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The Feasibility of Producing and Utilising Green Hydrogen as a Feedstock in Trinidad and Tobago

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ABSTRACT

This study addresses Trinidad and Tobago's (TT) heavy reliance on grey hydrogen from Steam Methane Reforming (SMR), contributing significantly to CO_2 emissions in the petrochemical sector. With rising hydrogen demand, especially for ammonia and methanol production, there is an imperative need to transition to green hydrogen. The study evaluates the economic feasibility of green hydrogen production in TT, assesses the potential impact on CO_2 emissions, and analyses external factors such as subsidies, market dynamics, and the Carbon Border Adjustment Mechanism (CBAM). A combined quantitative and qualitative approach, incorporating cost modelling, sensitivity analyses, and environmental impact assessments, was used to evaluate economic viability and external influences. The analysis utilises secondary data from governmental and industry reports, including techno-economic models and GHG inventories calculated in accordance with the IPCC 2006 Guidelines. Findings indicate economic viability for green hydrogen under specific market conditions, significant CO_2 mitigation potential, and opportunities for TT to establish a presence in the green hydrogen market. The impact of this transition could significantly reduce greenhouse gas (GHG) emissions, contributing to the nation's decarbonisation targets under its Nationally Determined Contributions (NDCs) while enabling economic diversification.

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1 INTRODUCTION

Trinidad and Tobago (TT) faces an urgent challenge due to its heavy reliance on grey hydrogen, produced through Steam Methane Reforming (SMR), which significantly contributes to greenhouse gas (GHG) emissions in the petrochemical sector. This dependency not only exacerbates environmental concerns but also poses economic risks due to fluctuating natural gas reserves and global carbon policy like the Carbon Border Adjustment Mechanism (CBAM). Moreover, the social implications include the need for a just transition to cleaner technologies, ensuring energy security while protecting jobs and livelihoods in a sector central to TT's economy.

TT’s position as a leading global exporter of ammonia presents both a challenge and an opportunity for the adoption of green hydrogen. While ammonia production is a major contributor to the petrochemical sector’s CO_2 emissions, it remains a cornerstone of the national economy. Transitioning to green hydrogen could reduce these emissions significantly, align with decarbonisation targets, and enhance TT's competitiveness in emerging green markets. The country's commitment to reducing GHG emissions and the diminishing natural gas reserves necessitate exploration of alternative hydrogen production methods and their economic feasibility.

The nation faces an increasing hydrogen demand, especially for ammonia and methanol production, necessitating a shift towards sustainable alternatives such as green hydrogen. While TT is a significant global exporter of ammonia, there exists a considerable gap between hydrogen demand and supply, indicating a potential market for green hydrogen.

This study aims to evaluate the economic feasibility of green hydrogen production in TT, assess the potential for CO_2 emissions reduction through transitioning from grey to green hydrogen and analyse external factors such as subsidies, market dynamics, and the CBAM that influence the adoption of green hydrogen.

Hydrogen, as versatile as the colours of the rainbow, presents a spectrum of possibilities. Amidst the hues of grey, blue, and green hydrogen, the focus of this exploration, centres on the transformative potential of green hydrogen in TT. TT presently relies on SMR to produce grey hydrogen, predominantly fuelling the production of ammonia and methanol; however, transitioning to blue hydrogen, through Carbon Capture Utilisation and Storage (CCUS), or green hydrogen from renewable sources, offers a pathway to a greener, more sustainable future.

In TT's petrochemical sector, responsible for over half of the country's CO_2 emissions, integrating clean hydrogen could be revolutionary[1]. The production of ammonia and methanol accounts for a significant portion of these emissions. Embracing green hydrogen offers a dual advantage: bridging fuel shortages and aligning with carbon-reduction goals outlined in the Paris Agreement, 2015[2].

The potential extends beyond mere production. TT holds the opportunity to establish a thriving green hydrogen industry, tapping into domestic markets, and exporting this commodity on an international scale. Leveraging existing expertise in energy production, TT can envision a substantial shift towards green hydrogen production, not just as an industry necessity but as a strategic economic asset.

Globally, the demand for hydrogen, primarily utilised in ammonia and methanol production, is on the rise, with projections indicating a 44% surge by 2030[3]. TT's geographical position and energy experience position it to play a pivotal role in meeting this escalating demand.

The production cost of grey hydrogen in TT is closely linked to the price of natural gas, the primary feedstock. While specific local production costs are not publicly detailed, the International Energy Agency (IEA) estimates that globally, grey hydrogen production costs range from USD 0.5 to USD 1.7 per

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kilogram, depending on natural gas prices[4]. Given TT's status as a major natural gas producer, its grey hydrogen costs are likely at the lower end of this range. However, fluctuations in natural gas prices present both an economic challenge and an opportunity when considering the transition to green hydrogen alternatives.

Economic feasibility analyses underscore the potential of green hydrogen. IEA’s cost of production, ranging from USD 3 to USD 8 per kilogram, is fundamental to this evaluation[4]. Sensitivity analyses, aligning production costs with fluctuating ammonia prices, showcase the financial viability of green hydrogen under specific market conditions.

Moreover, one ammonia-producing company in TT, transitioning entirely from grey to green hydrogen could mitigate millions of metric tons of CO_2e annually, constituting a significant reduction in the petrochemical sector's emissions. This reduction aligns with TT's National Determined Contributions (NDCs) and signifies a crucial step towards sectoral decarbonisation.

The financial landscape also warrants consideration, as emerging global subsidies and incentives, raise questions about TT's attractiveness to potential investors while market dynamics suggest the potential for TT to lead the charge in the green ammonia industry by potentially creating a separate market and even negotiating premium pricing strategies.

However, external factors, such as the EU's CBAM, could pose challenges to the market for grey hydrogen and ammonia, potentially driving a shift towards green alternatives. Additionally, the potential for carbon credit adds another dimension, offering TT an avenue not just to offset emissions but also to generate revenue by trading excess credits with nations falling short on emission targets.

TT stands at a critical juncture. Faced with diminishing natural gas reserves and committed to reducing GHG emissions, the nation stands poised to seize the moment. By investing in renewable energy and instituting enabling legislation, TT can spearhead the development of a hydrogen economy, capitalising on its inherent potential and driving forward a sustainable future.

The global landscape for hydrogen, particularly in the form of ammonia as an energy carrier, exhibits a substantial discrepancy between demand and supply. Dzombak's insights in 2018 on green hydrogen -TT, underscored a crucial imbalance, with countries across North America, Europe, Asia, and India consuming more ammonia than produced, resulting in a pronounced gap to be filled[5]. Dzombak[5] underscored the significance of various global hydrogen initiatives, highlighting the active involvement of countries in Southeast Asia, the European Union (EU), South Australia, and others. These initiatives not only emphasise the promotion of global hydrogen production but also have the potential to increase the demand for hydrogen imports. Fig. 1 illustrates the ammonia fertiliser and the energy carrier distribution in TT.

The magnitude of global hydrogen demand amounting to approximately 90 million metric tons in 2020 with 70 million metric tons being utilised as pure hydrogen and less than 20 million metric tons being mixed with carbon-containing gases to produce methanol and steel[3]. Notably, this demand predominantly caters to refining and industrial sectors, yet the production of hydrogen, largely sourced from fossil fuels, contributes to a staggering 900 million metric tons of CO_2 emissions annually[4].

Turning the lens to TT, the existing market demand for hydrogen, particularly in ammonia and methanol production, significantly exceeds the supply capacity. With a demand of 950,000 metric tons per year for ammonia and 1.3 million metric tons per year for methanol (totalling to approximately 1.4 million metric tons per year), the shortfall in 2019 reached approximately 400,000 tonnes of hydrogen annually for ammonia per methanol plants[6]. This glaring deficit signifies a substantial opportunity to bridge the supply gap within the nation (See Table 1), ensuring a sustainable hydrogen supply while reducing CO_2 emissions. As a major global exporter of ammonia, TT is well-positioned to capitalise on this market gap, leveraging

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its energy expertise to transition from grey to green hydrogen and establish itself as a leader in the emerging green hydrogen economy.

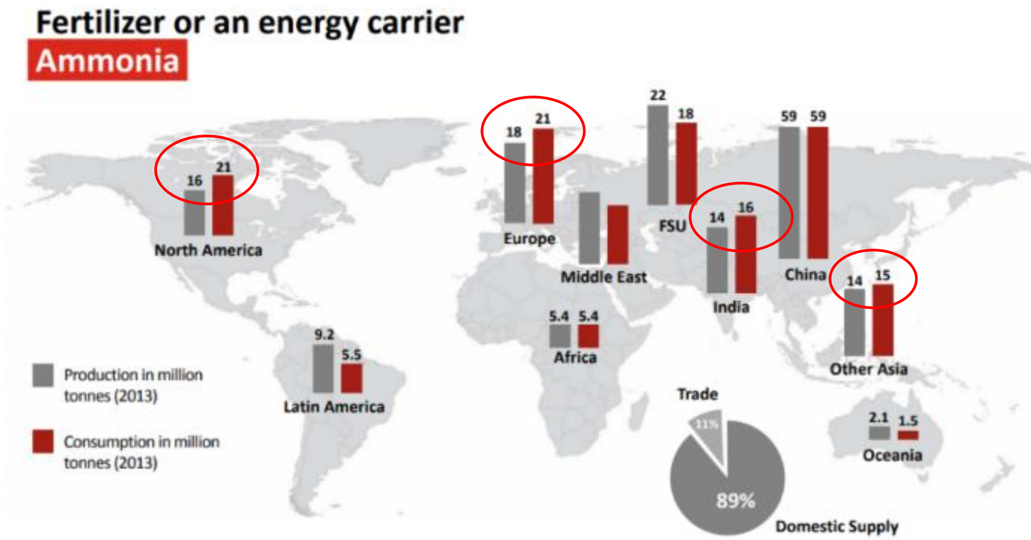

Fig. 1. Ammonia - fertiliser or energy carrier[5].

Table 1. Demand vs supply for hydrogen for ammonia and methanol in TT

Petrochemical	H_2 demand (Metric tons per year)[6]	H_2 supply (Metric tons per year) (based on 2019 deficit figures)	H_2 deficit (2019) (Metric tons per year)[6]
Ammonia	950,000	819,000	131,000
Methanol	1,300,000	1,013,000	287,000

TT, ranking as the second-largest exporter of ammonia globally, boasts export destinations such as the United States, Morocco, Mexico, Brazil, and Chile[7]. Leveraging its extensive expertise in energy production, TT has the potential to elevate hydrogen production to a larger scale, catering not only to domestic needs but also positioning itself as a key player in regional and international hydrogen markets.

TT's significant GHG emissions, amounting to approximately 53 million tonnes, with the petrochemical sector (predominantly methanol and ammonia) contributing about 58% to this total, underscore the critical need for robust emission inventories and targeted mitigation strategies[1]. This context aligns closely with the findings from a case study in Austria by Amon et al.[8], which highlighted the vital role of the Intergovernmental Panel on Climate Change (IPCC) guidelines in creating more accurate and transparent emission inventories[8]. Through leveraging methodologies aligned with IPCC guidelines, TT could improve the accuracy of its emission data, thus enabling the formulation and implementation of more effective emission reduction strategies in industry.

The advent of green hydrogen presents a promising avenue to supersede grey hydrogen in TT. Reports from the Inter-American Development Bank (IDB) reinforce this shift, hinting at the potential for redirected use of natural gas from grey hydrogen production toward areas of scarcity, such as Liquefied Natural Gas (LNG) production[9]. The establishment of an exclusive hydrogen production entity, NewGen

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Energy Limited, supported by technological enhancements and majority acquisition from Hydrogene de France (HDF), signifies a pivotal step. Projections for the NewGen Project, set to yield 27,000 metric tons of green hydrogen annually, aligning with TT's commitments to the Paris Agreement[10]. This strategic initiative not only addresses CO_2 emission reduction targets from one of its main emitting sectors but also holds the promise of sustainable growth and increased revenue streams for the nation.

This indicates that the assessment of economic feasibility and environmental impact is paramount, particularly in the context of producing green hydrogen. It underscores the significance of scrutinising the economic viability of green hydrogen production in TT, comparing it with international standards.

The techno-economic analysis conducted by Chung[11], showed projections of the cost of hydrogen underscore the imperative for sustained endeavours aimed at diminishing capital expenditure, enhancing electrolyser efficiency, and seamlessly incorporating more economically viable renewables into the electricity market. These persistent efforts are deemed essential to propel green hydrogen towards achieving cost parity with hydrogen derived from hydrocarbons. A study done by Babarit[12], findings indicated that for hydrogen to attain competitiveness in extensive industrial applications or grid integration, essential prerequisites include cost reductions and supportive measures[12]. As an illustration, a suggested approach involves the implementation of a carbon tax ranging from €50 to €200 per kg[12]. Nonetheless, these studies overlooked the potential revenue generation from hydrogen in the form of ammonia. Therefore, it is imperative to expand the discussion to include the significance of considering various factors that affect the adoption of green hydrogen within the distinctive context of TT, particularly in relation to its ammonia and petrochemical industry.

2 METHODOLOGY

2.1 Data collection

To address the gap in knowledge regarding the hydrogen supply-demand disparity and to evaluate the feasibility of transitioning from grey to green hydrogen in TT, an extensive review of existing literature was conducted, including academic papers, reports, and industry publications, focusing on global hydrogen demand and supply dynamics, existing production methods, environmental impact assessments, and technological advancements in green hydrogen production.

Data were gathered from reliable sources, including reports from the IEA, IDB, and presentations by experts such as Dzombak on hydrogen demand and supply in TT, emphasising the gap between demand and supply specifically for ammonia and methanol production.

Reliable reports from IDB included the assessment of the potential for displacing grey hydrogen with green hydrogen in TT, emphasising the redirection of natural gas resources and its implications for other sectors like LNG production.

2.2 Techno-economic analysis

The adoption of a techno-economic analysis (TEA) in this study is justified by its ability to comprehensively evaluate both the economic feasibility and environmental implications of transitioning from grey to green hydrogen production in TT. TEA combines key economic parameters and financial metrics, such as cost of production, payback periods, and profitability indicators, with environmental assessments to identify the most viable pathways for sustainable hydrogen production. This methodology is particularly appropriate in TT's context due to its reliance on natural gas-based grey hydrogen and the economic significance of the petrochemical sector. By aligning local production costs with international benchmarks, such as those from the IEA, TEA provides a systematic framework to compare the costs of transitioning to green hydrogen under varying market conditions, ammonia prices, and production scenarios.

The analysis was divided into several key components as presented below.

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Data collection

The data collection process involved utilising information from the Ministry of Energy and Energy Industries (MEEI) Consolidated Bulletins spanning 2021 to 2023. These bulletins provided valuable insights into Company X's average ammonia production, allowing for a comprehensive assessment of its operational output over this period[13]. By analysing this data, trends in ammonia production were identified, forming a critical foundation for further evaluation.

Additionally, the study examined green hydrogen production from a local company, Company X, with a focus on production costs and revenue generation. This evaluation considered Company X's annual hydrogen demand, allowing for a detailed financial and operational analysis. By integrating both ammonia and hydrogen production data, the study aimed to provide a holistic understanding of the company's position within the energy sector and the potential for sustainable energy transitions.

Cost analysis

The calculation of production costs was based on the International Energy Agency's (IEA) cost range of USD 3–8 per kilogram as a baseline[4]. This provided a standardized reference point for estimating the financial requirements associated with green hydrogen production. By applying this cost range, a realistic assessment of potential expenditures was established, ensuring alignment with global benchmarks.

To further assess economic feasibility, sensitivity analyses were conducted by correlating production costs with fluctuating ammonia prices from 2021 to 2023. This analysis was essential in determining the financial viability of green hydrogen production, particularly as TT explores the possibility of marketing green hydrogen in the form of green ammonia in the future[14]. The sensitivity analyses enabled a comprehensive understanding of how variations in market conditions could impact production costs and profitability.

Additionally, electrolysis models were evaluated to support the analysis, as presented in Table 2. This table outlines twelve distinct models, each designed to simulate production over a 20-year period. These models provided a structured framework for assessing long-term production trends, cost efficiency, and potential scalability, contributing to a more detailed evaluation of green hydrogen production and its integration into the ammonia market.

Key financial metrics, including Payback Period, Net Present Value (NPV) and Internal Rate of Return (IRR), were calculated for various green hydrogen production models utilising electrolysis. These metrics were essential in assessing the economic feasibility and long-term viability of the proposed models.

Table 2. Electrolysis models

Model	Ammonia price (USD) per metric tons	Cost of production for hydrogen (USD per kg)
1	547	3–8
2	547	2.9
3	547	2.5
4	547	2
5	547	1.5
6	1,500	8
7	1,500	5
8	1,500	3
9	314	3–8
10	314	2
11	314	1.7
12	314	1.5

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The Payback Period was determined as the point at which cumulative net cash flows reached zero, indicating the time required for the initial investment to be recovered. This measure provided insight into the financial sustainability and risk associated with each production model.

The NPV was calculated using Equation 1, where the Minimum Acceptable Rate of Return (MARR) was applied as the discount rate, *i* represented each specific period, and *n* represented the total number of periods analysed.

$$\text{NPV}=\sum_{i=0}^{n}\frac{\text{Net Cash Flow}_i}{(1+\text{MARR})^i} \tag{1}$$

The IRR was calculated as the return on investment, expressed as a percentage, using the IRR function in Microsoft Excel. This metric provided a measure of the project's profitability by identifying the discount rate at which NPV equals zero.

It is important to note that these financial assessments were conducted under a scenario where no taxes were applied. As such, the results reflect an idealized case and may differ when considering real-world taxation and regulatory factors.

2.3 GHG inventory

National Inventories have now become legally binding commitments under the United Nations Framework Convention on Climate Change (UNFCCC). The IPCC Inventory allows the harmonisation of reporting GHG inventories for main sectors such as energy, agriculture, waste, etc[15].

Microsoft Excel and the IPCC 2006 Guidelines were utilised to calculate greenhouse gas (GHG) inventories for Company X, leveraging data obtained from the Ministry of Energy and Energy Industries (MEEI) consolidated reports[15]. These calculations provided a comprehensive assessment of the company's emissions profile, ensuring alignment with internationally recognized methodologies for estimating GHG emissions. By integrating data from MEEI reports, the analysis aimed to establish an accurate baseline of Company X's carbon footprint.

Furthermore, an evaluation of GHG emissions, expressed in terms of CO_2-equivalent (CO_2e), was conducted to determine the environmental impact of current hydrogen production methods. This assessment also explored the potential for emission reductions through the adoption of alternative hydrogen production technologies, particularly green hydrogen. By comparing conventional hydrogen production with green hydrogen alternatives, the study aimed to highlight opportunities for emissions mitigation and support the transition towards more sustainable energy practices.

This methodology integrates financial evaluations (techno-economic analysis), and environmental impact assessments (GHG) inventory using IPCC guidelines) to comprehensively evaluate the feasibility of green hydrogen production and utilisation in TT. It leverages governmental data, industry reports, and established guidelines to assess economic viability, environmental sustainability, and technological suitability for transitioning to green hydrogen production methods. Fig. 2 explains the methodology of this study.

3 RESULTS AND DISCUSSION

3.1 Economic feasibility-sensitivity analyses

The analysis in Table 3 aims to discover the economic feasibility of green hydrogen production through different electrolysis models, considering varying ammonia prices and varying production costs. The primary focus is to determine the cost-effectiveness and payback period for each model, providing a comparative insight into the viability of green hydrogen in TT.

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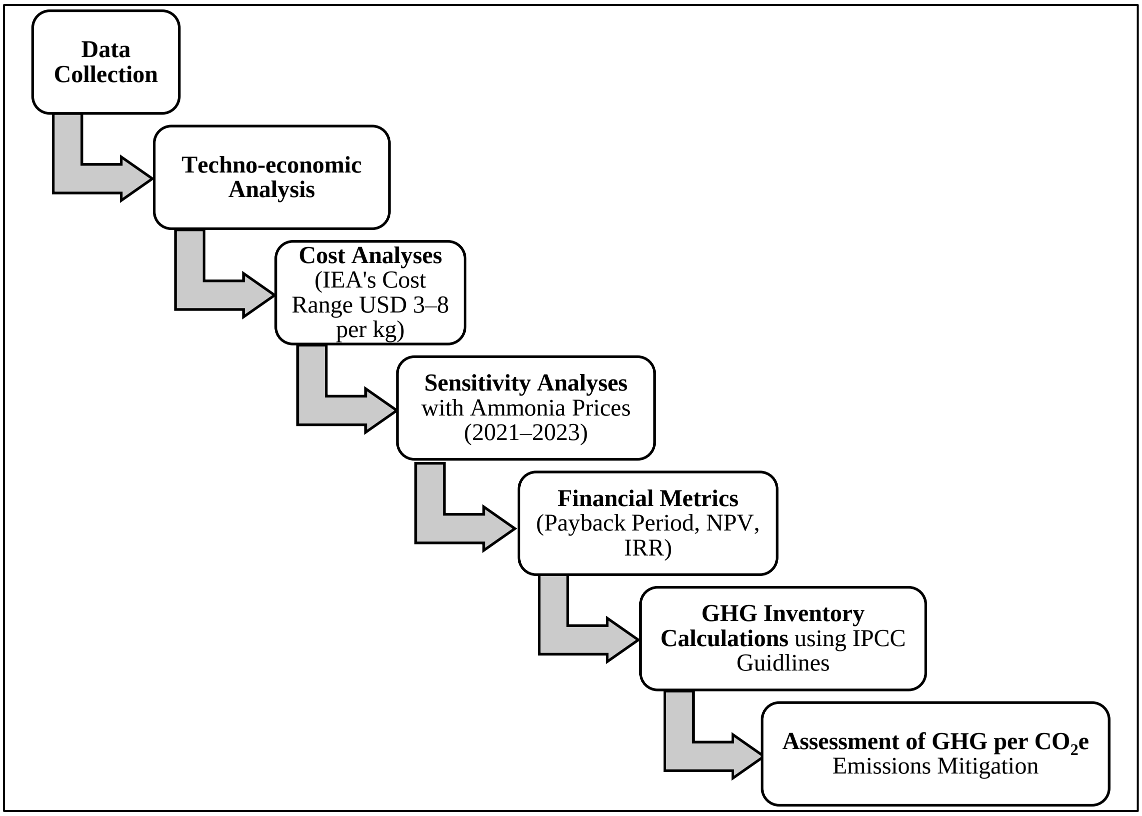

Fig. 2. Methodology.

In TT, hydrogen has the potential to be marketed as ammonia as the carrier, serving as a pivotal factor influencing revenue and economic viability. An economic feasibility assessment was undertaken for green hydrogen, and by extension, green ammonia, leveraging production data from Company X in TT. The analysis employed a cost of production range of USD 3–8, as indicated by the International Energy Agency (2021), guiding the conduct of a sensitivity analysis to ascertain feasibility[4]. Additionally, the assessment incorporated average ammonia prices spanning 2021 to 2023, enabling consideration of mid, higher, and lower price scenarios to enhance the robustness of the evaluation.

In 2021, an average ammonia price of USD 547 revealed the economic feasibility of green hydrogen, with an associated production cost of USD 2.9 per kg. This cost fell at the lower boundary of the IEA range of 3–8 USD, indicating a favourable scenario.

For the subsequent year, utilising a high ammonia price point in 2022 with an average ammonia cost of USD 1,500, the economic analysis demonstrated that green hydrogen production remained feasible even at the upper threshold of the IEA's estimated cost range of USD 3 to 8 per kilogram. At a higher production cost of USD 8 per kg, this scenario still reflected highly favourable market conditions, underscoring the viability of green hydrogen and green ammonia in a high-price environment.

Conversely, by employing a lower price point based on the average ammonia cost in 2023 (USD 314 as of May 2023), feasibility was demonstrated with a production cost of USD 1.6 per kg. However, any production cost above this threshold would render the process economically unviable. Notably, this cost fell below the IEA's specified range of USD 3-8, indicating a much-needed economic position to reduce the cost of production per kg to ensure economic feasibility is achieved, should investment be placed into green hydrogen.

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Table 3. Illustrates the most feasible cost of production per kg of hydrogen at varying ammonia prices

Models	Year	Average ammonia price Trinidad (USD per metric ton) per year[14]	Average cost of producing hydrogen (USD per kg H_2)[3]	Payback	NPV (USD)	IRR (%)	Feasibility
Electrolysis (Model 1)	2021 Ammonia price	547	3 to 8	Shortest Payback Year 15	Negative	4 (IRR with shortest Payback)	Not feasible
Electrolysis (Model 2)		547	2.9	Year 7	57,960,802	14	Feasible
Electrolysis (Model 3)		547	2.5	Year 3	604,775,915	47	Feasible
Electrolysis (Model 4)		547	2	Year 2	1,288,294,806	87	Feasible
Electrolysis (Model 5)		547	1.5	Year 1	1,971,813,696	128	Feasible
Electrolysis (Model 6)	2022 Ammonia price	1,500	8	Year 3	448,763,693	38	Feasible
Electrolysis (Model 7)		1,500	5	Year 1	4,549,877,041	279	Feasible
Electrolysis (Model 8)		1,500	3	Year 1	7,283,952,607	440	Feasible
Electrolysis (Model 9)	2023 Ammonia price	314	3 to 8	NA	NA	NA	Not feasible
Electrolysis (Model 10)		314	2	NA	NA	NA	Not feasible
Electrolysis (Model 11)		314	1.6	Year 9	37,880,021	13	Feasible
Electrolysis (Model 12)		314	1.5	Year 5	174,583,799	22	Feasible

These findings pose significant considerations for TT. To achieve optimal economic feasibility for green hydrogen, it becomes imperative to either elevate the ammonia price or decrease the cost of hydrogen production per kilogram. Strategic decision-making in this context has crucial implications for the renewable energy landscape in TT.

The findings are particularly important for TT due to its reliance on the petrochemical sector, where hydrogen serves as a critical feedstock for ammonia and methanol production. The economic feasibility of green hydrogen, demonstrated within the IEA's production cost range of USD 3 to 8 per kilogram under higher ammonia prices (above USD 547), highlights the opportunity to capitalise on favourable market conditions. This is particularly relevant as ammonia export revenues play a vital role in TT's economy.

However, the results also underscore a challenge, at lower ammonia price points (e.g. USD 314), green hydrogen production costs must fall significantly below the IEA benchmark to remain economically viable. This highlights the importance of incentives, such as subsidies or tax relief, to offset production costs and attract investment. Without such support, achieving cost competitiveness may remain a hurdle, particularly given fluctuating natural gas prices and TT's current dependence on grey hydrogen. Fig.3 shows the average annual net cash flows for twelve hydrogen production models.

Model 8 demonstrates the highest average annual net cash flow with an ammonia price of $1,500 and an average production cost of $3 per kg, indicating strong cash flows under favourable market conditions. This is followed by Model 7, which also has an ammonia price of $1,500 but with a higher production cost of $5 per kg. Despite the increased production costs, the high ammonia price ensures substantial cash flows. The third highest average annual net cash flow is observed in Model 5, with an ammonia price of $547 and a production cost of $1.5 per kg. The combination of lower production costs and moderate ammonia prices results in positive cash flows.

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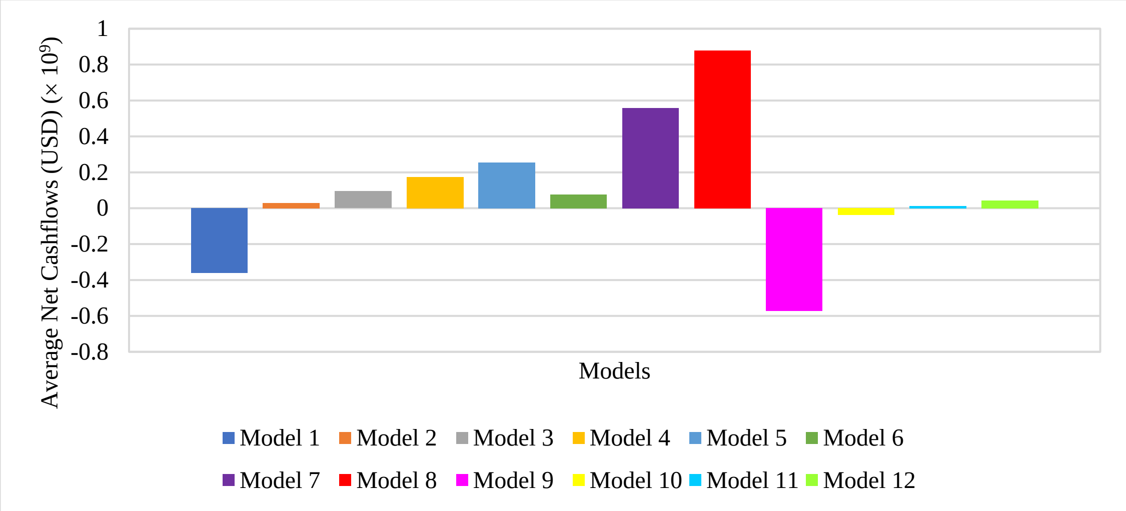

Fig. 3. Average annual net cash flows for twelve green hydrogen production models.

The net cash flows depicted in Models 7 and 8 suggest that green hydrogen can be economically viable under certain market conditions, particularly with favourable ammonia prices.

Mechanisms to improve feasibility for TT's petrochemical sector are considered in Table 4 and can include subsidies, grants, tax incentives, efficiency improvements, securing long-term purchase agreements for green ammonia at favourable prices, export opportunities, public-private partnerships to share risks and benefits, leveraging of international partnerships for expertise and resources, etc.

3.2 GHG mitigation

With the current annual ammonia production of 907,185 metric tons, Company X's contribution was calculated annually[13]. Transitioning all of Company X's grey hydrogen and grey ammonia production to green hydrogen and green ammonia, utilising solar or wind energy and electrolytic processes devoid of natural gas, can mitigate approximately 2.1 million metric tons per year of CO_2e.

It is noteworthy that the petrochemical sector in TT is responsible for approximately 58% of CO_2 emissions, equivalent to 30 million tonnes[1]. The mitigation of 2.1 million metric tons per year by Company X constitutes approximately 7% of the total CO_2e emitted by this sector. This is comparable to eliminating approximately 500,000 gasoline-powered passenger vehicles from the road for one year or sequestering the same amount of carbon as approximately 96.5 million mature trees do annually[16,17].

3.3 Considerations for TT

Technology

TT possess a wind potential of 25 GW, enabling the production of four million tonnes of green hydrogen annually[9]. With the rising demand for electrolytic and renewable energy technology, economies of scale may be realised as production volumes increase, potentially lowering unit costs. Continuous research and development in electrolyser technologies contribute to enhanced efficiency and reduced manufacturing costs, thereby facilitating a more economically feasible green hydrogen production (see Table 2).

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Subsidies

As nations like the US, Europe, and Australia introduce subsidies and financial incentives for green hydrogen (refer to Table 4), it becomes imperative to assess whether these measures could potentially dissuade new investors from TT. This consideration is crucial as TT navigates its decision-making processes and fulfils its commitments. Anticipated substantial cost reductions in the future are expected to enhance the cost-effectiveness of green hydrogen and green ammonia, positioning them as more competitive alternatives to grey ammonia.

Table 4. Considerations for the implementation of green hydrogen in TT

Technology	Subsidies	Market dynamics	CBAM	Carbon credits	Policy
Cost of electrolyser and renewable energy technology	US:	TT are already pioneers of the industry	Carbon Border Adjustment Mechanism	Offset GHG per earn revenue	− Critical to ensure economic competitiveness, support TT's climate commitments (NDCs),
	- IRA (up to 3 USD per kg[18]).	Currently green ammonia is being sold for the price of grey ammonia.	Non-EU producers		− Policy can provide incentives, reduce production costs, and create an enabling environment that attracts investment and fosters innovation.
	- Tier system	Separate market	Taxed based on carbon embedded into goods		− Can assist with addressing fluctuating natural gas prices and CBAM-related trade challenges.
	- 1:1:1 (USD1:1 kg:1 decade)	Premium pricing	Transitionary period began October 2023		− Capitalise on global green ammonia markets.
	Europe:				
	- Producers bid-Fixed Premium Up to €4 per kg[19]				
	- Aims for green hydrogen below €2 per kg by 2030[20]				
	Australia:				
	- A$2–4 per kg (from 2026–2027)[21]				

Market dynamics

TT has the potential to lead the green ammonia industry, leveraging its status as one of the world's largest ammonia exporters. While current market conditions equate green ammonia prices with grey ammonia, International Renewable Energy Agency (IRENA)[22] anticipates the emergence of a distinct

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market for green ammonia, presenting an opportunity for premium pricing[22]. This development offers a strategic pathway for countries like TT to engage in contractual agreements and derive benefits from selling green ammonia at a premium.

CBAM

The current European Union Emissions Trading System (ETS) encompasses EU member states, whereas the CBAM is designed to extend its jurisdiction to goods originating from external sources (such as TT), except for Iceland, Norway, Liechtenstein, and Switzerland[23].

The transitional period for the CBAM commenced on October 1, 2023, and is scheduled to conclude on January 1, 2026, as outlined in a report by Carbon Chain (2024)[23]. Notably, during this interim phase, emissions reporting is required, without 'financial adjustment.' Default values are to be utilised for the initial three reporting quarters, supplemented by the application of a CN Code, as stipulated by the Carbon Chain publication (2024)[23].

The permanent CBAM system will begin on 1 January 2026, when financial adjustment will be required via purchasing certificates. The free allowances under EU ETS will be phased out, as CBAM is phased in from 2026 to 2034[23]. This arrangement aims to facilitate a smooth integration of the CBAM within the broader context of emissions monitoring and compliance during the specified period.

During the transition period, the implementation of CBAM on grey hydrogen and ammonia exported to the EU will lead to a reduction in the revenue received by exporting nations such as TT as it can result in a fall in the price of grey hydrogen and ammonia.

The European Union's CBAM has the potential to impact TT's grey ammonia and grey hydrogen market by imposing taxes on imported goods based on their carbon embedded. This may lead to increased costs and reduced competitiveness for grey ammonia and grey hydrogen in the EU market, subsequently affecting trade and revenue. It prompts considerations of the potential motivation for countries, including TT, to invest in green hydrogen as a strategic move to balance the competitive landscape.

Carbon credits

Carbon credits offer more than just a means to offset GHG emissions; they also present an opportunity for TT to generate revenue by selling surplus credits to countries that fall short of their emission reduction targets. Alternatively, if TT participate in a carbon trading system in the future, producers of grey hydrogen-derived ammonia may incur increased costs due to the necessity of purchasing carbon credits. The trade or sale of a company's carbon quota for revenue has the potential to render processes like SMR (utilising natural gas) more expensive due to associated emissions.

In addition, it's worth noting that carbon credits can serve as a valuable tool for a country like TT. By participating in international carbon credit markets, the country can enhance its financial position, support emission reduction initiatives, and contribute to global sustainability goals. The revenue generated from the sale of carbon credits can be reinvested in renewable energy projects, further promoting environmental stewardship and economic growth.

Policy

The findings of this study carry significant practical and policy implications for TT. Given TT’s dependence on natural gas and grey hydrogen for ammonia and methanol production, transitioning to green hydrogen can help the country meet its NDCs, which aim for a 15% reduction in GHG emissions by 2030[24].

The study also underscores the importance of policy support and enabling frameworks. Policies like the National Climate Change Policy (NCCP) and the Green Hydrogen Roadmap can facilitate this transition by addressing cost competitiveness challenges[25,26]. Additionally, the development and implementation of a Renewable Energy Policy, would be a critical step to establish clear guidelines for integrating renewable energy into green hydrogen production. For instance, government-backed incentives or renewable energy

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investments could help bring down green hydrogen production costs, particularly when ammonia prices are lower. Furthermore, the Wind Resource Assessment Programme (WRAP) offers a pathway for integrating renewable energy into hydrogen production, leveraging offshore wind potential to reduce production costs[27].

These findings are pivotal for TT's industrial sector. Shifting to green hydrogen cannot only mitigate emissions but also position the country as a leader in the emerging green hydrogen market, creating new economic opportunities, attracting investment, and ensuring a just transition for workers in the energy sector. Aligning industrial changes with policies like the Just Transition Policy (that is currently before cabinet) and the Green Hydrogen Roadmap will be critical to achieving long-term sustainability while preserving economic stability[28].

4 CONCLUSION

In TT, the current hydrogen landscape relies on grey hydrogen, utilising natural gas exclusively as a feedstock which presents both a challenge and an opportunity for transitioning to green hydrogen. As the nation aligns with the Paris Agreement and works towards reducing GHG emissions, this study assessed the viability of producing and utilising green hydrogen in TT, highlighting its potential to address fuel shortages and the country's dependency on grey hydrogen as a feedstock. Through techno-economic analysis, green hydrogen production was found to be economically feasible under specific market conditions, especially when ammonia prices are favourable (above USD 547 and preferably closer to 1,500). Sensitivity analyses showed that feasible production costs ranged between USD 3 to 8 per kilogram aligning with the IEA benchmarks. Conversely, at lower ammonia prices (such as USD 314), it indicates that production costs must be significantly reduced to maintain feasibility. However higher ammonia prices enhanced the profitability of green hydrogen initiatives suggesting that with optimal pricing and supportive policies, green hydrogen could be a cost-effective solution for TT.

These findings are particularly relevant for TT's petrochemical sector, which is a cornerstone of the national economy and a major emitter of CO_2. Transitioning all of Company X's hydrogen and ammonia in the petrochemical sector from grey to green, can significantly reduce CO_2e emissions by approximately 2.1 million metric tons annually, which represents 7% of the sector's total emissions, contributing to the nation's decarbonisation targets under its NDCs.

The study also identified key external factors, such as subsidies, market dynamics, and the CBAM, that could influence the adoption of green hydrogen. To enable a successful transition from grey to green hydrogen, priority must be given to supportive policies, targeted subsidies and preferential access to green markets, securing premium prices to enhance cost competitiveness and economic viability. Strategic partnerships between government, industry, and international stakeholders should focus on the petrochemical sector to drive significant emissions reduction and position TT as a competitive exporter of green ammonia.

Equally important is addressing potential societal barriers such as limited awareness of green hydrogen's benefits, concerns over job losses in traditional energy sectors, and issues of affordability and equitable access to clean energy. Awareness campaigns, stakeholder engagement, and a just transition framework will be essential for ensuring public acceptance and can overcome potential barriers to adoption, ensuring a smooth and inclusive transition to a green hydrogen economy.

Overall, this research underscores the transformative potential of green hydrogen to TT's energy landscape by reducing emissions, strengthening economic resilience, and positioning the country as a leader in sustainable energy.

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CONFLICT OF INTEREST

The author declares that there was no conflict of interest.

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