
- 20 hrs operation with 100% H_2
- < 3 ppm NOx @15% O_2 at target temp. with N_2 diluent.
- NOx emissions for H_2 fuels likely similar to natural gas emissions that have been demonstrated for full scale combustor geometries.





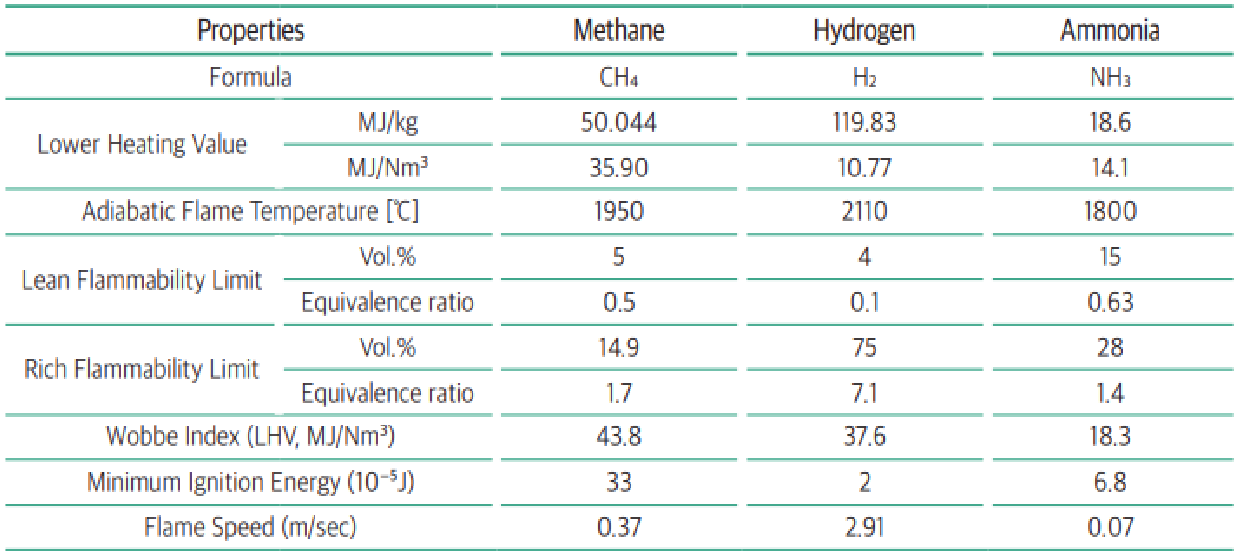
Ref: Proceedings of ASME Turbo Expo 2012, June 11-15, 2012, Copenhagen, Denmark, GT2012-69913; DEVELOPMENT AND TESTING OF A LOW NOX HYDROGEN COMBUSTION SYSTEM FOR HEAVY DUTY GAS TURBINES, W. York, W. Ziminsky, E. Yilmaz *

FY2022 Hydrogen Related R&D Investments

- **Hydrogen with Carbon Management:**
  - Solid Oxide Fuel Cells – materials, components, systems, reversible SOFC at utility scale;
  - Turbines – 100% H_2 firing, retrofit systems;
  - Gasification and reforming technologies
  - Materials for hydrogen turbines – CMCs
- **Point Source Carbon Capture:** Pre- and Post-combustion capture (gasification/reforming and industrial decarb.)
- **Crosscutting R&D:**
  - Energy Storage – large scale materials-based and H_2 storage, grid-scale energy storage;
  - Simulation Based Engineering /Integrated Energy Systems – Modeling and optimization tools for FE and FE-based and IES systems (IDAES)
- **21st Century Power Plants:** FEED studies for gasification-based carbon-negative power and hydrogen co-production

https://www.hydrogen.energy.gov/pdfs/review22/plenary5_program_panel_2022_o.pdf

Technical Updates: H2 Turbine

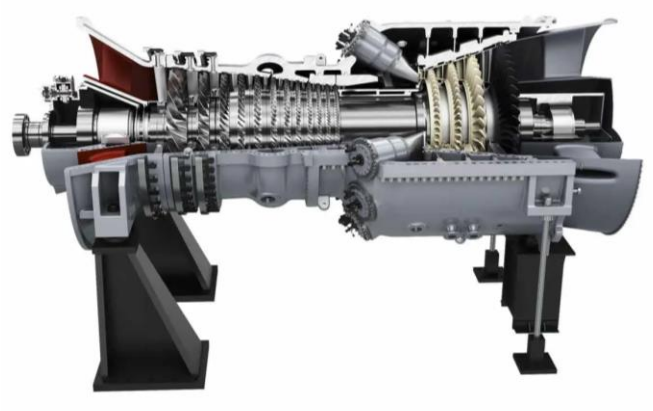


Properties		Methane	Hydrogen	Ammonia
Formula		CH_4	H_2	NH_3
Lower Heating Value	MJ/kg	50.044	119.83	18.6
	MJ/Nm^3	35.90	10.77	14.1
Adiabatic Flame Temperature [℃]		1950	2110	1800
Lean Flammability Limit	Vol.%	5	4	15
	Equivalence ratio	0.5	0.1	0.63
Rich Flammability Limit	Vol.%	14.9	75	28
	Equivalence ratio	1.7	7.1	1.4
Wobbe Index (LHV, MJ/Nm^3)		43.8	37.6	18.3
Minimum Ignition Energy (10^{-5}J)		33	2	6.8
Flame Speed (m/sec)		0.37	2.91	0.07

http://www.keei.re.kr/keei/download/focus/ef2203/ef2203_50.pdf

- University Turbines Systems Research —Focus on Hydrogen Fuels –made 6 awards in late FY21
- Key challenges
  - High flame temperature and flame speed
  - Thermal NOx control
  - Flame detection, sealing, and high flammability
  - May need flame dilution or higher efficiency air separation unit
- Major manufacturers: MHI, GE, and Siemens
- Performance (MHI): up to 64% for combined cycle and 99.6% reliability

Siemens SGT5-9000HL (50Hz)
Heavy Duty Gas Turbine



✓ Simple cycle output: up to 593 MWe
✓ Combined cycle output: 880 MWe (1X1) or 1,760 MW (2X1)
✓ Combined cycle efficiency more than 64%
✓ NOx down to 2 ppmvd with SCR or 25 ppmvd without SCR
✓ H2 blending up to 50 vol.% (7.5 wt.%)
✓ Price: $82,500,000 ($139/kW)

GEA33861 Report, 2019
Siemens Energy
DOE/NREL-2022/3812

RDD&D for H2 Turbine

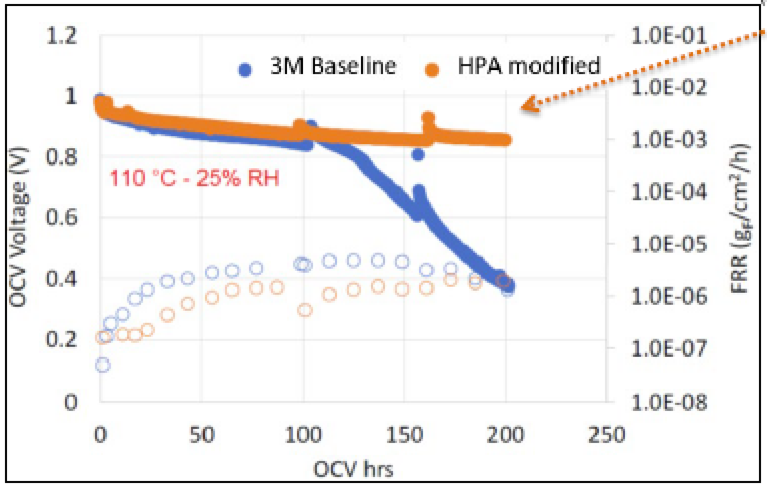
- Program target: 9 ppm NOx emissions for 100% H2 turbines and 2 ppm with selective catalytic reduction
- FECM launched six projects with emphasis on 1) dense, low-porosity, ultra-high temperature CMC and 2) multi-layered nano-ceramic coating in a hydrogen combustor
- R&D on ceramic matrix composite (CMC) components, which allow hydrogen turbines to operate at higher working temperatures, ultimately improving cycle efficiency.
- Raytheon Technologies Corporation — Pratt & Whitney Division plans to develop a 2700°F (1482°C)-class SiC/SiC CMC
- To develop a thermal barrier coating composed of a novel CMC material with desired thermal, thermomechanical, and moisture resistance properties to meet the goal of a 302°F to 392°F (150°C to 200°C) increase to the operational capabilities of CMCs at higher moisture contents in the combustor and turbine hot gas path. The multilayer thermal barrier coating will provide a potential of around 392°F (200°C) or 15% increase in temperature performance compared to the current state-of-the-art temperature capability.

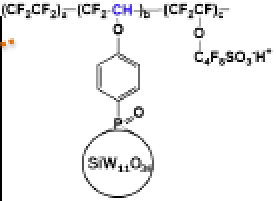
https://www.hydrogen.energy.gov/pdfs/us-national-clean-hydrogen-strategy-roadmap.pdf

Technical Updates: SOFC

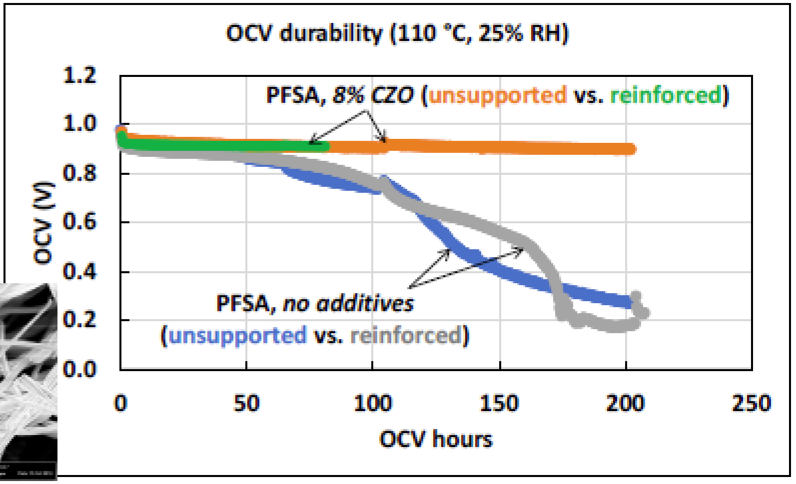
- SOFC performance: power generation up to 60% and CHP up to 90%
- RDD&D for larger capacity: Bloom Energy (500MW with SK in Gumi), FuelCell Energy, and Nexceris
- Major DOE on-going projects
  - Adaptive SOFC for Ultra High Efficiency Systems (FuelCell Energy): to achieve 70% electrical efficiency
  - Metal-Supported SOFCs for Ethanol-Fueled Vehicles (LBNL):
  - Hybrid SOFC/Turbogenerator for Aircraft (UM)
  - SOFC/Turbine Hybrid Power System Design and Development (NEXCERIS)
  - Efficient Reversible Solid Oxide Fuel Cell Systems: expected round trip efficiency at 60%; CHP up to 90%
  - Durable FC MEA thorough Immobilization of Catalyst Particle and Membrane Chemical Stabilizer (GM)

PFSA with immobilized heteropoly acid radical scavengers



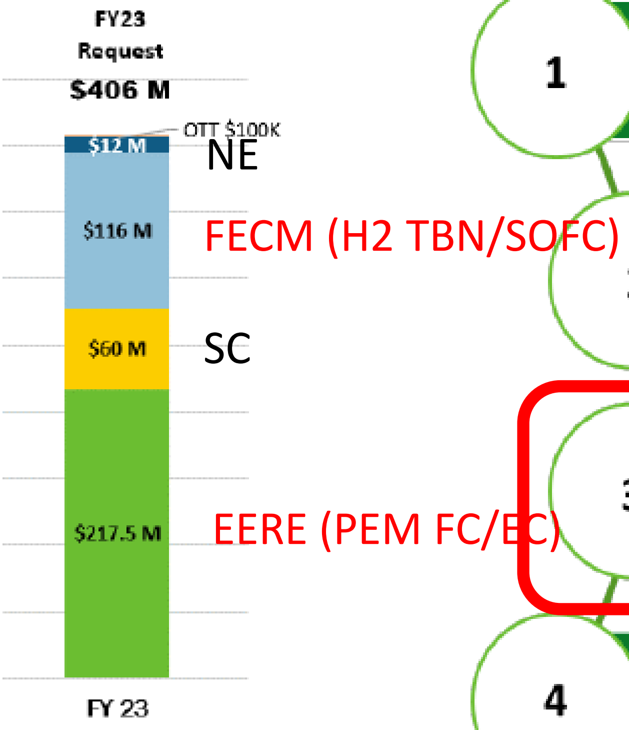


Dispersed CeZrO$_x$ (CZO) nanofibers



https://www.energy.gov/sites/default/files/2022-02/Fuel%20Cells%20%26%20Electrolyzers%20Supply%20Chain%20Report%20-%20Final.pdf
https://www.hydrogen.energy.gov/amr-presentation-database.html
https://www.hydrogen.energy.gov/pdfs/review22/plenary7_papageorgopoulos_2022_o.pdf

Fuel Cell Technologies: Key Milestones by 2030



	Program Priorities	RDD&D	Key Initiatives to Address Priorities
1	Low-Cost Clean Hydrogen Production	1.25 MW PEM EC	H2NEW, HydroGEN, ElectroCAT, Hydrogen Shot Incubator Prize, H2 Demos
2	Safe, Low-Cost Delivery and Storage Infrastructure	Up to 200 bar & 600 kg H2	H-Mat, HyBlend, HyMARC, SHASTA, C-Fiber Tanks, Liquefaction, Sensors
3	Low Cost, Durable, and Efficient Fuel Cells & Low-NO_x Turbines	1 MW PEM FC	M2FCT, ElectroCAT, Low-NOx Turbine RD&D
4	Enable End Use Applications at Scale		H2@Scale demos, Hydrogen Hubs, H2 Matchmaker

Examples from multiple offices across DOE

DOE Targets include:

Clean Hydrogen
- $1/kg production
- $2/kg delivery
- $9/kWh storage

Electrolyzers
- $150/kW
- 73% efficiency
- 80Khr durability

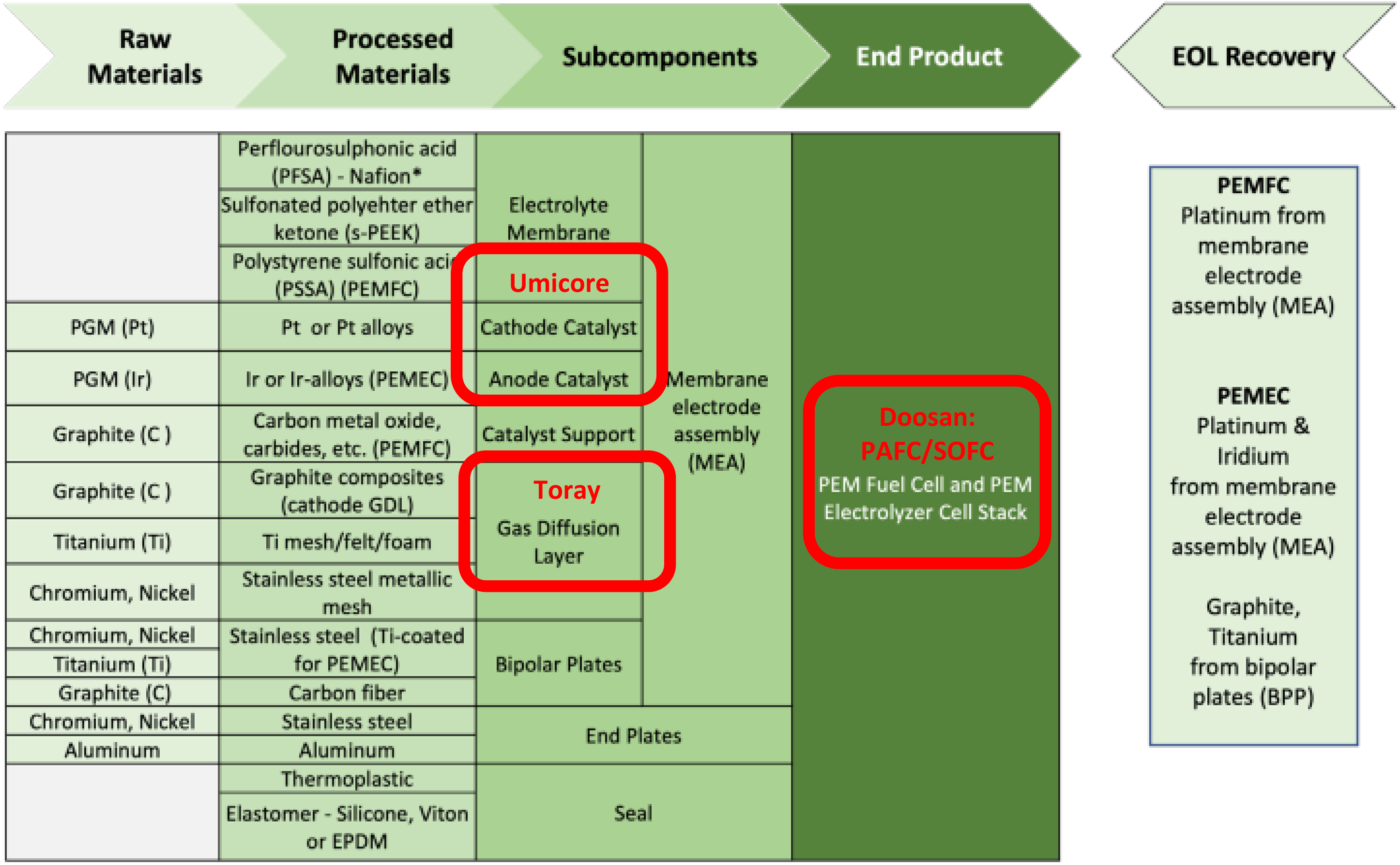
Fuel Cells for Heavy Duty Trucks
- $80/kW
- 25Khr durability

Enable EJ40 Priorities

DEI

https://www.energy.gov/sites/default/files/2022-06/hfto-amr-plenary-satyapal-2022-1.pdf

PEM FC &EC: Key Challenges and Weaknesses



Raw Materials	Processed Materials	Subcomponents		End Product
	Perflourosulphonic acid (PFSA) - Nafion*	Electrolyte Membrane	Membrane electrode assembly (MEA)	Doosan: PAFC/SOFC PEM Fuel Cell and PEM Electrolyzer Cell Stack
	Sulfonated polyehter ether ketone (s-PEEK)			
	Polystyrene sulfonic aci (PSSA) (PEMFC)	Umicore		
PGM (Pt)	Pt or Pt alloys	Cathode Catalyst		
PGM (Ir)	Ir or Ir-alloys (PEMEC)	Anode Catalyst		
Graphite (C)	Carbon metal oxide, carbides, etc. (PEMFC)	Catalyst Support		
Graphite (C)	Graphite composites (cathode GDL)	Toray Gas Diffusion Layer		
Titanium (Ti)	Ti mesh/felt/foam			
Chromium, Nickel	Stainless steel metallic mesh			
Chromium, Nickel	Stainless steel (Ti-coated for PEMEC)	Bipolar Plates		
Titanium (Ti)				
Graphite (C)	Carbon fiber			
Chromium, Nickel	Stainless steel	End Plates		
Aluminum	Aluminum			
	Thermoplastic	Seal		
	Elastomer - Silicone, Viton or EPDM			

EOL Recovery

PEMFC
Platinum from membrane electrode assembly (MEA)

PEMEC
Platinum & Iridium from membrane electrode assembly (MEA)

Graphite, Titanium from bipolar plates (BPP)

Figure 7. Key elements of PEMFC and PEMEC supply chains

- Weaknesses of US
  - Insufficient manufacturing capacity
  - Reliance of import: Pt, Ir, Graphite
  - High manufacturing costs
  - Technical advancements, capital investment, higher production volume
  - Lack of trained works with expertise in H2 and FC technologies
  - Lack of H2 infra/tax liability
  - Limited H2 transmission and storage infra

2.5 kW/g_{PGM} power =1.07 A/cm2 current density at 0.7 V after 25,000 hours equivalent accelerated stress test (AST)

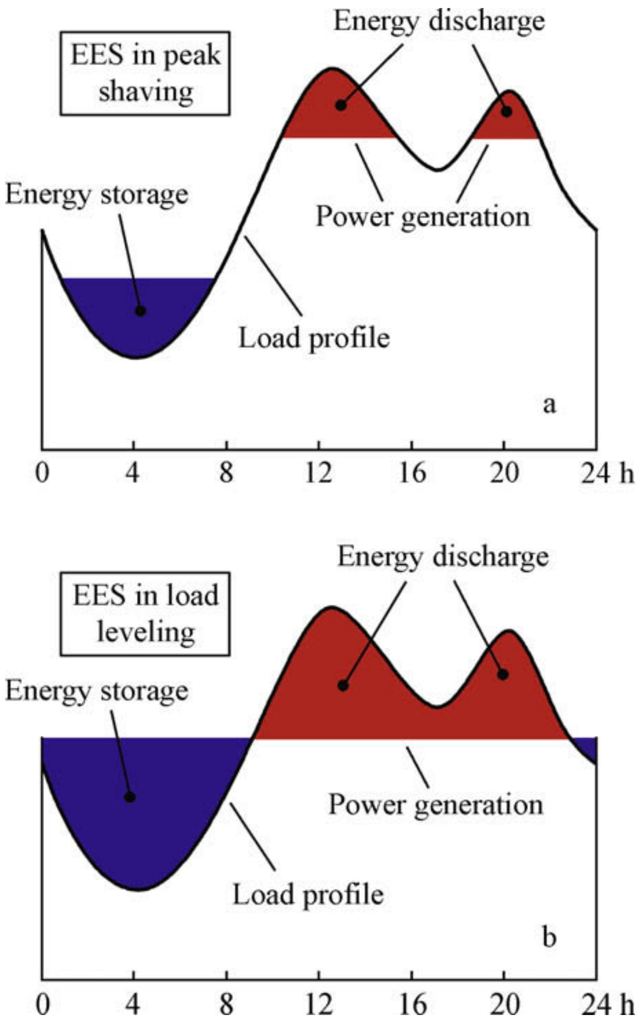
https://www.energy.gov/sites/default/files/2022-02/Fuel%20Cells%20%26%20Electrolyzers%20Supply%20Chain%20Report%20-%20Final.pdf

DOE NREL HFTO CRADA Call. 2021

Contents

- Perspectives of Hydrogen to Power Industries in the United States
  - Trends and Perspectives of Overall and Renewable Energy in US and Korea
  - Trends and Perspectives of Hydrogen Turbine and Fuel Cell in US
  - Impacts on Grids: Reliability and Potential Issues
  - Feasibility of Hydrogen to Electricity Business

Impact on Grids: Strength and Challenges



DOI: 10.5220/0007721501370142

	Strengths	**Potential Issues**	**Viable Resolutions**
Long distance transmission	Decentralized power generation to reduce strain on the grid and transmission loss	Challenges in power conversion efficiency of voltage and frequency for existing power transmission grids	Needs advanced AC/DC power converters or rectifiers depending on grids to load
Grid stability	Mitigating renewable intermittency and voltage regulations	Propagated intermittency or harmonic distortion of hydrogen-based power generation -> Directly related to the power exchange market depending on the hydrogen availability	- Requires advanced control systems, grid monitoring, and real-time data transfer to ensure and minimize fluctuations and variability - Positioning at peak-load possibly middle-load
Grid resilience	To back up unexpected outage or inclement weather	- Needs proper sizing for back up, capacity planning and system readiness - FC affected by temperature and humidity fluctuations - Inclement weather also impacts on the fuel cell systems; e.g., blocking pathways through porous gas diffusion layer and catalyst layer as preventing the movement of reactants - Vulnerable in long-term outage and inclement weather event	- Requires advanced heating and cooling technologies - Event monitoring with wireless sensor network - Islanded mode of operation can provide uninterrupted power during extended outages or severe weather events

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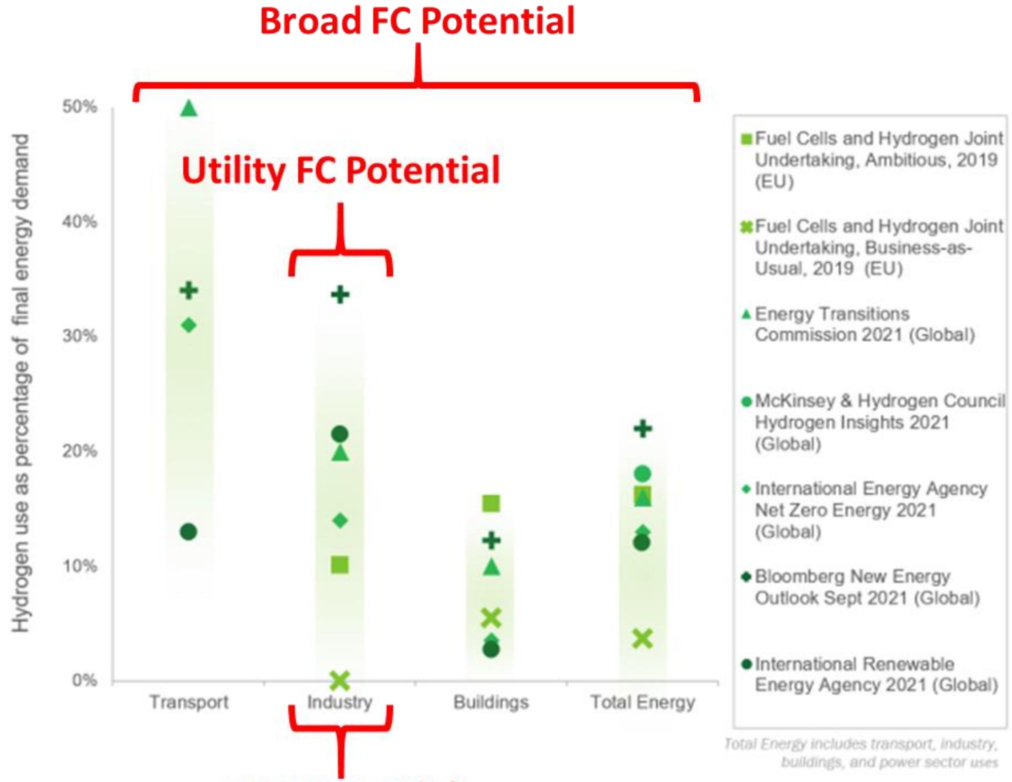
Considerations for H2 to Power Business

- Pre-requisite: low cost power and hydrogen generation closer to wholesale option
- To secure domestic manufacturing and supply chain that is independent of foreign sources of critical materials
- Potential impact on market: fuel cell vs. hydrogen turbine
- Any potential issues on the existing power grids
- Any potential issues on O&M
  - Degradation of catalyst and membrane
  - Impurities of hydrogen and water management
  - Thermal fatigues induced from excessive heat cycles
  - Contamination and corrosion issues to mitigate
  - Design off conditions from partial load operations
  - Resiliency to incremental weather/disaster
  - Securing engineers, technicians, and first responders, etc. to handle hydrogen and related technologies



Broad FC Potential

Utility FC Potential

TBN Potential

Total Energy includes transport, industry, buildings, and power sector uses

Figure 4: The range of hydrogen's role in final energy use according to global and regional estimates shows a wide range of applications in each sector. [32]

https://www.hydrogen.energy.gov/pdfs/us-national-clean-hydrogen-strategy-roadmap.pdf

Conclusions

- Postulates: Electrolytic hydrogen production would have minimized impact from the raw material costs, and follow up the trend of renewable power generation. Resiliency for inclement weather.
- Feasible to start up the hydrogen-based power generation business with 1) fuel cell and/or 2) hydrogen turbine?
  - Hydrogen as a secondary energy as well as energy carrier is viable for utilization only if 1) the end-user price of hydrogen is competitive, 2) the conversion efficiency of the system is competitive, and 3) no further emission is released.
- Any potential issues in loading to the existing grid?
  - In addition to the concerns and viable solutions discussed, the hydrogen-based power generation business may need to be competitive in the power exchange market depending on its position: either peak- or middle-load.
  - Both systems strongly rely on the hydrogen price and storage capacity, etc.

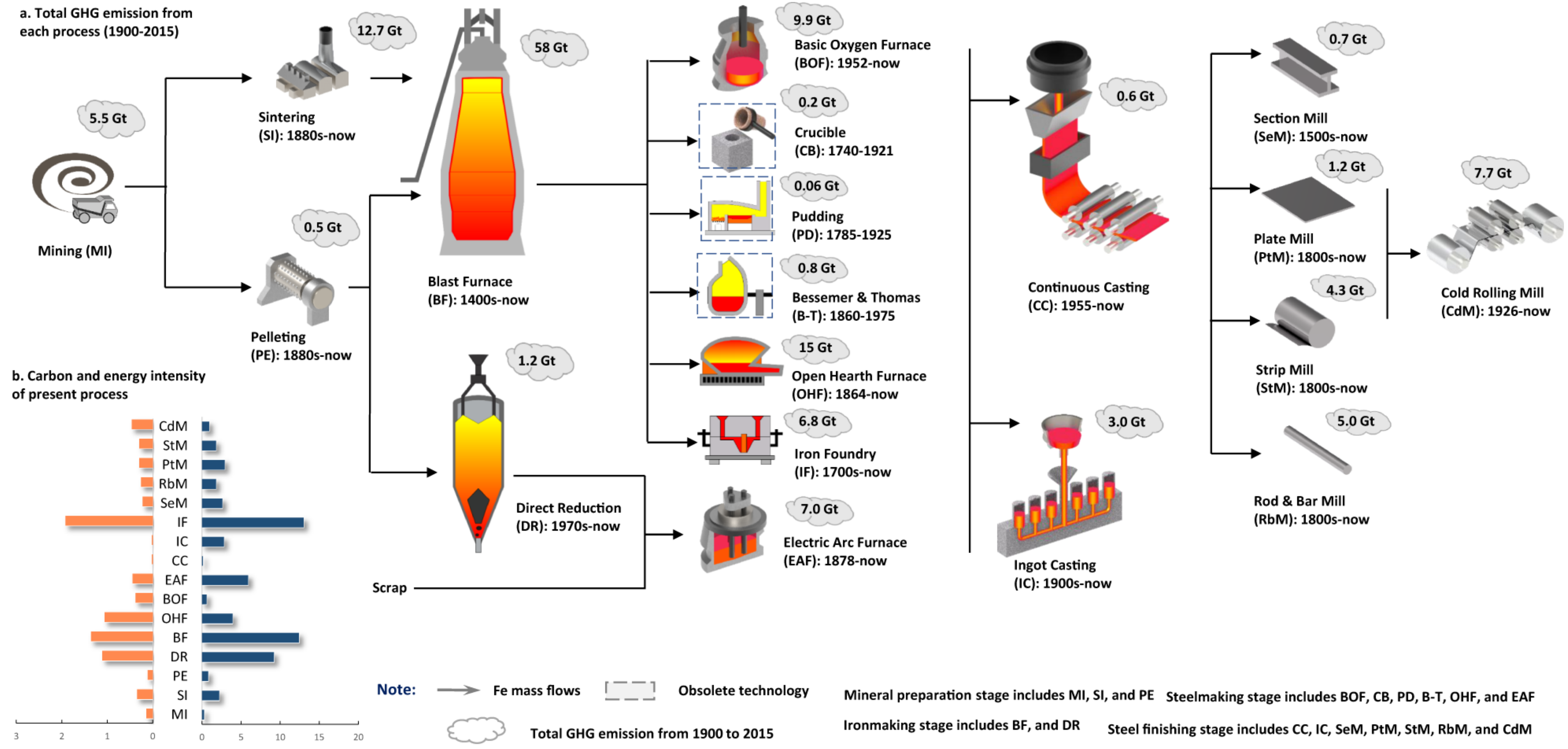
Overview

- Perspectives of Hydrogen to Power Industries in the United States
- Research Topics on Hydrogen Production/Utilization and Energy Recovery for Steelmaking Industry

Contents

- Research Topics on Hydrogen Production/Utilization and Energy Recovery for Steelmaking Industry
  - Topic 1: Hydrogen Production in Steelmaking Industry
  - Topic 2: Hydrogen Utilization in Steelmaking Industry

Steelmaking Processes and GHG Emissions



a. Total GHG emission from each process (1900-2015)

Mining (MI) 5.5 Gt

Sintering (SI): 1880s-now 12.7 Gt

Pelleting (PE): 1880s-now 0.5 Gt

Blast Furnace (BF): 1400s-now 58 Gt

Direct Reduction (DR): 1970s-now 1.2 Gt

Scrap

Basic Oxygen Furnace (BOF): 1952-now 9.9 Gt

Crucible (CB): 1740-1921 0.2 Gt

Pudding (PD): 1785-1925 0.06 Gt

Bessemer & Thomas (B-T): 1860-1975 0.8 Gt

Open Hearth Furnace (OHF): 1864-now 15 Gt

Iron Foundry (IF): 1700s-now 6.8 Gt

Electric Arc Furnace (EAF): 1878-now 7.0 Gt

Continuous Casting (CC): 1955-now 0.6 Gt

Ingot Casting (IC): 1900s-now 3.0 Gt

Section Mill (SeM): 1500s-now 0.7 Gt

Plate Mill (PtM): 1800s-now 1.2 Gt

Strip Mill (StM): 1800s-now 4.3 Gt

Rod & Bar Mill (RbM): 1800s-now 5.0 Gt

Cold Rolling Mill (CdM): 1926-now 7.7 Gt

b. Carbon and energy intensity of present process

Primary energy intensity (GJ/t)

GHG emission intensity (tCO_2/t)

Note: → Fe mass flows

▭ Obsolete technology

Total GHG emission from 1900 to 2015

Mineral preparation stage includes MI, SI, and PE

Ironmaking stage includes BF, and DR

Steelmaking stage includes BOF, CB, PD, B-T, OHF, and EAF

Steel finishing stage includes CC, IC, SeM, PtM, StM, RbM, and CdM

https://doi.org/10.1038/s41467-021-22245-6

EAF: Cycle and Energy Balance

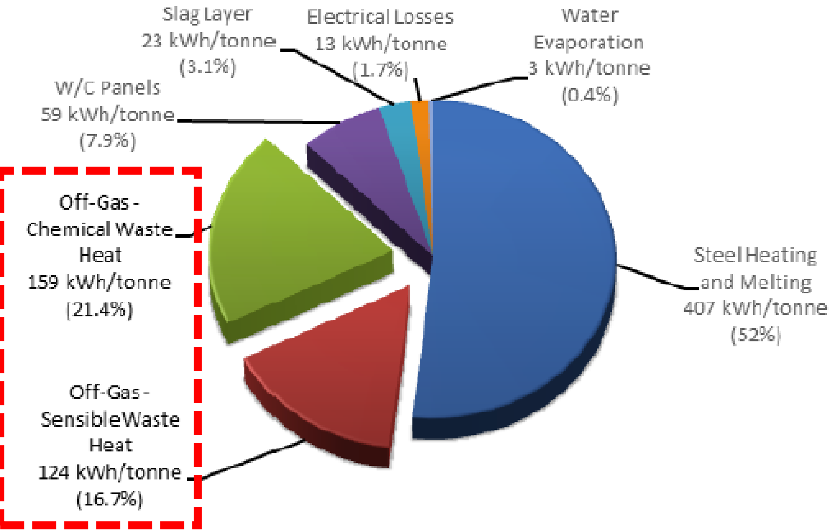


Figure 1: A large percentage (25–35%) of the total energy input for the EAF is lost as chemical and sensible heat.

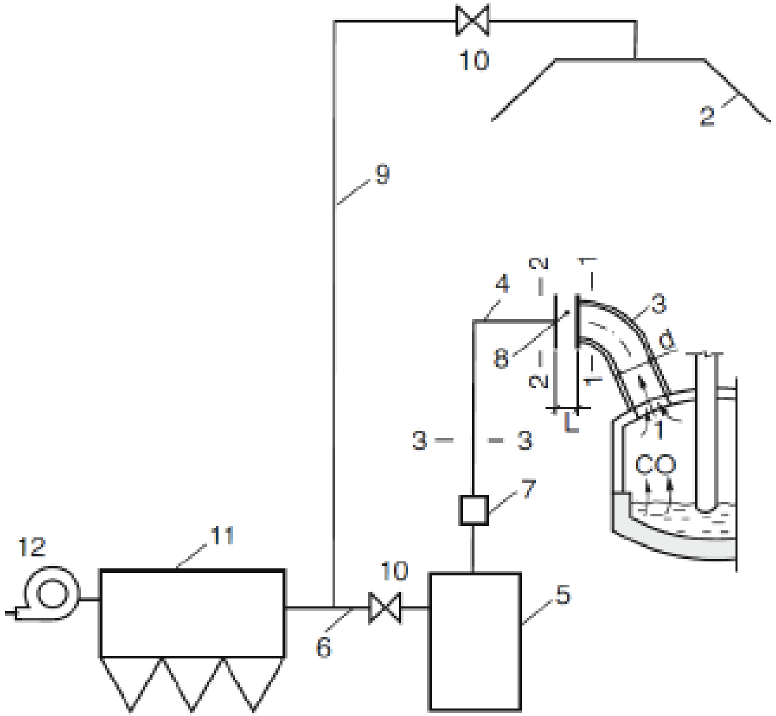


Figure 2 - Schematic diagram of evacuation and purification of gases from EAF [3].

1 – Opening in the furnace roof, 2 – the canopy hood, 3 – the roof elbow, 4 – the stationary gas duct, 5 – the drop out box, 6 – the gas duct, 7 – water quenching device, 8 – the air gap, 9 – the gas duct, 10 – off-gas flow rate control valves, 11 – the baghouse, and 12 – exhauster

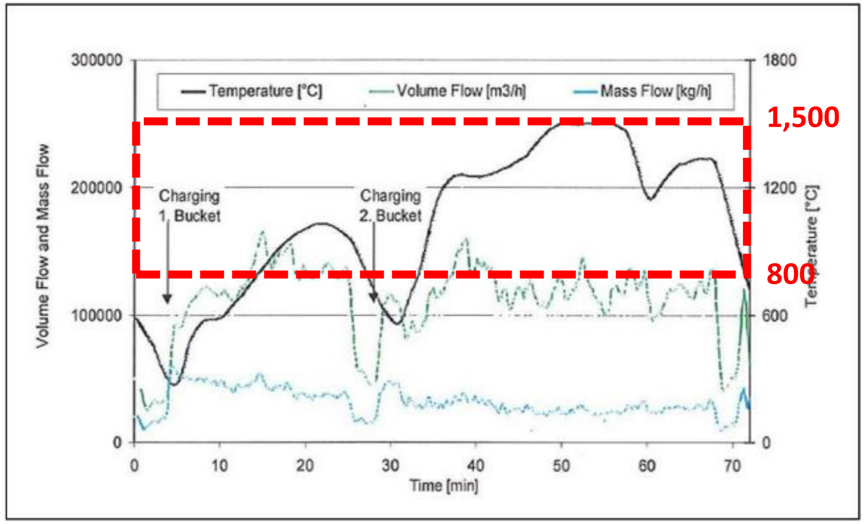
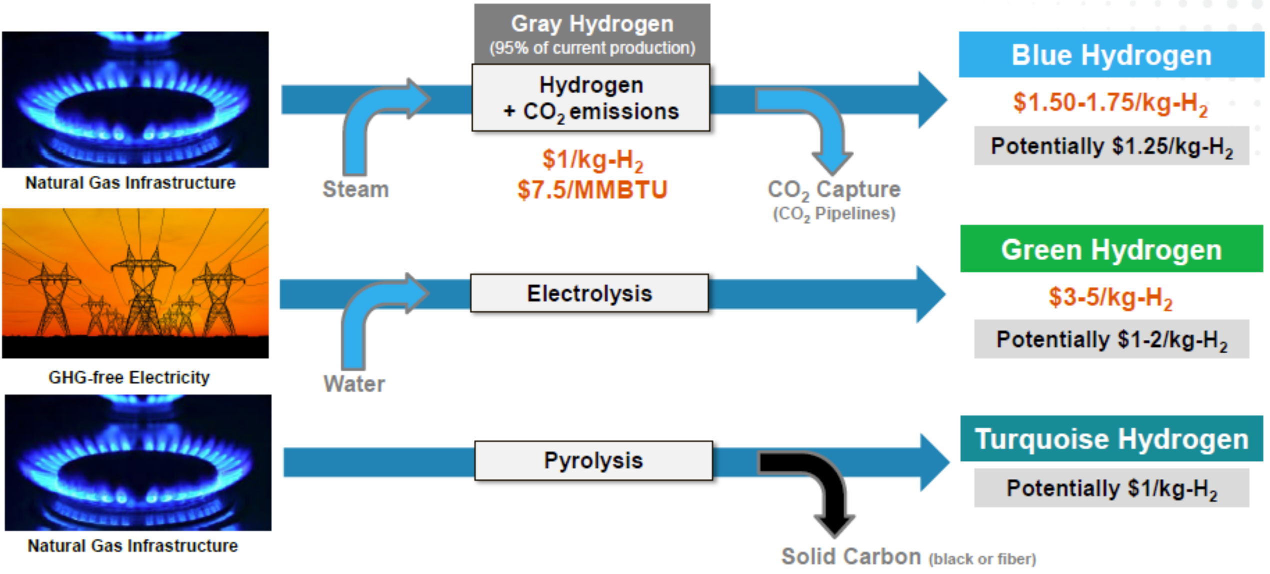


Figure 5 – Measured off-gas volume, mass flows, and temperature in a 145 ton/batch EAF [4].

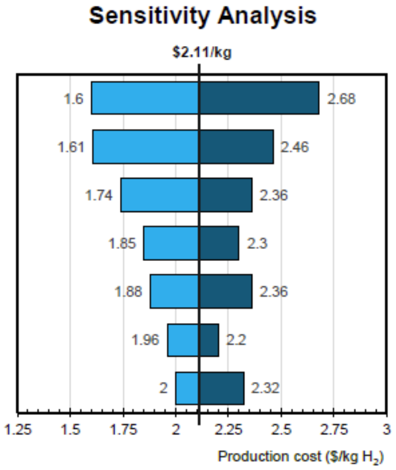
https://www.osti.gov/servlets/purl/1221728

Techno-Economic Analysis for Methane Pyrolysis



Process Section	Base Capital ($MM)	Contribution	Power (kWh$_e$/kg H_2)
Reactor[1]	1.96	20%	
Reactor Heating[2]	1.51	16%	12.0
Carbon Separation[3]	0.16	2%	
Hydrogen Purification[4]	6.00	62%	5.7
Total	**9.64**	**100%**	**17.7**

	10,000 kg/day
Total Capital Investment, $	15,700,000
Total Capital Investment, $/kg/day	1570
Natural Gas Feed, MSCFD	2270
Hydrogen Purity, mol%	99.999
Carbon Production, kg/d	29,950
Production Cost, $/kg H_2	
Capital	0.68
Electricity/Power[5]/Utilities	0.48
Consumables	0.65
O&M	0.30
Total Cost	**2.11**



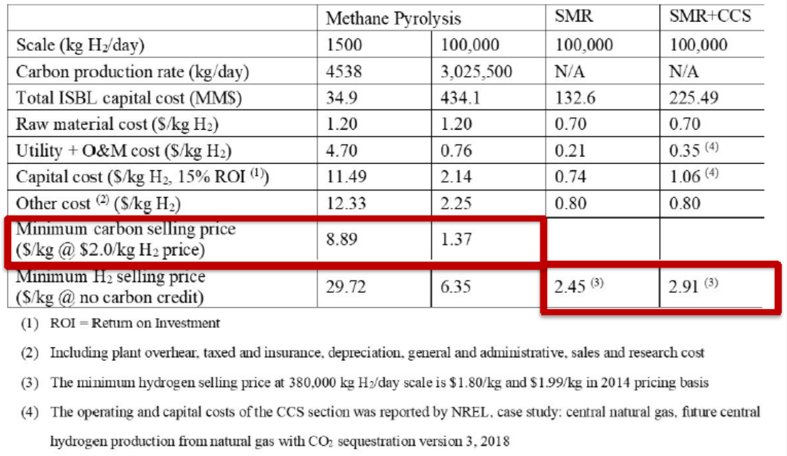
Parameter	Low	Base	High
Natural Gas Conversion (%)	90	25	10
Natural Gas Price ($/MMBTU)	1.0	3.0	5.0
Total Capital ($MM)	10.0	14.8	20.0
Capital Recovery Factor (%)	10.0	14.2	20.0
Electricity Price (¢/kWh)	2.0	3.0	5.0
Catalyst Loading (g/SLM feed)	5.0	10.0	20.0
Power Requirement (kWh/kg)	15.7	17.7	28.3

Even without carbon product credit

This demonstrates the potential to produce H_2 at <$2/kg

[1] Reactor capital: $2MM for 12 m^3 Inconel reactor, req. vol is 1.2 m^3
[2] Heating equipment: $80K for 7kWe
[3] Includes a cyclone and bag filter
[4] H_2 PSA + Compressor: $230,000 for 300 kg H_2/day
[5] Electricity at $0.03/kWh

Current Approaches vs. Methane Pyrolysis



	Methane Pyrolysis		SMR	SMR+CCS
Scale (kg H_2/day)	1500	100,000	100,000	100,000
Carbon production rate (kg/day)	4538	3,025,500	N/A	N/A
Total ISBL capital cost (MM$)	34.9	434.1	132.6	225.49
Raw material cost ($/kg H_2)	1.20	1.20	0.70	0.70
Utility + O&M cost ($/kg H_2)	4.70	0.76	0.21	0.35 (4)
Capital cost ($/kg H_2, 15% ROI (1))	11.49	2.14	0.74	1.06 (4)
Other cost (2) ($/kg H_2)	12.33	2.25	0.80	0.80
Minimum carbon selling price ($/kg @ $2.0/kg H_2 price)	8.89	1.37		
Minimum H_2 selling price ($/kg @ no carbon credit)	29.72	6.35	2.45 (3)	2.91 (3)

(1) ROI = Return on Investment

(2) Including plant overhear, taxed and insurance, depreciation, general and administrative, sales and research cost

(3) The minimum hydrogen selling price at 380,000 kg H_2/day scale is $1.80/kg and $1.99/kg in 2014 pricing basis

(4) The operating and capital costs of the CCS section was reported by NREL, case study: central natural gas, future central hydrogen production from natural gas with CO_2 sequestration version 3, 2018

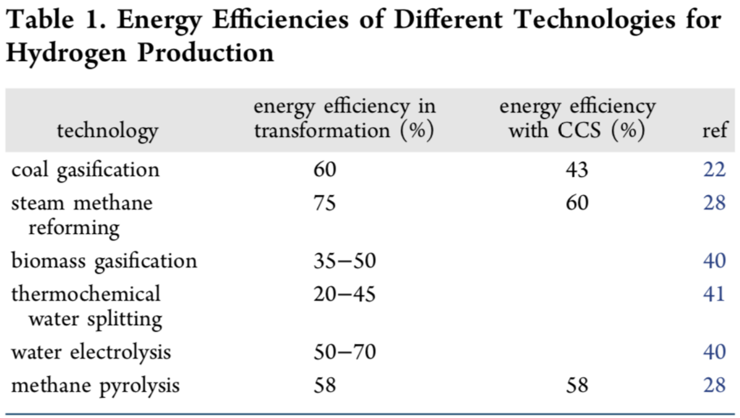
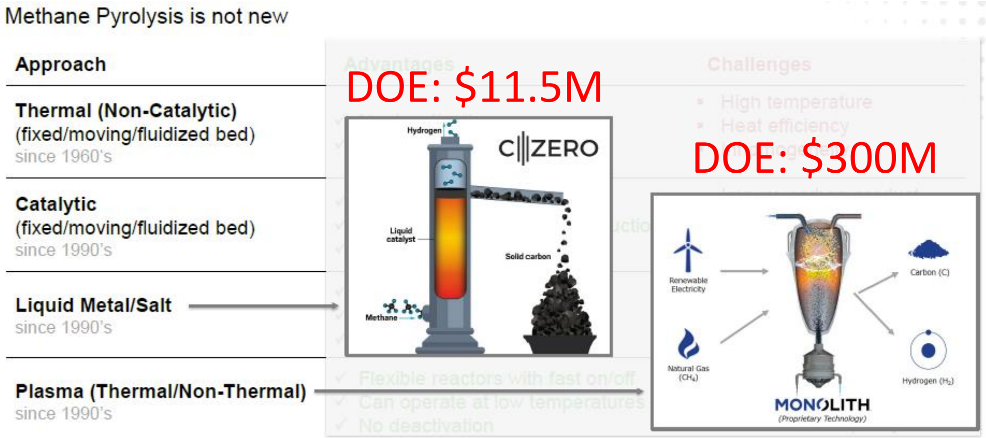


Table 1. Energy Efficiencies of Different Technologies for Hydrogen Production

technology	energy efficiency in transformation (%)	energy efficiency with CCS (%)	ref
coal gasification	60	43	22
steam methane reforming	75	60	28
biomass gasification	35–50		40
thermochemical water splitting	20–45		41
water electrolysis	50–70		40
methane pyrolysis	58	58	28



Methane Pyrolysis is not new

Approach

Thermal (Non-Catalytic) (fixed/moving/fluidized bed) since 1960's

Catalytic (fixed/moving/fluidized bed) since 1990's

Liquid Metal/Salt since 1990's

Plasma (Thermal/Non-Thermal) since 1990's

Advantages

Challenges

- High temperature
- Heat efficiency

✓ Flexible reactors with fast on/off
✓ Can operate at low temperatures
✓ No deactivation

DOE: $11.5M

DOE: $300M

https://www.hydrogen.energy.gov/pdfs/review20/h2045_dagle_2020_p.pdf

State of the Art of Hydrogen Production via Pyrolysis of Natural Gas, ChemBioEng Rev 2020, 7, No. 5, 150–158

Adapted from Bode A. et al. BASF. *ProcessNet Jahrestagung*. Aachen, Germany. 14 Sep 2016.

Potential Reactor Configurations

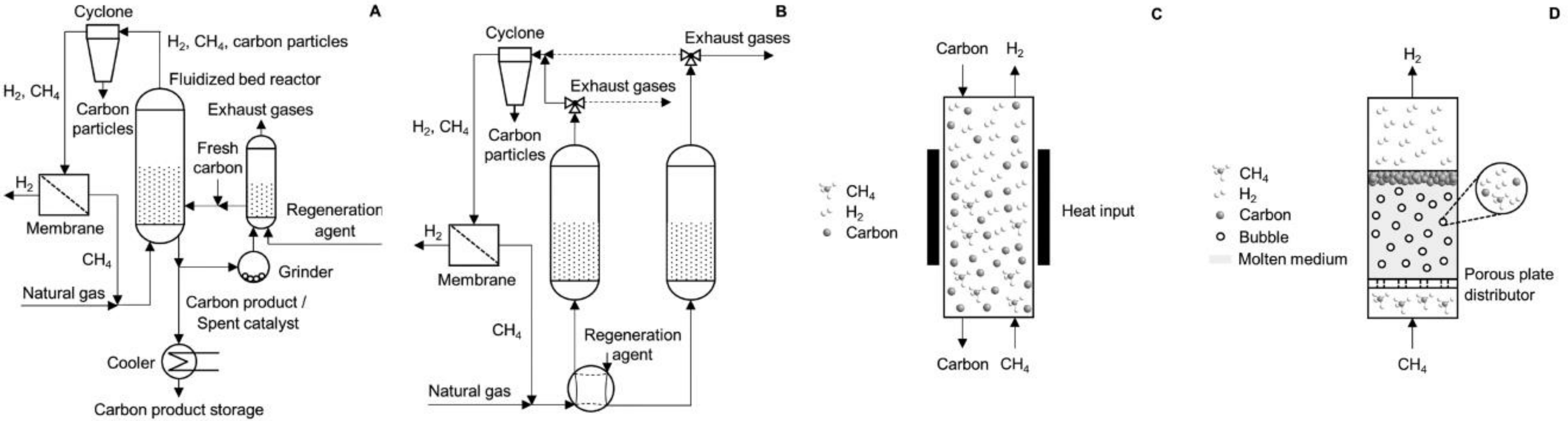
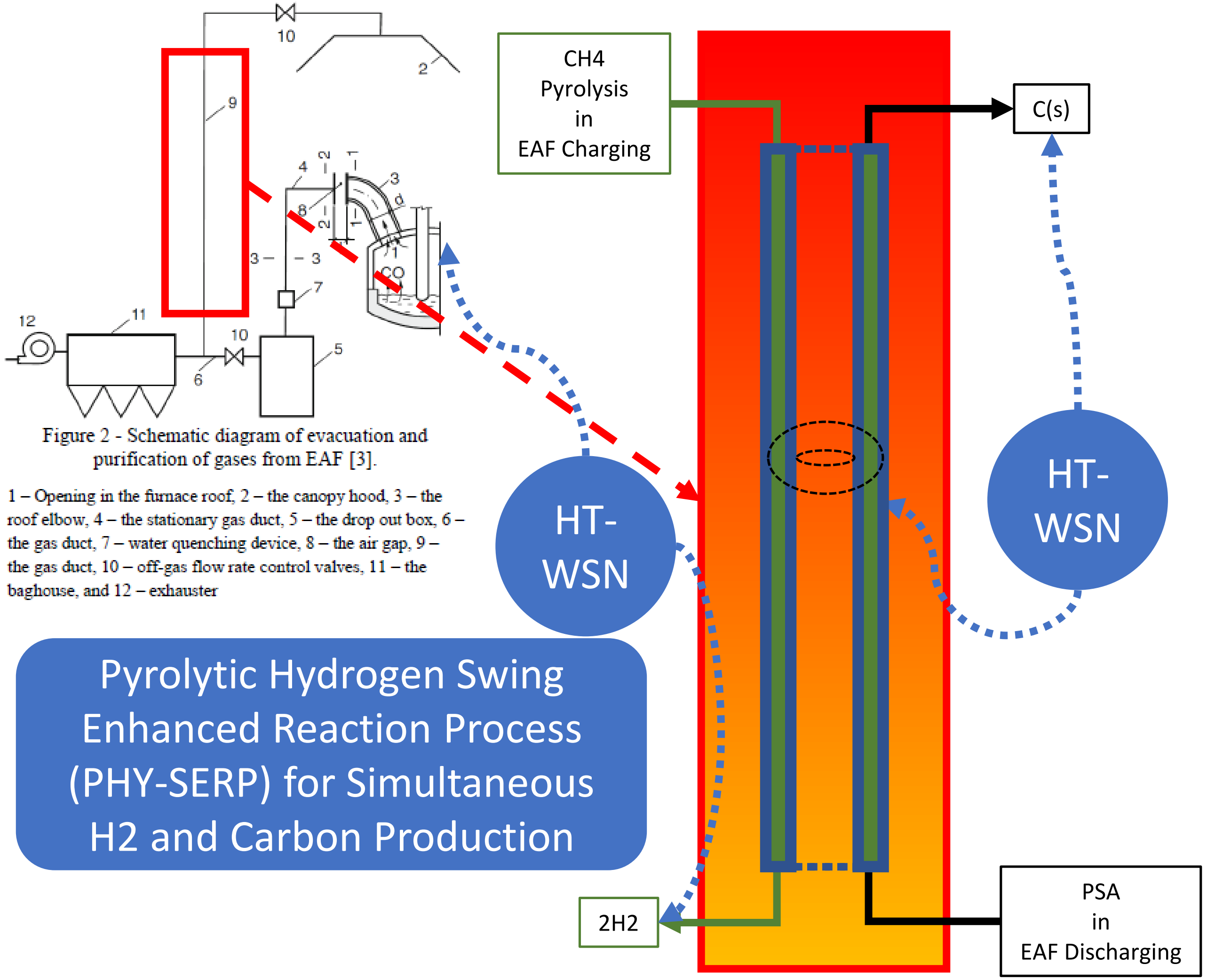


Figure 8. Potential reactor configurations for the industrial implementation of methane pyrolysis. (A) Fluidized-bed reactor with a catalyst regeneration unit according to refs 204 and 215. (B) Parallel reactors operating in a cyclic reaction-regeneration mode according to ref 199. (C) Moving-bed reactor according to ref 265. (D) Liquid bubble column reactor according to ref 263.

https://doi.org/10.1021/acs.iecr.1c01679

제철분야 수소생산 기술개발



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Pyrolytic Hydrogen Swing Enhanced Reaction Process (PHY-SERP) for Simultaneous H2 and Carbon Production

- 제철공정에 사용되고 있는 전기아크로에서 배출되는 약 800 - 1,500 °C 초고온 부생가스 ($CO/CO_2/N_2/H_2/H_2O$/분진) 는 사이클 간헐성, 분진 및 공간 등의 제약사항들로 인해서 폐열 에너지를 회수하지 못하고 대부분 water spray cooling tower를 통해서 버려지고 있는 실정임.
- 미국 및 유럽에서 개발중인 용융금속/용융염 또는 플라즈마를 이용한 메탄 열분해 (흡열반응) 공정은 필요한 초고온을 얻기 위해서 연소 또는 전기 에너지를 소모하고 있으며 안전성 등의 문제가 있음.
- 165톤급 전기아크로 충전시 배출되는 30 kg/s 이상의 부생가스 온도구간 (1,500 – 1,000 °C)의 엔탈피로 환산할 경우, charging cycle 동안 약 20 MW의 열에너지 회수가 가능함. (기존 냉각수 소모량: 약 5.8 kg/s)
- 제철 플랜트 전기아크로 초고온 부생가스 열회수와 메탄 열분해 시스템 수소생산 공정을 융합할 경우, 수소 1몰당 37.7 kJ 흡열조건 가정시, 해당공정 온도범위에서 이산화탄소 발생없이 최대 55 톤/일급의 무촉매 고순도 수소생산이 가능함.
- 제철 산업 측면에서, 부생가스 및 냉각수 배출로 인한 에너지 손실을 최소화하고 생산된 수소를 수소환원철 또는 후단부 제철공정에 공급함으로써 이산화탄소 발생을 저감시키고 탄소중립에 크게 기여할 수 있음.
- 필요한 핵심기술로써 전기아크로 부생가스 간헐성 완화기술, 시스템 융합기술, 초고온 열교환기 설계기술, 수소 및 고체탄소 무촉매 분리 및 정제기술 등이 있으며 제안자 정광국 교수는 국내 전력사들과의 협력연구개발을 통해 발전소 후단부 다상유동 열교환기 개발 및 플러그반응기 운전실험 등의 경험을 바탕으로 본 핵심기술 개발을 위한 exploratory idea를 갖고 있음.

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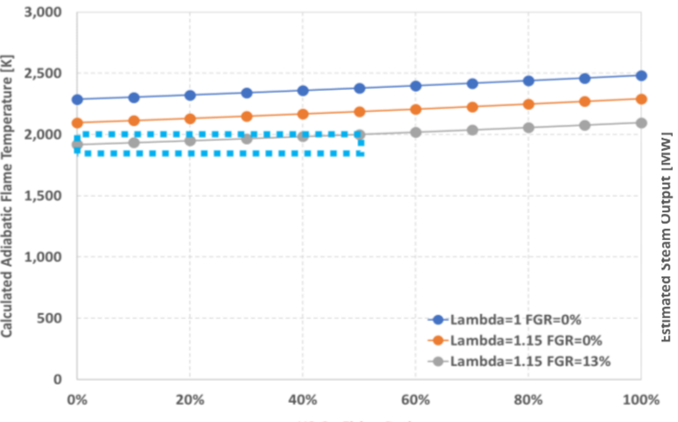
제철분야 수소 활용 기술개발



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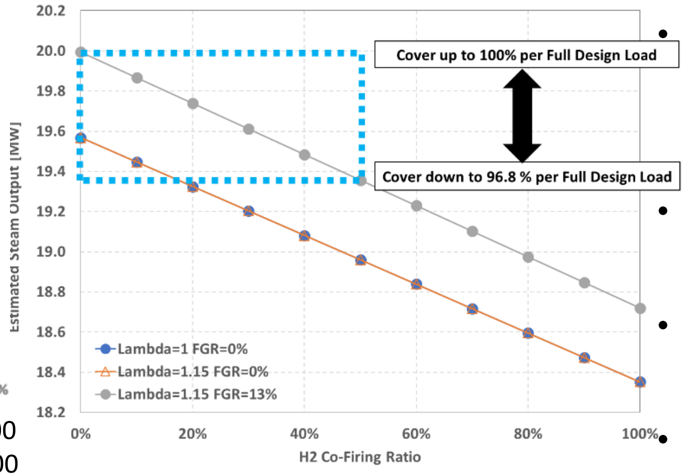
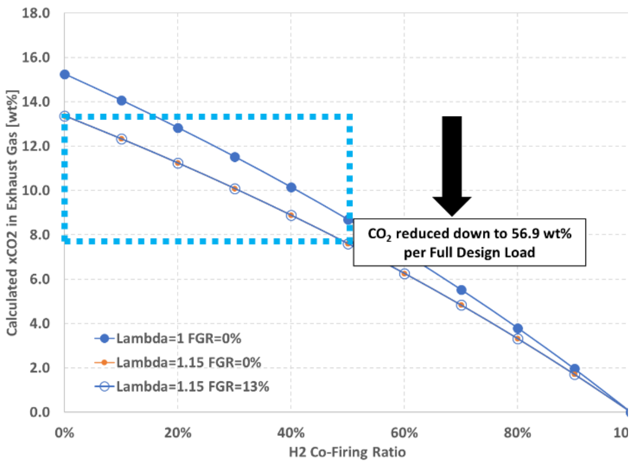
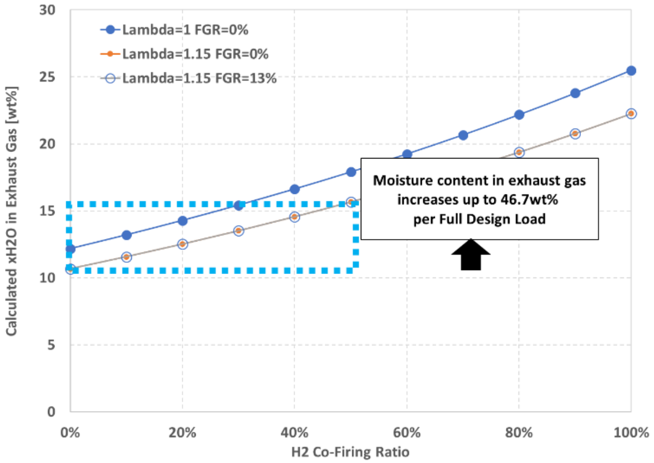
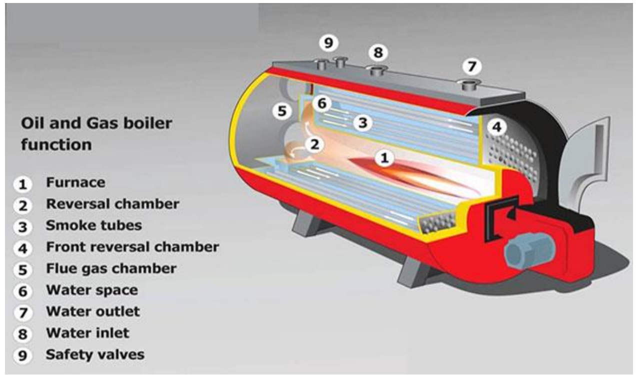
yH2: 0	43.5	67.3	82.2	92.5	100







- The feasible H2 co-firing ratio corresponding to the limiting case of AFT up to 2,000 K has been found as 0 % to 50 % (thermal equivalence): bounded by blue-dotted box -> 75.5 vol.% H2 and 26.4 wt.% H2
  - It was obvious that the flue gas recirculation has a critical role in matching the presumed design constraint.
- The subsequent steam output corresponding up to the 50 % H2 co-firing ratio has been estimated to cover from 100 to 96.8 % per the full design load due to the reduced mass flowrate of the combined fuel.
- At the H2 co-firing ratio 50%, the calculated CO2 emission has been reduced from 13.4 to 7.6 wt.% which is equivalent to the normalized reduction of CO2 emission up to 56.9 wt%.
- The hydrogen co-firing has impacted on the increased moisture contents in the exhaust from 10.7 to 15.7 wt.%, which is equivalent to the normalized increment of H2O emission up to 1.47 times.
- The co-firing H2 in the natural gas horizontal firetube boiler would be feasible by leveraging the steam output duties to the adjusted load in conjunction with minimal retrofit and high temperature silicon carbide (SiC) wireless sensors between the consumption and generation sites.
- Current research partners: A-State, UAF, BRS, & RIST



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Thank You!