Green Shipping Corridors in the Panama Canal under Climate Risk

SENACYT grant IDDS2024-051

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Evidence base used for this report

This report has been prepared as a technical and informational document to support discussion on Green Shipping Corridors (GSC) from the perspective of Panama. It is intended to inform dialogue among public institutions, industry, academia, and potential international partners. It should not be interpreted as legal, financial, investment, engineering, safety, regulatory, or commercial advice.

The report is based on the best available information at the time of writing. Sources were used in the following order of priority: first, peer-reviewed scientific publications; second, white papers and technical documents developed within the project; and third, industrial reports, public datasets, and other relevant sectoral references. When findings are based on peer-reviewed work, this is reflected through the corresponding citations. When findings are based on project-generated white papers, technical notes, algorithms, dashboards, or unpublished analyses, they are presented as project-derived results.

Some figures, tables, maps, estimates, and route-level indicators in this report are derived from algorithms developed within the project. These include, among others, estimates based on Automatic Identification System (AIS) data, vessel movement reconstruction, emissions modelling, energy demand calculations, and route or network analysis. These results should be interpreted as analytical estimates rather than official statistics, audited inventories, or regulatory determinations. They are subject to the quality and completeness of the input data, the assumptions used in the modelling process, and the methodological limitations described in the report.

Unless explicitly stated otherwise, the views, interpretations, and recommendations presented in this report are those of the authors and do not necessarily represent the official position of SENACYT, Georgia Tech Panama Foundation, the Panama Canal Authority, collaborating institutions, data providers, industry participants, public authorities, or any other organization mentioned in the document. The mention of specific routes, ports, technologies, fuels, companies, institutions, or potential partners does not imply endorsement, commitment, or a recommendation to invest.

The report is designed to support policy discussion, strategic planning, and future feasibility studies. Any operational, commercial, regulatory, infrastructure, or investment decision should be based on additional due diligence, direct consultation with relevant authorities and stakeholders, updated data, and project-specific technical, economic, environmental, safety, and legal assessments.

While reasonable efforts have been made to ensure consistency and accuracy, the authors do not assume responsibility for decisions, losses, damages, or consequences arising from the use of this report or from reliance on its estimates, scenarios, interpretations, or recommendations.

Policy brief

Panama should prepare now for green shipping corridors: organised maritime routes where governments, ports, shipping companies, fuel suppliers and cargo owners work together to reduce emissions while keeping trade reliable.

Panama can turn the Canal, ports and bunkering sector into a regional platform for cleaner, more resilient shipping. The priority is not to choose one fuel or one route immediately, but to prepare the institutions, data, infrastructure, safety systems and workforce that will allow Panama to capture this opportunity.

Why this matters

Shipping is moving toward lower emissions. The International Maritime Organization has agreed that international shipping should reach net-zero greenhouse gas emissions by or around 2050 and that zero or near-zero emission fuels should represent at least 5%, striving for 10%, of shipping energy by 2030. This creates pressure on ports and maritime countries to prepare for new fuels, new rules and new investment decisions.

For Panama, this is a strategic economic issue. The Canal, port system, maritime services and bunkering market already concentrate global ship traffic. If Panama prepares early, it can attract investment, support cleaner fuels, improve logistics reliability and strengthen its position as a gateway between Asia, the Americas and Europe. If it waits, future clean-fuel infrastructure and corridor partnerships may develop elsewhere.

What the evidence shows

1. Panama should think as a network hub, not only as one route. The analysis shows that Panama-connected shipping is spread across more than one thousand immediate previous or next port connections. This means that a narrow strategy focused only on one bilateral corridor would miss Panama's real advantage. Balboa and the Canal area can serve several services at once as a refuelling, coordination, monitoring and data platform.

2. Container shipping is the best starting point. Container vessels account for the largest share of Panama-related port visits and operate on more regular schedules than many other vessel types. This makes them easier to coordinate for early green shipping corridor planning, fuel offtake agreements, emissions monitoring and port readiness assessments.

3. Energy demand points to priority partners. At country level, the United States is the largest source of Panama-connected energy demand, while South Korea, Japan, China, Mexico and Ecuador are also important. At port level, demand is concentrated in specific clusters such as Busan/Masan, several Chinese ports, Yokohama, Savannah and Antwerp. These results can guide future feasibility studies and diplomatic engagement. Ongoing initiatives such as the Algeciras-Panama green and digital corridor should be considered within a broader plan of implementation.

4. Climate risk is part of corridor policy. The Canal depends on freshwater. El Niño-related drought conditions can reduce Gatun Lake levels, trigger draught and transit restrictions, affect vessel behaviour and create uncertainty for global trade. A green corridor connected to Panama must therefore be both low-carbon and climate-resilient.

5. Panama should prepare for a multi-fuel future. Liquified Natural Gas (LNG) may play a transitional role, methanol may support early deployment, ammonia has long-term potential for deep-sea shipping, hydrogen may begin in specialised uses, and shore power can reduce port-side emissions. Panama's best strategy is flexible infrastructure and regulation, not an early bet on a single fuel.

Policy priorities

Establish a green shipping corridor task force. Bring together the Panama Canal Authority, Maritime Authority of Panama, National Secretariat of Energy, Ministry of Environment, ports, fuel suppliers, universities, industry and international partners. The task force should coordinate priorities, avoid fragmented initiatives and prepare Panama's position in international corridor discussions.

Use data to select corridors. Adopt route-level indicators such as energy demand, vessel frequency, emissions, port readiness, climate exposure and partner availability. This will help Panama prioritise corridors based on evidence rather than only political visibility or commercial interest.

Prepare Balboa and the Canal area as a green bunkering and coordination hub. Assess land, safety zones, storage needs, emergency response, digital scheduling and possible fuel import partnerships. Panama does not need to produce all future fuels domestically; it can connect external green-fuel supply with concentrated maritime demand.

Integrate climate resilience into every corridor study. Future feasibility studies should include scenarios for water availability, draught restrictions, transit-slot availability, waiting times, salinity and vessel-segment behaviour. Reliable Canal operations are essential for any credible corridor strategy.

Invest in training and safety before large-scale deployment. Alternative fuels require new competencies for seafarers, port workers, fuel suppliers, regulators, emergency responders and instructors. Early training should focus on fuel handling, emissions accounting, digital analytics, emergency response and regulatory compliance.

Recommended next steps

- **Within 6 months:** create the national coordination mechanism and agree on a short list of candidate corridor partners. Suggestions should include ongoing initiatives such as the Algeciras-Panama green and digital corridor and the selected candidates under the Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping (MMMCZCS) pre-feasibility studies.
- **Within 12 months:** complete a corridor-screening exercise using energy demand, vessel frequency, port readiness, alignment to current legal regime, and climate-risk indicators.
- **By year 2:** engage with current feasibility studies (i.e. MMMCZCS) for one or two priority container-shipping corridor networks involving Panama, Asian port clusters and key ports in the Americas.
- **Between year 2 and year 5:** prepare safety rules, workforce training programmes and preliminary infrastructure plans for flexible bunkering and shore-power options.
- **Year 5 onward:** move from feasibility studies to pilot projects, linked to international finance and corridor partnerships.

Bottom line for policymakers

Green shipping corridors are not only an environmental agenda. For Panama, they are a competitiveness, water-security, logistics and investment agenda. The country has the location, traffic, institutions and technical evidence to lead in the region. The immediate policy challenge is to organise coordination, prepare flexible infrastructure, protect Canal reliability under climate risk and build the workforce needed for the maritime energy transition.

Executive summary

This report explains how Panama can use its strategic maritime position to participate in the development of Green Shipping Corridors (GSC) under conditions of climate risk. The Panama Canal, the national port system, the bunkering sector, and Panama's logistics platform already concentrate vessel traffic, energy demand, operational data, and maritime services in one of the world's most important trade locations. As international shipping moves toward lower greenhouse gas emissions, alternative fuels, and more transparent emissions monitoring, Panama has an opportunity to move from being primarily a transit hub to becoming a regional platform for maritime decarbonization, clean-fuel distribution, climate-resilient logistics, technical training, and international coordination.

The project GSC in the Panama Canal under Climate Risk financed by the Secretaría Nacional de Ciencia y Tecnología (SENACYT) in Panamá, developed a data-driven evidence base to support this discussion. Using AIS-derived vessel movements, vessel technical information, geographic polygons, climate and hydrological data, onboard operational data, expert surveys, and optimization models, the project estimated maritime energy demand, emissions, route connectivity, operational efficiency, climate-risk effects, alternative-fuel opportunities, and workforce needs linked to Panama. The report consolidates these results into a practical reference for public institutions, the Panama Canal Authority, ports, shipping companies, fuel suppliers, academia, training institutions, and international partners.

A central finding is that Panama should not approach GSC only as isolated point-to-point routes. The evidence shows that Panama-connected shipping is highly diversified, with more than one thousand immediate previous or next port connections. Although some routes and port clusters show especially high energy demand, particularly those involving the United States, South Korea, China, Japan, Mexico, Ecuador, Savannah, and the Busan/Masan cluster, Panama's strongest opportunity lies in a network-based corridor strategy. In this model, Balboa and the Canal area can act as a mid-route refuelling, coordination, monitoring, and data platform serving multiple services across the Americas rather than only one bilateral corridor.

The report also shows that climate risk must be integrated into corridor planning from the beginning. The Panama Canal depends on freshwater availability, and ENSO-related drought conditions can reduce Gatun Lake levels, trigger draught and transit restrictions, affect vessel scheduling, and change the cost and reliability of using the Canal. Evidence from the project and the literature indicates that these effects vary across vessel segments. Container services appear more resilient because they operate on fixed schedules and are more likely to secure reservations, while bulk carriers are more sensitive to cost, uncertainty, and potential rerouting. Climate resilience is therefore not separate from maritime decarbonization; it is a condition for credible and reliable GSC development connected to Panama.

The alternative-fuel assessment indicates that Panama should prepare for a flexible, multi-fuel future rather than betting on a single fuel pathway. Liquified Natural Gas (LNG) may play a transitional role, methanol may support early deployment in some corridors, ammonia has strong long-term potential for deep-sea shipping, hydrogen is more likely to begin in specialised applications, and shore power and hybrid systems can reduce emissions in port and during specific operational modes. Because Panama may not produce large volumes of alternative fuels domestically, its strategic opportunity is to connect external green-fuel supply with concentrated maritime demand around the Canal. This requires infrastructure planning, safety regulation, emergency response capacity, digital traffic coordination, and workforce training.

The project also highlights that technical infrastructure alone will not be enough. GSC development requires trained personnel, clear institutional roles, trusted data, regulatory readiness, and sustained stakeholder engagement. Training needs are especially important in alternative fuels, emissions measurement and reporting, energy efficiency, digital analytics, safety management, and port and bunkering operations. Panama can build on institutions such as MTCC Latin America, UMIP, UTP, the Panama Canal Authority, Georgia Tech Panama and international academic and technical partners to become a regional centre for maritime decarbonization knowledge, education, and applied decision support.

The report supports three types of decisions. First, it helps identify which routes, vessel segments, and partner ports should be prioritized for further feasibility studies. Second, it clarifies what Panama must prepare in terms of alternative-fuel infrastructure, safety systems, digital monitoring, climate-risk management, and training. Third, it proposes a phased implementation pathway: institutional preparation and knowledge development from year 1 to year 2, corridor-specific feasibility assessment from year 2 to year 5, pilot implementation and infrastructure development from year 5 to year 10, and regional expansion after year 10. Overall, the report concludes that Panama has the strategic assets, analytical capabilities, and institutional foundations to participate actively in future GSC, provided that decarbonization, climate resilience, operational efficiency, and capacity building are planned together.

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List of Acronyms

Acronym	Meaning
ACP	Panama Canal Authority
AHP	Analytic Hierarchy Process
AIS	Automatic Identification System
AMP	Maritime Authority of Panama
CAF	Development Bank of Latin America and the Caribbean
CH_4	Methane
CO_2	Carbon dioxide
CO_2e	Carbon dioxide equivalent
CWT	Canal Water Time
ENSO	El Niño Southern Oscillation
GDP	Gross Domestic Product
GHG	Greenhouse gas
GIS	Geographic Information System
GMN	Global Maritime Network
GSC	Green Shipping Corridor
IDB	Inter-American Development Bank
IMO	International Maritime Organization
JIT	Just-in-Time
LNG	Liquefied Natural Gas
LPG	Liquefied Petroleum Gas
LSTM	Long Short-Term Memory
MCDA	Multi-Criteria Decision Analysis
MDETI	Maritime Decarbonization Education and Training Initiative
MiAMBIENTE	Ministry of Environment of Panama
MMMCZCS	Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping
MMSI	Maritime Mobile Service Identity
MTCC	Maritime Technology Cooperation Centre

N_2O	Nitrous oxide
NHH	Norwegian School of Economics
ONI	Oceanic Niño Index
PCA	Panama Canal Authority
PSU	Practical Salinity Unit
SENACYT	Secretaría Nacional de Ciencia, Tecnología e Innovación
SOLAS	International Convention for the Safety of Life at Sea
UMIP	Universidad Marítima Internacional de Panamá
UNCTAD	United Nations Conference on Trade and Development
UTP	Universidad Tecnológica de Panamá

1

Introduction

1.1 Purpose of the Report

The **maritime sector** is entering a period of **profound transformation** driven by international commitments to reduce greenhouse gas (GHG) emissions and achieve net-zero shipping over the coming decades. The adoption of the 2023 International Maritime Organization (IMO) Strategy on the Reduction of GHG Emissions from Ships has accelerated the search for practical pathways to decarbonize maritime transport while maintaining the efficiency, safety, and reliability of global trade. Among the various approaches currently being explored, Green Shipping Corridors (GSC) have emerged as one of the most promising mechanisms for accelerating the early deployment of low and zero-emission shipping technologies through coordinated action among governments, ports, shipping companies, fuel suppliers, cargo owners, and financial institutions.

According to this international context, the **"Green Shipping Corridors in the Panama Canal under Climate Risk"** project was developed to evaluate how Panama can contribute to and benefit from the global transition toward sustainable maritime transport. The main goal of the project is to develop a comprehensive technical, operational, and economic assessment of GSC opportunities connected to Panama and the Canal. The project examines maritime emissions, vessel energy demand, trade patterns, climate risks, alternative marine fuels, and institutional readiness to identify the conditions required for the successful implementation of future corridors.

Unlike many existing GSC studies that focus primarily on individual trade routes or bilateral partnerships, this project adopts a **Panama-centered perspective**. Given the country's unique role as an interoceanic transit hub, a global logistics center, and one of the largest bunkering locations in the Americas, understanding how Panama can support corridor development requires an integrated assessment of maritime activity, emissions, energy systems, climate resilience, and institutional capacity. This perspective recognizes that Panama's contribution extends beyond facilitating vessel transits; it includes the potential to become a provider of clean marine fuels (green bunkering hub), digital services, emissions monitoring, technical expertise, and regional coordination for maritime decarbonization.

The purpose of this report is therefore to consolidate the principal technical findings of the project into a **comprehensive reference document** that supports dialogue among stakeholders. Rather than proposing a single GSC, the report provides the **scientific evidence, methodologies, and decision-support framework** necessary to identify, evaluate, and prioritize future corridor opportunities connected to Panama.

Ultimately, the report seeks to contribute to national and international discussions on maritime decarbonization by demonstrating how Panama's strategic location, existing maritime infrastructure, and growing technical capabilities can support the development of climate-resilient GSCs. It is intended to serve as a **foundation for future feasibility studies, investment decisions, policy development, international partnerships, and collaborative research** that advance sustainable maritime transport in Panama and throughout the Americas.

1.2 Why Green Shipping Corridors matter for Panama

Panama's strategic importance is primarily derived from the **Panama Canal**[1], one of the world's most significant maritime chokepoints. Connecting the Atlantic and Pacific Oceans, the Canal enables global trade between Asia, Europe, North America, and Latin America by providing one of the shortest and most efficient interoceanic routes. This concentration of vessel movements creates an exceptional opportunity to support coordinated emissions reduction initiatives across multiple trade routes simultaneously.[2]

The Canal is complemented by a highly developed **maritime and logistics ecosystem** that extends well beyond its locks. Panama hosts major **container ports** on both the Caribbean and Pacific coasts, an extensive **maritime services industry, multimodal logistics facilities, and special economic zones**. Together, these assets provide a mature operational environment capable of supporting future GSCs through cargo consolidation, transshipment, logistics services, digital information systems, and maritime support activities.

Another strategic advantage is Panama's long-established role as a **regional bunkering center**. Conventional marine fuel supply has been a core component of the country's maritime economy, supported by experienced fuel suppliers, storage terminals, and distribution infrastructure. As the IMO[3] advances its net-zero agenda for shipping, this existing bunkering capacity provides a valuable platform for the gradual introduction of sustainable marine fuels. Although significant investments in infrastructure, regulation, and safety systems will be required, Panama possesses many of the logistical and commercial conditions necessary to become a regional clean-fuel hub serving vessels operating throughout the Americas.

At the same time, the project recognizes that the future competitiveness of the Panama Canal will depend not only on decarbonization but also on its ability to **adapt to a changing climate**. Recent drought events have highlighted the vulnerability of Canal operations to reductions in freshwater availability, resulting in transit restrictions, increased waiting times, and disruptions to global supply chains. These events demonstrate that climate resilience must be **integrated into GSCs planning** from the outset. Investments in alternative fuels, digital traffic management, operational efficiency, and resilient infrastructure should therefore be designed to simultaneously reduce emissions and strengthen the reliability of Canal operations under future climate conditions.

Consequently, Panama is well positioned to evolve from a strategic transit corridor into a **regional platform for maritime decarbonization**. By combining its geographic location, world-class maritime infrastructure, institutional experience, and growing technical capabilities, the country can facilitate the deployment of GSCs that connect the Americas with USA, Europe and Asia while serving as a regional center for clean marine fuel distribution, emissions monitoring, capacity building, and international collaboration. In doing so, Panama can reinforce its long-standing role as a facilitator of global trade while contributing to the transition toward a more sustainable, resilient, and low-carbon maritime sector.

1.3 Scope of the Report

The document examines Panama's role in the maritime energy transition through an integrated assessment of shipping activity, infrastructure, and resilience. Using Automatic Identification System (AIS) data covering the geospatial activity of vessels, it estimates **vessel emissions and energy demand** associated with ships and trade routes connected to Panama, with particular attention to traffic transiting the Canal and calling at the nation's ports. The analysis further considers the implications of **climate variability** and long-term climate change for Canal operations, recognizing the strategic importance of water availability, operational reliability and forecasting. Against this backdrop, the report evaluates the prospects and requirements for **alternative marine fuels and bunkering services**, identifying the market conditions needed to support their deployment. It also highlights the **capacity-building and workforce training** essential for the safe handling of new fuels and technologies. Drawing on these findings, the report concludes with **recommendations for policymakers, industry stakeholders, and future research** aimed at strengthening Panama's position as a resilient and competitive hub for sustainable maritime transport.

It does not constitute a final investment decision nor provide complete feasibility studies. Ongoing efforts such as the Algeciras-Panama corridor and the work coordinated by the Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping (MMMC) are advancing those next steps.

2

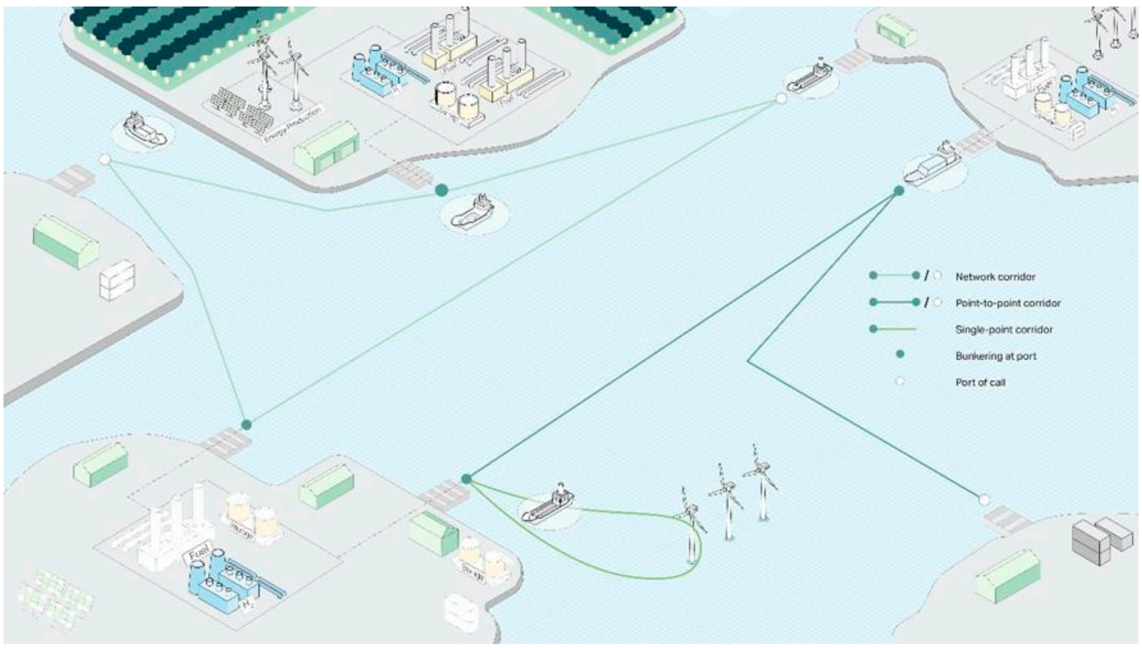
Conceptual Background: What is a Green Shipping Corridor?

2.1 Definition in Practical Terms

A **GSC** is a shipping route or network where public and private actors coordinate to reduce greenhouse gas emissions from maritime transport. It normally involves ships, ports, fuel suppliers, cargo owners, technology providers, regulators, and financial institutions. A corridor becomes green not only because a cleaner fuel is available, but also because the full system allows vessels to operate with lower emissions in a reliable and economically feasible way.

The MMMC defines GSCs as routes where commercial vessels operate using alternative, low-emission fuels or other low-carbon propulsion solutions, backed by the necessary fuel supply chains and port infrastructure.[4] Figure 1 shows the scheme of GSCs as defined by MMMC.

Figure 1. Green Corridors can be network, point-to-point, or single-point corridors.



Source: Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping.

Furthermore, the Global Maritime Forum defines GSCs as specific maritime trade routes where the transition to zero-emission shipping is catalysed by the public and private actions needed to accelerate the deployment of zero-emission vessels and fuels.[5]

2.2 Main components of a Green Shipping Corridor

A GSC begins with a **trade route** or market segment that exhibits sufficient and durable cargo demand, because predictable volumes, therefore energy demand, justify the substantial investments required in vessels, fuels, and infrastructure. **Ships** serving the corridor must be capable of operating on scalable low or zero-carbon fuels, while participating **ports** need safe **bunkering, storage, and handling facilities**. These port assets, in turn, depend on robust upstream **energy production and distribution systems** that can deliver sustainable fuels reliably and at competitive cost. Coordinated **safety standards and clear regulations** are indispensable to govern fuel quality, ship operations, and emergency response, thereby reducing uncertainty for investors and operators.

Equally important are what might be called the “software” elements of the corridor. **Specialized training** programs are needed to equip seafarers, terminal personnel, and first responders with the skills required to manage new fuels and technologies. **Transparent monitoring, reporting, and verification systems** provide credible evidence of emissions reductions and support compliance with evolving climate policies. Finally, **long-term commercial arrangements** among shipowners, cargo owners, ports, fuel suppliers, and public authorities help allocate risks and create the revenue certainty necessary for large-scale deployment. These **collaborative governance and market mechanisms** are as critical to success as the **physical infrastructure** itself.

2.3 Why Corridors Are Useful

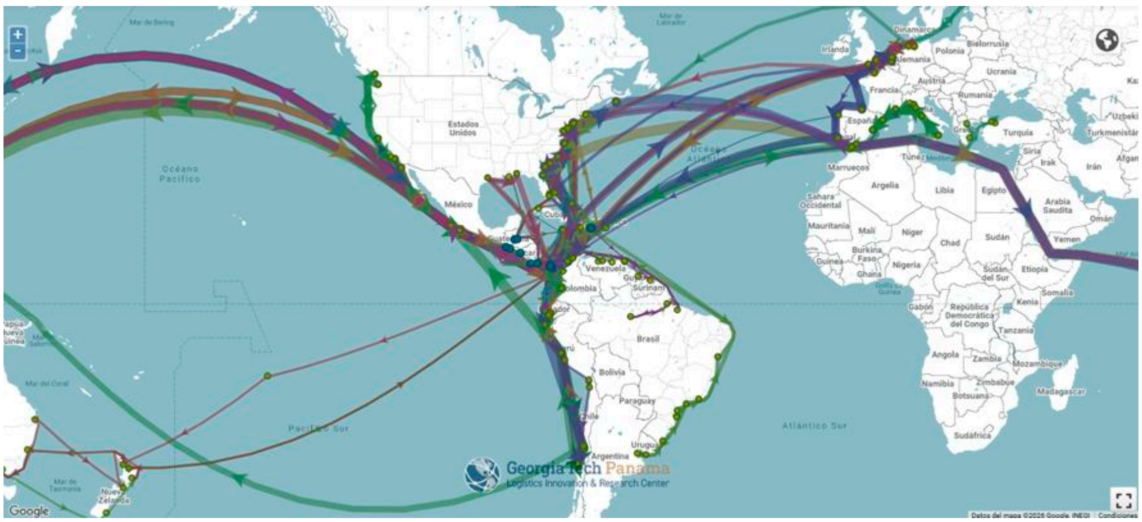
GSCs are valuable because they create a **controlled environment** in which the principal uncertainties of maritime decarbonization, such as fuel availability, technology performance, infrastructure needs, regulation, and commercial viability, can be addressed simultaneously. By **concentrating early investments and cooperation** on specific routes, a limited set of ports, and a defined group of shipping companies, cargo owners, fuel suppliers, and public authorities, corridors reduce coordination failures and provide clearer signals for investment. This targeted approach **lowers risk for first movers** and enables stakeholders to develop common standards, contractual arrangements, and operational practices that can later be replicated elsewhere.

Corridors also function as **real-world pilot projects**. They allow new fuels, bunkering systems, vessel technologies, and emissions-accounting frameworks to be tested under commercial operating conditions before being deployed at global scale.[6] The resulting experience generates **valuable technical and economic data, builds workforce expertise, and informs future regulation**, thereby accelerating the transition to zero-emission shipping while avoiding the costs and disruptions of attempting an immediate sector-wide transformation. These early successes can, in turn, catalyse broader market adoption and policy support for maritime decarbonization.

2.4 Panama´s Corridor Opportunity

Panama is uniquely positioned to participate in GSCs because the **geography of global trade** naturally concentrates traffic at the Canal. Maps of trade flows show that a large share of container, dry bulk, and tanker routes connecting Asia, the Americas, and Europe either transit the Canal or call at Panamanian ports. As a **transit hub**, Panama can facilitate the coordination of corridor partners and provide efficient passage for low- and zero-emission vessels. At the same time, its established **bunkering industry and port infrastructure** make it a promising location for the storage, blending, and distribution of future marine fuels, enabling the country to serve as a **regional fuel hub**. Figure 2 shows Panama’s maritime connectivity with the rest of the world.

Figure 2. Panama´s maritime connectivity, June 2026.



Source: Georgia Tech Panama.

Beyond its physical assets, Panama can contribute **digital and human capital** to the corridor ecosystem. The Canal and the nation’s logistics sector generate a wealth of **operational data** that can support emissions monitoring, route optimization, and performance benchmarking, positioning Panama as a leading data and monitoring platform. By **partnering** with shipping lines, cargo owners, and ports on route-based emissions reduction initiatives, the country can help demonstrate **scalable decarbonization pathways**. Finally, through **specialized education and workforce development programs**, Panama has the opportunity to become a centre of excellence for training and knowledge exchange on sustainable shipping for Latin America, amplifying the benefits of corridor development throughout the region.

3

Project Overview

3.1 General Objective

The general objective of the "Green Shipping Corridors in the Panama Canal under Climate Risk" project is to develop a **comprehensive technical, operational, and economic basis for identifying and evaluating opportunities** to establish **GSCs** connected to **Panama** and the **Panama Canal**. This entails assessing shipping activity and energy demand, the feasibility of alternative fuels and bunkering infrastructure, the implications of climate variability and long-term climate change for Canal operations and the workforce needs and training required for the corridors' deployment. By integrating these analyses, the project seeks to identify viable decarbonization pathways, evaluate their strengths and weaknesses, and provide evidence-based recommendations that will enable Panama to strengthen its role as a sustainable maritime hub and a leader in the transition to low-carbon shipping in the Americas.

3.2 Specific Objectives

- **Estimate emissions and energy demand by vessel type, route, port, and operating mode**.

Develop a high-resolution assessment of CO_2 emissions and energy demand associated with maritime traffic connected to Panama by using AIS data and vessel-specific technical characteristics. The analysis quantifies emissions according to vessel type, region, stop area, and operating mode, providing a detailed baseline to identify priorities and vessel segments for decarbonization and the potential demand for alternative marine fuels.

- **Evaluate climate risk and its effect on Canal operations.**

Assess the vulnerability of the Panama Canal and the surrounding maritime logistics system to climate variability and long-term climate change. The assessment examines the effects of changing precipitation patterns, droughts, water availability, extreme weather events such as El Niño phenomenon, and other climate-related hazards on Canal operations, vessel transit capacity, navigation reliability, and supply chain resilience. The objective is to identify the effects of adaptation measures, such as Just in Time (JIT) arrivals, that enhance the long-term reliability of one of the world's most strategic maritime corridors.

- **Analyse alternative fuels and possible distribution networks.**

Evaluate the technical, economic, and logistical feasibility of supplying low and zero-carbon marine fuels such as LNG, methanol, or ammonia to vessels operating through Panama. The study identifies potential fuel demand, infrastructure requirements, storage and bunkering needs, safety considerations, and opportunities to integrate Panama into regional and global clean-fuel supply chains.

- **Identify workforce and training gaps.**

Assess the human capital requirements associated with the transition to low-carbon shipping by identifying knowledge, technical, and operational gaps among stakeholders. The objective is to define priority training programs, certification requirements, and institutional partnerships needed to safely manage alternative fuels, new vessel technologies, digital systems, and emissions monitoring.

- **Develop open-access tools for monitoring and public access to data.**

Design and implement open-access digital tools that integrate AIS data, emissions estimates, vessel activity, and energy demand into interactive platforms for analysis and visualization. These tools are designed to improve transparency, facilitate evidence-based decision-making, support academic research, and enable government agencies, industry stakeholders, and the public to monitor progress toward maritime decarbonization objectives.

- **Support recommendations for policy and industry.**

Translate the project's technical findings into recommendations that support public policy, investment planning, and private sector decision-making. These recommendations aim to address regulatory frameworks, infrastructure development, fuel deployment strategies, climate adaptation, workforce development, and collaborative governance mechanisms that can accelerate the implementation of GSCs and strengthen Panama's competitiveness as a regional hub for sustainable maritime transport.

3.3 Project Outputs

- **Emissions estimation model.**

The project developed a robust, AIS-based emissions estimation model capable of quantifying CO_2 emissions and energy demand from vessels operating in the Panama Canal and connected maritime routes. The model estimates emissions by vessel type, region, stop area, and operating mode, providing a transparent and reproducible analytical framework that can support future research, infrastructure planning, and policy development. The model also enables the evaluation of decarbonization scenarios based on the adoption of alternative marine fuels and operational improvements.

- **Public dashboard.**

An interactive, web-based public dashboard (SEAnalytics) was developed to provide open access to key project results. The platform visualizes emissions, energy demand, trade flows, and potential GSCs routes through maps and charts. Designed to promote transparency and stakeholder engagement, the dashboard will serve as a decision-support tool for government agencies, researchers, industry representatives, and the general public.

- **Scientific publications.**

The project generated peer-reviewed scientific publications that advance knowledge on maritime decarbonization, climate risk, alternative marine fuels, workforce development, and GSCs. These publications present the project's methodologies, datasets, analytical models, and policy implications, contributing to the international scientific literature and promoting Panama as a case study for sustainable maritime transport and climate resilience.

- **Training workshops.**

A series of technical workshops and capacity-building activities were organized for government institutions, maritime authorities, port operators, shipping companies, academic institutions, and students. These workshops disseminated project findings while strengthening national capabilities in emissions estimation, AIS data analysis, climate risk assessment, alternative fuel technologies, training, and green shipping corridor planning.

- **Conference presentations.**

Project results were presented at national and international conferences focused on maritime transport, climate change, energy transition, logistics, and port management. These presentations facilitated knowledge exchange, foster collaboration with international experts, and increase the visibility of Panama's efforts to promote sustainable shipping and maritime decarbonization.

- **Thesis and student outputs.**

The project supported the education and professional development of undergraduate and graduate students through research theses, internships, and technical reports. Students actively participated in data analysis, model development, software tools, and scientific dissemination, contributing to the development of a new generation of researchers and professionals specialized in sustainable maritime transport and climate resilience.

- **Industrial report and recommendations.**

A comprehensive industrial report synthesizes the project's technical findings and translates them into practical recommendations for policymakers, the Panama Canal Authority, port operators, shipping companies, fuel suppliers, investors, and other stakeholders. The report identifies opportunities, challenges, investment priorities, policy options, and implementation pathways for developing GSCs, strengthening climate resilience, expanding alternative fuel infrastructure, and positioning Panama as a regional hub for maritime decarbonization. This report aims to provide an evidence-based roadmap to support strategic planning and future investments in the country's maritime and logistics sector.

4

Data and Methodology

This report is based on a **mixed evidence base** developed through the project. The work makes use of vessel movement data, emissions estimation, climate and hydrological analysis, engineering assessment of alternative fuels, optimization models for fuel demand and bunkering locations, and survey-based analysis of workforce and training gaps. The objective is to provide a practical basis for identifying Green Shipping Corridor opportunities from the perspective of Panama. A summary of the data and its application is provided in Appendix Table A1.

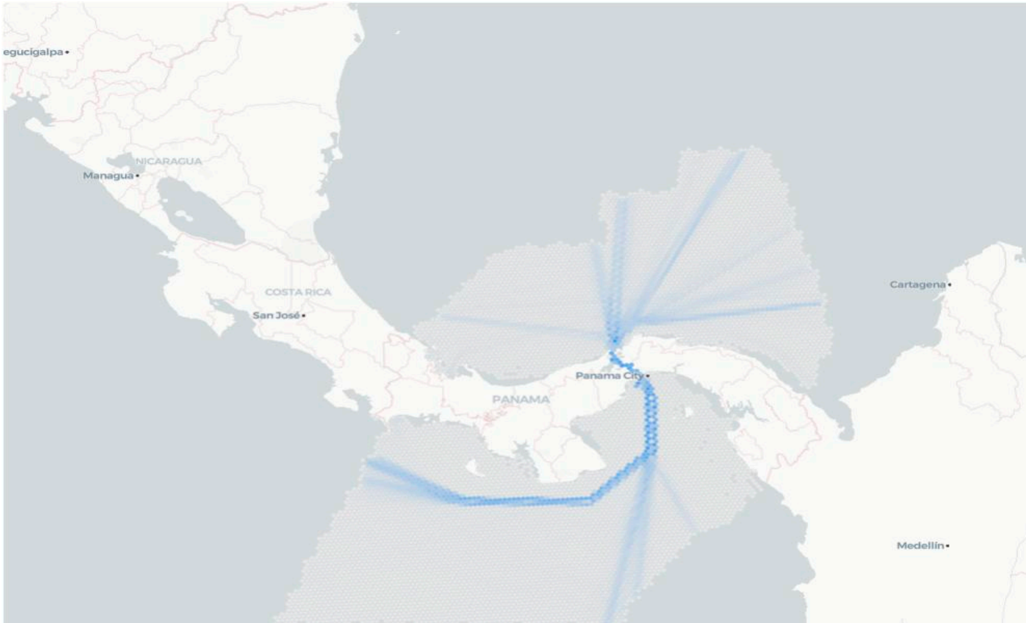
A central methodological contribution of the project is the **estimation of maritime energy use and emissions from vessel activity data**. Following the bottom-up approach used in the Fourth IMO GHG Study, the estimates are derived from vessel movements, technical characteristics, operating modes, and route information, rather than from aggregated fuel-sales data. For Panama, the project developed a processing pipeline that transforms raw AIS data from the UN Global Platform into indicators for analysis and visualization in SEAnalytics**, publicly available at the MTCC Latin America website (https://stats.mtcclatinamerica.com)**. The pipeline combines AIS records from 2019–2025 with vessel technical data, geographic polygons, climate and hydrological information, and Python-based processing to estimate energy use and CO_2, CH_4, and N_2O emissions by route, vessel type, operating mode, year, and geography. AIS is a vessel-tracking system that broadcasts information such as a ship's identity, position, speed, course, and timestamp. Under SOLAS requirements, AIS is mandatory for passenger ships regardless of size and for cargo ships of 300 gross tonnage and above engaged on international voyages, as well as cargo ships of 500 gross tonnage and above not engaged on international voyages.

4.1 Evidence Base and Data Sources

The first group of data relates to vessel movements and Panama-connected maritime activity. **AIS vessel position data** were used to reconstruct vessel movements, including arrivals to Panama, departures from Panama, transits through the Panama Canal, visits to ports and anchorages, and route segments before and after the Panama call. AIS records include vessel position, speed overground, course, timestamp, and vessel identifiers such as MMSI and IMO numbers. These data were complemented with **vessel technical characteristics,** including vessel type, gross tonnage, deadweight, main and auxiliary engine power, year of build, size category, and other parameters required for energy and emissions estimation.

The second group of data relates to geography. The analysis uses **port and geographic polygons** to identify when a vessel enters or exits relevant locations, including Canal waters, locks, anchorage areas, port areas, coastal areas, and broader Panama-connected route segments. These polygons are essential because they allow the analysis to distinguish sailing, manoeuvring, waiting, port stay, anchorage, energy density, and Canal transit activity. Figure 3 shows the main polygon used to identify vessel visits to Panama, while the dark blue heatmap highlights the spatial concentration of vessel emissions within the study area. For identifying visits of vessels to ports abroad, polygons were generated using the World Port Index 2019 database.[7]

Figure 3. Main polygon defining Panama territorial waters.



Source: SEAnalytics.

The third group of data relates to **climate and hydrology**. Climate indicators, Gatun Lake water levels, and other operational variables were used to examine how water availability and climate variability affect Canal operations. Canal Water Time (CWT), as defined by Fuentes and Munim[8], combines AIS-derived operational statistics with Gatun Lake water levels and the Oceanic Niño Index (ONI), an indicator of El Niño conditions.

The fourth group of data comes from **high-resolution industry information** provided through the collaboration with Laskaridis Shipping. Unlike AIS data, which record external vessel movements, the Laskaridis data provide high resolution vessel operational information. In the alternative fuels and hybrid propulsion study by Yuksel et al.[9], energy and fuel-consumption data were recorded at one-minute intervals for two bulk carrier case-study vessels operating on routes that included Panama Canal transits. These data were used to evaluate alternative fuels, hybrid propulsion configurations, cold ironing, and the environmental and economic implications of different technical options.

The fifth group of data comes from **surveys and expert input**. The training and competency gap study by Diaz Jimenez et al.[10] used a mixed-methods design combining literature review, structured expert surveys, and an Analytic Hierarchy Process (AHP) to identify and prioritize maritime education and training needs for decarbonization in Panama. The study highlights gaps in alternative fuels, emissions measurement and reporting, energy-efficient technologies, digital analytics, and regulatory compliance.

The final group of outputs consists of **project-generated databases and indicators**, including energy demand, emissions estimates, route-level statistics, origin-destination pairs, and dashboard-ready datasets. These outputs are used in this report to describe Panama's maritime emissions profile, identify route and partner opportunities, and support corridor-selection discussions.

4.2 Scope of Analysis

The geographic scope is centred on the Panama Canal, but the analysis treats the Canal as part of a wider maritime system. This is important because the energy and emissions associated with Panama are not limited to the locks. They also include sailing toward Panama, waiting at anchorage, manoeuvring, port activity, Canal transit, and onward voyages after leaving Panama. This can be considered Scope 3[11] emissions from the perspective of the Panama maritime cluster. While emissions were estimated for the purpose of the project, the scope of the analysis used in the report will be the energy used by vessels calling to Panama. This focus aims at a rapid assessment of the fuel volume required to cover such demand.

For **Panama-connected traffic**, the analysis considers vessels arriving in Panama, vessels departing from Panama, vessels transiting through the Canal, and vessels visiting Panamanian ports or anchorage areas. For each relevant voyage, the project considers the segment from the previous port before Panama to the next port after Panama. This creates a practical boundary for estimating the emissions and energy demand associated with Panama's role in the voyage. Previous and subsequent port visits are estimated based on vessel calls before and after passing through Panama. Port polygons are generated using a 5-nautical-mile buffer around each port's geographic location, as defined by the World Port Index.[7] When two or more port buffers overlap, the port area is defined as a merged polygon covering the matching ports.

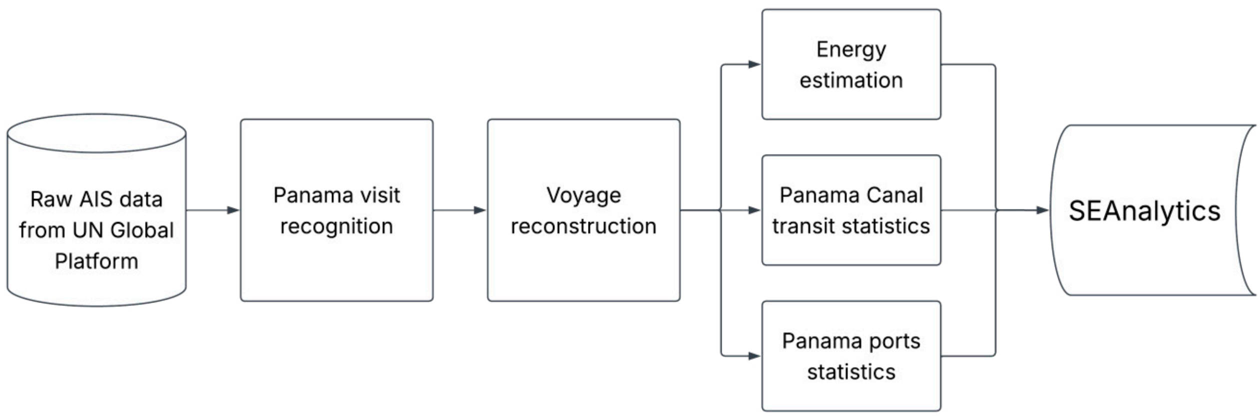
The vessel scope includes the main vessel categories observed in Panama-connected traffic: container vessels, bulk carriers, tankers, gas carriers, general cargo vessels, and passenger vessels when available in the SEAnalytics database. For route and partner identification, the emphasis is stronger on container vessels because they tend to operate on more regular services, have the highest concentration of energy for vessels transiting the Panama Canal[2] and are therefore more suitable for early GSC planning. Bulk carriers, tankers, and gas carriers remain relevant for operational efficiency, alternative fuel assessment, and future corridor opportunities, but container routes provide the clearest starting point for repeated point-to-point or region-to-region partnerships.

4.3 Methods used across the Project Studies

The project relies on different methods that were used depending on the research question. The methods, their output, main indicators, and use in the green corridors assessment are summarized in Appendix Table A2.

For vessel movement, energy and emissions estimation, and Canal and port efficiency, the project follows the methodology described in Fuentes and Adland2. The results of the algorithmic pipeline are displayed in SEAnalytics, with the framework summarized in Figure 4. The pipeline cleans and filters AIS data from the UN Global Platform by removing or treating invalid positions, duplicated records, impossible speeds, and inconsistent observations. Vessel tracks are then matched with geographic polygons to identify port calls, anchorage stays, Canal approaches, Canal transits, and voyage segments. The resulting indicators are aggregated by vessel type, route, year, geography, and operating mode.

Figure 4. SEAnalytics general framework.



Source: Developed by the authors.

For climate risk and Canal operations, the project reconstructs weekly operational indicators and combines them with hydrological and climate variables. The Canal Water Time analysis in Fuentes and Munim[8] uses AIS-derived arrivals, transits, waiting indicators, vessel behaviour, Gatun Lake water levels, and the ONI. It then compares statistical time-series models and machine learning models, including LSTM and Random Forest approaches, and uses fixed-effects panel regression to isolate the effect of El Niño Southern Oscillation (ENSO) on Canal operations.

For alternative fuels, hybrid propulsion, and cold ironing, the project uses a scenario-based engineering and environmental assessment. The Laskaridis case-study data provide high-resolution operational profiles for two bulk carriers. These profiles are used to benchmark conventional operation against alternative configurations, including dual-fuel engines, diesel-electric and mechanical propulsion, fuel cell/battery electrification, ammonia, LNG, methanol, biodiesel, hydrogen-related configurations, and cold ironing. The study evaluates both tank-to-wake and well-to-wake emissions and also includes economic indicators such as levelized cost of energy.

For life-cycle emissions, the alternative fuel assessment distinguishes between emissions produced onboard the vessel and emissions associated with fuel production and supply. In practical terms, tank-to-wake results describe what happens during vessel operation, while well-to-wake results include upstream fuel production and delivery. This distinction is essential for GSCs because fuel may reduce onboard emissions but still generate significant emissions if its production pathway is not low carbon.

For green ammonia demand and bunkering locations, the project uses a spatial optimization model defined by Cerda et al[12]. The model estimates where ammonia bunkering infrastructure could be located, how much capacity would be required, which vessels or routes could adopt the fuel, and how carbon prices would affect the economic case. The model considers shipowners, bunkering infrastructure developers, and fuel suppliers together, instead of assuming that demand for alternative fuels already exists. This is important because GSCs require both supply and demand to emerge at the same time.

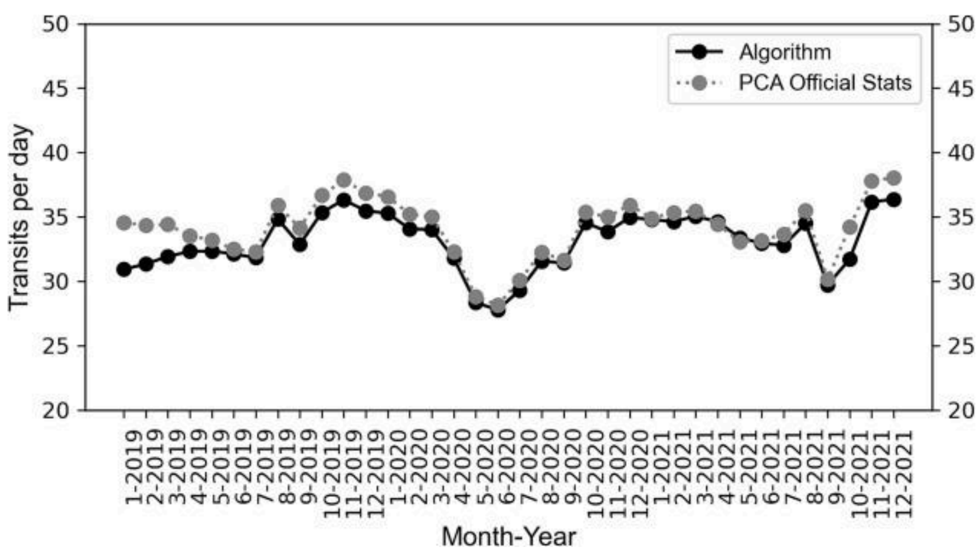
For workforce and training capacity, the project uses a mixed-methods approach. The training study combines a literature review, structured surveys with maritime professionals, and an AHP to prioritize competency needs. This allows the project to move beyond general statements about training and identify which competencies matter most for Panama's maritime transition, including alternative fuels, emissions reporting, digitalization, regulation, and cross-sector collaboration.

4.4 Quality Control, Validation and Limitations

Quality control was applied at several levels. For AIS-based analysis, records were checked for invalid coordinates, duplicated messages, impossible speeds, and inconsistent vessel tracks. Detected events were tested against geographic sequences to confirm that port calls, anchorages, and Canal transits were plausible. Vessel records were matched with technical characteristics using identifiers such as IMO number, MMSI, vessel name, and vessel type where available.

The AIS-derived Canal indicators were also compared with official Canal statistics where comparable information was available. In Fuentes and Munim[8] AIS-derived estimates were compared with Panama Canal Authority monthly statistics (Figure 5), and the comparison showed a close fit between the two series. This type of validation is important because AIS-derived results are analytical estimates and should not be treated as official operational records.

Figure 5. Transits reported by the Panama Canal and detected by the AIS-derived estimates.



Source: Fuentes and Adland.[2]

The Laskaridis data provides an additional form of validation and calibration support. Because this data comes from onboard monitoring systems, they allow the project to compare model assumptions with high-resolution operational profiles.

The emissions and energy estimates used in this project rely strictly on the Fourth IMO GHG Study[13]. That study identifies uncertainties related to AIS data, vessel activity reconstruction, draught information, assumptions about weather and hull fouling, vessel technical parameters, and transport-work estimation. These uncertainties become especially relevant when results are disaggregated by ship type, route, or carbon-intensity metric. In addition, the central assumption of the admiralty formula—that power is proportional to the cube of speed—has been shown to overestimate power for some vessel types.[14] For this reason, the method is most useful for identifying patterns, comparing relative contributions, and supporting corridor screening. Final investment, regulatory, or operational decisions should therefore be complemented with company-reported fuel data, port records, and project-specific validation.

Survey-based results were controlled through expert selection, structured criteria, and the AHP prioritization process. These results reflect expert judgment and sector experience, but they should still be interpreted as a structured assessment of training needs rather than a census of all maritime professionals in Panama.

The main limitations are related to data completeness, assumptions, and scope. AIS data may contain gaps, missing transmissions, duplicated records, or inconsistent vessel identifiers. Vessel technical characteristics may be incomplete or require matching from external databases. Fuel type and engine-load assumptions are necessary for large-scale emissions estimation but may differ from actual vessel operation. AIS-derived operational times may also differ from official definitions because physical arrival, administrative arrival, and operational readiness are not always the same.

For alternative fuel and life-cycle analysis, results depend on assumptions about fuel pathways, engine configurations, conversion efficiencies, upstream emissions factors, fuel prices, and technology maturity. For optimization models, results depend on assumptions about carbon prices, production costs, vessel retrofit costs, infrastructure costs, and route demand. For workforce analysis, results depend on the composition of expert respondents and the criteria included in the survey and AHP model.

For this reason, the results in this report should be interpreted as an evidence base for screening, prioritization, and strategic discussion. They are not a substitute for project-specific feasibility studies, engineering design, commercial due diligence, safety assessment, or regulatory approval.

5

Panama’s Maritime Energy Demand Profile

5.1 Overview of Panama-Connected Shipping Activity

Under a descriptive assessment, the selection of potential GSC partners can be informed by identifying the ports with the strongest connectivity to Panama. An initial analysis of point-to-point corridors, defined as routes with either an origin or a destination in Panama and based solely on AIS data, indicates that an average of **17,904 annual port calls** between 2020 and 2025 included a Panamanian port in their schedule. Figure 6 presents the monthly distribution of these visits, showing the scale and temporal variation of Panama related maritime activity.

Figure 6. Monthly vessels' visits to Panama.

Source: Authors' calculations.

The distribution of ports of call presented in Table 1 indicates that most vessel visits to Panama are associated with the **Panama Canal transits, accounting for 60.8% of the total.** These are followed by visits to ports on the Atlantic side and, to a lesser extent, ports on the Pacific side. This suggests that, from the perspective of coordinating port calls for decarbonization strategies, the Panama Canal could serve as a central coordinator for GSC initiative. Its central role in managing transit schedules, its authority over navigation through the Canal and navigational approaches, and its function as a maritime chokepoint may help overcome implementation barriers for operational decarbonization measures, including Just-in-Time arrivals.[2]

Table 1. Percentage of vessels' visits per port in Panama.

Port of call	Visits percentage
Panama Canal North Transit	31.1%
Panama Canal South Transit	29.7%
Manzanillo International Terminal	12.9%
Colon Container Terminal	5.9%
Panama Ports Company Balboa	5.6%
Panama Ports Company Cristobal	4.7%
PSA	4.0%
PATSA	1.2%
Others	4.9%

Source: Developed by authors.

The distribution of **port calls is heavily dominated by container vessels**, as shown in Table 2. This reflects the fact that most port-handling activity in Panama is associated with container traffic, and that the Panama Canal provides one of the fastest routes for several of the world's densest container trade lanes. Given Panama's limited production of industrial bulk commodities, such as iron ore, grain, and crude oil, its future role is expected to remain strongly oriented toward container handling and the passage of container vessels. At the same time, the LNG and LPG markets deserve close attention, as they have gained strategic importance amid recent shifts in global trade routes.

Table 2. Percentage of vessels' visits per category in Panama.

Vessel type	Visits percentage
Container	42.8%
Bulk carrier	12.5%
Chemical tanker	11.8%
Liquified gas tanker (LNG & LPG)	9.7%
General cargo	4.1%
Oil tanker	4.1%
Service tugs	2.9%
Refigerated bulk	2.7%
Cruise ships	1.5%
Others	7.9%

Source: Developed by authors.

Several advanced GSC initiatives have used the relationship between ports, cargo flows, and exported commodities as an indicator for selecting GSC and partner ports, often in a point-to-point configuration. A clear example is the Australia–East Asia iron ore corridor, whose feasibility study was coordinated by the Global Maritime Forum.[15] In that case, the market of interest was bulk carriers serving relatively homogeneous iron ore exports from Western Australia. This homogeneity helped bring cargo interests, such as Rio Tinto, and port authorities, such as the Pilbara Ports Authority, into the corridor discussion. By focusing on a specific market, vessel type, and route, the initiative was able to identify current and projected energy demand, key implementation barriers, the availability of fuel feedstock within the port's economic reach, and the political momentum needed to bridge the price gap between conventional and alternative fuels. If this logic is applied to Panama, **the market with the greatest decarbonization potential is container shipping.** The heterogeneity of markets converging in Panama, also gives the opportunity that the development of the decarbonization strategy for one market could drive the decarbonization of another market segment.

Identifying the ports connected to Panama, help in recognizing the most relevant candidates for a point-to-point GSC configuration. Table 3 displays the five most frequent ports connected to Panama. However, the low individual percentages, together with the record of 1,032 ports where vessels called immediately before or after Panama, indicate that **a narrow point-to-point strategy may not be fully aligned with Panama's current network configuration.** Instead, these results point towards a broader network-based corridor approach, in which Panama acts as a coordinating hub across multiple routes and partner ports.

Table 3. Percentage of vessels' trips from or to Panama.

Port	**% of trips from/to**
Guayaquil, Ecuador	3.4%
Buenaventura, Colombia	3.1%
Kingston, Jamaica	2.9%
Masan, South Korea	2.8%
Savannah, USA	2.7%

Source: Developed by authors.

Although port visits provide an approximate indication of service potential and market interest, they do not show how much alternative fuel Panama would need to supply to meet future demand. Fuel demand varies across market segments because vessel operating speeds, engine types, voyage lengths, and operating profiles differ substantially. For this reason, the following section introduces an energy-demand analysis of vessels calling at Panamanian ports or transiting the Panama Canal.

5.2 Energy Demand by Route

Using AIS-derived vessel movements and the methodology of the Fourth IMO GHG Study[13], this section estimates the energy required by vessels travelling to or from Panama, measured from the immediate previous port of origin to Panama or from Panama to the immediate next port of destination. This bottom-up approach makes it possible to estimate energy demand at different levels of detail, including country, port, route, vessel type, and origin-destination pair. The results provide an indication of the potential alternative-fuel demand that Panama could help supply as a maritime transit and bunkering hub.

Having a clear signal of energy demand is important for low-carbon fuel investments because it helps identify where future demand is likely to be concentrated, which routes could justify early bunkering infrastructure, and which country or port partners may offer sufficient scale for corridor development. In this context, energy demand should be interpreted as a market indicator.

Figure 7 compares estimated energy demand by country for vessels using Panama as part of their route. The results show that the United States accounts for the largest share of energy demand, which is consistent with its position as one of the Panama Canal's most important uses. South Korea, Japan, and China also represent major sources of demand, reflecting the long distances to Panama and the significant cargo volumes associated with these routes. At the regional level, countries such as Mexico and Ecuador also emerge as relevant potential partners for future GSC development.

Figure 7. Estimated vessel energy demand by country for routes connected to Panama.

Source: SEAnalytics. Note: Circle size indicates the estimated annual energy demand of vessels travelling to or from each country through Panama-connected routes.

A different picture shows when the analysis is narrowed to the port level. As shown in Table 4, the highest energy-demand routes are strongly linked to Asian ports, particularly **Busan and Masan in**

South Korea, which together account for 11.4% of the estimated annual energy demand among Panama-connected routes. Chinese ports also represent a significant share of demand, with Zhoushan, Qingdao, Yantian, Xiamen, and Lianyungang all appearing among the top-ranked ports. This concentration suggests that, although the United States leads at the country level, several of the most energy-intensive port connections are associated with long-distance routes between Asia and Panama-connected services.

Table 4. Top 10 ports with the highest energy demand for routes connected to Panama.

Country	Port	Avg. Energy per year (GWh)	%
South Korea	Busan and Masan	6,647.5	11.4
China	Zhoushan	1,679.6	2.8
South Korea	Ulsan	1,522.5	2.6
China	Qingdao	1,438.7	2.4
China	Yantian	1,348.0	2.3
Japan	Yokohama	1,218.2	2.1
China	Xiamen	1,207.4	2.0
USA	Savannah	980.5	1.7
Belgium	Antwerpen	920.8	1.6
Rep. China (Taiwan)	Kao	862.6	1.4
China	Lianyungang	850.9	1.3

Source: Developed by authors.

In a port-to-port analysis, which reflects a point-to-point corridor configuration, candidate GSCs can be identified by examining the origin-destination pairs with the highest energy demand across the full route. Table 5 shows that several high-demand connections involve South Korean ports and ports on the Atlantic coast of the United States, suggesting that these route pairs deserve further assessment as potential corridor candidates. However, the results also highlight the strategic importance of Panama as a mid-route refuelling and coordination hub. Because many alternative fuels have lower energy density than conventional heavy fuel oil, vessels may face reduced sailing autonomy or require larger onboard storage volumes. Locating green bunkering infrastructure in Panama could therefore help reduce range constraints, allow vessels to refuel at an intermediate point, and serve multiple route pairs through a single shared infrastructure platform. Compared with a corridor model in which only the origin and destination ports provide fuel, a Panama-based hub could improve scalability, distribute investment risk across several connected routes, and strengthen the case for a broader network-based GSC strategy.

Table 5. Top 10 routes with the highest energy demand for routes connected to Panama.

Port Origin	Country Origin	Port Destination	Country Destination	Avg. Energy per year (GWh)	%
Busan and Masan	South Korea	Savannah	USA	2,240.7	3.8
Busan and Masan	South Korea	Baytown	USA	1,170.3	2.0
Yantian	China	Savannah	USA	675.2	1.2
Masan	South Korea	Kingston	Jamaica	627.7	1.0
Xiamen	China	Savannah	USA	530.0	0.9
Beaumont	USA	Lianyungang	China	504.6	0.8
Masan	South Korea	Mobile	USA	456.6	0.8
Charleston	USA	Tokyo	Japan	439.6	0.7
Yantian	China	Baytown	USA	427.9	0.7
Charleston	USA	Masan	South Korea	420.6	0.7

Source: Developed by authors.

A broader analysis of the regional energy-demand network provides a clearer basis for defining a network-based corridor configuration. By examining port calls and the associated energy demand of vessels travelling to and from ports in the Americas, the analysis can assess whether Panama has a strong case for positioning itself as a green bunkering hub, or whether alternative-fuel infrastructure should be prioritized elsewhere in the regional network. Building on the previous findings, which show that container shipping represents the segment with the highest energy demand and the clearest decarbonization potential, the following analysis focuses on container vessel movements.

5.3 Network Analysis of Container Shipping Routes to the Americas

For this analysis we consider each port to be a node across a network and every edge (i.e. arc connecting the nodes) will have the weight of the average energy sum for a year, using a sample from 2019 to 2024. All container port calls in the Americas is considered. On average the network includes **127,228 GWh** of energy across, it is defined by **364 nodes and 7,630 edges.**

In terms of degree centrality, which indicates how well connected a node is within the network, Figure 8 shows that Panama, particularly the Pacifc cluster of Balboa and Rodman/PSA, dominates container shipping routes in the Americas. Savannah, on the U.S. Atlantic coast, also shows strong connectivity. Ports such as Caucedo in the Dominican Republic offer flexibility as intermediate stops on longer routes, including services toward Europe. Santos in Brazil also represents a relevant case for GSC development, particularly because of Brazil's capacity to expand renewable energy and its position as the world's second-largest producer of liquid biofuels after the United States.[16] From Panama's perspective, given the limited prospects for producing large volumes of alternative fuels domestically, it may be strategically sensible to bring alternative fuels closer to the areas where maritime energy demand is concentrated and work as green bunkering hub.

Figure 8. Top 10 ports by degree centrality in the Americas container energy-demand network. The labels Cristobal and Balboa represent the ports at the Atlantic and Pacific entrances of the Panama Canal, respectively.

Source: Developed by authors.

Eigenvector centrality measures not only how many connections a port has, but also how important its connected ports are within the wider network. In this analysis, a port has higher eigenvector centrality when it is strongly connected to other highly connected or high-demand ports, making it a useful indicator of potential green bunkering hubs.

When edges are weighted by energy demand and eigenvector centrality is used, the results shown in Figure 9 indicate that Balboa remains an important node in the network, with a level of centrality comparable to the Masan/Busan port cluster in South Korea. This suggests that a network-based corridor serving routes to the Americas with alternative fuels could be supported by both Masan/Busan and Panama, with Balboa acting as a mid-route refuelling point for onward connections across the region. The results also suggest that a high-potential GSC could initially focus on container vessels operating between these port clusters.

Figure 9. Top ports by eigenvector centrality in the Americas container energy-demand network. The label Balboa represents the ports at the Pacific entrances of the Panama Canal.

Source: Developed by authors. Note: Network links are weighted by the average annual energy demand of container vessel movements between ports from 2019 to 2024.

Further evidence supporting **Panama's potential role as a green bunkering hub** is provided by Cerda et al.[12] The study develops an integrated cost-optimization model that jointly determines which container vessels should be retrofitted, where bunkering facilities should be located, how much capacity should be installed, and whether the green ammonia should be supplied from Magallanes or Antofagasta, a Chile as a supplier centred perspective. Under the baseline scenario in which Chile supplies the regional market, carbon prices of USD 220/tCO_2 or less do not trigger investment. At USD 230/tCO_2, the model selects eight bunkering facilities and 145 vessel retrofits, while at USD 320/tCO_2 it selects 66 facilities and 1,647 retrofitted vessels, with green ammonia supplying approximately 92% of the network's potential energy demand. Balboa shows up as a persistent strategic location because of the concentration of energy demand associated with the Panama Canal and long-distance services arriving from Asia. Except at the initial investment threshold, approximately 20% of the ammonia demand is supplied through Balboa in the scenarios analysed. The results also show that Magallanes is selected before Antofagasta because of its lower assumed production cost, with Antofagasta entering only after Magallanes reaches its supply-capacity limit. From a strategic perspective, early agreements between Chilean fuel producers and Panamanian actors for ammonia storage, handling, and bunkering in Balboa could provide Chile with access to concentrated maritime demand while strengthening Panama's position as a regional distribution hub. The results highlight some important conclusions. First, the use of Market Based Measures (i.e. IMO Net Zero Framework) is necessary to trigger the transition. Second, the transition from LNG as a fuel to green fuels only triggers at high levels of CO_2 taxation. Finally, Chile apparent distance from the energy demand dense route could be compensated by early agreements with Panama.

5.4 Interpretation for Green Shipping Corridor Planning

The evidence presented in this section suggests that corridor planning for Panama should not rely only on identifying the single route with the highest energy demand. High energy demand is an important first filter because it shows where a future market for alternative fuels may exist, but it does not automatically identify the most feasible GSC candidate. A strong corridor candidate should also combine operational regularity, repeated vessel services, partner availability, port readiness, fuel-supply feasibility, safety capacity, and institutional alignment. From this perspective, the results point toward a network-based corridor strategy in which Panama, and particularly Balboa, functions as a mid-route refuelling and coordination hub rather than only as one end of a point-to-point corridor.

The port-call analysis shows that Panama-connected shipping is highly diversified. Although the Panama Canal accounts for the largest share of vessel visits, the immediate previous and next ports are distributed across more than one thousand port connections. This weakens the case for a narrow strategy based only on one bilateral port pair. Instead, it supports a broader approach in which Panama coordinates several route segments and serves different markets simultaneously. The predominance of container vessels in port visits further strengthens the case for starting with container shipping, because this segment combines high traffic volumes, more regular services, and clearer opportunities for long-term coordination among carriers, ports, fuel suppliers, and cargo interests.

The energy demand results refine this interpretation. At the country level, the United States represents the largest concentration of energy demand associated with Panama-connected routes, while South Korea, Japan, China, Mexico, and Ecuador also appear as relevant markets. At the port level, however, the strongest demand is concentrated in specific Asian and North American port connections, especially the Busan/Masan cluster in South Korea, several Chinese ports, Yokohama, Savannah, and Antwerp. This difference between the country-level and port-level results is important: it shows that corridor selection should not be based only on national trading relationships, but also on the actual port clusters and vessel movements where energy demand is concentrated.

The network analysis provides further evidence for this approach. Degree centrality indicates that Balboa is one of the most connected container-shipping nodes in the Americas, while the energy-weighted eigenvector centrality analysis shows that Balboa remains important when the strength of connected routes is measured by energy demand. Its centrality is comparable to the Masan/Busan cluster, suggesting that a corridor linking Asia, Panama, and onward services in the Americas could have stronger strategic value than a single isolated port-pair initiative. In this configuration, Panama could support several connected services through shared bunkering, monitoring, coordination, and emissions-accounting infrastructure.

This interpretation is also consistent with the ammonia bunkering optimization results. The model shows that Balboa emerges as a persistent strategic location when green ammonia is considered for container shipping in the Americas, especially because of the concentration of energy demand associated with the Panama Canal and long-distance services arriving from Asia. The results suggest that Panama does not need to be the main producer of alternative fuels to play a central role. Its strongest opportunity may be to connect external green-fuel supply, such as potential production in Chile or other regional suppliers, with concentrated maritime demand around the Canal.

For practical GSC planning, the evidence therefore points to three priorities. First, Panama should use energy demand and port-call frequency as screening indicators to identify where the largest potential fuel markets exist. Second, it should prioritize routes and port clusters where container services are regular enough to support long-term fuel offtake, bunkering investment, and emissions monitoring. Third, it should evaluate corridor candidates not only as point-to-point routes, but as parts of a wider network in which Balboa and the Panama Canal can serve as a shared refuelling, coordination, and data platform. This approach would allow Panama to reduce the risk of investing around a single route while increasing the value of alternative-fuel infrastructure for multiple services across the Americas.

6

Route and Partner Identification from the Panama Perspective

6.1 Selection Criteria

While the quantitative analysis gives an idea of potential first partners, the identification of priority GSC should follow a structured multi-criteria assessment framework that integrates technical, economic, environmental, and strategic considerations. From Panama's perspective, the objective is not only to identify routes with the greatest decarbonization potential, but also those that strengthen the country's role as a global maritime hub, facilitate investment in alternative fuels, and enhance the resilience and competitiveness of the Panama Canal and its logistics ecosystem. The proposed framework evaluates candidate corridors using the following criteria.

- **Total energy demand.**

Priority should be given to routes with high aggregate energy demand, as these represent the greatest opportunity for reducing fossil fuel consumption and creating a viable market for low- and zero-carbon marine fuels. Estimating energy demand through AIS-derived vessel activity allows the identification of routes where sufficient fuel demand exists to justify investments in bunkering infrastructure and fuel production. High-demand corridors also improve the commercial viability of future fuel supply chains by increasing economies of scale.

- **Emissions reduction potential.**

Routes should be evaluated according to their potential contribution to GHG emissions reduction. This criterion considers total CO_2 equivalent emissions, fuel consumption intensity, vessel characteristics, and operational profiles. Corridors serving high emission vessel segments such as large container ships, liquified gas tankers, or bulk carriers offer greater opportunities to achieve measurable climate benefits and support national and international decarbonization objectives.

- **Frequency and regularity of voyages.**

GSCs are more likely to succeed when vessels operate on predictable and recurrent schedules. Frequent and regular services enable stable fuel demand, improve infrastructure utilization, and reduce commercial uncertainty. Scheduled liner services, particularly in container shipping, generally provide more favorable conditions for corridor implementation than irregular tramp shipping because fuel suppliers and ports can better anticipate operational requirements.

- **Container or cargo market relevance.**

Candidate routes should represent economically significant trade flows for Panama. Priority should be given to corridors supporting major container services, high-value cargoes, strategic exports and imports, or commodities that generate sustained maritime traffic. Since container shipping accounts for a large share of Panama Canal transits and operates on fixed schedules, it constitutes an attractive initial market for corridor development. Nevertheless, bulk, tanker, LNG, LPG, and vehicle carrier segments should also be evaluated where substantial energy demand exists.

- **Presence of repeat operators.**

The participation of shipping companies that regularly operate along the same routes is essential for establishing long-term commercial partnerships. Repeat operators facilitate coordinated investments in vessels, fuel procurement, bunkering infrastructure, and emissions reporting.

Existing collaborations among shipowners, cargo owners, fuel suppliers, and ports reduce implementation risks and increase the likelihood of successful corridor deployment.

- **Port readiness.**

Both origin and destination ports should possess or demonstrate the capacity to develop the infrastructure necessary to support alternative marine fuels. This includes storage facilities, bunkering systems, safety management procedures, emergency response capabilities, regulatory approvals, and digital monitoring systems. Port readiness should also consider available land, connectivity with logistics infrastructure, and institutional capacity to implement new technologies.

- **Potential for alternative fuel supply.**

An essential criterion is the ability to establish reliable, scalable, and economically competitive supply chains for future marine fuels. The assessment should consider proximity to renewable energy resources, existing fuel terminals, industrial clusters, import and export capabilities, and opportunities for local production of alternative fuels. Corridors connected to regions with emerging clean-fuel production projects offer significant long-term advantages.

- **Strategic relationship with Panama.**

Routes should reinforce Panama's strategic role within global maritime trade. Priority should be given to trade lanes that depend heavily on Panama Canal transits, connect with Panamanian ports, or strengthen the country's logistics platform. Candidate partners should also demonstrate strong institutional relationships with Panamanian maritime stakeholders, including the Panama Canal Authority, ports, shipping companies, logistics operators, and government agencies. This criterion ensures that corridor development contributes directly to Panama's economic competitiveness and maritime leadership.

- **Regional development value.**

GSCs should generate benefits that extend beyond emissions reductions. The evaluation should consider opportunities to stimulate industrial development, attract investment, create high-skilled employment, promote technology transfer, strengthen regional supply chains, and enhance Latin America's participation in the global energy transition. Corridors that support broader economic diversification and regional cooperation should receive higher priority.

- **Alignment with international funding or policy initiatives.**

Finally, candidate corridors should be assessed according to their compatibility with international climate policies, financing mechanisms, and collaborative initiatives. Alignment with the IMO GHG Strategy, the Clydebank Declaration, the Green Shipping Challenge, multilateral development bank programs, and climate finance opportunities can significantly improve access to technical assistance, concessional financing, and international partnerships. Selecting corridors that support global decarbonization priorities increases the probability of successful implementation and long-term sustainability.

These criteria should be integrated into a **Multi-Criteria Decision Analysis (MCDA)** framework,[17] where each candidate route receives a weighted score based on quantitative indicators (e.g., annual energy demand, CO_2 emissions, voyage frequency) and qualitative assessments (e.g., policy alignment, port readiness, strategic importance). The framework enables transparent comparison among potential corridors and supports evidence-based decision-making for prioritizing investments and partnerships.

From Panama's perspective, the highest-priority corridors will be those that combine **high energy demand, significant emissions reduction potential, regular vessel traffic, mature port infrastructure, strong alternative fuel opportunities, and strategic value for the Panama Canal and the national logistics sector**. Such corridors will not only accelerate maritime decarbonization but also position Panama as a leading regional platform for clean marine fuels, sustainable shipping services, and climate-resilient maritime trade.

6.2 Partner Types

The successful development of a GSC through Panama requires a broad coalition of public institutions, private-sector stakeholders, research organizations, and international partners. Because GSCs involve simultaneous changes in vessel technology, fuel supply, port infrastructure, regulatory frameworks, and commercial arrangements, no single organization can implement them independently. Instead, they depend on coordinated action across the entire maritime value chain, where each stakeholder contributes distinct technical, financial, operational, and policy capabilities.

- **Panama Canal Authority.**

The Panama Canal Authority (ACP) would play a central coordinating role in the development of a GSC. As the administrator of one of the world's most strategic maritime passages, the ACP possesses extensive operational data, centrality of authority[2], vessel traffic information, and technical expertise that can support corridor planning and implementation. The Authority can facilitate dialogue among international shipping companies, ports, and governments, while incorporating decarbonization objectives into Canal operations, transit services, and long-term sustainability strategies. In addition, the ACP can provide critical information for emissions estimation, energy demand assessments, and climate risk analyses associated with Canal operations.

- **Port operators.**

Port operators including bunkering terminals, container terminals, bulk terminals, and logistics facilities located on both the Atlantic and Pacific coasts would be responsible for developing the infrastructure necessary to support alternative marine fuels. Their role includes investments in fuel storage, bunkering systems, safety equipment, emergency response capabilities, digital monitoring systems, and vessel servicing facilities. Ports also serve as innovation hubs where new operational procedures and technologies can be demonstrated before broader deployment.

- **Shipping lines.**

Shipping companies are among the primary actors in any green shipping corridor because they operate the vessels that will transition to low- and zero-carbon fuels. Their participation involves investing in new vessels or retrofitting existing fleets, securing long-term fuel supply agreements, sharing operational data, and collaborating on pilot projects. Regular shipping services are particularly important because predictable vessel schedules provide the demand certainty needed to justify investments in alternative fuel infrastructure.

- **Fuel suppliers.**

Fuel suppliers are responsible for ensuring the availability, storage, distribution, and delivery of alternative marine fuels. They must develop reliable bunkering operations that comply with international safety standards while maintaining fuel quality and supply reliability. Their collaboration with ports, shipping companies, and energy producers is essential for establishing commercially viable fuel supply chains.

- **Energy producers.**

Energy producers including renewable energy developers and hydrogen producers represent the upstream component of the corridor. Their investments determine the long-term availability and competitiveness of green marine fuels such as LNG, methanol and ammonia. Collaboration between energy producers and the maritime sector is fundamental for aligning production capacity with future shipping demand.

- **Cargo owners.**

Cargo owners play an increasingly important role in maritime decarbonization because their procurement decisions influence shipping markets. Large importers, exporters, manufacturers, and retailers can stimulate demand for low-carbon shipping by incorporating emissions reduction requirements into freight contracts and sustainability commitments. Long-term cargo commitments help reduce commercial risk and encourage investment in green vessels and fuel infrastructure.

- **Maritime Authority of Panama.**

The Maritime Authority of Panama (AMP) is responsible for establishing the regulatory framework that enables the safe and efficient deployment of alternative marine fuels. Its responsibilities include vessel certification, compliance with international maritime conventions, implementation of International IMO regulations, port state control, flag state administration, and maritime safety oversight. The AMP also plays an important role in coordinating national maritime policies, including the National Action Plan that supports shipping decarbonization.

- **National Secretariat of Energy.**

The National Secretariat of Energy is responsible for coordinating national energy policy and facilitating the integration of alternative fuels into Panama's broader energy transition. Its participation includes evaluating future energy demand from shipping, supporting investments in renewable energy generation, promoting hydrogen and synthetic fuel development, coordinating alliances with alternative fuel providers at a regional level, and coordinating policies that connect the maritime sector with national energy planning.

- **Environmental authorities.**

Environmental institutions including the Ministry of Environment (MiAmbiente) provide oversight of environmental regulations, climate policy, environmental impact assessments, and national greenhouse gas mitigation strategies. These agencies ensure that corridor development is consistent with Panama's climate commitments, biodiversity protection objectives, and environmental permitting requirements while supporting climate adaptation measures that enhance the resilience of maritime infrastructure.

- **Academic and training institutions.**

Universities, research centers, and maritime training institutions contribute to scientific knowledge, technical innovation, and workforce development. They support the project through emissions modeling, climate risk assessments, fuel technology research, economic analyses, and policy evaluation. In addition, they develop specialized education and certification programs to prepare seafarers, engineers, port personnel, regulators, and emergency responders for the safe management of alternative fuels and emerging maritime technologies.

- **International cooperation agencies.**

International cooperation agencies play a critical role in providing technical expertise, policy guidance, capacity building, and financial resources to accelerate the development of GSCs. Organizations such as the **IMO** support the development of international regulations, technical standards, and capacity-building initiatives for maritime decarbonization. The **Global Maritime Forum** and the **MMMC** contribute technical knowledge, analytical methodologies, and stakeholder engagement strategies for corridor planning and implementation. Multilateral development banks including the **World Bank**, the **Inter-American Development Bank (IDB)**, and the **Development Bank of Latin America and the Caribbean (CAF)** can provide financing and technical assistance for port modernization, alternative fuel infrastructure, and climate-resilient logistics systems.

A particularly important partner for Panama is the **European Union's Global Gateway GSCs initiative**, which seeks to supports the development of GSCs through technical assistance, stakeholder partnerships, feasibility studies, policy dialogue, and the mobilization of public and private investment. Its objective is to accelerate maritime decarbonization by connecting European ports with strategic global partners, strengthening sustainable fuel supply chains, enhancing port infrastructure, and promoting equitable access to low carbon shipping technologies.

Integrated Partnership Approach

The effectiveness of a Green Shipping Corridor ultimately depends on coordinated governance across the entire maritime value chain. Rather than operating independently, these partners must collaborate to align investments, harmonize regulations, share operational data, develop fuel supply chains, establish safety standards, and create commercially viable business models. Such a collaborative approach reduces investment risk, accelerates technology deployment, and enhances Panama's ability to position itself as a regional hub for sustainable maritime transport and clean marine fuel distribution.

7

Climate Risk and Panama Canal Operations

7.1 Why Climate Risk Matters

Climate risk is central to Panama's role in global maritime trade because the Panama Canal depends on freshwater availability to operate its lock system. Periods of low rainfall and drought reduce water levels in Gatun Lake, which can limit vessel drafts, reduce daily transit capacity, increase waiting times, and affect the reliability of the Canal as a global trade route. For this reason, climate risk is an operational, commercial, and strategic issue for Panama's maritime sector.

One of the clearest examples of this vulnerability is the influence of ENSO. During El Niño conditions, Panama can experience drier-than-normal periods that place additional pressure on the Canal watershed. Because the same water system supports both Canal operations and public water supply, managing climate risk requires balancing the reliability of international shipping with the water needs of the population. The Panama Canal Authority's efforts to explore additional water-source solutions therefore send an important signal: **long-term Canal competitiveness depends on responsible water management, operational adaptation, and climate resilience.**

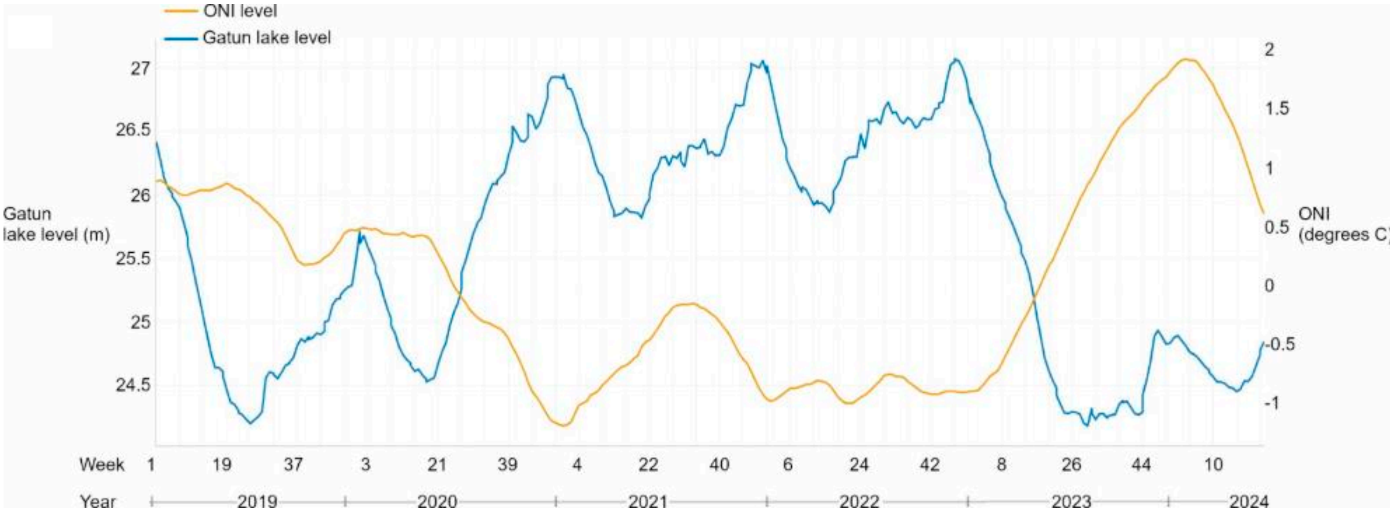
Although climate literature does not provide a single consensus on how climate change will affect future ENSO behaviour (refer to Cai et al.[18]f or an analysis on the topic), the evidence suggests that climate variability and long-term climate change can interact in ways that intensify operational risk. Stronger or more frequent drought conditions would affect Canal performance, vessel scheduling, cargo reliability, and emissions, especially if ships need to wait longer, sail at inefficient speeds, or consider alternative routes. This makes the connection between maritime decarbonization and climate adaptation especially important for Panama. A GSC strategy should therefore not focus only on alternative fuels and emissions reduction; it should also strengthen the resilience of Canal operations under future climate uncertainty. From Panama's perspective, this is consistent with the broader case for a green bunkering hub, because the country's strategic value depends on maintaining reliable Canal operations while serving a large and consistent concentration of maritime energy demand associated with transits. Next sections build on this argument by presenting the evidence base that links climate variability, ENSO, water availability, and Canal operations. It combines results derived from this project, including AIS operational indicators, Gatun Lake water levels, restriction records, and CWT estimates, with findings from the existing literature on ENSO, drought, hydrology, and maritime reliability.

7.2 ENSO and Canal constraints

ENSO and Gatun Lake, the Panama Canal's main water reservoir, have a marked relationship, as illustrated in Figure 10. In this section, ENSO conditions are measured using the Oceanic Niño Index (ONI), a standard indicator that tracks sea-surface temperature anomalies in the central equatorial Pacific and is commonly used to identify El Niño and La Niña phases. Positive ONI values (higher than 0.5) indicate warmer-than-normal Pacific conditions associated with El Niño, while negative values (-0.5) indicate La Niña conditions. Castrellón et al.[19] observed a -0.36 Pearson correlation between the ENSO index and Gatun Lake levels, and -0.64 after the expansion of the

Panama Canal. More recently, Fuentes and Munim[8] identified an even stronger negative correlation of -0.82 for the most recent events.

Figure 10. Gatun lake and ONI levels from 2019 to 2024.

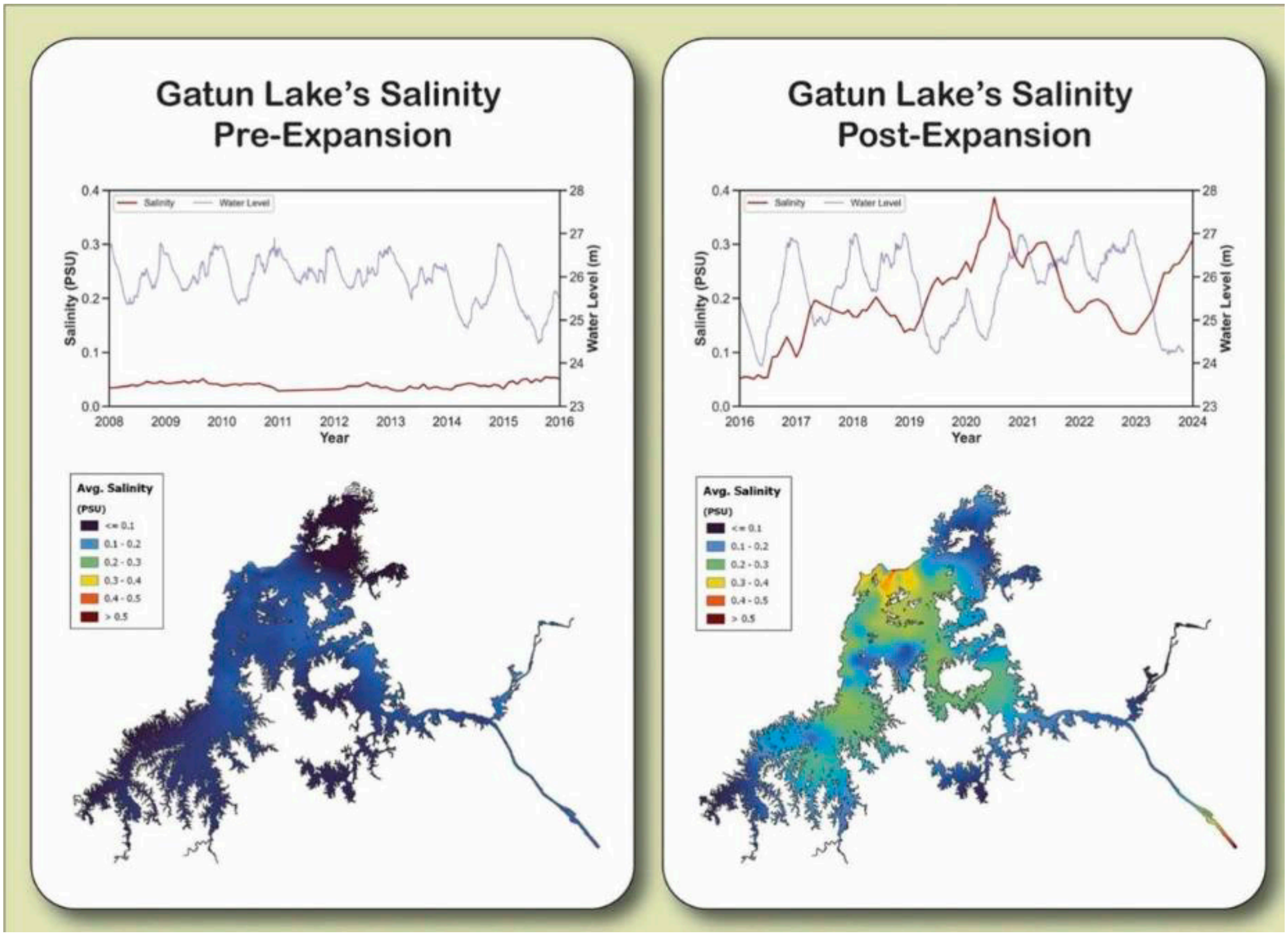


Source: Fuentes and Munim.[8]

However, reduced water availability is not the only concern associated with climate variability. Low lake levels also interact with a longer-term water-quality challenge: the increasing salinity of Gatun Lake.

Castrellón et al.[19] provide evidence of a substantial change in Gatun Lake's salinity following the Panama Canal expansion as illustrated in Figure 11. Before the expansion, average salinity in the lake was below 0.05 Practical Salinity Units (PSU). After the expansion, the average increased to approximately 0.21 PSU, representing an increase of more than four times. The highest values were observed close to the Neo-Panamax locks, averaging approximately 0.6 PSU near the Agua Clara locks on the Atlantic side and 0.5 PSU near the Cocolí locks on the Pacific side. Salinity in the Culebra Cut averaged approximately 0.1 PSU after the expansion.

Figure 11. Gatun lake salinity pre and post Panama Canal expansion.



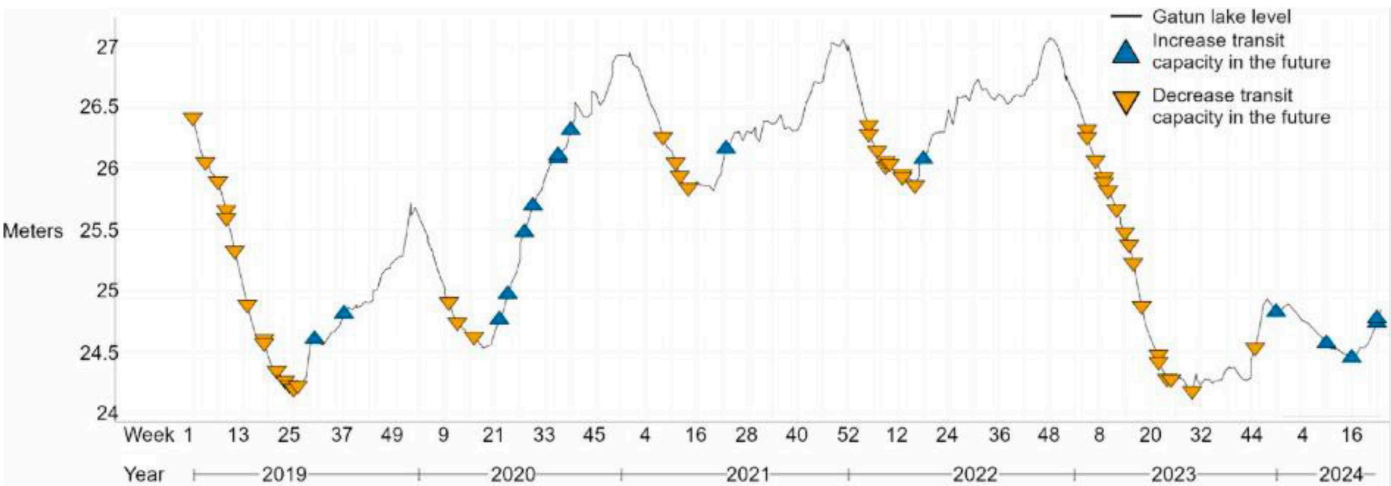
Source: Castrellón et al.[19]

The results also indicate that salinity varies with hydrological conditions. Average salinity was weakly and negatively correlated with Gatun Lake water levels, with changes in salinity generally occurring one to two months after changes in lake level. In June 2020, average salinity reached a peak of 0.39 ± 0.19 PSU, one month after the lake level declined to 24.5 metres, its second-lowest level during the previous decade. The study also identified a statistically significant increasing salinity trend during post-expansion El Niño periods, although caution is needed when generalising these results, as salinity peaks may occur after an El Niño event has ended and wetter conditions have begun. Higher salinity can also make drinking-water treatment more difficult.

7.3 Operational Implications

Building on the evidence reported by Fuentes and Munim[8], Figure 12 shows how ENSO disruption is translated into operational management decisions at the Panama Canal. As Gatun Lake levels decline, the Panama Canal Authority tends to issue advance notices that prepare users for lower operational capacity, either through reduced maximum allowable draughts or limits on the number of daily transits. The timing of these announcements indicates that restrictions are not reactive measures implemented once water levels are already low. Instead, they form part of a forward-looking adjustment process that gives shipping lines, agents, and booked vessels time to revise transit plans. This is particularly visible during the low-water episodes of 2019 and 2023, when communication on capacity reductions became more frequent as lake levels moved closer to critical thresholds. A review of historical restriction records further indicates an asymmetric pattern in PCA communication: reductions in capacity are commonly announced several weeks before implementation, often around four to six weeks in advance, whereas increases in capacity following water-level recovery are generally communicated much closer to the effective date, frequently within the same week. This asymmetry suggests that uncertainty management is stricter when the Canal is moving into a constrained operating regime than when restrictions are being relaxed.

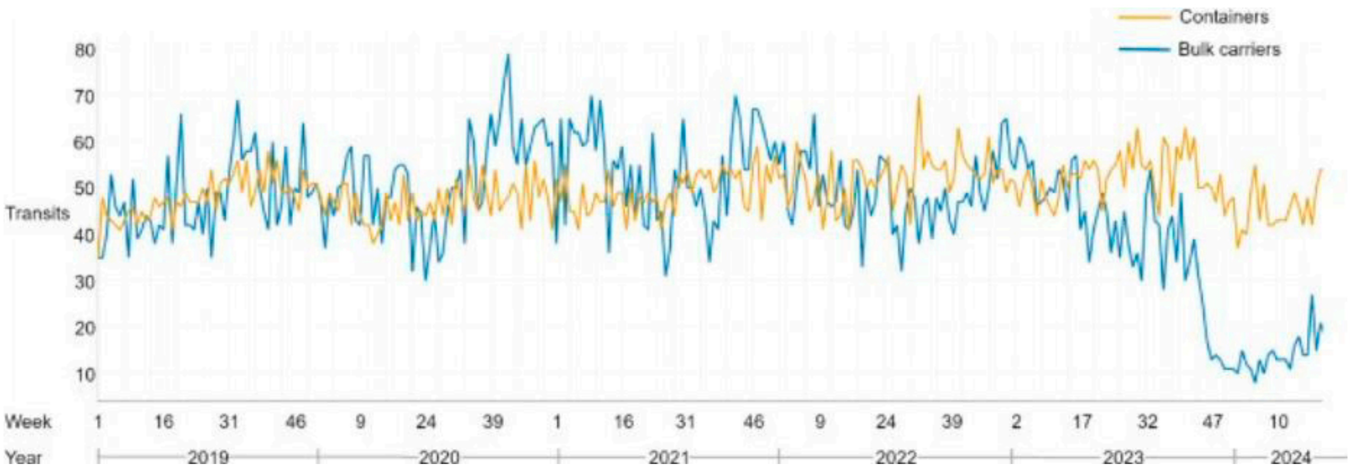
Figure 12. Gatun lake water level and restriction information published by the PCA.



Source: Fuentes and Munim.[8]

These restrictions also matter from the shipowner's perspective because they affect both the cost and predictability of using the Panama Canal. As shown in Figure 13, bulk-carrier transits declined during El Niño restriction periods, while container-vessel traffic remained comparatively stable. They interpret this difference as a reflection of segment-specific operating models. Container services typically operate on fixed schedules and carry more time-sensitive cargo, making them more likely to secure reservations as part of normal voyage planning. Bulk carriers, by contrast, are generally more sensitive to transit costs and operational uncertainty and may delay or reroute when the cost of obtaining a reservation exceeds the economic benefit of using the Canal. The shift toward mandatory reservations during the 2023 drought therefore did not affect all shipping segments equally and may have favoured operators with greater ability to pay for priority access. Using the fixed-effects results reported in Table 6, Fuentes and Munim[8] estimate that a one-unit increase in the ONI, lagged by six weeks, is associated with a reduction of approximately 3.6 bulk-carrier transits, compared with a much smaller reduction of approximately 0.3 container-vessel transits.

Figure 13. Number of transits in the PC for container and bulk carrier segments.



Source: Fuentes and Munim.[8]

Table 6. Fixed effects regression result on number of transits.

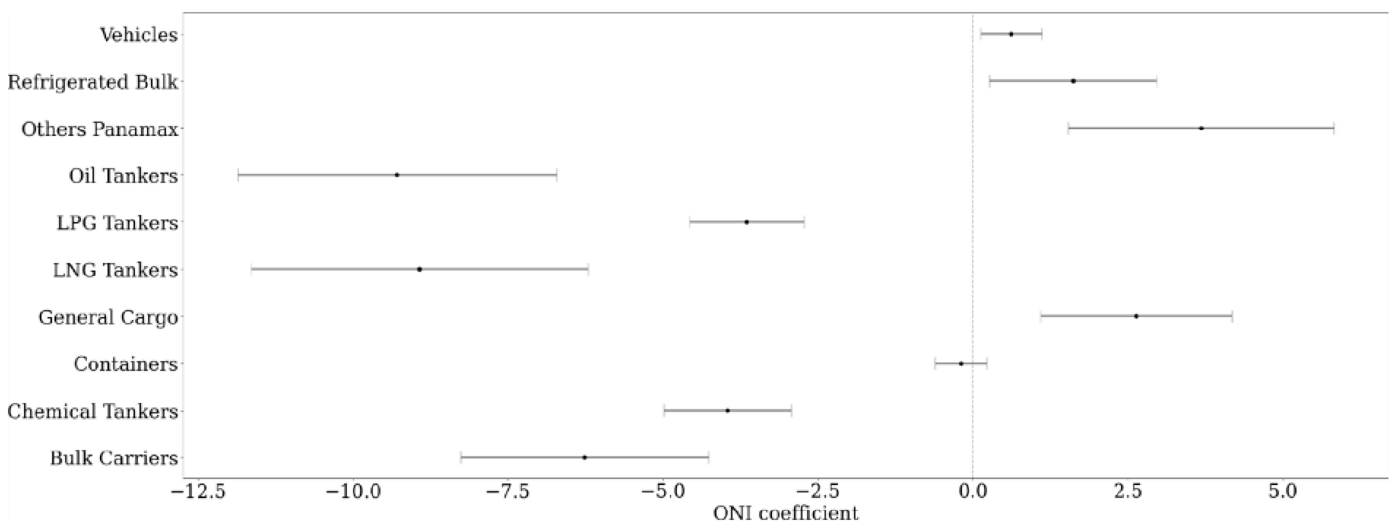
Variables	Number of transits			
	Bulk carriers	**Containers**	**LNG tankers**	**Oil tankers**
ONI 6 weeks lag	−3.563***	−0.273***	−0.110	0.0951
	(0.232)	(0.086)	(0.157)	(0.090)
NeoPanamax transit	−14.922***	4.775***	2.678***	−1.288***
	(0.310)	(0.144)	(0.129)	(0.154)
Northbound transit	3.149***	2.694***	−0.916***	−0.518***
	(0.335)	(0.142)	(0.287)	(0.154)
Constant	16.711***	8.150***	2.648***	4.996***
	(0.199)	(0.102)	(0.129)	(0.113)
Monthly fixed effects	Yes	Yes	Yes	Yes
R-squared	0.609	0.497	0.157	0.100
Observations	1083	1530	271	557
df	14	14	14	14

*Source: Fuentes and Munim.[8] Notes: Clustered standard errors. Significance levels: * p<0.1; ** p<0.05; ***p<0.01*

These decisions can produce wider economic effects when disruptions occur simultaneously at several maritime chokepoints. The *Review of Maritime Transport 2024* by UNCTAD[20] estimates that the combined disruptions affecting the Panama Canal and the Red Sea–Suez route reduced global real GDP by approximately 0.06 per cent. The estimated effects were greater for least developed countries and Small Island Developing States, reaching approximately 0.07 and 0.11 per cent, respectively. These estimates represent the compounded consequences of climate-related constraints in Panama and Houthi-related disruptions in the Red Sea. The diversion of bulk carriers from the Panama Canal may nevertheless have contributed to these effects by increasing sailing distances, fuel consumption, freight costs and delivery times, particularly for vulnerable economies dependent on imported food, energy and raw materials.

The results also show that climate-related restrictions can affect operational efficiency, not only the number of transits. As shown in Figure 14, ENSO affects CET, defined as the total time vessels spend waiting for and completing a Canal transit. For bulk carriers, Fuentes and Munim[8] found that a one-unit increase in the ONI, lagged by six weeks, is associated with an average reduction of about six hours in CWT. Although this result may seem counterintuitive because drought conditions reduce capacity, it suggests that stricter reservation rules and tighter scheduling can reduce inefficient waiting behaviour. Under normal conditions, some vessels may sail faster than necessary to arrive early, only to wait at anchorage before transit. This “sail fast, then wait” pattern increases fuel consumption and emissions without improving service reliability. Under a more constrained and reservation-based operating regime, vessels have stronger incentives to align their sailing speed with their expected transit slot, reducing unnecessary waiting time and potentially lowering emissions, closer to a JIT arrival strategy.

Figure 14. Effect on ENSO into the Canal Water Times per vessel segment.



Source: Fuentes and Munim.[8]

7.4 Climate Implications to GSCs

For Panama, a GSC cannot be separated from climate adaptation. The evidence presented in this section shows that ENSO-related drought conditions can reduce Gatun Lake levels, trigger draught and transit restrictions, change vessel-segment behaviour, and affect the predictability of Canal operations. These effects matter directly for corridor planning because a GSC depends not only on the availability of low-carbon fuels, but also on the reliability of the route, the confidence of shipping lines, and the ability of ports and Canal authorities to coordinate operations under changing conditions.

The first implication is that climate resilience should become part of corridor feasibility assessment. Candidate corridors connected to Panama should be evaluated not only according to energy demand, emissions reduction potential, fuel availability, and port readiness, but also according to their exposure to Canal operating restrictions during low-water periods. Routes that depend heavily on the Canal may remain attractive for GSC development because they concentrate demand and shorten voyage distances, but their long-term value depends on the ability to maintain predictable transit conditions. This means that corridor studies should include scenarios for water availability, draught limits, transit-slot availability, waiting times, and the operational response of different vessel segments.

The second implication concerns emissions. Climate-related restrictions can increase emissions if vessels experience longer waiting times, sail at inefficient speeds, or reroute through longer alternatives. At the same time, the evidence on CWT suggests that stricter scheduling and reservation systems can reduce some forms of operational inefficiency, especially the “sail fast, then wait” behaviour observed in parts of the bulk-carrier segment. This creates an important opportunity for GSC design: operational measures such as better transit-slot information, improved arrival coordination, and JIT arrival practices can become climate-adaptation and emissions-reduction tools at the same time.

The third implication is that corridor planning should recognize differences across vessel segments. Container services appear more resilient to restriction periods because they operate on fixed schedules, carry time-sensitive cargo, and are more likely to secure reservations as part of normal voyage planning. This strengthens the case for using container shipping as an initial focus for Panama-connected GSCs. Bulk carriers, by contrast, appear more sensitive to cost, uncertainty, and reservation requirements. For this segment, the corridor opportunity may lie less in immediate alternative-fuel deployment and more in operational-efficiency measures, improved scheduling, and better information sharing during constrained periods.

The fourth implication is that future fuel and bunkering investments should be designed for reliability under climate uncertainty. If Panama positions Balboa and the Canal area as a green bunkering hub, users will expect not only fuel availability but also predictable access, safe operations, and dependable coordination between bunkering, port calls, and Canal transits. This reinforces the need to integrate alternative-fuel infrastructure with digital traffic management (i.e. digital corridors), hydrological monitoring, reservation systems, emergency planning, and climate-risk communication. A fuel hub that cannot offer operational reliability during drought periods would be less attractive to shipping lines, even if the fuel supply itself is technically available.

Overall, the climate-risk evidence supports a broader interpretation of GSC for Panama. A corridor should not be understood only as a low-carbon fuel route; it should be treated as a resilient maritime service system.

8

Alternative Fuels, Bunkering, and Energy Infrastructure

8.1 Alternative Fuel Options

The transition towards low- and zero-carbon shipping is expected to rely on a portfolio of alternative fuels and propulsion technologies rather than a single universal solution. Differences in vessel size, voyage length, fuel availability, infrastructure requirements, and technology readiness mean that several fuels are likely to coexist during the maritime sector's decarbonization pathway. Consequently, ports and maritime hubs should prepare for a multi-fuel future while maintaining the flexibility to accommodate evolving technologies.

Liquefied Natural Gas (LNG) has emerged as the most mature alternative fuel currently available for deep-sea shipping. Compared with conventional fuel oil, LNG can reduce tank-to-wake carbon dioxide emissions while significantly lowering sulphur oxide, particulate matter, and nitrogen oxide emissions. However, methane slip during engine operation and throughout the fuel supply chain can reduce its overall climate benefit, depending on the engine technology and operating conditions. Nevertheless, existing operational experience, commercial availability, and expanding bunkering infrastructure have positioned LNG as an important transition fuel for many shipping companies. Concerns regarding methane slip and the long-term compatibility of LNG with net-zero objectives suggest that its role is likely to be transitional rather than permanent.[21]

Methanol has attracted increasing attention because it can be handled as a liquid fuel using infrastructure that is relatively familiar to the maritime sector. This simplifies storage, transportation, and bunkering compared with gaseous fuels. When produced from renewable sources, methanol can provide substantial reductions in life-cycle greenhouse gas emissions while offering operational flexibility for both newbuild and retrofitted vessels. Its growing commercial interest indicates that methanol may become one of the earliest widely adopted low-carbon fuels, particularly along major international shipping corridors.[22] Nevertheless, its environmental performance depends strongly on the production pathway, highlighting the importance of life-cycle assessment. Renewable e-methanol and sustainable biomethanol can offer substantially greater greenhouse gas reductions than fossil-derived methanol.

Ammonia is widely regarded as one of the most promising long-term fuel options for deep-sea shipping due to its potential to eliminate carbon emissions at the point of use. Recent research demonstrates that ammonia-based propulsion systems can achieve significant greenhouse gas reductions, particularly when combined with renewable production pathways and complementary technologies such as hybrid propulsion and shore power. However, ammonia also introduces important challenges related to toxicity, crew safety, fuel handling, and emergency response. Its successful deployment therefore depends not only on technological maturity but also on comprehensive safety frameworks and dedicated port infrastructure.[23]

Hydrogen represents another zero-carbon fuel pathway when produced using renewable electricity. Its application within fuel cell systems offers high efficiency and eliminates carbon emissions during operation. Nevertheless, hydrogen currently faces significant practical constraints, including low volumetric energy density, demanding storage requirements, and high production costs. These limitations suggest that hydrogen is more likely to play an important role in specialised applications, demonstration projects, and shorter-distance operations during the early stages of adoption, while technological advances continue to improve its commercial viability.[24]

Biofuels provide an opportunity to reduce emissions using existing vessel designs and fuel supply systems. As many biofuels can be used as *drop-in fuels*, either directly or blended with conventional marine fuels, they offer an attractive option for reducing emissions without requiring extensive modifications to existing engines, onboard fuel systems, or bunkering infrastructure. However, the overall environmental performance of biofuels depends heavily on feedstock selection and production pathways. Questions surrounding sustainability, feedstock availability, and life-cycle emissions mean that biofuels are unlikely to represent a complete long-term solution but may provide an important transitional option for parts of the global fleet.[25]

Alongside alternative fuels, **electrification technologies** are becoming increasingly important components of maritime decarbonization. Shore power enables vessels to switch off auxiliary engines while berthed, substantially reducing local air pollution, noise, and, where electricity is generated from low-carbon sources, greenhouse gas emissions within port areas. As electricity grids become progressively cleaner, the environmental benefits of shore power are expected to increase further. Although shore power does not reduce emissions during navigation, it represents an effective measure for improving air quality in ports while supporting broader decarbonization objectives.[26]

Hybrid propulsion systems complement alternative fuels by integrating conventional engines with batteries, fuel cells, waste heat recovery systems, and other electrical components. Rather than replacing marine engines entirely, hybrid systems optimise energy use across different operating conditions, improving fuel efficiency while reducing emissions. Recent research demonstrates that combining hybrid propulsion with alternative fuels and shore power can deliver greater environmental benefits than implementing any individual technology in isolation. This systems-based approach is likely to become increasingly important as shipping transitions toward net-zero emissions.[27]

What the evidence makes clear is that no single fuel will dominate across all vessel types and trade routes. The choice of fuel will depend on vessel size, operating profile, voyage length, and the maturity of supply chains connected to traffic. For ports and maritime hubs, infrastructure flexibility will therefore be essential to remain competitive as the sector transitions.

8.2 Panama´s Role as a Bunkering and Distribution Hub

Panama occupies a unique position within the global maritime network. As one of the world's most important maritime chokepoints, the Panama Canal connects major east-west and north-south trade routes while facilitating thousands of vessels' transits each year. This strategic location provides Panama with opportunities that extend beyond Canal operations, positioning the country as a potential hub for future alternative fuel distribution.

Importantly, Panama does not need to become a major producer of alternative fuels to play a leading role in maritime decarbonization. Instead, its greatest advantage lies in **connecting international fuel producers with global shipping demand**. Like existing conventional bunkering operations, alternative fuels can be imported, stored, blended where appropriate, and distributed to vessels operating along major international trade lanes.

The existing maritime services ecosystem further strengthens this opportunity. Panama already possesses extensive experience in bunkering operations, ship services, logistics, pilotage, vessel traffic management, and port operations. These established capabilities provide a strong institutional and operational foundation upon which alternative fuel infrastructure can be developed. Expanding existing bunkering services to include low- and zero-carbon fuels may therefore represent a more practical pathway than creating entirely new supply chains. Importantly, few locations worldwide combine such high vessel traffic volumes, established bunkering services, and connectivity across multiple global trade routes. This unique combination provides Panama with a strong competitive advantage for supporting the future distribution of alternative marine fuels and the development of GSCs.

Research centred on Panama Canal operations also demonstrates that the Canal's location can partially offset one of the principal challenges associated with many alternative fuels, namely their lower energy density. Fuels such as ammonia, methanol, and hydrogen generally require larger storage volumes than conventional marine fuels, affecting cargo capacity and voyage planning. A strategically located **refuelling hub** within the Canal corridor reduces the distance between bunkering opportunities, allowing vessels to replenish fuel more frequently while maintaining operational flexibility. This becomes particularly important for long-haul shipping routes crossing the Pacific and Atlantic Oceans.

As international GSCs continue to emerge, Panama can position itself as a **regional distribution center** where multiple fuel pathways coexist. Rather than supporting only one technology, future bunkering facilities may need to accommodate LNG during the transition period while gradually expanding infrastructure for methanol, ammonia, shore power, and eventually hydrogen-based applications. Such flexibility would allow Panama to **respond to changing market conditions** while maintaining its competitiveness as global fuel preferences evolve.

8.3 Energy Demand and Infrastructure Matching

The development of alternative fuel infrastructure should be guided primarily by **shipping demand** rather than national fuel production potential. While considerable attention is often given to where fuels are produced, infrastructure investments are ultimately justified by where ships require fuel, how much energy they consume, and which routes they operate.

The AIS-based energy demand analyses developed within this project provide an evidence base for prioritizing future bunkering investments according to actual vessel traffic, energy demand, and route characteristics, rather than anticipated production capacity alone.

The analysis undertaken for Panama Canal operations demonstrates that vessel energy demand varies considerably depending on ship characteristics, voyage profiles, operational speeds, and time spent in ports. Consequently, infrastructure planning should be based on realistic assessments of shipping activity rather than generalized expectations of future fuel demand.

This demand-driven perspective is particularly relevant for international maritime hubs such as Panama. As vessels operating on different routes adopt different fuel pathways, ports will need to accommodate a diverse mix of fuel requirements. Some trade lanes may initially favour LNG or methanol because of their higher technological maturity, while others may gradually transition toward ammonia or hydrogen as these fuels become commercially available. Infrastructure planning should therefore remain sufficiently flexible to support multiple scenarios instead of committing prematurely to a single fuel pathway.

The concept of GSCs reinforces this approach. Corridors are not simply transport routes but integrated systems linking vessel deployment, fuel supply, port infrastructure, and regulatory coordination. Successful implementation therefore depends on matching fuel availability with actual operational demand throughout the corridor. The Panama Canal's strategic location makes it particularly suitable for this role, serving as an energy distribution node connecting numerous international trade routes and serving as a strategic energy distribution node.

Infrastructure investments should also consider **long-term scalability**. Initial facilities may focus on commercially mature fuels while incorporating designs that allow future expansion toward zero-carbon alternatives as technologies develop and demand increases. Such phased development reduces investment risk while ensuring that infrastructure remains compatible with evolving international regulations and market conditions.

8.4 Safety and Operational Requirements

The successful deployment of alternative fuels depends not only on infrastructure but also on the development of robust safety, operational, and regulatory frameworks. Many emerging marine fuels possess characteristics that differ significantly from conventional petroleum products, requiring new operational procedures throughout the maritime sector.

Each fuel introduces **specific handling requirements**. LNG requires cryogenic storage systems[21], methanol presents toxicity and fire risks[22], ammonia demands strict controls because of its toxicity[23], and hydrogen requires specialised storage and leak detection systems[24]. Consequently, ports must develop fuel-specific bunkering procedures that address safe transfer operations, emergency shutdown systems, ventilation requirements, and environmental protection measures.

Workforce development is equally important. Seafarers, terminal personnel, emergency responders, pilots, and port authorities will all require specialised training to safely manage alternative fuel operations. Training programs should extend beyond technical procedures to include emergency preparedness, risk assessment, accident response, and coordination among different stakeholders.

Emergency response capability represents another critical component of infrastructure readiness. Ports planning to supply alternative fuels should ensure that firefighting equipment, medical response systems, hazardous material procedures, and evacuation plans are adapted to the characteristics of each fuel. Close collaboration between port authorities, shipping companies, fuel suppliers, and national regulatory agencies will be essential to maintain safe operations.

International regulatory developments, including the IMO International Code of Safety for Ships using Gases or other Low-flashpoint Fuels (IGF Code), provide an important regulatory foundation for the safe implementation of alternative marine fuels.

Regulatory clarity will also influence investment decisions. International regulations continue to evolve as alternative fuels mature, making harmonised standards increasingly important for shipowners and infrastructure developers. Aligning Panama's national regulations with emerging international standards will reduce uncertainty, facilitate private-sector investment in alternative fuel infrastructure, and support the country's role as a future GSC hub.[28]

8.5 Fuel-Specific Opportunities and Barriers

The assessment undertaken in this report indicates that each alternative fuel offers distinct advantages and faces different implementation challenges. Rather than competing directly, these fuels are likely to occupy complementary roles within the maritime energy transition. Table 7 summarizes the comparison between alternative fuels and usable technologies from the Panama Canal perspective.[9]

Table 7. Alternative Fuel and Technology Comparison for the Panama Canal.

Fuel or technology	Decarbonization role	Panama requirements	Main barriers / corridor role
LNG	Potential transition fuel with lower CO2 than fuel oil, but with methane slip concerns.	Storage, bunkering procedures, and alignment with existing capabilities.	Uncertain long-term climate role; possible bridge option for selected segments.
Methanol	Moderate to high benefit depending on the production pathway.	Liquid fuel storage, bunkering procedures, safety protocols, and reliable green supply.	Green supply and price remain barriers; possible early corridor fuel.
Ammonia	High zero-carbon potential at point of use, especially for long-haul shipping.	Specialized storage, bunkering, toxicity management, crew safety, and emergency response.	Cost, readiness, and safety are key barriers; long-term zero-carbon corridor option.
Hydrogen	Zero CO2 at use if produced from renewable energy.	Compressed or cryogenic storage, strict safety systems, and specialized operations.	Storage density and cost limit early uptake; pilot or specialized applications.
Shore power	Reduces port-side emissions from auxiliary engines while vessels are berthed.	Grid capacity, port electrification, connection standards, and operational coordination.	Investment and electricity supply are barriers; useful port decarbonization component.

Source: Developed by authors.

LNG currently provides the most practical transition pathway because commercial technologies and bunkering experience already exist. However, its long-term contribution will depend on addressing methane emissions and maintaining compatibility with increasingly ambitious climate targets.

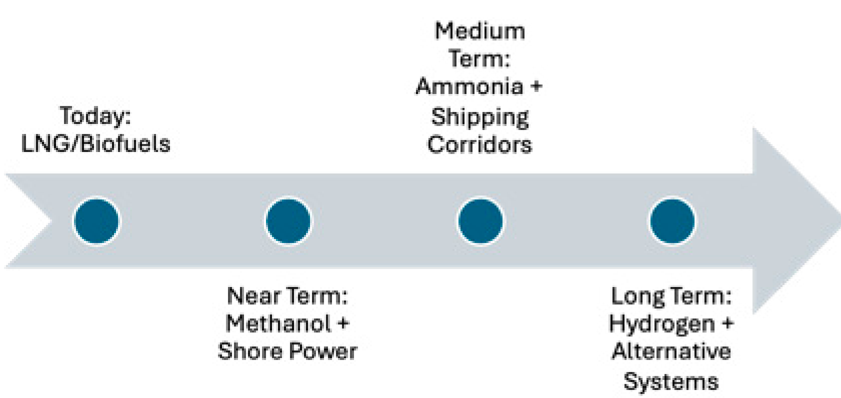
Methanol offers an attractive balance between operational simplicity and emissions reduction potential. Its liquid state simplifies storage and handling, making it a strong candidate for early deployment along international shipping corridors. Continued expansion will nevertheless depend on increasing supplies of renewable methanol at competitive prices.

Ammonia appears to offer one of the strongest long-term pathways for deep-sea decarbonization. Although substantial technical and safety challenges remain, its potential to support zero-carbon shipping makes it an important strategic fuel for future maritime corridors. Dedicated bunkering facilities, safety regulations, and workforce training will be fundamental prerequisites for widespread adoption.

Hydrogen presents significant environmental advantages but remains constrained by storage limitations, infrastructure costs, and fuel availability. Its near-term role is therefore likely to focus on pilot projects, specialised vessels, and applications where operational characteristics align with existing technological capabilities.

Shore power represents one of the most readily deployable measures for reducing emissions within ports. While it cannot replace alternative fuels during navigation, it complements broader decarbonization strategies by reducing emissions during berthing and improving local air quality. Expanding port electrification therefore provides immediate environmental benefits while supporting longer-term fuel transitions. Figure 17 indicates a representative alternative fuel transition pathway scenario for the Canal.

Figure 15. Illustrative alternative fuel transition pathway.



Source: Developed by authors.

For Panama, the sequencing of alternative fuel adoption matters as much as the choice of fuel itself. The Canal's traffic profile, dominated by long-haul container vessels, bulk carriers, and tankers operating on transoceanic routes, suggests that methanol and LNG offer the most immediate deployment opportunities, while ammonia represents the most promising long-term strategic option given its zero-carbon potential for deep-sea shipping. Rather than treating all fuels as equally viable from the outset, Panama's infrastructure planning should therefore prioritize existing bunkering capabilities in the near term while laying the regulatory and safety groundwork for ammonia and hydrogen as these fuels approach commercial readiness.

9

Workforce, Training and Institutional Capacity

9.1 Why Training Matters

Training is a precondition for maritime decarbonization. The transition to alternative fuels, digital monitoring systems, route-level emissions analytics, and more data-intensive operational management requires new competencies for seafarers, port personnel, regulators, instructors, and shore-based technical staff. In the Panamanian context, where the Canal, ports, bunkering services, and maritime logistics interact at high intensity, the workforce must be able to interpret operational data, understand fuel-specific risks, comply with evolving IMO requirements, and translate technical evidence into practical operational decisions.

9.2 Main Competency Gaps

- Alternative fuels: competency gaps remain in fuel properties, bunkering safety procedures, storage and handling requirements, fuel-specific hazards, emergency response, and the operational implications of methanol, ammonia, hydrogen, LNG, and drop-in biofuels.
- Emissions measurement and reporting: additional skills are needed in activity-based emissions estimation, interpretation of AIS-derived indicators, data quality control, carbon-intensity metrics, and alignment with IMO monitoring and reporting expectations.
- Energy efficiency: there is still a need for stronger applied knowledge in voyage optimization, speed management, just-in-time arrival concepts, hull and propulsion efficiency, auxiliary load management, and ship-port interface performance improvement.
- Digital analytics: project work showed the importance of capabilities in dashboard use, data visualization, route-level analysis, basic statistical interpretation, and digital tools that support operational and policy decisions.
- Regulatory compliance: stakeholders repeatedly pointed to limited familiarity with the practical regulatory pathway for alternative fuels, including the interaction between IMO rules, safety codes, flag-state implementation, port procedures, and future national requirements.
- Safety management: decarbonization introduces new operational risks, so competency development must cover hazard identification, safe bunkering interfaces, emergency preparedness, incident response, and the human element associated with new onboard technologies.
- Port and bunkering operations: skills gaps are also evident in terminal readiness, fuel transfer interfaces, custody and scheduling coordination, vessel-port communication, and the operational procedures needed for future low-carbon bunkering services.

9.3 Institutions and Stakeholders

Institutional capacity in Panama depends on coordinated action. UMIP and MTCC Latin America play a central role in maritime education, regional outreach, and technical dissemination; UTP contributes research capacity and analytical support; Georgia Tech Panama Foundation provides an important project and innovation platform; and the leading role of the Panama Canal Authority, port actors, shipping companies, fuel suppliers, and service providers connect training needs with real operational challenges. International academic and technical collaboration, including exchanges with institutions such as NHH and Liverpool John Moores University, is equally important because it helps align local capacity-building efforts with global debates on analytics, climate risk, alternative fuels, and maritime decarbonization; this multi-institutional perspective is also consistent with the competency and governance need.

9.4 Capacity-Building Roadmap

A practical capacity-building roadmap for Panama should combine curriculum reform, short-cycle industry training, instructor development, applied demonstration, and stronger links between evidence generation and operational decision-making. In this context, the Maritime Decarbonization Education and Training Initiative (MDETI) developed by the MTCC Latin America provides a useful structuring framework because it organizes training around the fundamentals of decarbonization, GHG emissions, global regulation and compliance, operational mitigation strategies, alternative fuels and energy sources, technological innovation, and case-based industrial applications; this orientation is aligned with the priority dimensions.

This education and capacity-building approach is consistent with the project findings that identify workforce competence development, technological integration, and regulatory alignment as priority dimensions for Panama's maritime transition toward shipping decarbonization.

- Update curricula: use MDETI as a reference framework to embed alternative fuels, lifecycle emissions concepts, digital vessel-performance monitoring, climate-risk awareness, and corridor planning topics into engineering, navigation, port, and maritime management programs.

- Develop short courses for industry: create modular training for ship operators, port personnel, surveyors, regulators, and managers focused on immediate implementation needs rather than only academic theory.

- Train instructors: establish a train-the-trainer pathway so that faculty and technical instructors can teach emerging fuel systems, data tools, safety protocols, and regulatory developments with confidence and consistency.

- Create demonstration modules: use simulators, case studies, fuel-handling scenarios, and practical demonstrations on energy efficiency, bunkering interfaces, and emissions reporting to turn concepts into operational skills.

- Link the MTCC Latin America dashboard (SEAnalytics – Shipping Energy Analytics) to education and training: integrate the project's AIS-based dashboard, route-level indicators, and emissions datasets into classroom exercises, thesis work, executive education, and applied policy laboratories.

- Coordinate with regulators and operators: institutionalize regular coordination among academia, the Panama Canal, maritime authorities, port operators, and industry so that training content evolves in line with operational needs and regulatory change.

10

Stakeholder Engagement and Knowledge Transfer

10.1 Activities Conducted

A sequenced workshop program was established through MTCC Latin America and UMIP, beginning with the July 2024 regional workshop in Panama on the role of the banking sector in maritime decarbonization, followed by the March 2025 GMN Phase II regional workshop in Panama on energy-efficiency technological solutions, which consolidated a high-level regional platform for dialogue among maritime authorities, academia, industry, banks, classification societies, and international partners.

Stakeholder engagement and knowledge transfer should be treated as an implementation mechanism for GSC development, not only as dissemination. In this project, engagement took place through a series of regional workshops, national training activities, technical exchanges, academic presentations, corridor-related meetings, and dashboard demonstrations involving maritime authorities, ports, universities, financial actors, international cooperation agencies, and industry representatives. These activities are introduced in this section because they provide practical examples of how Panama can structure future engagement: as a continuous process that connects evidence generation, technical dialogue, institutional coordination, training, and follow-up action. The objective is therefore not only to report what was done, but to show how these experiences can inform a more systematic model for translating research results into operational learning, policy discussion, investment readiness, and regional cooperation.

- First, engagement should be sequenced from awareness-raising to applied implementation. One relevant example is the set of regional workshops organized through MTCC Latin America and UMIP. These workshops included, among others, a July 2024 session in Panama on the role of the banking sector in maritime decarbonization and a March 2025 GMN Phase II regional workshop on energy-efficiency technological solutions. The first activity helped introduce the financial dimension of the transition, while the second moved the discussion toward practical mitigation options. Future engagement should follow this progression by guiding participants from general decarbonization awareness toward corridor-specific questions on fuel demand, port readiness, financing, safety, and implementation responsibilities.
- Second, knowledge transfer should combine regional consistency with adaptation to the national interest. This lesson comes from the GMN Phase II national workshops carried out in Honduras, Colombia, Guatemala, and Mexico, where common themes such as emissions reduction, energy efficiency, alternative fuels, and maritime training were adapted to different institutional and operational contexts. For Panama, this suggests that future stakeholder engagement should avoid a single generic message and instead tailor discussions to the needs of maritime authorities, ports, shipping companies, energy actors, financial institutions, universities, and training centres.
- Third, engagement should connect scientific evidence with decision-making tools. During the project, research results were presented in academic and technical settings, including international conference participation and exchanges with researchers and practitioners working on maritime decarbonization. These activities helped test the project's

assumptions, expose preliminary findings to external scrutiny, and refine the way results are communicated. Future knowledge transfer should build on this experience by linking scientific outputs more directly to practical products, including competency frameworks, training modules, dashboard indicators, and policy-oriented summaries that stakeholders can use in planning and institutional decision-making.

- Fourth, Panama should continue using high-level regional convening spaces to align corridor actors. A relevant example is the Global Gateway GSC and Hubs Regional Workshop for Latin America and the Caribbean, held at UMIP in January 2026 with the support of the European Commission and the Ministry of Foreign Affairs of Panama. This event brought together discussions on corridor development, sustainable fuels, greening ports, maritime safety, and transition finance. Future engagement should build on this experience by using Panama as a regional platform where governments, ports, fuel suppliers, financiers, classification societies, and shipping companies can jointly identify corridor opportunities and implementation barriers.
- Fifth, knowledge transfer should include applied technical sessions focused on operational capabilities. One example is the February 2026 virtual workshop on calculations and emissions tracking for container vessels, coordinated with the Panama Canal Authority and the Port Authority of the Bay of Algeciras. This session introduced practical approaches for understanding emissions monitoring, interpreting indicators, and discussing corridor-related decision-making. Similar sessions should be institutionalized around topics such as AIS-based emissions estimation, energy-demand analysis, shore-power assessment, fuel-safety procedures, and route-level corridor screening.
- Sixth, engagement should be linked to real corridor initiatives and demonstration opportunities. The Panama-Algeciras Green and Digital Maritime Corridor provides an example of how project knowledge can be connected to an active corridor process. MTCC Latin America’s participation in this initiative, including the June 2026 workshop on port electrification in Algeciras and Cádiz, shows the transition to implementation, such as terminal electrification, port readiness, and practical implementation barriers. Future activities should therefore be connected to specific corridor candidates, port-pair discussions, bunkering-readiness assessments, or pilot projects.
- Seventh, stakeholder engagement should deliberately bring together technical, financial, regulatory, and operational perspectives. Across the project, discussions included contributions from maritime researchers, Panama Canal specialists, classification societies, financial institutions, shipping companies, and academic partners such as UMIP, UTP, NHH, Liverpool John Moores University, and Georgia Tech Panama Foundation. This range of participation shows that GSC development cannot be addressed by one sector alone. Future engagement should preserve this diversity by ensuring that discussions include not only maritime and port actors, but also energy producers, banks, insurers, regulators, training institutions, cargo interests, and international cooperation agencies.
- Eighth, knowledge-transfer products should become reusable institutional assets. One example is the MDETI, which converts project knowledge into a structured learning

framework covering GHG emissions, regulation and compliance, operational mitigation, alternative fuels, technological innovation, and industrial case applications. Future outputs should follow this model by producing training materials, case studies, dashboard exercises, policy briefs, and technical guidance that remain useful after individual workshops have concluded.

- Finally, engagement should include mechanisms for feedback, documentation, and continuity. The project generated a record of knowledge exchange through dashboard presentations, emissions and efficiency sessions, technical visits, research collaboration, and official workshop reports. These outputs show the importance of documenting not only what was presented, but also what stakeholders asked, what barriers they identified, and what follow-up actions were suggested. Future activities should therefore systematically record lessons learned, stakeholder priorities, unresolved questions, and agreed next steps so that each engagement activity contributes to a cumulative learning process for Panama and the wider region.

10.2 Lessons from Stakeholders

- The stakeholder lessons presented in this section are derived from the project's workshops, technical exchanges, corridor-related meetings, dashboard demonstrations, and discussions with maritime, academic, public-sector, financial, and industry actors. These lessons should be understood as practical guidance for designing future engagement, rather than as isolated feedback from individual events.
- First, stakeholders value ambition, but they need practical evidence and implementation guidance that can be used in planning, investment, regulation, and operations. Future engagement should therefore translate high-level decarbonization goals into concrete questions: which routes are relevant, which fuels are realistic, which actors need to coordinate, what infrastructure is required, and what decisions must be taken first.
- Second, stakeholders need clear route-level evidence. Across the project activities, participants showed strong interest in emissions, energy demand, traffic density, vessel type, and port-pair information that can help identify realistic corridor partners. This suggests that future knowledge-transfer activities should avoid relying only on general statements about Panama's strategic position and should instead use route-by-route evidence to support discussion.
- Third, engagement products should use a limited set of simple indicators. Public institutions, industry representatives, and non-specialist decision-makers need information that can be understood, compared, and monitored over time. Indicators such as annual energy demand, emissions by vessel type, port-call frequency, waiting time, fuel-readiness status, and training gaps can help stakeholders move from general dialogue to measurable priorities.

- Fourth, stakeholders respond best to recommendations that are linked to operational choices. The project discussions showed that industry and public actors are more likely to engage when recommendations relate to scheduling, fuel options, terminal electrification, bunkering-readiness, safety procedures, data sharing, and training priorities. Future engagement should therefore combine strategic discussion with practical implementation pathways.
- Fifth, stronger institutional coordination is needed. The project activities showed that corridor development cannot be advanced separately by the Canal, maritime authorities, ports, academia, shipping lines, fuel suppliers, financial actors, and international partners. Future stakeholder engagement should create structured spaces where these actors can compare priorities, identify dependencies, assign responsibilities, and avoid fragmented initiatives.
- Sixth, stakeholders need clearer information about fuel readiness and regulation. A recurring concern was the uncertainty surrounding infrastructure timing, safety procedures, regulatory treatment, terminal electrification, emergency response, and the practical readiness of Panama and partner ports for alternative fuels and shore-power solutions. Knowledge transfer should therefore include technical and regulatory briefings that help stakeholders understand what is already possible, what remains uncertain, and what preparatory steps are required.
- Finally, stakeholder engagement should be treated as a learning cycle. Each workshop, technical meeting, dashboard presentation, or corridor exchange should generate a record of questions, barriers, data needs, and proposed follow-up actions. This would allow Panama to build a cumulative knowledge base for future GSC planning rather than restarting the conversation with each new initiative.

10.3 Role of Panama in Regional Dialogue

The project also shows how Panama’s role in regional dialogue should be developed. Panama should not be positioned only as a transit country or as the location of the Canal, but as a knowledge-producing, convening, and coordinating platform for maritime decarbonization in Latin America and the Caribbean. This role is supported by the combination of Canal operations, port activity, bunkering potential, AIS-based evidence, emissions monitoring, terminal electrification discussions, climate-risk analysis, and workforce development generated through the project. Future engagement should use this combination to give Panama a clearer regional function: producing evidence, hosting technical dialogue, connecting corridor actors, supporting training, and helping translate international decarbonization agendas into practical regional action.

This role should be developed through a structured regional engagement model. Panama can use platforms such as MTCC Latin America, UMIP, SEAnalytics, Global Gateway-related exchanges, GMN Phase II activities, and corridor initiatives such as the Panama-Algeciras Green and Digital Maritime Corridor to convene governments, ports, fuel suppliers, financiers, shipping companies, classification societies, training institutions, and researchers. In practical terms, this means moving from occasional participation in regional events toward a more deliberate function as a hub for evidence-based dialogue, technical capacity building, corridor screening, regulatory learning, and investment preparation. By doing so, Panama can strengthen its credibility in discussions linked to the IMO agenda, regional GSC development, and cross-regional partnerships, while ensuring that knowledge generated through the project remains useful beyond the project period.

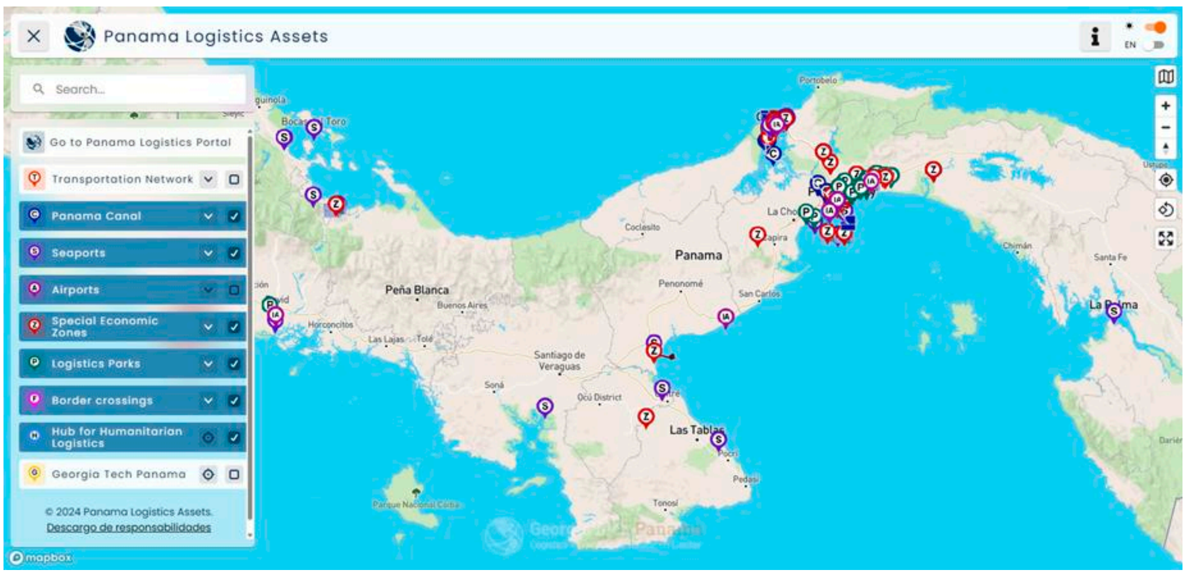
11

Main Findings

Finding 1: Panama has a strategic position for corridor development.

Panama possesses a unique comparative advantage for the development of GSCs due to the convergence of four strategic assets: the Panama Canal, a highly developed port system, one of the largest bunkering markets in the Americas, and an integrated logistics platform connecting global supply chains. The evidence from the energy-demand and network analyses further shows that this advantage is not limited to Panama's role as an origin or destination. Balboa and the Canal area can function as a mid-route refuelling, coordination, monitoring, and data platform serving multiple container services across the Americas. This is particularly relevant because Panama-connected traffic is highly diversified, with more than one thousand immediate previous or next port connections, which makes a narrow point-to-point corridor strategy less suitable than a broader network-based approach. Figure 18 shows Panama logistics asset's strategic locations.

Figure 16. Panama Logistics Assets.



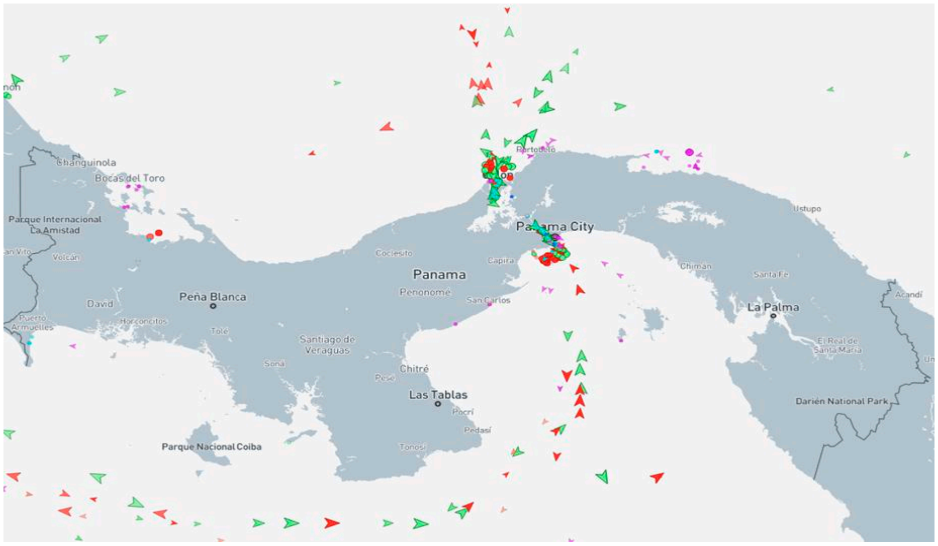
Source: Georgia Tech Panama.

These characteristics make Panama an attractive location for implementing GSCs because they enable the concentration of vessel traffic, fuel demand, and logistics services in a single geographic area. Rather than competing with individual ports, Panama can provide integrated transit, bunkering, digital services, and coordination across multiple international trade routes. Consequently, the country's competitive advantage extends beyond the Canal itself to its ability to connect shipping companies, ports, cargo owners, and fuel suppliers within a regional decarbonization ecosystem.

Finding 2: AIS-based data can support corridor selection.

The project demonstrates that AIS data provide a robust and objective basis for identifying and prioritizing potential GSCs. By integrating AIS vessel movements with ship technical characteristics and emissions estimation models, it is possible to quantify greenhouse gas emissions, fuel consumption, energy demand, voyage frequency, vessel types, and operational profiles for individual trade routes connected to Panama.

Figure 17. Vessel traffic through Panama.



Source: Marine Traffic.

This evidence-based approach allows corridor selection to move beyond qualitative assessments toward data-driven decision-making. Routes with high traffic density, significant energy demand, frequent services, and substantial emissions reduction potential can be objectively identified and compared. The results show that the United States accounts for the largest country-level share of Panama-connected energy demand, while South Korea, Japan, China, Mexico, and Ecuador also emerge as relevant markets. At the port level, the strongest energy-demand signals are concentrated in specific Asian and North American port clusters, especially Busan/Masan, Chinese ports such as Zhoushan, Qingdao, Yantian, Xiamen and Lianyungang, Yokohama, Savannah, and Antwerp. This distinction is important because corridor selection should not be based only on national trade relationships, but also on the actual port clusters and vessel movements where energy demand is concentrated. The resulting datasets provide an analytical foundation for prioritizing corridors based on measurable environmental, operational, and market indicators.

Finding 3: Panama-connected GSC planning should follow a network-based corridor strategy.

The analysis in Section 5 indicates that Panama should not rely only on a single point-to-point corridor model. Although individual routes and port pairs show high energy demand, Panama-connected shipping is distributed across a wide network of ports and services. Container vessels represent the largest share of port visits and provide the clearest starting point for GSC development because they combine high traffic volumes, more regular services, and stronger opportunities for long-term coordination among carriers, ports, fuel suppliers, and cargo interests.

The network analysis reinforces this conclusion. Balboa appears as one of the most connected container-shipping nodes in the Americas by degree centrality, and it remains strategically important when connections are weighted by energy demand using eigenvector centrality. Its centrality is comparable to the Masan/Busan cluster, suggesting that a corridor linking Asia, Panama, and onward services in the Americas may have greater strategic value than an isolated bilateral route. In this configuration, Panama can support multiple connected services through shared bunkering, monitoring, emissions-accounting, and coordination infrastructure.

Finding 4: Operational efficiency remains an important mitigation opportunity through JIT arrivals and improved scheduling.

While alternative marine fuels are expected to play a central role in achieving long-term maritime decarbonization, the project finds that significant emissions reductions can already be achieved through improvements in operational efficiency. Measures such as **JIT arrival**, optimized voyage planning, enhanced scheduling coordination, digital information sharing, and reduced anchorage waiting times enable vessels to operate at more efficient speeds, lowering fuel consumption and greenhouse gas emissions without requiring immediate changes in propulsion technology.

For the Panama Canal, these operational improvements are particularly relevant because vessel arrivals depend on transit scheduling, water availability, port operations, and global supply chain dynamics. The climate-risk analysis shows that ENSO-related restrictions can affect not only the number of transits, but also operational efficiency. In some cases, stricter reservation rules and tighter scheduling may reduce inefficient “sail fast, then wait” behaviour, especially for bulk carriers, by encouraging vessels to align sailing speed with expected transit slots. Better coordination among shipping companies, ports, and Canal operations can therefore reduce unnecessary waiting, fuel consumption, and emissions while also strengthening the Canal’s reliability under climate-related constraints.

Finding 5: Climate risk must be integrated into corridor planning and Canal reliability.

The project highlights that climate resilience should be considered a core component of GSC planning rather than a separate environmental issue. The Panama Canal depends on freshwater availability to operate its lock system, making it particularly vulnerable to changing precipitation patterns, prolonged droughts, and increasing climate variability. The evidence reviewed in Section 7 shows a strong negative relationship between ENSO conditions and Gatun Lake levels, with recent studies reporting correlations as high as -0.82 for the most recent events. Low lake levels can trigger draught restrictions, reduce daily transit capacity, increase operational uncertainty, and affect the reliability of Panama-connected trade routes.

The climate-risk findings also show that impacts vary by vessel segment. Container services appear more resilient during restriction periods because they operate on fixed schedules and are more likely to secure reservations, while bulk carriers are more sensitive to cost, uncertainty, and potential rerouting. Climate-related constraints also interact with water-quality concerns, including increasing salinity in Gatun Lake after the Canal expansion, which can create additional pressure on water management. Consequently, the feasibility and long-term reliability of GSCs connected to Panama cannot be evaluated solely on the basis of emissions or fuel availability. Corridor planning should include water availability, draught limits, transit-slot availability, waiting times, vessel-segment behaviour, and operational resilience under future climate uncertainty.

Finding 6: Alternative fuel deployment requires flexible infrastructure, safety systems, and training.

The transition to low- and zero-carbon marine fuels is not solely a technological challenge but also an institutional, regulatory, and human-capacity challenge. The deployment of fuels such as LNG, methanol, ammonia, hydrogen, sustainable biofuels, and e-fuels requires specialized storage facilities, bunkering infrastructure, safety management systems, emergency response procedures, fuel quality standards, and dedicated supply chains. The results from Section 5 suggest that Panama's strongest opportunity may be to connect external green-fuel supply with concentrated maritime demand around the Canal, rather than relying on large-scale domestic fuel production. This makes flexible, fuel-agnostic infrastructure particularly important.

The project also identifies a significant knowledge gap in Panama regarding the regulatory and safety aspects of alternative marine fuels. While the country possesses considerable expertise in conventional bunkering and maritime logistics, further capacity building is needed to understand emerging international regulations, fuel handling protocols, risk assessment methodologies, and the implementation of IMO guidelines for new marine fuels. In parallel, specialized training programs will be required for seafarers, port personnel, regulators, emergency responders, and maritime service providers to ensure the safe and efficient adoption of these technologies. Addressing these institutional and human-capacity needs will be as important as investing in physical infrastructure.

Finding 7: Panama can become a regional platform for data, training, and coordination.

Beyond its role as a maritime transit hub, Panama has the opportunity to become a regional centre for knowledge generation, digital innovation, and capacity building in sustainable shipping. Through the **GSCs in the Panama Canal under Climate Risk** project, new analytical capabilities have been developed, including AIS-based emissions estimation methodologies, energy demand assessments, climate-risk analyses, and digital visualization tools such as **SEAnalytics**. These resources provide an evidence-based platform for monitoring vessel activity, evaluating decarbonization scenarios, and supporting strategic planning for GSCs.

The project also demonstrates the value of integrating scientific research, government institutions, industry stakeholders, and academia to support maritime decarbonization. Building on these capabilities, Panama can establish itself as a regional hub for technical training, research collaboration, policy dialogue, and data sharing on sustainable shipping. Such a role would strengthen regional cooperation, support the implementation of future GSCs across Latin America and the Caribbean, and position Panama not only as a facilitator of global trade but also as a leader in maritime innovation and climate-resilient transport.

12

Recommendations

The findings of this project indicate that Panama possesses significant comparative advantages for participating in future GSCs. However, realizing these opportunities will require coordinated action across government institutions, industry stakeholders, ports, academia, and international partners. The recommendations presented below build upon the technical analyses conducted throughout the project, including AIS-based emissions estimation, energy demand assessment, climate risk evaluation, alternative fuel analysis, and stakeholder identification. Together, these recommendations provide a roadmap for strengthening Panama's readiness to support the decarbonization of international shipping while maintaining the competitiveness and resilience of the Panama Canal and the national maritime sector.

12.1 Public Institutions

The successful development of GSCs requires coordinated governance across multiple sectors, including maritime transport, energy, infrastructure, environment, and international cooperation. Because corridor development involves decisions that extend beyond individual institutions, Panama should establish a **national coordination mechanism** that brings together the ACP, AMP, the National Secretariat of Energy, MiAmbiente, port operators, academia, and representatives of the private sector. Such a mechanism would facilitate strategic planning, information exchange, policy alignment, and stakeholder coordination throughout corridor development.

The project demonstrates that AIS-based analyses provide an objective basis for identifying candidate corridors. Consequently, public institutions should adopt **route-level emissions, energy demand, vessel traffic, and operational data** as primary criteria for selecting priority trade routes and international partners. Decisions regarding future corridor development should therefore be evidence-based rather than driven solely by commercial interest or political priorities.

Maritime decarbonization should also be integrated into Panama's broader **national energy strategy**. Future planning for alternative fuels, renewable electricity generation, and associated infrastructure should explicitly consider projected demand from international shipping. Aligning maritime transport with national energy planning will improve investment efficiency, support energy diversification, and strengthen Panama's competitiveness as an emerging clean marine fuel hub.

Climate resilience should become a permanent component of corridor planning. Future feasibility studies and investment decisions should incorporate climate projections, water availability scenarios, and operational resilience assessments to ensure that corridor infrastructure remains reliable under changing environmental conditions. Given the dependence of Canal operations on freshwater resources, integrating climate adaptation into maritime planning is essential for maintaining long term operational reliability.

Public institutions should continue supporting **data transparency and digital monitoring**. The analytical capabilities developed through this project, including AIS-based emissions estimation and the SEAnalytics platform, demonstrate the value of accessible data for evidence-based policymaking. Expanding open-access maritime datasets, while respecting commercial confidentiality, will strengthen research, investment planning, and international collaboration.

12.2 Industry

Private sector participation will be fundamental to the implementation of GSCs Shipping companies, cargo owners, fuel suppliers, logistics providers, and terminal operators should actively **participate in future corridor feasibility studies** to ensure that technical analyses reflect operational realities, commercial constraints, and market opportunities.

The project demonstrates the value of operational information derived from AIS data; however, additional collaboration with industry could further **improve analytical accuracy**. Where commercially feasible, shipping companies and port operators should voluntarily share operational information related to vessel performance, fuel consumption, port calls, and voyage planning to improve emissions estimation, energy demand projections, and infrastructure planning.

Industry stakeholders should also **identify vessel categories and trade routes** that are technically and commercially **suitable** for early demonstration projects. Regular container services, vehicle carriers, LNG carriers, and other shipping segments with predictable schedules may provide favorable conditions for pilot GSCs due to their operational regularity and recurring port calls.

Companies involved in fuel supply and maritime logistics should evaluate their **readiness to support alternative fuels** by assessing storage capacity, bunkering infrastructure, fuel handling procedures, safety systems, and investment requirements. Early planning will reduce implementation risks as demand for low and zero carbon marine fuels increases.

Industry should actively support **workforce development** by participating in training initiatives, sharing technical expertise, and collaborating with educational institutions to prepare the future maritime workforce for emerging fuel technologies and operational practices.

12.3 Ports and Bunkering Actors

Ports and bunkering service providers will play a central role in enabling future GSCs. Existing **infrastructure** should be evaluated to determine its suitability for handling alternative marine fuels. These assessments should identify infrastructure gaps, investment priorities, and opportunities to integrate new fuel systems into existing port operations.

The transition toward alternative fuels also requires comprehensive **safety planning**. Ports should evaluate their emergency response capabilities, firefighting systems, fuel handling procedures, occupational safety protocols, and environmental protection measures to ensure compliance with emerging international standards. Developing these capacities before commercial deployment will reduce operational risk and facilitate regulatory approval.

Where technically and economically feasible, ports should explore the implementation of **shore power (cold ironing)** to reduce emissions from vessels at berth. Although shore power alone will not achieve shipping decarbonization, it represents an important complementary measure that can improve local air quality and reduce greenhouse gas emissions from port operations.

Effective **coordination** among ports, shipping companies, fuel suppliers, and Canal operations should also be strengthened to support efficient fuel distribution, optimize vessel scheduling, and facilitate the gradual introduction of new marine fuels. Such collaboration will reduce investment uncertainty while improving the operational efficiency of future corridors.

12.4 Academia and Training Institutions

Academic institutions have an essential role in supporting Panama's transition toward sustainable maritime transport through **education, applied research, innovation, and technical capacity building**. Universities and maritime training centers should update existing **curricula** to incorporate emerging topics related to maritime decarbonization, including greenhouse gas emissions estimation, alternative marine fuels, climate risk, digital maritime systems, and environmental regulation.

The datasets and analytical tools generated by this project, including AIS databases, emissions models, energy demand analyses, and the SEAnalytics platform provide valuable educational resources that should be integrated into **undergraduate and graduate teaching**, student research projects, and professional training programs. Expanding the use of these tools will strengthen national expertise in maritime analytics and evidence-based decision-making.

Academic institutions should also develop **specialized courses and professional training programs** focused on emissions accounting, life-cycle assessment, alternative fuel technologies, maritime energy systems, artificial intelligence applications, geographic information systems (GIS), and maritime data analytics. These programs will help prepare engineers, regulators, port personnel, and maritime professionals for the evolving needs of the shipping industry.

Panama should strengthen i**nternational academic collaboration** through joint research projects, faculty exchanges, graduate student mobility, and participation in global maritime research networks. Partnerships with universities, research centres, international organizations, and industry will accelerate knowledge transfer while increasing Panama's visibility as a regional centre of excellence in maritime decarbonization.

12.5 Future Research

Although this project establishes a comprehensive technical foundation for evaluating GSCs in Panama, several research priorities remain.

Future studies should undertake **corridor-specific feasibility assessments** that examine technical, operational, environmental, and commercial conditions for individual trade routes identified through the project's emissions and energy demand analyses. These assessments should evaluate infrastructure requirements, stakeholder readiness, financing mechanisms, and implementation timelines.

Additional research should expand the evaluation of alternative fuels through **life-cycle greenhouse gas emissions assessments and techno-economic analyses**, allowing comparisons among hydrogen-derived fuels, biofuels, synthetic fuels, and conventional marine fuels under different market scenarios.

Future work should also develop **fuel supply chain models** capable of evaluating production pathways, import and export logistics, storage systems, transportation networks, and fuel availability for Panama's maritime sector. These analyses will support long-term infrastructure planning and national energy policy.

Given the increasing impacts of climate variability on Canal operations, future research should integrate **climate change scenarios** into maritime transport models to evaluate the long-term resilience of GSCs under different hydrological and operational conditions.

The project also highlights opportunities to apply **network analysis** to better understand trade connectivity, recurring shipping services, vessel interactions, and strategic partnerships among ports connected through Panama. Such analyses could improve partner selection and identify routes with the greatest potential for collaborative emissions reductions.

Finally, future research should investigate **innovative business models** capable of supporting pilot GSCs. These studies should examine mechanisms for risk sharing, public-private partnerships, long-term fuel supply agreements, cargo owner participation, carbon pricing, climate finance, and international cooperation. Developing financially viable implementation models will be essential for translating technical feasibility into operational GSCs.

13

Implementation Roadmap

The implementation of GSCs in Panama should follow a phased approach that progressively builds the technical, institutional, regulatory, and commercial conditions necessary for successful deployment. The findings of this project indicate that Panama already possesses many of the strategic assets required to support future corridors, however, realizing these opportunities will require coordinated action among stakeholders.

Rather than attempting to deploy alternative fuels immediately at large scale, the roadmap proposes a sequence of activities that gradually reduces uncertainty, strengthens institutional readiness, and enables pilot projects before broader implementation.

Phase 1. Institutional Preparation and Knowledge Development (Year 1 to Year 2)

The first phase focuses on establishing the institutional and analytical foundations necessary for corridor development. During this stage, Panama should strengthen coordination among government agencies, ports, industry, academia, and international organizations while expanding the technical evidence generated through this project.

Priority actions include establishing a national Green Shipping Corridor coordination mechanism, integrating AIS-based emissions and energy demand analyses into national maritime planning, and identifying priority trade routes based on objective technical criteria. At the same time, institutions should begin evaluating existing regulations governing alternative marine fuels and identify areas requiring future regulatory development.

Capacity building should also become a national priority. Universities, maritime academies, and professional training centres should update educational programs to include maritime decarbonization, alternative fuels, emissions accounting, and climate resilience. The analytical tools developed during this project, including SEAnalytics, should be expanded and made available to researchers and decision-makers to support evidence-based planning.

Expected outputs

- National coordination framework established.
- Priority Green Shipping Corridor candidates identified.
- National emissions and energy demand database operational.
- Initial regulatory gap assessment completed.
- Expanded academic and professional training programs.

Phase 2. Corridor Planning and Feasibility Assessment (Year 2 to Year 5)

The second phase focuses on evaluating the technical, economic, environmental, and commercial feasibility of specific GSCs connected to Panama. Building upon the evidence generated during Phase 1, detailed corridor studies should be conducted for candidate routes identified through AIS analyses.

These studies should assess vessel demand, energy requirements, emissions reduction potential, infrastructure needs, climate risks, alternative fuel supply chains, financing mechanisms, and stakeholder readiness. Particular attention should be given to identifying shipping companies, ports, fuel suppliers, cargo owners, and governments willing to participate in pilot corridor initiatives.

During this phase, Panama should also strengthen international collaboration with organizations such as the International Maritime Organization (IMO), the Global Maritime Forum, the Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping, Global Gateway, the World Bank, the Inter-American Development Bank, and regional partners to mobilize technical assistance and investment.

Ports and bunkering companies should simultaneously begin preliminary engineering studies for alternative fuel infrastructure while evaluating operational safety, emergency response capacity, and environmental permitting requirements.

Expected outputs

- Corridor-specific feasibility studies completed.
- Strategic international partners identified.
- Alternative fuel infrastructure plans prepared.
- Climate resilience integrated into corridor planning.
- Initial financing strategies developed.

Phase 3. Pilot Implementation and Infrastructure Development (Year 5 to Year 10)

Once feasibility has been demonstrated, Panama should initiate pilot GSCs on selected trade routes that present favorable technical and commercial conditions. These pilot projects should initially focus on shipping services characterized by regular schedules, repeat operators, and predictable energy demand, thereby reducing commercial uncertainty.

Infrastructure investments should include fuel storage facilities, bunkering systems, digital monitoring platforms, safety equipment, and emergency response capabilities appropriate for the selected fuel pathways. Parallel investments in integrated digital traffic management systems and Just-in-Time (JIT) arrival optimization should improve operational efficiency while reducing emissions during the transition period.

Comprehensive workforce training should accompany infrastructure deployment. Port personnel, fuel suppliers, vessel operators, regulators, emergency responders, and inspectors should receive specialized instruction on alternative fuel handling, operational safety, and regulatory compliance.

Continuous monitoring of pilot projects will be essential to evaluate operational performance, emissions reductions, economic viability, safety outcomes, and stakeholder experiences.

Expected outputs

- Pilot GSCs operational.
- Alternative fuel bunkering facilities commissioned.
- Workforce training programs implemented.
- Digital monitoring systems operational.
- Performance monitoring and emissions reporting established.

Phase 4. Regional Expansion and Long-Term Integration (Year 10 onward)

The final phase focuses on expanding successful pilot corridors into a broader regional network while strengthening Panama's role as a Latin American platform for maritime decarbonization. Lessons learned during pilot implementation should inform future corridor development, regulatory improvements, infrastructure expansion, and investment planning.

During this stage, Panama should continue expanding its capabilities in alternative fuel distribution, digital emissions monitoring, maritime analytics, and climate-resilient logistics. The country can also strengthen its position as a regional centre for technical training, applied research, and international cooperation by sharing methodologies and analytical tools developed through this project.

Long-term planning should support the integration of GSCs with Panama's national energy transition strategy, renewable energy development, hydrogen economy initiatives, and climate adaptation policies. Continuous research should evaluate emerging fuels, evolving international regulations, technological innovation, and changing trade patterns to ensure that corridor development remains aligned with global maritime decarbonization objectives.

Expected outputs

- Expansion of GSCs to additional trade routes.
- Panama established as a regional clean marine fuel hub.
- Regional maritime training and research programs expanded.
- Mature digital emissions monitoring platform.
- Continuous policy evaluation and corridor optimization.

This phased approach is consistent with international implementation frameworks, while tailoring the sequence of actions to Panama's institutional, operational, and climate context.

14

Conclusions

This report demonstrates that **Panama** is well positioned to play a **leading role** in the development of GSCs. Its strategic location at the intersection of major global trade routes, together with the Panama Canal, a mature port and logistics network, and extensive experience in maritime services, provides a **strong foundation for supporting the decarbonization of international shipping**. GSCs should therefore be viewed not only as an environmental initiative but also as a **strategic opportunity** to strengthen Panama's competitiveness and reinforce its position as a global maritime hub.

The analyses conducted in this project provide a robust technical basis for **informed decision-making**. By integrating Automatic Identification System (AIS) data with vessel characteristics and energy and emissions models, the project demonstrates that corridor identification can be supported through objective, route-level evidence. This approach enables stakeholders to **prioritize** trade routes, vessel segments, and international partners according to measurable indicators such as energy demand, emissions reduction potential, voyage frequency, and market relevance.

The results also show that significant emissions reductions can be achieved through operational improvements while alternative fuels continue to develop. Measures such as Just-in-Time (JIT) arrivals, improved voyage planning, and enhanced scheduling coordination offer practical, near-term opportunities to improve fuel efficiency and reduce greenhouse gas emissions. These **operational strategies** can complement future investments in low- and zero-carbon fuels while increasing the overall efficiency and reliability of maritime transport through Panama.

The project further concludes that **climate resilience** must become an **integral component** of Green Shipping Corridor planning. The increasing frequency of droughts affecting water availability in the Panama Canal demonstrates that climate risks have direct implications for vessel transits, logistics performance, and global supply chains. Future corridor development should therefore integrate climate adaptation, operational resilience, and infrastructure planning to ensure that decarbonization efforts remain effective under changing environmental conditions.

The assessment of alternative marine fuels indicates that successful deployment depends on the **simultaneous development of infrastructure, regulatory frameworks, safety standards, workforce capabilities, and commercial partnerships**. While Panama possesses important advantages as an established bunkering and logistics centre, additional efforts are required to strengthen regulatory readiness, technical expertise, and investment planning to support the safe and efficient introduction of alternative fuels.

Beyond its physical infrastructure, Panama has the opportunity to position itself as a **regional platform for maritime data, innovation, and capacity building**. The methodologies, emissions models, energy demand analyses, and digital tools developed through this project, including the SEAnalytics platform, provide valuable resources for supporting evidence-based policymaking, research, workforce training, and international collaboration. These capabilities can help establish Panama as a regional centre for maritime analytics and Green Shipping Corridor development in Latin America.

The implementation of GSCs will require **coordinated action among public institutions, industry, ports, academia, and international partners**. A phased approach that begins with institutional coordination, corridor-specific feasibility studies, regulatory development, workforce training, and pilot projects will reduce uncertainty and create the conditions necessary for larger-scale deployment. Continued collaboration and transparent data sharing will be essential to transform technical potential into commercially viable corridor initiatives.

Finally, this report concludes that Panama possesses the **strategic assets, analytical capabilities, and institutional foundations** needed to participate in the development of GSCs. By combining data-driven planning, operational efficiency, climate resilience, alternative fuel preparedness, and international cooperation, Panama can **strengthen its role in global maritime trade** while contributing to the decarbonization of the shipping sector. The findings, methodologies, and recommendations presented in this report provide a practical roadmap for guiding **future investments, partnerships, and policy decisions** that will support the implementation of **GSCs** connected to **Panama**.

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Appendices

Table A1. Data used by project studies.

Data source	Coverage period	Unit of Analysis	Main variables	Used for	Main limitation
AIS data	2019–2025	Vessel position message; vessel track; voyage segment	MMSI, IMO, timestamp, latitude, longitude, speed, course, heading, vessel type	Reconstruction of vessel movements, port calls, anchorage stays, Canal transits, routes, origin-destination pairs, operating modes	Missing messages, irregular transmission frequency, duplicated records, invalid positions, possible mismatch in vessel identifiers
Vessel technical databases	Matched to vessels observed in 2019–2025	Vessel	Vessel type, size, gross tonnage, deadweight, main engine power, auxiliary engine power, year built, draught, fuel/engine assumptions	Estimation of energy demand and emissions by vessel type, route, and operating mode	Not all vessels have complete technical data; some parameters require assumptions or vessel-type averages
Geographic polygons	Project-defined	Port area, anchorage, Canal area, lock area, route segment	Polygon boundaries, port/anchorage labels, Canal areas, geographic classification	Detection of port visits, anchorage periods, Canal approaches, Canal transits, and route segments	Polygon definitions may simplify real operational areas; small boundary changes can affect event detection
Climate and hydrological data	2019–2025, depending on variable	Weekly/monthly climate and water indicators	Gatun Lake levels, ENSO indicators, Oceanic Niño Index, precipitation/hydrological indicators, operational restrictions where available	Analysis of climate risk, Canal Water Time, water availability, and operational impacts on vessel flows	Climate effects are indirect; causality is difficult to isolate; data frequency may differ from vessel activity data
Laskaridis shipboard data	Case-study voyages, exact dates to confirm	Vessel sensor record; one-minute operational observation	Fuel consumption, power demand, propulsion data, electrical load, engine/load profiles, voyage segments	Engineering assessment of hybrid propulsion, alternative fuels, cold ironing, tank-to-wake and well-to-wake scenarios	Limited to two bulk carrier case studies; not representative of the full Panama-connected fleet
Expert surveys	Study period to confirm	Survey respondent; expert judgment	Training needs, competency gaps, technology readiness, alternative fuels knowledge,	Assessment of workforce, training, and	Results depend on expert sample, survey

			emissions reporting, digital skills, regulatory awareness	institutional capacity for maritime decarbonization in Panama	design, and subjective judgment
SEAnalytics/project emissions databases	2019–2025	Vessel-route-mode-year record; aggregated route or geography	Energy demand, CO_2, CH_4, N_2O, CO_2e, vessel type, route, operating mode, year, geography	Core analytical base for report statistics, route prioritization, emissions profile, and corridor selection	Derived from model assumptions; should be treated as analytical estimates, not official inventories

Table A2. Methods used by project studies.

Study or output	Main data used	Method	Main indicator produced	Relevance for Green Shipping Corridors
AIS emissions model	AIS vessel position data, vessel technical characteristics, geographic polygons, route information, and emissions factors	Bottom-up emissions estimation based on vessel activity, operating mode, vessel characteristics, speed, engine power, and load assumptions	Energy demand, fuel use, CO_2, CH_4, N_2O, and CO_2e by vessel type, route, geography, year, and operating mode	Provides the emissions and energy baseline for Panama-connected shipping. It identifies where emissions occur and which routes or vessel segments should be considered first for corridor planning.
Chokepoint operational efficiency study	AIS data, Panama Canal geofences, vessel characteristics, Canal transit and waiting-time estimates, and Canal scheduling rules	AIS-based reconstruction of Canal transits and waiting times, followed by speed-reduction and scheduling scenarios for incoming vessels	Potential CO_2e reductions from improved Canal operational efficiency, reduced waiting, and pre-arrival speed adjustment	Shows that operational measures can reduce emissions before full alternative-fuel deployment. This is important for early Green Shipping Corridor actions.
Canal Water Time and climate risk study	AIS-derived Canal Water Time, vessel activity indicators, Gatun Lake levels, Oceanic Niño Index, and operational variables	Weekly panel reconstruction, time-series models, machine-learning prediction models, and fixed-effects analysis of ENSO-related effects	Predicted Canal Water Time, transit reliability indicators, and climate-related effects on Canal operations	Links climate variability to Canal reliability, waiting time, and route planning. This helps corridor partners understand climate risk as part of corridor feasibility.
Laskaridis alternative fuel and hybrid propulsion study	One-minute onboard energy and fuel-consumption data from two bulk carrier case-study vessels, vessel specifications, fuel properties, and cost assumptions	Scenario-based environmental and economic assessment of hybrid propulsion, dual-fuel engines, fuel cells, batteries, waste-heat recovery, alternative fuels, and cold ironing	Tank-to-wake and well-to-wake emissions, fuel consumption, local pollutants, and levelized cost of energy	Provides an engineering-based view of how alternative fuels, shore power, and hybrid systems could perform on Panama Canal-connected voyages.
Green ammonia bunkering optimization model	2024 AIS data for containerships with ports of call in the Americas, route-level energy demand, port locations, ammonia supply assumptions, bunkering costs, and carbon-price scenarios	Spatial cost-optimization model integrating shipowner decisions, bunkering infrastructure location and capacity, fuel supply, retrofitting, and carbon price	Green ammonia demand, bunkering locations, infrastructure capacity, retrofitted vessels, and carbon-price thresholds	Supports identification of potential alternative-fuel demand, infrastructure locations, and partner ports for ammonia-based corridors in the Americas.
Training and competency gap study	Literature review, expert surveys, focus groups, and input from maritime professionals and training stakeholders in Panama	Mixed-methods analysis using structured surveys and Analytic Hierarchy Process for competency prioritization	Priority competency gaps, institutional readiness, and proposed maritime education and training framework	Identifies the human-capacity requirements for Green Shipping Corridors, including alternative fuels, emissions monitoring, digital skills, safety, and regulatory readiness.
Dashboard and SEAnalytics databases	Project-generated energy and emissions databases, route and origin-destination information, vessel type, operational mode, year, and geography	Data aggregation, visualization, route comparison, dashboard publication, and indicator generation	Public dashboard indicators, route-level statistics, emissions and energy trends, maps, and downloadable data	Converts project results into a shared monitoring and decision-support tool for authorities, industry, academia, and potential corridor partners.

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