CLEAN ENERGY
SOLUTIONS CENTER
ASSISTING COUNTRIES WITH CLEAN ENERGY POLICY

An Initiative of the Clean Energy Ministerial

Hydrogen to Support Climate Targets

Hydrogen and Analytical Tools Webinar Series

February 21, 2024

Housekeeping - Zoom

- This webinar is **being recorded** and will be shared with attendees.
- You will be **automatically muted** upon joining and throughout the webinar.
- Please use the **chat feature** to add comments and share input.
- Please use the **Q&A function** in your toolbar to ask questions.
- If you have **technical issues**, please use the chat feature to message Sophie Schrader or Isabel McCan.
- You can adjust your audio through the **audio settings.** If you are having issues, you can also dial-in and listen by phone. Dial-in information can be found in your registration email.
- We will be launching a **survey** when the event ends. Your feedback is highly valuable to us!

CLEAN ENERGY
SOLUTIONS CENTER
ASSISTING COUNTRIES WITH CLEAN ENERGY POLICY

An Initiative of the Clean Energy Ministerial

Overview of the Clean Energy Solutions Center

Presented by Jal Desai, Clean Energy Solutions Center

The Clean Energy Solutions Center

OBJECTIVE

To accelerate the transition of clean energy markets and technologies.

RATIONALE

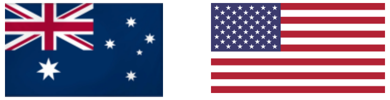
Many developing governments lack capacity to design and adopt policies and programs that support the deployment of clean energy technologies.

AMBITION/TARGET

Support governments in developing nations of the world in strengthening clean energy policies and finance measures

ACTORS

Leads:



Operating Agent:

Partners:

More than 40 partners, including UN-Energy, IRENA, IEA, IPEEC, REEEP, REN21, SE4All, IADB, ADB, AfDB, and other workstreams etc.

ACTIONS

- **Deliver** dynamic services that enable *expert assistance*, *learning, and peer-to-peer sharing of experiences. <u>Services are offered at no-cost to users.</u>*
- **Foster** dialogue on emerging policy issues and innovation across the globe.
- **Serve** as a first-stop clearinghouse of clean energy policy resources, including policy best practices, data, and analysis tools.

UPDATES

Website:
www.cleanenergyministerial.org/initiatives-campaigns/clean-energy-solutions-center

Factsheet:
www.nrel.gov/docs/fy22osti/83658.pdf

Requests: Now accepting Ask an Expert requests!

The Clean Energy Solutions Center

CLEAN ENERGY SOLUTIONS CENTER
ASSISTING COUNTRIES WITH CLEAN ENERGY POLICY

CLEAN ENERGY MINISTERIAL
Advancing Clean Energy Together

Ask an Expert Service

- Ask an Expert is designed to help policymakers in developing countries and emerging economies identify and implement ***clean energy policy*** and finance solutions.
- The Ask an Expert service features a network of more than **50** experts from over **15** countries.
- Responded to **300+** requests submitted by **90+** governments and regional organizations from developing nations since inception

Training and Capacity Building

- Delivered over **300** webinars training more than **20,000** public & private sector stakeholders.

Resource Library

- Over **1,500** curated reports, policy briefs, journal articles, etc.

CLEAN ENERGY SOLUTIONS CENTER
ASSISTING COUNTRIES WITH CLEAN ENERGY POLICY

isa INTERNATIONAL SOLAR ALLIANCE

Expert Connections Empower
Bankable Solar Projects

For additional information and questions, reach out to Jal Desai, NREL, jal.desai@nrel.gov

CLEAN ENERGY
SOLUTIONS CENTER
ASSISTING COUNTRIES WITH CLEAN ENERGY POLICY
An Initiative of the Clean Energy Ministerial

Hydrogen to Support Climate Targets

Presented by Daniella Rough, National Renewable Energy Laboratory

Webinar Speakers

Daniella Rough

International Project Manager

National Renewable Energy Laboratory

Steve Hammond

Senior Research Advisor in the Mechanical and
Thermal Engineering Sciences Directorate

National Renewable Energy Laboratory

Pingping Sun

Hydrogen and Electrification
Analysis Group Leader

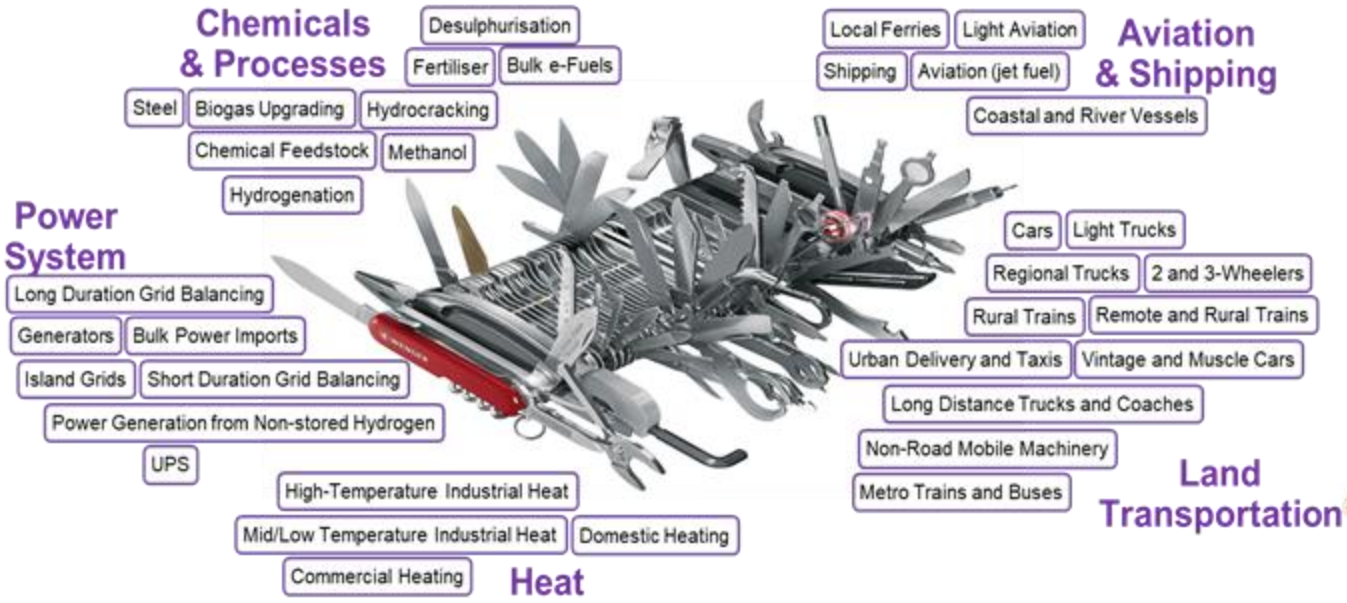
Argonne National Laboratory

Agenda

Speaker	Topic	Duration
Daniella Rough	Hydrogen for Climate Targets	10 mins
Steve Hammond	Potential for hydrogen, and its derivatives, to decarbonize domestic, commercial, and hard-to-decarbonize sectors	20 mins
Daniella, Steve, Pingping	Q&A	20 mins
Pingping Sun	Overview and demonstration of the greenhouse gases, regulated emissions, end energy use in technologies (GREET) model	30 mins
Daniella, Steve, Pingping	Q&A	25 mins

Hydrogen – Climate's Swiss Army Knife?

You can do almost anything with a Swiss Army Knife…



Chemicals & Processes

Desulphurisation
Fertiliser
Bulk e-Fuels
Steel
Biogas Upgrading
Hydrocracking
Chemical Feedstock
Methanol
Hydrogenation

Aviation & Shipping

Local Ferries
Light Aviation
Shipping
Aviation (jet fuel)
Coastal and River Vessels

Power System

Long Duration Grid Balancing
Generators
Bulk Power Imports
Island Grids
Short Duration Grid Balancing
Power Generation from Non-stored Hydrogen
UPS

Land Transportation

Cars
Light Trucks
Regional Trucks
2 and 3-Wheelers
Rural Trains
Remote and Rural Trains
Urban Delivery and Taxis
Vintage and Muscle Cars
Long Distance Trucks and Coaches
Non-Road Mobile Machinery
Metro Trains and Buses

Heat

High-Temperature Industrial Heat
Mid/Low Temperature Industrial Heat
Domestic Heating
Commercial Heating

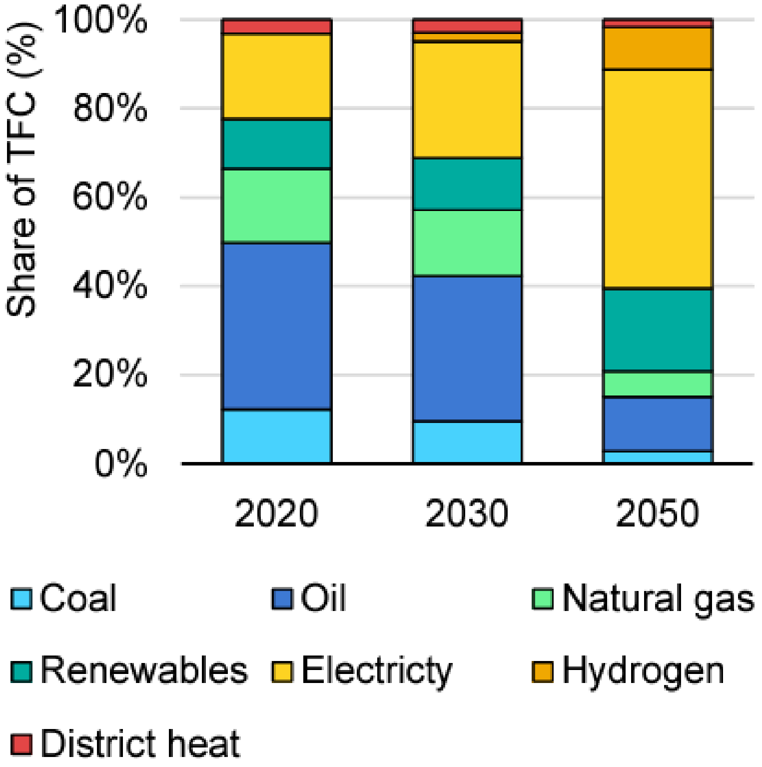
Source: Michael Liebreich/Liebreich Associates, Clean Hydrogen Ladder, Version 5.0, 2023.Concept credit: Adrian Hiel, Energy Cities. Image: Wenger (concept credit: Paul Martin). *CC-BY 4.0*

But would you build your house with one?

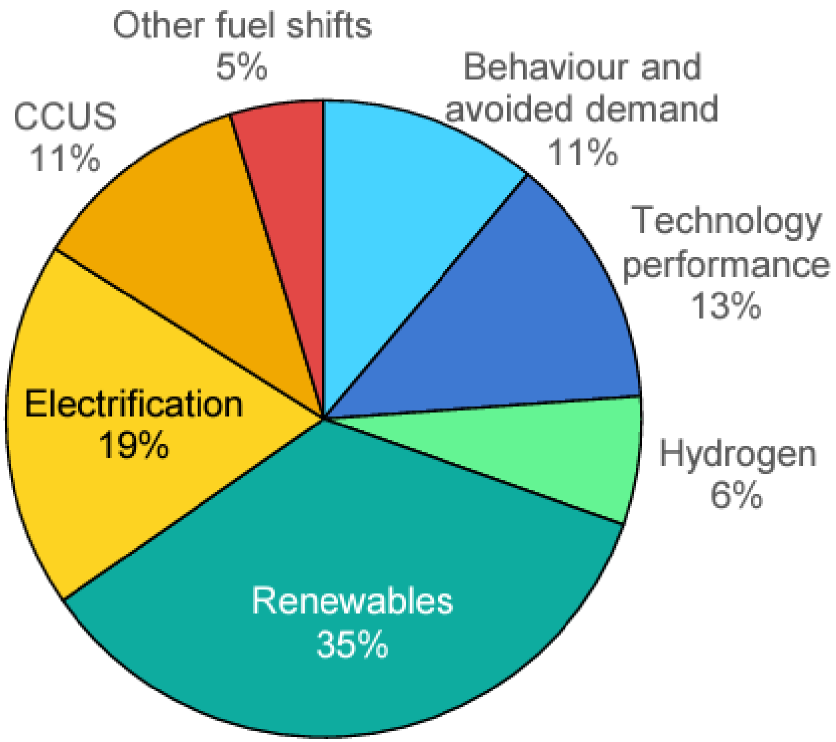
Global Emissions Abated by Hydrogen by 2050

Hydrogen is an important part of the Net zero Emissions Scenario, but is only one piece of the puzzle

Share of total final energy consumption by fuel in the NZE, 2020-2050

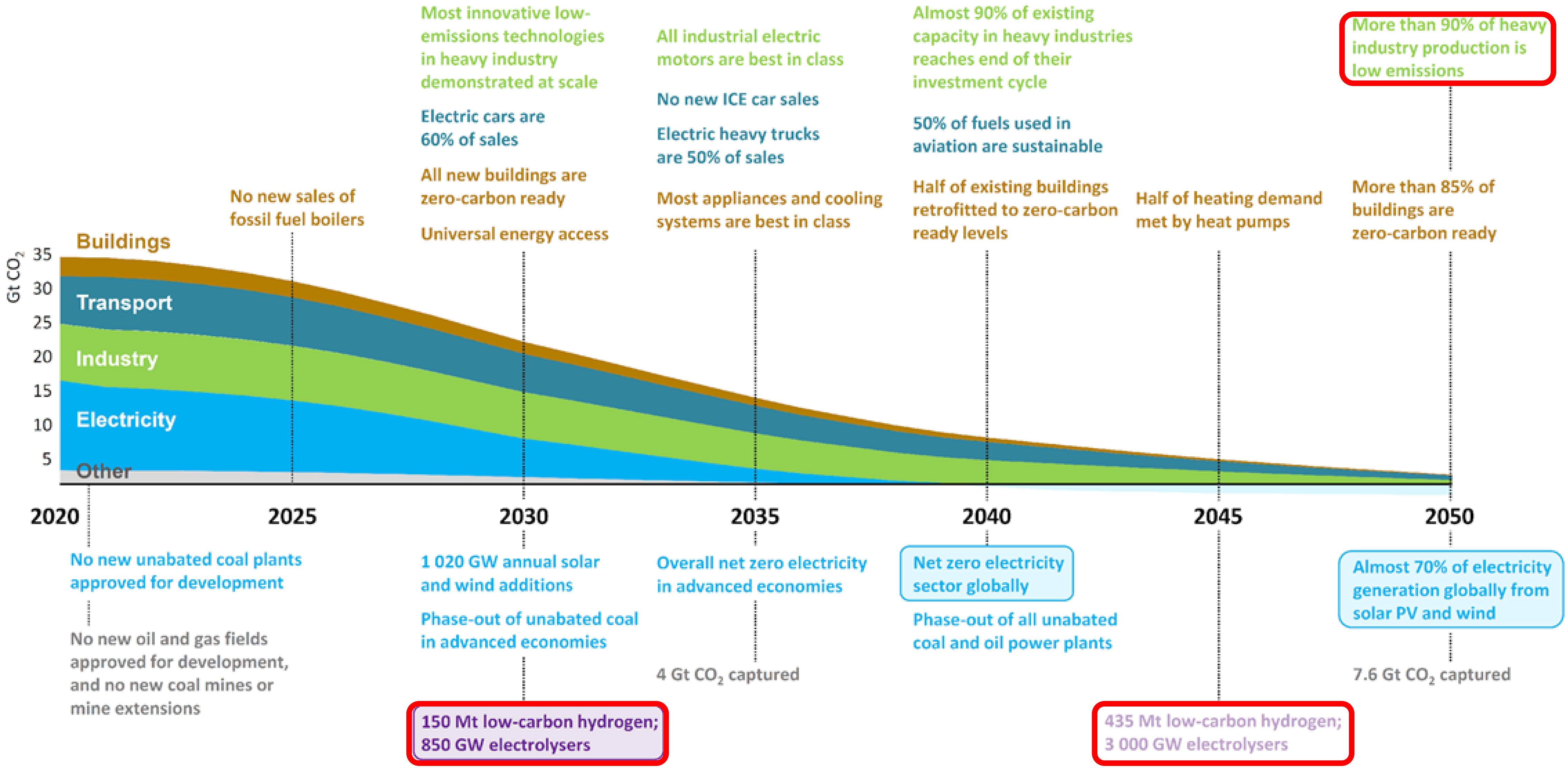


Cumulative emissions reduction by mitigation measure in the NZE, 2021-2050



Source: https://iea.blob.core.windows.net/assets/5bd46d7b-906a-4429-abda-e9c507a62341/GlobalHydrogenReview2021.pdf

The Path Toward a Net-Zero Emissions Energy Sector by 2050



No new unabated coal plants approved for development

No new oil and gas fields approved for development, and no new coal mines or mine extensions

No new sales of fossil fuel boilers

Most innovative low-emissions technologies in heavy industry demonstrated at scale

Electric cars are 60% of sales

All new buildings are zero-carbon ready

Universal energy access

1 020 GW annual solar and wind additions

Phase-out of unabated coal in advanced economies

150 Mt low-carbon hydrogen; 850 GW electrolysers

All industrial electric motors are best in class

No new ICE car sales

Electric heavy trucks are 50% of sales

Most appliances and cooling systems are best in class

Overall net zero electricity in advanced economies

4 Gt CO_2 captured

Almost 90% of existing capacity in heavy industries reaches end of their investment cycle

50% of fuels used in aviation are sustainable

Half of existing buildings retrofitted to zero-carbon ready levels

Net zero electricity sector globally

Phase-out of all unabated coal and oil power plants

Half of heating demand met by heat pumps

435 Mt low-carbon hydrogen; 3 000 GW electrolysers

More than 90% of heavy industry production is low emissions

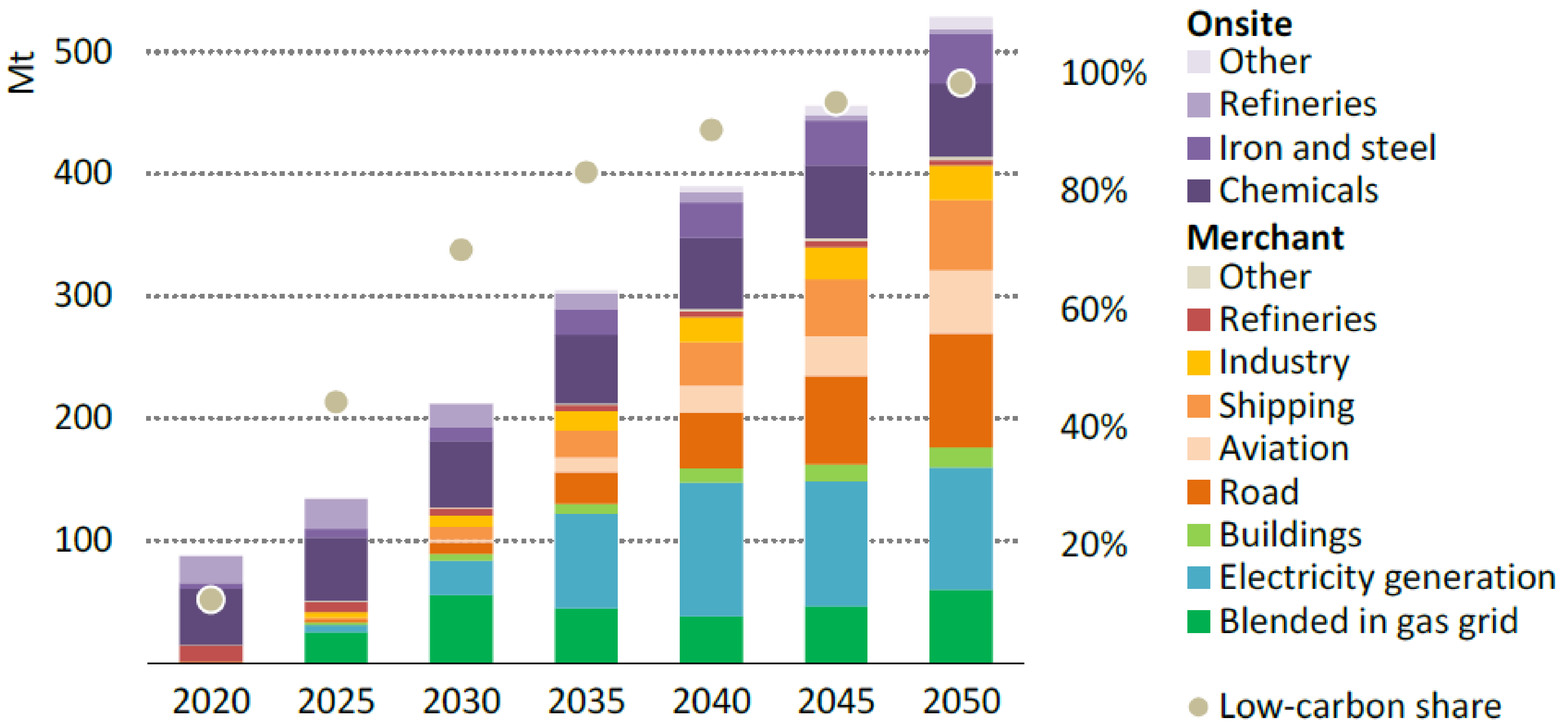
More than 85% of buildings are zero-carbon ready

Almost 70% of electricity generation globally from solar PV and wind

7.6 Gt CO_2 captured

Ref: https://unfccc.int/sites/default/files/resource/NZE2050_Worsdorfer_IEA.pdf

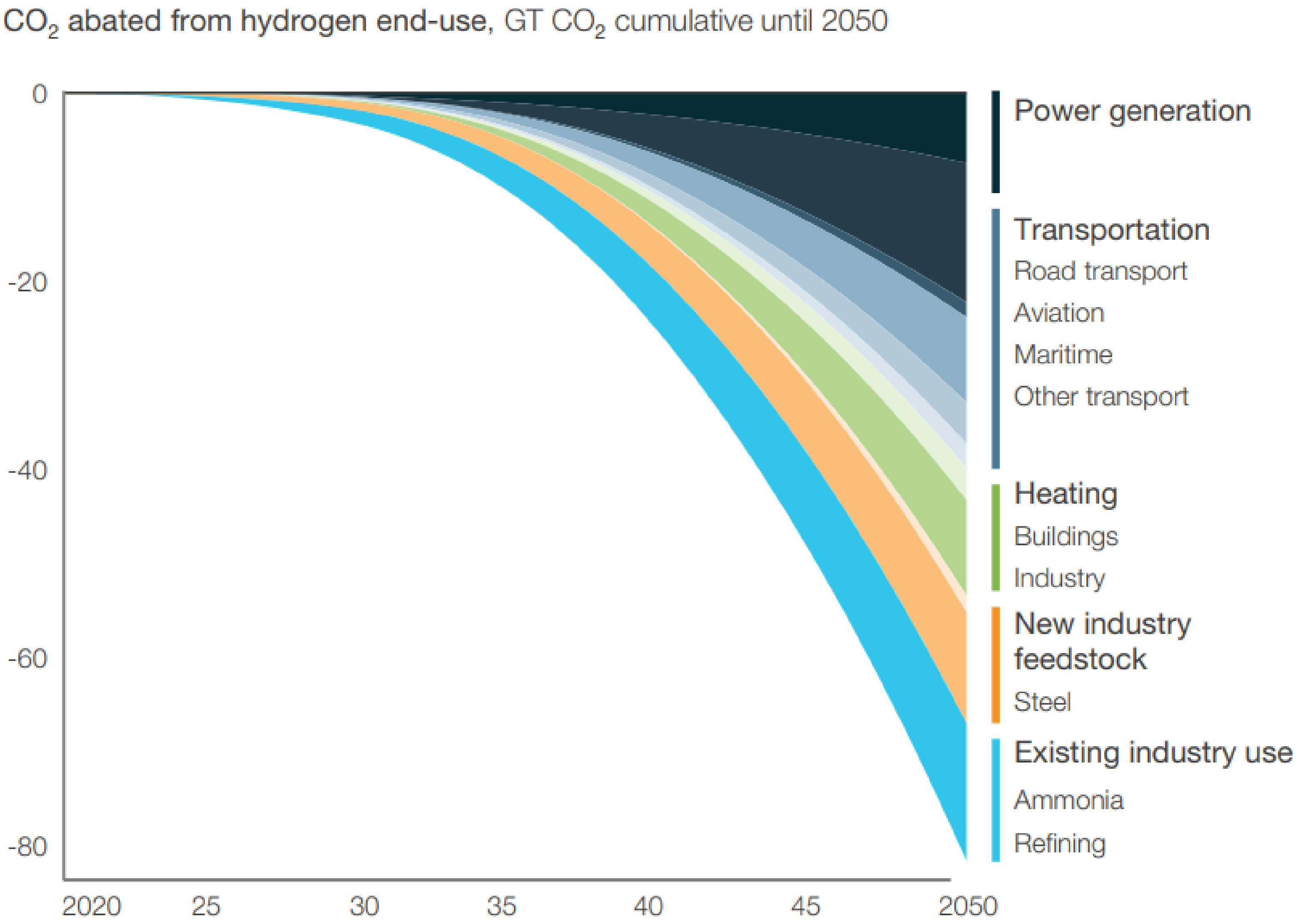
Hydrogen Deployment Pathway for a Net-Zero Emissions



- Hydrogen demand is projected to grow (> 5-fold increase from 2020 to 2050)
- Diversified hydrogen demand (new applications, e.g., e-fuels, hydrogen blending, seasonal storage, etc.)
- Increase in decarbonized hydrogen production (new technologies, e.g., renewable-driven water electrolysis)

Source: https://www.iea.org/reports/net-zero-by-2050

Global Emissions Abated by Hydrogen by 2050



Sources: https://hydrogencouncil.com/wp-content/uploads/2021/11/Hydrogen-for-Net-Zero.pdf

Hydrogen in Industrial Decarbonization

Steve Hammond, Jen King and “green steel” team

February 21, 2024

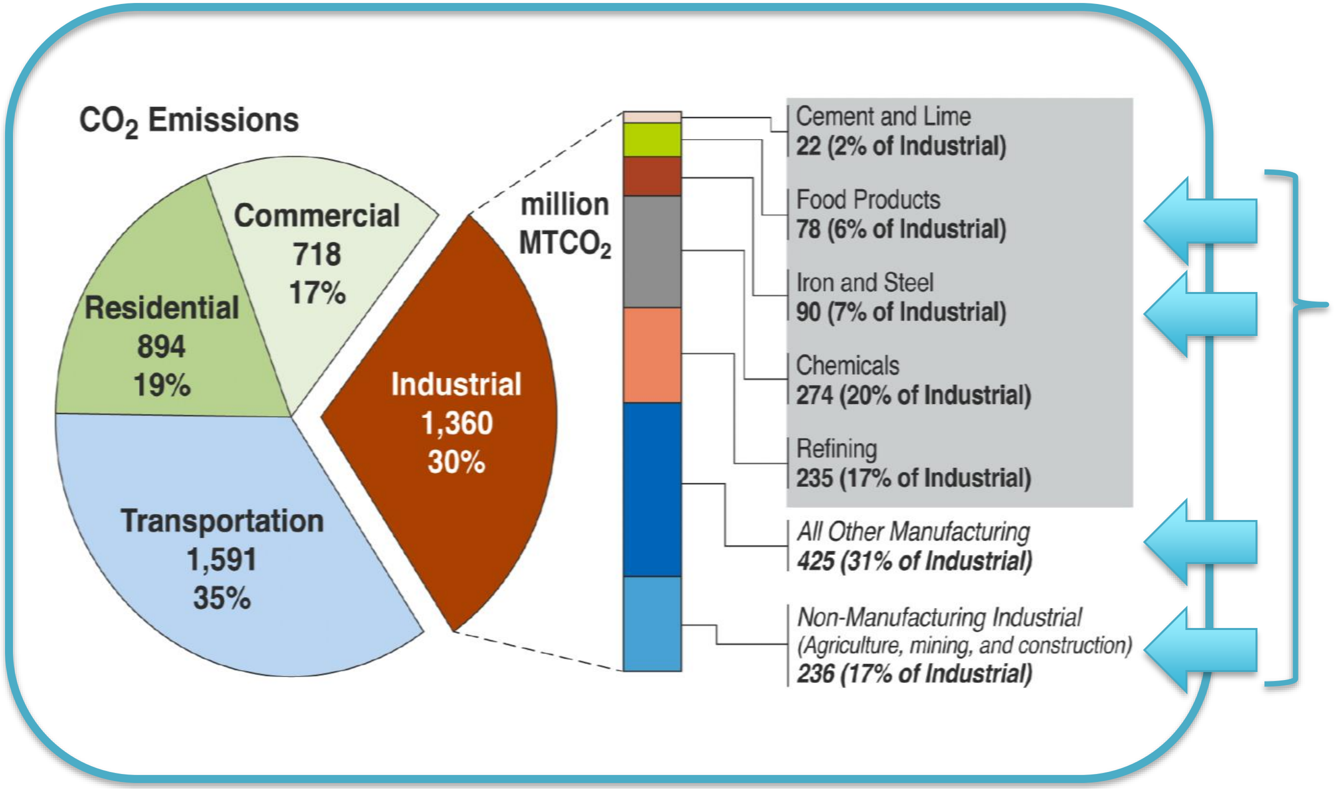
Photo from iStock-627281636

Outline

1. Industrial Decarb Challenge
2. Iron / Steel
3. E-Fuels
4. Wrap up

Industrial Decarbonization Grand Challenge

U.S. goal: net zero GHG emissions economy-wide by 2050.



Over 50% of industrial emissions come from a disparate range of industries and applications.

CREATING NEW SOLUTIONS FOR HARD-TO-ABATE SECTORS

SHARE OF GLOBAL YEARLY CO_2 EMISSIONS:

7%	6%	2%	3%	2%
Iron & Steel	Chemical & Petrochemicals	Aviation	Cement	Shipping

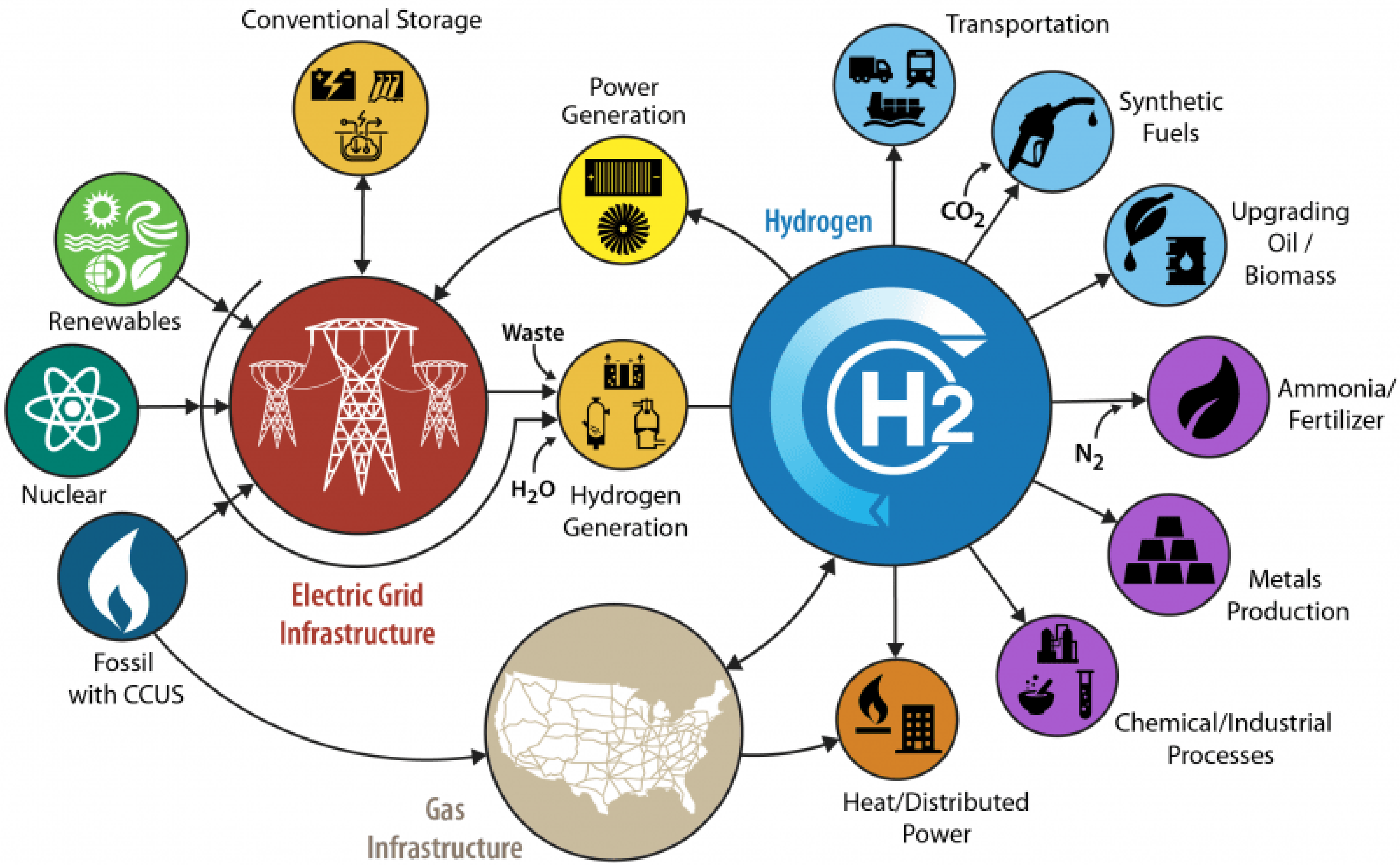
Source: Climate Watch, the World Resources Institute (2020)

Decarbonizing hard-to-abate sectors cannot be achieved directly thru electrification…. They need fuels.

Success requires a **holistic** approach, integrating **multiple diverse technologies** and processes that have not previously worked together.

H2@SCALE

U.S. Department of Energy (DOE) initiative that brings together stakeholders to advance affordable hydrogen production, transport, storage, and utilization to enable decarbonization and revenue opportunities across multiple sectors.

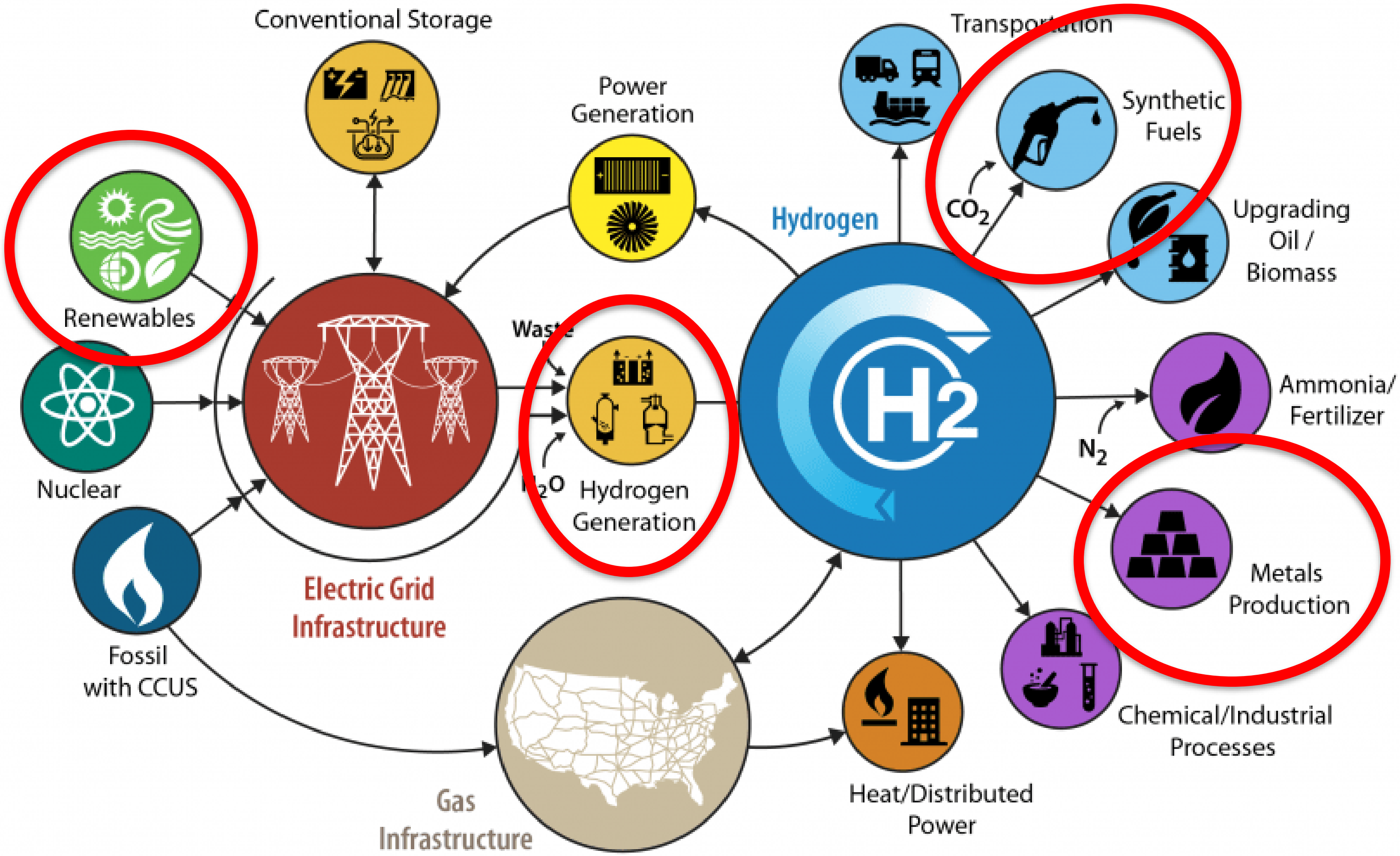


H2@SCALE

U.S. produces ten million metric tons of hydrogen annually.

Most of this hydrogen is produced via centralized reforming of natural gas.

Deployments of clean alternatives, such as electrolysis, are rapidly increasing.



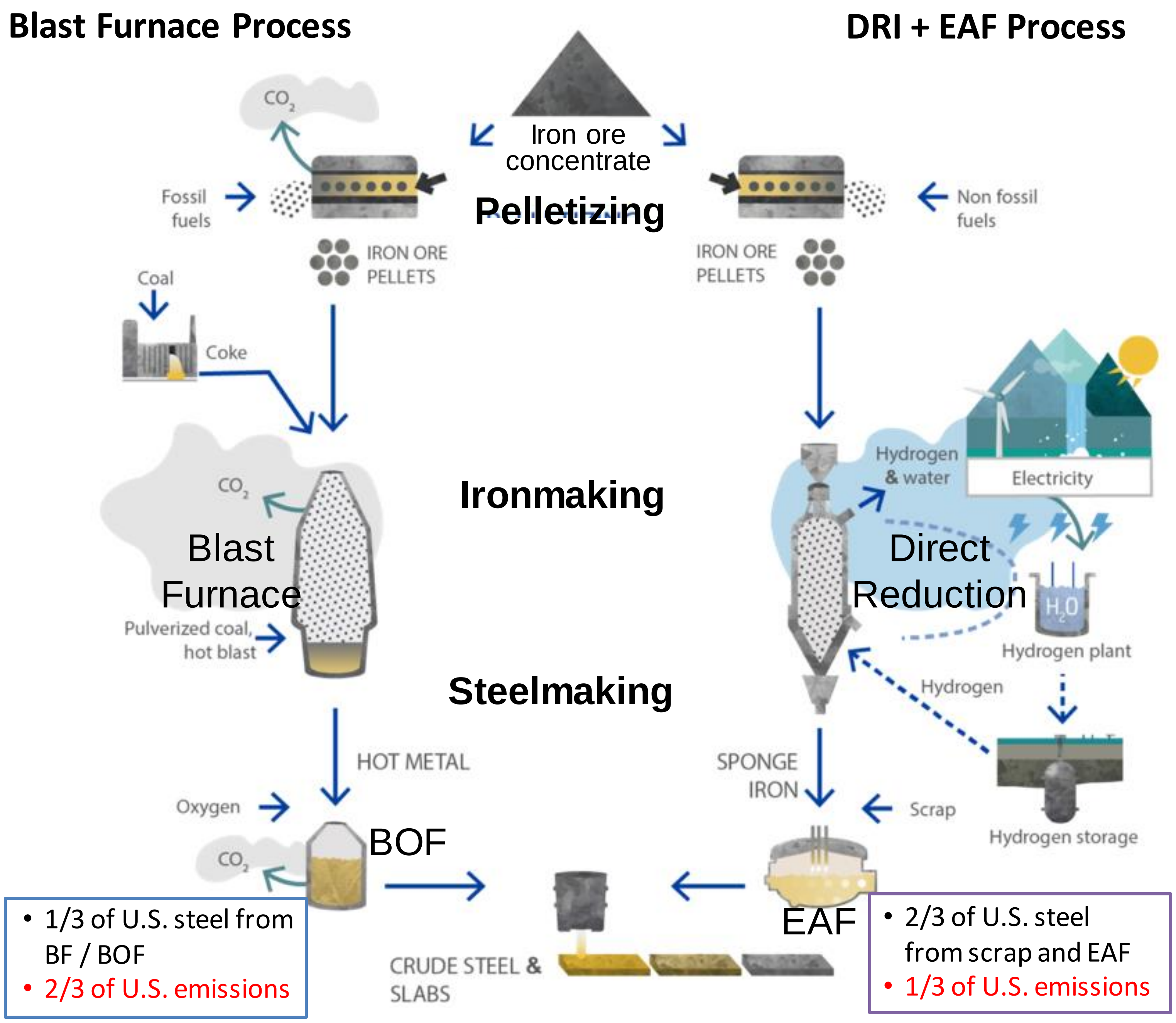
Iron and Steel 101

Today: ~8% of global GHG emissions.

2 Routes for U.S. Steel Production:

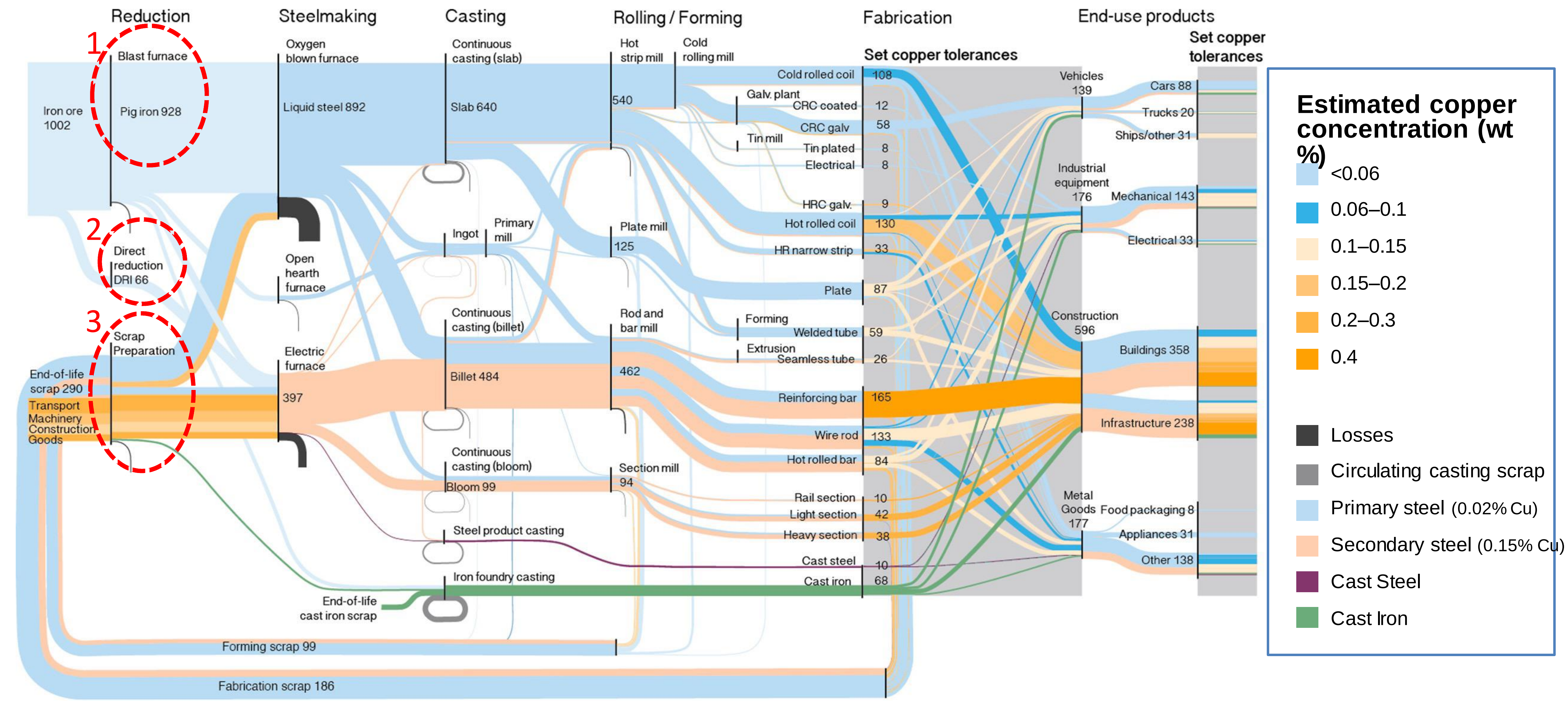
- Blast Furnace (BF) and
- Electric Arc Furnace (EAF)

Challenge: Develop cost competitive, zero emission technologies and infrastructure appropriate for U.S. feedstocks and full spectrum of steel end use products.



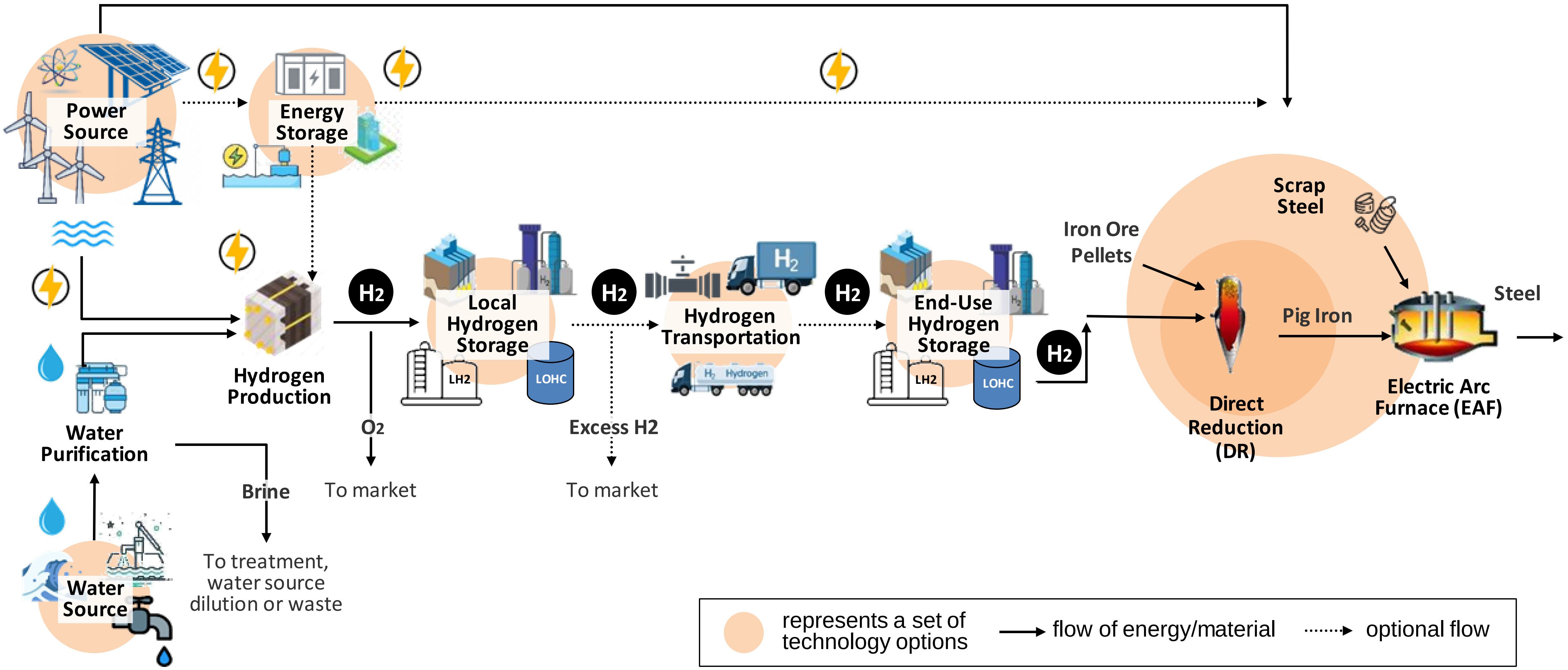
- 1/3 of U.S. steel from BF / BOF
- 2/3 of U.S. emissions

- 2/3 of U.S. steel from scrap and EAF
- 1/3 of U.S. emissions



High-Level View of Iron/Steel

1. Develop alternatives to the ~30 U.S. Blast Furnaces
2. Scale up the use of Direct Reduction, using H2 rather than methane.
3. Improve approach to scrap preparation to remove impurities (mostly copper).



● represents a set of technology options
→ flow of energy/material
⇢ optional flow

Full Integrated System

Renewables to H2 to Steel

END-USE:

- Simplified diagram
- Ancillary equipment not depicted

Big Picture: Water, Electricity, H2, and Iron

- It takes about **9L of DI water** and **55kWh of electricity** to produce **1 kg of H2 in a PEM electrolyzer**.
- It takes about **80-120kg of H2** to produce **1 tonne of metallic iron** from iron ore.

To replace one blast furnace that produces 1M Tonne metallic iron per year, it takes:

- About 80,000 – 120,000 tonnes of H2 per year,
- 4,400,000,000 to 6,600,000,000 kWh electricity (about 1 GW), and
- 720,000,000L to 1,080,000,000L DI water (about 2,000 acre-feet)

*Iron/Steel production is a "**steady-state**" industrial process, 7x24x365.*

Pipelines and storage provide **essential infrastructure** to get H2 to where it is used and buffer between variable generation and steady state end use.

* Note that the numbers here are not exact, +/- 10%, meant to give a sense of scale

H2 and Iron

The DOE Industrial Decarbonization Roadmap discusses the important role H2 plays in decarbonizing iron and steel.

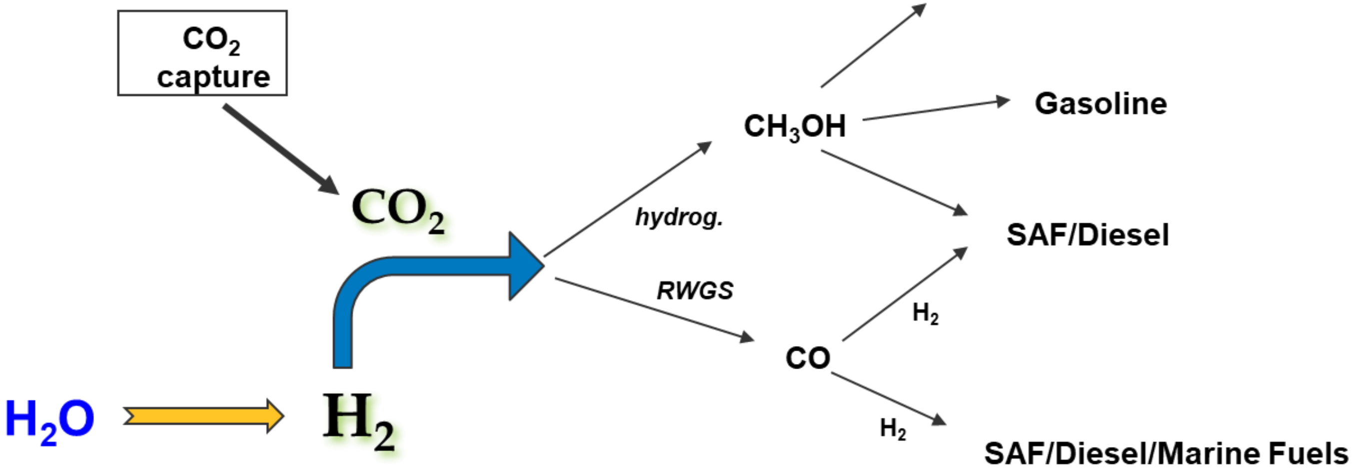
The Roadmap is largely silent on the critical role that H2 storage plays.

Using H2 for iron ore reduction, economic viability is reached at an H2 procurement cost of $1.70 per kg, while achieving a CO2 emission reduction of 76% at the plant site*.

To account for lower quality U.S. iron ores, increased energy for beneficiation, and reduced EAF yields, getting the LCOH *delivered* closer to $1/kg will be needed to spur industry change and rapid adoption of low/no carbon processes using clean H2.

* Rosner, Papadias, Brooks, Yoro, Ahluwalia, Autrey, and Breunig, "Green steel: design and cost analysis of hydrogen-based direct iron reduction" ChemRxiv, March 2023.

E-Fuels - First Generation Technologies



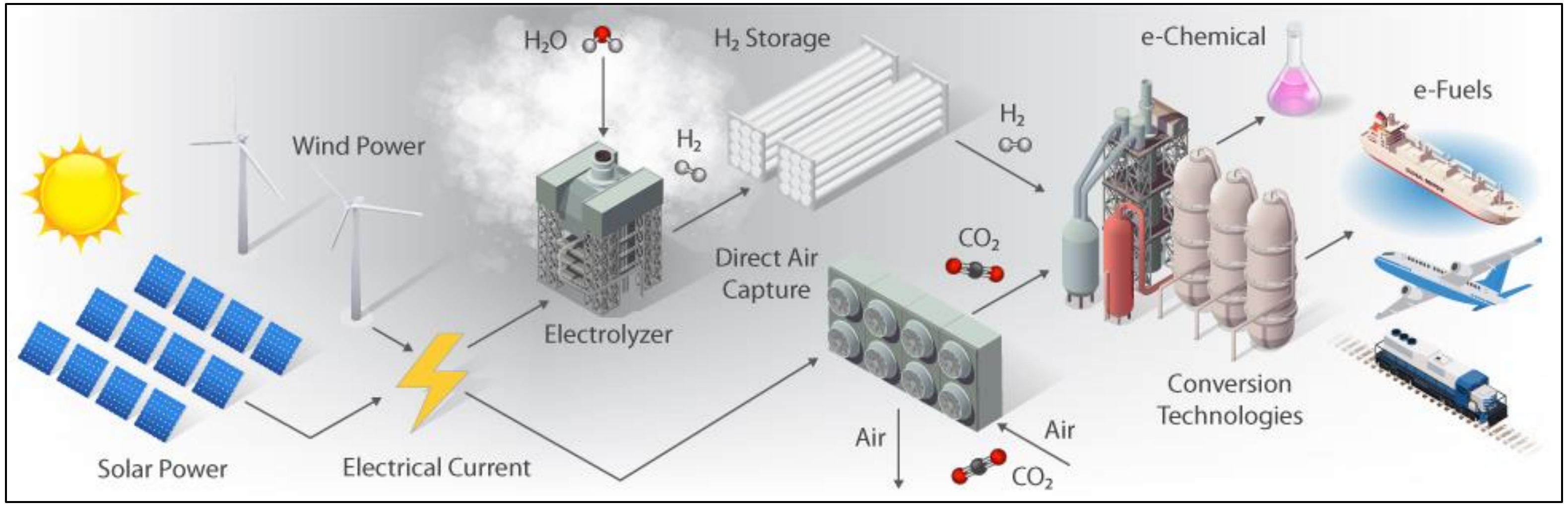
First Generation DAC Technologies – Based on either solid adsorbents or liquid absorbents. Relatively high capital expense and operation expense due to non-optimal materials and process configurations.

Established Conversion Technologies – Based on either methanol conversion technologies or Fischer Tropsch technologies. Require multiple process steps and separations to generate on-spec fuels.

Lack of Integration - No real integrated demonstration projects utilizing renewable electrons, DAC technologies, and conversion technologies to final fuels such as Jet Fuel.

Conceptual E-fuels Production

- Integrated System: Green Electrons, H2 from water, captured CO2 captured, to generated Fuels and Chemicals.
- E-fuels demonstration system would advance direct air capture technologies of CO2, green hydrogen generation technologies, and emerging conversion technologies.



E-Fuels

Initial e-fuels demand could be driven by aviation.

e-fuels will also be used for shipping and rail.

E-chemicals

Potential long-term sink for CO_2.

E-fuels Production Basics

- Depending on the product it is approximately 0.35 kg of H2 and 2.5 kg of CO2 to generate 1 liter of e-fuels.
- Almost all the electricity draw will be at the electrolyzer…. Splitting water takes effort!
- There will of course be electrical demand for pumps and compressors, but they pail in comparison to the electrolyzer..

System Component	Proportion of Electrical need
DAC Unit	7.46%
Electrolyzer	91.40%
RWGS	0.72%
Fischer Tropsch	0.49%

Aviation

Approximately 55% of current U.S. electricity production needed to displace 100% of U.S. jet fuel consumption with e-fuels

Shipping

IEA estimates that around 70 million tonnes of either ammonia or methanol — requiring between 12.6 million and 14 million tonnes of H2 — would be required to make up a 10% share of fuels in the maritime sector by 2030*

*IEA recent report, *The Role of E-Fuels in Decarbonizing Transport*

Conclusions and Key Insights

U.S. IRA policy is a game changer for H2 production.

- Behind the meter, integrated H2 systems qualify for the full clean 45V H_2 \$3/kg credit.
- Absent H2 pipelines…
- H2 storage cost is a potential barrier to industrial decarbonization.

H2 storage plays the key role to buffer between low-cost, clean H2 production from renewables and steady state industrial end uses (iron/steel, e-fuels, etc.)

Renewable resource and industry end use drive required H_2 storage capacity.

Current bulk H2 storage costs range between ~\$0.02/kg (salt caverns) and ~\$2.93/kg (pressure vessel storage).

Low-cost, bulk H2 storage technologies that are ~4x salt caverns is needed for regions that don’t have access to geological storage.

Acknowledgements

NREL Transforming ENERGY

Elenya Grant
Steve Hammond
Jen King
Masha Koleva
Matt Kotarbinski
Evan Reznicek

Argonne NATIONAL LABORATORY

Amgad Elgowainy
Kyuha Lee
Pingping Sun

BERKELEY LAB

Hanna Breunig
Fabian Rosner

OAK RIDGE National Laboratory

Madhu Chinthavali
Joao Pinto

Sandia National Laboratories

Brian Ehrhart
Myra Blalock

Work presented here funded by HFTO and WETO

Open Discussion

www.nrel.gov

Photo from iStock-627281636

NREL
Transforming ENERGY

FEBRUARY 21, 2024

PRESENTATION AT CLEAN ENERGY SOLUTIONS CENTER WEBINAR

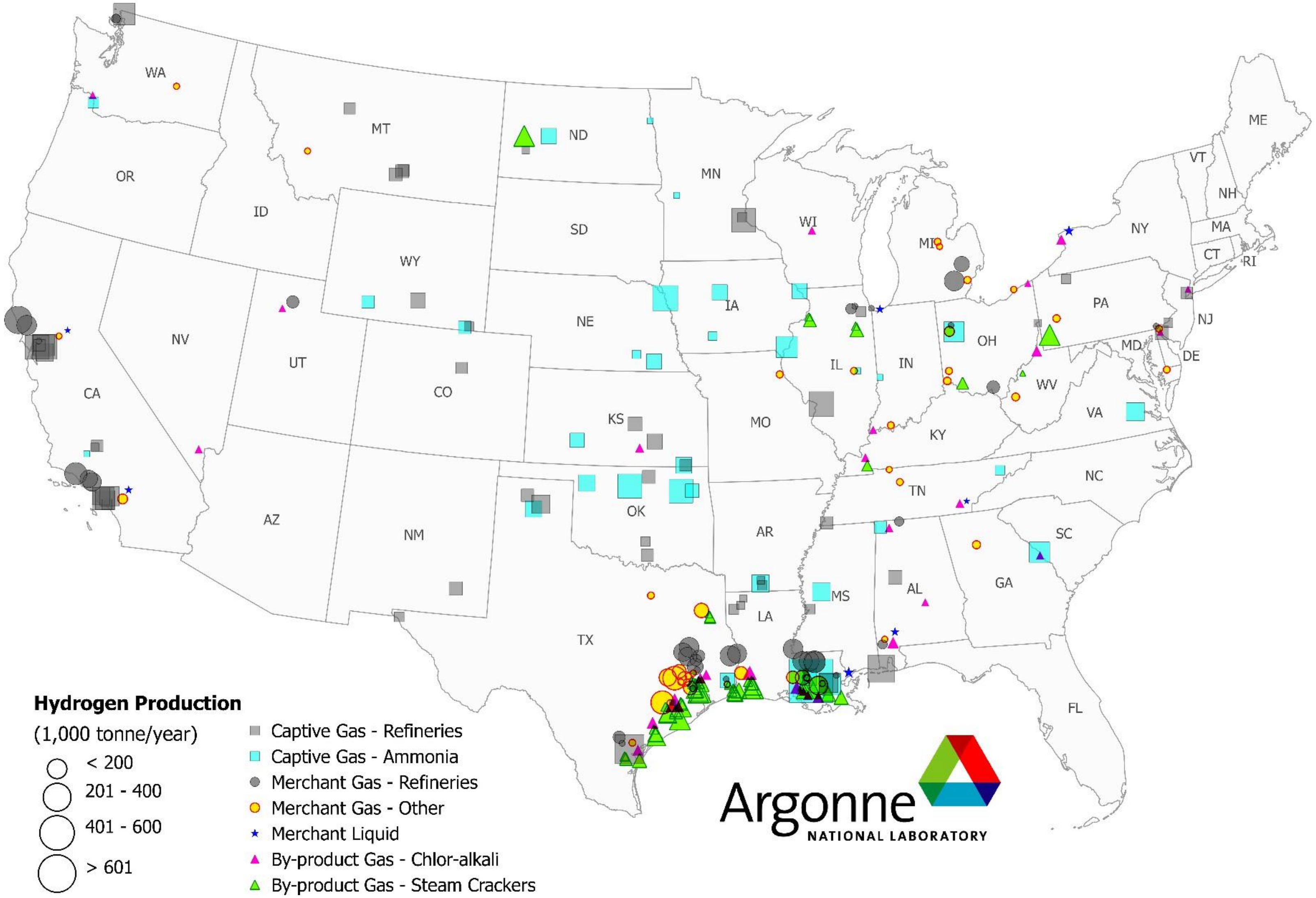
GREET® Environmental Analysis of Current and Future Hydrogen Production and Utilization in the United States

Pingping Sun, PhD

Hydrogen and Electrification Analysis Group Leader

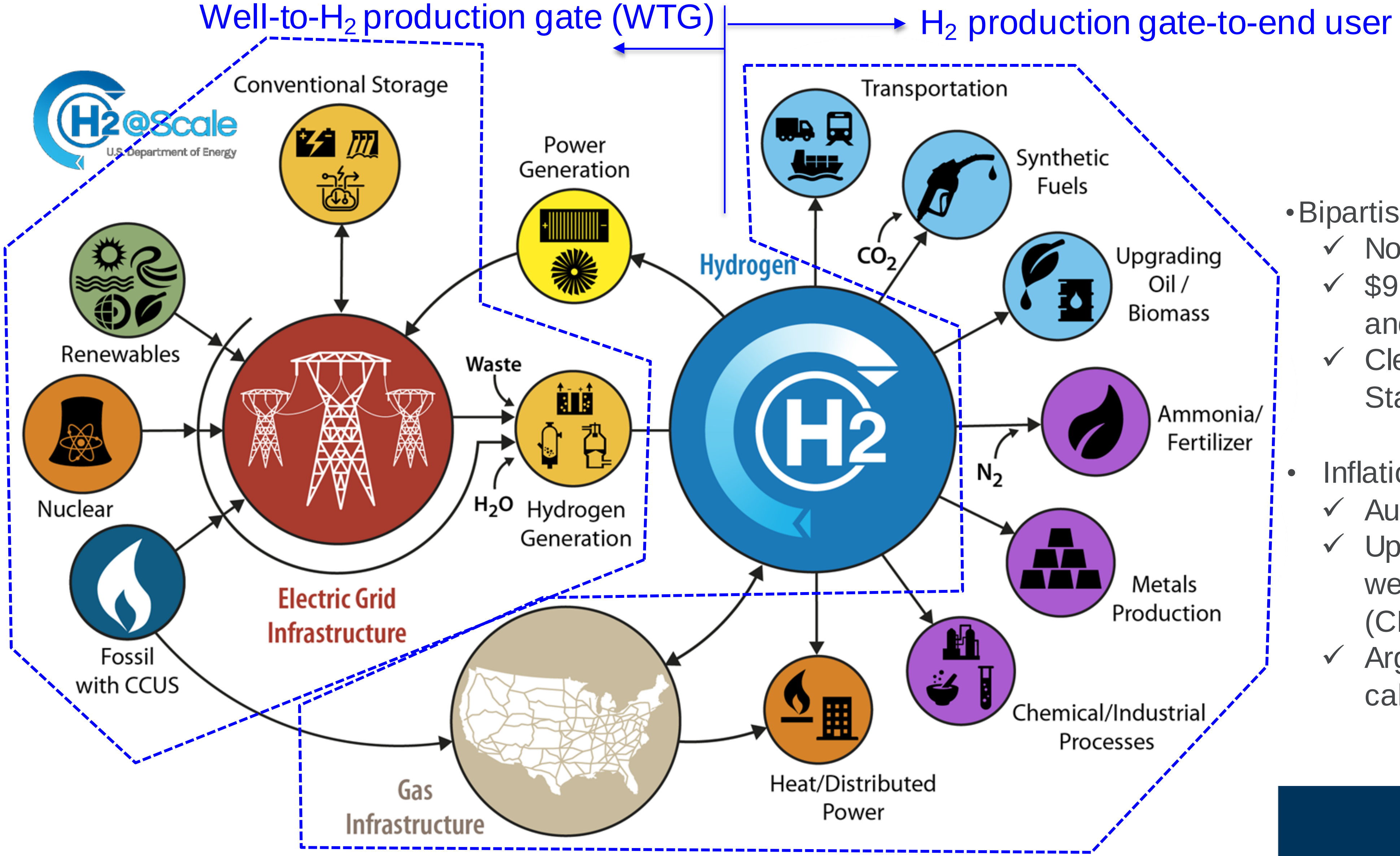
Argonne National Laboratory

Today, more than 10M metric tons of hydrogen are produced in the U.S. annually, mainly from steam methane reforming of natural gas



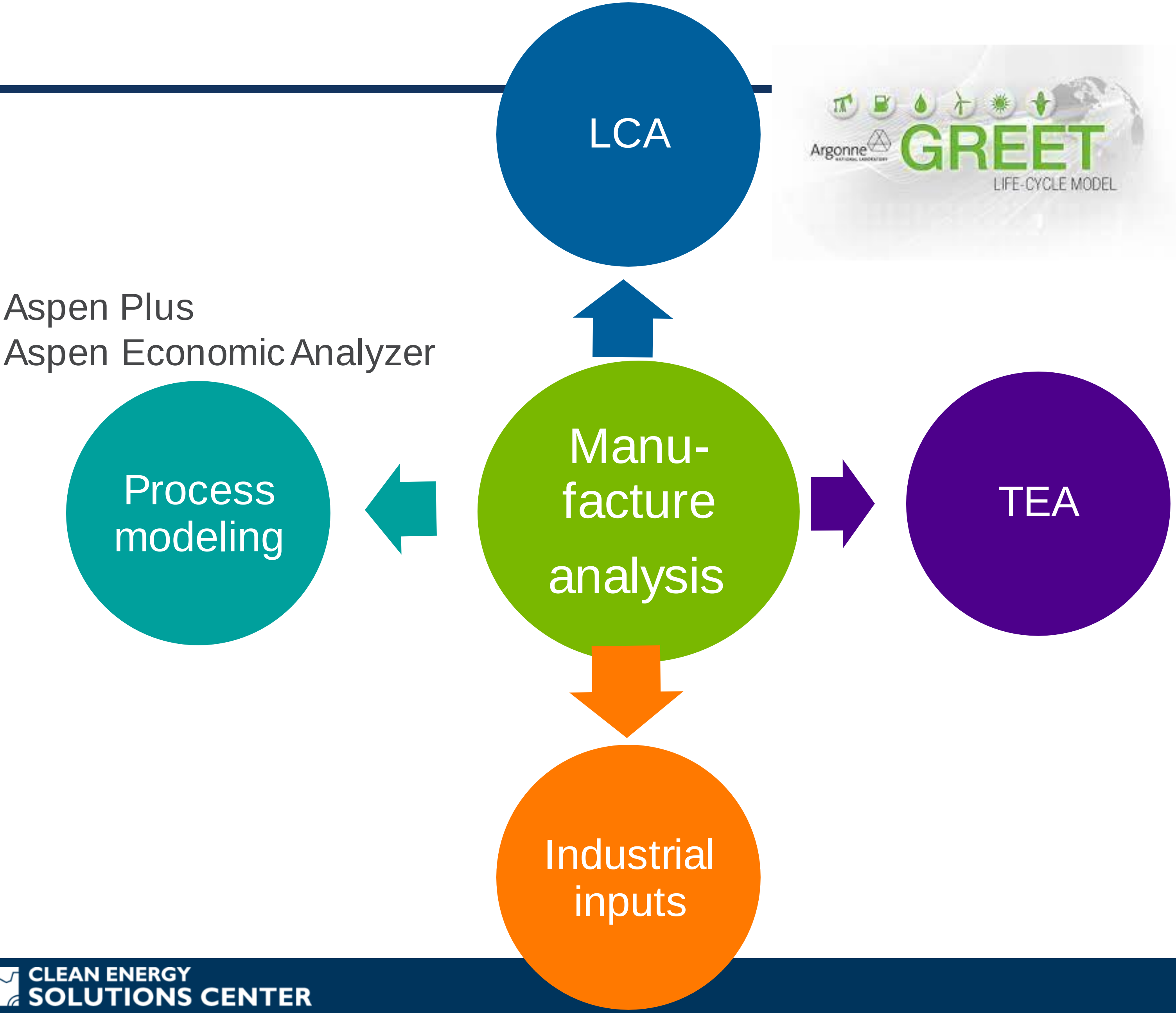
Argonne NATIONAL LABORATORY

H2@Scale is a DOE initiative that identifies pathways for production and utilization of clean H_2



- Bipartisan Infrastructure Law (BIL)
  - ✓ November 2021
  - ✓ \$9.5B for clean H_2 production and deployment
  - ✓ Clean Hydrogen Production Standard (<4 $kgCO_{2e}/kg_{H2}$)
- Inflation Reduction Act (IRA)
  - ✓ August 2022
  - ✓ Up to \$3/kg credit based on H_2 well-to-gate carbon intensity (CI)
  - ✓ Argonne GREET model for CI calculations

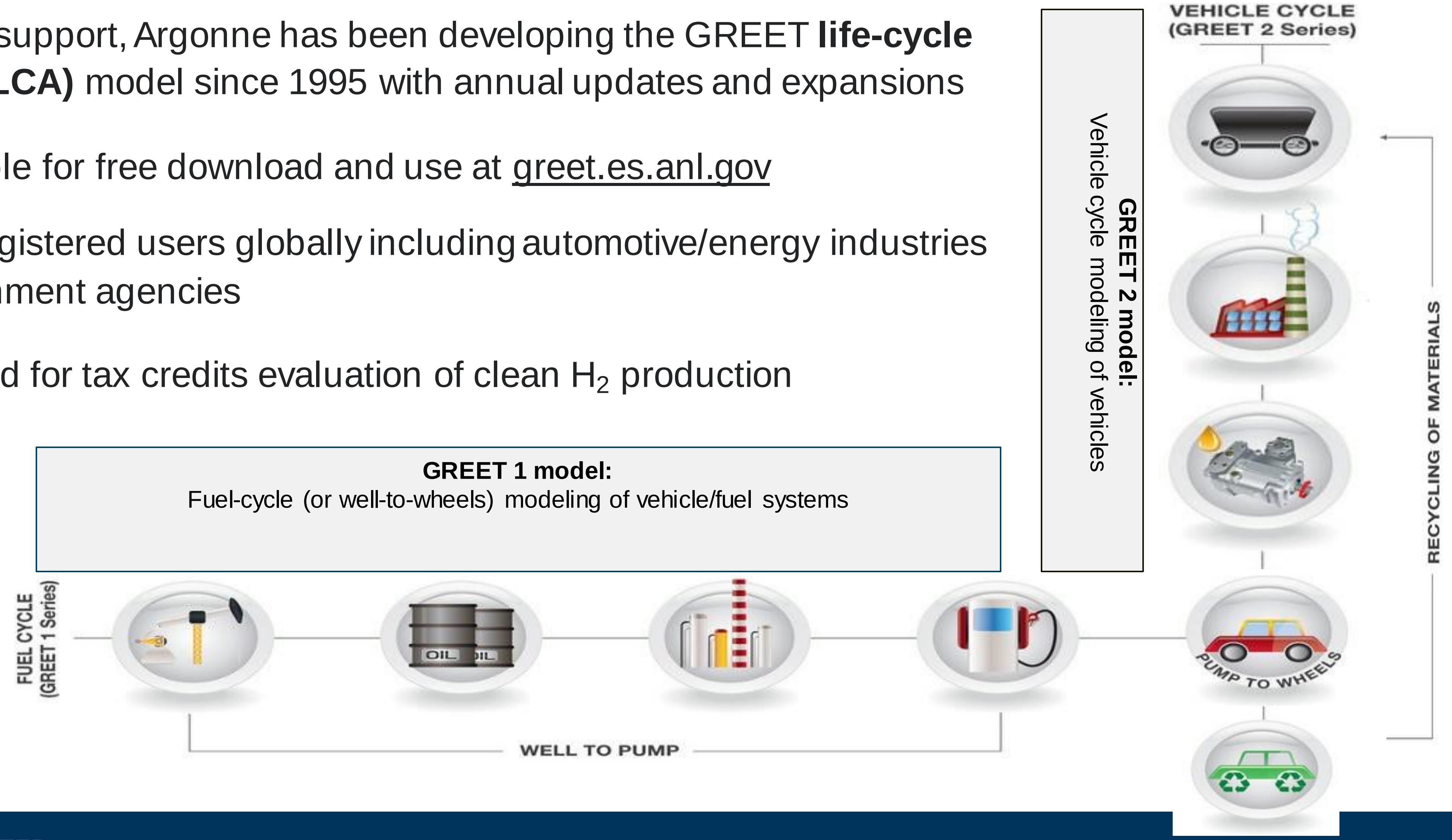
Decarbonization analysis tool



- Industrial decarbonization is analyzed TEA and LCA, based on process modeling and industrial inputs.
- Process modeling provides energy and emission profiles based on thermodynamics, kinetics, engineering principals, etc.
- Deep understanding of manufacture process and technology is the key to identify decarbonization potential with the consideration of feasibility and economics.

The GREET® (<u>G</u>reenhouse gases, <u>R</u>egulated <u>E</u>missions, and <u>E</u>nergy use in <u>T</u>echnologies) model

- With DOE support, Argonne has been developing the GREET **life-cycle analysis (LCA)** model since 1995 with annual updates and expansions
- It is available for free download and use at <u>greet.es.anl.gov</u>
- >55,000 registered users globally including automotive/energy industries and government agencies
- Will be used for tax credits evaluation of clean H_2 production



GREET 1 model:
Fuel-cycle (or well-to-wheels) modeling of vehicle/fuel systems

GREET 2 model:
Vehicle cycle modeling of vehicles

GREET sustainability metrics include energy use, criteria air pollutants, GHG, and water consumption

Energy use

- Total energy: fossil energy and renewable energy
- Fossil energy: petroleum, natural gas, and coal
- Renewable energy: biomass, nuclear energy, hydro-power, wind power, and solar energy

Resource availability and energy security

Air pollutants

- VOC, CO, NOx, PM_{10}, $PM_{2.5}$, and SOx
- Estimated separately for total and urban (a subset of the total) emissions

Human health and environmental justice

Greenhouse gases

- CO_2, CH_4, N_2O, black carbon, and albedo
- CO_{2e} of the five (with their global warming potentials)

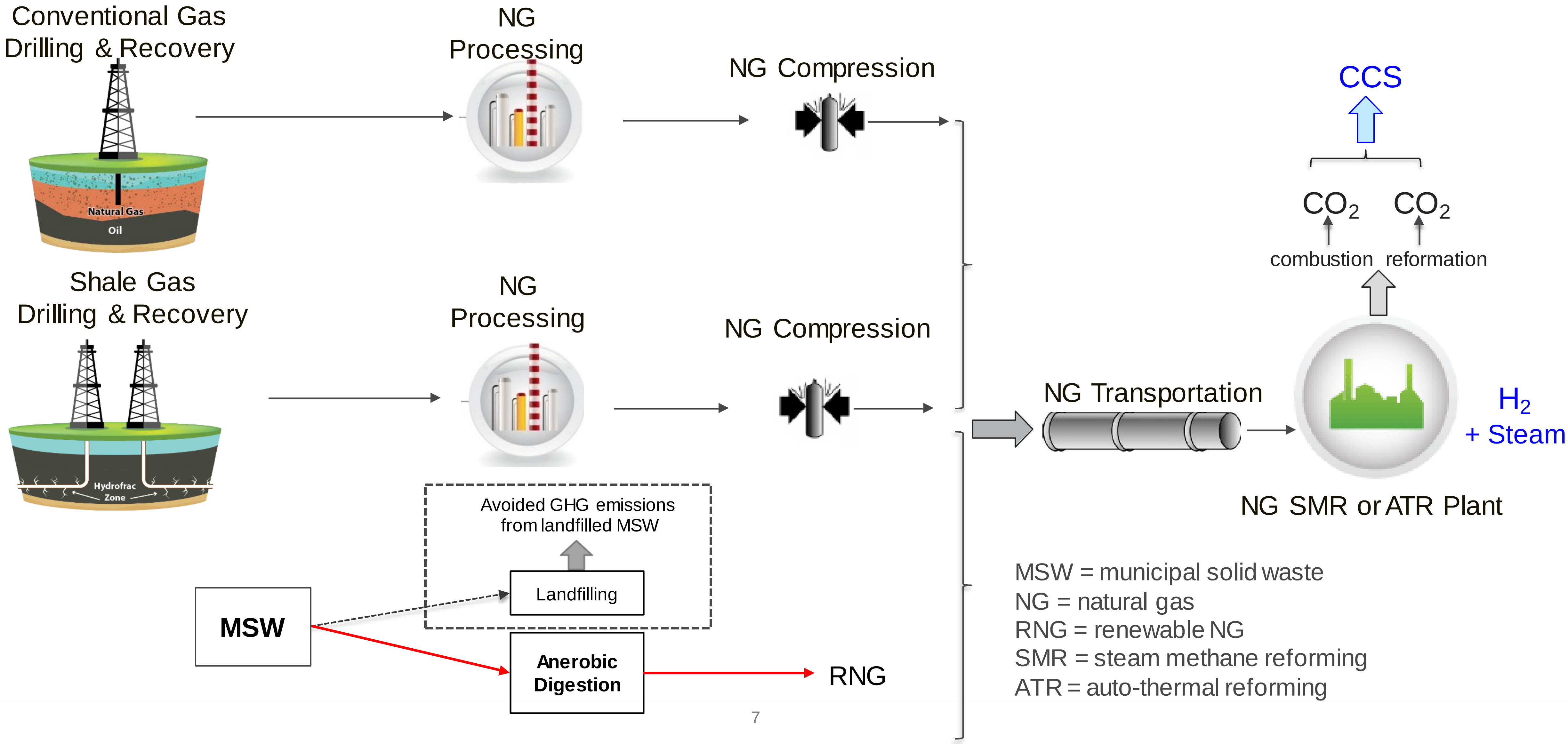
Global warming impacts

Water consumption

- Addressing water supply and demand (energy-water nexus)

Regional/seasonal water stress impacts

Hydrogen production via CH_4 reforming, w/ and w/o CCS



Conventional Gas Drilling & Recovery

Natural Gas

Oil

NG Processing

NG Compression

Shale Gas Drilling & Recovery

Hydrofrac Zone

NG Processing

NG Compression

Avoided GHG emissions from landfilled MSW

Landfilling

MSW

Anerobic Digestion

RNG

NG Transportation

CCS

CO_2 CO_2

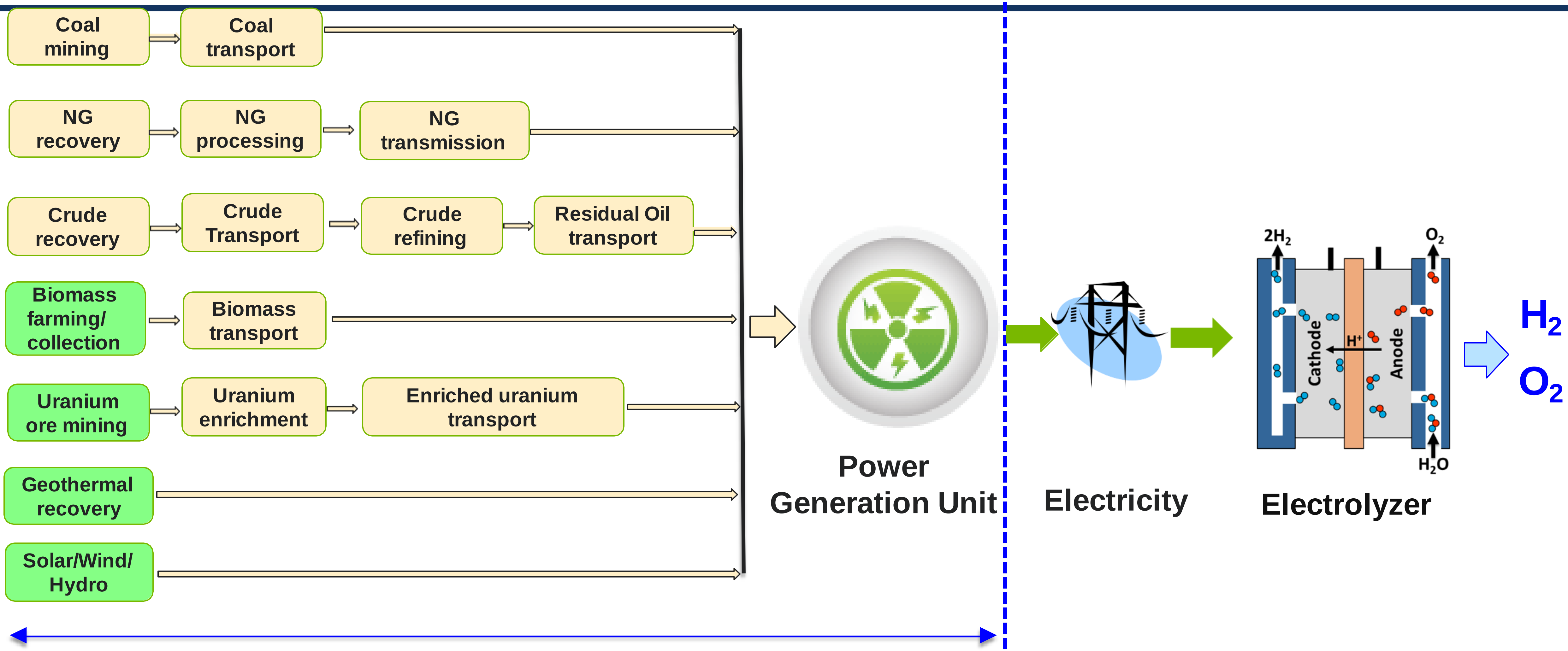
combustion reformation

H_2 + Steam

NG SMR or ATR Plant

MSW = municipal solid waste
NG = natural gas
RNG = renewable NG
SMR = steam methane reforming
ATR = auto-thermal reforming

Hydrogen production via water electrolysis



Coal mining → Coal transport

NG recovery → NG processing → NG transmission

Crude recovery → Crude Transport → Crude refining → Residual Oil transport

Biomass farming/ collection → Biomass transport

Uranium ore mining → Uranium enrichment → Enriched uranium transport

Geothermal recovery

Solar/Wind/ Hydro

Power Generation Unit

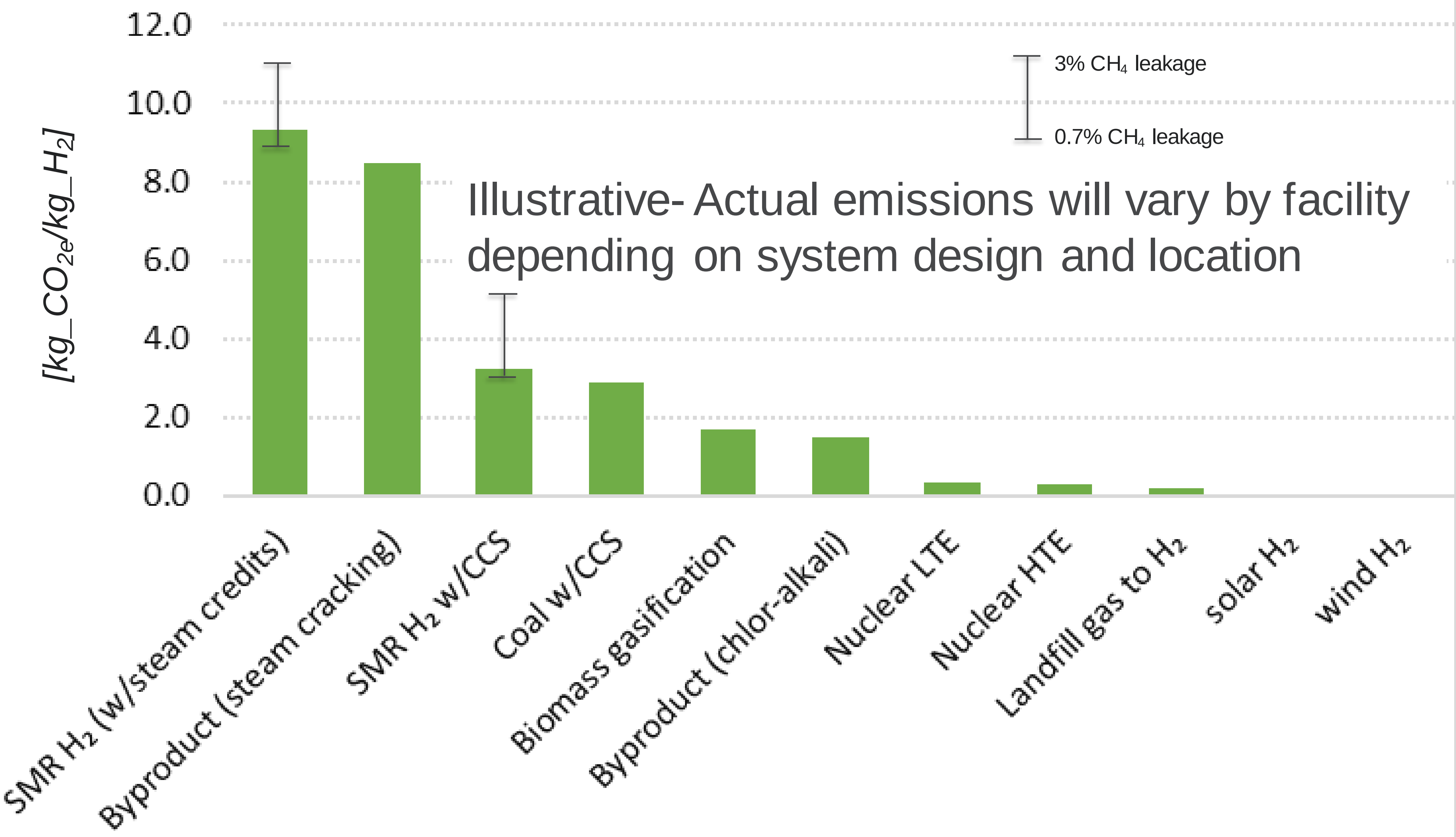
Electricity

Electrolyzer

Emission sources Upstream of Electrolyzer

Well-to-gate (WTG) GHG emissions of hydrogen production pathways

SMR= Steam Methane Reforming;
CCS=Carbon Capture and Sequestration;
LTE=Low-Temp Electrolysis;
HTE=High-Temp Electrolysis;
LFG=Landfill Gas



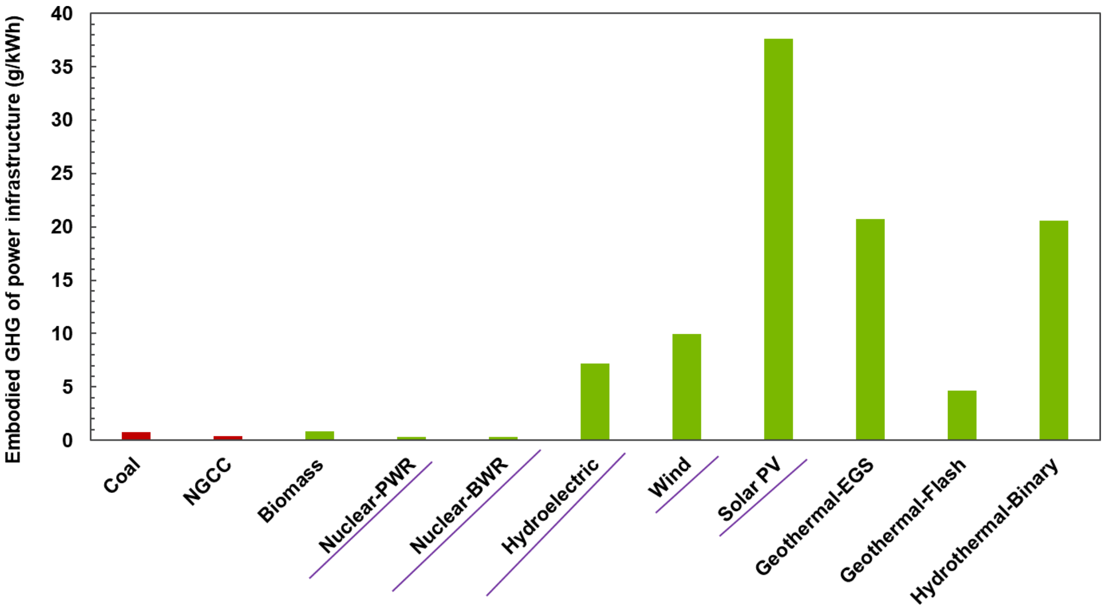
Illustrative- Actual emissions will vary by facility depending on system design and location

https://greet.es.anl.gov/files/hydrogenreport2022

CLEAN ENERGY SOLUTIONS CENTER
ASSISTING COUNTRIES WITH CLEAN ENERGY POLICY

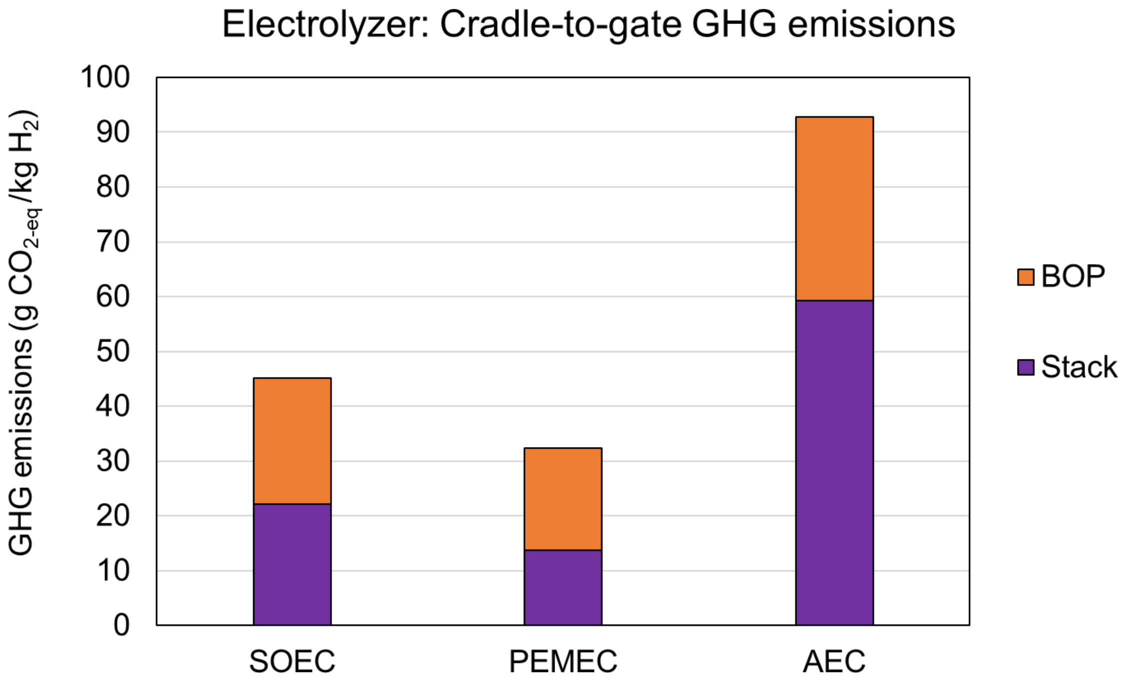
Embodied emissions of power generation CapEx is important for H_2 production via electrolysis

- ***Analyze emissions from renewable and nuclear power infrastructure manufacturing and construction, and associated upstream material production***
  - ➢ Reflect recent progress in renewable power technologies
  - ➢ Analyze key parameters affecting lifetime electricity generation
  - ➢ Compare embodied emissions of different power generation technologies (in functional unit of per kWh electricity generated)



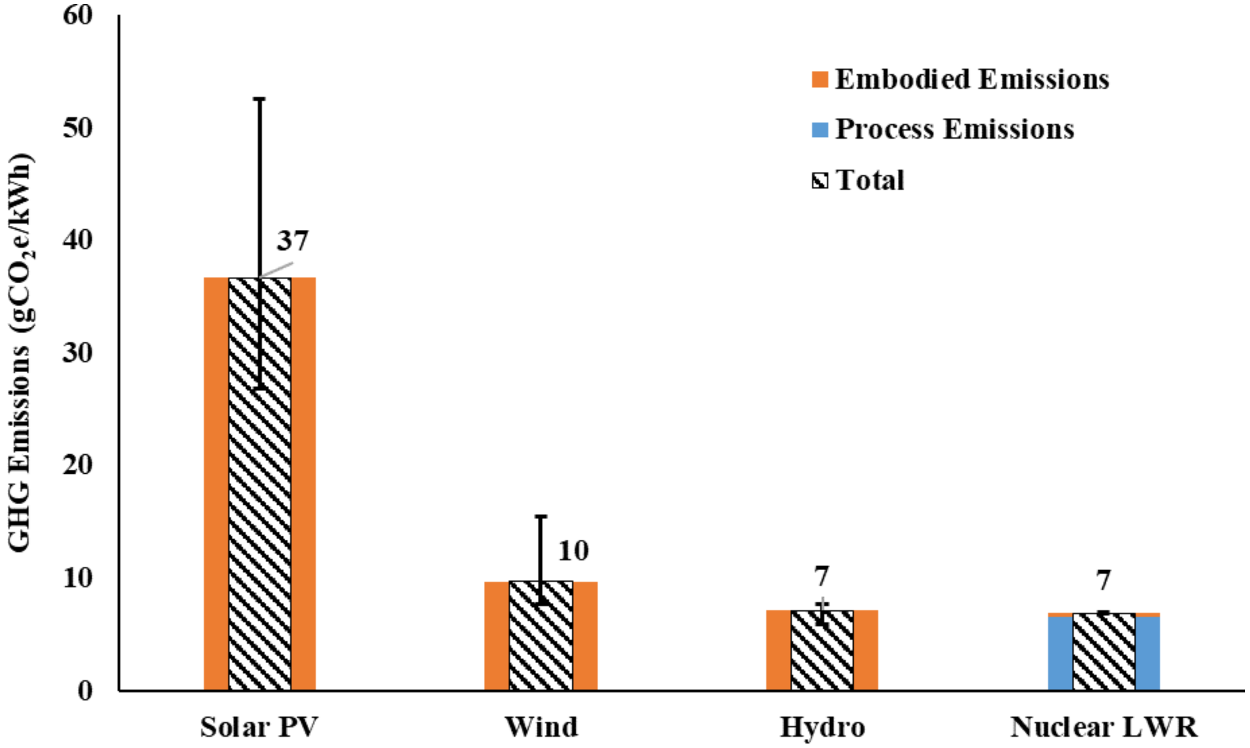
- ***Incorporate embodied emissions analysis of power infrastructure in GREET***

CapEx embodied GHG emissions of low-carbon power generators and water electrolyzers



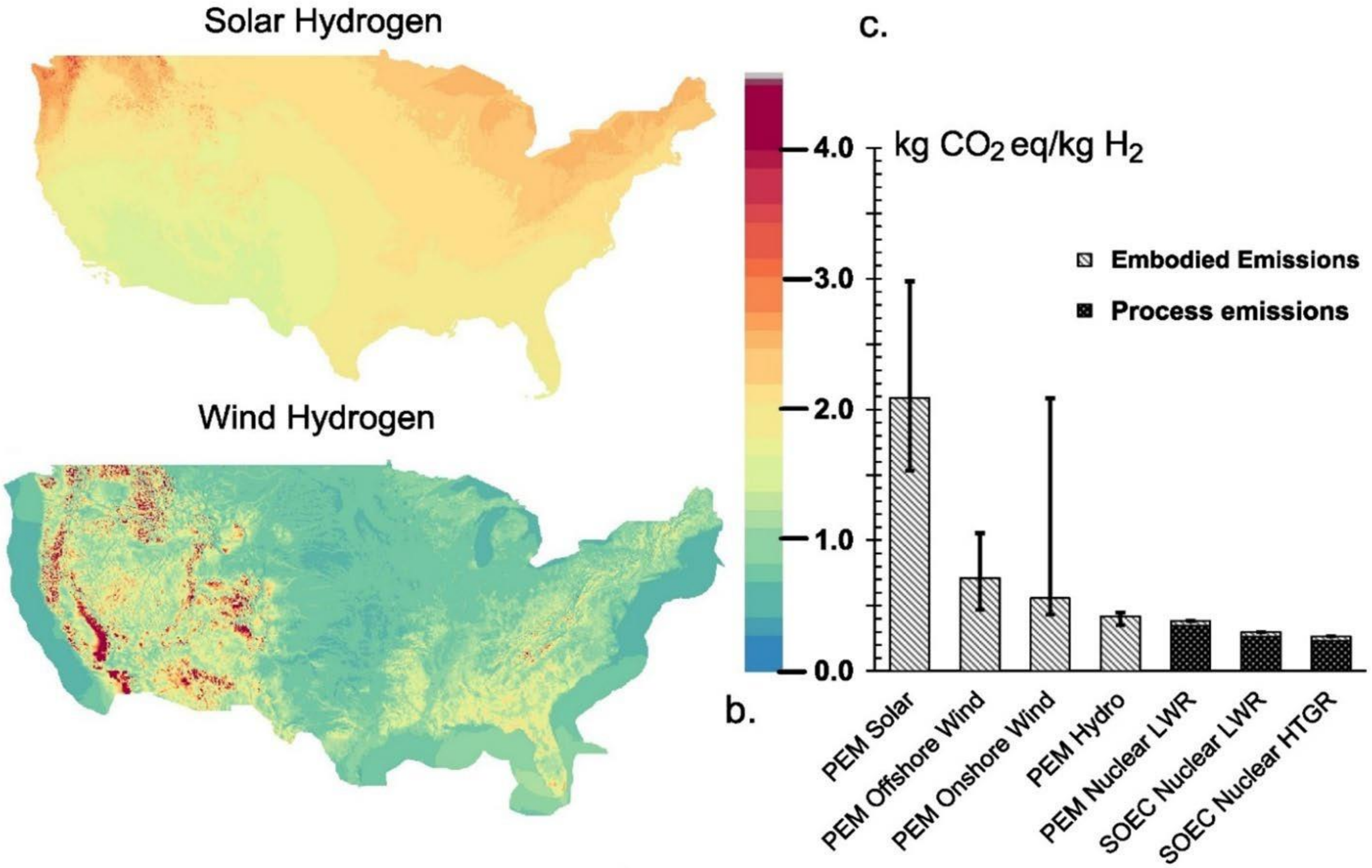
SOEC=Solid Oxide Electrolysis Cell
PEMEC=Polymeric Exchange Membrane Electrolysis Cell
AEC=Alkaline Electrolysis Cell

Embodied GHG emissions of different electricity infrastructure (per kWh of electricity)



Publications forthcoming

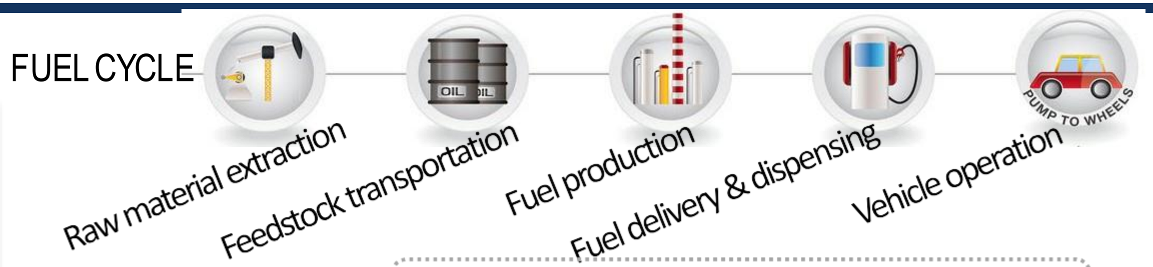
Impact of CapEx embodied GHG emissions on renewable H_2 production



Publications forthcoming

GREET evaluates heavy-duty trucks Well-to-Wheels (WtW) emissions for various vehicle classes and powertrain technologies

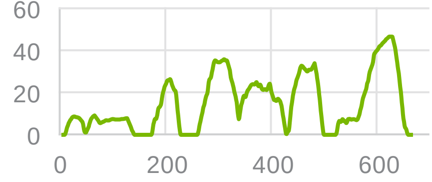
GREET LIFE-CYCLE MODEL



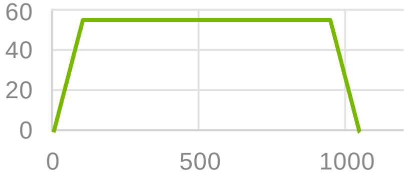
MHDV module

Fuel economy (FE)	Air emissions
○Autonomie	○EPA MOVES

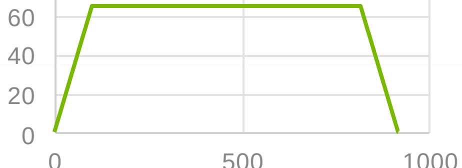
→ Well-to-Wheels (WTW) Analysis



ARB Transient Cycle



55 MPH Cycle



65 MPH Cycle

AUTONOMIE

Provide FE for the three driving cycles

Non-idle →

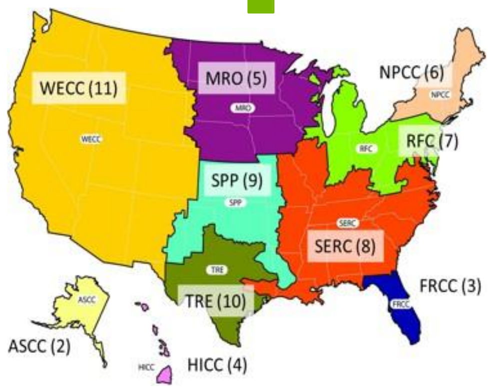
Fleet DNA

Idle ↓

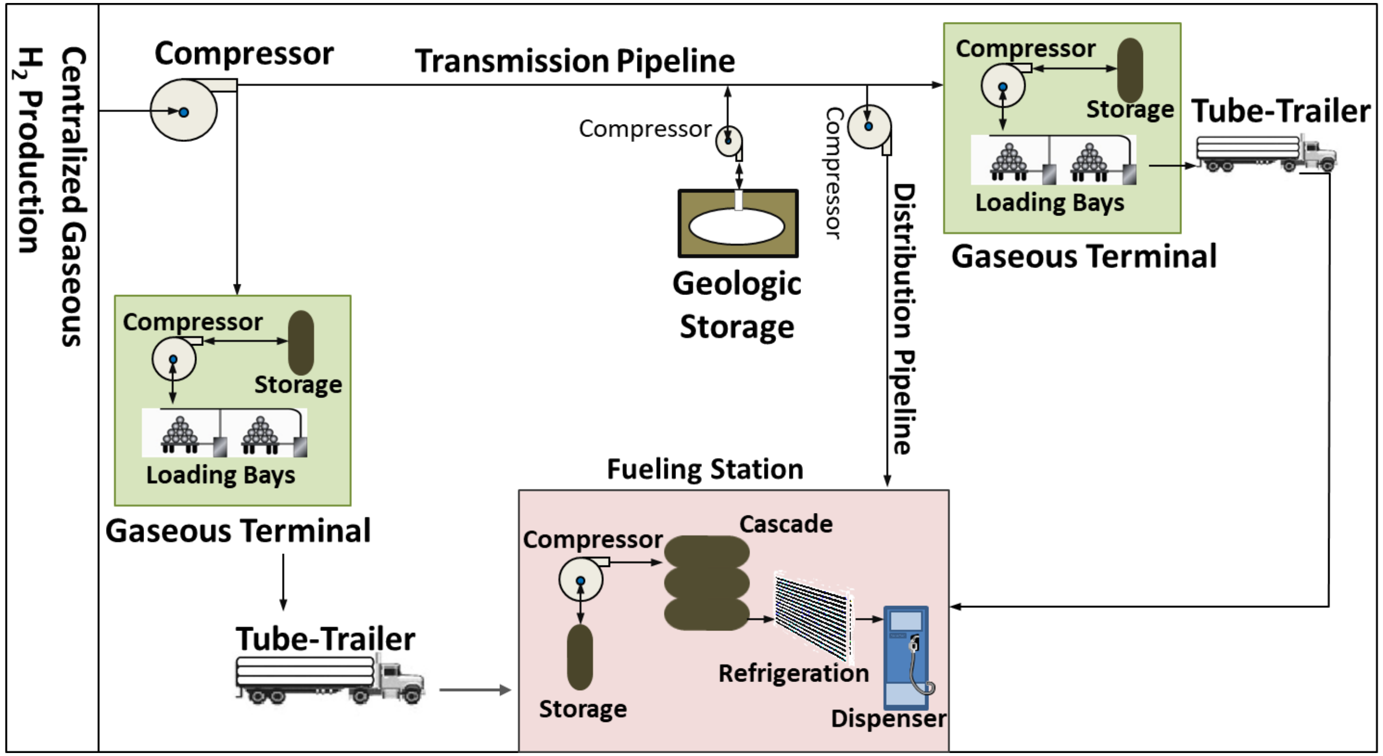
Composite FE

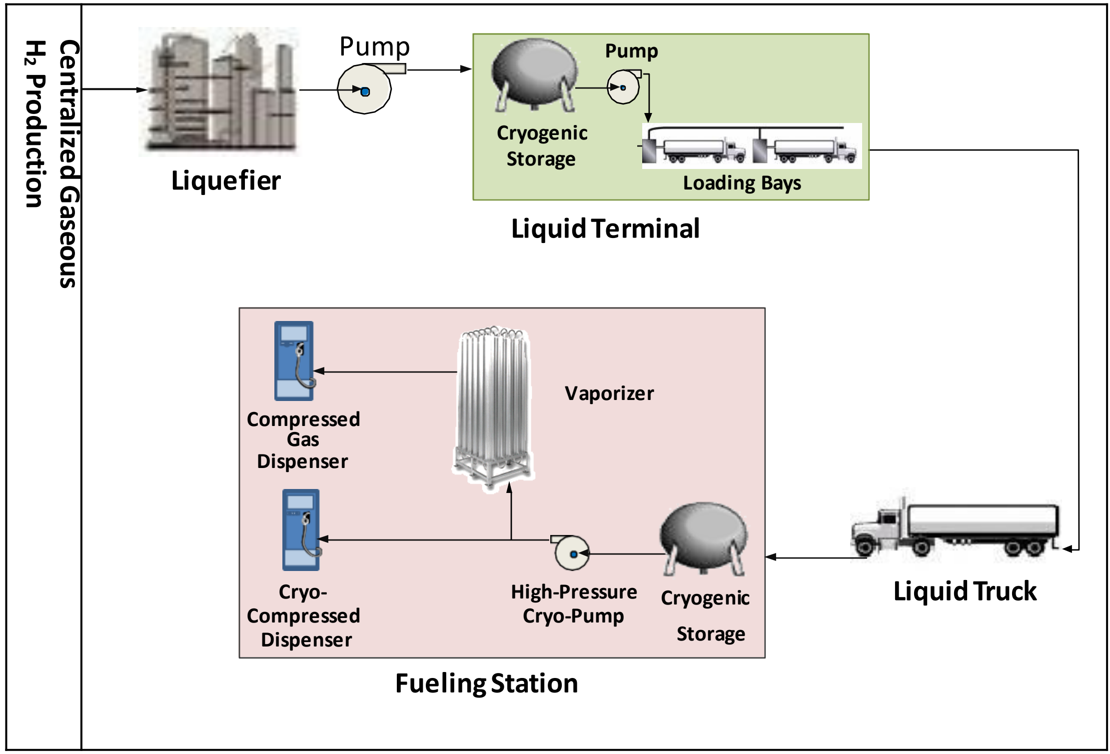
→ GREET LIFE-CYCLE MODEL

MOVES Motor Vehicle Emission Simulator

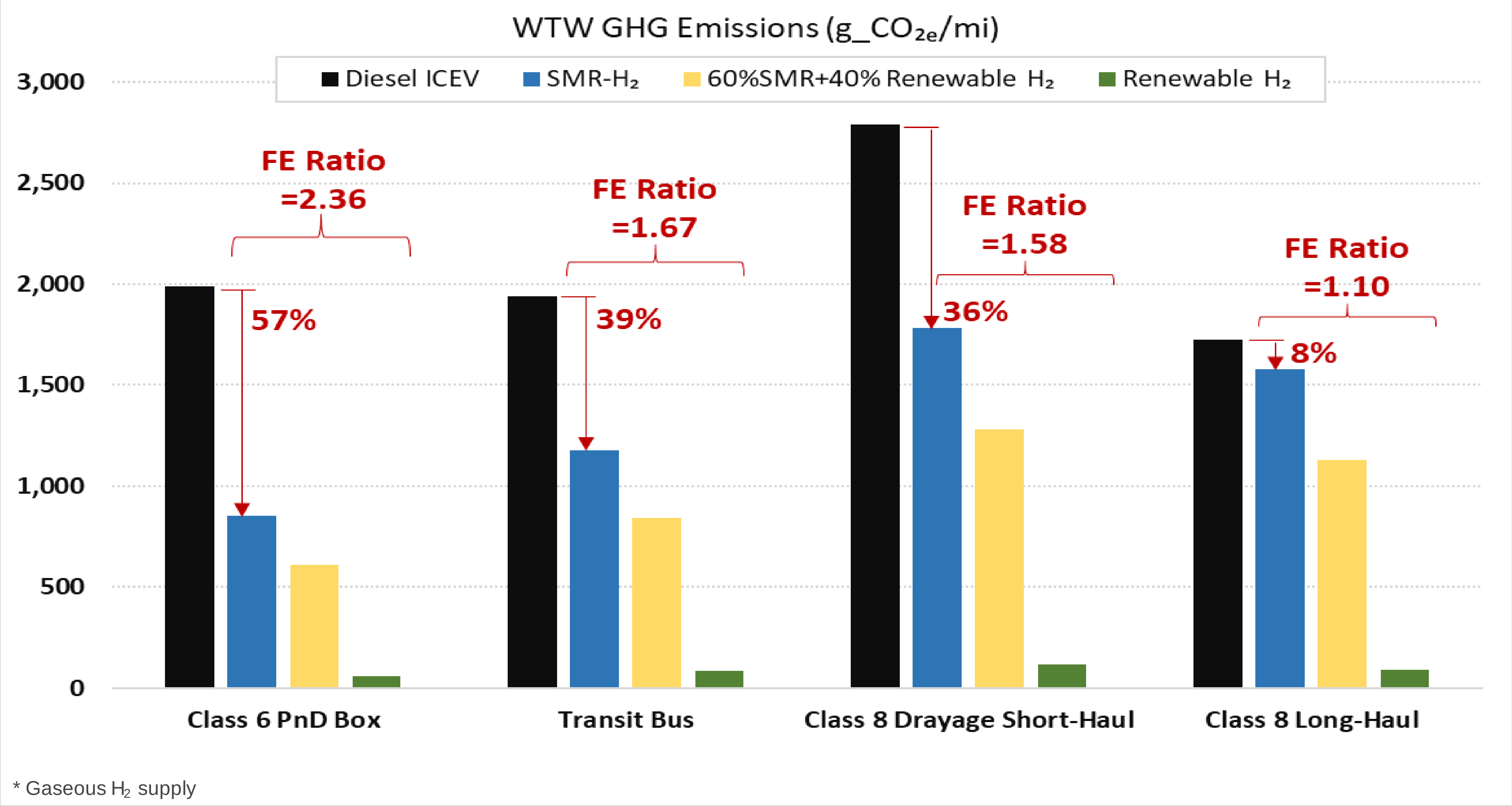


Hydrogen delivery involves energy intensive processes such as compression, liquefaction and trucking





WtW GHG emissions of SMR-H_2 relative to diesel varies by fuel economy ratio of FCEVs with conventional ICEVs (results shown for gaseous H_2 delivery)



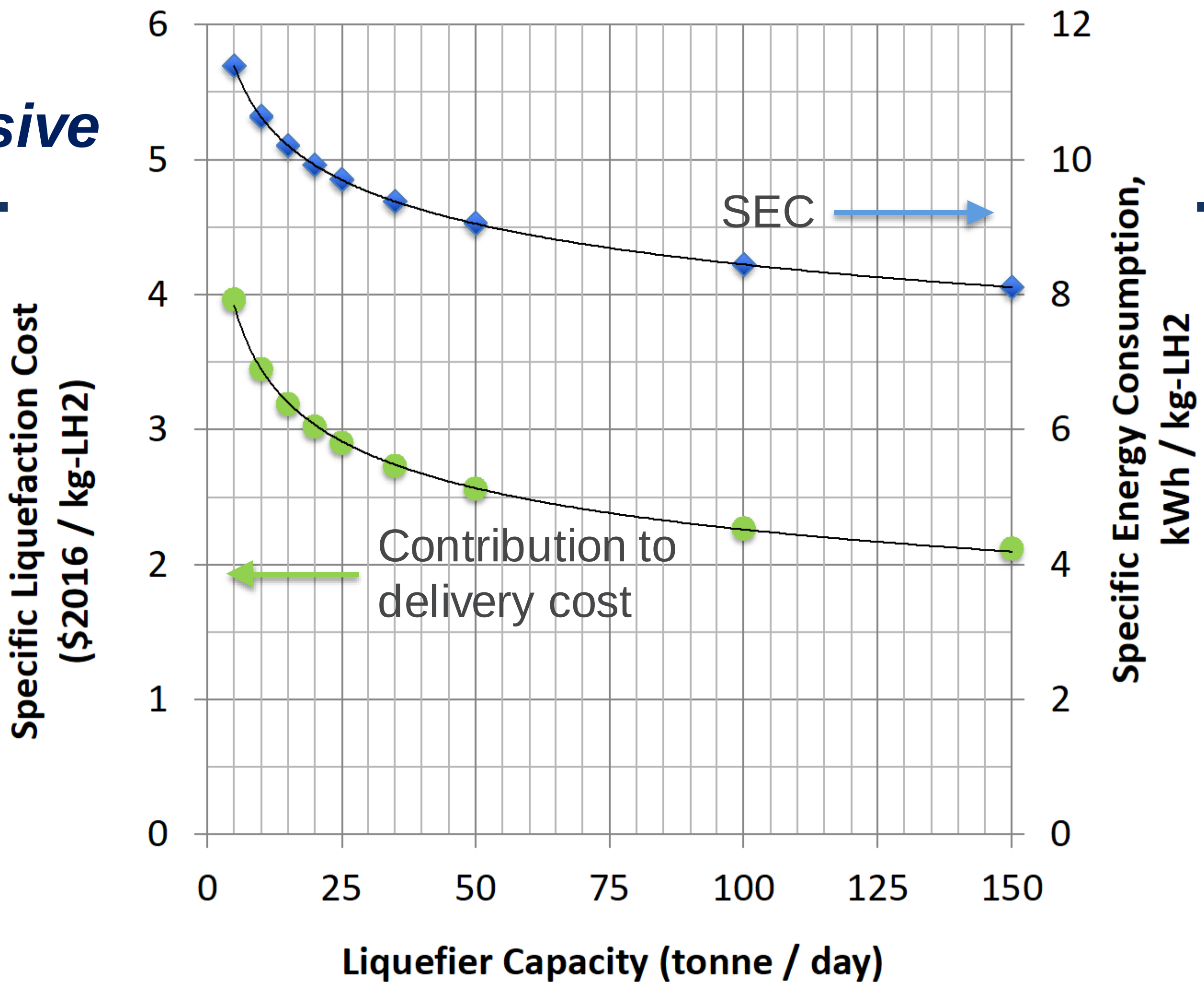
* Gaseous H_2 supply

✓WTW: Well-To-Wheels ✓GHG: Greenhouse Gas ✓FE: Fuel Economy ✓SMR: Steam Methane Reforming

https://www.sciencedirect.com/science/article/pii/S0378775318304737

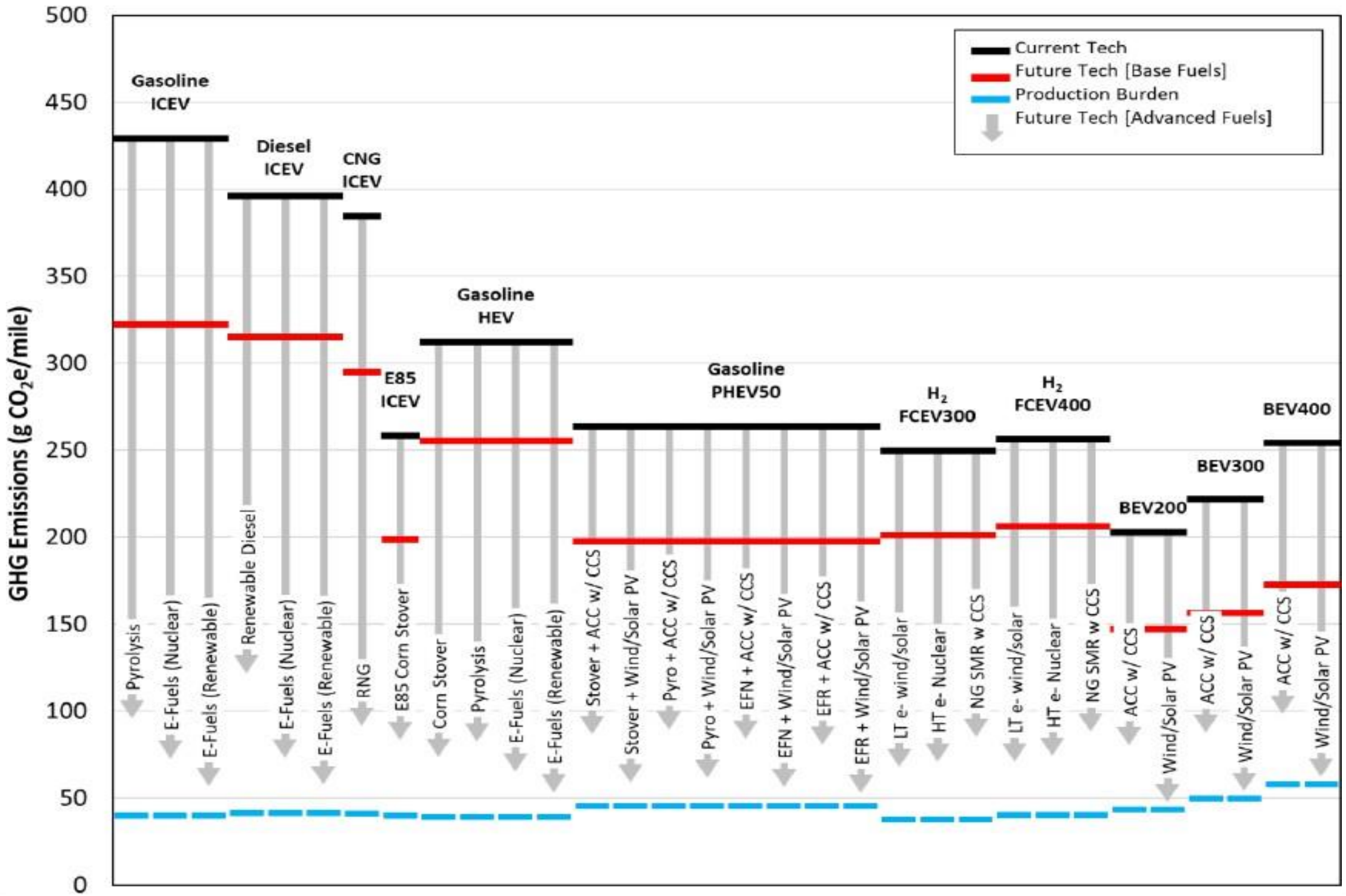
H_2 liquefaction is energy and cost intensive

- Scaling laws based on aggregation of industry input
  - Liquefier CAPEX
  - Specific energy consumption (*SEC*)
- Modeling and analysis in the literature suggest SEC can potentially be as low as 6 kWh/kg
- *SLC* – Specific liquefaction cost



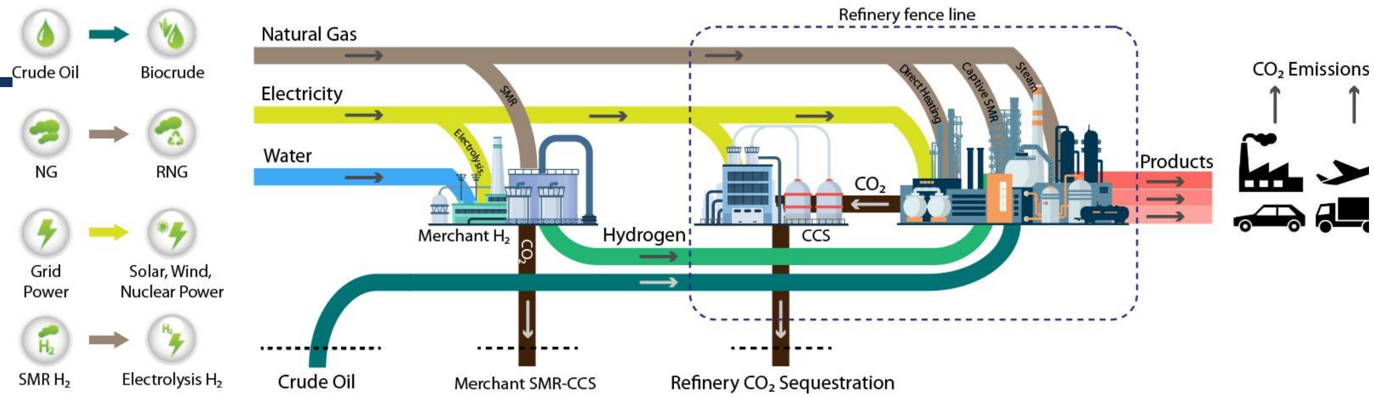
Delivered	Liquefier	SLC	SEC	GHG Emissions 2021 (US mix)
	5 tpd	$4.0 / kg-LH2	11 kWh / kg	4.8 $kgCO_{2e}$ / kgH_2
30 tpd	33 tpd	**$2.8 / kg-LH2**	**9.4 kWh / kg**	**4.1 $kgCO_{2e}$ / kgH_2**
120 tpd	130 tpd	**$2.1 / kg-LH2**	**8.2 kWh / kg**	**3.6 $kgCO_{2e}$ / kgH_2**

Cradle-to-Grave (C2G) includes both WtW and vehicle manufacturing emissions



https://greet.anl.gov/publication-c2g_lca_us_ldv

Refinery CO_2 reduction opportunities



- Refinery CO_2 emission is intensive, owing to extensive combustions at various supply stages.
- Decarbonization opportunities exist for onsite emission, WTG and WTW.
  - Switching fossil-based energy sources to renewable or low carbon sources, e.g. switching NG and grid electricity to RNG and clean electricity.
  - Implementing CO_2 capture and storage.
  - Replacing or blending crude oil with fungible biocrude or low carbon crude oil.


Environmental Science & Technology

pubs.acs.org/est

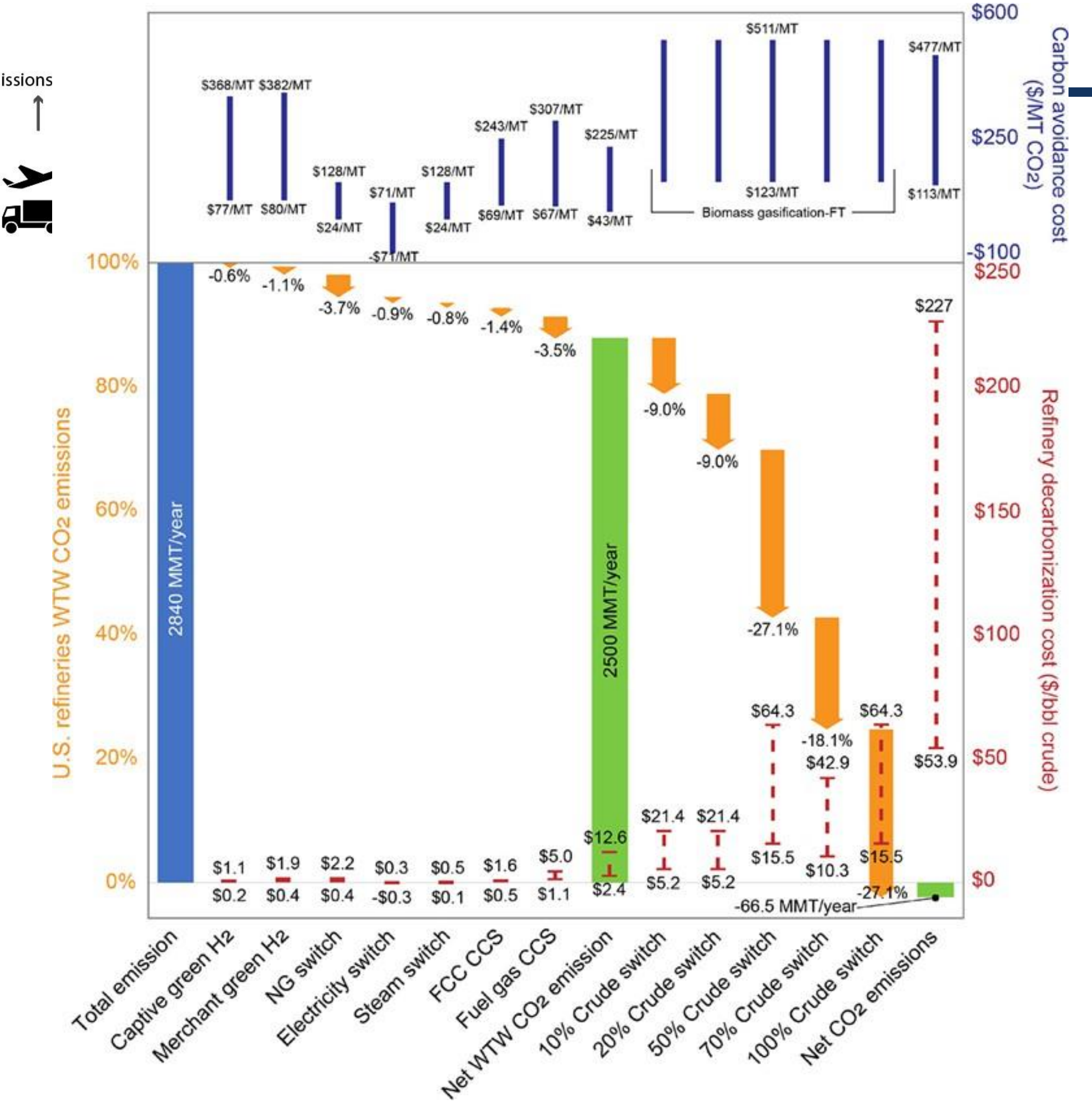
Article

An Analysis of the Potential and Cost of the U.S. Refinery Sector Decarbonization

Pingping Sun,* Vincenzo Cappello, Amgad Elgowainy, Pradeep Vyawahare, Ookie Ma, Kara Podkaminer, Neha Rustagi, Mariya Koleva, and Marc Melaina

Cite This: *Environ. Sci. Technol.* 2023, 57, 1411−1424

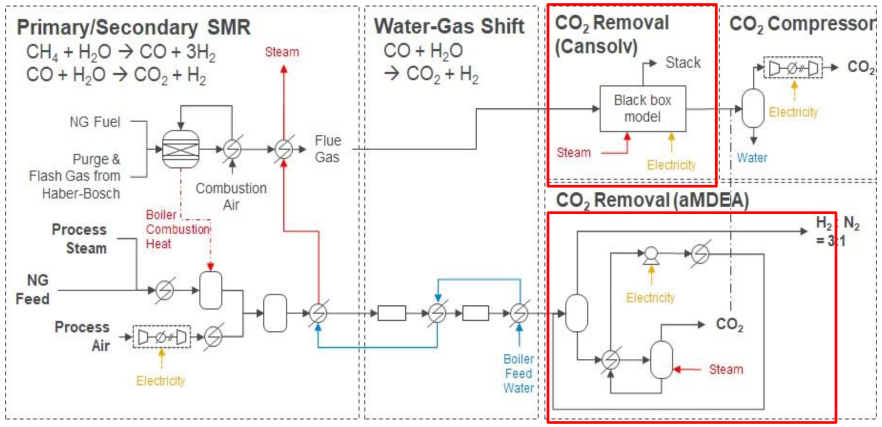
Read Online



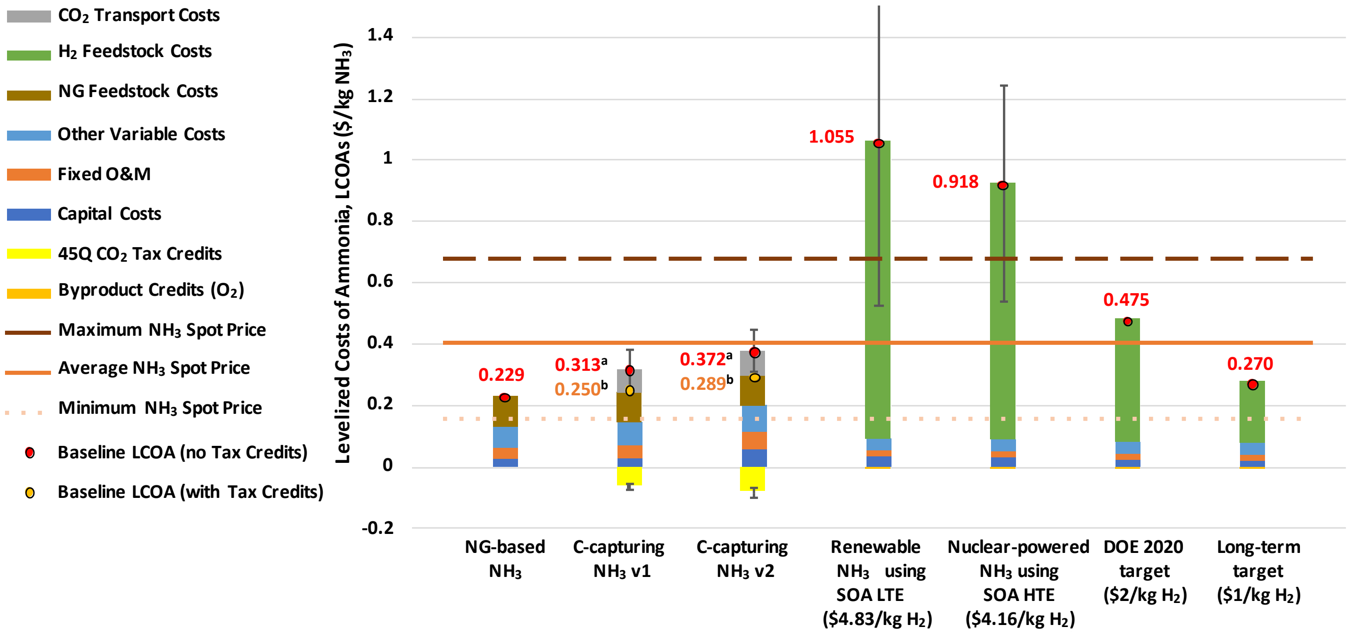
U.S. refinery decarbonization potential based on 2019 refinery operation data

Ammonia as fertilizer, fuel and H_2 carrier

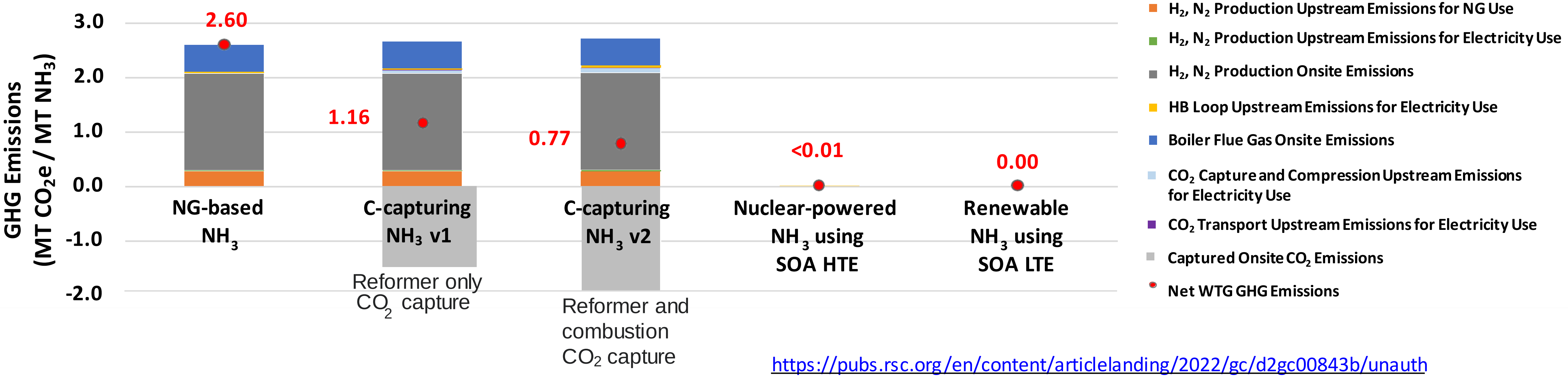
- Ammonia production process modeling



- Techno-economic analysis

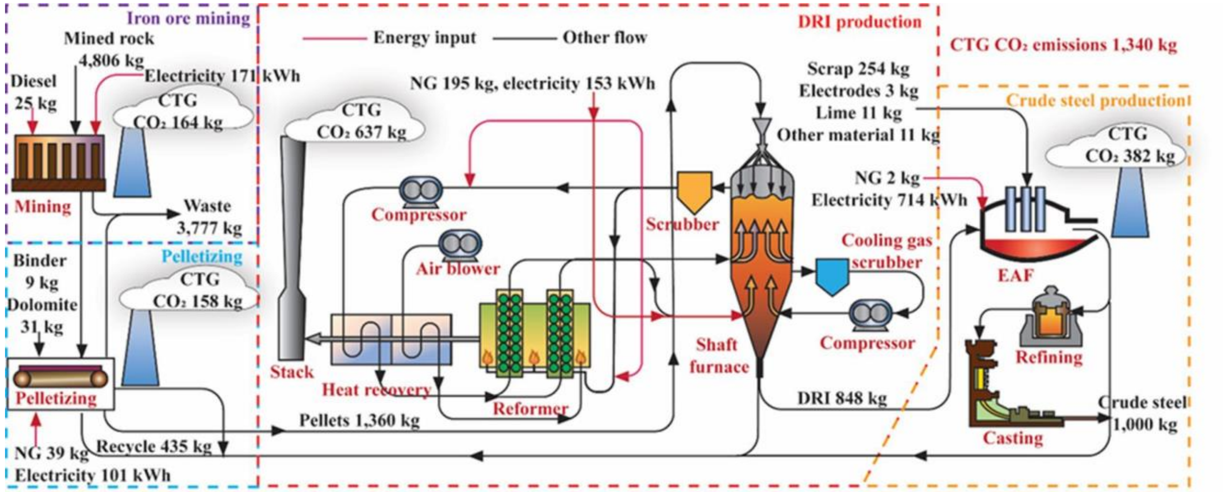


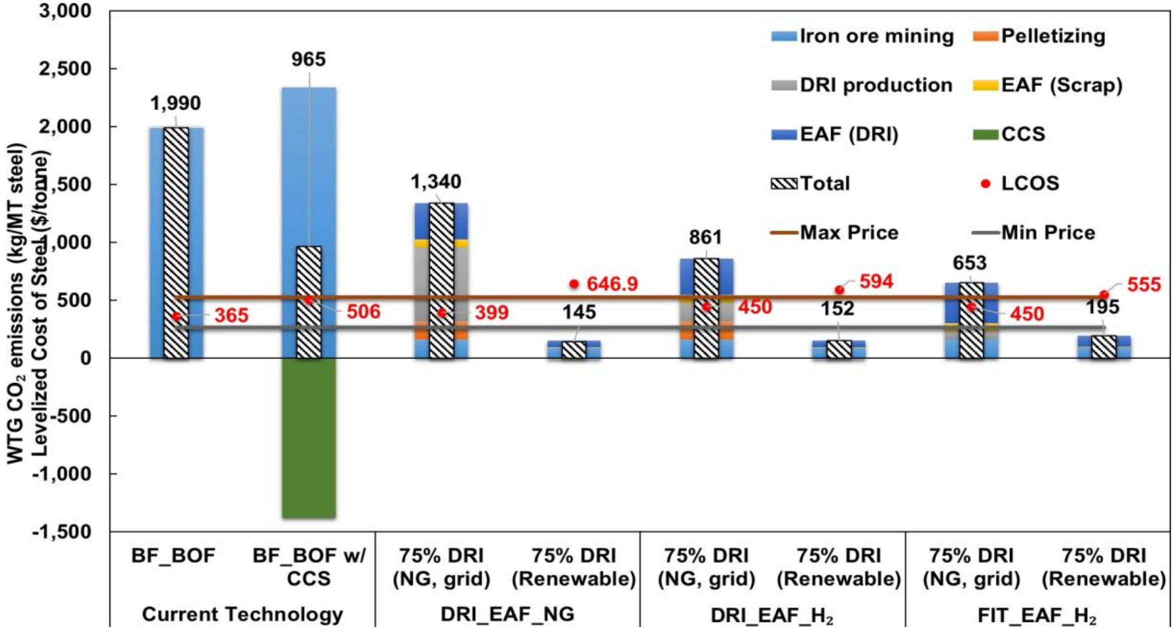
- Well-to-gate emissions

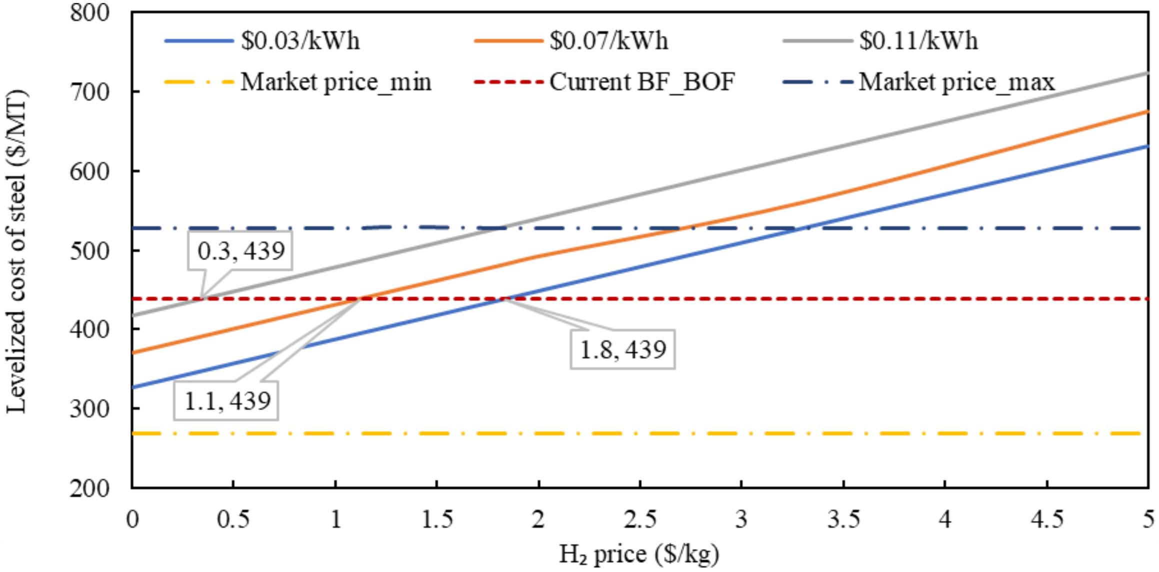


https://pubs.rsc.org/en/content/articlelanding/2022/gc/d2gc00843b/unauth

Steel production using hydrogen in DRI technology







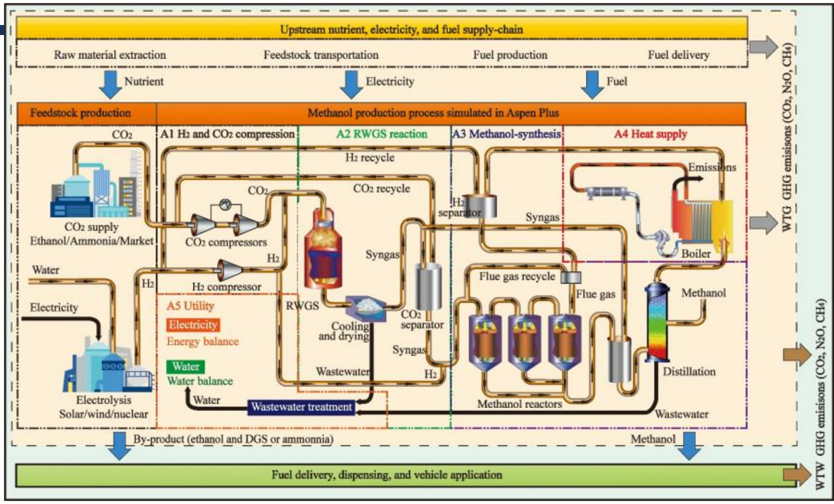
- NG=$3.7/GJ, Elec =$0.07/kWh, H_2=$1.3/kg
- The production cost with DRI-NG-EAF is similar with that of BF-BOF
- DRI-H_2 is more costly, and sensitive to H_2 price
- For DRI-H_2 steel to reach price parity with market price, H_2 cost needs to be $1-2/kg H_2
- IRA 45V incentivize DRI with H_2

Cost and Life Cycle Analysis for Deep CO2 Emissions Reduction for Steel Making: Direct Reduced Iron Technologies - Zang - steel research international - Wiley Online Library

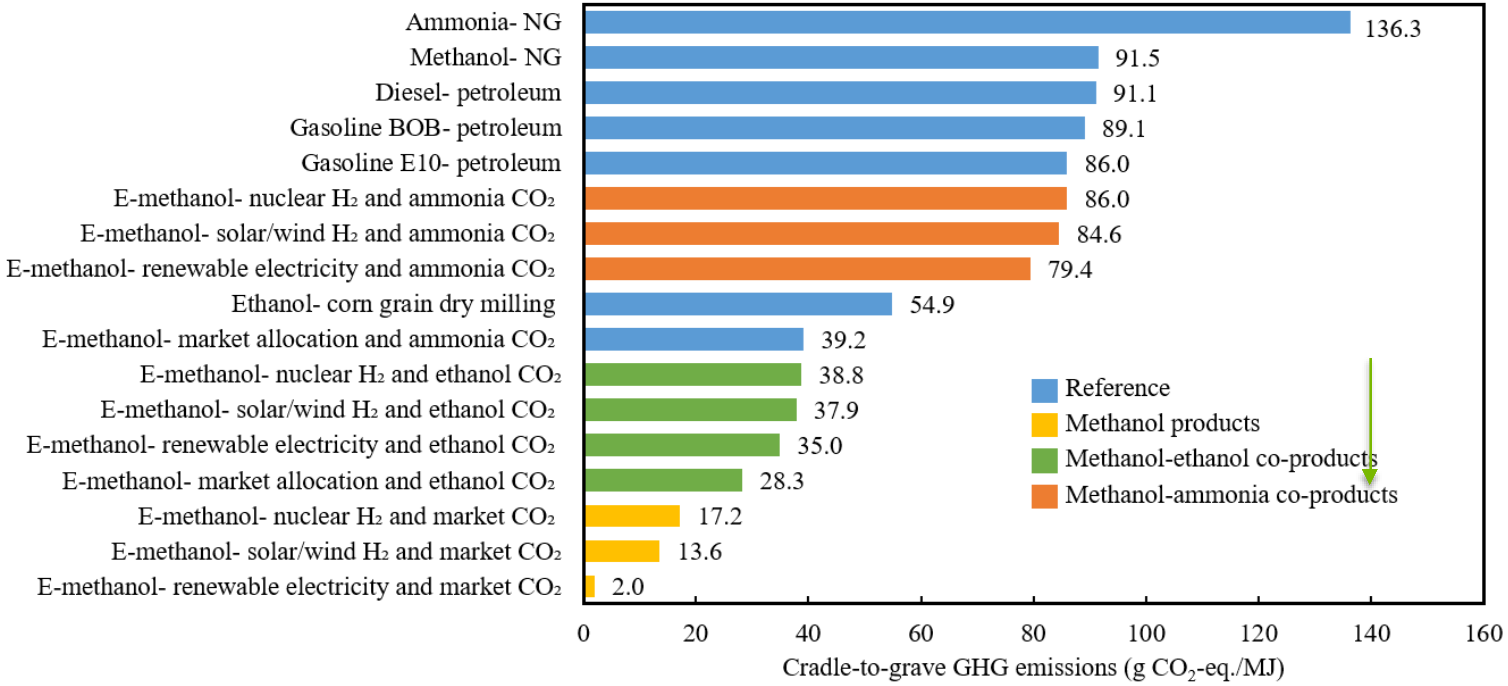
e-methanol as chemical, fuel, H_2 carrier

- Methanol can be synthesized by using CO_2 and H_2 via RWGS and methanol reaction
- $CO_2 + H_2 \rightarrow$ syngas $\rightarrow$ methanol

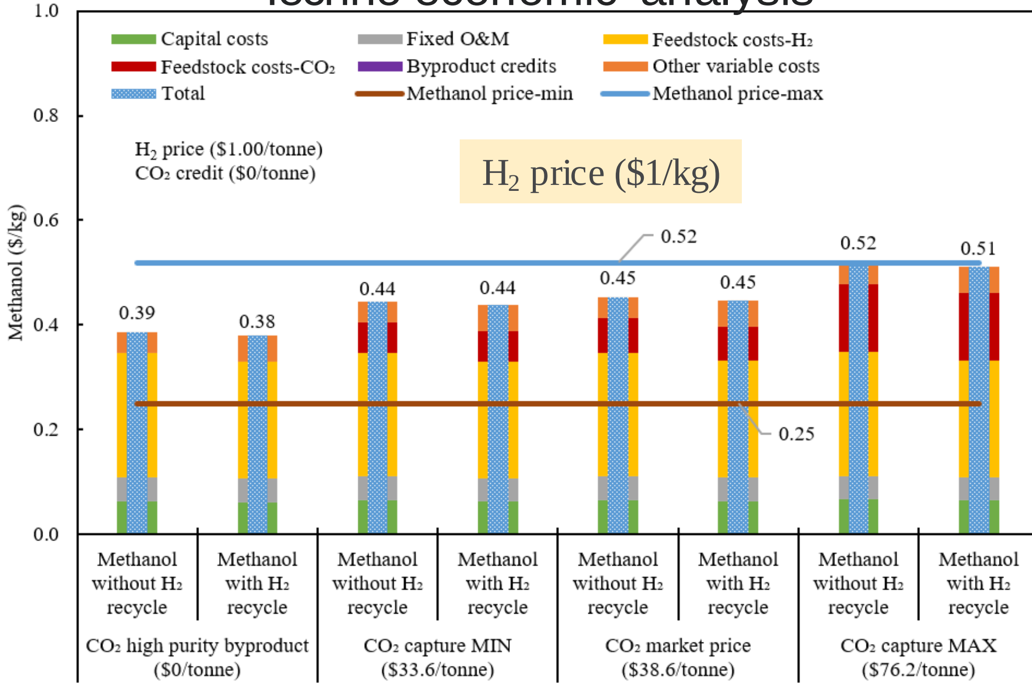
- Conversion process modeling



- Well-to-gate GHG emissions



- Techno-economic analysis

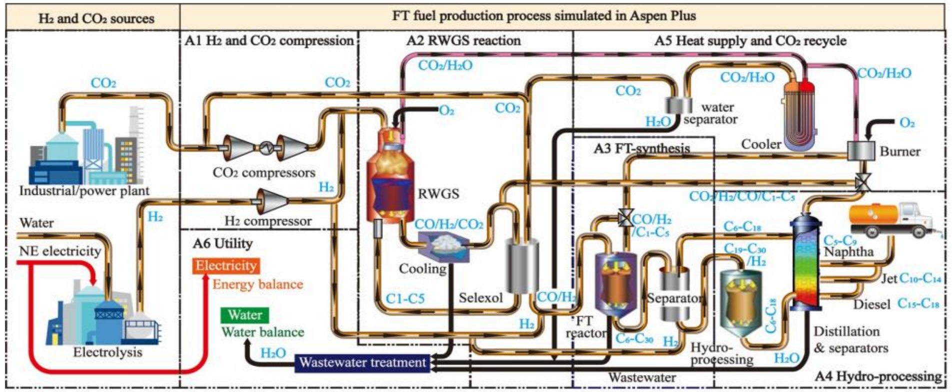


https://pubs.acs.org/doi/10.1021/acs.est.0c08237

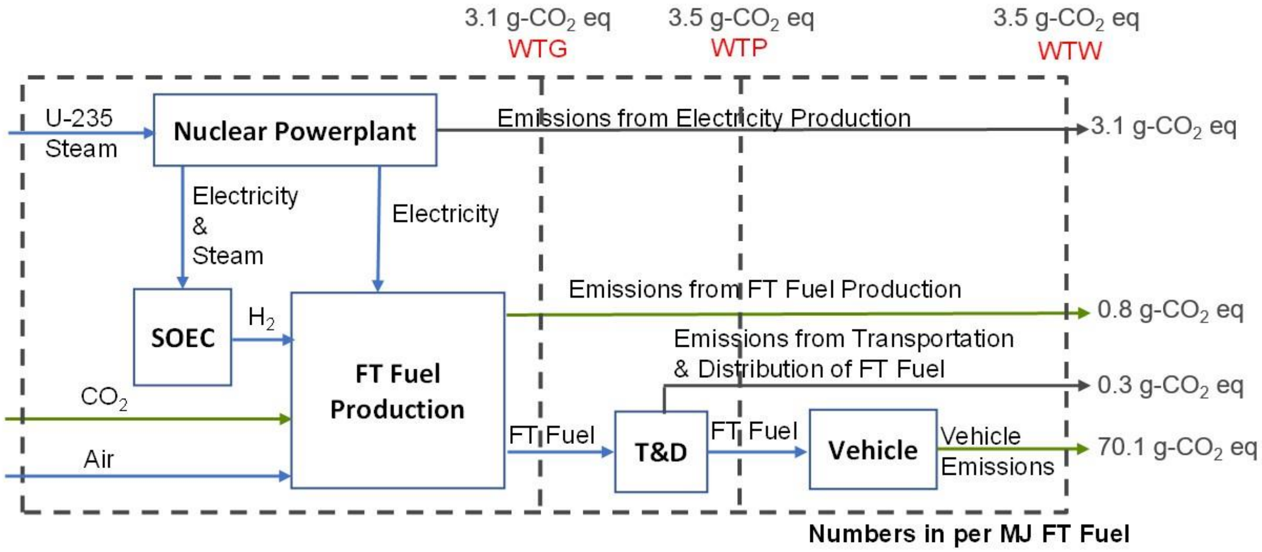
e-fuels via Fischer-Tropsch (FT) process using H_2 + CO_2

- FT fuels can be synthesized by using CO_2 and H_2 via RWGS and FT reaction

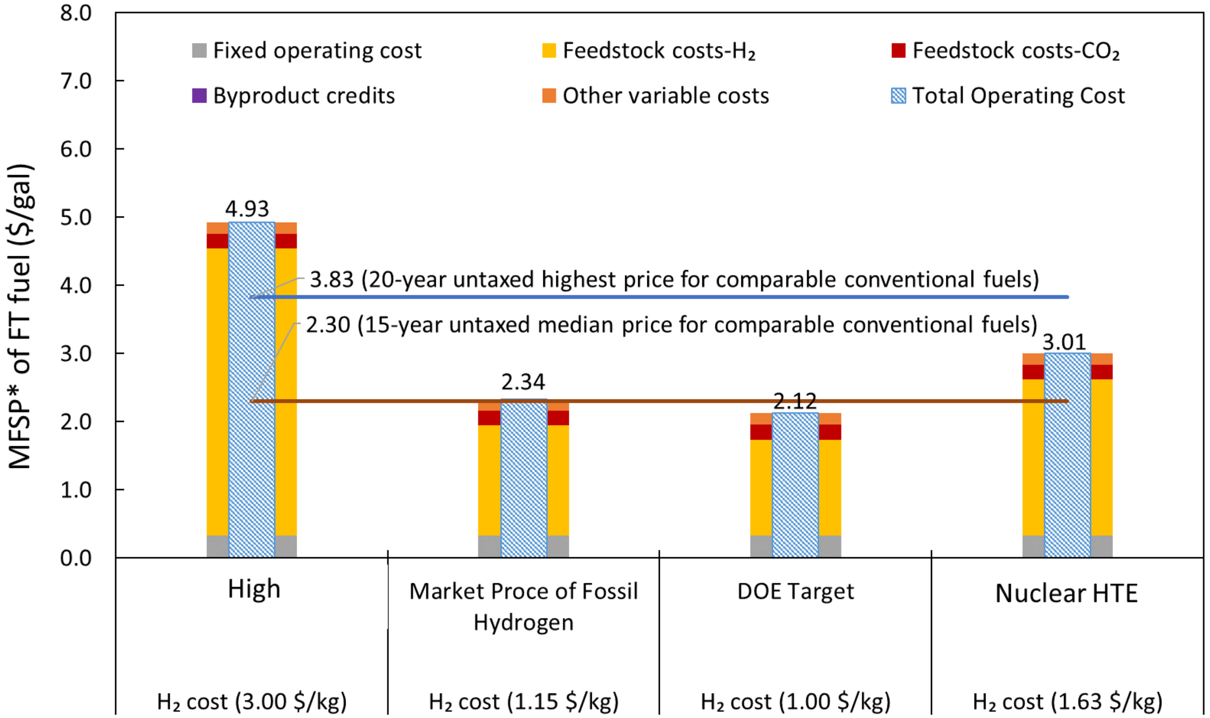
- Conversion process modeling



- Well-to-gate emissions
- CO_2 + H_2 → syngas → FT fuels



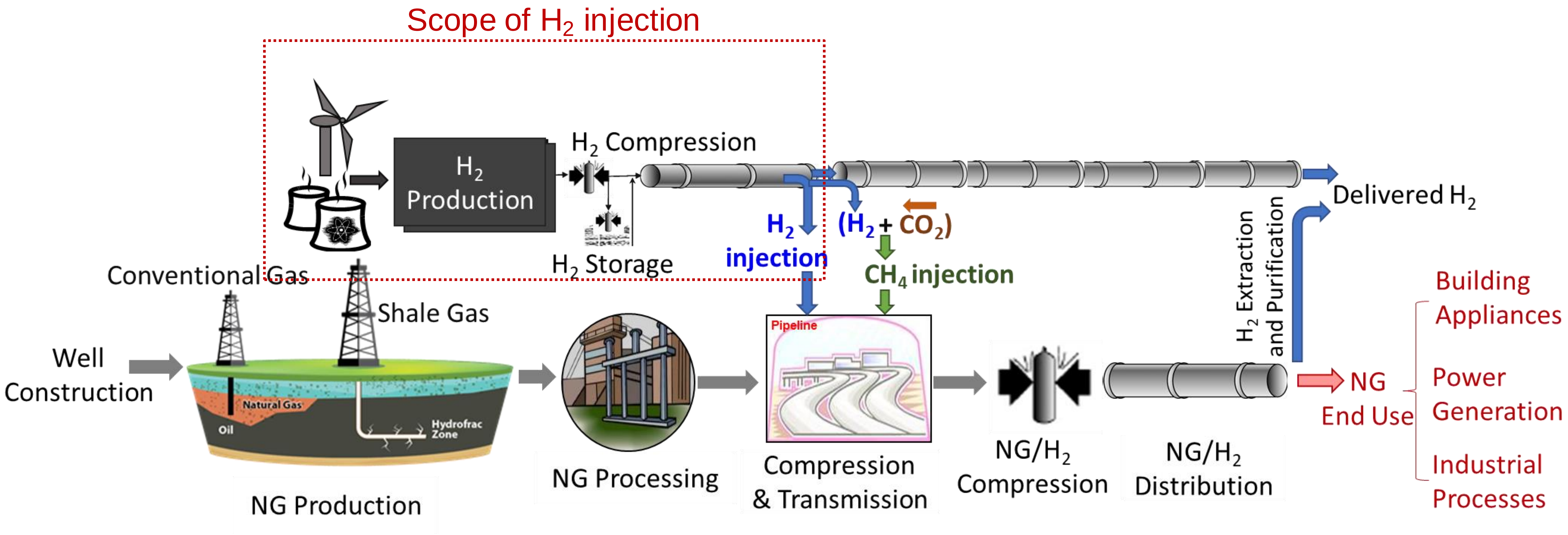
- Techno-economic analysis



*MSFP=minimum fuel selling price

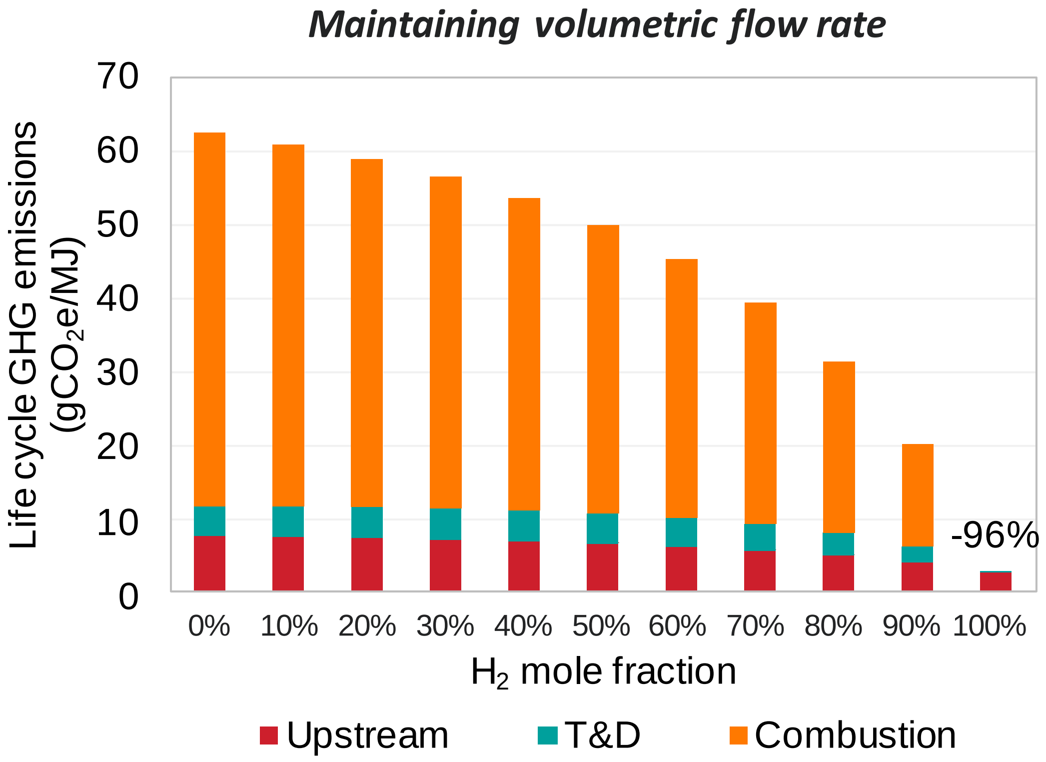
https://www.osti.gov/biblio/1868524

H_2 Blending with natural gas: Energy, Environmental and economic Implications

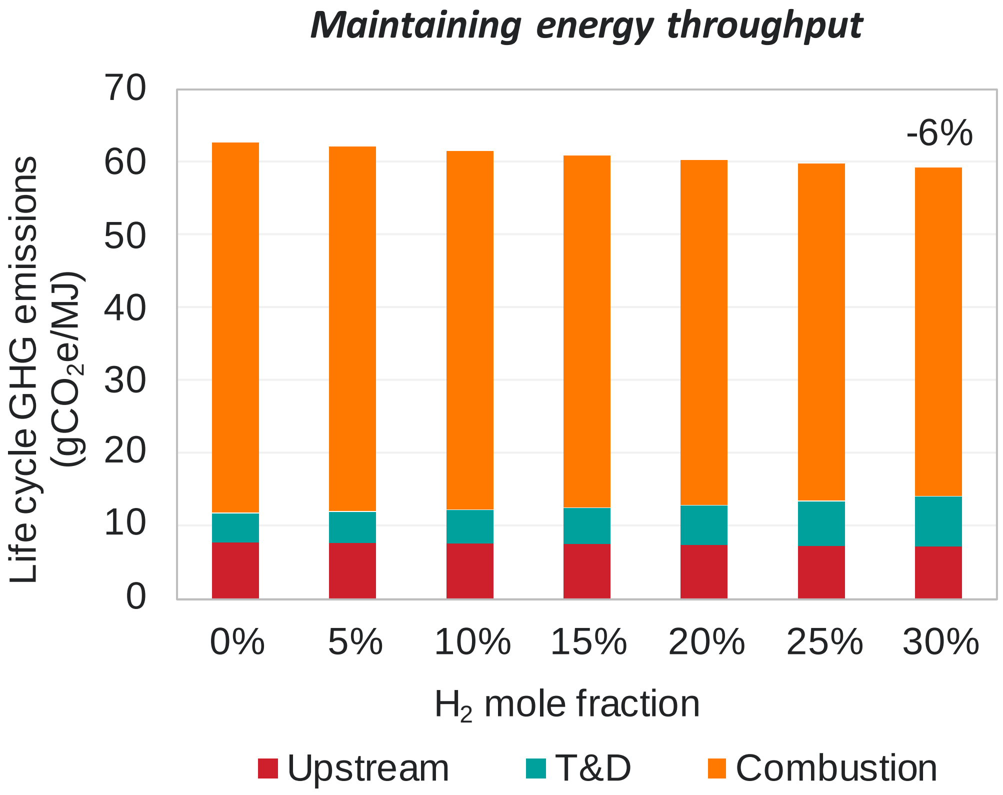


Life cycle GHG emissions – Low-carbon H_2 (LTE with nuclear power)

- For a **constant energy delivery scenario**, T&D emissions increased with the H_2 content due to higher compression energy demand and fugitive emissions partially offsetting the benefit of blending zero carbon H_2
- The net life cycle emissions are still reduced (-6%) at x_{H2}=30% due to lower H_2 upstream and combustion emissions of blend



Maintaining volumetric flow rate



Maintaining energy throughput

Acknowledgment

Hydrogen TEA and LCA at Argonne have been supported by DOE’s Office of Energy Efficiency and Renewable Energy’s Hydrogen and Fuel Cell Technologies Office (HFTO) for over two decades

Thank You!

aelgowainy@anl.gov

Our models, tutorials and publications are available at:

https://greet.es.anl.gov/

https://hdsam.es.anl.gov/

Thank you!

Questions? Contact Expert@CleanEnergySolutions.org.

The next installment in this series will focus on technical considerations.

Register today!