Green hydrogen opportunities for the Caribbean

CARIBBEAN CENTRE FOR RENEWABLE ENERGY & ENERGY EFFICIENCY

Green Hydrogen Opportunities for the Caribbean

Inter-American Development Bank, November 2022

Authors:

Jorge Luis Hinojosa (Hinicio)
Saúl Villamizar (Hinicio)
Nathalia Gama (Hinicio)

Editors:
Gary Jackson (CCREEE)
Joseph Williams (CDB)
Gabriel Castellanos (IRENA)
Roberto G. Aiello, Christiaan Gischler, Augusto Bonzi (IDB)

CONTENT

FIGURES

BOXES

ACRONYMS

BEF	Battery Electric Ferry
BESS	Battery Energy Storage System
BEV	Battery Electric Vehicle
CAGR	Compound Annual Growth Rate
CAPEX	Capital Expenditures
CARICOM	Caribbean Community
CCREEE	Caribbean Centre for Renewable Energy and Energy Efficiency
CCUS	Carbon Capture, Use & Storage
CDB	Caribbean Development Bank
ESS	Energy Storage System
FC	Fuel Cell
FCEF	Fuel Cell Electric Ferry
FCEV	Fuel Cell Electric Vehicle
GHG	Greenhouse Gas
GO	Guarantee of Origin
HFO	Heavy Fuel Oil
H_2	Hydrogen
H_2SS	Hydrogen Storage System
ICEV	Internal Combustion Engine Vehicle
ICEF	Internal Combustion Engine Ferry
IDB	Inter-American Development Bank
IRENA	International Renewable Energy Agency
LCOE	Levelized Cost of Energy
LCOH	Levelized Cost of Hydrogen
OPEX	Operational Expenditures
PV	Photovoltaic

RE	Renewable Energy
SMR	Steam Methane Reforming
TCO	Total Cost of Ownership
TOE	Ton of Oil Equivalent
VRE	Variable Renewable Energy

PROLOGUE

The Caribbean countries have collectively identified as a priority the goal to enhance their energy security with resilient and low-carbon technologies while improving reliability, affordability, and sustainability of energy services. The objective of this report is to contribute to the ongoing discussion on the role that green hydrogen can play in the Caribbean to support the achievement of this overarching goal and to provide an overview and guide in relation to the options for decision-makers in this area.

This report therefore explores the emerging opportunities for the region to 1) decarbonize its energy systems and uses (electricity, land and maritime transportation, and industrial applications), and 2) to take advantage of the region's vast untapped renewable energy resources for further development and creation of new business in this rapidly emerging market for the export of green hydrogen. The report also defines the different types of hydrogen (green, blue, grey), and identifies the potential applications and main drivers for the adoption and production of green hydrogen in the region, while outlining the limitations or challenges to be considered.

The methodology of a comparative analysis of case studies is utilized to illustrate the potential and economic competitiveness of green hydrogen versus conventional technologies in the areas of renewable energy storage and maritime transport. It further explores the possibility of inter-Caribbean hydrogen supply and the prospect of using the Caribbean's vast renewable resources for green hydrogen production and export. While the case studies focus on the Bahamas, Barbados, Guyana, Jamaica, Suriname, and Trinidad and Tobago, they are meant to be representative and applicable across the region. They highlight, importantly, that with the expected decline in the cost of production of green hydrogen, even greater opportunities may be created for the Caribbean for furthering the energy transition by broader applications in the region as well as for increasing the trade balance through the export of green commodities.

Joseph Williams
Coordinator, Sustainable Energy
CDB

Gary Jackson
Executive Director
CCREEE

Roberto G. Aiello
Principal Regional Energy Specialist
IDB, Energy Division

Acknowledgements:

The Inter-American Development Bank (IDB) wishes to recognize and thank the Caribbean Centre for Renewable Energy and Energy Efficiency (CCREEE), the Caribbean Development Bank (CDB), and the International Renewable Energy Agency (IRENA) for their inputs and collaboration during the commissioning of this joint report and for their continuing interest and support for the achievement of energy transformation in the Caribbean. The team thanks Michelle Hallack, Rochelle Johnson (IDB, Energy Division), and Hillary Alexander for their review and inputs.

Executive Summary

The decarbonization of the energy, transport, and industrial sectors is an essential part of achieving net-zero CO_2 emissions, to limit global warming to 1.5°C above pre-industrial levels. Green hydrogen is emerging as one of the most versatile climate change mitigation tools, since it possesses a unique potential to decarbonize hard-to-abate sectors such as freight transport, energy-intensive industries, and power systems highly dominated by fossil fuels. It also holds an alternative to produce fuels and chemical feedstocks locally, using renewable energy without dependence on imported fuel, energy, or commodities. Green hydrogen is produced from the electrolysis of water powered by renewable energy (RE), which splits the H_2O molecule into its constituent elements: hydrogen and oxygen. It is thus a zero-carbon molecule, flexible for use either for energy applications, powering mobility, or as an industry feedstock.

Even though green hydrogen is currently expensive for most applications at a global level, the exponential decrease in RE costs in the last decade and the expected accelerated cost-reduction of hydrogen technologies in the upcoming years are projected to drive an increase in the attractiveness of green hydrogen worldwide, as shown in reports from the IEA, IRENA, WEC, and others.

As Caribbean countries are in the early stages of developing their renewable energy potential, there are opportunities for renewable energy production cost to decline, enabling green hydrogen to get closer to achieving cost-competitiveness, and could eventually become economically viable and a more broadly adopted solution.

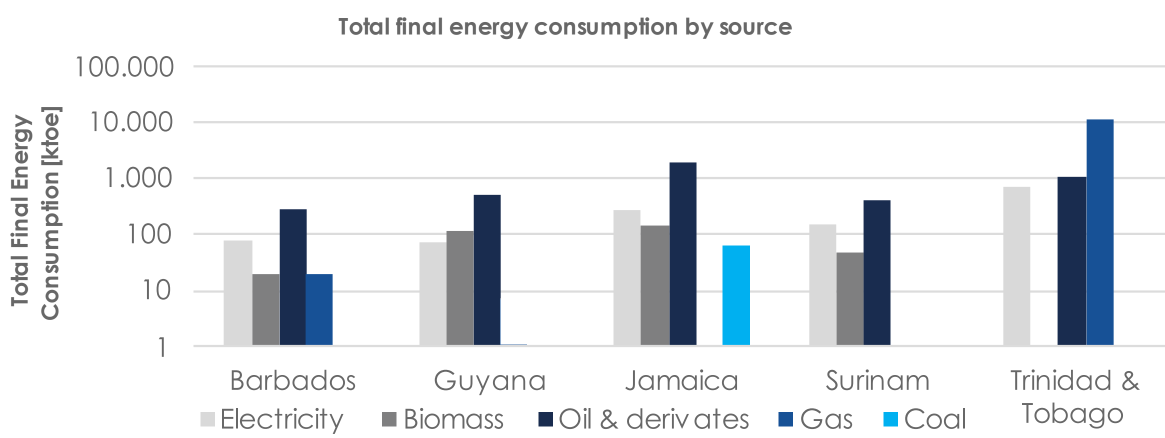


Figure 1. Total final energy consumption by source. Source: (OLADE, 2019)

Achievement of this objective is challenged by the fact that electricity tariffs are high, as is the average unit cost of developing and operating renewable energy projects owing to the lack of economies of scale, compared to the situation in larger continental countries[1].

It is worth highlighting that, among the factors which might drive the development of a hydrogen economy in the Caribbean, there is a need for most of the countries to reduce their high reliance on fossil fuels (see **Figure 1**), as well as their abundant and untapped renewable energy potential (see **Figure 2**). In addition, national renewable energy targets and the need for energy security and reliability are drivers that can influence the uptake of hydrogen in the coming years.

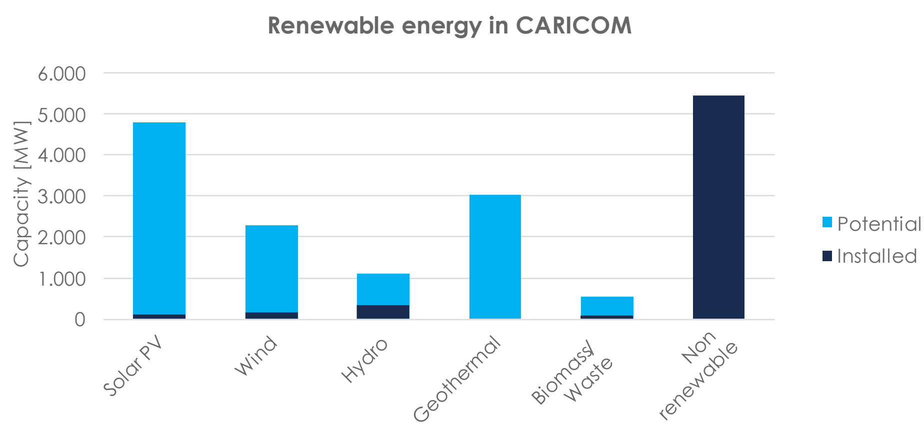


Figure 2. Cumulated CARICOM Renewable Energy Potential vs Installed Capacity. Source: (CCREEE, 2020))

Considering the importance of reducing the region's reliance on fossil fuels and the range of possibilities that may arise from harnessing its renewable energy resources, one of the main objectives of this study is to demonstrate the potential green hydrogen opportunities in the Caribbean through the development of case studies. These case studies aim to provide an overview of the role that green hydrogen can play in the Caribbean to decarbonize its energy systems and use, including the generation of low-carbon electricity, the substitution of fossil fuels in maritime transport, and in exports within Caribbean countries.

The case study selection process comprised three main phases. First, a documentary review of the energy and economic context of the Caribbean region, from sources such as reports from the IDB, CARICOM, CCREEE, and IRENA. Second, the more relevant hydrogen applications were filtered to identify a short-list. The criteria for case selection included the identification of major barriers (such as lack of infrastructure or reduced potential demand), availability of data, and low competitive advantage of the H_2 application compared to the incumbent technologies. Finally, three study cases were

[1] Reported CAPEX for RE technologies in the Caribbean is up to 2x the CAPEX in other countries of the LAC region; i.e. Caribbean PV CAPEX 2400 USD/kW in 2019 (IDB, 2020)vs Mexico PV CAPEX 1238 USD/kW in 2019 (IRENA, 2020).

selected following the recommendations and feedback from relevant stakeholders. These were developed to illustrate the potential use and economic competitiveness of the respective hydrogen solution in the Caribbean, also comparing them to other low-carbon alternatives when available.

The first selected case study is focused on renewable power storage, given that the deployment of energy storage systems such as those with hydrogen and fuel cells can improve grid reliability, availability in case of electricity shortages and outages, and enable higher integration of variable renewable energy into the power grid. When comparing hydrogen storage with battery energy storage, it was found that by 2030 hydrogen systems would be the least-cost alternative for multi-day energy storage.

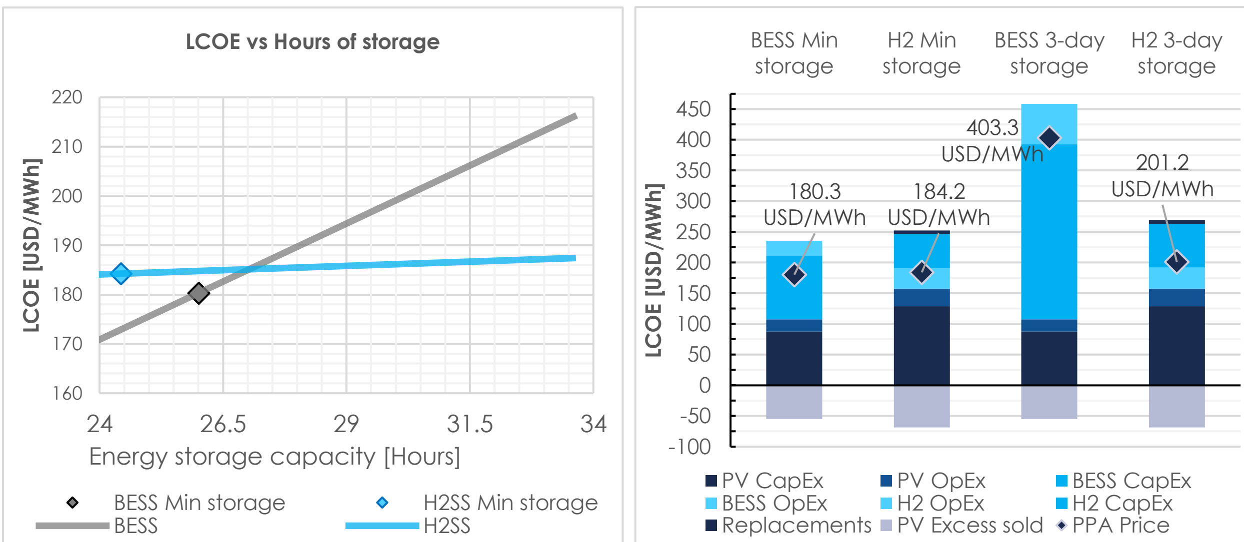


Figure 3. LCOE Breakdown by cost component (left) and
LCOE as function of the power storage capacity in time (right).

The second case study assessed the competitiveness of diesel, battery-electric, and hydrogen-powered passenger ferries using a Total Cost of Ownership analysis. The assessment showed that for high daily usage conditions, a hydrogen-powered ferry would be the only feasible decarbonization alternative among those studied. Additionally, if a pilot were to commence development in 2022 with an aim of being operational in 2025, it could potentially be cost-competitive with its diesel counterpart over its lifetime. For shorter routes, hydrogen-powered ferries could be almost as cost competitive as a battery electric in 2030, and both cheaper owned than a diesel-powered ferry.

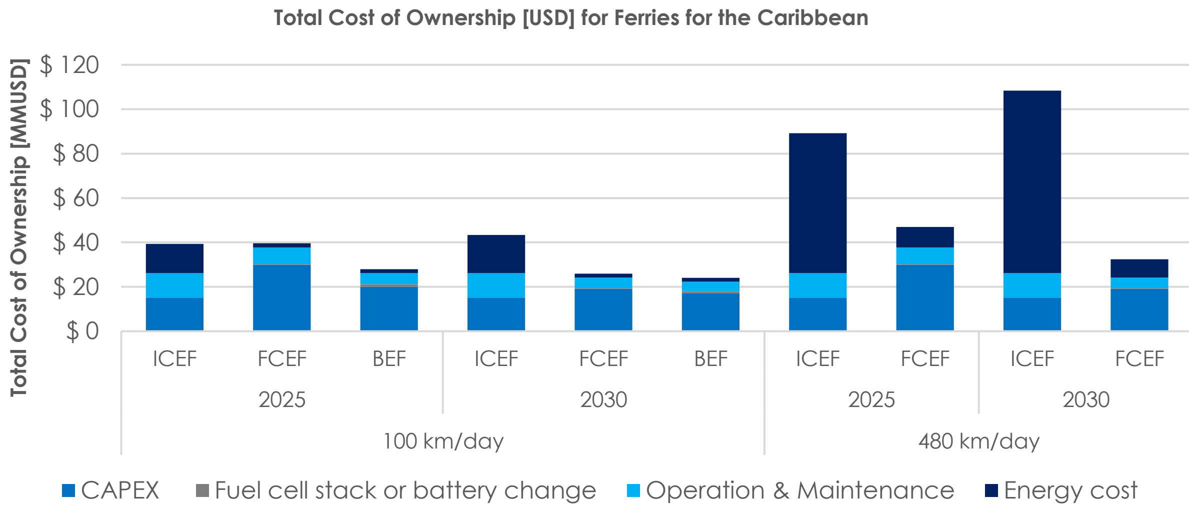


Figure 4: ***TCO for the different technologies and use scenarios assessed.***

The third case study explored the possibility of hydrogen exports within the Caribbean region. Green hydrogen and its derivatives such as ammonia or synthetic fuels, are seen as a means for countries with vast renewable energy resources to export this potential to destinations with projected demands for low-carbon hydrogen which are higher than they can self-supply, thereby creating new opportunities for potentially producing and exporting nations. The target markets lie mainly in countries that have established ambitious hydrogen goals in their national strategies, but which already acknowledge their inability to produce it on their own in the volumes and at the costs required for its wide-scale adoption. This is the case for countries such as Japan, South Korea, and many within the European Union.

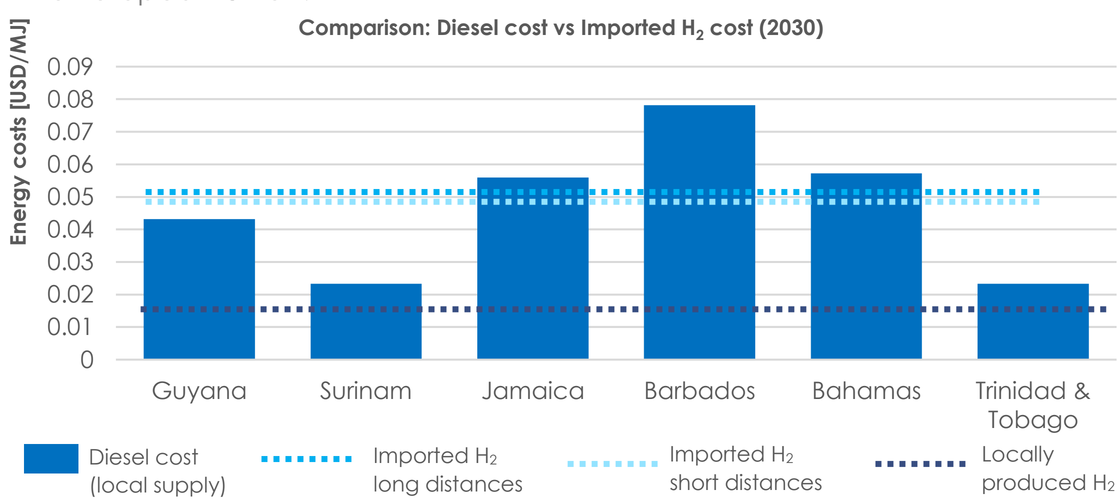


Figure 5. Comparison between diesel costs and green hydrogen production or import. This excludes potential hydrogen subsidies, and the environmental costs or carbon taxes that could potentially be added to the costs of diesel.

The case study analyses the cost competitiveness of exporting green hydrogen in its liquid form, as the selected means for maritime transport, and compares it to the cost of diesel available in the studied countries within the Caribbean. Results show that inter-Caribbean green hydrogen exports could be competitive in 2030 against the local diesel supply in Barbados and similar to the cost of diesel in the Bahamas and Jamaica.

Besides the study cases, this report briefly discusses other opportunities for the Caribbean industrial decarbonization by substitution of the current grey hydrogen supply with green hydrogen for oil refining and ammonia production; the production of liquid synthetic fuels (hydrocarbons made with green H_2 and captured CO_2); hydrogen in heavy-duty road vehicles; and the use of green hydrogen in the reutilization of waste, either from syngas obtained from the gasification of biomass, or steam reforming of biomethane, potentially contributing to a more circular economy in the region. The production of fertilizer using green ammonia is also under consideration in the region, however, that alternative is not addressed in this report and would require further studies.

Finally, the last section of the report presents the main conclusions and recommendations, highlighting the relevant role of hydrogen in providing the storage needed to enable firm renewable energies, and as an attractive option for maritime mobility, achieving cost-competitiveness with diesel, as well as the advantages for the region if a joint green hydrogen Inter-Caribbean market is deployed. The prospect of aiming for the Caribbean to become a self-supplied green hydrogen region is laid out as an approach that could provide numerous advantages and opportunities. On the other hand, overseas exports of green hydrogen are expected to face challenges related to the scale and cost of the RE supply and the associated green hydrogen production. These scale and cost challenges could be partly addressed by the region tapping its vast geothermal and wind energy potential for producing green hydrogen and would need to be analyzed in further studies.

Among the main challenges for green hydrogen to be economically competitive are market scalability and integration along with the need for broad coordination, long-term vision and planning at the national and regional levels. Correctly aligned incentives and synergies, including regulatory and policy harmonization, will be essential for hydrogen export and import markets to developed, including international cooperation and coordination for sharing knowledge and building local capacities. National hydrogen strategies and possibly, a Caribbean Hydrogen Strategy and Regional Hydrogen Roadmaps by application-sector, could be essential to target and unlock the potential of the region more viably, by harnessing each country's strengths and unique capacity to contribute to the development of a strong regional hydrogen ecosystem.

1. HYDROGEN: A GLOBAL TREND

Green hydrogen is produced from the electrolysis of water powered by renewable energy, which splits the H_2O molecule into its constituent elements: hydrogen and oxygen. It is thus a zero-carbon molecule, versatile for in energy applications, powering mobility, or as an industry feedstock. The reverse process, carried out in devices called fuel cells, uses oxygen from the air and the stored hydrogen to produce electricity, having only water vapor as a by-product. These are the two angular technologies that have enabled green hydrogen to become an emerging topic in the latest years in the global climate and energy space. This has happened due to a combination of factors, most of which could help create new opportunities in the Caribbean.

Among the first of these factors is the increasing drive by governments and corporations across the world to take climate action, and **green hydrogen possesses a unique potential to decarbonize transport, energy, and industry, particularly in hard-to-abate sectors. It also holds an alternative to produce fuels and chemical feedstock locally using renewable energy without dependency on imported fuel, energy, or commodities markets.** It thus opens the door to a *new universe of low-carbon applications based on renewable energy*, also known as **Power-to-X**, such as **Power-to-Mobility**, **Power-to-Gas**, **Power-to-Ammonia**, and **Power-to-Power**, for example. Although currently expensive for most applications at a global level (with projected levelized costs of 4-8 USD/kg), accelerated cost reductions in hydrogen technologies and RE are widely expected, with estimates projecting cost reductions as high as 80-90% by 2030, relative to 2020, so that it can compete with gray H2 which is commonly at 1-2 USD/kg today. This in turn would make hydrogen technologies a carbon-neutral and economically competitive solution for a wide range of applications starting as soon as the middle of this decade.

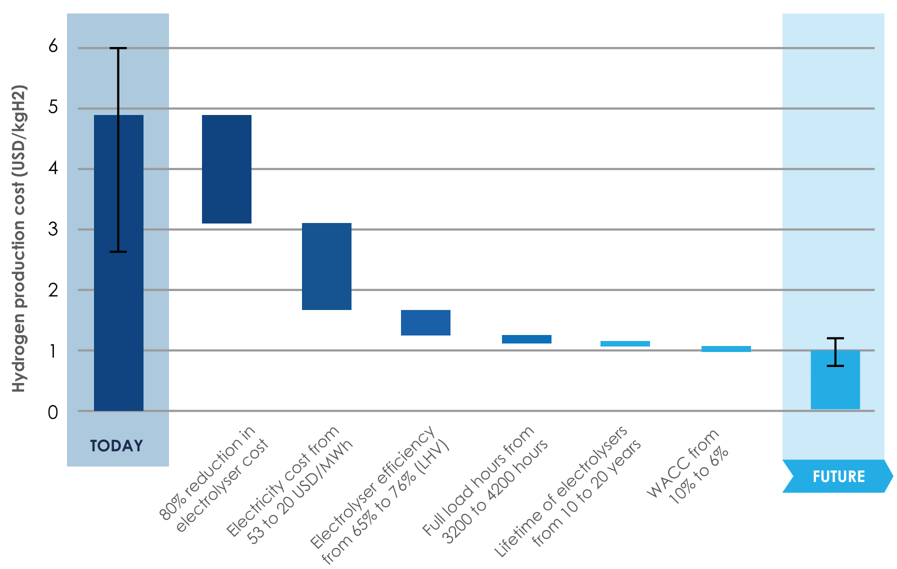


Figure 6. Factors contributing to the reduction of green hydrogen cost towards 2030.
Source: Hinicio based on IRENA, 2020.

BOX 1-1 HYDROGEN BASICS

Hydrogen is the most abundant chemical element in the universe, representing around 75% of its mass. On planet Earth, hydrogen atoms are vastly found in organic compounds and water, but it is very scarce as a naturally occurring gas.

Consequently, hydrogen must be produced, or extracted, from other compounds such as natural gas or water. There are a variety of processes to do so which use different feedstock sources. These methods are usually labeled by colors, but there is no consensus on the precise definitions. The most broadly used hydrogen color conventions, are grey, blue, and green. However, regardless of the label, they are all the same H_2 molecule with an energy density of 33 kWh/kg, which is higher than any fossil fuel.

Gray hydrogen:

This is the label given to the hydrogen produced from fossil forces, mainly from natural gas or coal (mostly in China). Its most common production process is through Steam Methane Reforming (SMR), by reforming the methane molecule (CH4) with high temperature steam, producing, hydrogen (H_2) and carbon dioxide (CO_2) in a mass relation of 1:8 to 1:12. This is currently the mainstream production method, satisfying nearly 50% of the world's current hydrogen demand. While Gray hydrogen is produced at very low costs, it is intense in GHG emissions at 9 $kgCO_2e/kgH_2$.

Hydrogen is also obtained through the gasification of coal and can be obtained through the same process over almost any organic compound, oil, biomass, waste, although no color has been yet assigned.

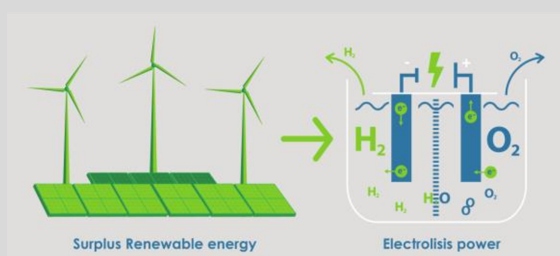
Blue hydrogen:

This label refers to the production of Gray hydrogen, based of fossil resources, coupled to a Carbon Capture & Storage (**CCS**) system. The share of carbon emissions that needs to be captured for the H_2 to be considered blue remains in discussion and there is no consensus, but it ranges between 80% and 95%. However, there are additional concerns such as the leakage of methane upstream.

Green hydrogen:

This label refers to hydrogen produced by the electrolysis of water powered by renewable energy, with negligible GHG emissions. Alternatively, green hydrogen can be produced via the reformation of biomethane, in a process similar to Gray H_2 production but supplied with biogas coming from the digestion of organic matter.

Green hydrogen production



Hydrogen (H_2) has been used as an industrial gas for more than 60 years, mainly as feedstock for the petrochemical industry and the production of ammonia and methanol, as well as other applications such as the manufacture of semiconductors, steel, flat glass, margarines, and synthetic resins. The current hydrogen global demand stands at 90 million tons per year[2] (IEA, 2021a), from which it is estimated that Trinidad & Tobago produces around 1.5 million tons per year (IRENA, 2022). This could signal that Trinidad & Tobago has the potential to become a large off-taker of green hydrogen for ammonia production, becoming an important player in the regional hydrogen ecosystem. This would be more likely to accelerate once green ammonia achieves cost-competitiveness.

Most of the H_2 consumed worldwide is produced via Steam Methane Reforming (SMR) (**gray hydrogen)**, a process in which the methane molecule is reformed with high temperature steam at high pressure, resulting in carbon dioxide (CO_2), carbon monoxide (CO), and H_2. Hydrogen production currently has a significant climate impact. In 2020 it was responsible for 900 Mt of CO_2 equivalent emissions (IEA, 2021a). However, there are also low-carbon production pathways such as SMR or coal gasification with Carbon Capture & Storage (CCS) (**blue hydrogen)**; electrolysis powered by renewable energy (**green hydrogen)**; and pyrolysis of methane, among others (see **Box 1-1**). These low-carbon production pathways and hydrogen's polyvalent uses make this molecule a versatile decarbonization tool.

Many nations worldwide have recognized the current trend towards the use of hydrogen as a key element for the decarbonization of their economy. In the last two years, the number of countries that released national strategies or road maps for clean hydrogen has increased from three to over twenty, and there are also around sixteen national strategies under development and around forty countries with policy discussions, official statements, or preliminary pilot projects (WEC, 2021).

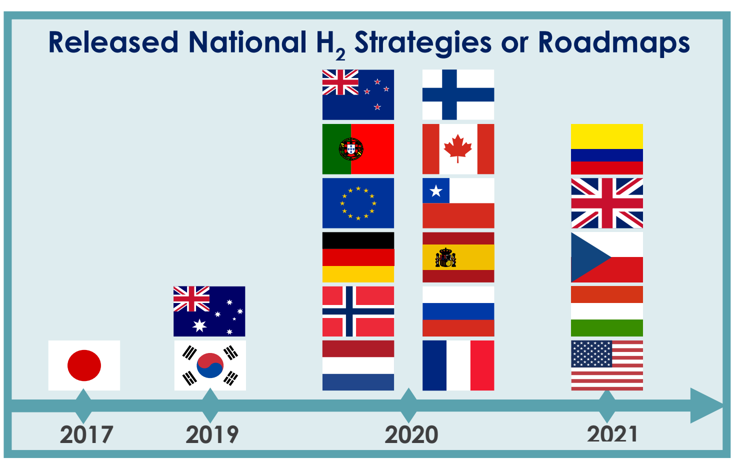


Figure 7. National strategies or Roadmaps release timeline[3]. Source: Hinicio

[2] Data from 2020, it is composed by 70 MMtons of pure hydrogen plus 20 MMtons of a mixture with carbon-containing gases
[3] Up to December 2021.

These countries consider the production pathway of low-carbon hydrogen according to their available resources, whether they have high renewable energy potential for producing green hydrogen or a well-stablished oil & gas industries for producing blue hydrogen.

1.1. Main factors fueling the uptake of hydrogen

There are three factors that have heavily influenced the uptake of hydrogen in the global climate and energy space in the last few years, including some related to the increase in efficiency and cost reduction of RE and hydrogen technologies, as well as more ambitious decarbonization mandates and incentives by countries around the world. These factors are described below.

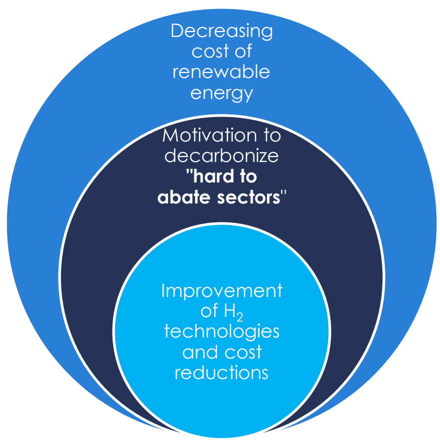


Figure 8. Factors that have driven the current wave of clean hydrogen. Source: Hinicio

i) The costs of renewable energy have decreased exponentially in the last decade. RE is a key cost component of green hydrogen, generally representing around 50-70% of its production cost. Its ongoing decline will be essential in reducing the costs of green hydrogen. For example, the global average levelized cost of energy (LCOE) of solar PV has fallen from 381 USD/MWh in 2010 to 57 USD/MWh in 2020, representing an 85% cost reduction within 10 years. This has also been the case for other renewable energy technologies, such as onshore wind, offshore wind, and concentrated solar power, which have had cost reductions between 48% to 68% during the same period (IRENA, 2021).

The reduction in the cost of renewable power supply will increase the attractiveness of green hydrogen because it has heavily improved hydrogen economics.

The cost of green hydrogen production depends mainly on three factors: (1) the capital cost of the H_2 generation equipment; (2) the cost of the renewable energy supply; and (3) the operating hours of the electrolyzer, as shown in **Figure 9**. The cost of the energy supply varies depending on the renewable technology and the locally available resource. The electrolyzer capacity factor depends on the abundance and dispatchability of the renewable energy sources, as well as the relation between the installed power generation and the electrolyzer capacities, which are usually optimized for cost reduction.

The cost of water for green hydrogen production represents less than 2% of the total hydrogen production cost. In locations with limited access to fresh water, the use of water treatments is required, due to the high purity water needed by electrolysis. *Adding a desalination process would increase the energy requirement of the hydrogen production but this is insignificant in comparison to powering the electrolyzer*. Desalination with reverse osmosis, for example, could add an energy cost of USD $0.53–1.50 per m3 of clean water produced (Rebecca R. Beswick, 2021), leading to a reduced increase in levelized cost of electrolytic hydrogen production of around USD $0.02 per kg of hydrogen (M. A. Khan, 2021).

As Caribbean countries are in the early stages of developing their renewable potential, there are plenty of opportunities to achieve cost reductions for renewable energy production, enabling green hydrogen to get closer to achieving cost-competitiveness and eventually become economically viable and a more broadly adopted solution.

However, this will not come without its challenges as Caribbean countries may struggle to achieve renewable production costs as low as neighboring continental countries, which can benefit more greatly from economies of scale, and have lower installation and maintenance costs. This dynamic is described in further detail in **Figure 12. *Final Energy consumption by Source for some Caribbean countries. Data source: (OLADE, 2019)***

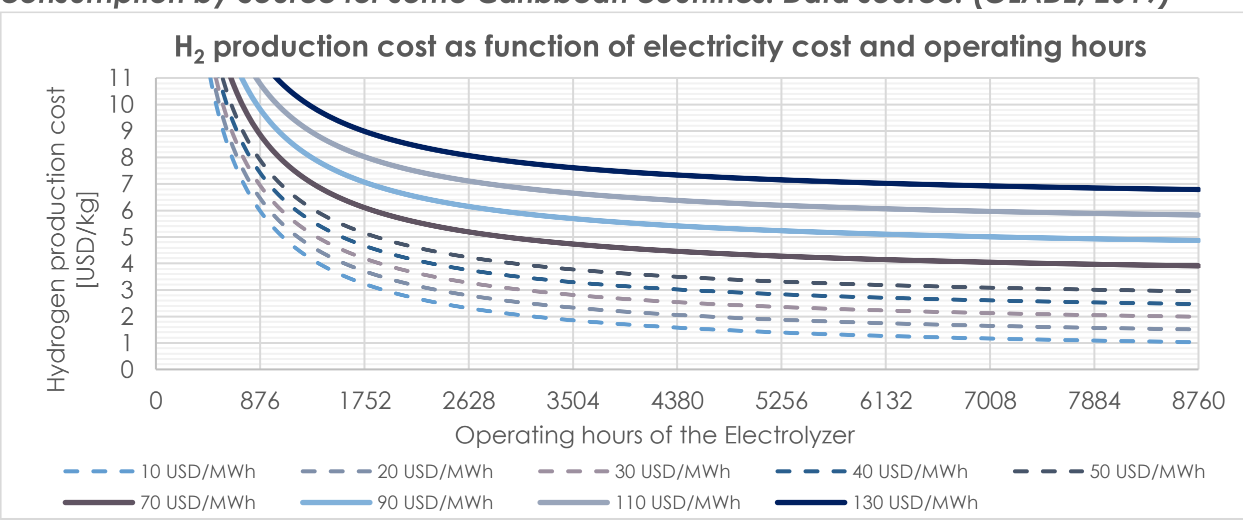


Figure 9. H_2 production cost as a function of electricity price and operating hours[4]. Source: Hinicio.

[4] For the **Figure 9**, the CAPEX and OPEX of the electrolyzer are assumed at, 650 USD/kW and 6% of CAPEX per year, respectively; the cost was evaluated with a return rate was fixed at 7%, an electrolyzer efficiency of 48 kWh per kg of H2, and a 20-year lifespan. In solid lines, the reported Caribbean CAPEXOPEXCAPEXOPEXLCOEs in (IDB, 2020).

ii) In the last decade, H_2 technologies have become more efficient, cheaper, and able provide a wider range of services due to their enhanced flexibility[5]; and this trend is expected to continue. For example, with the increase of renewable energy share (*mostly variable*) in national power systems, there is a need for grid flexibility and storage capacity. Solar and wind renewable sources are subject to intra-day and seasonal variations and current hydrogen production and power generation technologies can now provide flexibility, fostering the integration of variable renewable energies into the grid. They can participate in the flattening, or firming, of variable renewable energy production profiles through the re-electrification of hydrogen for power generation via **fuel cells** or energy consumption via **electrolyzers** producing hydrogen to provide long-term energy storage using hydrogen storage tanks, which are a low-cost solution.

	2012	2017	2020	2023
Energy consumption @ rated power (kWh/kgH2)	57-60	55	52	50
Common production @ rated power (kg/day)	100	500	1,000+	1,000+
Capex @ rated power (M€/(t/d))	8	3.7	2	1.5
Degradation @ rated power during 8000 hours / year	2%-4% / year	2% / year	1.5% / year	<1% / year
Operational flexibility without hazarding the degradation (% of nominal capacity)	5% -100%	5% -150%	0% - 200%	0% - 300%
Ramp-up time from min to max production	1 min	10 s	2 s	<1 s
Delay to start H_2 production from cold start	5 min	2 min	30 s	10 s

Table 1. Hydrogen production technological evolution. Data source: (Horizon 2020, 2018)

This matter has been broadly studied[6] in order to verify the opportunity for electrolyzers and fuel cells to participate in grid services markets and it has been proved that these technologies can respond rapidly enough to provide grid services such as contingency reserves, load-following and regulation (Eichman et al., 2014)

[5] Refers to the ability of changing their load in a short period of time without reducing the lifetime of the equipment.

[6] Some of the projects that studied Hydrogen role in grid services: H2Future, DEMO4Grid, BALANCE, HPEM2Gas, HyBalance, MYRTHE. Source: (QualyGrids, 2016)

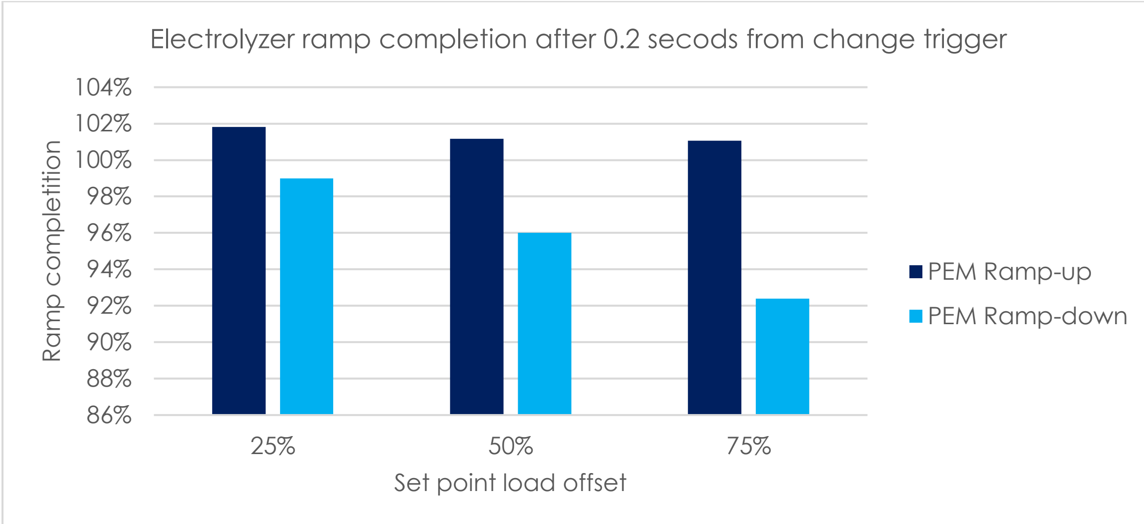


Figure 10. ***Electrolyzer response to a set-point change at different shares of load. Data source: (Eichman et al., 2014)***

iii) There is an increased drive to take actions to achieve the COP21's objective of limiting the rise of global warming under 1.5ºC by 2100. Recent reports confirm that global emissions are currently not on the targeted trajectory. The latest report of the IPCC, the Sixth Assessment Report, unveiled that the globe has already warmed 1.1ºC; thus, **the 1.5ºC target is most unlikely to be achieved unless deep reductions in GHG emissions occur**. It is estimated that net zero emissions must be reached by 2050 to have realistic chances of achieving the target; otherwise, it is most likely to reach a temperature of 2.7ºC by 2100 (IPCC, 2021).

There is a challenge to decarbonize hard-to-abate sectors, in which technology options are limited, such as heavy-industry and long-haul transport; and to decarbonize countries with limited renewable resources where low-carbon hydrogen might be key to achieve climate targets.

"Countries' pledges to reduce their emissions are currently not in line with the projected pathway necessary to limit global warming to 1.5°C" (IPCC, 2018)

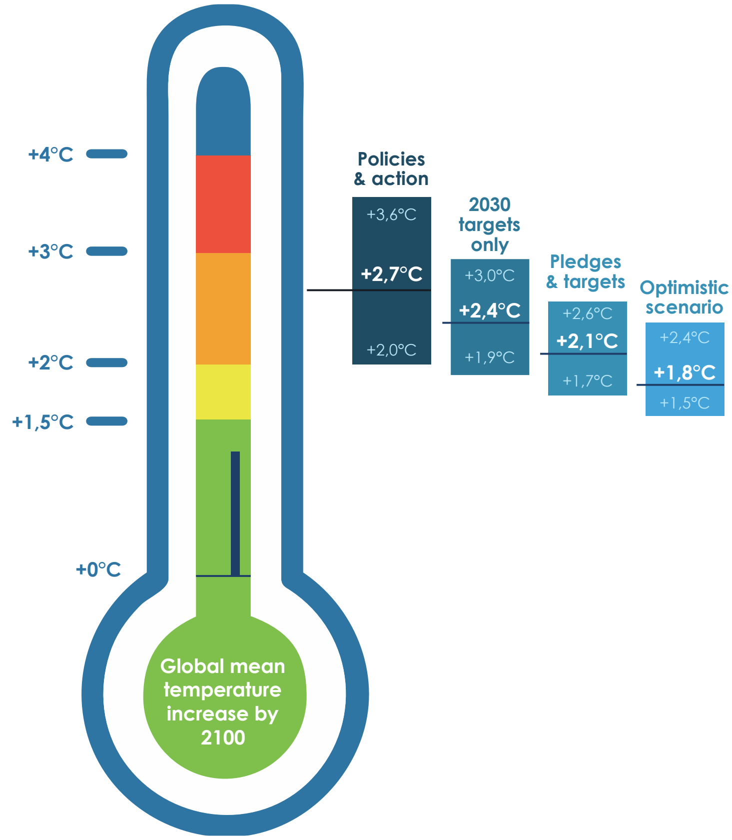


Figure 11. CO_2 emission pathways for estimates of action & policies, 2030 targets, long-term pledges, and optimistic scenarios. Source: (Hinicio based on Climate Action Tracker, 2021)

Consequently, hydrogen is ever more recurring in international climate conversations. During the last COP26, held in Glasgow, hydrogen was in the spotlight of the discussions. One of the resulting five "Glasgow Breakthroughs" is to ensure that affordable low-carbon hydrogen is globally available by 2030, to which several countries committed[7] (Race to Zero, n.d.). The main topics discussed around hydrogen were defined based on international experiences and best practices, and the following could be replicated in the Caribbean region:

- Fostering the market for low-carbon hydrogen and alignment efforts to reduce the cost of production and supply.
- Ensuring the abatement of greenhouse gases along the full hydrogen value chain.
- Promoting the hydrogen transition through financial support, carbon pricing and trading, and international hydrogen trading.
- Low-carbon hydrogen certification and guarantee of origin (GO) schemes.

[7] List of signing countries: Australia; Azerbaijan; Belgium; Canada; Chile; China; Denmark; Egypt; European Union; Finland; France; Germany; Guinea Bissau; Holy See; India; Ireland; Israel; Italy; Japan; Kenya; Lithuania; Norway; Mauritania; Morocco; Namibia; Netherlands; Portugal; New Zealand; Panama; Republic of Korea; Serbia; Slovakia; Spain; Sweden; United Kingdom; United States of America.

2. WHY HYDROGEN IN THE CARIBBEAN?

This chapter aims to provide the main factors that might contribute to the uptake of hydrogen applications within the Caribbean, considering the regional context. Despite the diversity of the region in terms of geographic location and energy production and final uses, four main factors have been identified that represent important potential drivers for the deployment of the hydrogen market in the each analyzed country, providing potential opportunities and a momentum for local development and the decarbonization of relevant economic sectors.

2.1. Elevated reliance on fossil resources, mostly from imports

Countries in the Caribbean are diverse in terms of geographic location, surface area, economic activities, and energy supply sources. Most of them exhibit a heavy reliance on fossil fuel resources and their derivates for transportation and power generation, with some nations showing a full dependency on them. This has several unfavorable consequences including elevated energy costs, exposure to the supply and cost volatility of international oil and fuel markets, in addition to being a significant contributor to these countries' own carbon emissions. Recent international events have exemplified the extent of the risks and level of exposure experienced by developing economies from this reliance on external energy sources.

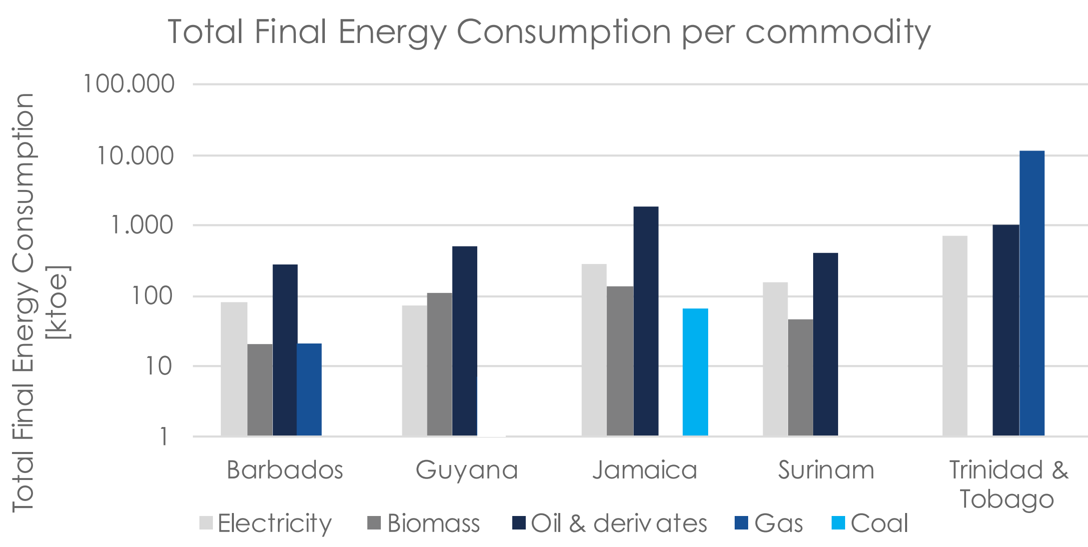


Figure 12. Final Energy consumption by Source for some Caribbean countries. Data source: (OLADE, 2019)

As presented in the **Figure 12**, most of the energy needs are covered directly by fossil fuel resources, which unveils the exposure of their economy to oil & gas price volatility (see **Figure 13**), for both imports and exports of these commodities. Electrification of industrial processes or transportation, whenever possible, will reduce this dependency only if power is produced from renewable resources. However, there will be some processes which won't be viable to electrify, and hydrogen could play a key role to decarbonize these hard-to-abate sectors.

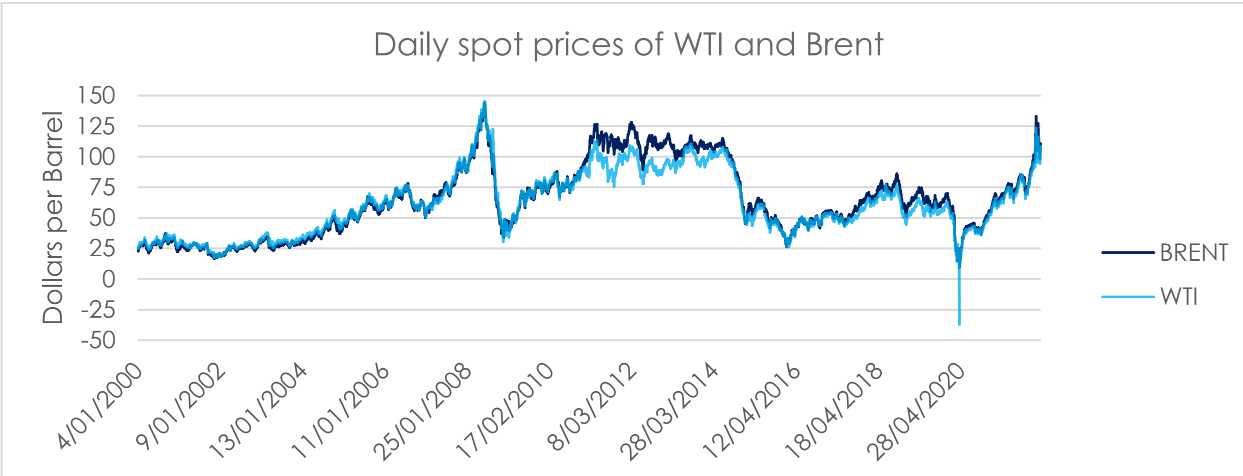


Figure 13. Daily Oil spot prices since 2000. Data source: (EIA, 2022)

Many Caribbean countries' power systems rely on diesel, heavy fuel oil (HFO), or natural gas, yet only few of them hold significant oil and gas reserves, and even fewer have refining capacity. Therefore, for countries which must import these fuels, commodities such as electricity or fuels for transport tend to cost substantially more than the average in Latin America. This can be noted in the difference in the costs of electricity of countries which mostly export and import energy sources. **Net energy importer countries, such as Jamaica or the Bahamas, have an electricity tariff around 215 to 310 USD/MWh, based on**

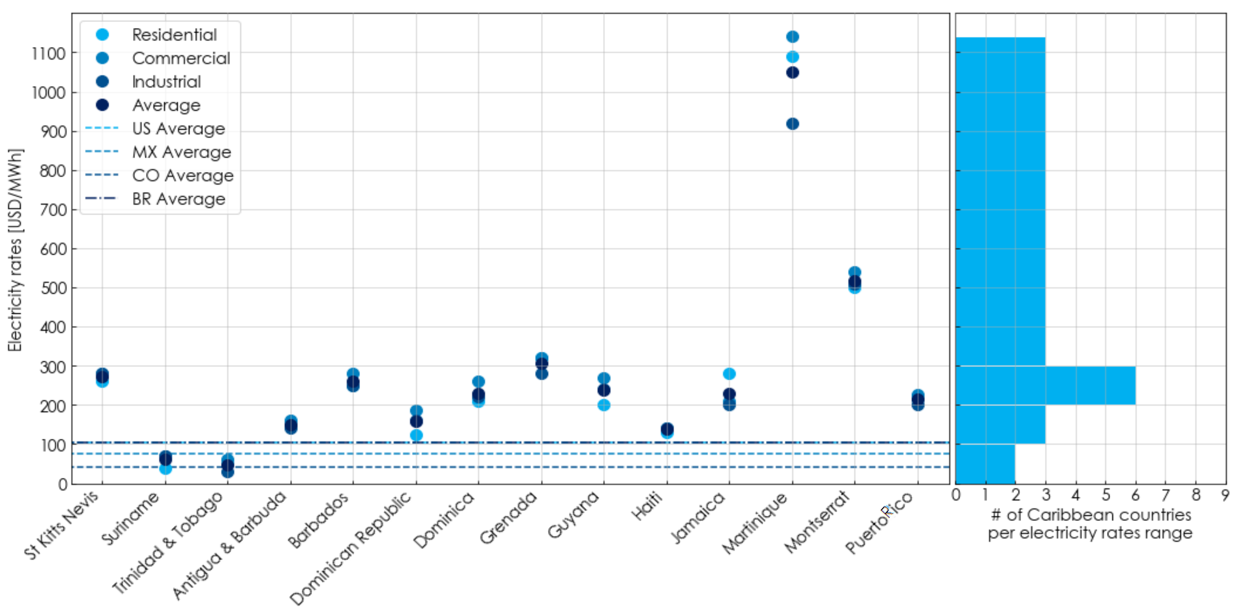


Figure 14. Electricity rates for Caribbean countries compared to other rates in the continent

the fuel price, while in net exporters, such as Trinidad & Tobago or Suriname, the tariff is around 25 to 60 USD/MWh (IDB, 2019),as shown in **Figure 14.**

2.2. Abundant and untapped renewable energy potential

In terms of renewable energy, *Caribbean countries have a vast untapped potential* (See **Figure 15**). Most of them have already set important renewable energy targets in the medium term but are still lagging to achieve them, partly because of the inadequacy of the regulatory frameworks —an area of opportunity—, the up-front capital requirements which have remained high, elevated installation costs, finding appropriate site availability and that many of the grids are not yet ready to manage high load variations, inherent with a higher penetration of variable renewable energy sources in the power grid.

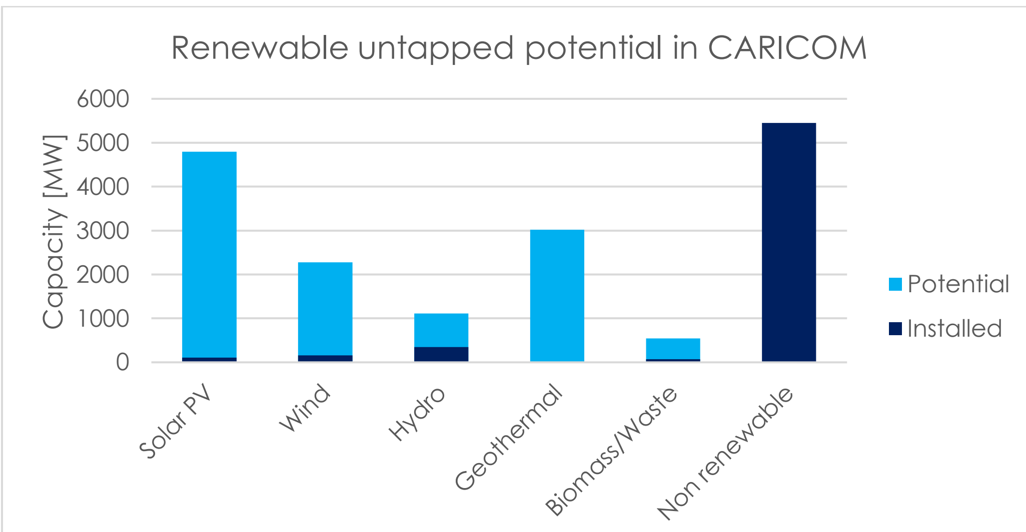


Figure 15 Renewable energy potential per source for the CARICOM countries aggregated. Data source: (CCREEE, 2020)

The region could aim to self-supply an increasing portion of its energy needs for power, transportation, and industry, being green hydrogen a potential enabler to do so. Either helping to integrate higher shares of untapped variable renewable energy into the power systems with long-term, flexible energy storage; producing green hydrogen or derived fuels to power hardly electrifiable vehicles; or directly burning hydrogen for industrial, building, and residential heat requirements. Hydrogen has the technical potential to supply many of the region's energy needs with a clean molecule, produced using the locally abundant renewable energy sources. In a way, **green hydrogen could potentially allow vehicles, water heaters, cooking stoves, industrial furnaces, and many other applications to run with renewable energy, with negligible carbon emissions, and sourced from a 100% local supply**, once the production facilities have been installed and in operation and with the adequate investments for supply infrastructure and end the retrofit or conversion of end-use equipment. For that to happen, **hydrogen technologies would need to be cost-competitive, and measures should be put in place to compensate for the limited scalability possible in island states, which is a necessary factor to help drive down hydrogen production costs**.

2.3. One step towards energy independence and enhanced reliability

Green hydrogen will provide the opportunity to produce fuels and feedstocks locally in countries with abundant and low-cost renewable energy potential. Either within the country or based on exchanges within the Caribbean, and **if produced at competitive costs, green hydrogen could become a commodity that will enable the region to reduce its dependency on imports of oil and its derivatives, with stable long-term prices which avoid the oil market price fluctuations and volatility**. The high costs of fuel in most Caribbean countries, compared to other regions, could facilitate green hydrogen to be an economically competitive solution in the short to medium term, enabling a broader deployment within an earlier time horizon. The conditions required for Caribbean countries to achieve this cost-competitiveness are further explored in the case study of inter-Caribbean hydrogen exports, found in a later section of this report.

Additionally, using **green hydrogen as an energy vector could allow countries to have multiple days of energy supply's storage as reserves to use in the events of interruptions in the energy supply**, specifically, for example, in the delivery of electricity caused by failures in the power grid or fuel supply due to natural disasters or other causes. This could also provide a greater reserve margin to respond and supply energy in response to an emergency making use of isolated generation systems to power microgrids or fueling vehicles, while also serving as a resilient alternative energy infrastructure that is less vulnerable than the power grid to weather or climate events with the flexibility of being transported by road, pipelines, or using power distribution systems to produce hydrogen when imported fuel supply is limited.

Green hydrogen could increase energy security, reliability, and availability in Caribbean countries by providing both a share of self-supplied fuel and readily available, low-cost energy reserves. Caribbean countries rely on petroleum products as the source of approximately 70% of their primary energy consumption. Oil importing countries in the Caribbean have reported to spend up to 15% of their annual GDP on fuel imports, which make them highly vulnerable to oil and gas imports. Most of the Caribbean countries have set important renewable energy targets, including the Caribbean Community (CARICOM), which has set an initial target of 47% renewable energy contribution to total electricity generation in the region by 2027. Considering the untapped resources of the region, renewable energy is available for green hydrogen production and green hydrogen could be used as a means to exchange renewable energy between Caribbean countries, and to have multi-day energy reserves at relatively low-cost, as shown in the Power-to-Power case study presented in this report.

2.4. Key to carbon neutrality & renewable energy targets

Most Caribbean countries have adopted national renewable energy targets as a key strategy to make use of their natural resources and decarbonize their energy matrices. One of the challenges faced is that the region's largest energy-consuming countries have scarce firm renewable energy potential, which could come from sources such as geothermal or hydropower. Instead, their most readily accessible renewable potential option is from variable sources, mainly solar and wind, either on-shore or off-shore (which has some additional cost challenges, not thoroughly addressed in this report). Since **power systems were not designed for the level of variability characteristic of these options, they can only receive a certain amount of energy from variable sources, unless costly grid-modernization upgrades (including battery energy storage) are pursued to facilitate higher penetration of renewable energy**. This has been the case for most power systems around the world and the Caribbean is no exception.

Hydrogen provides a good means for long-term, yet flexible power storage. Excess electricity generation from renewables can be stored using an electrolyzer to convert it to hydrogen for re-electrification in later hours of supply shortage. Furthermore, **hybrid hydrogen and battery energy storage systems can be designed and optimized to be more cost-efficient than, for example, solar PV plus battery systems alone** (Hinicio, 2017).

Moreover, there are some Caribbean countries with a geothermal potential that exceeds by a factor greater than 100x their current peak demand. **Green hydrogen and its derivates could represent an option to export this excess energy without extensive submarine transmission cables between islands and create new opportunities.**

3. KEY OPPORTUNITIES FOR THE CARIBBEAN

3.1. Renewable-powered future (Power-to-Power)

Energy storage systems (ESS) can improve grid reliability and response capacity in the face of electricity shortages and outages and enable higher integration of variable renewable energy (VRE) into the power system. This becomes even more relevant in isolated grid contexts like those found in many Caribbean countries.

For VRE sources, unlike firm power plants (including hydro), power system planning cannot be guaranteed with certainty, as power generation may change drastically within seconds and can be influenced by weather variability and climate change. Additionally, unlike power turbines, they do not provide inertia to provide proper frequency response to the grid. Therefore, the stability and security of the supply must depend on power generation systems that can be controlled reliably and with certainty, such as the more conventional natural gas or hydro, for example, or using ESS when integrating VRE.

Hydrogen can serve as a long-term storage solution of renewable energy, providing a clean energy carrier when there is a requirement of storage for longer periods than batteries, for example, for back up energy for power outages and system reliability, or being able to fully supply different power demand profiles without any requirements from the grid. Hydrogen can be re-electrified through an electrochemical reaction in a fuel cell (FC) or through its combustion as a fuel gas in internal combustion engines (ICE) or power turbines. In general, fuel cells are used for smaller scale power systems, under 20 MW, where flexible power generation is required, and turbines that burn a mix of hydrogen and natural gas are generally employed for larger scale and steady generation. The operational flexibility of fuel cells and electrolyzers enables them to additionally provide ancillary services to the power grid.

Besides energy reliability, **power generation is the main source of GHG emissions in the Caribbean, with over 75 million tons of CO_2 emitted during 2020 by the CARICOM member countries. Additionally, using green hydrogen to store renewable energy could provide opportunities for Caribbean countries to integrate higher shares of renewable energy into their power systems**, being more cost-competitive than energy storage using batteries or supplying electricity directly from the grid under certain scenarios as has been proven by previous studies, like the Antigua and Barbuda report done by IRENA, shown in **Box 3-1**, and the case study developed for this report, portrayed in **Box 3-2**. Both cases show cost-competitive examples of hydrogen storage systems.

Early pioneers of this technology are already tapping into the potential it has in the region, with technically sound and economically viable projects. HDF Energy is a hydrogen power company that currently has project developments in the pipeline to provide a steady power supply at competitive costs using renewable energy sources coupled with battery and hydrogen storage systems at least in Barbados, French Guiana, and Martinique, as shown in **Box 3-5**.

Box 3-1 Baseload PPA complemented with storage with batteries vs hydrogen and fuel cells in 2030

As mentioned before, hydrogen plays a unique role when it comes to completely decarbonize power systems that are highly dominated by fossil fuels, which is the case in most of the Caribbean countries. Given the grid constraints that can emerge in a 100% RE system, energy storage is a cornerstone element to allow a high renewable energy penetration level, providing ancillary services such as reserve power that can be supplied to the electric system to ensure balance when faced with high variability in the loads or generation sources.

Among existing alternatives of energy storage, hydrogen energy storage systems (H_2SS) can not only increase the flexibility and resiliency of sustainable energy supply systems but can also provide added value in centralized storage where batteries (BESS) are not cost-competitive, usually when the energy storage requirements extend over a certain number of hours. This could be the case for some Caribbean countries to provide energy reserves. According to the World Bank's GovData 360 (WB GovData360, n.d.), most Caribbean countries have a system average interruption duration index (SAIDI) higher than the world median, which means that in countries such as Guyana, the average total duration of power outages in 2017 achieved 133 hours (Guyana Power & Light Inc., 2017). Although many issues can affect the quality of power supply, having a medium-term power storage can provide a mayor degree of reliability of supply and security in the power system.

A case study was developed to explore the potential adoption and assess the competitiveness of renewable energy and hydrogen power storage and re-electrification systems in the Caribbean, comparing their cost-competitiveness with systems using RE and battery storage only and comparing both with the current electricity supply from the grid, derived entirely from fossil sources.

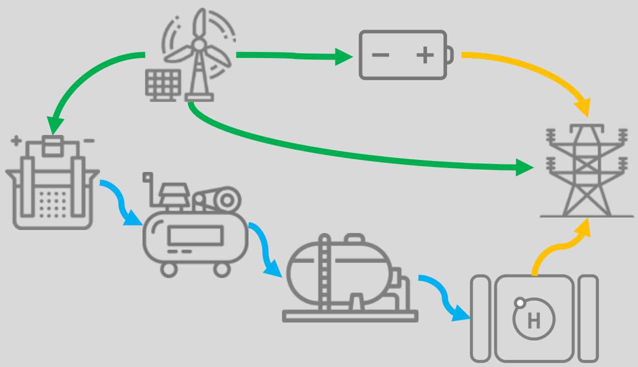


Figure 16 Schematic representation of the model

Two energy storage systems were assessed to compare the costs of using solar PV to comply a daily power demand profile (through day and night as well). One is a Battery Energy Storage System (BESS) and the second one is a Hydrogen Storage System (H_2SS). The H_2SS consists of an electrolyzer, compression and storage devices, and a fuel cell where H_2 is re-electrified.

The renewable generation and storage systems' sizes were optimized to obtain the least cost of energy for a 20-year operation lifetime of the plant. An average solar radiation and a daily demand profile for the Caribbean were considered, as well as assumptions for technology costs in 2030 and two storage requirement scenarios.

The results show that, **by 2030 the H2SS is projected to be cost-competitive** being only 2% more costly than the BESS even for the minimal storage capacity to comply with the PPA. **When having a long-term power storage reserve, hydrogen storage is the most competitive alternative providing energy at half the LCOE than batteries.**

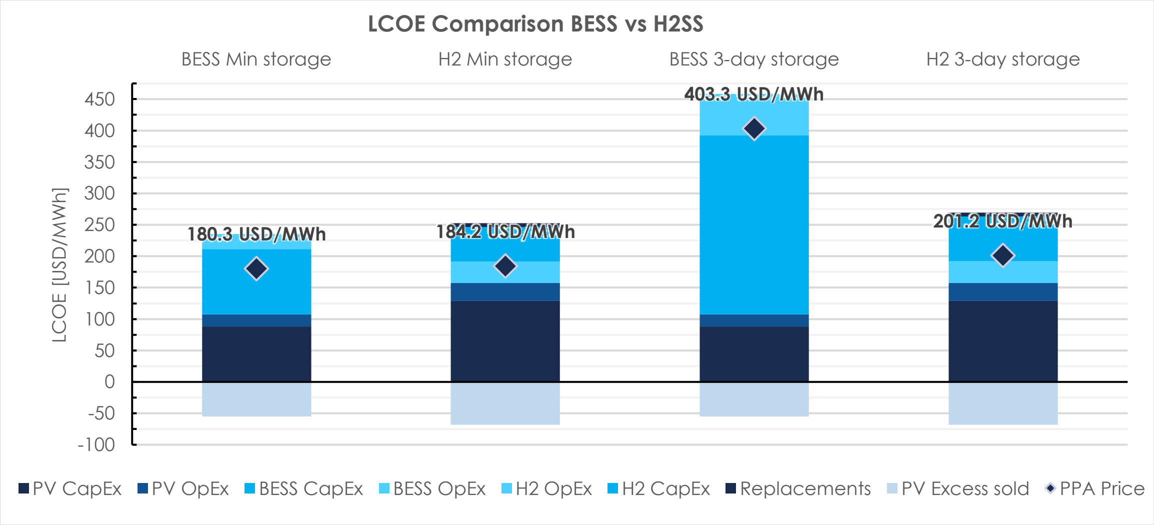


Figure 17 LCOE Breakdown by cost component

As energy reliability and availability are important issues in the Caribbean, having multi-day power reserves may prove to be valuable in the context of energy security. With this in mind, **if more than 27 hours of storage are needed, then hydrogen storage becomes the most cost-competitive option** even when compared with isolated conventional fossil generation, storage with batteries, or power from the grid[8].

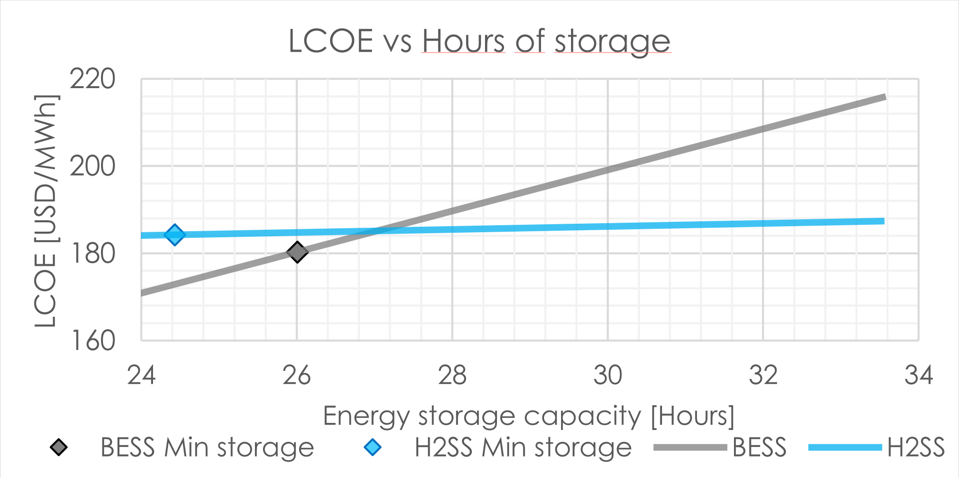


Figure 18 LCOE as function of the power storage capacity in time.

This is because **the cost of increasing the storage capacity for batteries in 1 MWh is 9 times higher than increasing hydrogen tank's capacity to store 1 MWh more** (additional 62.5 kgH$_2$). Therefore, hydrogen storage and use systems could temporarily operate independently in the case of natural disasters when fuel delivery is not available and could be supplied by road if should the power grid not be able.

[8] *Current LCOE generation are in the range of 200-250 USD/MWh for diesel and 150-220 USD/MWh and HFO, respectively. The lowest LCOE should increase 2% annually to meet parity cost with Storage systems by 2030.*

Conclusions from the Power-to-Power Case Study	
Cost of energy vs fossil fuels	**By 2030, Solar PV + battery or hydrogen storage systems have the potential to provide cleaner and cheaper energy than fossil fuels at a cost around 180 USD/MWh.** Caribbean electricity generation relies heavily on imported diesel and HFO, which have reported LCOEs **between 150 to 270 USD/MWh for 2019. Their expected growth in costs will make them more expensive than the H2SS before 2030.**
Energy reliability	**Batteries and hydrogen provide similar costs to meet the PPA requirements (180 USD/MWh for BESS vs 184 USD/MWh for H2SS). When requiring more than 27 hours of storage to enhance reliability, hydrogen becomes the most competitive option.** This grows as the energy storage requirement increases with half the cost of batteries for a 3-day reserve. **The cost of increasing the storage capacity for batteries in 1 MWh is 9 times higher than increasing hydrogen tank's capacity to store 1 MWh more (additional 62.5 kg H_2).** Hydrogen storage systems could provide higher resistance to storms and hurricanes than the electric grid and the alternative to be supplied by road transport if the grid is not available.
Renewable energy integration	**Electrolyzers and fuel cells can also enhance VRE integration into the grid by smoothing renewable energy generation profiles, helping store surplus energy, and providing ancillary services, as shown in previous studies performed for the region. However, a dedicated study must be performed to provide quantitative results for VRE integration with hydrogen Caribbean countries.**

Hydrogen energy storage systems could be the most competitive solution if multi-day power storage reserves were implemented as a measure to increase energy reliability and availability in the region. Their deployment could also contribute to the substitution of hydrocarbon imports for energy independence and integration of renewables in the Caribbean.

Figure 19: Conclusions from the case study on Power-to-Power in the Caribbean, described in Box 3-2.

Box 3-2 Antigua and Barbuda: Renewable Energy Roadmap: 100% RE with hydrogen

The IRENA assisted the Government of Antigua and Barbuda to evaluate potential pathways to achieve a 100% renewable energy supply by 2030 in both the power and transport sectors. Currently, Antigua and Barbuda's power system is highly dominated by fossil fuels with just 3.6% of the electricity share coming from renewables. The LCOE for the current fossil power generation is 150 USD/MWh.

Different scenarios were considered to provide the Government with the least-cost pathway for a 100% renewable energy power system by 2030, including a scenario considering 100% RE, plus the production of green hydrogen from renewables. The optimization and analysis of the scenarios has shown that the **initial capital cost decreases by almost half when green hydrogen is added to the system, from USD 738 million in the 100% RE without hydrogen, to USD 403 million using H_2 technologies.**

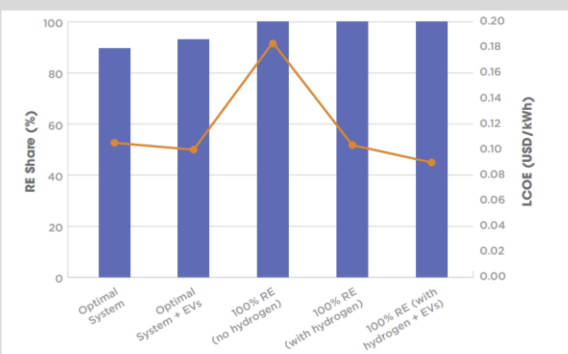


Figure 20 Roadmap for Antigua and Barbuda – renewable energy share and cost of electricity in different scenarios. Source: (IRENA, 2022).

On the other hand, the LCOE in this scenario is the same as the LCOE for the optimal system[9], around 105 USD/MWh, and significantly lower than the LCOE calculated for the 100% RE scenario with no hydrogen of 184 USD/MWh.

This means that with the same levelized cost of electricity, Antigua and Barbuda can achieve a 100% renewable energy share.

Figure 21 shows the total net present cost for each component for both the optimal power system (with diesel generator and batteries) and the 100% RE with hydrogen scenario. The evident overall lower net present cost for hydrogen components compared to diesel generator and large battery system enables more renewable energy to replace fossil fuels and greatly reduce the need for batteries, using green hydrogen to produce power when both solar and wind are not available.

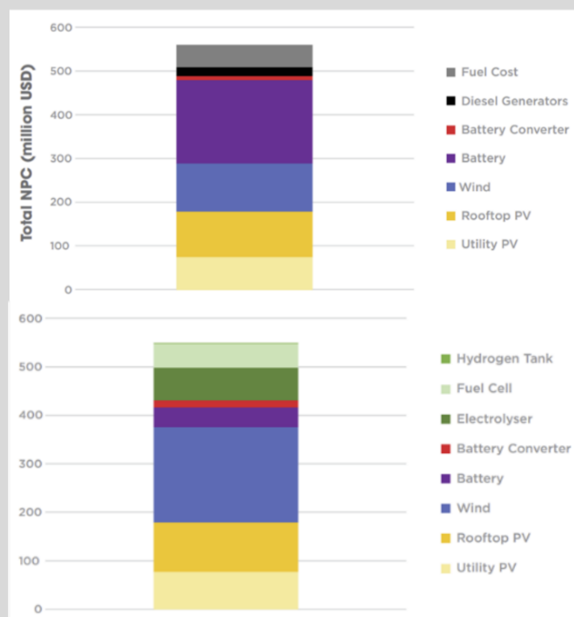


Figure 21 Net present cost by component for both scenarios: optimal (top) and 100% RE with hydrogen (bottom). Source: (IRENA, 2022).

Therefore, the optimization results have shown that not only can Antigua and Barbuda reach the target of a 100% renewable energy share with green hydrogen production, but it can do so in a cost-efficient manner.

[9] *This scenario analyzed the current Government plans along with additional renewable energy capacity based on land availability and extra capacity. It is the less-cost scenario based on net present cost.*

3.2. Sustainable transport systems

3.2.1. Maritime transport

Within the Caribbean, maritime transportation is pivotal for the export and import of goods as well as for inter-island personal transportation and tourism. In terms of decarbonization, it offers an opportunity for improvement and a unique challenge given its highly decentralized nature and a maritime fleet boasting vessels with different sizes and daily travel distances.

Currently, worldwide efforts are being deployed to decarbonize maritime transport. For large ships, hydrogen derivates are being considered to be used as fuel such as ammonia, while for smaller vessels pure hydrogen systems using fuel cells and electric powertrains are being explored.

For small ships, hydrogen can be used as a gas or a liquid, depending on the vessel technology and the infrastructure available at port for refueling hydrogen. Also, hydrogen for the maritime sector can enable its use in other applications around the port activity, following the emerging global trend to place ports as 'Hydrogen Hubs', which gather many hydrogen off-take applications in a single site, as explained in Section 3.4.

Figure 22. World's first hydrogen-powered ferry delivered to Norwegian owner Norled. Source: Hydrogen Central, 2021.

The shipping industry in the region relies heavily on low-grade bunker fuels, mostly imported, which have a high cost and are intensive in GHG emissions. There is a wide variety of inter-island passenger transport routes using ferries, which could be an interesting alternative for hydrogen-powered vessels. There are routes with high daily usage, many of which make numerous daily displacements with distances longer than those that can be traveled using battery-powered electric ferries, which have a range limited to a few dozen kilometers as was found for commercially available units. Thus, inter-island transportation could be a first step into the decarbonization of maritime transportation with the use of green hydrogen-powered vessels, possibly the most cost-competitive alternative in the short term, as shown in the case study on passenger ferries described in **Box 3-4**.

The case study found that, considering project-development timelines, **a hydrogen ferry pilot in the Caribbean starting development in 2022 could potentially be cost-competitive with its fossil-fuel counterpart over its lifetime. In fact, hydrogen ferries acquired as soon as 2025 could be an alternative with a competitive cost and zero GHG emissions**, particularly for long travel distances or routes with high intensity of use. This is provided that green hydrogen could be produced at a cost of 5 USD/kg for its supply into the hydrogen refueling stations (HRS), and deployed at a price of around 8 USD/kg at the HRS. This cost difference is accounting to the costs of dispatch associated with the compression and transport as well as fees from the HRS.

For shorter routes with travel for example 100 km/day, battery electric ferries acquired in 2025 would be the option with the least cost of ownership among those studied. However, buying and operating a hydrogen ferry could be similar in cost to a conventional diesel-powered ferry. By 2030, the cost of both the battery electric and the hydrogen fuel cell ferry would be considerably lower than the diesel unit, with only a 10% difference over the vessels' lifetime in favor of the battery electric ferry[10].

The adoption of hydrogen ferries in the Caribbean could help bridge the knowledge gap of implementing hydrogen technology and lead to getting larger units and fleets operating in 2030. Furthermore, it could be a steppingstone to the development of hydrogen-powered maritime transport in the region.

Other decarbonization alternatives include biomethane or natural-gas powered ferries, however they were not studied within the scope of this report and would require further analysis to assess against the hydrogen-powered alternative.

---

[10] The cost competitiveness of these alternatives was assessed in a Total Cost of Ownership (TCO) analysis, which is showcased in Box 3-3. The assumptions for the cost evolution of diesel and electricity were based on their historic registries as found in The World Bank's DataBank for the "Pump price for diesel fuel" and in GovData360 for the "Price of electricity", respectively, as available for the studied countries. Different compound annual growth rates (CAGR) were assumed for each fuel. In the case of diesel, it was of 6.63%; in the case of electricity of -1% based on the current goals to increase share of renewable energy in the power matrix, which is expected lower electricity prices. In the case of hydrogen, a -3% CAGR in the cost of hydrogen supplied at refueling stations was calculated based on the forecasted costs of solar PV and electrolysis technologies and assumptions from Hinicio's database. These cost evolutions as assumed for the TCO Analysis can be found in Figure 24.

Box 3-3 Hydrogen-powered ferries

A case study was developed to explore the potential of hydrogen ferries in the Caribbean. The competitiveness of **diesel**, **battery-electric**, and **hydrogen**-powered passenger ferries was assessed, through a **Total Cost of Ownership (TCO) analysis.** This was done for vessels following routes considering low (100 km/day – 16h/day) and high (480 km/day – 16h/day) use intensity. The analysis was performed to compare the cost of each vessel technology in the **2025 and 2030 timeframes** for both intensities of use.

The assessment considered the cruise speeds, the autonomy and potential recharge times, which ruled out electric ferries for the high use intensity scenario.

Metal Shark RTA 2 (ICEF)

Baumüller Qi-Fu No. 1 (BEF)

SWITCH Sea Change (FCEF)

Figure 23 Commercial ferries taken as reference, one for each technology assessed.

For each energy source, an evolution of costs was assumed based on their historic price data. In the case of diesel a cost increase was assumed, and for electricity a cost decrease based on the expectation of a growing share of lower-cost renewable electricity in the energy mix. In the case of hydrogen, a continuous reduction the cost of supply at the refueling station was calculated based on the forecasted decrease in costs of solar PV and electrolysis technologies, the two main cost components of green H_2 production.

Information from the ferry manufacturers, industry articles, regional energy reports, the Hinicio technical database and the considerations for defining the case study were taken as inputs for the TCO analysis.

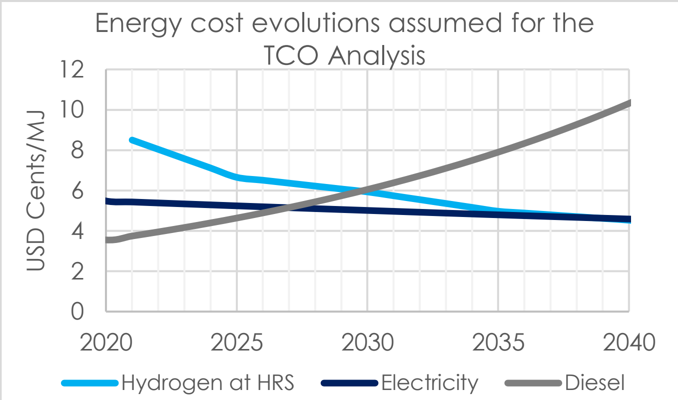


Figure 24 Assumed Cost evolution of the energy sources powering the ferries. Source: Hinicio analysis.

The resulting TCO analysis, shown in Figure 25, unveils that by acquiring a H_2 ferry in 2025 and operating it through its lifetime could be as cost competitive as for a diesel unit, with the advantage that the hydrogen can be produced locally and carbon free. **For short routes, the electric ferry will still be the lowest cost option. By 2030 the hydrogen ferry will be more expensive than the battery electric, with a total cost under 10% higher.**

For the long-range scenario, battery ferries were not assessed as their lower cruise speed[1] and longer recharging times[2] make it unfeasible for them to cover such distance even if running continuously for 24 hours. **As longer distances represent higher fuel needs**, the cost gap between diesel and hydrogen increases drastically, favoring H_2 ferries. This makes **the cost of owning an H_2 ferry roughly half when acquiring it in 2025 and less than a third of the diesel unit when purchased in 2030.**

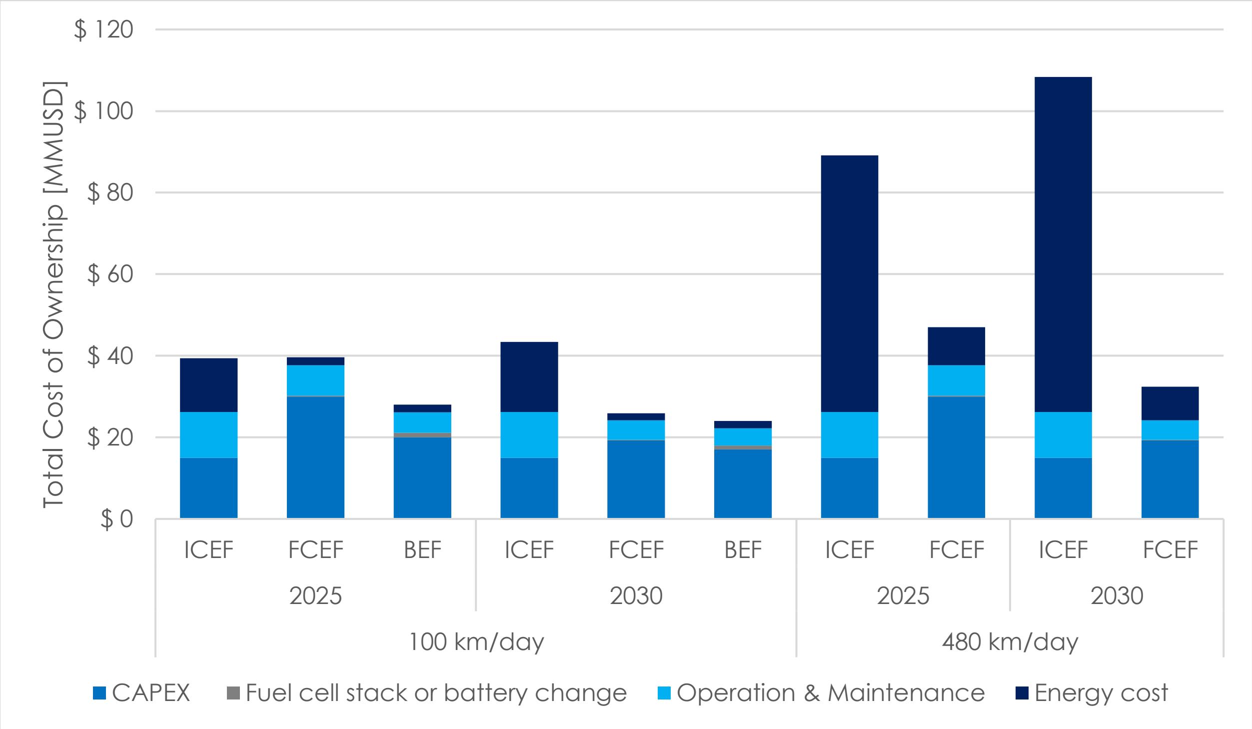


Figure 25: TCO for the different scenarios assessed. Source: Hinicio.

A single battery electric ferry will be competitive for routes such as:

- Anguilla – Saint Martin (6 round trips per day max.)
- Guyana – Suriname (20 round trips per day max.)
- Saint Kitts – Nevis (3-12 round trips per day max.)

By 2030, hydrogen ferries will be only 10% higher in cost for these routes as well.

A single hydrogen ferry will be competitive in routes such as:

- Grenada – Carriacou (4 round trip per day max.)
- Trinidad – Tobago (1 round trip per day max.)
- Saint Lucia – Martinique (3 round trip per day max.)

The hydrogen ferry could be the lowest cost alternative in the short term for these routes, with the added benefit of having zero carbon emissions and being powered with locally produced fuel.

3.2.2. Heavy-duty road vehicles

Road transport, worldwide, has the highest reliance on fossil fuels among all economic sectors, being responsible for around 7-9%[11] of the world's GHG emissions in 2019 (2.4 $GtCO_2$). In the Caribbean context, transport represents nearly the half of the final energy consumption for most countries[12] and the second greatest source of CO_2 emissions, with some exceptions such as Trinidad & Tobago where the share is low due to its vast industrial activity, but is still comparable in size to that of Jamaica's (OLADE, 2019).

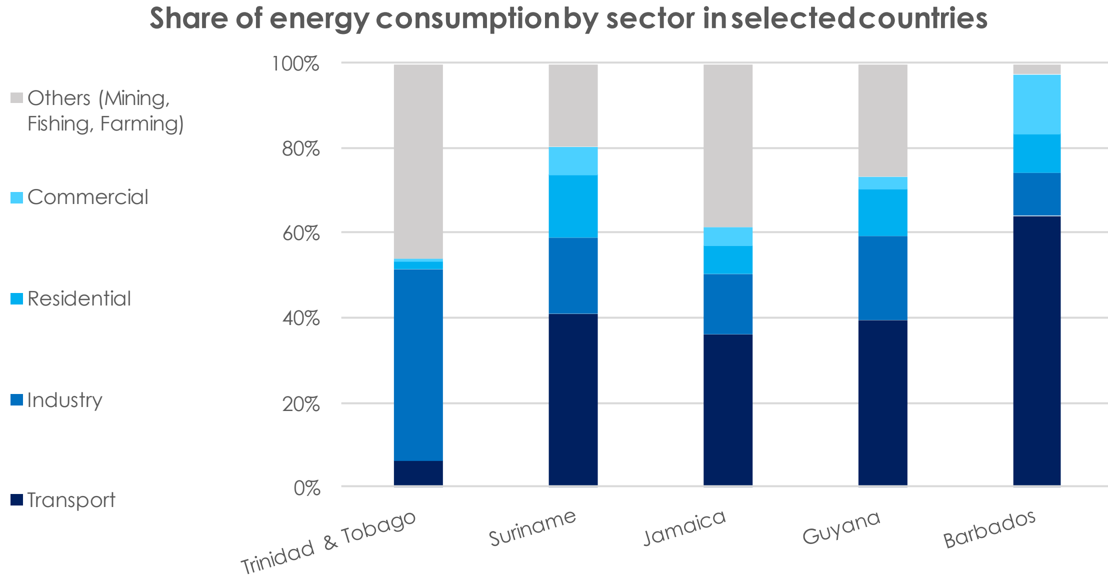


Figure 26. Share of energy consumption by sector in some Caribbean countries. Data source: (OLADE, 2019)

Hydrogen-powered vehicles are electric vehicles. They use compressed hydrogen to refuel and store energy and run it on-demand through a fuel cell to generate electricity and drive an electric powertrain, which provides motion to the vehicle. They do not use internal combustion engines, which are much less energy efficient. Unlike battery electric vehicles, they can be fully recharged in a few minutes, in times similar to diesel or gasoline vehicles, and can make use of hydrogen's high energy density to provide long driving ranges without adding much weight to the vehicle.

However, the production of hydrogen through renewable-powered electrolysis, its compression and transport, and then re-electrification through a fuel cell come with additional energy inefficiencies and associated costs, which puts them in disadvantage relative to battery electric vehicles, which have high recharge and use efficiencies. This explains why **hydrogen fuel cell electric vehicles (FCEV) are particularly competitive for applications which benefit from short refueling times, require long distance ranges, and a**

[11] Estimated from data available at IEA database. (IEA, 2021b)

[12] This statement considers energy consumption of all road transport sectors (light-passenger, personal, and heavy duty).

reduced load or passenger capacity, which can more commonly seen in heavy-duty freight and passenger transport.

Figure 27. Hydrogen-powered (FCEV) heavy-duty vehicle and hydrogen refueling station.

Currently **in the Caribbean there are decarbonization initiatives to electrify** the private and urban road transport, which is amenable to **the short travel-distances,** where EVs tend to be an increasingly competitive solution. Nevertheless, there is a considerable demand of freight transport, with truck fleet sizes for the Caribbean ranging from of a few thousand to hundreds of thousand[13] trucks (CCREEE, 2021). The size of the fleet, and **the versatility of hydrogen could open the door for FCEVs to take a place to contribute to the decarbonization of the sector** while transition to fueling vehicles with renewable energy abundant in the region.

The large-scale deployment of zero-emission vehicles is considered vital to meet climate targets globally. **Fuel cell and hydrogen heavy-duty trucks and buses embody a highly promising zero-carbon alternative** as it fulfills all requirements, although they tend to be most competitive in an environment that demands long distances and low recharging times, where FCEVs outperform battery electric vehicles. Up to this point, no clear use cases have been identified in the region. **The use of hydrogen in heavy-duty transport must therefore be assessed on a case-by-case basis.**

3.2.3. Synthetic fuels

Green hydrogen also holds the potential to disrupt the transport sector with the production of synthetic fuels. Synthetic fuels, also known as syn-fuels or **e-fuels, are produced using green hydrogen and CO2 captured from CCU systems[14].** For example,

[13] From thousands to hundred thousands.

[14] Currently, the Delegated Acts of EU consider up to 2035 CO2 Captured from activities listed in ETS mechanisms (oil refineries, offshore platforms, and industries that produce iron and steel, cement and lime, paper, glass, ceramics, and chemicals) and afterwards only non-fossil origin will be allowed.

clean methanol, the simplest alcohol, can be produced from green hydrogen and captured carbon, which can be then synthetized into other fuels. The advantage of these new commodities is that there is **no need to modify current equipment nor infrastructure**.

If low production costs can be achieved, synthetic fuels could open the possibility to power the current vehicle fleet using the region's renewable energy sources. This could be the case for all modes of transportation, being a solution under study today, particularly by the air travel industry. The same could be the case for industrial heat and power applications that currently run on liquid fossil fuels. Like other hydrogen technologies, synthetic fuels will face the challenge of achieving cost parity with diesel and gasoline, or kerosene for aviation. Another setback is the considerably lower energy efficiency when compared to battery electric vehicles or hydrogen fuel cell electric vehicles. A third and perhaps most significant obstacle is the requirement of an abundant and constant source of CO_2 to synthesize with hydrogen into the new, carbon-neutral fuel, limiting the locations where its production could be possible.

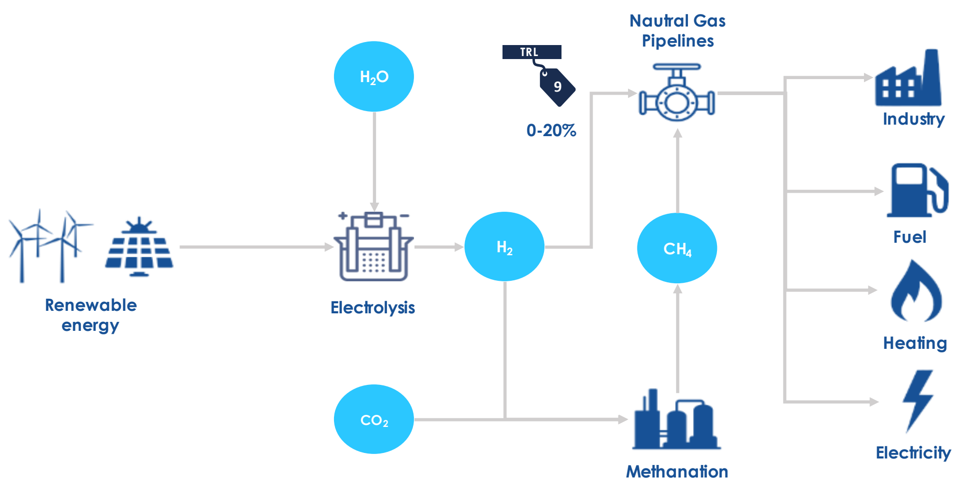


Figure 28. Synthetic methane production process. Source: Hinicio.

On the other hand, as mentioned above, syn-fuels have the significant advantage of requiring minimal to no adjustments in the current supply and end-use infrastructure, which is particularly attractive when the upfront cost of vehicle electrification poses an insurmountable challenge for the decarbonization of transport. Additionally, **synthetic fuels could provide a relatively easy way to transport and exchange green hydrogen, and thus renewable energy, among Caribbean nations and even third parties**, where supply and cost competitiveness allow it. **Synthetic fuels could use the same transport, distribution, storage, and terminal infrastructure as conventional liquid fossil fuels, requiring no additional investments in upgrades to neutralize their GHG emissions, so public incentives could be focused on the green hydrogen production and fuel synthesis processes**, following the motivation to reduce the transport sector's carbon emissions.

Box 3-4 HDF Energy's projects in the Caribbean

HDF Energy is a global pioneer in hydrogen power, developing and operating large scale Hydrogen-to-Power infrastructure to provide firm or on-demand electricity from renewable energy sources. Renewstable® is a concept developed by the firm, which implies producing firm renewable electricity, complementing intermittent renewable resources (solar and wind) with a long-term on-site hydrogen and battery energy storage systems. HDF Energy's hydrogen projects in the Caribbean are described below.

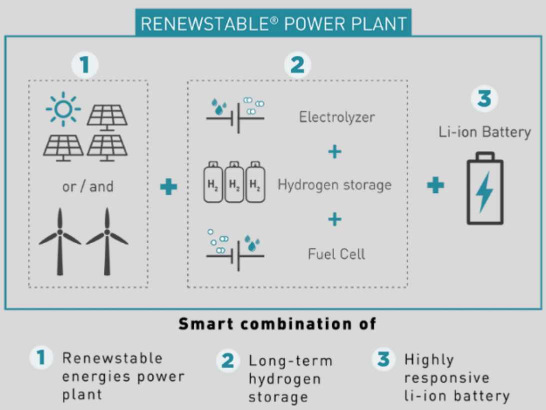


Figure 29 Renewstable Power Plant.
Source: (HDF, n.d.)

RSB – Barbados

Figure 30. Dual use of solar energy plus agriculture on the site in Barbados, promoted by HDF.
Source: (RSB and HDF, n.d.)

The government of Barbados has set a 100% renewable energy target by 2030. Renewstable Barbados (RSB) from HDF allows taking advantage of the island's solar resources to supply clean, resilient, and stable electricity to 16,000 inhabitants. Some of the benefits of the project include **energy independence**, due to RSB will reduce imports by 13 million liters of fuel per year representing 13.6 million $BDS/year (6.7 million USD/year). Also, it will provide **clean and stable electricity**, since RSB hybrid system offers a stable, grid-friendly, renewable generation and storage solution that releases energy during the day and at night while minimizing the use of Lithium batteries. The project includes a PV solar plant, a BESS, and a long term H2SS. In addition, RSB will host a Barbadian Blackbelly sheep farm that produces both meat and skins while keeping the land fertile, active, and well maintained, contributing to **food security**.

CEOG - French Guiana

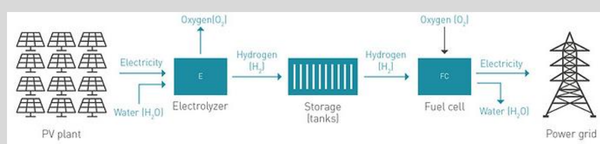


Figure 31 CEOG project diagram.
Source: (CEOG and HDF, n.d.)

The French Western Guiana power plant (*Centrale Electrique de l'Ouest Guyanai,* CEOG) is an innovative multi-megawatt power plant designed to produce reliable and clean electricity. The plant will provide energy at a cheaper cost than the grid and firm power all year long, day and night, to 10,000 homes in Western Guiana. CEOG is currently the greatest project worldwide of a power generating plant storing intermittent renewable energy using hydrogen.

CEOG will deliver a set production of electricity – called baseload – of 10 MW from 8 am to 8 pm, and 3 MW from 8 pm to 8 am the next day, free of greenhouse gas emission. This electricity will be provided through the combination of a PV plant, large and long-term energy storage in the form of hydrogen, and short-term storage with batteries. The power generated by CEOG will be distributed on French Guiana's grid and its production will be framed in a 20-year contract.

CLEARgen – Martinique

The CLEARgen Demo project consists of a 1 MW fuel cell in the Refinery of SARA (Société Anonyme de Raffinerie des Antilles). It produces electricity from the hydrogen outlet of the refinery. The location of the CLEARgen site is in Martinique, an overseas territory of France. The project uses some of the by-product hydrogen co-produced in the refinery process. This hydrogen must be purified before being injected into the fuel cell where it then reacts with the oxygen of the air to produce water and electricity. CLEARgen started operating in 2019 and the system will continue to run for a minimum of 15 years. One of the main benefits of the project was the consolidation of HDF's Renewstable® offer, being the steppingstone for the posterior development of the CEOG project in French Guiana.

NewGen green hydrogen – Trinidad & Tobago

NewGen Energy Limited (NewGen), is the first project of Kenesjay Green Limited and aims to be aligned to Trinidad & Tobago's agenda to increase its current and new production capacity and to strengthen its position as an industry innovator for the energy transition. HDF has acquired 70% of the green hydrogen production project, that will be the world's largest clean hydrogen producing facility of its kind, using a mix of solar PV and other non-specified low-carbon energy sources. The hydrogen output from the project is intended as a "green" input to ammonia production at the Trinidad Nitrogen Company (Tringen) facilities at the Point Lisas Industrial Estate, meeting 20% of the hydrogen requirement of the plant. Once implemented, the project will save approximately 200,000 tCO2 per year. The project will focus on production of hydrogen from an industrial electrolysis process powered by carbon-neutral electricity and "green" electricity from renewable sources.

3.3. Industrial decarbonization

Hydrogen is an industrial gas that has been used for more than 60 years, and demand tends to be highly concentrated in this sector around petrochemical facilities. Hydrogen is mainly used as feedstock for the petrochemical industry in the refineries and for the ammonia and methanol production. Among the first pilot projects of low-carbon hydrogen to be deployed globally are those for the substitution of grey hydrogen with blue or green H_2 for these applications. Substitution of grey hydrogen with blue or green H_2 are among the first pilot projects deployed globally for these applications, as they are seen as low-hanging fruits, even when facing cost challenges when competing with the inexpensive grey hydrogen supply, since no infrastructure changes are required to make use of the low-carbon hydrogen. This is not the case for other applications such as power generation or transport, where new supply and end-use infrastructure must be acquired and tested, adding supplementary investment requirements and risks to the projects.

Finding an economically viable way to substitute grey hydrogen with green hydrogen for oil refining and ammonia production in the Caribbean could set the base to test production technologies at a large scale, with the advantage of potentially having large-volume off-take secured in a single consuming facility. Additionally, the scale could help provide a low-cost supply of green H_2 to test in other applications.

3.3.1. Feedstock for the petrochemical industry.

The oil refining industry is one of the main hydrogen demand sources currently. In 2020, demand was close to 40 million tons of hydrogen (IEA, 2021a). Hydrogen is used for various processes in this industry, such as reducing the amount of sulfur in fuels, and hydrocracking. Most of the hydrogen for these purposes is produced via steam methane reforming (SMR), as well as reforming of by-products from the refining process such as naphtha, and hydrogen obtained itself as a byproduct of the process.

Over the past several years, a number of challenges have emerged in the Caribbean's refining sector. During the 2010's the largest oil refineries (processing 40k barrels per day crude) had to shut-down operations due to financial problems[15]. More currently, after the COVID-19 pandemic, some Caribbean governments are expecting to relaunch the economy with the reactivation of their refineries. This presents a clear opportunity for the **inclusion of green hydrogen in the reactivation of the region's refineries and could be the first step into testing its production process at scale and contribute to reduce this industry's climate emissions.**

3.3.2. Ammonia

Ammonia production is currently the second largest demand source for hydrogen globally, with **33 million tons of demand in 2020** (IEA, 2021a). Most of the ammonia is produced through the Haber-Bosch process by combining hydrogen with nitrogen from the atmosphere into the NH_3 molecule. Most of the ammonia consumed worldwide is

[15] Point-a-Pierre refinery in Trinidad & Tobago idled in 2015 (175 kbbl/day); HOVENSA in St. Croix shuttered in 2012 (646 kbbl/day); Citgo refinery in Aruba halted in 2012 (235 kbbl/day).

used to produce fertilizers, as it has a high content of nitrogen. Therefore, **fertilizers represent around 70% of ammonia's current demand**. Ammonia is also used in smaller shares as refrigerant and as feedstock for other applications such as the manufacture of explosives, plastics, pesticides, etc.

In fact, ammonia production was one of the main reasons for the promotion of electrolytic hydrogen production in the 90's in countries with no natural gas reserves for its production, but sooner it became cheaper to trade it overseas (World Bank, 2020). Currently, 10% of ammonia produced is traded in international markets, and up to 30% is destined to its derivates such as urea (IEA, 2021c). Ammonia trading prices are highly correlated with natural gas; thus, they are volatile and exposed to geopolitical tensions. Green hydrogen would enable clean and local ammonia production at constant prices which could lead to more stable food prices.

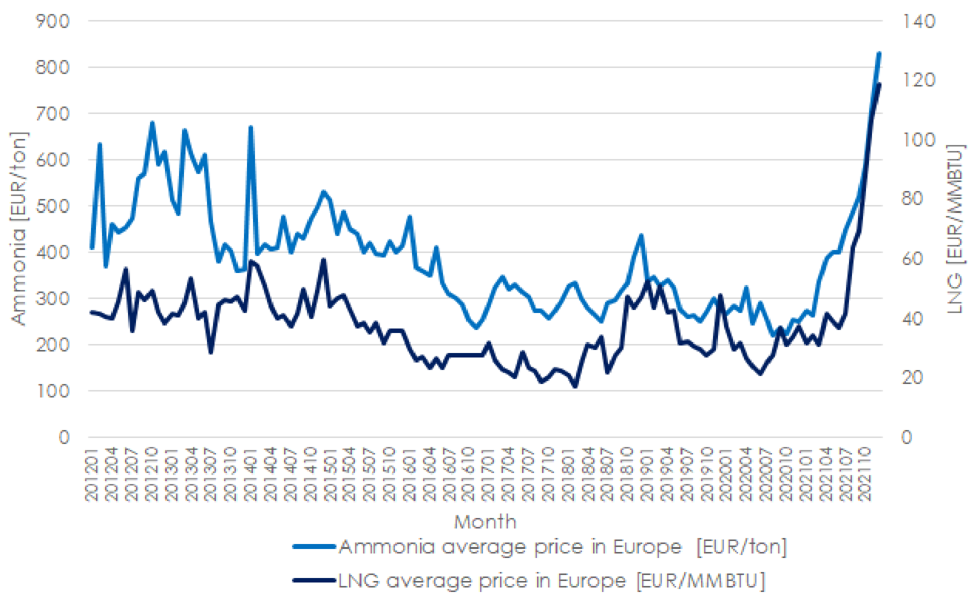


Figure 32. Import prices for LNG and Ammonia in Europe

Moreover, **ammonia is a liquid at ambient temperature and pressure, making it a versatile carrier to export green hydrogen.** As national decarbonization and hydrogen strategies continue to unfold, some countries like Japan and South Korea are targeting the direct use of green ammonia in applications such as power generation, transport, and combined heat and power systems. This, along with the expected gradual substitution of conventional ammonia with green ammonia to produce fertilizers and other compounds, is expected to drive a large green ammonia demand in the upcoming years. Actually, **the ammonia export value chain is the most technologically mature among the hydrogen carriers, being able to leverage on a wide array of existing infrastructure** for its transport, storage, and terminals.

Ammonia produced with green hydrogen (green ammonia) can cost around 2-3 times the cost of conventional grey ammonia. Nonetheless, **a broad number of investors, governments and developers are looking at green ammonia with many projects in the**

pipeline of multi-GW of electrolysis scale and multi-billion dollar of investment from countries which aim to use it as a means to export excess, low cost, and abundant renewable energy resources.

In 2020, **Trinidad and Tobago was the 3th largest exporter of ammonia in the world** (OEC, 2021) and produced around 4.3 million tons per year, demanding around 20% of the country's natural gas consumption. In that year, **Trinidad and Tobago also demanded approximately 750 kton of H_2 which would require over 10 GW of electrolysis if it were to be supplied fully with green H_2**. This considers a utilization factor for the electrolyzer above 40%, which could likely be achieved with hybrid (solar PV + wind supplying energy simultaneously) power to electrolysis systems[16]. **Supplying Trinidad and Tobago's ammonia production processes with green hydrogen could set the base for large-scale green ammonia production in the region and could be the starting point for a green ammonia export network within the Caribbean and potentially to external consumers.** This would also help decarbonize a key industrial sector in the country and help it advance in its renewable energy targets, currently set to achieve a 47% as a share total electrical capacity by 2027 (and 55% by 2030), up from less than 11.5% in 2020.

3.3.3. Contributing to more circular economies

Some Caribbean countries, with low land availability due to their insular context, present problems with the disposal of waste. Landfills are overfilled in some of the countries exceeding the environmental and health limits (Brunn, 2021). In order to face this issue, some French Caribbean islands feature Waste-to-Energy plants, where waste is incinerated to produce heat and power (IDB, 2016). However, incineration plants might create harmful air pollutants and ashes must also be disposed of.

A much cleaner option is waste gasification, which produces Syngas and ashes can be reused as by-product for making cement, sandblasting and asphalt filler ("Waste to Energy Gasification," n.d.). Syngas is mainly composed by hydrogen, CO_2 and CO, and with the proper treatment clean hydrogen could be produced.

In 2021, Valecom, an energy solutions provider from Martinique signed a Letter of Intent with the company Ways2H to transform up to 9,000 tons per annum of waste into renewable hydrogen, which could be used to power clean mobility solutions in the island. (Fuel Cells Bulletin, 2021). Some of the promoters of this technology claim that hydrogen costs by this method might halve those of green hydrogen (Collins, 2020) or even be lower than grey hydrogen (POWER Magazine, 2022). These claims are based on the fact of double income, that is, income earned for the disposal of waste and earned for the hydrogen.

Additionally, other green hydrogen production pathways could be explored, such as biomass gasification, where locally available biomass waste could be revalorized into green hydrogen for local consumption or for exports within the Caribbean. Although this

[16] If the electrolyzer works with a capacity factor of 80%, possibly from a firm renewable energy source such as geothermal or hydro, the required installed capacity would be reduced to around 5.5 GW of electrolysis.

approach has been less explored at the global level, it could enhance a circular economy approach and could be an alternative to transport biomass across islands for centralized hydrogen production by SMR to achieve lower production costs.

3.4. Exports and a Caribbean Hydrogen Hub

3.4.1. The international green hydrogen export market

Green hydrogen and its derivatives such as ammonia or synthetic fuels, are seen as a means for countries with vast renewable energy resources to export this potential to destinations with higher low-carbon hydrogen demand than they can self-supply, creating new opportunities locally for the producing and exporting nations. The target markets lie mainly in countries that have established ambitious hydrogen milestones in their national strategies, but which already acknowledge their inability to produce it on their own in the volumes or at the cost required for its ubiquitous adoption. This is the case for countries such as Japan, South Korea, and many within the European Union.

The international export market is expected to be very competitive, highly sought-after by developing countries across the world with abundant and low-cost renewable energy resources. Therefore, **countries aspiring to become green hydrogen exporters are on the race to secure very low costs of renewable power with elevated capacity factors and put in place the necessary mechanisms to drive down hydrogen production costs** to compete in what is projected to be a dynamic multibillion-dollar market within the next few decades. Countries such as Australia, Chile, Brazil, Saudi Arabia, and many more have already green hydrogen or ammonia export projects in development, and are securing agreements with potential importing countries, ports, and companies.

3.4.2. Green hydrogen export opportunities within the Caribbean

Hydrogen could represent an opportunity for sharing renewable energy potential in between countries across the region. For example, Caribbean countries with untapped renewable potential exceeding domestic demand could realize the value of this energy by producing and exporting green hydrogen and avoid the cost of laying submarine cables (or to complement a sub-marine interconnection strategy in specific cases).

The Caribbean could aim to become a green hydrogen-independent region. This would be enabled by larger production in countries with high renewable potential and low production costs, and inter-island exports to those countries which would not have the capability to produce it at the cost and quantity required to fully self-supply. **Hydrogen could be produced using the region's vast array of renewable resources**, including solar PV, onshore and offshore wind, geothermal, hydro, and potentially marine energy, **so long as they can provide a suitable combination of low costs of electricity and high-capacity factors which would in turn yield the lowest-cost green hydrogen production**.

A case study was developed to explore the cost competitiveness of hydrogen exports within the Caribbean, as shown in **Box 3-5**. The results show that **Inter-Caribbean hydrogen exports from potential exporting countries such as Jamaica, Suriname or Guyana to potential importing countries such as Barbados, Bahamas, or Trinidad and Tobago could**

be cost-comparable with fossil fuels in the region by 2030, in USD per energy content basis, with imported costs of hydrogen at $0.061-0.064/MJ vs the diesel costs of $ 0.052-0.059/MJ**. In countries with export potential such as Guyana and Jamaica, the local production cost of green hydrogen would be cheaper than diesel, allowing them to potentially satisfy local energy demand as well.**

Additionally, green hydrogen exports could make use of the Caribbean's vast geothermal energy resources, mainly available in the Eastern Caribbean. Some of these countries have a geothermal energy potential that could meet more than 100 times the current peaks. As an example, Montserrat has a peak demand of 2.1 MW, but a geothermal energy potential of 940 MW. This amount of energy will hardly ever fully be consumed by the country but could be exported to countries inside the region in the form of hydrogen, ammonia, or e-fuels, as long as low-cost and largely concentrated power generation can be achieved from this source for it to be an economically viable solution.

The same could apply to producing hydrogen using offshore wind energy. While the region has an acknowledged broad offshore wind energy capacity, a major challenge for its use in green hydrogen production is due to the higher costs relative to onshore wind and other renewable sources such as solar PV. In a market where renewable electricity cost is the highest determinant for competitiveness, this would be the first obstacle to be addressed. The second would be centralizing power generation such that economies of scale could be achieved for low-cost hydrogen production.

It is noteworthy that there are significant ongoing efforts to support countries in the Eastern Caribbean to de-risk and develop their geothermal energy potential. For example, the Caribbean Development Bank (CDB) through its GeoSmart Initiative[17], provides a range of suitable financing solutions (in the form of grants, contingent grants, and concessional loans) and technical assistance support to the countries. Most of these resources are available under the Sustainable Energy Facility for the Eastern Caribbean Program funded by the IDB.

The main countries targeted under the GeoSmart Initiative are Dominica, Grenada, St. Kitts and Nevis, St. Lucia, and St. Vincent and the Grenadines. The geothermal energy projects in Dominica, and St. Kitts and Nevis are the most advanced, with various levels of drilling successfully completed (or underway). The projection is for a geothermal power plant (of capacity at least 10 MW) to be established in one of these countries as early as 2025. In parallel with the development of their geothermal energy resources, the countries have also commenced the elaboration of green hydrogen strategies. CDB and IDB are also supporting a regional study aimed at assessing potential for geothermal energy in the Eastern Caribbean to support intra-regional trade in green commodities (hydrogen/ammonia), which will also consider the role of sub-marine interconnection of electricity grids to optimize electricity supplies among the countries.

[17] https://www.caribank.org/publications-and-resources/resource-library/booklets-brochures/cdb-geosmart-initiative

In addition, in 2020 the IBD and CDB also conducted an ocean energy study[18] to assess the technical potential of offshore wind in nine Caribbean countries and are jointly pursuing a de-risking initiative in this area. **Although the region's extensive geothermal and offshore wind energy resources were not assessed in this report, they are currently targeted by the region to become key sources for green hydrogen production, especially if low production costs can be achieved to meet the required competitiveness for export of green hydrogen or its derivatives.**

3.4.3. A Caribbean hydrogen ecosystem

The term "**hydrogen hub**" commonly refers to a location where hydrogen is used for many applications such as maritime and land transport, industry feedstock, injection into the gas network, power and heat applications, as well as exports, in many cases with a local or nearby location of the hydrogen production facilities. This enhances the hydrogen production economics by securing off-take of the hydrogen at different costs, concentrating hydrogen infrastructure, specialists, and technicians. The actors involved also take advantage of the generated synergies to reduce the risk and further attract capital, public incentives, new project developments, specialized companies and talent to the hub's location.

The Caribbean could build hydrogen hubs around large potential demand centers such as refineries, ammonia production facilities, and export terminals. Ideally, a hub could combine more than one of the above for a higher concentrated demand and enhanced economics. As mentioned in the previous section on industrial decarbonization, these large demand centers could be the backbone for regional development of hydrogen applications, allowing to test and deploy production and end-use technologies at the lowest cost possible for different applications from the same production site.

Moreover, **the Caribbean could aim to place itself as one distributed, self-sufficient green hydrogen ecosystem. This could uphold the unique potential for the region to collaboratively make use of its abundant renewable energy resources, while reducing dependency on fossil fuel imports, lowering energy costs, being at the forefront of decarbonization efforts globally, and creating new economic opportunities for its people.** This would require the coordination of efforts across the region, as is detailed in the conclusions and recommendations of this report.

3.4.4. Green hydrogen exports overseas

A scenario where the Caribbean could become a major exporter is still unclear, as at the moment it faces some challenges yet to be overcome, mainly associated with the scale and cost of green hydrogen production. According to different analyses carried out for

[18] Ocean energy in the Caribbean: technology review, potential resource and project locational guidance. IDB, 2021. https://publications.IDB.org/publications/english/document/Ocean-Energy-in-the-Caribbean-Technology-Review-Potential-Resource-and-Project-Locational-Guidance.pdf

importer countries such as South Korea or Germany and for exporters like Chile or Australia, the countries in the Caribbean should produce hydrogen for less than 3 USD/kg in 2030 to be competitive in the international H_2 market. **To achieve that hydrogen cost, renewable energy costs should be around 20 USD/MWh. Achieving renewable energy costs as low as 20 USD/MWh and elevated capacity factors could be a gamechanger, enabling the Caribbean to export its excess hydrogen production to high demand countries at competitive prices.** This could be laid out as a long-term target for countries and renewable energy developers to achieve.

Potential hydrogen exporting countries share two characteristics: very high renewable potentials (thousands of GW) and low H_2 production costs (under 3 USD/kg by 2030)

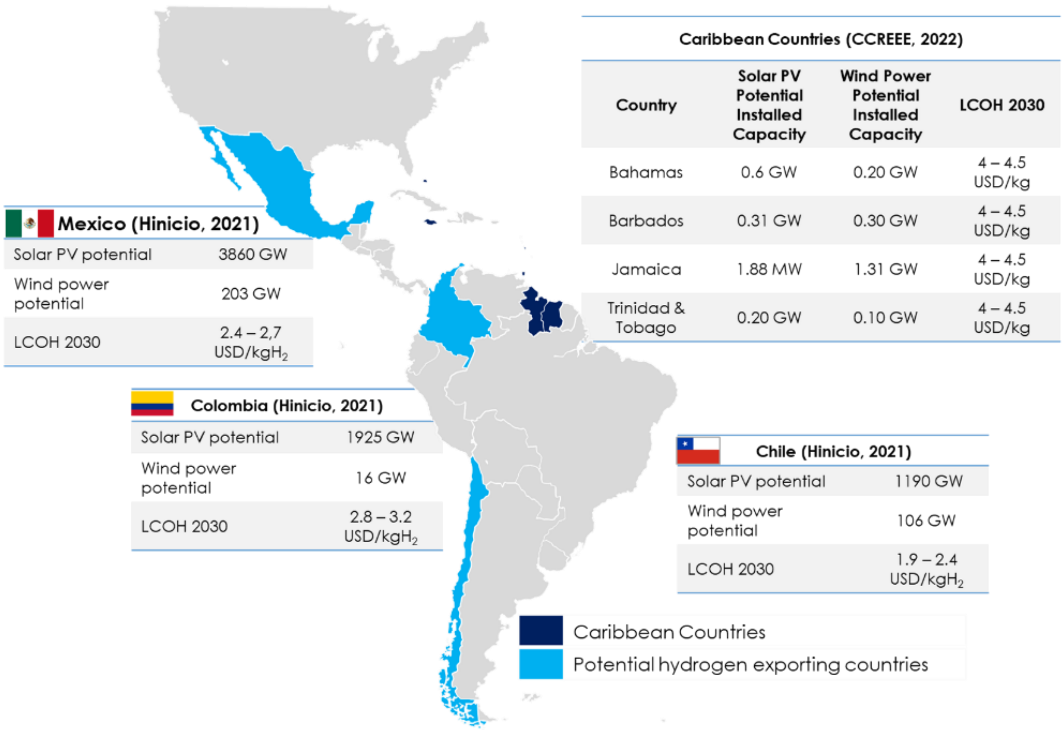


Figure 33. Potential hydrogen exporting countries characteristics. Source: Hinicio.

Also, renewable energy technical potential might be unable to result in the cost reduction effects through large scale projects in the Caribbean when compared to other countries in other regions and especially in Latin America, where it will likely face its most direct competition. As reference, countries such Chile, Colombia and Mexico report untapped renewable potential of thousands of GW while in the Caribbean countries this figure is under 15 GW for the whole CARICOM[19] (see **Figure 15**).

Caribbean countries must therefore embark on the quest to coordinate efforts to reduce green hydrogen production costs in the region, create synergies to centralize production, and find unique markets which they could supply at competitive costs. This could be an area of extensive further research and exploration.

[19] The sum of the reported potentials for the CARICOM countries is around 12 GW.

Box 3-5 Inter-Caribbean Hydrogen Exports

The cost-competitiveness of (liquid) green hydrogen exports between Caribbean countries was assessed against imported fossil fuels. For this analysis, two generic country archetypes were considered:

- **Exporters:** Countries with high renewable potential (solar, wind*, geothermal, or maritime) and enough land availability. Also, at least 1 GW of potential installed capacity, based on references from international developments.
- **Importers:** Caribbean countries with under 1 GW of potential installed RE capacity and identified potential H_2 off-takers within their economy.

Also, export activities have fixed cost components and a variable cost due to the shipping distances. For this case, two route examples were studied (the shortest and longest export routes between the studied Caribbean countries), to provide a range applicable to all possible routes' ranges:

- **Short distance:** Guyana to Trinidad and Tobago
- **Long distance:** Suriname to Bahamas

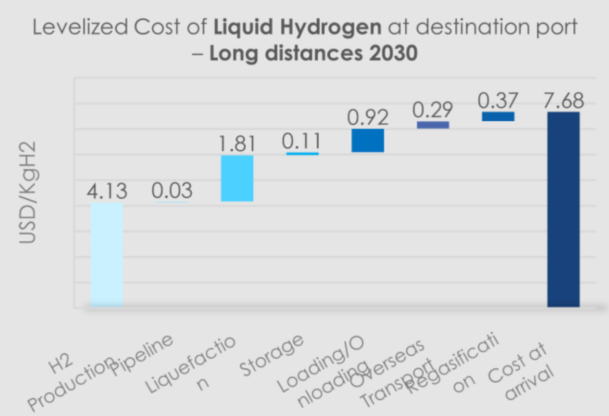


Figure 34. Breakdown of the LCOH at the port of destination for the long route in 2030.

*Off-shore wind was not considered in this analysis and could be explored in further studies.

In the short distance scenario, **the cost of hydrogen at the port of destination is 1.75 times the cost of production, 7.26 USD/kgH₂**, because the hydrogen liquefaction and loading & unloading stages are intensive electricity consumers, and Caribbean countries' **electricity prices in 2030 could range from 80 to 260 USD/MWh** (where liquefaction represents 25% of the cost).

In the long-distance scenario, despite the **distance being 5x compared to the short distance case**, the cost of **overseas transport** only doubles and contributes **4%** to the cost of hydrogen at destination which rises up to **7.68 USD/kgH₂**.

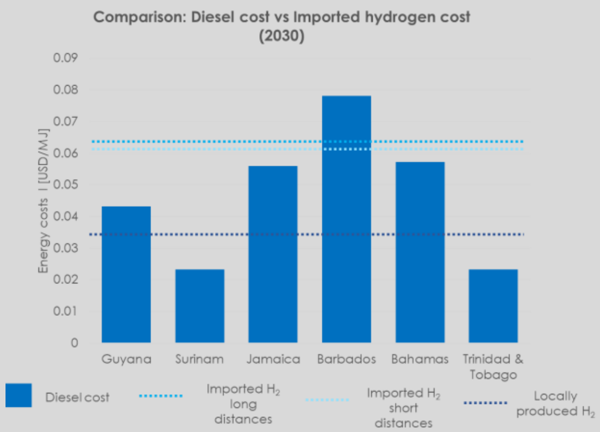


Figure 35. Comparison between Diesel costs and Green Hydrogen production or import

Without any carbon tax considered, and assuming that the costs of fossil fuels in the Caribbean could increase at an annual rate between 5% and 7.75% from 2021 to 2030, the cost of a common fuel such as diesel could range from 0.85 USD / L to 2.81 USD / L. At these costs, in terms of energy, **inter-Caribbean green hydrogen exports could be competitive or comparable in 2030 against diesel, depending on the country.**

4. CONCLUSIONS & RECOMMENDATIONS

Caribbean countries face diverse energy challenges due to their geographical and economic contexts that might be seen as opportunities. They are over-reliant on imported fossil fuels mainly in the form of petroleum products to power their economies, and electricity grids are isolated. Their indigenous renewable energy resources (mainly solar and wind energy – which are variable) are being slowly developed. The main potential baseload renewable energy options are hydropower and geothermal. Hydropower is scarce or nil in most Caribbean countries and geothermal resources are yet to be fully deployed and are only available for certain countries. Therefore, most nations continue to rely on imported fossil fuels to provide firm power and reduce the exposure to grid instabilities. **Hydrogen could provide the storage needed to enable variable renewable energy options to provide firm-clean-energy. This could be the lowest-cost alternative when medium and long-term energy storage is required for energy resiliency purposes**, especially for cases where systems combine batteries and hydrogen technologies.

Moreover, aside from oil refining and ammonia production, Caribbean countries have relatively small projected hydrogen demands which may make it difficult to reduce unit costs through the scaling-up of projects. This could make it less attractive for equipment manufacturers to establish operations in a given country, hindering access to the technologies, and highlights the **need to consider a regional hydrogen ecosystem perspective, and the necessity of sector coordination to identify and exploit industrial synergies which could make for better business cases.** This could in turn reduce the cost-gap between green hydrogen and the incumbent alternative. **Further exploration must be conducted to identify specific hydrogen applications which could be cost-competitive in the short term.**

An example of an application projected to be economically viable in the near term is the case for maritime transport with hydrogen-powered passenger ferries, which could possibly be cost-competitive for long routes if deployed as soon as within the next three years. Actually, **a hydrogen-powered ferry pilot with high daily usage starting development in 2022 and operations in 2025, could potentially be cost competitive with its diesel counterpart over its lifetime. This could help bridge the knowledge gap to enable a broader deployment of hydrogen technologies for the maritime sector.** Such scenario applies particularly in cases where electrification is not a viable alternative, such as long-distance travel or applications which require continuous use during the day and would not allow for the necessary time required to recharge the batteries for other electricity-powered alternatives.

While overseas exports of green hydrogen will face challenges related to the scale and cost of the renewable energy supply, the prospect of developing the Caribbean aiming to become a self-supplied green hydrogen ecosystem could potentially provide numerous advantages and opportunities. This concept is based on the strategy of establishing the target to fulfill the region's hydrogen demand first, producing it in countries with low-cost excess renewable energy resources and importing it from within the Caribbean to countries with limited production potential due to constraints of geographical, scale, or cost nature.

This approach towards **a joint green hydrogen economy could help alleviate some of the region's current challenges for an accelerated and broad deployment of hydrogen technologies, along with the benefits it could bring**. The generally high costs of fuel and electricity in the region make hydrogen technologies a comparatively less expensive option, which could in turn allow it to achieve cost-competitiveness years in advance. **The region's diversity could enable each country to assume the role it is best fit for in the hydrogen ecosystem,** whether being a large-scale producer, an export hub, an off-taker for a specific application, a talent training provider, a center for equipment manufacturers to place maintenance capacities; to name a few examples. An overall regional perspective could help adopt some of the benefits and strengths of hydrogen hubs throughout the region.

Considering it will take some years for green hydrogen to be economically competitive, broad coordination of institutions, governments, and economic sectors, as well as long-term vision & planning of H_2 infrastructure are required along with risk-tolerant and patient capital and correctly aligned incentives and synergies. For a hydrogen export & import market to exist, mechanisms will need to be put in place to boost local demand in multiple applications, e.g., mobility, power, heat, feedstock. For the case of hydrogen exporters, these mechanisms should focus on driving the development of large H_2 production projects, facilitating access to renewable energy and hydrogen infrastructure.

National Hydrogen Strategies could play a relevant role in accelerating the deployment of green hydrogen in the region, as has been demonstrated by numerous countries across the globe. Moreover, **a Caribbean Hydrogen Strategy could be a tool to help fully untap the potential of the region, harnessing each country's strengths and unique capacity to contribute to the development of a regional hydrogen economy**. A regional hydrogen strategy and **regional hydrogen roadmaps by application segment (e.g., maritime transport, power storage, exports) could serve as common guidelines towards which to align national policies**, as well as regionally coordinated policies, funding, and incentives for capacities and project development.

International cooperation and alignment are necessary to strategically enhance efforts, share knowledge in green hydrogen and ammonia technologies, project development, business models, end-use markets, among other areas. Building on this approach, it would be possible to develop national and/or regional capacity-building strategies, leveraging the region's aggregated demand to lower costs to expand its technical capacities and encourage hydrogen technologies OEMs to deploy supply and maintenance capabilities locally, and integrate regional knowledge bases and guidance for green hydrogen projects, technologies, and capabilities development.

5. Bibliography

Brunn, M., 2021. Fixing the Caribbean's solid waste problem. RECYCLING magazine. URL https://www.recycling-magazine.com/2021/03/19/fixing-the-caribbeans-solid-waste-problem/ (accessed 4.4.22).

CCREEE, 2020. Energy Report Cards. CCREEE. URL https://www.ccreee.org/erc/ (accessed 4.5.22).

CEOG, HDF, n.d. Principe de fonctionnement | France [WWW Document]. ceog. URL https://en.ceog.fr/operatingprinciples (accessed 4.25.22).

Climate Action Tracker, 2021. Warming Projections Global Update.

Collins, L., 2020. "It's much cheaper to produce green hydrogen from waste than renewables" | Recharge [WWW Document]. Recharge | Latest renewable energy news. URL https://www.rechargenews.com/transition/its-much-cheaper-to-produce-green-hydrogen-from-waste-than-renewables/2-1-801160 (accessed 4.4.22).

EIA, 2022. Spot Prices for Crude Oil and Petroleum Products [WWW Document]. PETROLEUM & OTHER LIQUIDS. URL https://www.eia.gov/dnav/pet/pet_pri_spt_s1_d.htm (accessed 4.22.22).

Eichman, J., Harrison, K., Peters, M., 2014. Novel Electrolyzer Applications: Providing More Than Just Hydrogen (No. NREL/TP-5400-61758, 1159377). https://doi.org/10.2172/1159377

Fuel Cells Bulletin, 2021. Ways2H and Valecom waste-to-hydrogen facility for Martinique. Fuel Cells Bulletin 2021, 10. https://doi.org/10.1016/S1464-2859(21)00567-8

Guyana Power & Light Inc., 2017. OPERATING STANDARDS AND PERFORMANCE TARGETS.

HDF, n.d. HDF | Our solutions [WWW Document]. URL https://www.hdf-energy.com/en/our-solutions/ (accessed 4.25.22).

Horizon 2020, 2018. Review of electrolysis technologies and their integration alternatives.

IDB, 2020. Sustainable Energy Paths for the Caribbean. Inter-American Development Bank. https://doi.org/10.18235/0002236

IDB, 2019. Unveiling the Natural Gas Opportunity in the Caribbean. Inter-American Development Bank. https://doi.org/10.18235/0001716

IDB, 2016. Solid Waste Management in the Caribbean: Proceedings from the Caribbean Solid Waste Conference.

IEA, 2021a. Global Hydrogen Review 2021. OECD. https://doi.org/10.1787/39351842-en

IEA, 2021b. Tracking Transport 2021 – Analysis [WWW Document]. IEA. URL https://www.iea.org/reports/tracking-transport-2021 (accessed 4.5.22).

IEA, 2021c. Ammonia Technology Roadmap: Towards more sustainable nitrogen fertiliser production. OECD. https://doi.org/10.1787/f6daa4a0-en

IPCC, 2021. Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press.

IPCC, 2018. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty 630.

IRENA, 2022. Geopolitics of the Energy Transformation: The Hydrogen Factor. Abu Dhabi.

IRENA, 2021. Renewable Power Generation Costs 2020.

IRENA, 2020. Renewable Power Generation Costs 2019.
OEC, 2021. Ammonia (HS: 2814) Product Trade, Exporters and Importers | OEC [WWW Document]. OEC - The Observatory of Economic Complexity. URL https://oec.world/en/profile/hs92/ammonia?yearSelector1=tradeYear1 (accessed 4.2.22).
OLADE, 2019. Panorama energético de América Latina Y El Caribe 2019. OLADE. URL https://www.olade.org/publicaciones/panorama-energetico-de-america-latina-y-el-caribe-2019/ (accessed 4.5.22).
POWER Magazine, 2022. Green hydrogen from waste now a reality. URL https://www.powermag.com/press-releases/green-hydrogen-from-waste-now-a-reality/ (accessed 4.4.22).
Race to Zero, n.d. Glasgow Breakthroughs [WWW Document]. Climate Champions. URL https://climatechampions.unfccc.int/system/glasgow-breakthroughs/ (accessed 4.22.22).
RSB, HDF, n.d. RSB | RENEWSTABLE BARBADOS [WWW Document]. RSB | RENEWSTABLE BARBADOS. URL https://www.renewstable-barbados.com (accessed 4.25.22).
Waste to Energy Gasification, n.d. . Global Syngas Technologies Council. URL https://globalsyngas.org/syngas-technology/syngas-production/waste-to-energy-gasification/ (accessed 4.4.22).
WB GovData360, n.d. GovData360: Getting electricity: System average interruption duration index (SAIDI) [WWW Document]. GovData360. URL https://govdata360.worldbank.org/indicators/h2d96dbda?country=BRB&indicator=42570&countries=JAM,GUY,TTO,BHS&viz=bar_chart&years=2019&indicators=944&compareBy=region (accessed 4.22.22).
WEC, 2021. Working paper | National hydrogen strategies 20.
World Bank, E.S.M.A., 2020. Green Hydrogen in Developing Countries. World Bank, Washington, DC. https://doi.org/10.1596/34398