Life Cycle Analysis of Hydrogen Production via Plasma Pyrolysis of Natural Gas

Impact of Different Co-Product Management Strategies

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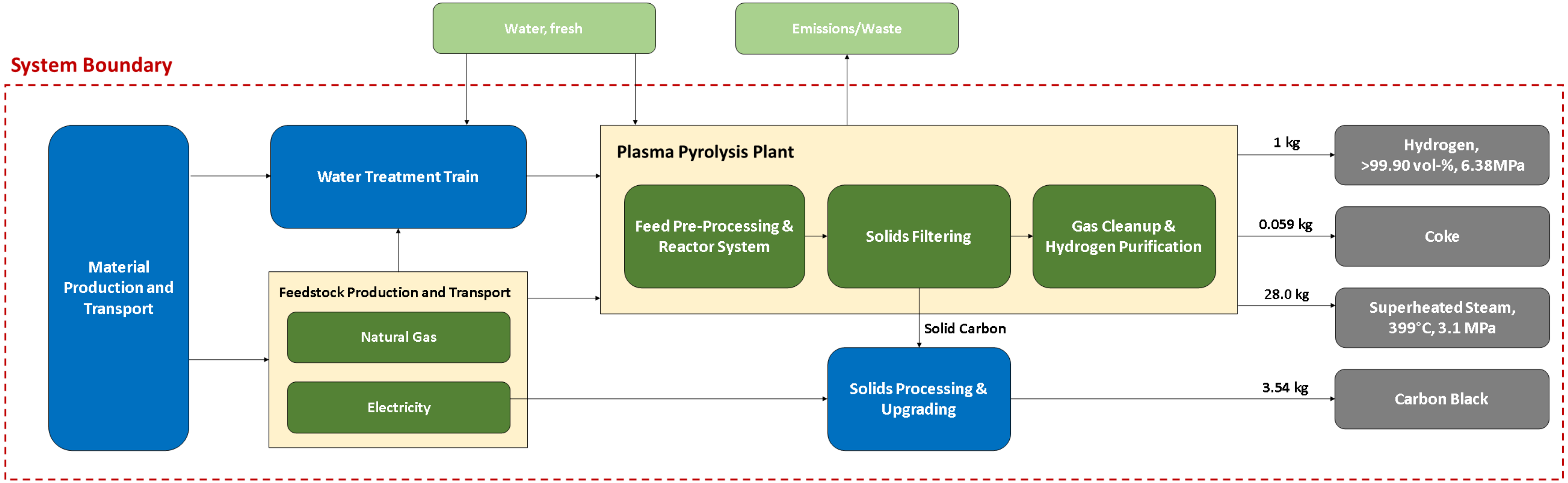
Background

- A 2023 Department of Energy report exploring technology and market cost drivers related to hydrogen production identified methane pyrolysis as a promising emerging technology [1].
- Methane pyrolysis involves the decomposition of methane into gaseous hydrogen and solid carbon by-products, including nanoparticles.
- Several methane pyrolysis concepts exist, including catalytic, thermal, and plasma.
- Plasma pyrolysis is the most advanced methane pyrolysis concept, with a technology readiness level of 6 to 8 [2].
- NETL evaluated the cost and emissions of hydrogen produced by a natural gas plasma pyrolysis system by performing a techno-economic analysis (TEA) and life cycle analysis (LCA).

Methodology

- Study meets the general requirements of ISO 14040 and ISO 14044 [3,4].
- Goal: Evaluate the life cycle impacts of plasma pyrolysis system and compare results to conventional technologies.
- Scope: Includes U.S. Average, Midwest, and Renewables scenarios.
- Functional Unit(s): Hydrogen, >99.90 vol-%, 6.38 Mpag; carbon black; coke; superheated steam, 399 °C, 3.10 MPa.
- Life Cycle Impact Assessment: Considers global warming potential (GWP) using characterization factors from Intergovernmental Panel on Climate Change (IPCC) Sixth Assessment Report (AR6) using a 100-year time horizon [5].

System Boundary



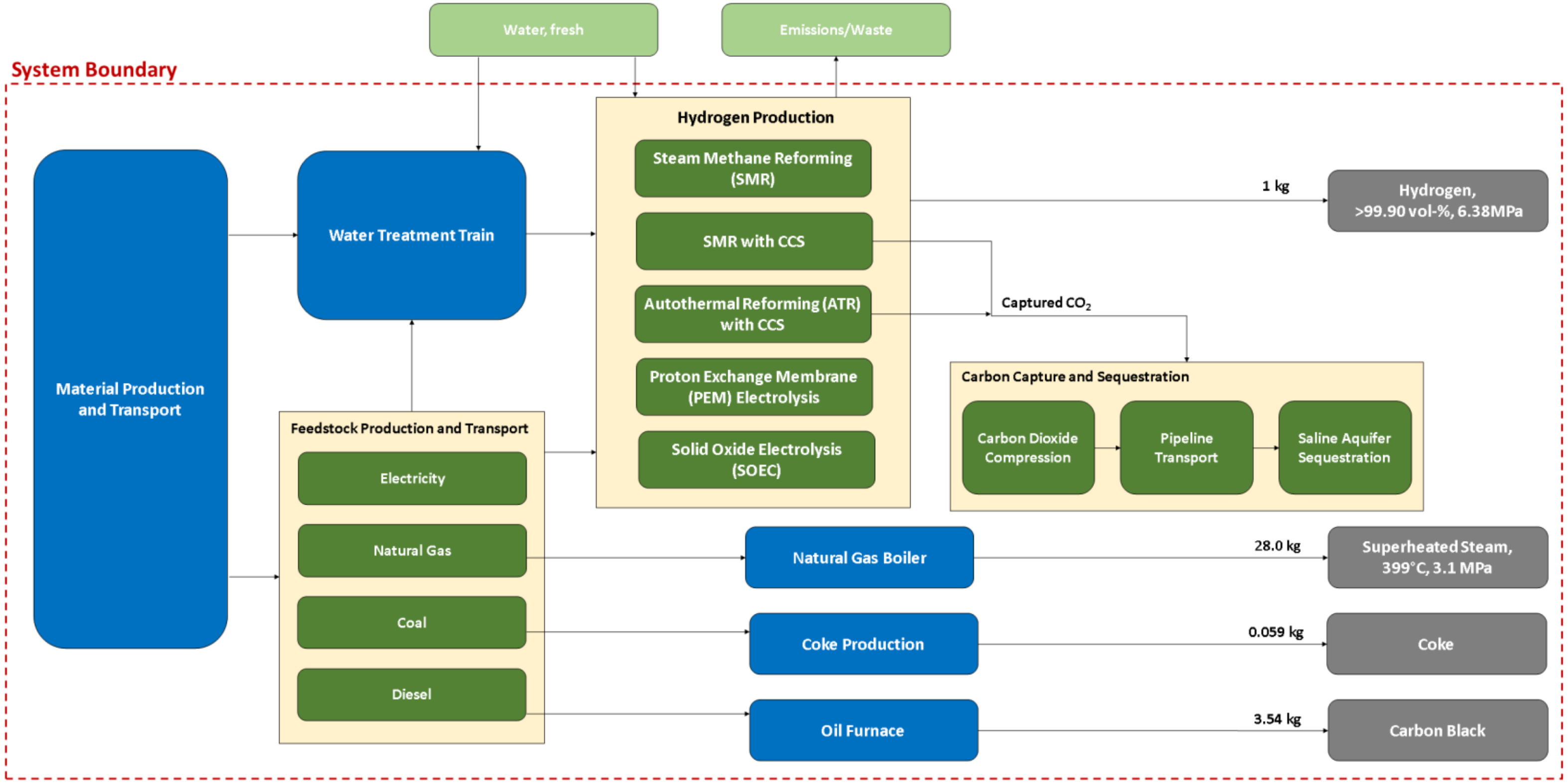
Plasma Pyrolysis

- The system boundary includes operation of the plasma pyrolysis plant, inclusive of all upstream energy and material production.
- The system boundary excludes construction of the plasma pyrolysis plant (assumed negligible).

System Boundary

Comparison System

- System boundary of comparison system is consistent with plasma pyrolysis facility.
- Conventional hydrogen production scenarios include:
  - Steam methane reforming (SMR).
  - SMR with carbon capture and storage (CCS).
  - Autothermal reforming (ATR) with CCS.
  - Proton exchange membrane (PEM) electrolysis.
  - Solid oxide electrolysis (SOEC).



Co-Product Management

General Approach

ISO 14044 procedure for allocation includes the following hierarchy [4]:

1. Avoid allocation
   a. By subdividing processes.
   b. By expanding the product system.
2. Allocate based on the underlying physical relationships between products.
3. Allocate based on other relationships between products.

Co-product management methods explored in this analysis include:

- System expansion*
- System expansion + displacement
- Causal allocation
- Mass allocation
- Energy allocation

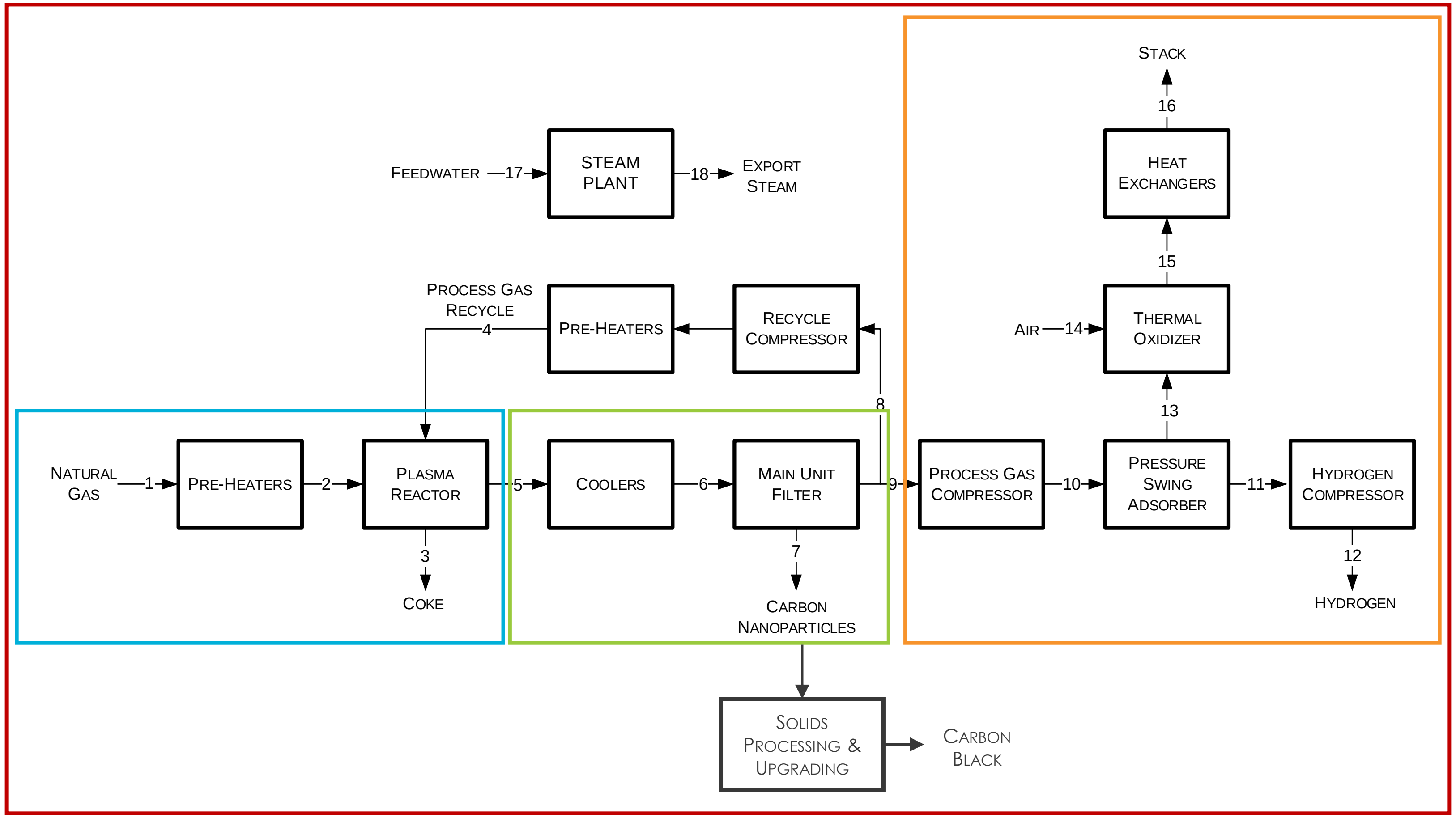
Product	Mass Produced (kg)	Mass Allocation Factor	Higher Heating Value (MJ/kg)	Energy Allocation Factor
Hydrogen	1	0.0307	139	0.414
Carbon Black	3.54	0.109	29.9	0.314
Coke	0.0590	0.00181	29.6	0.00517
Superheated Steam	28.0	0.859	3.21	0.267

*Primary method applied

Co-Product Management

Causal Allocation Approach

- Black box is subdivided into three sections.
- Subdivision cuts out steam generation and solid carbon upgrading.
- At each subdivided block, mass or molar allocation is applied according to stream table data.



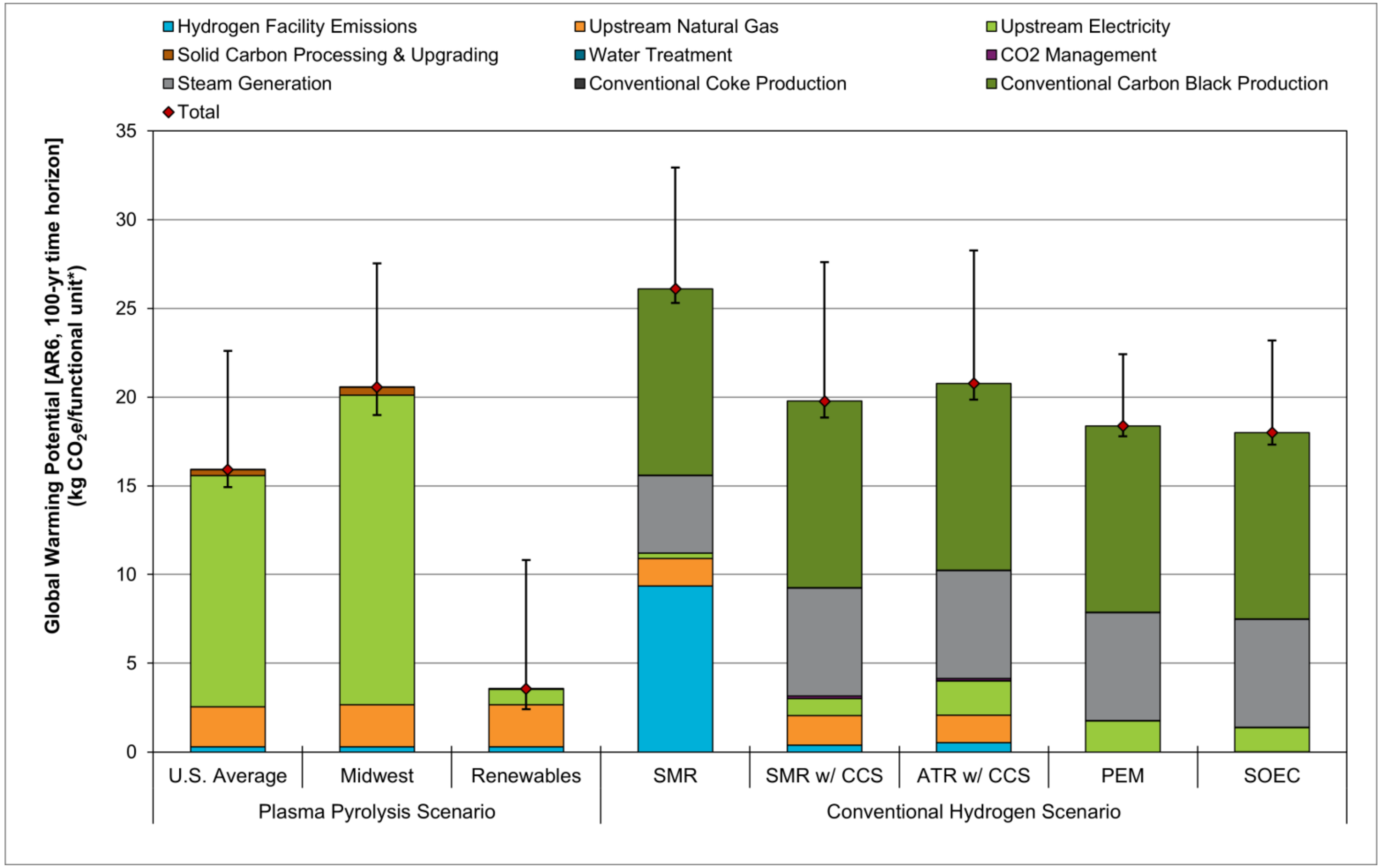
Types and Sources of Data

Category	Source	Sensitivity
Plasma Pyrolysis Facility Data	NETL Plasma Pyrolysis Report (Unpublished)	None.
Solids Processing & Upgrading	Diab et al. 2022 [6]	None.
Upstream Electricity	NETL Electricity Life Cycle Inventory [7], NETL CO2U Renewables Mix [8]	U.S. Average and Midwest: Monte Carlo analysis with 1,000 simulations run on emissions data with lognormal uncertainty. Renewables: low represented by 100% wind, high represented by 100% solar.
Upstream Natural Gas	NETL Natural Gas Baseline [9]	U.S. Average: low represented by Gulf of Mexico Offshore gas, high represented by Uinta Conventional gas. Midwest: low represented by Appalachian Shale gas, high represented by Uinta Conventional gas.
Municipal Water Treatment	EPA Drinking Water Treatment Models [10]	None.
Conventional Hydrogen Production	NETL Fossil Hydrogen Baseline [11], Henriksen et al. 2024 [12]	None.
CO_2 Transport and Storage	NETL Gate-to-Grave LCA of Saline Aquifer Sequestration of Carbon Dioxide [13]	None.
Conventional Steam Generation (natural gas boiler, 85% efficiency)	NETL Fossil Hydrogen Baseline [11]	None.
Conventional Carbon Black Production (oil furnace method)	Ecoinvent [14], NETL Petroleum Baseline [15]	None.
Conventional Coke Production (destructive distillation of bituminous coal)	U.S. Life Cycle Inventory [16], EPA AP-42 Chapter 12 [17], NETL Coal Mining and Delivery Baseline [18]	Monte Carlo analysis with 1,000 simulations run on upstream coal parameters, primarily impacting coal mine methane emissions.

Results

Multi-Product Functional Unit

- GWP of plasma pyrolysis scenarios:
  - U.S. Average: 15.9 kg CO_2e/FU.
  - Midwest: 20.6 kg CO_2e/FU.
  - Renewables: 3.56 kg CO_2e/FU.
- In all cases, significant high-end uncertainty is driven by natural gas techno-basin.
- U.S. average plasma pyrolysis scenario is lower than electrolysis cases, and Midwest plasma pyrolysis scenario is comparable to ATR with CCS.
- Results show that electricity source has a major impact on the resulting GWP of the plasma pyrolysis system.

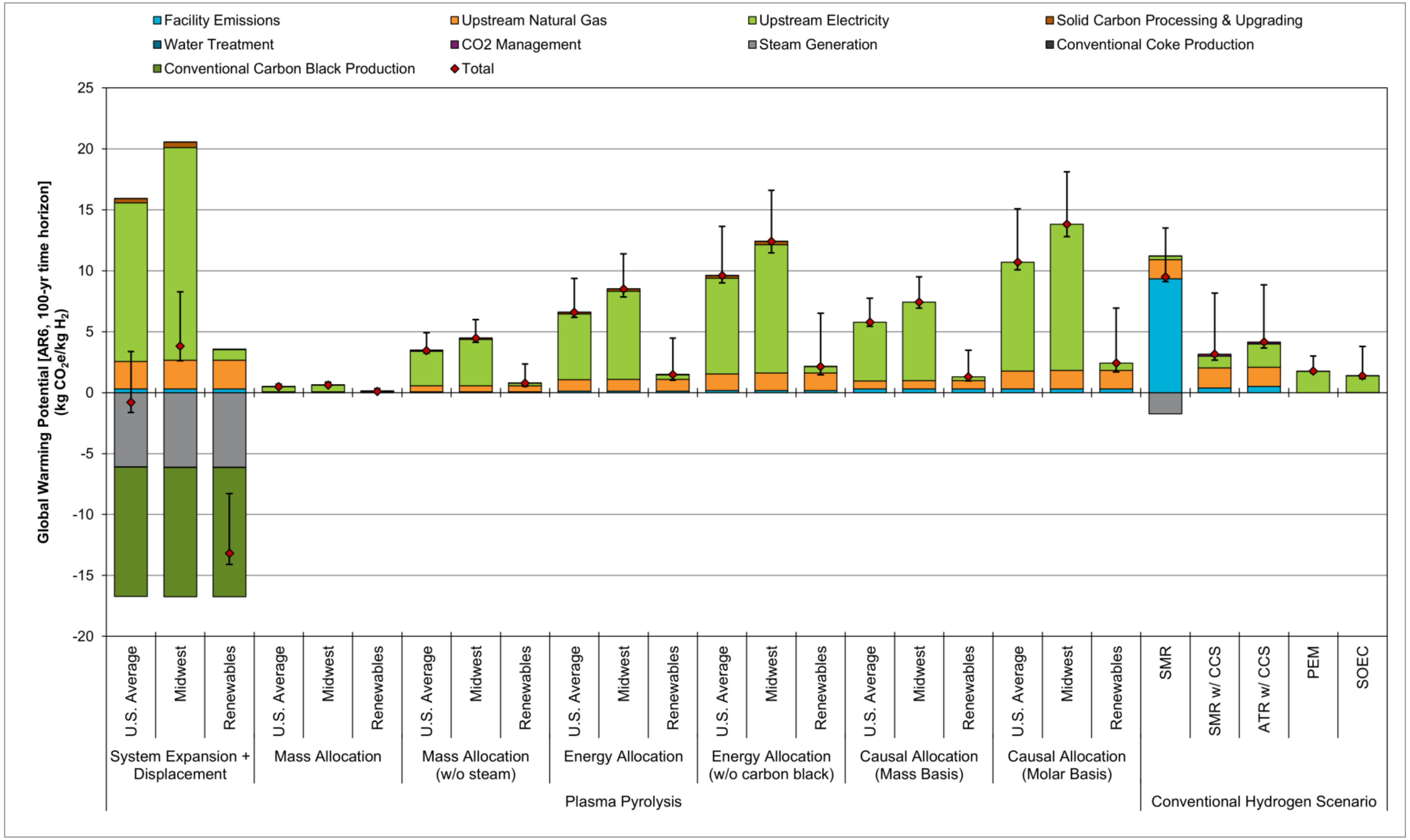


*Functional unit (FU): 1 kg of hydrogen, >99.90 vol-%, 6.38 MPag; 3.54 kg of carbon black; 0.0590 kg of coke; 28.0 kg of superheated steam, 399 °C, 3.1 MPa

Results

Single-Product Functional Unit

- GWP results vary greatly depending on co-product management strategy.
  - For U.S. average, results vary from -0.791 kg CO_2e/kg H_2 to 10.7 kg CO_2e/kg H_2.
- Comparing to conventional hydrogen production:
  - Causal allocation approaches result in a higher GWP than conventional approaches with carbon capture.
  - Mass allocation results are lower than PEM and SOEC.



Conclusions

- Plasma pyrolysis is a promising hydrogen production technology that may play a key role in U.S. domestic energy production.
- Scenarios highlight the importance of electricity source in resulting GWP.
- Natural gas basin variability introduces a significant range in emissions results.
- Co-product management strategy has a significant impact on resulting GWP.
  - This highlights the importance of performing sensitivity analyses with several allocation procedures, an element of ISO 14044 that tends to be overlooked in product LCAs.
  - Such uncertainty is crucial to capture in comparative LCAs, as it may impact the conclusions drawn.

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