

Transforming Ammonia Production: Evaluating Energy Trends and Carbon Management Strategies in Trinidad and Tobago

Dillon Asa Ramsook*, Rean Maharaj, and Donnie Boodlal

ABSTRACT

The ammonia industry of Trinidad and Tobago (T&T) remains vital to its national economy, consuming approximately 17% of the country's total natural gas supply as of 2023. Given the critical need to align the sector with global decarbonization efforts, this study evaluates the economic resilience, energy efficiency trends, and environmental footprint of the ammonia industry over two decades (2004–2023). Findings indicate that national ammonia plant utilization rates have declined to roughly 70% due to persistent natural gas supply constraints, causing energy intensity to rise to approximately 40.41 MMBtu per metric ton of ammonia (NH₃). However, improved production levels closer to the design capacity positively correlate with enhanced operational efficiency. Employing the IPCC (2006) Tier 2 guidelines for greenhouse gas (GHG) accounting, this study demonstrates that the strategic utilization of ammonia-derived CO₂ in existing downstream processes (urea and methanol synthesis) can significantly decrease the sector's net CO₂ emissions by approximately 60–80%. Furthermore, the analysis identified promising decarbonization pathways, including the adoption of carbon capture, utilization, and storage (CCUS), renewable hydrogen integration, and targeted process optimization strategies. This research emphasizes the necessity of robust, data-driven policy frameworks, strategic public-private sector partnerships, and proactive international collaboration to effectively navigate the transition toward a lower-carbon ammonia sector. These measures are crucial for T&T in both environmental stewardships and their competitive advantage amid evolving global carbon market conditions.

Keywords: Ammonia, carbon intensity benchmarking, energy efficiency analysis, process emissions assessment.

Submitted: June 23, 2025

Published: August 25, 2025

 10.24018/ejenergy.2025.5.4.172

Process Engineering Unit, The University of Trinidad and Tobago, Trinidad and Tobago.

*Corresponding Author:
e-mail: dillon.ramsook@utt.edu.t

1. INTRODUCTION

Ammonia (NH₃) is central to global agriculture, industry, and emerging energy applications. Approximately 80% of the ammonia produced globally supports nitrogen-based fertilizers, significantly enhancing crop yields to feed nearly half of the world's population [1]. Additionally, ammonia is crucial for manufacturing plastics, explosives, and pharmaceuticals and is increasingly considered a viable carbon-neutral hydrogen carrier and maritime fuel [2]. The global ammonia market, valued at USD 72.3 billion in 2022, is anticipated to expand by 5.8% annually by 2030 owing to rising food demand and decarbonization efforts [3]. However, ammonia production remains fossil-fuel-dependent, contributing approximately 1.8% of

global CO₂ emissions, highlighting the urgent need for sustainable production pathways [1].

Trinidad and Tobago (T&T), a major ammonia exporter producing over 5.6 million metric tons annually, leverages abundant natural gas resources, utilizing 17% of its national gas supply for ammonia synthesis via steam methane reforming (SMR) [4], [5]. This industrial complex, which includes ammonia, methanol, urea, and UAN, contributes approximately 12% of Trinidad and Tobago (T&T)'s GDP and supports over 30,000 jobs [6]. However, this sector faces challenges due to finite gas reserves and significant environmental impacts. T&T's ammonia production emits 3.5–4.0 MT CO₂/MT NH₃, exceeding global benchmarks of 2.2–2.8 MT CO₂/MT NH₃ due to outdated infrastructure and suboptimal processes [1], [7].



Growing global decarbonization efforts, including initiatives such as the Paris Accord and emerging carbon border adjustment mechanisms (CBAMs), could threaten T&T's competitive market position unless emission standards are met [8]. Advancements in blue with carbon capture, utilization, and storage (CCUS) and green ammonia (renewable hydrogen-based) further shift global markets, presenting competitive pressure [9]. For T&T, integrating CCUS technologies or adopting hydrogen-natural gas hybridization provides pragmatic solutions to reduce emissions and maintain economic viability [10], [11]. This study evaluates the ammonia sector of T&T, examines gas supply dynamics and CO₂ utilization opportunities, and identifies actionable decarbonization strategies aligned with climate targets.

2. LITERATURE REVIEW

2.1. Global Overview of Ammonia Production and Market Dynamics

Ammonia production primarily relies on the century-old Haber-Bosch process, which transforms global agriculture through synthetic nitrogen fertilizers. Despite improvements such as advanced catalysts, waste heat recovery, and pressure swing adsorption, the process remains energy-intensive, consuming 1–2% of global energy and emitting approximately 1.8% of anthropogenic CO₂ [12], [13]. Feedstock choices heavily influence these emissions, notably in coal-dependent regions such as China, whose ammonia production generates 2.5–3.5 times more CO₂ per ton than gas-based systems [14].

Although approximately 80% of the global ammonia is utilized in agriculture, new applications in energy storage, hydrogen transport, and maritime fuel are emerging. Japan, for example, plans a 20% ammonia-coal blend in thermal power plants by 2030, whereas European projects assess ammonia as a hydrogen carrier for steel decarbonization [1], [15], [16]. However, scaling green ammonia production through renewable electrolysis remains economically and technically challenging [17].

Feedstock availability and policies drive these regional disparities. Gas-rich nations such as Russia and the U.S. benefit from competitive pricing, whereas coal-dependent countries face growing pressure to implement CCUS [18]–[20]. Countries such as Australia and Saudi Arabia leverage abundant renewable resources to establish large-scale green ammonia plants, positioning themselves as future leaders [21], [22]. Simultaneously, carbon border adjustment mechanisms (CBAMs) threaten high-emission ammonia producers, potentially reshaping global trade [23].

“Blue” ammonia, integrating CCS with conventional SMR processes, is becoming attractive in regions with mature gas infrastructure, such as Norway and the U.S. Gulf Coast [24]. Conversely, green ammonia remains more expensive but is expected to become cost-competitive by 2030 owing to falling renewable energy and electrolyzer costs [5], [25]. Hybrid strategies, blending green hydrogen with conventional SMR production, could provide practical transitional solutions that are particularly relevant for gas-dependent nations such as T&T [26].

2.2. T&T's Petrochemical Ecosystem: Ammonia as a Strategic Pillar

Supported by its abundance in natural gas reserves, T&T has established a globally recognized petrochemical sector, with ammonia serving as a cornerstone of its industrial landscape [27]. Over the past six decades, a range of ammonia facilities have been commissioned at the Point Lisas Industrial Estate, each adopting various process technologies (e.g., Braun, Fluor, M.W. Kellogg, and Kellogg Advanced Ammonia Process) and benefiting from proximity to upstream gas sources. Table I provides an overview of major ammonia producers, their start-up years, technologies, and reported capacities according to the Ministry of Energy and Energy Industries (MEEI) [27]. Key ammonia facilities, including start-up years, capacities, and technologies, are listed in Table I [28]–[32].

A notable constraint in assessing the T&T's ammonia sector is the lack of up-to-date capacity data. Although Table I reflects official or historically published capacities, unpublicized debottlenecking projects, partial shutdowns, or indefinite closures complicate year-to-year comparisons. For instance, because of the private operating agreements of some plants, the base capacities may be adjusted internally without corresponding public disclosures. Similarly, corporate decisions such as those leading to Nutrien's partial closure may not be systematically captured in national databases and only in company-specific reports.

Despite these operational and reporting challenges, ammonia remains a strategic pillar of the petrochemical ecosystem of T&T. Historically, the sector has contributed 10%–12% of the national GDP while employing thousands of workers across production, maintenance, logistics, and ancillary services [33]. Ammonia's role in T&T's broader gas-based industries is further amplified by its downstream linkages to methanol, urea, and other nitrogen-based products, such as UAN. These interdependencies not only reinforce T&T's position as a premier exporter of bulk petrochemicals but also highlight its influence on state revenue and foreign exchange earnings.

However, to maintain global competitiveness in the rapidly evolving energy and fertilizer market, stakeholders must address persistent data gaps and operational constraints. Ongoing natural gas supply volatility has led to suboptimal utilization rates, raising questions about the long-term resilience of T&T ammonia plants [34]. Moreover, the advent of CBAM—notably the European Union's “carbon tax” on high-emission imports—poses a significant risk for T&T's export-oriented ammonia sector if carbon intensity remains high [35]. Similar levies are under consideration in other markets, potentially exacerbating the competitiveness gap for producers operating older and less efficient plants. As global demand shifts toward low- or zero-carbon ammonia, accurately tracking each facility's capacity, energy intensity, and emissions is essential for evaluating potential decarbonization strategies and formulating timely policy interventions.

TABLE I: MAJOR AMMONIA PLANTS IN TRINIDAD AND TOBAGO: START-UP YEARS, TECHNOLOGIES, AND ANNUAL PRODUCTION CAPACITIES

Plant	Start-up year	Technology	Capacity (MT NH ₃ /year)	Description
Yara trinidad limited	1959	Braun	285,000	Ceased operations in 2019 due to global restructuring [28]
Tringen I	1977	Fluor	500,000	Joint venture between NGC and global industry partners.
Tringen II	1988	Braun	495,000	Reported production suggests internal upgrades.
Nutrien 01	1981	M.W. Kellogg	445,000	Formerly PCS; partial closure (340,000 MT) in 2020 [30].
Nutrien 02	1981	M.W. Kellogg	445,000	
Nutrien 03	1996	Braun	250,000	
Nutrien 04	1998	KAAP	650,000	
Point lisas nitrogen limited	1998	KAAP	650,000	Operates under long-term gas contracts.
Caribbean nitrogen company	2002	KAAP	650,000	Proman-led joint venture.
Nitrogen 2000 (N2K)	2004	KAAP	650,000	
AUM ammonia	2009	KAAP	650,000	Operated by proman group.

2.3. Environmental Impact and Green House Gas (GHG) Emissions in Ammonia Production

Ammonia production in T&T generates significant GHG emissions because of its reliance on SMR, where CO₂ is released during both hydrogen production and natural gas combustion in high-temperature reformers [36]. According to the IPCC 2006 Guidelines, ammonia-related emissions fall under the IPPU sector, and given available national data from the MEEI, the Tier 2 methodology is most applicable for estimating emissions in T&T [37]. This method uses the annual ammonia output, fuel consumption data, and carbon content factors to derive emissions specific to local process conditions.

Studies such as Zhou *et al.* [38] and Chen *et al.* [39] support the IPCC's Tier 2 application, demonstrating how detailed sectoral inventories enable both trend tracking and mitigation scenario modelling. These studies show that emissions can be reduced through feedstock changes, efficiency improvements, and long-term adoption of CCUS or biorefineries.

IPCC guidelines further simplify accounting by combining feedstock and fuel emissions, allowing the total SMR-related CO₂ to be reported as one figure under IPPU [37]. While this improves completeness, net emissions could be overestimated if CO₂ is reused downstream. In T&T, the by-product CO₂ from ammonia production is partially consumed during the synthesis of methanol and urea. However, national reports such as the Third National Communication (TNC) do not currently reflect these offsets, leading to potential inaccuracies [40].

Additional complexity arises because some methanol plants may produce CO₂ independently via partial oxidation of natural gas. In the absence of plant-level transfer data, stoichiometric approximations can be used to estimate CO₂ utilization in urea and methanol. Although not exact, this approach offers a practical solution for inventory refinement until better disaggregated data become available [41].

2.4. Decarbonization Pathways and Economic Resilience in Gas-Dependent Economies

Transitioning to low-carbon ammonia in gas-dependent economies, such as T&T, requires balancing technological advancement with economic resilience. Blue ammonia, integrating CCUS with SMR, can reduce CO₂ emissions by up to 90%, while green ammonia, derived from renewable-powered electrolysis, offers zero-emission output but remains costlier, with cost parity expected post-2030 [42], [43]. Given T&T's limited land for large-scale renewables, fully green pathways may not be feasible in the short term. However, hybrid solutions—blending renewable hydrogen with SMR—represent a pragmatic step forward [44].

Saygin *et al.* [45] underscored the importance of assessing energy efficiency, emissions, and environmental impacts across ammonia pathways to guide investment. For T&T, these analyses are critical given the sector's centrality to GDP and its exposure to emerging carbon regulations, such as CBAMs.

It is vital to maintain a reliable gas supply. Cross-border projects (e.g., Dragon Gas with Venezuela) and LNG reallocation strategies offer short-term solutions, although geopolitical risks persist [46]. Simultaneously, the sector's overreliance on natural gas raises concerns about diversification. While gas currently yields the highest return for ammonia production, Mersch *et al.* [47] estimated that blue ammonia is approximately 50% more expensive than conventional gas-based ammonia, with green ammonia even costlier, albeit more viable under CO₂ pricing schemes.

Strategic investments in non-energy sectors or value-added petrochemicals can hedge against global market shifts. Complementary policies, such as carbon taxes or feed-in tariffs, and international partnerships for technology transfer are key enablers [48]. However, stakeholder divergence poses challenges: global operators may resist green investments, while local communities prioritize employment and equity [49], [50].

Mechanisms such as T&T's Just Transition Commission could mediate these tensions by channelling CCUS revenues into retraining and community-scale renewable

projects [51], ensuring a just and inclusive pathway for decarbonization.

2.5. Economic and Logistical Challenges of Implementing CCUS and Renewable Hydrogen in T&T

Implementing decarbonization pathways such as CCUS, as well as renewable hydrogen integration, presents several economic, technical and logistical challenges specific to T&T. While the theoretical potential for these technologies has been acknowledged, the practical feasibility depends heavily on infrastructure readiness, investment climate, and regulatory support.

2.5.1. CCUS Deployment Constraints

The application of CCUS in T&T, particularly within the ammonia sector, hinges on the availability of suitable geological storage, transport infrastructure, and high-purity CO₂ streams. Boodlal *et al.* (2018) estimated that T&T can capture approximately 8 million tonnes of CO₂ per year from industrial sources, but the development of storage reservoirs—onshore or offshore—requires comprehensive site-specific assessments. Additionally, there is currently no fully developed legal or regulatory framework to govern CO₂ transport and sequestration [11]. High capital costs associated with compression, pipeline installation and long-term monitoring further exacerbate these barriers.

2.5.2. Renewable Hydrogen Integration

While green hydrogen offers a long-term decarbonization pathway, its viability in T&T is limited by the current scale of renewable energy deployment. Electrolysis systems require stable and low-cost electricity, which is challenging in the context of T&T's fossil-fuel-dominated energy mix [5]. Hydrogen production also demands substantial investments in water treatment (e.g., desalination), electrolyser systems, and hydrogen storage and distribution infrastructure. Without a clear national hydrogen policy or demand-side commitments (such as long-term off-take agreements), early-stage projects may struggle to achieve economic viability [40].

2.5.3. Regional Relevance

The University of Trinidad and Tobago's CCUS feasibility work highlights the potential for CO₂-EOR in depleted oil fields, but emphasizes that site-specific geotechnical assessments are needed. Additionally, Caribbean-based studies show that countries like Barbados and Dominica are piloting renewable hydrogen and ammonia strategies using small-scale solar-powered electrolyzers and storage hubs, although scale and export-readiness remain limited. These experiences underline the importance of financing mechanisms, cross-sector collaboration, and regulatory alignment for implementation in small gas-dependent economies like T&T.

3. OBJECTIVES

The primary objective of this study was to critically assess the ammonia sector in T&T, focusing on its economic resilience, environmental impact, and potential

pathways for decarbonization in light of international trends and drivers. Given the sector's strategic importance to the national economy and its significant contribution to GHG emissions, this review seeks to bridge data gaps, recommend areas for additional collection, and provide actionable insights to inform policies and industrial practices. The objectives of this study are as follows:

1. Quantifying the allocation of natural gas across T&T's petrochemical sectors, with a focus on ammonia production, to understand the sector's dependency on finite gas reserves and its implications for long-term sustainability.
2. The energy intensity of ammonia production at the national level was assessed by comparing historical and current trends to identify factors influencing operational efficiency and resource utilization.
3. Develop the latest GHG inventory for the ammonia sector using the IPCC (2006) Tier 2 guidelines, accounting for both process and fuel-related CO₂ emissions, and identifying the key emission hotspots within the production process.
4. The extent to which CO₂ emissions from ammonia production can be captured and utilized in the synthesis of ammonia derivatives and methanol from process stream capture, thereby evaluating the sector's contribution to circular carbon practices and its potential for reducing net emissions.
5. Explore possible technological and policy interventions, including CCUS and integration with renewable energy sources, to support the transition toward low-carbon ammonia production. Provide evidence-based recommendations for stakeholders, including policymakers, industry leaders, and environmental regulators, to enhance the sector's competitiveness, while aligning with national and international climate commitments.

4. METHODOLOGY

This study employed a multi-tiered approach to assess, review, and provide context for the performance and environmental impact of T&T's ammonia sector and identify its indicative GHG inventory due to downstream uses of CO₂. The analytical steps used in this study are outlined in Fig. 1, which presents the methodological framework applied to assess the ammonia sector's emissions and performance.

4.1. Data Compilation and Conversion

Monthly natural gas production and utilization data (MMSCF/day) were obtained from MMEI reports [52]. These data include sectoral allocations to ammonia, methanol, LNG, power generation, and other minor sectors. To compare consumption on an energy basis, a conversion factor of 1 MMSCF = 1037 MMBtu was applied.

First, the monthly MMSCF/day values were multiplied by the conversion factor to determine the MMBtu/day, which were then aggregated into an annual figure by scaling to the total number of days in each calendar year



Fig. 1. Methodological framework for assessing energy trends and CO₂ emissions in T&T's ammonia sector.

between 2004–2023. This step enables the calculation of yearly sectoral gas consumption and facilitates direct comparisons across different petrochemical processes.

4.2. Sectoral Allocation Analysis

Using the annualized MMBtu figure, the fraction of natural gas allocated to each key sector (ammonia, methanol, and LNG) was determined using (1), and natural gas utilization was calculated by sector percentage:

Share of Sector (k) (%)

$$= \frac{\text{Annual MMBtu Consumed by Sector, } k}{\text{Total Annual MMBtu Produced}} \times 100\% \quad (1)$$

where discrepancies arose between the total natural gas produced and total utilized (typically around 4%); possible reasons are discussed.

4.3. Ammonia Plant Utilization

Individual ammonia plant production data (MT of ammonia per year) were collected from publicly available sources (e.g., company reports and industry publications). Each plant's published nominal capacity (in MT/year) was compared with its actual annual output to compute the

capacity utilization rate in (2), calculating the utilization rate for individual ammonia plants:

Utilization Rate (%)

$$= \frac{\text{Annual Ammonia Production (MT)}}{\text{Published Capacity (MT)}} \times 100\% \quad (2)$$

Any observed anomalies, such as production exceeding publicly stated capacity, were investigated for potential unpublicized capacity upgrades or reporting discrepancies.

4.4. Energy Intensity of Ammonia Production

A national-level energy intensity or ratio for ammonia production was calculated using (3), similar to other studies [38], [45], by dividing the total annual MMBtu of natural gas allocated to ammonia by the total annual ammonia production (in metric tons), and calculating the national level energy ratio per ton of ammonia:

$$\text{Energy Ratio} \left(\frac{\text{MMBtu}}{\text{MT NH}_3} \right) = \frac{\text{Annual MMBtu of Natural Gas for Ammonia}}{\text{Annual Ammonia Produced (MT)}} \quad (3)$$

This ratio served as a proxy for the overall energy intensity of the ammonia sector in T&T.

4.5. GHG Inventory Estimation

Following the IPCC (2006) Tier 2 Guidelines [37], the total fuel requirement (TFR_i) for fuel type *i* used in ammonia production is given by (4). Similar methods have been used in studies cited in the literature [38], [39]. Total fuel requirement calculation according to IPCC [37]

$$\text{TFR}_i = \sum_j (\text{AP}_{ij} \text{FR}_{ij}) \quad (4)$$

where AP_{ij} is the annual ammonia production (metric tons) using fuel type *i* in process *j* and FR_{ij} is the specific fuel consumption for fuel type *i* in process *j* (GJ/tonne ammonia).

Total Gross CO₂ emissions (E_{CO₂}) were then computed in (5), total gross CO₂ emissions for ammonia production:

$$E_{\text{CO}_2} = \sum_i (\text{TFR}_i \times \text{CCF}_i \times \text{COF}_i) \times \frac{44}{12} - R_{\text{CO}_2} \quad (5)$$

where TFR_i is the total fuel requirement for fuel type *i* (GJ), CCF_i is the carbon content factor (kg C/GJ), COF_i is the carbon oxidation factor (fraction), 44/12 is the conversion of carbon (C) to CO₂ (molecular mass ratio), and R_{CO₂} is the mass of CO₂ recovered for downstream use (e.g., urea or methanol).

4.6. CO₂ Utilization in Downstream Products

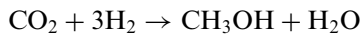
As direct data on CO₂ usage for urea and methanol production at each plant were unavailable, stoichiometric relationships were used to estimate the volume of CO₂ consumed. Two primary reactions are considered in this study.

- *Urea Synthesis:*



where the molar masses for CO₂ is 44.09 g/mol, and urea is 60.06 g/mol, every 1 mol of urea formed, 1 mol of CO₂ is consumed, thus 1 tonne of urea requires 44.09/60.06 or 0.73 CO₂ per tonne of urea.

- *Methanol Synthesis:*



where the molar masses for methanol is 32.04 g/mol, every 1 mol of methanol formed, 1 mol of CO₂ is consumed, thus 1 tonne of urea requires 44.09/32.04 or 1.38 CO₂ per tonne of methanol.

Given annual urea and methanol production data [52], estimates were computed using (6) and (7), respectively.

Equation (6), estimate for CO₂ required for urea production:

$$\text{CO}_2 \text{ for Urea} \approx \text{Urea Production (tonnes)} \times 0.73 \quad (6)$$

Equation (7), estimate for CO₂ required for methanol production:

$$\begin{aligned} \text{CO}_2 \text{ for Methanol} &\approx \text{Methanol Production} \\ &(\text{tonnes}) \times 1.38 \end{aligned} \quad (7)$$

Although this study assumes that all urea and methanol in T&T utilize CO₂ derived from ammonia production, such an assumption may not align with the actual sourcing of CO₂ across all facilities; in practice, not every urea or methanol plant in T&T relies solely on ammonia-based CO₂. However, applying this assumption allows for a theoretical assessment of maximal CO₂ utilization and its corresponding effect on net emissions, where data are not available.

4.7. Net CO₂ Emissions and Intensity

The possible net CO₂ emissions attributable to ammonia were determined by subtracting the estimated CO₂ used in urea and methanol production from the total gross ammonia-related CO₂ emissions in (8), possible net CO₂ emissions from downstream utilization in Urea and Methanol production:

$$\begin{aligned} \text{Net CO}_2 &= E_{\text{CO}_2}^{(\text{ammonia})} - (\text{CO}_2 \text{ for Urea} \\ &+ \text{CO}_2 \text{ for Methanol}) \end{aligned} \quad (8)$$

Finally, the net CO₂ emissions intensity (MT CO₂ per MT of ammonia) was computed by dividing the net ammonia CO₂ emissions by the total ammonia production. Year-to-year variations were analyzed to determine whether changes stemmed from fluctuations in ammonia production volumes, shifts in downstream CO₂ utilization, improvements in process efficiency, and/or changes in natural gas supply constraints. The analysis follows IPCC (2006) guidelines and excludes other greenhouse gases (e.g., CH₄, N₂O). Process emissions from ammonia plants typically stem from SMR, where the feed stream exhibits a very high CO₂ concentration (often exceeding 95 mol%), while the fuel stream contains a combustion-related CO₂ fraction.

4.8. Data Gaps and Assumptions

A summary of data limitations and assumptions used in this analysis is provided in Table II. Future studies could address these issues by collecting more granular data for T&T.

4.9. Sensitivity and Uncertainty Considerations

While this study provides a national-level assessment of ammonia production and associated CO₂ emissions in T&T, several assumptions and data limitations introduce inherent uncertainties. Table II previously outlined key data gaps and assumptions; here, we briefly explore how deviations from those assumptions could impact the results.

4.9.1. CO₂ Utilization Assumption

This study assumes that all CO₂ used in urea and methanol production is derived from ammonia plants. In reality, methanol facilities may generate CO₂ via partial oxidation independently. If only 50% of the estimated downstream CO₂ is sourced from ammonia production (rather than 100%), the calculated net CO₂ emissions would increase by approximately 1.2–1.8 Mt annually, depending on methanol/urea output in a given year. This corresponds to a ~20%–25% increase in net emissions relative to the current estimates.

TABLE II: KEY DATA GAPS AND ASSUMPTIONS IN AMMONIA SECTOR ANALYSIS FOR TRINIDAD AND TOBAGO

#	Gap	Description	Assumption
1	Plant-specific gas consumption	Facility-level gas use unavailable. National-level data used to approximate sector-wide averages.	National values reflect average sector performance.
2	Capacity revisions and retrofits	Unpublicized debottlenecking or shutdowns may skew nominal capacity data.	Published capacity is reasonably representative.
3	CO ₂ capture and allocation	Lack of plant-level CO ₂ capture/utilization data.	All urea/methanol CO ₂ assumed to come from ammonia synthesis (best-case scenario).
4	Downstream production figures	Limited disaggregated plant data for methanol and urea production.	National-level production figures assumed consistent with stoichiometry.
5	Temporal averaging and reporting	Rounding and monthly averaging from MEEI datasets may introduce minor discrepancies.	These discrepancies (~4%) do not affect core trends.
6	Technology and operational variability	Aggregated data masks plant-to-plant variability in age, efficiency, and maintenance.	Sector-wide analysis assumed to represent weighted average conditions.

4.9.2. Plant-Level Efficiency Variation

The national energy intensity ratio assumes sectoral averages. Literature (e.g., Saygin *et al.*, 2023) suggests that older SMR-based plants may have energy intensities 10–15% higher than newer plants. If older facilities dominate production during low-output years, the true energy intensity could be underestimated by 3–5 MMBtu/tonne NH₃.

4.9.3. Production Data Variability

Some plant capacities and outputs were approximated due to missing or outdated public disclosures. A $\pm 5\%$ error in ammonia production estimates (rounding or corporate reporting lag) would translate to a ± 1.8 – 2.0 MMBtu/tonne variation in energy intensity and ± 0.15 Mt CO₂ fluctuation in gross emission values.

4.9.4. Gas Allocation Rounding

MEEI gas allocation data were averaged monthly and may mask peak/dip events. A $\pm 4\%$ discrepancy, already acknowledged, could slightly shift intersectoral trends, particularly between ammonia and methanol.

4.9.5. Impact on Policy Interpretation

Even accounting for these uncertainties, the overarching trends—such as the link between low production and higher energy intensity, or the importance of downstream CO₂ reuse—remain valid. However, these factors highlight the need for disaggregated plant-level data to support policy actions and international reporting requirements (e.g., under ISO 14064 or IPCC Tier 3 frameworks).

5. RESULTS & DISCUSSION

5.1. Sectoral Analysis

In 2023 (Fig. 2), LNG accounted for 47% of gas consumption, followed by methanol (22%), ammonia (17%), and power generation (11%). The remainder is distributed among smaller sectors, including cement, ammonia derivatives, and gas-to-liquid processes. LNG, methanol, and ammonia remain the backbone of the T&T's gas economy,

collectively consuming over 85% of the total supply. Natural gas allocation in 2023 shows LNG, ammonia, and methanol as dominant consumers (Fig. 2).

Historically (Fig. 3), LNG has maintained a ~55% share of national gas use, with methanol and ammonia at ~16% each, and power generation at ~8%. This distribution remained steady until 2014, when gas production began to decline. In response, T&T prioritized gas allocation to LNG given its higher export value. Despite these measures, the output continued to fall, and LNG's share of LNG temporarily dipped in 2021 before rebounding in 2022–2023.

These trends reveal persistent challenges in gas supply security and raise concerns regarding long-term sustainability. T&T's cross-border efforts, such as the Dragon Gas Project with Venezuela, may help stabilize supply and sustain downstream output if geopolitical uncertainties are resolved [53], [54]. However, such efforts must be paired with refined gas utilization data and sector-level reporting to support informed decisions in the transitioning global energy landscape.

5.2. Plant Utilization

Fig. 4 compares the annual utilization rates of ammonia plants over two decades, illustrating operational fluctuations and plant-level disparities. Although some facilities have undergone unpublicized capacity revisions, limiting straightforward comparisons, several performance patterns are evident. Yara's plant (green rhombus) operated consistently above the national average until its 2019 closure, which impacted the national utilization figures [55]. Tringen I (orange circle) and Tringen II (green cross) also often exceeded the national average, although Tringen I experienced a decline between 2011 and 2015 due to gas shortages, reaching 53% in 2014. Tringen II reported a throughput above its known design capacity, suggesting possible internal upgrades that were not formally disclosed.

Nutrient facilities (green circle, blue square before 2018) maintained utilization above 80% in most years, with dips in 2022 and 2023. The company's continued investment in Trinidad and Tobago, home to over 35% of its global ammonia output, demonstrates strong confidence

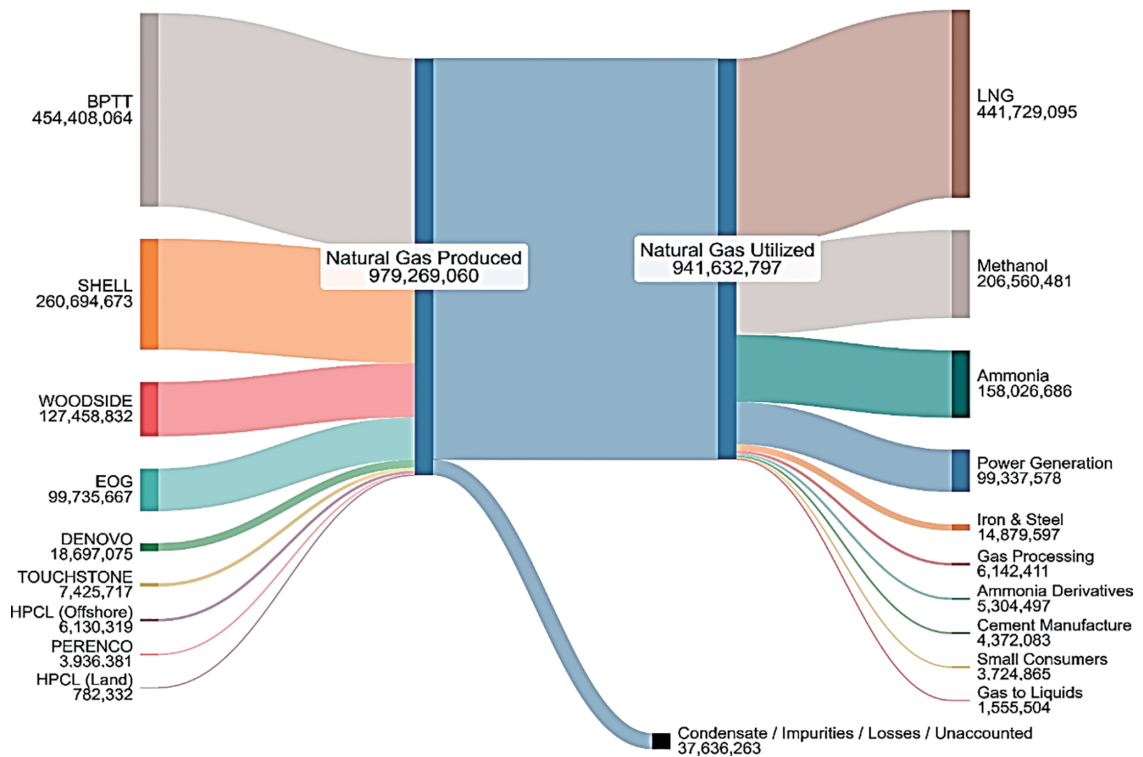


Fig. 2. Sectoral distribution of natural gas utilization in T&T, 2023 (MMBtu). Production is concentrated, with BPTT and Shell contributing 73% and smaller producers supplying the rest. A gap of ~4% between production and utilization was noted, likely due to condensate removal, impurities, system losses, or averaging errors from the MEEI [6]. These discrepancies highlight the need for more precise accounting in order to guide energy planning.

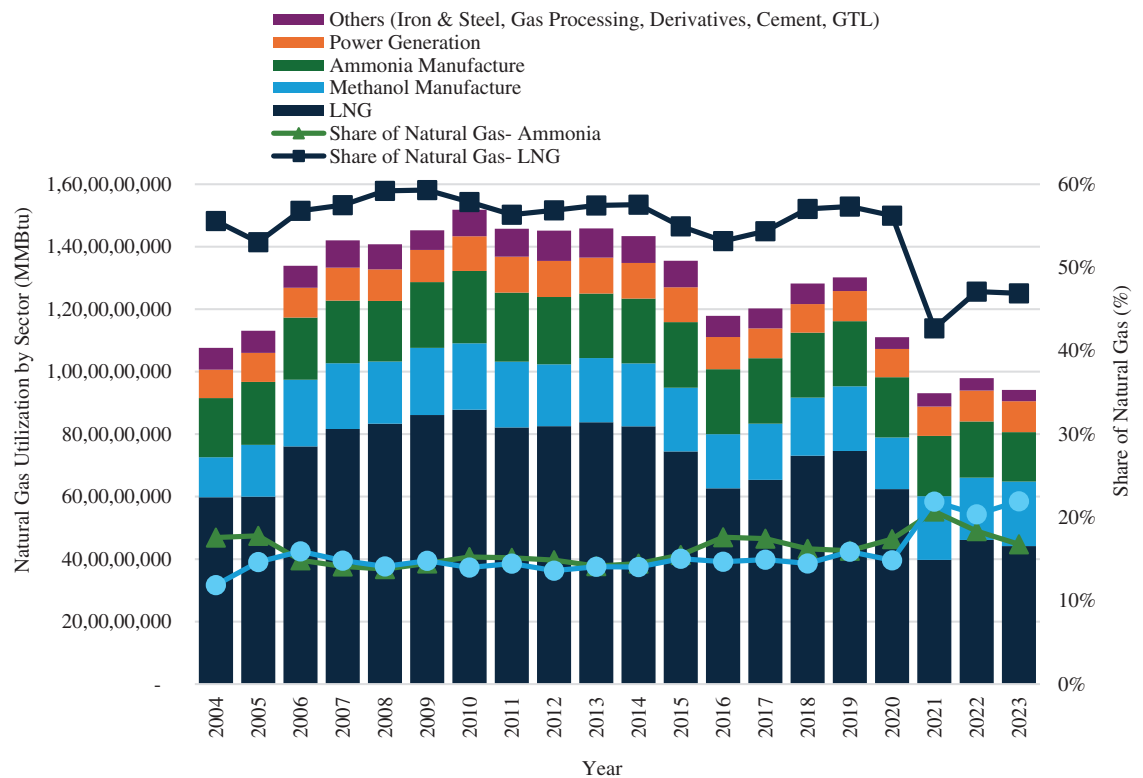


Fig. 3. Trends in sectoral natural gas allocation in T&T, 2004–2023.

in the local gas availability and future production [56]. PLNL (purple rhombus) consistently recorded some of the highest utilization levels, supported by a recently renegotiated gas-supply agreement [29], [31]. CNC (green star), N2000 (dark blue triangle), and AUM complex (dark red

dashed line), all operated by Proman, faced challenges during 2013–2015 [32]. The AUM complex also recorded lower ammonia output between 2010 and 2018, although recent government-Proman negotiations have improved near-term supply expectations [57].

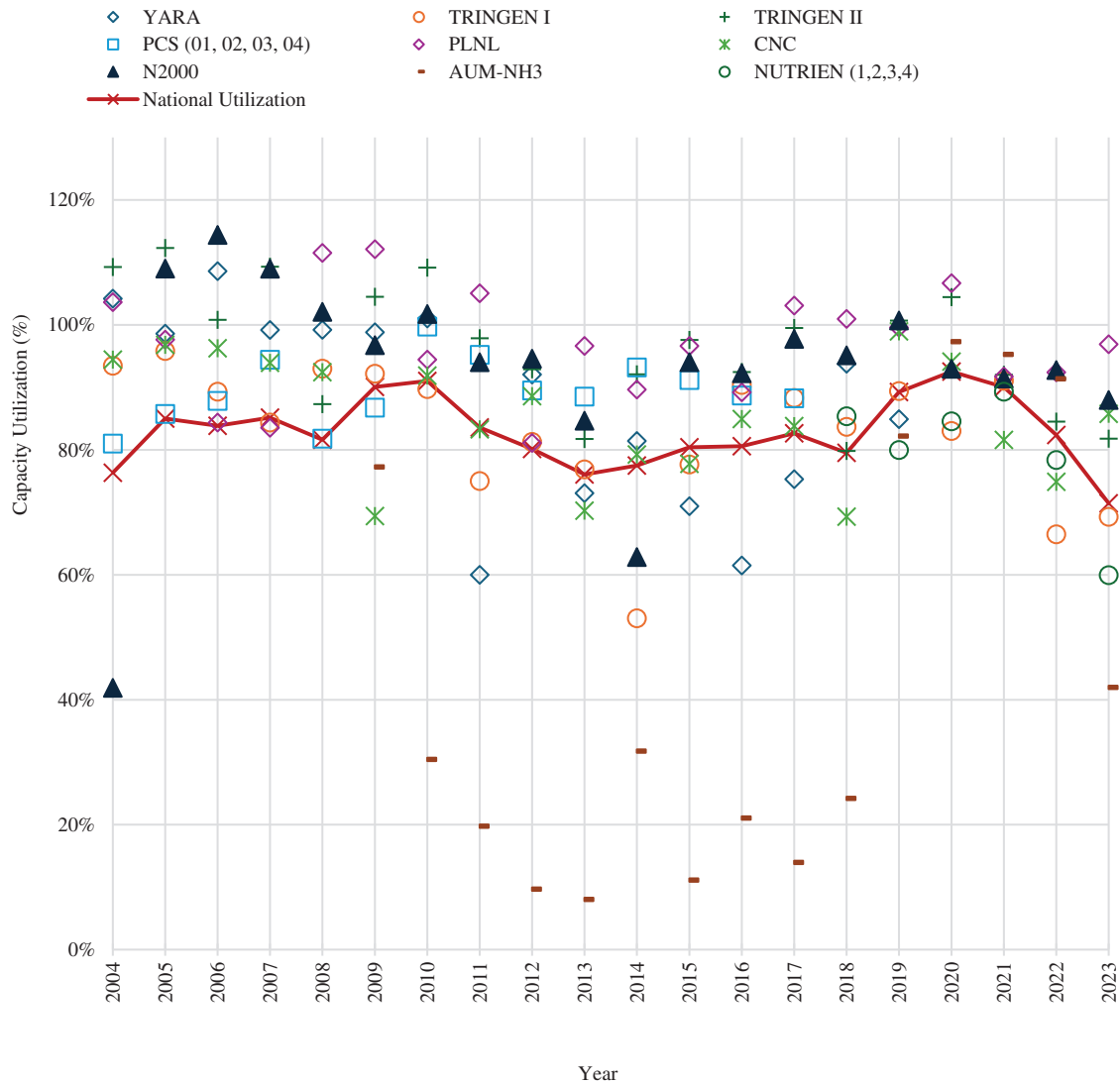


Fig. 4. Annual capacity utilization rates across ammonia plants in T&T, 2004–2023.

The national utilization rate (red line) remained stable until 2011, dipped mid-decade, rebounded in 2019, and declined again by 2023 owing to renewed gas constraints. Outliers, such as Tringen II's 109% utilization in 2005, suggest potential internal capacity upgrades or reporting discrepancies. However, without plant-level verification, these explanations remain speculative and warrant further investigation. Future gas supply agreements, including cross-border fields, may improve plant performance, although the preliminary 2024 data suggest ongoing volatility [58].

5.3. Energy Intensity

Fig. 5 compares T&T's total annual ammonia production (dark blue bars) with the national-level ratio of natural gas consumption per ton of ammonia produced (red line), revealing an inverse correlation between production volumes and energy intensity. In general, a higher ammonia output corresponds to a lower energy use per ton, reflecting operational efficiency, whereas lower production volumes tend to coincide with elevated energy intensity. The inverse relationship between ammonia production volumes and energy intensity is depicted in Fig. 5.

From 2005 to 2010, average production exceeded five million metric tonnes, with the energy ratio steady at 38–40 MMBtu/tonne NH_3 , indicating efficient operations supported by reliable gas supplies and stable plant performance. However, production declined between 2011 and 2016, and the energy ratio rose to 42–45 MMBtu/ton. This increase likely resulted from intermittent gas availability and suboptimal load conditions, which reduced efficiency. It is hypothesized that older facilities may consume more energy when operating below design capacity, though the absence of plant-level operational data limits this conclusion.

Fluctuations are evident between 2017 and 2023. The ratio reached a low of approximately 38 MMBtu/tonne in 2019 before rising to 40 MMBtu/tonne–41 MMBtu/tonne in 2022–2023, which is attributed to renewed gas constraints. These inefficiencies underscore how throughput shortfalls reduce the effective use of the plant infrastructure and mechanical systems.

As plant-level gas consumption data remain unavailable, this analysis draws on national aggregates, which obscure the variations linked to plant age, technology, and maintenance practices. Newer plants with modern controls may perform more efficiently than legacy units

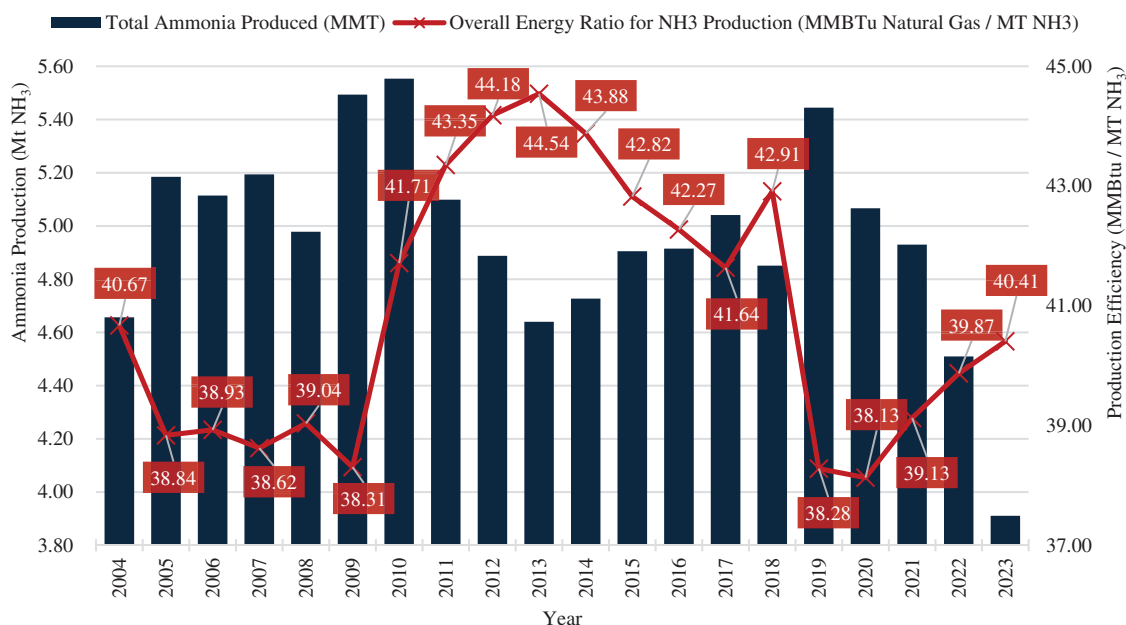


Fig. 5. National ammonia production and corresponding energy intensity trends, 2004–2023.

that operate under partial loads [48]. A disaggregated dataset would enhance insights and offer policymakers and industry stakeholder opportunities to target energy-saving measures.

Ultimately, the national trend emphasizes the link between higher ammonia output and better energy efficiency. To support long-term sector viability, T&T must secure a consistent gas supply and consider targeted upgrades to aging facilities to reduce energy intensity and optimize operations under current resource constraints.

5.4. Net CO₂ Emissions

5.4.1. Gross CO₂ Emissions from Ammonia Production

Fig. 6 presents the annual CO₂ emission profile for the ammonia sector of T&T, distinguishing between gross emissions from ammonia production (green bars), CO₂ utilization in methanol and urea production (dark blue and orange bars, respectively), and the resulting net CO₂ emissions attributed to ammonia (light blue bars). The gross CO₂ emissions represent the sum of process- and fuel-related emissions, and their fluctuations closely mirror ammonia production trends. For instance, peak emissions observed around 2009–2010 align with higher production volumes, whereas more recent declines reflect reduced ammonia output owing to natural gas supply constraints [5]. Gross emissions and estimated CO₂ reuse are visualized in Fig. 6, which highlights key emission sources and sinks.

5.4.2. CO₂ Utilization in Methanol and Urea

Methanol synthesis is the most significant sink. In some years, methanol plants, particularly those integrated with ammonia complexes, captured as much as 64% of the available CO₂ stream [60]. These facilities capitalize on the concentrated CO₂ byproduct of ammonia synthesis, thereby substantially offsetting the sector's gross emissions. Urea production, while also co-located at certain sites, accounts for a smaller fraction of CO₂ reuse, estimated to be approximately 2% of the total generated.

Nonetheless, both processes contribute significantly to reducing net emissions, especially in years when urea and methanol outputs are elevated.

5.4.3. Trends in Net CO₂ Emissions Intensity

The light-blue bars in Fig. 6 capture the remaining CO₂ released into the atmosphere after accounting for these two utilization streams. Notably, net emissions tended to decline in years when methanol and urea production was high, reflecting successful on-site carbon re-utilization. However, even during such years, the proportion of CO₂, primarily from combustion-related fuel emissions, remains unutilized. This underscores the persistent opportunities for expanded carbon capture, utilization, and storage CCUS initiatives, especially if future investments enable additional methanol or urea capacity or unlock alternative downstream applications for CO₂ [59].

However, there are data limitations that warrant further consideration. The precise composition of the vented stream—including potential contributions from CH₄, N₂O, or other trace gases—was not directly measured, and plant-by-plant data were unavailable for this analysis. Consequently, differences in facility design, technology vintage, and operational efficiency could not be assessed. It is plausible that older ammonia plants exhibit higher CO₂ intensities, whereas newer or recently upgraded facilities may achieve more effective CO₂ capture and utilization.

The findings reinforce that integrated ammonia–methanol–urea production complexes in T&T are capable of significantly reducing net emissions through effective internal reuse of CO₂ and can be explored to further reduce existing emissions to the atmosphere as well as a revenue source. As the country works to stabilize its gas supply and decarbonize its industrial base, scaling up CO₂ utilization via expanded downstream capacity or new CCUS pathways is critical for improving the environmental performance of the ammonia sector and supporting national sustainability goals.

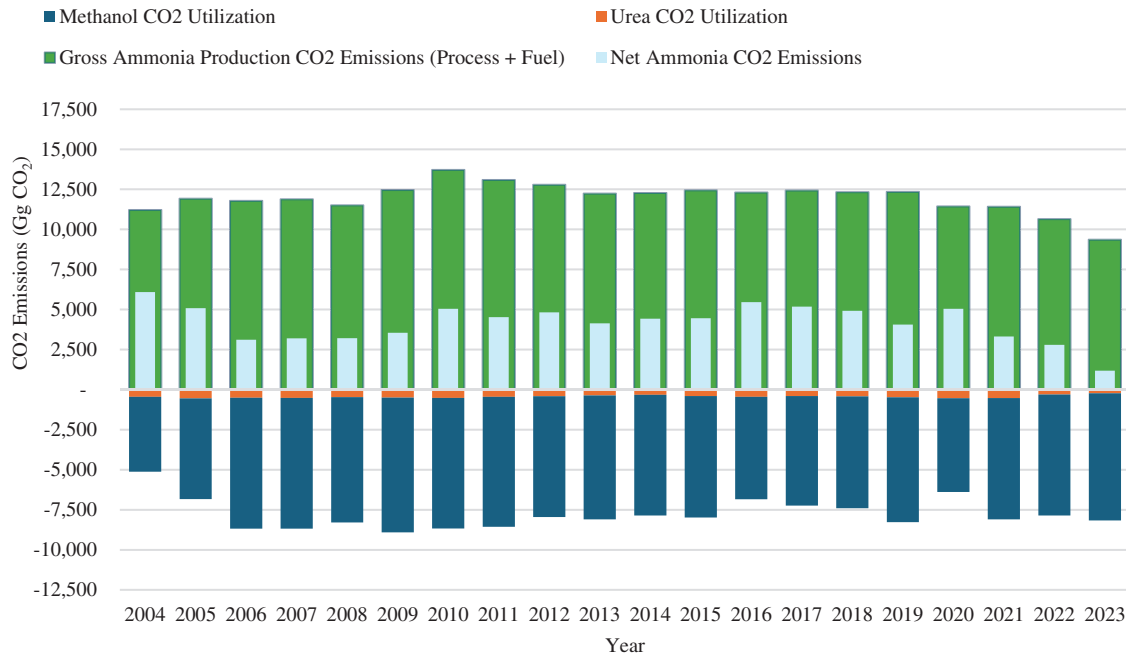


Fig. 6. Gross CO₂ emissions, estimated reuse in methanol and urea, and resulting net emissions in T&T's ammonia sector, 2004–2023.

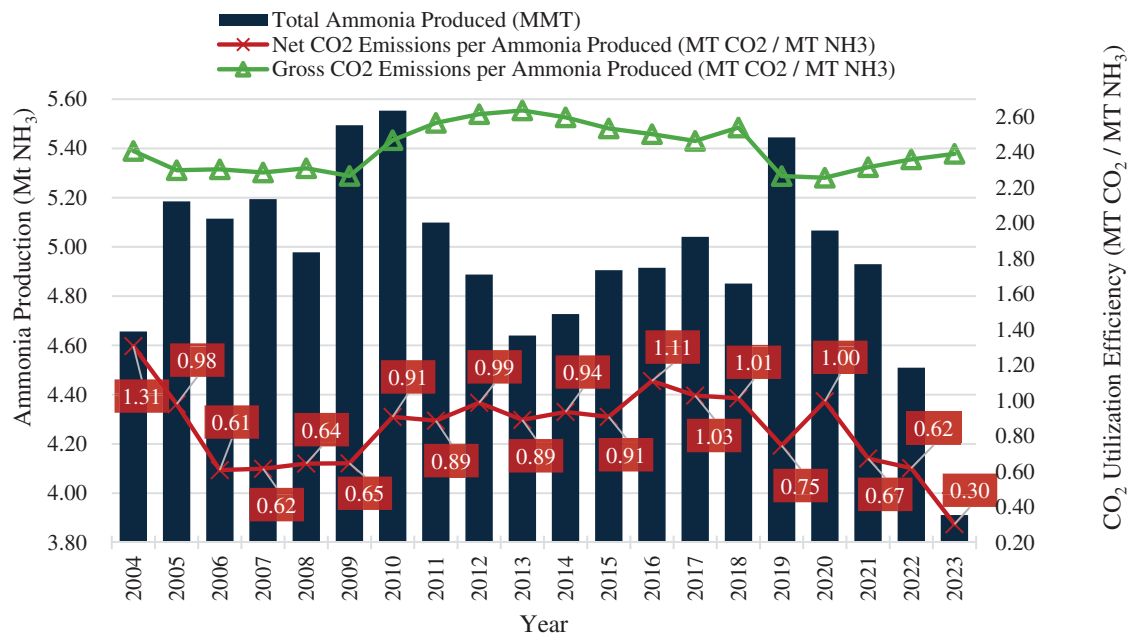


Fig. 7. Trends in gross and net CO₂ emissions per tonne of ammonia produced in Trinidad and Tobago (2004–2023).

Fig. 7 compares the total ammonia production in T&T (blue bars) with both net CO₂ emissions per ton of ammonia produced (red line) and gross CO₂ emissions per ton (green line), offering insights into the environmental performance of the sector over time. Consistent with earlier trends, periods of high ammonia output tended to coincide with lower emissions intensity (measured in MT CO₂ per MT NH₃), suggesting improved operational efficiency during these years. This relationship supports the notion that facilities tend to operate more efficiently when running closer to the design capacity, benefiting from enhanced thermal integration and optimized energy use. Fig. 7 tracks year-on-year changes in gross and net CO₂ emissions per tonne of ammonia, revealing operational efficiency trends.

Interestingly, from 2020 to 2023, a divergence between energy intensity and emission intensity was observed. Energy consumption per ton of ammonia increased, indicating less efficient fuel use; the net CO₂ emissions per ton of ammonia declined. This suggests a possible offsetting effect, potentially due to increased downstream CO₂ utilization. However, without disaggregated plant data, this relationship remains hypothetical. Several factors could explain this anomaly. Upgrades to methanol and urea plants as well as improved integration between ammonia production and downstream processes may have enhanced the sector's ability to divert CO₂ away from atmospheric release. Selective catalytic reduction (SCR) and emerging CCUS applications can also contribute to this decline in net emissions [61].

In parallel, targeted plant efficiency improvements may also play a role. Operators may have implemented technological upgrades, such as improved reformer units, better catalysts, or enhanced heat recovery systems, all of which reduce the carbon footprint per unit of output [62]. These efficiency measures, even when fuel consumption increases slightly, can lead to reductions in CO₂ emissions per ton of ammonia if more CO₂ is captured or reused.

The configuration of operating plants also influences national emission trends. It is possible that newer, more efficient facilities were prioritized, while older units were intermittently operated, although this cannot be confirmed in the absence of plant-specific data. This shift in operational mix could lower the national average emission intensity. In addition, policy signals and evolving market dynamics may encourage producers to adopt low-carbon strategies. For instance, climate-related targets or feedstock pricing mechanisms may incentivize more sustainable production practices, while the growing demand for low-carbon ammonia in export markets may drive the early adoption of emission-reducing technologies [63].

Nevertheless, while national-level data point toward progress, additional granularity is required to validate these trends. Disaggregating the national inventory by plant would help identify which facilities are leading improvements and where further efficiency gains can be achieved. Such insights are essential for scaling best practices and targeting investments in retrofits and new builds.

Ultimately, the data suggest that T&T's ammonia industry is on a path toward lower net CO₂ intensity, but confirming and sustaining this trajectory will require improved data collection and adherence to standardized reporting frameworks such as IPCC or ISO 14064. These tools can support both national emissions accounting and international competitiveness while enabling the sector to strategically decarbonize amid ongoing supply and climate pressure.

The results demonstrate both the necessity and potential for decarbonizing T&T's ammonia sector through a combination of technological advancements and strategic policy interventions. While current CO₂ utilization in downstream products such as methanol and urea partially offsets emissions, significant opportunities remain to reduce the sector's carbon footprint.

One of the most promising avenues is the deployment of CCUS technology. Given the high-purity CO₂ streams from ammonia production, particularly from SMR, CCUS could capture up to 90% of net process-related emissions. However, its feasibility hinges on developing a CO₂ transport infrastructure and regulatory frameworks to support storage, particularly offshore. In the short term, partial CCUS integration—focusing on process emissions—offers a cost-effective entry point with the potential to scale as infrastructure matures. Additionally, increasing the CO₂ utilization capacity in methanol and urea production or exploring new downstream applications could further enhance carbon circularity.

Another critical pathway involves the gradual integration of renewable hydrogen into ammonia production. While full-scale green ammonia may be limited by the

current renewable energy capacity, hybrid models that partially replace natural gas-derived hydrogen with electrolytic hydrogen can significantly lower emissions. Technological improvements in modular electrolyzers and declining renewable energy costs globally may accelerate this transition, especially when supported by international climate finance mechanisms.

Complementary to these measures, energy-efficiency improvements through process optimization, advanced control systems, and equipment retrofits can yield immediate emission reductions. The correlation observed between high production rates and improved energy efficiency highlights the importance of maintaining stable operation to minimize energy intensity.

Achieving these decarbonization goals requires a robust policy framework. The emergence of CBAMs in key export markets, such as the EU, emphasizes the need for verifiable emission reductions to maintain global competitiveness. National policies could include carbon pricing, incentives for CCUS and renewable integration, and support for energy-efficiency projects. Additionally, fostering public-private partnerships and participating in international climate initiatives can attract investment and facilitate technology transfer.

A long-term national strategy for the ammonia sector, aligned with T&T's climate commitments, should set clear decarbonization targets, outline technology deployment timelines, and integrate transition principles to support workforce reskilling and social equity. By embedding these strategies into broader economic planning, T&T can strengthen the resilience and sustainability of its ammonia industry, while contributing meaningfully to global climate goals.

5.5. Comparative Benchmarking with Other Ammonia Exporters

To contextualize T&T's ammonia sector, it's instructive to compare emission intensity and trade dynamics with global peers:

- *T&T*: Current estimates place its CO₂ emissions at approximately 2.4 t CO₂ per tonne of NH₃, as reported using EU CBAM methodology [7]. Export markets like the EU with free emission allowances declining from ~1.53 t CO₂/t NH₃ in 2026 to zero by 2034 underscore escalating competitiveness risks [7].
- *Global Benchmarks*: Traditional ammonia production globally averages between 1.8 to 2.4 t CO₂ per tonne, depending on feedstock and process use [1], [25]. T&T aligns with the upper end of this range, indicating relatively higher carbon intensity.
- *U.S.—Gray vs. Low-Carbon Ammonia*: U.S. conventional (gray) ammonia production emits around 2.3 t CO₂ per tonne, largely from natural gas-based SMR. However, emerging low-carbon (blue/green) projects—such as a Gulf Coast initiative aiming for up to 70% emissions reductions by 2030—indicate rapid decarbonization trajectories

Implications for T&T:

This benchmarking highlights that T&T's ammonia sector remains carbon-intensive relative to decarbonizing competitors, raising flags under CBAM regimes and anticipating global low-carbon demand. Such contextual comparison reinforces the urgency for adopting CCUS, renewable or hybrid hydrogen pathways, and energy efficiency upgrades to improve competitiveness and meet evolving regulatory thresholds.

6. CONCLUSION

This study reviews the ammonia sector of T&T, underscoring its economic significance, reliance on natural gas, and notable GHG emissions. Despite operational resilience, ongoing challenges include gas supply constraints, energy efficiency variations, and elevated CO₂ emissions, which highlight the importance of improved plant-specific data collection to better understand performance disparities and inform targeted interventions. Decarbonization strategies such as CCUS, renewable hydrogen, and process optimization present viable pathways. Strategic policy, regulatory frameworks, and international cooperation, especially aligning with carbon accountability measures such as the EU's CBAM, are critical. Addressing carbon intensity proactively ensures environmental responsibility and economic competitiveness and supports T&T's alignment with national climate goals and international carbon-pricing initiatives.

7. SUMMARY: KEY FINDINGS AND POLICY IMPLICATIONS

- T&T's ammonia sector is a major energy and emissions hotspot, consuming ~17% of national natural gas and emitting an estimated 2.4 t CO₂ per tonne of NH₃, placing it at the upper end of global intensity benchmarks.
- Plant utilization rates have declined due to natural gas constraints, reducing efficiency and increasing energy intensity (up to 40–41 MMBtu/t NH₃ in recent years).
- Downstream reuse of CO₂ in methanol and urea production can offset 60%–80% of gross ammonia-related emissions, highlighting the value of integrated production complexes.
- Decarbonization pathways such as CCUS and green or hybrid hydrogen offer viable mitigation options, but economic and infrastructure barriers persist in T&T's context.
- Comparative benchmarking shows that T&T's emissions intensity exceeds low-carbon ammonia projects in the U.S., underscoring risks from emerging carbon border adjustment mechanisms (CBAMs).

Recommendations include: enhanced monitoring and data transparency, targeted process upgrades, policy incentives for low-carbon technologies, and strategic investment in CO₂ reuse and hydrogen readiness.

ACKNOWLEDGMENT

The authors acknowledge the Ministry of Energy and Energy Industries (MEEI) of Trinidad and Tobago for creating the public datasets that were essential for this study. We would also like to express special thanks to Ms. Amy Clark for assistance with the preparation of this research paper.

CONFLICT OF INTEREST

The authors declare no potential conflicts of interest with respect to the research, authorship, or publication of this article.

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