

Life Cycle Assessment of Hydrogen Production Pathways Across Canada: Evaluating Methane Pyrolysis as a Traditional Low Carbon Solution

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Hydrogen is increasingly viewed as a central component of Canada's long-term decarbonization strategy, especially in sectors where direct electrification remains challenging. As provinces work to cut emissions while maintaining reliable energy systems, understanding the life-cycle impacts of emerging hydrogen pathways has become essential. This study applies an ISO 14040/14044-aligned, cradle-to-gate life cycle assessment (LCA) to compare *methane pyrolysis* with electrolysis and steam methane reforming with carbon capture and storage (SMR-CCS). Three methane pyrolysis configurations, *molten-metal gas-fired*, *molten-metal hydrogen-fired*, and *plasma-based*, are evaluated using provincial electricity grid data, upstream natural gas emissions, and established LCA databases. Results show that molten-metal hydrogen-fired pyrolysis and electrolysis generally achieve the lowest greenhouse gas (GHG) emissions in provinces with clean electricity. Plasma-based pyrolysis performs well only under very low-carbon grids due to its high electricity demand. Water use also varies, molten-metal gas-fired pyrolysis has the lowest national water footprint, while electrolysis and plasma systems show higher water use in fossil-intensive regions. A key distinction of methane pyrolysis is its production of solid carbon rather than CO₂, creating potential revenue streams. Plasma systems typically yield carbon black, while molten-metal reactors can produce higher-value graphitic carbon. However, long-term feasibility depends on the development of stable carbon markets.

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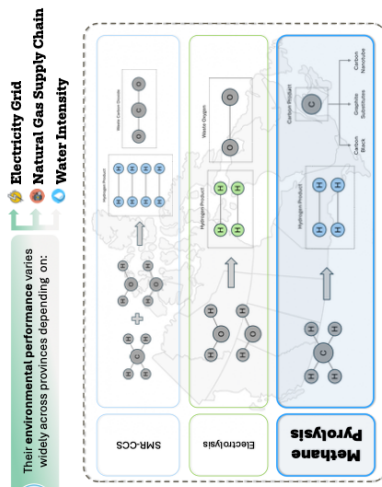
Life Cycle Assessment of Hydrogen Production Pathways Across Canada: Evaluating Methane Pyrolysis as a Transitional Low-Carbon Solution

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WHY HYDROGEN MATTERS FOR CANADA'S NET-ZERO FUTURE

- Hydrogen is an essential energy carrier to Canada's net-zero strategy.
- 22% of global energy by 2050 (hydrogen projected role)
- 96% of today's H₂ is fossil-based (mainly from Steam Methane Reforming (SMR))



- How do the greenhouse gas (GHG) emissions and water footprint of major hydrogen pathways change across provinces with different electricity grids and natural gas supply chains?
- Under what regional conditions does methane pyrolysis outperform electrolysis and SMR with carbon capture and storage (CCS)?
- Which hydrogen pathway is most suitable for each provincial energy system?

Use Life Cycle Assessment (LCA) to identify the conditions under which individual hydrogen pathways have potential in Canada by showing where electrolysis is limited by high electricity demand and water needs, where SMR-CCS is limited by local CO₂ storage availability, and where methane pyrolysis becomes a strong alternative.

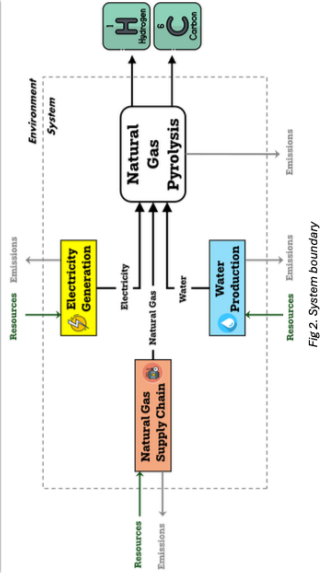
Approach

- Complete a cradle-to-gate LCA, including all impacts from natural gas extraction, electricity and water supply, and reactor operations up to the point hydrogen exits the plant.
- Functional Unit: 1 kg H₂
- Mid point indicators: GHG emissions, Water footprint

Key Inputs

- Mass and energy balances taken from Shokrollahi et al. (2024) (Aspen Plus® simulations)
- Provincial grid intensity: Canada energy regulator (2025)
- Upstream NG emissions: Fuel LCA model
- Water footprint data: direct water use taken from Shokrollahi et al. (2024). Indirect water use from OpenLCA EF v3 method + peer reviewed studies.

SYSTEM BOUNDARY AND TECHNOLOGIES MODELLED



Molten Metal Gas-Fired

Natural gas combustion heats the molten metal bath (lith, iron, nickel). (900-1200 °C)

Molten Metal H₂-Fired

Hydrogen combustion heats the molten metal instead of natural gas. (900-1200 °C)

Plasma

Electric plasma arc (ionized gas) creates extremely high temperature. (1500-4000 °C)

Fig. 2. System boundary

Fig. 3. Methane pyrolysis process configurations

Methane pyrolysis offers potential for producing hydrogen and valuable carbon material from natural gas. This research aims to provide a comprehensive assessment of the process at an industrial scale.

Techno Economic Assessment (TEA) (evaluate long-term economic feasibility)

- Carbon market potential (offset H₂ production cost)
- Carbon product type (Quality + Form of solid carbon)
- Potential carbon market (balancing hydrogen yield and carbon output)

Fig. 7. Conceptual model of methane-to-hydrogen and carbon co-production

RESULTS

Across all provinces, the H₂-fired pyrolysis configuration demonstrates the lowest GHG emissions.

- Gas-fired: consistently higher GHG.
- Plasma: depends on provincial electricity carbon intensity.
- Very low in low-carbon-intensity provinces (QC, MB, BC), extremely high in fossil-heavy grids (NS, NU).



Fig. 4. Provincial GHG emissions for pyrolysis technologies

- Darker shading reflects higher GHG (top) or water consumption (bottom).
- Lowest-GHG pathway varies across provinces depending on the carbon intensity of the electricity grid.
- Natural-gas upstream emissions are the same nationwide.
- Electricity grid mix is the main driver of GHG differences.

Fig. 5. Provincial optimal hydrogen pathway based on GHG performance

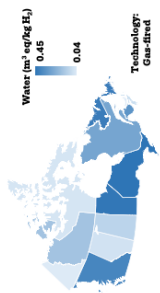


Fig. 6. Provincial optimal hydrogen pathway based on water-use performance

Gas-fired pyrolysis consumes less water. The water footprint is much higher for Plasma and H₂-fired pyrolysis as both rely heavily on electricity generation and cooling systems.

FUTURE WORK

Methane pyrolysis offers potential for producing hydrogen and valuable carbon material from natural gas. This research aims to provide a comprehensive assessment of the process at an industrial scale.

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