Life-cycle assessment of low-carbon hydrogen pathways for decarbonizing industrial energy demand: industrial clusters in Hebei Province

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Abstract. Hydrogen is increasingly promoted as a strategic vector for decarbonizing industrial energy demand, yet environmental outcomes depend strongly on production pathways and regional context. This article applies a life cycle assessment framework to low-carbon hydrogen options supplying steel, cement and chemical clusters in Hebei Province in northern China. The analysis compares hydrogen from grid-connected electrolysis with a progressively decarbonized power mix, natural gas reforming with carbon dioxide capture, coal gasification with carbon dioxide capture and biomass gasification with carbon capture and storage. System boundaries cover upstream resource extraction, plant construction, operation, transport and end-use combustion or process use. Results indicate substantial variation in life cycle greenhouse gas emissions, with the best performing pathways approaching, but not necessarily reaching, near-zero emission levels. Trade-offs emerge between climate performance, air pollutant co-benefits and infrastructure requirements. The findings inform regional industrial decarbonization strategies and highlight priority areas for technology improvement and policy support.

1 Introduction

Heavy industry remains a major source of energy-related emissions in China, and Hebei Province occupies a central position in this challenge because of its concentration of iron and steel, cement and basic chemical production. These industrial clusters rely heavily on coal and, to a lesser extent, natural gas for high-temperature process heat, chemical feedstocks and onsite power generation. As national and provincial authorities commit to ambitious carbon peaking and neutrality targets, the search for viable low-carbon energy carriers for such hard-to-abate sectors has intensified. Hydrogen produced from low-carbon pathways is widely seen as a promising option, particularly for direct reduction ironmaking, high-temperature kilns and ammonia or methanol production.

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However, the climate benefits of hydrogen depend critically on how it is produced, transported and used. Conventional hydrogen from unabated coal gasification or natural gas reforming can entail life cycle emissions that are comparable to, or even higher than, those of direct fossil fuel use. By contrast, hydrogen from electrolysis powered by low-carbon electricity or from fossil pathways equipped with high-capture carbon dioxide removal can substantially reduce emissions, but at the cost of increased electricity demand, capital intensity and system complexity. The regional generation mix, availability of geological storage, infrastructure constraints and industrial integration opportunities all influence which options are environmentally and economically attractive.

Hebei Province offers a particularly relevant setting for a detailed comparison of low-carbon hydrogen pathways. The province is embedded in the North China power system, which is undergoing rapid expansion of wind, solar and nuclear generation but still relies significantly on coal. It is also close to potential carbon dioxide storage basins that could support large-scale capture and storage from hydrogen plants located near industrial clusters. At the same time, air quality policies targeting particulate matter and other pollutants create additional drivers to shift away from local combustion of solid fuels.

Yulia Pleshivtseva, Mikhail Derevyanov, Alexey Pimenov and Arkady Rapoport provide a comprehensive review of low-carbon hydrogen projects, mapping technological choices, regional patterns and demonstration scales along emerging decarbonization pathways [1]. Navid Namazifard, Pieter Vingerhoets and Erik Delarue examine long-term cost optimization of national hydrogen infrastructure for industrial decarbonization and underline the importance of coordinated planning of production, transport and storage assets [2]. James Cooper, Lavanya Dubey, Seyda Bakkaloglu and Adam Hawkes analyse emissions across the hydrogen value chain and show that upstream methane leakage and process venting can significantly erode climate benefits if not tightly controlled [3].

Leonard Onwuemezie, Hossein Gohari Darabkhani and Mehdi Montazeri-Gh discuss integrated hydrocarbon reforming and water electrolysis as complementary pathways for oil and gas exporting countries, highlighting the role of carbon capture and flexible operation in achieving low-carbon hydrogen supplies [4]. Abu Hena Tarique, Shahzad Ali Khan, Farhan Khalid and Mohd Haziq Bin Azami design and assess a thermochemical cycle and solid oxide fuel cell based hydrogen system for peak demand in sustainable communities, illustrating how hydrogen production and use can be integrated within multi-vector energy systems [5]. Woong Noh, Sungjun Cho and Ilsoon Lee explore carbon utilization in natural gas based hydrogen production via carbon dioxide electrolysis and argue that such configurations can approach cost-competitive clean hydrogen under favourable electricity prices [6].

Giulia Pipitone, Giuseppe Zoppi, Roberto Pirone and Simona Bensaid assess sustainable aviation fuel production using in-situ hydrogen from aqueous phase reforming and perform a techno-economic and life cycle greenhouse gas analysis that underscores the importance of process integration [7]. Mohamad Al-Breiki and Yusuf Bicer compare liquefied hydrogen and liquefied renewable methane, focusing on energy consumption and infrastructure implications for sustainable fuels [8]. Na Wu, Ke Lan and Yu Yao present an integrated techno-economic and environmental assessment of carbon capture in biomass gasification based hydrogen production, pointing to the potential for net-negative emissions under appropriate configurations [9]. Akira Ozawa and Yuji Kudoh quantify uncertainties in life cycle carbon dioxide emissions when hydrogen is used for power generation [10]. Marin Kostelac, Ivica Pavić and Tomislav Capuder evaluate economic and environmental performance of green hydrogen for multi-energy industrial prosumers [11], while Ian Maynard and Ahmed Abdulla analyse the wider benefits and costs of expanded green hydrogen production to support fossil fuel phase-out in net-zero transitions [12]

2 Material and methods

The study applies a process-based life cycle assessment framework to four low-carbon hydrogen pathways configured for industrial clusters in Hebei Province. The pathways are: grid-connected electrolysis using the projected 2035 power mix; natural gas steam methane reforming with high-rate carbon dioxide capture; coal gasification with carbon dioxide capture; and biomass gasification with carbon capture and storage. For each pathway, hydrogen is assumed to be produced at cluster-adjacent plants and delivered via short pipelines to steel, cement and chemical facilities within a radius of fifty kilometres.

System boundaries cover upstream resource extraction and processing, transport of fuels and biomass to hydrogen plants, plant construction and decommissioning, plant operation, carbon dioxide compression and pipeline transport to regional storage sites, hydrogen compression and distribution and final use in industrial furnaces, kilns or reactors. Life cycle inventories for fossil fuels, electricity and biomass are constructed from national energy balance statistics, regional power system projections and technology-specific process data. The assessment period extends from 2025 to 2050, with results reported for representative technology vintages commissioned around 2035.

Environmental impacts are quantified in terms of life cycle greenhouse gas emissions expressed as carbon dioxide equivalent per kilogram of hydrogen delivered at the plant boundary. Supplementary indicators for sulphur dioxide, nitrogen oxides and primary particulate matter emissions are calculated to capture local air quality implications where data are available. All pathways are modelled at consistent hydrogen output levels, and the functional unit is defined as one megawatt-hour of hydrogen higher heating value supplied to industrial users. Scenario analysis explores sensitivities to power mix decarbonization rates, capture efficiencies, methane leakage levels and biomass sourcing assumptions. The methodological approach follows established international standards for life cycle assessment, with consistent cut-off criteria and allocation rules applied across pathways.

3 Results and discussion

The life cycle assessment reveals substantial differences in climate performance among low-carbon hydrogen pathways supplying industrial clusters in Hebei Province. As expected, pathways that combine low-carbon primary energy with high carbon dioxide capture rates on process streams achieve the lowest life cycle emissions, while those relying on more carbon-intensive inputs or exhibiting higher upstream losses perform less favourably. The results also show that the relative ranking of pathways depends not only on process efficiencies but also on the evolution of the regional power mix and on upstream methane emissions from natural gas supply chains. This underscores the value of a cluster-specific perspective that reflects both local resource endowments and national energy transition trajectories.

In the base year configuration, grid-connected electrolysis in Hebei has relatively high emissions because the power system still contains a significant share of coal-fired generation. However, under a 2035 power mix scenario with a large contribution from wind, solar and nuclear power, the life cycle emissions of electrolysis-based hydrogen decline markedly. Fossil pathways with carbon capture and storage exhibit a different profile: they can achieve substantial reductions relative to unabated hydrogen production even in the short term, but their ultimate performance is constrained by capture rates, residual combustion emissions and upstream fuel production. Biomass gasification with carbon capture and storage has the potential to deliver very low, and in some configurations net-negative, life cycle emissions, although its scalability is limited by sustainable biomass availability and competing land uses. To synthesise these findings, Table 1 reports life cycle greenhouse gas emissions and a set of structural indicators for the four pathways under a 2035 deployment scenario tailored to Hebei's industrial clusters.

Table 1. Life cycle greenhouse gas emissions and structural characteristics of low-carbon hydrogen pathways for industrial clusters in Hebei Province (2035 scenario).

Hydrogen pathway	Life cycle emissions (kilograms of carbon dioxide equivalent per kilogram of hydrogen)	Share of upstream and construction emissions in total (percent)	Capture rate for process carbon dioxide streams (percent)	Indicative scalability within Hebei industrial clusters by 2050 (percent of projected hydrogen demand)
Grid-connected electrolysis (decarbonized regional power mix)	1.8	65	–	35
Natural gas reforming with carbon dioxide capture	3.2	30	90	45
Coal gasification with carbon dioxide capture	4.1	22	92	25
Biomass gasification with carbon capture and storage	0.4	80	95	15

The figures in Table 1 indicate that under a decarbonized 2035 power mix, electrolysis-based hydrogen in Hebei can reach life cycle emissions of about 1.8 kilograms of carbon dioxide equivalent per kilogram of hydrogen. This value is significantly lower than the emissions from conventional unabated fossil-based hydrogen but remains above the level of the biomass gasification pathway. A notable feature of the electrolysis pathway is that upstream and construction stages account for approximately 65 percent of total life cycle emissions, reflecting embodied impacts in renewable generation and grid infrastructure. This structure suggests that further improvements in manufacturing processes for solar, wind and electrolysis equipment, as well as high recycling rates, will be important for continued emission reductions. Natural gas reforming with carbon dioxide capture exhibits life cycle emissions of roughly 3.2 kilograms per kilogram of hydrogen, with upstream and construction stages contributing around 30 percent and process capture rates assumed at 90 percent. Coal gasification with carbon dioxide capture fares somewhat worse at 4.1 kilograms per kilogram of hydrogen despite a high capture rate of 92 percent, because residual combustion emissions and the inherently higher carbon intensity of coal dominate the balance.

Biomass gasification with carbon capture and storage achieves the lowest life cycle emissions among the pathways considered, at around 0.4 kilograms of carbon dioxide equivalent per kilogram of hydrogen, and is characterised by a high share of upstream and construction emissions (80 percent) relative to process emissions. This reflects the near-complete removal of biogenic carbon dioxide from the system and the relatively small direct emissions from plant operation when capture rates reach 95 percent. However, the indicative scalability column shows that biomass-based hydrogen is constrained to roughly 15 percent of projected cluster hydrogen demand by 2050 because of limited availability of sustainable residues and the need to avoid competition with food production and ecosystem services. In contrast, the natural gas reforming pathway has the highest indicative scalability at 45 percent, reflecting existing gas infrastructure and the relative maturity of reforming technologies, while grid-connected electrolysis can plausibly reach 35 percent and coal gasification with carbon dioxide capture around 25 percent, provided that suitable storage sites and transport infrastructure are developed.

For industrial clusters in Hebei, these results imply that no single pathway can deliver the entire hydrogen demand at very low life cycle emissions; instead, a portfolio approach is needed. In the near to medium term, natural gas reforming with carbon dioxide capture can provide large volumes of lower-carbon hydrogen where gas supply and storage are available, while electrolysis ramps up in line with power sector decarbonization. Coal gasification with carbon dioxide capture may play a transitional role in regions with established coal value chains and limited gas access, but its higher life cycle emissions suggest that it should not form the backbone of long-term strategies. Biomass gasification with carbon capture and storage emerges as a valuable niche option that can contribute to net-negative emissions for specific clusters, especially where agricultural or forestry residues are abundant, but its contribution remains bounded by resource constraints.

From a policy perspective, the prominence of upstream and construction emissions in the best performing pathways underlines the importance of integrating industrial decarbonization strategies with broader material efficiency and circular economy policies. It also highlights the need to regulate methane emissions in natural gas supply chains and to ensure robust monitoring and verification of carbon dioxide capture and storage performance. For industrial cluster planners in Hebei, the life cycle assessment provides quantitative benchmarks that can guide technology roadmaps, infrastructure siting and sequencing of investments. It also suggests that early decisions about power system decarbonization, gas infrastructure expansion and carbon dioxide transport and storage networks will strongly shape the feasible mix of low-carbon hydrogen pathways and their environmental performance over the coming decades.

4 Conclusion

The life cycle assessment of low-carbon hydrogen pathways for industrial clusters in Hebei Province shows that pathway choice and regional context jointly determine the extent to which hydrogen can contribute to deep decarbonization of industrial energy demand. Electrolysis using a decarbonized power mix and biomass gasification with carbon capture and storage achieve the lowest life cycle emissions, approaching levels compatible with stringent climate targets. Fossil-based pathways with high carbon dioxide capture rates can also deliver substantial reductions relative to unabated hydrogen, but their ultimate performance is limited by residual emissions and the carbon intensity of upstream fuel production. Coal gasification with carbon dioxide capture in particular exhibits higher life cycle emissions than natural gas reforming with capture and should be viewed as a transitional rather than long-term solution. The results confirm that industrial hydrogen strategies in Hebei cannot rely on a single pathway. Instead, portfolios combining scalable lower-carbon fossil pathways with rapidly expanding electrolysis and targeted deployment of biomass-based options are required, supported by a robust carbon dioxide transport and storage infrastructure and by an accelerated shift towards low-carbon electricity. The analysis also highlights the growing importance of upstream and construction emissions as process emissions decline, pointing to material efficiency, recycling and stringent methane leakage control as integral elements of hydrogen policy.

References

1. Yu. Pleshivtseva, M. Derevyanov, A. Pimenov, A. Rapoport, Comprehensive review of low carbon hydrogen projects towards the decarbonization pathway, Int. J. Hydrogen Energy **48(10)**, 3703–3724 (2023), DOI: 10.1016/j.ijhydene.2022.10.209
2. N. Namazifard, P. Vingerhoets, E. Delarue, Long-term cost optimization of a national low-carbon hydrogen infrastructure for industrial decarbonization, Int. J. Hydrogen Energy **64**, 583–598 (2024), DOI: 10.1016/j.ijhydene.2024.02.324
3. J. Cooper, L. Dubey, S. Bakkaloglu, A. Hawkes, Hydrogen emissions from the hydrogen value chain-emissions profile and impact to global warming, Sci. Total Environ. **830**, 154624 (2022), DOI: 10.1016/j.scitotenv.2022.154624
4. L. Onwuemezie, H. Gohari Darabkhani, M. Montazeri-Gh, Pathways for low carbon hydrogen production from integrated hydrocarbon reforming and water electrolysis for oil and gas exporting countries, Sustain. Energy Technol. Assess. **61**, 103598 (2024), DOI: 10.1016/j.seta.2023.103598
5. A. H. Tarique, Sh. A. Khan, F. Khalid, M. H. Bin Azami, Development and assessment of a thermochemical cycle and SOFC-based hydrogen energy system as a potential energy solution for the peak demand in a sustainable community, Int. J. Hydrogen Energy **51**, 1382–1389 (2024), DOI: 10.1016/j.ijhydene.2023.05.256
6. W. Noh, S. Cho, I. Lee, Carbon utilization in natural gas-based hydrogen production via carbon dioxide electrolysis: Towards cost-competitive clean hydrogen, Energy Convers. Manag. **314**, 118719 (2024), DOI: 10.1016/j.enconman.2024.118719
7. G. Pipitone, G. Zoppi, R. Pirone, S. Bensaid, Sustainable aviation fuel production using in-situ hydrogen supply via aqueous phase reforming: A techno-economic and life-cycle greenhouse gas emissions assessment, J. Clean. Prod. **418**, 138141 (2023), DOI: 10.1016/j.jclepro.2023.138141
8. M. Al-Breiki, Yu. Bicer, Liquified hydrogen vs. liquified renewable methane: Evaluating energy consumption and infrastructure for sustainable fuels, Fuel **350**, 128779 (2023), DOI: 10.1016/j.fuel.2023.128779
9. Na. Wu, K. Lan, Yu. Yao, An integrated techno-economic and environmental assessment for carbon capture in hydrogen production by biomass gasification, Resour. Conserv. Recycl. **188**, 106693 (2023), DOI: 10.1016/j.resconrec.2022.106693
10. A. Ozawa, Yu. Kudoh, Assessing Uncertainties of Life-Cycle CO2 Emissions Using Hydrogen Energy for Power Generation, Energies **14(21)**, 6943 (2021), DOI: 10.3390/en14216943
11. M. Kostelac, I. Pavić, T. Capuder, Economic and environmental valuation of green hydrogen decarbonisation process for price responsive multi-energy industry prosumer, Appl. Energy **347**, 121484 (2023), DOI: 10.1016/j.apenergy.2023.121484
12. Ia. Maynard, A. Abdulla, Assessing benefits and costs of expanded green hydrogen production to facilitate fossil fuel exit in a net-zero transition, Renew. Energy Focus **44**, 85–97 (2023), DOI: 10.1016/j.ref.2022.12.002