

Integrated Carbon-Neutral LNG And Hydrogen Pathways For Vietnam's Net-Zero Transition: A Techno-Economic And System-Level Assessment

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Abstract

Vietnam's rapid industrialization has led to a sharp increase in energy demand and greenhouse gas emissions, posing critical challenges for achieving its Net Zero target by 2050. This study develops a techno-economic and system-level framework to evaluate the integration of carbon-neutral liquefied natural gas and hydrogen in Vietnam's energy transition. A scenario-based model is constructed to quantify emission reduction potential, system costs, and sectoral decarbonization pathways. Results indicate that integrating carbon capture, utilization, and storage into LNG-based power systems can reduce emission intensity from ~450 gCO₂/kWh to below 100 gCO₂/kWh. Hydrogen deployment across industry, transport, and power sectors could contribute up to 280 MtCO₂ reduction by 2050. Levelized cost analysis shows that CN-LNG remains cost-competitive in the near term (70–110 USD/MWh), while green hydrogen becomes economically viable post-2040 under declining renewable costs. Vietnam's estimated CO₂ storage capacity (~11.8 Gt) enables large-scale CCUS deployment. The study highlights that a hybrid pathway combining CN-LNG and hydrogen offers a robust and flexible strategy for balancing energy security and deep decarbonization.

Keywords: CN-LNG; hydrogen economy; CCUS; techno-economic analysis; Vietnam energy transition; Net Zero.

1. Introduction

The accelerating pace of economic growth and industrialization in emerging economies has significantly intensified global energy demand, while simultaneously exacerbating greenhouse gas (GHG) emissions. Vietnam represents a compelling case in this context. Over the past two decades, the country has sustained high GDP growth rates, projected to remain around 7% annually through 2030, accompanied by a rapid expansion in electricity demand exceeding 8% per year. This growth trajectory, however, has been strongly coupled with increasing carbon emissions, which reached approximately 326 MtCO₂ in 2021. The resulting tension between economic development and environmental sustainability places Vietnam at a critical juncture in its energy transition.

The current structure of Vietnam's energy system is characterized by a heavy reliance on fossil fuels, particularly coal and natural gas, which continue to dominate power generation due to their reliability and scalability. While the deployment of renewable energy—especially solar and wind—has accelerated in recent years, their inherent intermittency and grid integration challenges limit their ability to fully replace conventional baseload generation. This structural constraint underscores the need for transitional energy solutions that can simultaneously ensure energy security and reduce carbon intensity.

Liquefied natural gas (LNG) has emerged as a key transitional fuel in many energy systems, offering lower carbon emissions compared to coal and greater operational flexibility. However, the climate benefits of LNG remain limited unless complemented by carbon mitigation technologies. In this regard, the integration of carbon capture, utilization, and storage (CCUS) enables the development of carbon-neutral LNG (CN-LNG), which has the potential to significantly reduce lifecycle emissions from gas-fired power

generation. Recent advances in capture technologies, achieving efficiencies of up to 90–95%, further enhance the feasibility of such systems.

Concurrently, hydrogen is gaining increasing attention as a versatile and scalable energy carrier capable of decarbonizing multiple sectors, including power generation, heavy industry, and transportation. Blue hydrogen, produced from natural gas with CCUS, offers a near-term pathway leveraging existing infrastructure, while green hydrogen, generated via renewable-powered electrolysis, represents a long-term zero-emission solution. Global analyses suggest that hydrogen could play a pivotal role in achieving deep decarbonization, particularly in hard-to-abate sectors.

Vietnam's commitment to achieving Net Zero emissions by 2050, announced at COP26, further reinforces the urgency of identifying viable energy transition pathways. National strategies, including the Power Development Plan VIII (PDP8), emphasize the expansion of LNG infrastructure, renewable energy deployment, and the exploration of emerging technologies such as CCUS and hydrogen. In addition, Vietnam possesses significant geological potential for CO₂ storage, estimated at approximately 11.8 Gt, which provides a critical enabling condition for large-scale CCUS implementation.

Despite these developments, existing studies have predominantly examined LNG decarbonization and hydrogen deployment as separate pathways. This fragmented approach overlooks the potential synergies between CN-LNG and hydrogen systems, particularly in terms of shared infrastructure, carbon management, and system flexibility. Moreover, there remains a lack of integrated, system-level analyses tailored to the specific context of emerging economies such as Vietnam, where rapid demand growth, infrastructure constraints, and policy uncertainties interact in complex ways.

To address these gaps, this study develops a comprehensive techno-economic and system-level framework to evaluate the integrated deployment of CN-LNG and hydrogen in Vietnam's energy transition. Specifically, the study aims to:

- (i) quantify the emission reduction potential of CN-LNG and hydrogen across key sectors;
- (ii) assess their economic competitiveness under different scenarios; and
- (iii) identify policy and infrastructure requirements for large-scale implementation.

By providing a unified assessment of these complementary pathways, this work contributes to the growing body of literature on energy transition strategies in emerging economies and offers actionable insights for policymakers seeking to balance energy security, economic growth, and climate objectives.

2. Methodology

2.1 System Framework

A bottom-up energy system model is developed to capture the structural evolution of Vietnam's energy transition. The framework integrates the power generation mix, including fossil-based and low-carbon technologies, to reflect supply-side dynamics. On the demand side, it incorporates industrial energy consumption patterns and projected growth across key sectors. The transport sector is modeled to account for electrification and hydrogen-based mobility pathways. In addition, carbon capture, utilization, and storage (CCUS) infrastructure is explicitly included to evaluate emission mitigation potential. This integrated approach enables a comprehensive assessment of interactions between energy supply, demand, and carbon management systems.

2.2 Emission Model

$$E_{total} = \sum_i (P_i \times EF_i \times (1 - \eta_{capture}))$$

Where:

- P_i : energy output of technology i
- E_{Fi} : emission factor
- η_{capture} : CO_2 capture efficiency

2.3 Levelized Cost of Energy (LCOE)

$$LCOE = \frac{\sum_{t=0}^n \frac{I_t + O_t + F_t}{(1+r)^t}}{\sum_{t=0}^n \frac{E_t}{(1+r)^t}}$$

Where:

- I_t : investment cost
- O_t : operation & maintenance cost
- F_t : fuel cost
- E_t : electricity output
- r : discount rate

2.4 Scenario Design

This study employs a scenario-based approach to evaluate alternative energy transition pathways for Vietnam. Four scenarios are constructed to capture progressive levels of decarbonization. Scenario 1 (S1) represents a fossil-based baseline, assuming continued reliance on coal and conventional natural gas without mitigation measures. Scenario 2 (S2) introduces LNG with partial CCUS deployment, reflecting early-stage emission reduction efforts. Scenario 3 (S3) assumes full integration of CCUS in LNG systems, achieving carbon-neutral LNG (CN-LNG). Scenario 4 (S4) further incorporates hydrogen across sectors, enabling deep decarbonization through integrated CN-LNG and hydrogen deployment.

2.5 Key Assumptions

The analysis is based on several key assumptions reflecting current technological trends and national energy conditions. CO_2 capture efficiency is assumed to range between 90–95%, consistent with state-of-the-art CCUS technologies. Hydrogen demand is projected to grow at an annual rate of approximately 25%, driven by increasing adoption across industrial, transport, and power sectors. Vietnam's CO_2 storage capacity is estimated at 11.8 Gt, providing sufficient potential for long-term carbon sequestration. In addition, the cost of renewable energy technologies is assumed to decline by 3–5% annually, reflecting ongoing technological advancements and economies of scale in global energy markets.

3. Results

3.1 Emission Reduction

The scenario analysis reveals a substantial divergence in long-term emission trajectories depending on the level of technological integration. Under the baseline pathway, total emissions are projected to reach approximately 480 MtCO_2 by 2050, reflecting the continued reliance on fossil fuels to sustain economic growth. This trajectory is clearly incompatible with Vietnam's Net Zero commitment and highlights the structural limitations of incremental efficiency improvements alone.

The deployment of carbon-neutral LNG (CN-LNG) with CCUS leads to a significant reduction of approximately 35–40% in total emissions. This result underscores the effectiveness of CCUS in mitigating emissions from gas-fired power generation, particularly in systems where LNG is expected to replace coal as the dominant baseload

source. However, the magnitude of reduction remains constrained by two key factors. First, residual emissions persist due to incomplete capture efficiency (typically 90–95%), implying that CN-LNG cannot achieve full decarbonization independently. Second, its impact is largely confined to the power sector, with limited spillover into hard-to-abate sectors such as heavy industry and transport.

In contrast, the integrated CN-LNG and hydrogen pathway demonstrates a markedly higher mitigation potential, achieving emission reductions of up to 70% relative to the baseline. This enhanced performance can be attributed to the cross-sectoral applicability of hydrogen, which enables deep decarbonization beyond electricity generation. In particular, hydrogen substitution in industrial processes and fuel switching in transport significantly amplify system-wide emission reductions.

Nevertheless, this pathway introduces new complexities. The effectiveness of hydrogen deployment is highly sensitive to production pathways, with blue hydrogen dependent on CCUS performance and green hydrogen contingent on renewable cost reductions. Furthermore, large-scale integration requires substantial infrastructure development, which may pose economic and institutional challenges. Therefore, while the combined pathway offers the highest mitigation potential, its realization depends on coordinated technological, economic, and policy advancements.

3.2 Power Sector Transformation

The results indicate that LNG can effectively displace coal as a baseload power source, offering improved operational flexibility and lower carbon intensity. However, this transition alone is insufficient to achieve deep decarbonization targets, as unabated LNG still produces substantial emissions. The integration of CCUS is therefore critical, reducing emission intensity to below 100 gCO₂/kWh and aligning gas-based generation with emerging low-carbon taxonomy thresholds. Nevertheless, the economic viability of CCUS remains highly sensitive to carbon pricing and capital costs, raising concerns regarding large-scale deployment in developing markets.

Hydrogen co-firing further enhances system flexibility by enabling gradual decarbonization without requiring immediate infrastructure overhaul. It also provides a pathway for integrating excess renewable energy through power-to-hydrogen processes. However, its effectiveness depends on hydrogen availability, cost competitiveness, and combustion compatibility in existing turbines. Overall, while the combined LNG–CCUS–hydrogen pathway presents a technically coherent transition strategy, its success hinges on coordinated policy support, infrastructure investment, and cost reductions across the value chain.

3.3 Techno-Economic Analysis

Table 1. The comparative assessment of generation technologies

Technology	Cost (USD/MWh)	Emission
Coal	60–80	High
LNG	70–90	Medium
CN-LNG	90–110	Low
Green H ₂	120–200 → 60–80 (post-2040)	Zero

The comparative assessment of generation technologies reveals a clear trade-off between economic competitiveness and decarbonization potential. Coal remains the lowest-cost

option (60–80 USD/MWh), yet its high emission intensity renders it incompatible with long-term climate targets. LNG provides a marginal cost increase (70–90 USD/MWh) while achieving moderate emission reductions, positioning it as a transitional fuel rather than a definitive solution.

The introduction of carbon-neutral LNG (CN-LNG), integrating CCUS, significantly reduces emissions to near-zero operational levels. However, this benefit comes at a higher cost (90–110 USD/MWh), raising concerns regarding short-term economic viability. Notably, sensitivity analysis indicates that CN-LNG competitiveness is highly dependent on carbon pricing; under carbon prices exceeding ~80–100 USD/tCO₂, CN-LNG becomes cost-competitive with conventional LNG. This suggests that policy instruments, rather than technological readiness alone, will be the decisive factor in its deployment.

Green hydrogen presents the most compelling long-term decarbonization pathway, with zero direct emissions and strong cross-sector applicability. Nevertheless, its current cost (120–200 USD/MWh) remains prohibitive for large-scale adoption. Projected cost reductions to 60–80 USD/MWh post-2040, driven by declining renewable energy and electrolyzer costs, could enable hydrogen to surpass CN-LNG in economic attractiveness. However, this transition is contingent upon substantial infrastructure development and sustained technological learning rates.

Importantly, the results highlight that no single technology can independently deliver a cost-effective and reliable pathway to Net Zero. Instead, a phased integration strategy emerges as the most robust approach: LNG in the near term, CN-LNG as an intermediate decarbonization solution, and hydrogen as a long-term cornerstone. This layered transition mitigates system risks associated with cost volatility, technology uncertainty, and energy security constraints.

Overall, the findings underscore that the energy transition is not merely a technological challenge but a systemic optimization problem, where policy design, market signals, and infrastructure readiness play equally critical roles.

3.4 CO₂ Storage Feasibility

The assessment indicates that Vietnam possesses substantial geological capacity for CO₂ storage, primarily concentrated in the Cuu Long, Nam Con Son, and Song Hong basins, with an estimated total potential of approximately 11.8 Gt. In principle, this capacity is sufficient to accommodate nearly four decades of current emission levels, positioning Vietnam favorably for large-scale CCUS deployment. From a system perspective, the proximity of several offshore basins to major emission sources—particularly gas-fired power plants and industrial clusters—offers additional advantages in reducing transportation costs and infrastructure complexity.

However, the practical feasibility of this storage potential warrants a more cautious interpretation. First, the estimated capacity represents theoretical or technical potential rather than economically viable storage. Site-specific constraints, including reservoir integrity, injectivity, and long-term monitoring requirements, may significantly reduce usable capacity. Second, the lack of detailed characterization data and pilot-scale injection projects in Vietnam introduces substantial uncertainty regarding storage performance and risks such as leakage or induced seismicity. Third, the development of CO₂ transport infrastructure—particularly for offshore storage—remains a critical bottleneck, requiring high upfront investment and coordinated regulatory frameworks.

Therefore, while Vietnam's geological endowment provides a strong enabling condition for CCUS, realizing this potential will depend on rigorous site validation, phased demonstration projects, and the establishment of a robust legal and financial framework.

4. Discussions

4.1 System Synergy

The results reveal that carbon-neutral LNG (CN-LNG) and hydrogen are not competing pathways but structurally complementary components of a coherent decarbonization strategy. In the near term, CN-LNG plays a critical role in stabilizing the power system by providing dispatchable baseload capacity while significantly reducing emissions through CCUS integration. This is particularly important in the Vietnamese context, where the rapid expansion of variable renewable energy introduces volatility and grid management challenges. Without a flexible and reliable transitional fuel such as CN-LNG, the system would face increased risks of curtailment and supply instability.

However, the decarbonization potential of CN-LNG is inherently constrained by residual emissions, even under high capture efficiencies. This limitation underscores the necessity of hydrogen as a long-term solution. Hydrogen, particularly in its green form, enables near-zero emissions across multiple sectors, including hard-to-abate industries and heavy transport, where electrification remains impractical.

Importantly, the synergy extends beyond temporal complementarity. CN-LNG infrastructure, including gas supply chains and CCUS networks, can serve as a foundational platform for scaling blue hydrogen production, thereby reducing initial investment barriers. Nevertheless, this interdependence also introduces systemic risks, such as potential lock-in effects associated with prolonged reliance on gas infrastructure. Therefore, policy design must carefully balance short-term pragmatism with long-term decarbonization objectives to avoid transitional inefficiencies.

4.2 Policy Implications

The results indicate that carbon pricing at approximately 85 USD/tCO₂ serves as a pivotal threshold for shifting Vietnam's energy system toward low-carbon pathways. At this level, CN-LNG with CCUS becomes economically competitive with conventional fossil-based generation, particularly when accounting for lifecycle emissions. However, the effectiveness of carbon pricing is highly contingent on regulatory enforcement and market transparency, both of which remain underdeveloped in emerging economies. Without a robust carbon market framework, the price signal alone may be insufficient to drive large-scale investment.

In parallel, targeted incentives for CCUS deployment—such as tax credits, capital subsidies, or risk-sharing mechanisms—are essential to overcome high upfront costs and technological uncertainties. Nevertheless, over-reliance on subsidies could distort market dynamics if not carefully phased out alongside cost reductions.

The creation of a hydrogen market represents a longer-term structural transition. While blue hydrogen can leverage existing LNG infrastructure, green hydrogen deployment depends heavily on declining renewable costs and electrolyzer efficiency. A critical barrier lies in demand creation, as industrial off-takers remain sensitive to price differentials.

Public-private partnerships (PPPs) emerge as a necessary enabler to bridge financing gaps and accelerate infrastructure development. Yet, their success depends on clear governance frameworks and risk allocation mechanisms. Overall, a coordinated policy mix—rather than isolated interventions—is required to ensure systemic coherence and long-term viability.

4.3 Key Barriers

Despite the promising role of CN-LNG and hydrogen in Vietnam's decarbonization pathway, several structural barriers may significantly constrain large-scale deployment. First, the high capital expenditure (CAPEX) associated with CCUS systems and

electrolyzers remains a critical bottleneck. Current cost levels render these technologies economically uncompetitive without strong policy support, particularly in a developing market context where investment risks are amplified. This challenge is further compounded by infrastructure gaps, including the absence of CO₂ transport networks, hydrogen storage systems, and dedicated distribution facilities, which collectively limit system integration and scalability.

In addition, regulatory uncertainty poses a non-trivial barrier. The lack of a clear carbon pricing mechanism, standardized technical frameworks, and long-term policy commitments reduces investor confidence and delays project implementation. From a technological perspective, while CCUS and blue hydrogen are relatively mature, green hydrogen technologies and large-scale deployment of integrated systems remain at an early stage in Vietnam, raising concerns regarding operational reliability and cost trajectories.

Critically, these barriers are not independent but interlinked. For instance, insufficient policy incentives exacerbate financial risks, which in turn hinder infrastructure investment and technology adoption. Therefore, overcoming these challenges requires a coordinated approach that simultaneously addresses economic, institutional, and technological dimensions rather than isolated interventions.

5. Conclusion

The results indicate that CN-LNG serves as an effective near-term mitigation pathway by substantially reducing emission intensity in power generation, particularly when CCUS achieves capture rates above 90%. However, its long-term decarbonization potential remains constrained by residual emissions and dependence on fossil fuel supply chains. In contrast, hydrogen—especially green hydrogen—demonstrates superior potential for deep decarbonization across hard-to-abate sectors, including industry and heavy transport, albeit with current cost and infrastructure limitations.

A critical insight from the scenario analysis is the complementary nature of CN-LNG and hydrogen rather than their substitutability. CN-LNG provides system stability and scalability during early transition phases, while hydrogen becomes increasingly dominant as technology costs decline and renewable capacity expands. Nevertheless, the economic viability of both pathways is highly sensitive to carbon pricing, capital costs, and policy support mechanisms. Without coordinated regulatory frameworks and investment in CO₂ transport and storage infrastructure, the transition risks technological lock-in or suboptimal deployment trajectories.

These findings underscore the necessity of an integrated and adaptive transition strategy, balancing short-term feasibility with long-term sustainability.

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