Power-to-X Colombia 2.0

A Study on Business Cases for Hybrid Fuel Production based on Biogenic Feedstocks and Green Hydrogen in Colombia

In the context of

Implemented via

Partners

FRAUNHOFER INSTITUTE FOR SOLAR ENERGY SYSTEMS ISE

POWER-TO-X COLOMBIA 2.0

Fraunhofer ISE

A Study on Business Cases for Hybrid Fuel Production based on Biogenic Feedstocks and Green Hydrogen in Colombia

Lucas Edenhofer
Ramy Essam
Christopher Hebling
Robert Szolak
Christoph Hank

Fraunhofer Institute for Solar Energy Systems ISE

September 2026

This study was carried out as part of the **CatalHyst** project, a bilateral collaboration between the Federation of German Industries (**BDI**) and the Cámara de Hidrógeno y Gases Renovables **ANDI Naturgas**, funded by the Federal Ministry for Economic Cooperation and Development **BMZ** and implemented by **Sequa gGmbH**.

Table of Contents

List of Abbreviations

Abbreviation	Explanation
ASTM	American Society for Testing and Materials
ATJ	Alcohol-to-Jet
ASU	Air Separation Unit
BESS	Battery Energy Storage System
BtX	Biomass-to-X
CAPEX	Capital expenditure
CHP	Combined Heat and Power
DAC	Direct Air Capture
ETS	Emissions Trading System
FEED	Front-End Engineering Design
FID	Final Investment Decision
GHG	Greenhouse gas
GIS	Geographic Information System
IEA	International Energy Agency
ISCC	International Sustainability and Carbon Certification
LCF	Low-Carbon Fuel
LCOH	Levelized Cost of Hydrogen
LFG	Landfill Gas
MCDA	Multi-Criteria Decision Analysis
NCC	Net Conversion Cost
OPEX	Operational expenditure
PBtX	Hybrid Power-to-X / Biomass-to-X
PEM	Polymer Electrolyte Membrane
PFD	Process Flow Diagram
PPA	Power Purchase Agreement
PtX	Power-to-X
PV	Photovoltaic
RED	Renewable Energy Directive
RFNBO	Renewable Fuels of Non-Biological Origin
SAF	Sustainable Aviation Fuel
TRL	Technology Readiness Level
UPME	Unidad de Planeación Minero-Energética
VLSFO	Very Low Sulphur Fuel Oil
WWTP	Wastewater Treatment Plant

Executive Summary

Power-to-X Colombia 2.0 (PtX-COL 2.0) is a follow-up study conducted by Fraunhofer ISE in 2025–2026, building on the techno-economic foundation established in the first Power-to-X Colombia study. The predecessor study confirmed that Colombia holds world-class renewable energy potential but showed that this potential is heavily concentrated in La Guajira, where it established production-cost benchmarks for green hydrogen and its derivatives at three hub locations. It also highlighted a critical gap: the absence of concrete first-mover projects targeting high-value, carbon-containing products such as methanol and sustainable aviation fuel (SAF), despite growing EU demand for exactly these molecules in the aviation and maritime sectors.

Against this background, PtX-COL 2.0 deliberately shifts the focus from a pure-electrolysis perspective toward hybrid concepts that combine renewable electricity with the country's substantial biogenic carbon base and make use of existing industrial, logistical, and grid infrastructure, rather than requiring the extensive new infrastructure build-out that large-scale PtX development in La Guajira would entail. Therefore, this study is focused on hybrid Power-to-X/Biomass-to-X (PBtX) supply chains designed for near-term bankability rather than greenfield, pure-electrolysis scale-up, leveraging low-cost residue and waste feedstocks, mature conversion processes, existing industrial infrastructure, and identified regulatory sweet spots on both sides of the Atlantic. The analysis indicates that the most promising near-term opportunities lie in maritime fuel value chains and sustainable aviation fuel (SAF), where Colombia can combine renewable energy with biogenic carbon resources and existing industrial and logistics infrastructure. Renewable ammonia may additionally offer a promising pathway for low-emission fertiliser production and, potentially, for maritime fuel or hydrogen-carrier applications.

The study is structured in two phases. **Phase 1** maps the Colombian hydrogen project landscape, establishes the relevant EU and Colombian regulatory framework, conducts a GIS-based mapping of biogenic feedstocks and infrastructure boundary conditions, and develops an evaluation tool for green hydrogen and PBtX first-mover and pilot projects. **Phase 2** builds on this foundation through the conceptualization of three promising first-mover projects, targeted techno-economic assessments, and discussion of the suggested concepts in the context of short-term project realization, focusing on three departments:

- Atlántico (Barranquilla)
- Bolívar (Cartagena)
- Valle del Cauca (Cali)

Of the 72 unique hydrogen projects in Colombia identified across the ANDI, UPME, IEA and CatalHyst databases, representing over 9 GW of announced capacity, only 7 projects (1.6 GW) target carbon-containing molecules such as methanol or synfuels, despite Colombia's extensive biogenic carbon potential to target high-value EU offtake markets in the aviation and maritime sector. This capacity gap is particularly relevant for the sectors identified as having the strongest potential for early PtX deployment—maritime fuels, SAF, and potentially hydrogen-based fertilizers. Hence, this capacity gap is the central strategic rationale for the three first-mover concepts developed in Phase 2: a landfill-gas-to-methanol facility in Bolívar, a bioethanol-to-SAF facility via Alcohol-to-Jet (ATJ) in Valle del Cauca, and — as a complementary concept that connects back to the classic renewable electricity pathway while leveraging the existing industrial, grid, and port infrastructure — a 100 kt/a renewable ammonia facility in Atlántico.

The project-landscape review shows that most announced capacity remains at feasibility or pre-feasibility stage. The MCDA tool developed in Phase 1 provides a framework for testing which projects may progress, but it was not applied to the full 72-project dataset within this study.

The central finding is that Colombia's competitive advantage in future sustainable fuels markets, both domestic and export-oriented, does not rest solely on cheap renewable electricity, as in the La Guajira-centric findings of PtX Colombia 1.0, but on the combination of solar and hydropower resources, biogenic feedstocks, existing industrial infrastructure, and access to decent port infrastructure in the coastal and sugarcane-belt corridors. In particular, the assessment points to maritime value chains and SAF as the most compelling near-term opportunities for sustainable PtX products, while renewable ammonia may additionally offer potential for the fertilizer sector and as a maritime fuel or hydrogen carrier. Regulatory sweet spots exist on both sides of the Atlantic: the relaxed temporal-correlation rules under Colombian Decree 1476/2022, and the transitional additionality exemption under Commission Delegated Regulation (EU) 2023/1184 that allow existing hydropower to be used for RFNBO production until 2038 for electrolyzers commissioned before 2028. Taken together, these enable Colombian first-movers to enter high-value EU-linked markets earlier and at materially lower technical and financing risk than pure greenfield electrolysis projects.

1 Introduction

1.1 Background

Colombia possesses substantial renewable energy potential, but its most attractive resources are geographically concentrated in La Guajira, a region that also faces meaningful social and infrastructural constraints for near-term large-scale project development. The first Power-to-X Colombia study, conducted in 2024 on behalf of the Federation of German Industries (BDI) and the World Energy Council, demonstrated that Colombia hosts some of the most competitive renewable energy resources globally, with levelized costs of hydrogen (LCOH) at gate reaching as low as 3.3 EUR/kg in 2030 and projected to fall to 2.7 EUR/kg by 2040 [1]. This finding, however, raised a further strategic question for a follow-up study: if Colombia's electricity-cost advantage is so heavily concentrated in one remote and infrastructurally challenging area, what near-term pathways exist for the country to enter high-value PtX export markets?

Colombia's broader green hydrogen ambitions are documented in its National Hydrogen Roadmap, which targets 1–3 GW of installed electrolysis capacity and 50 kt of blue hydrogen production by 2030 [2]. At the same time, the EU market has developed a growing and increasingly binding demand for sustainable aviation fuel (SAF) and renewable maritime fuels. PtX-COL 2.0 was therefore designed to identify where in Colombia first-mover concepts could be realized at attractive cost, whether through hybrid configurations based on biogenic and carbon-containing feedstocks or through projects that capitalize on existing industrial, port, and grid infrastructure rather than requiring extensive greenfield build-out. On this basis, the study first assessed the current project landscape and then developed targeted first-mover concepts rooted in Colombia's feedstock availability and industrial geography.

The study has the explicit goal of moving from a nationwide screening of Colombia’s Power-to-X potential to concrete, techno-economically grounded first-mover concepts that industry can take into feasibility and pre-FEED.

The study was conducted by Fraunhofer ISE together with the CatalHyst project. The CatalHyst project represents a bilateral cooperation initiative between the Federation of German Industries (BDI) and the Cámara de Hidrógeno y Gases Renovables ANDI Naturgas, funded by the Federal Ministry for Economic Cooperation and Development (BMZ)

1.2 Goal and scope of the Study

PtX-COL 2.0 sets out to close three gaps identified in the first project. First, it expands the feedstock perspective beyond dedicated wind and solar electricity to include biogenic gases and biomass residues as carbon carriers, enabling Biomass-to-X (BtX) and hybrid Power-to-X/BtX (PBtX) pathways. Second, it assesses the regulatory environment with sufficient precision to identify actionable sweet spots for early market entry under both EU and Colombian frameworks. Third, it delivers concretely conceptualized first-mover projects with site-specific system layouts, stakeholder maps, technology maturity assessments, indicative economics, and risk analyses for the three focus departments.

The geographic focus was deliberately shifted away from La Guajira toward the industrialized coastal corridor and the sugarcane belt of Valle del Cauca, where existing industrial infrastructure, biogenic feedstocks, and port logistics create near-term project opportunities.

The term "first-mover" refers to concepts developed for the first time in this study that, in the opinion of the study's authors, are suitable for short- to medium-term further development (pre-FEED, FEED) and exploration. It takes into account, both here and in the conceptual developments, the necessary technical facilities for the provision, conversion, and storage of energy and materials for the respective energy sources under consideration.

The companies identified in this study result from the applied methodology and are intended to illustrate potential roles as offtakers, stakeholders, technology providers, or project anchors. Their inclusion does not imply any formal partnership, commercial commitment, or investment decision. The identified actors are not exhaustive, and the flagged projects should be understood as conceptual case studies rather than finalized project structures or confirmed agreements.

1.3 Structure of this Report

This report is structured in five chapters. Chapter 2 describes the Phase 1 and Phase 2 methodology. Chapter 3 presents the Phase 1 results, covering the Colombian hydrogen project landscape, the EU and Colombian regulatory framework, the GIS-based mapping of biogenic feedstocks and infrastructure constraints, the concept of the project evaluation tool, and the hydrogen project development roadmap. Chapter 4 covers the Phase 2 first-mover project conceptualizations for Bolívar, Valle del Cauca, and Atlántico. Chapter 5 synthesizes cross-cutting findings and recommendations.

2 Methodology

2.1 Phase 1: H_2 Landscape, Regulations, GIS Mapping & Evaluation Tool

Phase 1 comprises four parallel workstreams. The first is the systematic mapping and consolidation of hydrogen project databases: four sources (ANDI, UPME [3], IEA [4], and CatalHyst) were matched and deduplicated using a project-level identity-matching approach, cross-referencing project name, location, technology, and announced capacity to identify overlapping entries across the primary databases. This consolidation methodology underpins both the capacity outlook and the project evaluation tool presented in Chapter 3.

The second workstream is a regulatory assessment of the EU and Colombian frameworks relevant to hydrogen and PtX project development. This workstream analyzed the evolving demand-side requirements in the EU, particularly under RED III, ReFuelEU Aviation, FuelEU Maritime, and the EU ETS, and contrasted them with Colombia's still predominantly supply-side regulatory framework. Particular attention was given to identifying regulatory sweet spots for Colombian first-mover projects, including RFNBO transition rules, advanced-biofuel eligibility, and the implications of Colombian Decree 1476 for renewable electricity sourcing.

The third workstream is a comprehensive GIS-based mapping of biogenic feedstock availability and infrastructure constraints across the three focus departments. It extends the GIS methodology from PtX Colombia 1.0 — which focused on renewable energy potential and hub site selection — to now also cover landfill gas, wastewater treatment plant (WWTP) biogas, agricultural residues (sugarcane, rice, oil palm, banana, corn), forest residues, and livestock manure. For each feedstock stream, quantity, composition, EU RED III fuel category, and suitable supply-chain configurations were assessed. In addition, the analysis incorporated spatial and logistical factors relevant for project development, including potential product offtakers, transport and grid infrastructure, conflict-affected and protected areas, as well as other land-use constraints.

The fourth workstream is the development of an Excel-based Multi-Criteria Decision Analysis (MCDA) tool for evaluating hydrogen projects in Colombia, together with a structured six-phase hydrogen project development roadmap. The tool was designed to assign a probability score (likelihood of becoming operational), a suitability score (holistic project performance), and an information completeness score to individual projects, based on criteria including development stage, offtake agreement, regulatory compliance status, financing readiness, infrastructure access and socio-environmental factors. In parallel, a six-phase hydrogen-project development roadmap was formulated, covering: (1) concept development and pre-feasibility; (2) project definition and feasibility; (3) engineering, procurement and permitting; (4) construction; (5) commissioning and start-up; and (6) operation and optimisation. The tool and roadmap were developed and handed over as practical assets for Colombian project developers and industry stakeholders to structure activities toward FID. The tool was not fully applied by the study team to score the entire 72-project database within the scope of this report. The roadmap was tailored specifically to the Colombian project-development context.

2.2 Phase 2: First-Mover Project Conceptualization

The first-mover and hybrid concept methodology rests on four guiding principles that were applied consistently across all three focus departments:

1. Leveraging low-cost feedstocks by utilizing residue and waste biomass and biogenic gases to reduce feedstock costs while bringing sustainable carbon into the system for methanol, SAF and other products.
2. Utilizing mature processes and existing infrastructure, combining proven conversion technologies such as electrolysis, reforming, gasification and synthesis with repurposed industrial assets to minimize technology and CAPEX risk.
3. Kick-starting regional hydrogen hubs that integrate production, distribution and offtake within each department as a first step toward localized hydrogen ecosystems.
4. Targeting regulatory sweet spots on both the EU and Colombian sides, explicitly designing concepts to benefit from RFNBO transition rules, advanced-biofuel eligibility and Colombia's more flexible electricity-sourcing regulations.

Figure 1 depicts these four principles that were utilized to establish first-mover concepts in Atlántico, Bolívar, and Valle del Cauca.

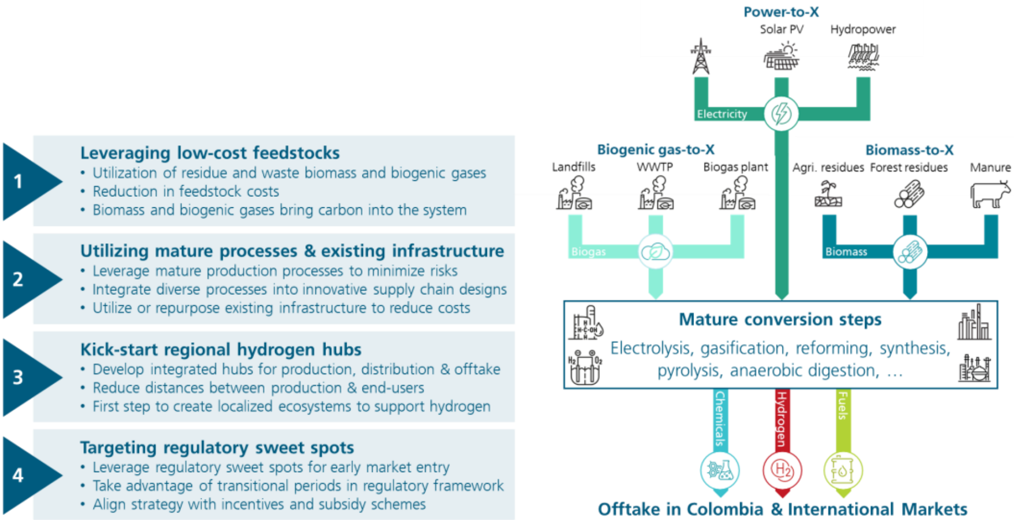


Figure 1: Guidelines for first-mover hybrid concepts in Colombia

Phase 2 applies a structured project conceptualization methodology to develop and compare multiple technology routes for each focus department. For each department, a comprehensive assessment of renewable and biogenic feedstock availability, infrastructure, offtake options, and project constraints was first compiled as a department overview. Based on this, up to six distinct project concepts per department were screened and characterized by scale, impact, integration complexity, risk, and cost level, of which only one representative concept per department is presented in depth in Chapter 4. The selected first-mover concepts were then subject to a deeper analysis covering system layout and description, technology and integration risk assessment by sub-process, indicative CAPEX breakdown, priority levers for cost reduction, stakeholder mapping, regulatory gap analysis, risk register, and next steps at various analysis depths.

3 Results – Phase 1

3.1 Hydrogen Project Landscape in Colombia

A systematic mapping of the Colombian hydrogen project landscape shows that the 72 unique hydrogen projects identified across the ANDI, UPME [3], IEA [4], and CatalHyst project databases are heavily concentrated in hydrogen and ammonia, with only 7 projects targeting carbon-containing molecules such as methanol or synfuels.

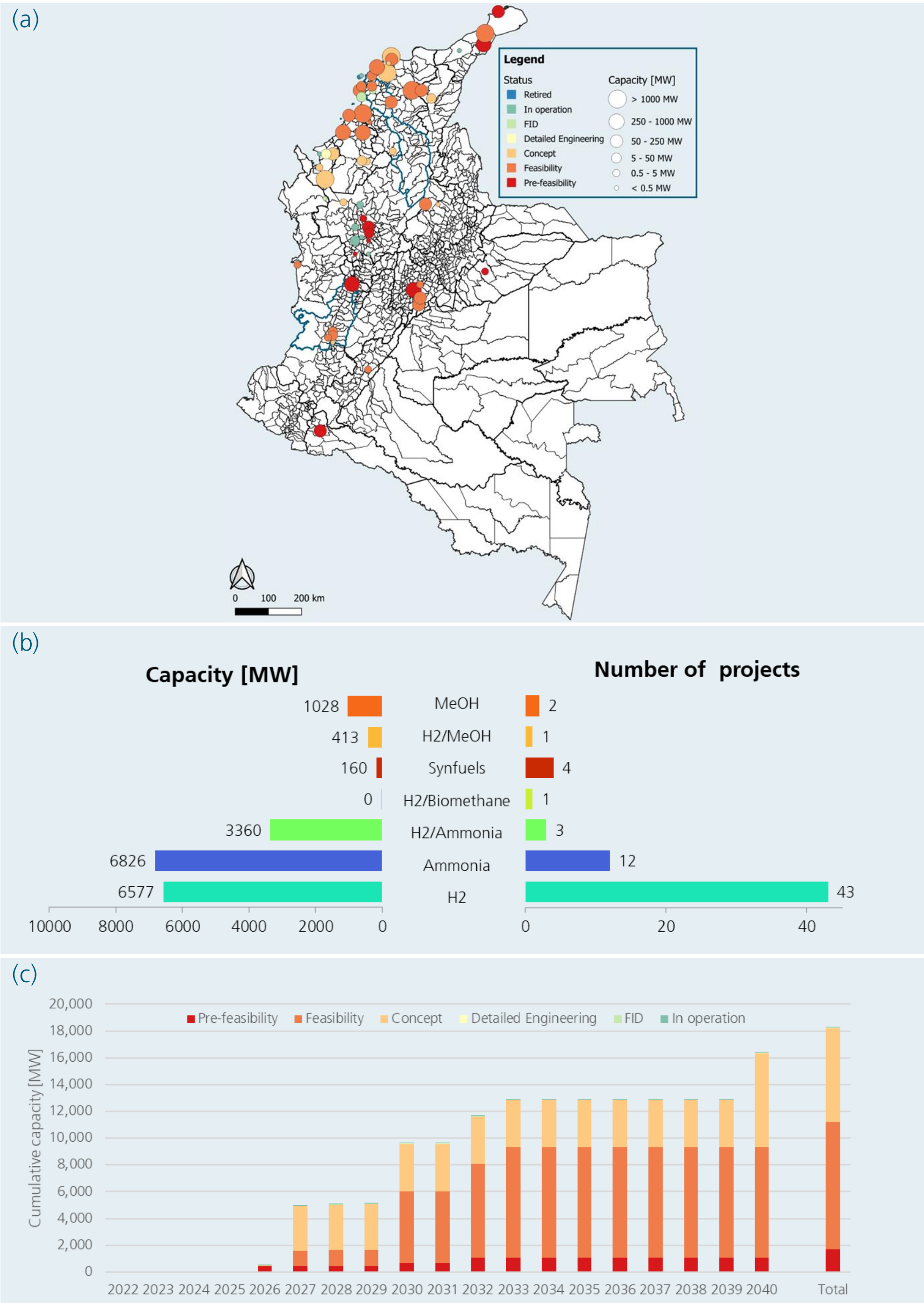


Figure 2: Hydrogen and derivatives project landscape in Colombia with (a) spatial distribution differentiating project status and capacity, (b) breakdown of target product, capacity and number of projects, and (c) timeline of cumulative capacity based on project announcements

Of the four source databases, ANDI listed 36 projects, UPME 50, IEA 26, and CatalHyst 44, yielding the consolidated dataset of 72 unique projects representing over 9 GW of announced capacity.

The majority of announced capacity, nearly 9 GW, is in feasibility or pre-feasibility stage, creating a pronounced gap between project announcements and the FID-ready pipeline needed to achieve Colombia's 2030 National Hydrogen Roadmap target of 1–3 GW of installed electrolysis capacity [2]. Delays from financing gaps, regulatory hurdles, and grid constraints mean that realistic capacity growth will lag significantly behind announced timelines. The spatial project distribution, breakdown of target product by capacity and number of projects, and the timeline of cumulative announced capacity are presented in Figure 2.

3.2 Regulatory Framework for PBtX Projects in Colombia

EU framework: Demand creation through binding targets

The EU regulatory framework has matured substantially since the first PtX Colombia study and now constitutes the primary demand driver for future Colombian PBtX exports. The relevant instruments span four categories: (1) non-fossil fuel definitions and fuel categories (RED III Delegated Acts defining RFNBO, advanced biofuels, recycled carbon fuels, and low-carbon fuels [5], [6], [7]); (2) demand mandates (ReFuelEU Aviation and FuelEU Maritime [8], [9]); (3) carbon pricing (EU ETS and Carbon Border Adjustment Mechanism [10]); and (4) enabling infrastructure (AFIR, Hydrogen and Gas Decarbonisation Package [11], [12], [13]).

Electricity supply and hydrogen production: For hydrogen and hydrogen-derived products, the RED III Delegated Acts define strict additionality, temporal correlation, and geographical correlation requirements for RFNBO eligibility. Under the additionality transition period, electrolyzers commissioned before 1 January 2028 may use existing renewable electricity sources, including Colombian hydropower, without additionality compliance for a period of ten years, provided temporal and geographical correlation are still met [5]. This transition window is a key enabler for early-mover projects in Colombia.

Carbon sourcing: For carbon sources in methanol and SAF production, the Delegated Acts define a hierarchy of valid carbon sources for RFNBO production: Direct Air Capture (DAC), biogenic CO_2 from RED-compliant feedstocks, and, for a transitional period, captured fossil CO_2 from eligible industrial activities subject to an effective carbon-pricing system. Captured CO_2 from fossil-fuel combustion for electricity generation must be incorporated into the fuel before 2036, while the corresponding deadline is extended to 2041 for other qualifying activities [6]. The analysis confirms that industrial CO_2 from Colombian cement plants is viable in the near-to-medium term, but creates stranded asset risk after 2041, while biogenic CO_2 from fermentation and biomethane upgrading offers long-term regulatory certainty but can complicate project realization because of seasonal production profiles and the need to match CO_2 availability with continuous plant operation.

Demand mandates: Aviation and maritime are the first end-use sectors with formalized, binding demand drivers for renewable hydrogen-derived fuels because they are among the hardest-to-abate segments, with limited direct electrification options and a significant contribution to global greenhouse gas emissions. In response, the EU has introduced mandates through ReFuelEU Aviation and FuelEU Maritime that create guaranteed markets for sustainable aviation fuels (SAF) and renewable maritime fuels. ReFuelEU Aviation introduces increasing SAF blend mandates, including an average minimum share of synthetic aviation fuels (RFNBO-SAF) of 1.2% during 2030–2031 and 2.0% during 2032–2034 [9]. Non-compliance penalties are set at a minimum of twice the price differential between SAF and conventional jet fuel for fuel suppliers, and twice the average annual aviation fuel price for non-tanked quantities for aircraft operators [9]. Although not yet formalized, a 'Book & Claim' mechanism under ReFuelEU Aviation (Article 15) can represent a potential game-changer for Colombian SAF producers: physical SAF could be consumed domestically in Colombia while environmental attributes are transferred to EU fuel suppliers or airlines, eliminating the need for physical export logistics. The procedure is highlighted in Figure 3. However, the mechanism is optional, subject to future Delegated Acts, and carries implementation uncertainty. Industry bodies are actively lobbying for inclusion, but until formalized, Colombian SAF can only access the EU compliance market via physical export and uplift at EU airports. The recommended strategy is therefore to design first-mover projects for physical export while monitoring Book & Claim development and engaging proactively in the IATA/ICAO registry process.

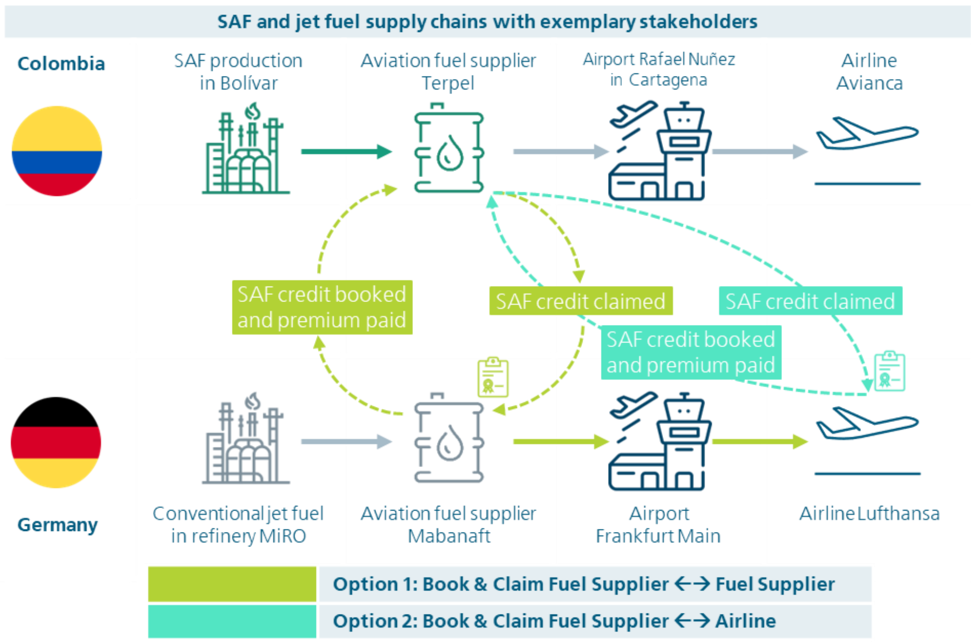


Figure 3: Potential future Book & Claim procedure under the ReFuelEU aviation

FuelEU Maritime establishes a well-to-wake GHG-intensity reduction requirement for ships above 5,000 GT. RFNBO uptake is monitored, and if the RFNBO share of in-scope onboard energy is below 1% in the 2031 reporting period, a 2% RFNBO subtarget applies from 1 January 2034, subject to the safeguards in the Regulation. Until the end of 2033, eligible RFNBO energy may also receive a multiplier of two in the GHG-intensity calculation. The Regulation also introduces a non-compliance penalty based on EUR 2,400 per tonne of VLSFO energy equivalent [8]. FuelEU Maritime is particularly relevant for Colombia because 50% of the energy used on voyages between an EU port and a third-country port falls within the Regulation's scope. In parallel, the EU ETS covers 50% of emissions from extra-EU voyages. Accordingly, routes such as Cartagena–Rotterdam or Barranquilla–Hamburg can create compliance value for sustainable methanol used in dual-fuel vessels, subject to fuel certification and lifecycle-GHG performance.

Colombian framework: Enabling supply, missing demand signals

Colombia's domestic regulatory framework has made material progress since 2021, but remained focused on supply-side enablement rather than demand creation until 2026. Law 2099, introduced in 2021, set legal definitions of blue hydrogen and renewable hydrogen as non-conventional renewable energy sources. Decree 1476 (2022) permits the use of grid electricity for renewable hydrogen production if backed by a Power Purchase Agreement. Decree 1597 (2024) extended the framework to define low-emission hydrogen and hydrogen derivatives. Regarding a GHG limit for produced hydrogen the Ministries of Mines and Energy and of Environment jointly issued

Resolución 0900 de 2026 in July 2026, establishing Colombia's first national threshold for low emission hydrogen: a maximum lifecycle-GHG intensity of 3.6 kg CO_2 eq per kg of H_2 produced, measured under a "cradle to production gate" scope [14]. On 4 August 2026, the Colombian Government approved **CONPES 4210**, the country's first dedicated National Hydrogen Policy, establishing an intersectoral roadmap for the development of low-emission hydrogen and its derivatives through 2031 [15]. The policy aims to strengthen the entire hydrogen value chain—from production and infrastructure to transport, end-use applications, technology and regulation—while supporting Colombia's decarbonisation and industrial transformation. It is expected to mobilise close to **USD 1.6 billion in investment**, creating an important framework for scaling up Colombia's hydrogen economy and leveraging its significant renewable energy potential.

The key implication of the EU–Colombia regulatory gap is that Colombian projects targeting EU export must comply with EU rules, because Colombian certification is insufficient for EU market access. Resolution 0900 establishes the national lifecycle-GHG threshold and general verification framework for classifying hydrogen as low-emission. However, Colombia does not yet have a fully operational, internationally recognised certification and chain-of-custody system equivalent to the schemes required for EU market access. Colombian projects targeting EU compliance markets must therefore demonstrate compliance with the applicable EU sustainability, RFNBO and certification requirements. EU regulations drive PtX demand through binding quotas and carbon pricing, while Colombia supports supply through tax incentives and fiscal benefits for non-conventional renewables (Law 1715, Law 2099), but lacks PtX-specific premium mechanisms or long-term offtake guarantees.

A critical near-term regulatory sweet spot identified in this study is the combination of the more strict RFNBO production criteria with Colombia's more flexible grid-balancing rules under Decree 1476 via a mass-balance approach, which allow the renewable share in the electricity mix to be demonstrated through contracted PPA volumes and origin evidence rather than strict real-time physical matching. This split-product approach can materially improve electrolyzer full-load hours and reduce levelized production costs compared to a design constrained to full-chain RFNBO compliance.
Regarding electricity utilization for green hydrogen production in Colombia the utilized electricity shall be based on either self-generated electricity or electricity sourced from the grid. In the latter case, ensuring a demonstrable link to electricity from Non-Conventional Renewable Energy Sources (FNCER) appears particularly relevant for establishing the renewable character of the hydrogen produced. This must be supported through bilateral electricity supply agreements with FNCER generators, complemented by renewable energy certificates issued by independent third parties in accordance with recognized international standards and verifiable through publicly accessible registries.

Fuel Category Classification for Hybrid PBtX

A key regulatory contribution of PtX-COL 2.0 is the systematic classification of hybrid PBtX product eligibility under EU RED III. The analysis crosses four biogenic feedstock scenarios (biogas from residues/manure; wastewater treatment gas; landfill gas; wood waste gasification) with four electricity supply cases (RFNBO-compliant renewable electricity; non-RFNBO renewable electricity with electrolysis-coupling before 2028; the same after 2028; and grid electricity). The combination of these scenarios and cases are visualized in Figure 4. The RFNBO output share is calculated via the relevant renewable hydrogen input relative to the sum of bio-syngas and renewable hydrogen input on a lower-heating-value basis.

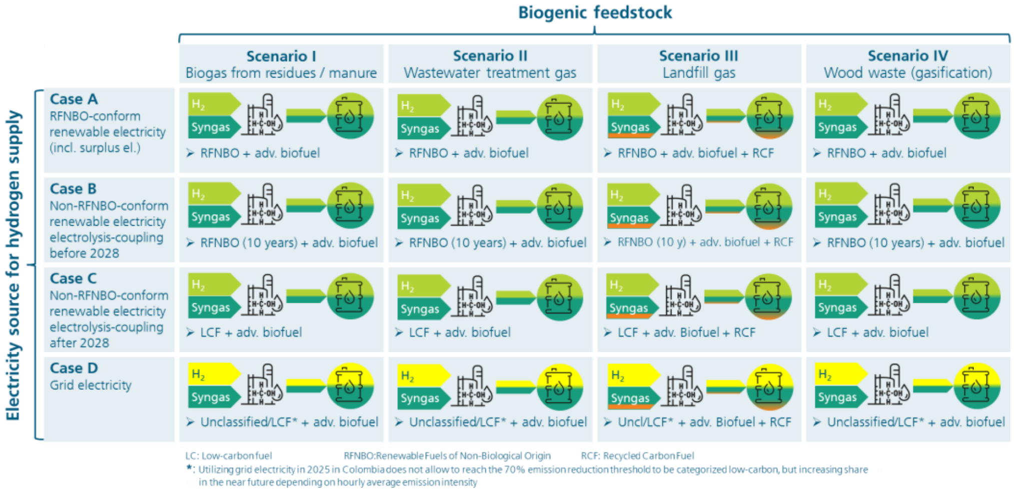


Figure 4: Fuel categories for methanol & SAF based on PBtX from an EU perspective

Hybrid PBtX concepts combining biogenic feedstocks with RFNBO-compliant hydrogen may allow separately allocated product fractions to qualify as RFNBO and advanced biofuel, subject to the applicable allocation methodology, sustainability certification and lifecycle-GHG accounting. This could enable access to different compliance markets and potential price premiums with the two highest-value categories under ReFuelEU Aviation and FuelEU Maritime. However, the achievable premium and treatment of each fraction must be confirmed for the specific product, target market and certification scheme..

3.3 GIS-Based Mapping of Feedstocks and Project Constraints

Renewable electricity sources

All three focus departments rely primarily on solar PV as the renewable energy backbone, consistent with the findings of PtX Colombia 1.0. Colombian solar PV power generation grew from 0.5 TWh in 2022 to 2 TWh in 2024, with large contiguous high-suitability areas around Barranquilla, Cartagena, and northern Valle del Cauca [1], [16]. Atlántico and Bolívar have limited onshore wind potential but benefit from proximity to the Caribbean offshore wind zone, where Colombia's first offshore leasing round resulted in a 425 MW bid cleared in December 2024, with a 350 MW offshore wind farm now in pre-construction near Barranquilla [17]. Valle del Cauca has minimal wind potential and relies on hydropower and biomass CHP (Combined Heat and Power) as firm renewable supply: Colombia's installed hydropower capacity exceeds 13 GW, including the 2.5 GW Ituango Dam now in partial operation, with a further 1.2 GW of planned extensions [18]. The RFNBO transition period allowing existing hydropower to be used without additionality compliance until 2038, for plants commissioned before 2028, is particularly valuable in Valle del Cauca. Figure 5 provides an overview of suitable PV potential area, as well as existing and planned hydropower plants in Colombia.

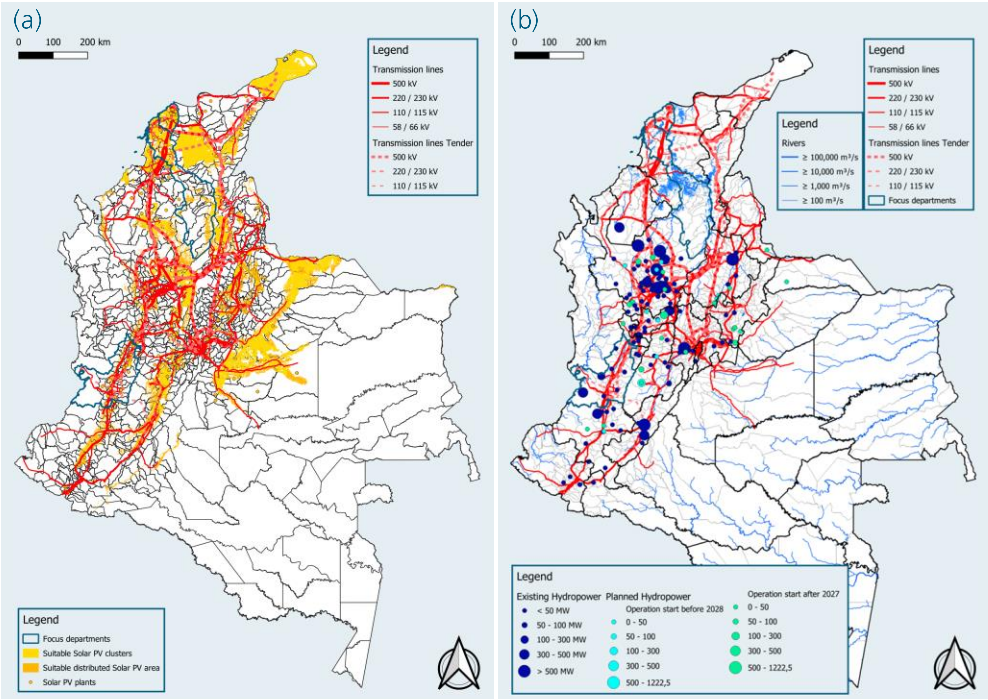


Figure 5: GIS-based mapping of (a) suitable PV potential area and (b) existing/planned hydropower in Colombia

Biogenic feedstocks

The GIS mapping reveals that Colombia's biogenic feedstock base is large and geographically differentiated across the three focus departments.

Landfill gas is a methane- and CO_2-rich gas generated by the decomposition of municipal solid waste in sanitary landfills. It is available in all three focus departments via established gas collection and control systems. Colombia operates 266 final disposal sites processing over 12 Mt/a of waste, with a large share of sanitary landfills [19]. Landfill gas composition of approximately 50% CH_4 and 45% CO_2 classifies predominantly as advanced biofuel under EU RED III, with a minor recycled carbon fuel fraction. Total landfill throughput from the 21 largest facilities amounts to approximately 10.6 Mt/a.

Wastewater treatment plant biogas is produced through anaerobic digestion of sewage sludge by Colombian wastewater treatment plants (WWTPs) with a high methane content, as illustrated by plants such as PTAR El Salitre in Bogotá, where biogas is around 70% methane and 28% CO_2. Major urban centers in Atlántico, Bolívar and Valle del Cauca (including Barranquilla, Cartagena and Cali) have sewerage systems and WWTP infrastructure, offering potential for biogas recovery [20]. WWTP biogas qualifies under EU RED III predominantly as advanced biofuel, with any documented non-renewable carbon fraction eligible as recycled carbon fuel, subject to sustainability certification and feedstock-specific verification.

Sugarcane residues and bioethanol co-products represent the most significant biogenic feedstock for Valle del Cauca: Colombia operates six co-located sugar-bioethanol production sites, concentrated in the Cauca River valley [21]. Key streams include:

- **Bagasse** — fibrous residue left after crushing sugarcane stalks to extract juice. Over 4.5 Mt/a available in Valle del Cauca; largely used for on-site cogeneration but a commercially available surplus exists for new projects at attractive offtake prices.
- **Sugarcane harvest residues** (RAC) — leaves and tops left in the field after mechanized or green harvesting. Over 1.5 Mt/a generated in Valle del Cauca;

currently underutilized with low conflict-of-use risk, but complicated by field logistics and pre-treatment supply chains.

- **Vinasse** — the nutrient-rich liquid residue from ethanol fermentation and distillation. Approximately 900 million liters per year of diluted vinasse produced from ethanol operations; currently applied as fertilizer via land application.
- **Fermentation CO_2** — the biogenic carbon dioxide released during sugar-to-ethanol fermentation. Generated at roughly 0.06 t_{CO_2} per ton of processed sugarcane, at high CO_2 concentration; largely untapped today and well-suited for methanol or SAF synthesis, although availability may vary with mill operating schedules, ethanol output and maintenance periods and should therefore be confirmed using site-specific production data.

Agricultural residues such as rice (husks and straw), corn (stover and cobs), and coffee (pulp and stems) are generated in significant volumes in central and southern Bolívar and Valle del Cauca. These low-value by-products of harvesting and primary processing are often burned, landfilled or left on fields, making them attractive PBtX feedstocks for gasification or pyrolysis, provided that collection, densification and aggregation logistics are adequately addressed [22]. Palm oil glycerol from biodiesel plants in Atlántico and Bolívar provides a low-value residue stream suitable for steam reforming or gasification to syngas at small-to-medium scale.

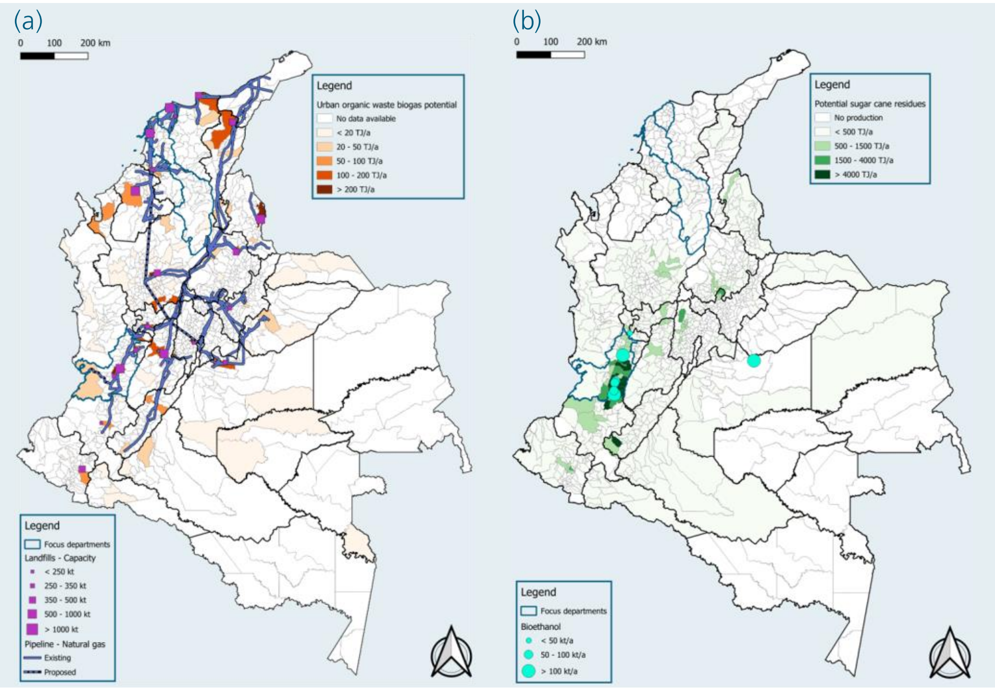


Figure 6: GIS-based mapping of residue streams (a) landfill gas and (b) sugarcane harvest residues and bioethanol production

Livestock residues in the focus departments are mainly cattle, pig and poultry manure, with very high annual quantities dominated by cattle (about 99 Mt/a nationally) and significant contributions from poultry (3.4 Mt/a) and pigs (2.8 Mt/a) [22]. This moist, nutrient-rich manure is highly suitable for anaerobic digestion to biogas and subsequent biomethane upgrading, offering advanced-biofuel potential under EU RED III, but its use is constrained by decentralised production, collection logistics and high water content.

Figure 6 highlights the spatial distribution of two relevant biogenic feedstock sources. Table 2 in Appendix A1 reports annual residue and manure masses, corresponding energy potential and national shares for key crops (rice, banana, coffee, sugarcane, corn, oil palm) and livestock (poultry, cattle, pigs) in the three focus departments versus

Colombia, highlighting Valle del Cauca's dominance in sugarcane and manure streams and Bolívar's strong rice and corn residues.

These differentiated feedstock profiles directly inform the first-mover concept selection in Chapter 4: landfill gas underpins the Bolívar methanol concept, while sugarcane residues and bioethanol form the core resource base for the Valle del Cauca SAF concept.

Infrastructure, product offtakers and constraint areas
Infrastructure analysis confirms that Cartagena and Barranquilla benefit from dense natural gas pipeline networks, spatially developed high-voltage transmission grids at 220–500 kV, multiple free trade zones (15 in Cartagena, 9 in Barranquilla, 12 in Valle del Cauca as of 2025), and established port infrastructure for chemical product handling. Refinieries, ports, airports and fertilizer production, provide existing downstream integration anchors for methanol, ammonia and SAF. In addition, the existing multipurpose pipelines may offer a future logistics option for SAF, but compatibility, product-segregation requirements, access rights and required modifications must be assessed with the pipeline operator. Utilization of existing pipelines for SAF distribution to major hubs such as Bogotá, Medellín and Barranquilla could reduce the need for new dedicated transport infrastructure.
Figure 7 presents an overview of existing power transmission and gas pipeline infrastructure, alongside recorded conflict-related fatalities between 2020 and 2024 [23].

Grid expansion remains a material constraint in all three departments: the transmission network faces congestion, and new large-scale PtX loads will require dedicated connection concepts, new substations, and alignment with transmission expansion queues, largely outside the direct control of project developers.

Railway infrastructure lacks the electrification and reliability for fuel transport without major investment, and DME blending into existing LPG pipelines is technically feasible only up to a 20% share.

Conflict areas, predominantly affecting rural and border regions, are of moderate relevance for the focus departments, with Atlántico showing the lowest conflict event density of the three, though security, insurance, and bankability implications must still be factored into project planning [23]. Environmental and cultural protection requirements — indigenous reserves, black community councils, forest reserves, Ramsar wetlands, and national/departmental protected areas — are largely manageable in Atlántico and near Cartagena, while southern Bolívar and the eastern/western flanks of Valle del Cauca require more careful site selection and stakeholder engagement.

Free trade zones in the focus departments offer a reduced 20% income tax rate on export income, versus the standard 35%, and customs exemptions on imported equipment, though they provide no PtX-specific financial incentives.

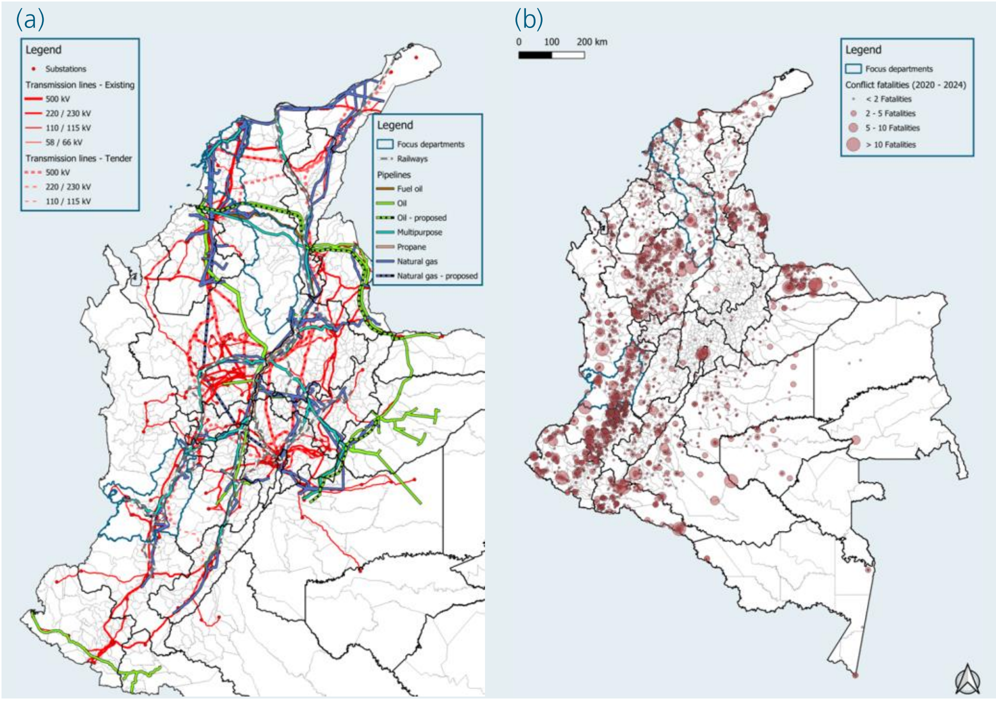


Figure 7: Spatial distribution of (a) high-voltage power transmission lines, gas pipeline corridors, and (b) conflict-related fatalities (2020–2024) [23]

Hydrogen project evaluation tool and project roadmap

The project-landscape review indicates a material gap between announced capacity and an FID-ready pipeline. The MCDA framework developed in Phase 1 can support a future project-by-project assessment of development stage, regulatory readiness, infrastructure access and information completeness. However, the tool was not applied to all 72 projects within the scope of this report. The review underlines the strategic importance of a small number of bankable first-mover projects — such as those conceptualized in Chapter 4 — as catalysts that can de-risk the broader Colombian hydrogen and PtX market and demonstrate bankability to subsequent waves of investors.

A further Phase 1 output is a structured roadmap for hydrogen project development, covering six phases from concept development through operation and optimization:

1. Concept Development and Pre-Feasibility
2. Project Definition and Feasibility
3. Engineering, Procurement and Permitting
4. Construction
5. Commissioning and Start-Up
6. Operation and Optimization

The roadmap defines building blocks for each phase, including market and resource assessment, plant site selection, initial concept design, financial analysis, permitting, environmental impact assessment (EIA), front-end engineering design (FEED), procurement, construction, and operations. This framework serves as a practical reference for project developers in Colombia to structure their activities and identify the critical path to FID, and is applied as the underlying logic for the "next steps" sections of each first-mover concept in Chapter 4. The roadmap is visualized in Figure 8.

Figure 8: Six-phase project development pathway for Hydrogen and Power-to-X projects, covering concept development, feasibility and permitting, engineering and procurement, construction, commissioning, and operation and optimization.

4 Results – Phase 2: First-Mover Project Concepts

Chapter 4 introduces the PtX, BtX and PBtX project potential at department level and then narrows down to the most promising site-specific opportunities in Bolívar, Valle del Cauca and Atlántico. In each department, one selected project concept is subsequently described in greater technical, economic and regulatory detail, providing a concrete first-mover blueprint for implementation. Each concept is accompanied by a dedicated highlight module (for example, a technical deep-dive for Bolívar or priority cost-reduction levers for Atlántico) to illustrate critical design and bankability insights.
The companies identified in this study as potential offtakers, anchors, stakeholders or technology providers arise from the methodological process. Their inclusion does not imply formal partnership, commercial relationship, purchase agreement, investment decision, or commitment to participate in future Power to X projects on the part of the organizations mentioned. Nor does it constitute an exhaustive list or a preference over other companies operating in the same market; other actors not mentioned in the study may be equally suitable depending on the future evolution of the project, the market, and commercial conditions. The flagship projects are conceptual case studies and should not be interpreted as finalized project structures or confirmed commercial agreements.

4.1 Bolívar Concept: Methanol from Landfill Gas

Department overview
Bolívar, with Cartagena as its central hub, offers highly favorable starting conditions for a first-mover PtX project. The region combines major industrial assets (including Ecopetrol's Reficar refinery and Yara's 130 kt/a ammonia plant) with established port infrastructure at Cartagena and Mamonal, and several free trade zones, creating a strong basis for industrial integration and export-oriented project development. The renewable energy base is dominated by solar PV, supported by high irradiation levels in the identified PV clusters, whereas wind potential is limited and local hydropower is not available.

In addition, Bolívar provides a comparatively diverse biogenic feedstock base, including several landfills, the Cartagena wastewater treatment plant, and relevant rice, corn, and oil-palm residues in central and southern parts of the department. This feedstock profile, together with the existing gas pipeline network, refinery integration potential, free trade zones, and strong maritime logistics, makes Cartagena particularly suitable for residue-based and industrially integrated PBtX concepts. Potential offtake anchors include Yara, Reficar, Rafael Núñez Airport, and the Cartagena port system, although these should at this stage be treated as preliminary market interfaces rather than secured customers. Key constraints remain grid capacity, renewable electricity cost, limited water availability from the Canal del Dique, and land-use restrictions linked to forest and peasant-reserve zones in southern Bolívar.

Building on these favorable starting conditions, the Bolívar screening identified a broader portfolio of

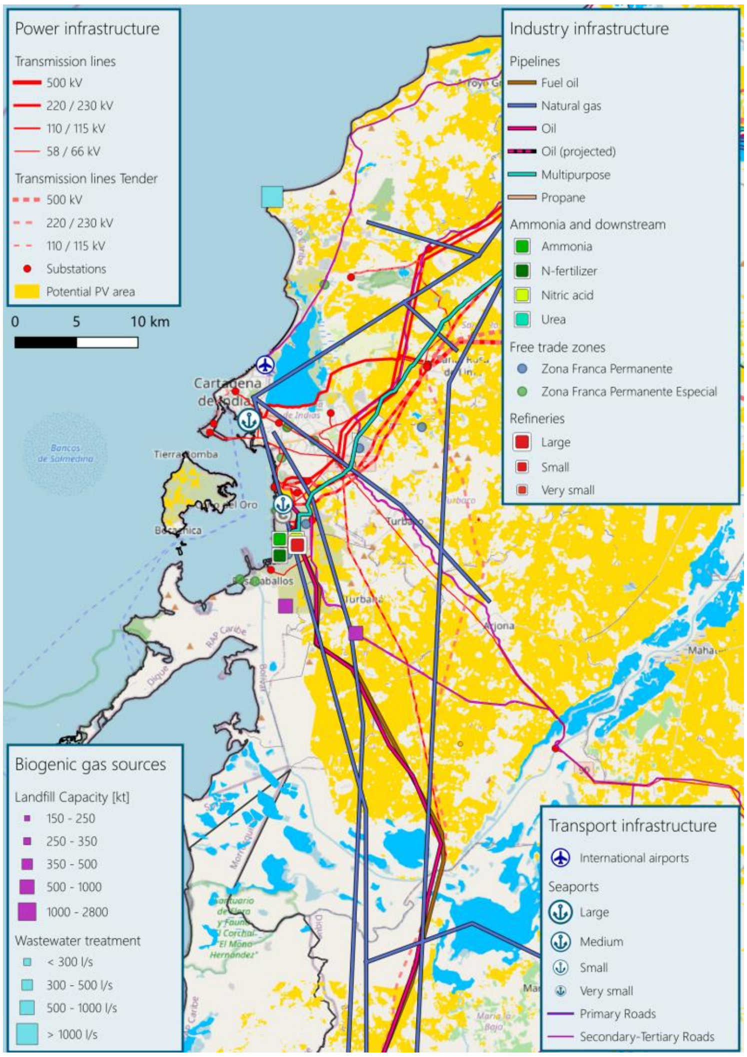


Figure 9: Department-level PtX/PBtX overview for Bolívar, showing renewable resources, biogenic feedstocks, infrastructure & offtake anchors

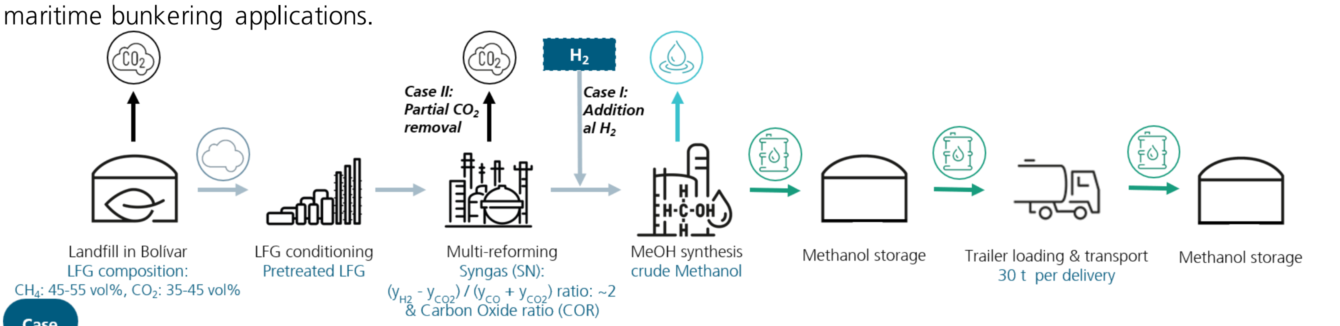
potential first-mover concepts beyond the selected landfill-gas-to-methanol pathway. These included SAF from landfill gas via a methanol-to-jet route at Reficar, biomethane injection from landfill gas, renewable hydrogen for partial substitution in Yara's ammonia value chain, as well as wastewater- and rice-residue-based methanol concepts. Taken together, these options underline that Bolívar is not only suitable for a single project idea, but constitutes a broader PtX/PBtX opportunity space centered on Cartagena's combination of industrial integration, residue availability, and port-based offtake interfaces.

Selected project concept

The preferred first-mover concept in Bolívar is a medium-scale methanol plant based on captured landfill gas from one of the local landfills. Landfill gas is converted to syngas via multi-reforming and subsequently upgraded to methanol using a conventional $Cu/ZnO/Al_2O_3$ synthesis route, as highlighted in Figure 10. Two process configurations were assessed:

- **Case I:** no CO_2 removal, with supplementary H_2 from a small PEM electrolyzer powered by dedicated solar PV
- **Case II:** CO_2 removal without additional H_2

The resulting methanol output is intended for trailer-based transport either to the Reficar refinery or to the Port of Cartagena, where it could serve refinery integration needs or maritime bunkering applications.



Case									
I	LFG	9.6 Mio. Nm³/a	9.3 Mio. Nm³/a	~15.82 kt/a	0.72 kt_{H2}/a	~11.32 kt/a	3 x 100 m³	7 deliveries per week	3 x 200 m³
II	LFG	9.6 Mio. Nm³/a	9.3 Mio. Nm³/a	~9.85 kt/a	-	~7.35 kt/a	2 x 100 m³	5 deliveries per week	2 x 200 m³

Figure 10: System layout for the LFG-based methanol production in Bolívar

From a strategic perspective, this concept combines several advantages that make it attractive as a first-mover option. It draws on an available non-utilized landfill gas stream that is already collected at site, thereby avoiding dependence on entirely new upstream feedstock chains. At the same time, it relies on comparatively mature conversion technologies and a predominantly biogenic carbon source that aligns well with RED III advanced biofuel classification. This creates a comparatively robust regulatory basis while also opening two promising offtake pathways through refinery integration and maritime fuel supply in Cartagena.

Highlight: Technical insights

The following section provides a detailed technical exploration of the field of reforming and is based in part on the activities of the Fraunhofer SHIFT project (Sector Coupled Systems for Heat, Industry, Fuels and Transport in Chile, Fraunhofer ISE (2024)). The developments were adapted to local conditions and feedstocks and updated as part of the PtX-COL 2.0 project.
The objective of the developed project concept is to evaluate alternative process configurations for converting available biogenic landfill gas (LFG) from a local landfill into methanol and to identify the principal cost drivers along the conversion chain. In

particular, the assessment compares syngas adjustment strategies based on renewable H_2 addition via electrolysis and on CO_2 removal, while maintaining a constant syngas stoichiometric number (SN ≈ 2), which is required for efficient methanol synthesis.

As illustrated in the process flow diagram (PFD) and economic assessment summarized in Figure 12, both (Case I and Case II) share the same methanol synthesis section, whereas the upstream syngas production route is modified to achieve the target syngas composition. This techno-economic modelling framework enables a direct comparison of the influence of syngas production on methanol yield and overall process economics.

The technical analysis is based on a simplified PFD integrating landfill gas, syngas production, syngas compression and downstream methanol synthesis. The modelling confirms that methanol production from landfill gas is technically feasible, however, it is highly sensitive to the selected syngas production strategy, including gas pretreatment and multi-reforming [24].
To ensure comparability between the investigated process configurations (Case I and Case II), the methanol synthesis loop was kept identical, while only the syngas conditioning section was varied to reach the required stoichiometric number (SN~2). The raw landfill gas is a biogenic CO_2-rich stream with typical compositions of CH_4 45-55 vol.% and CO_2 35-45 vol.%, along with trace impurities. Accordingly, additional processing steps are required prior to syngas production, following state-of-the-art gas pretreatment including desulfurization, dewatering, and removal of trace contaminants [25].

Following pretreatment, the approximately 13.05 kt/a biogenic landfill gas undergoes multi-reforming, comprising catalytic Partial oxidation (POX), steam-reforming (SR), and dry-reforming (DR), complemented by process-specific syngas adjustment to obtain the required synthesis gas composition. In the hydrogen-assisted configuration (Case I), renewable hydrogen supplied by a dedicated PEM electrolyzer ~ 20 $MW_{el.}$ is added to increase the H_2/CO_x ratio and improve carbon utilization, resulting in a methanol production of approximately 11.3 kt/a. In the CO_2-removal configuration (Case II), the syngas composition is adjusted by removing excess CO_2 upstream of multi-reforming and methanol synthesis, yielding approximately 7.4 kt/a.

To enable delivery of the syngas to the methanol synthesis section, the syngas-compression stage employs multistage compression with intermediate cooling to raise the syngas pressure to the synthesis-loop pressure. This section is represented explicitly in the process layout, since compression requirements contribute materially to both electricity demand and capital cost. For the methanol loop itself, the reaction kinetics were modeled using a Fraunhofer ISE kinetic reactor model developed and experimentally validated on an industrial catalyst ($Cu/ZnO/Al_2O_3$). Phase separation in the condenser and flash unit was represented using an experimentally validated thermodynamic model, while compressors and heat exchangers were modeled on the basis of mass and energy balances [26], [27].

To ensure a consistent comparison between the process configurations, the multi-reforming sub-process was operated at 800 °C and atmospheric pressure, while the methanol synthesis loop was maintained at 76 bar and 250 °C using a kinetic reactor model [26], [27]. The reforming conditions were selected to achieve a target syngas stoichiometric number (SN ≈ 2), with carbon formation mitigated through the controlled addition of O_2 and/or H_2O. These operating conditions were chosen to provide a robust basis for comparative assessment; however, further optimization of the integrated reforming and methanol synthesis process, together with rigorous experimental validation of the reactor models, is still required to improve predictive accuracy and overall process performance.

The presence of inert species in biogenic syngas, particularly nitrogen and methane, requires a purge stream to prevent their accumulation in the methanol loop. The purge design therefore involves a trade-off between hydrogen efficiency and methanol yield on the one hand, and recycle ratio and plant size on the other: lower purge fractions improve reactant utilization but lead to higher inert accumulation, which in turn increases recycle flow rates and thus equipment sizing and capital expenditure. This effect is particularly relevant for biogenic feedstocks, where inert concentrations are non-negligible.

For the techno-economic comparison, the normalized net conversion cost (NCC) was used as the main economic indicator. The NCC includes annualized capital expenditures, calculated by the annuity method [28], as well as total operating expenditures associated with converting biogenic landfill gas into crude methanol. Feedstock costs were excluded due to the lack of reliable pricing data for landfill gas, enabling a consistent comparison of the process configurations. Equipment costs were derived from literature-based cost tables and converted into regression curves, allowing calculation of specific equipment costs for the simulated capacities. Peripheral costs and standard industrial cost adders were subsequently included using established factorial method [28].

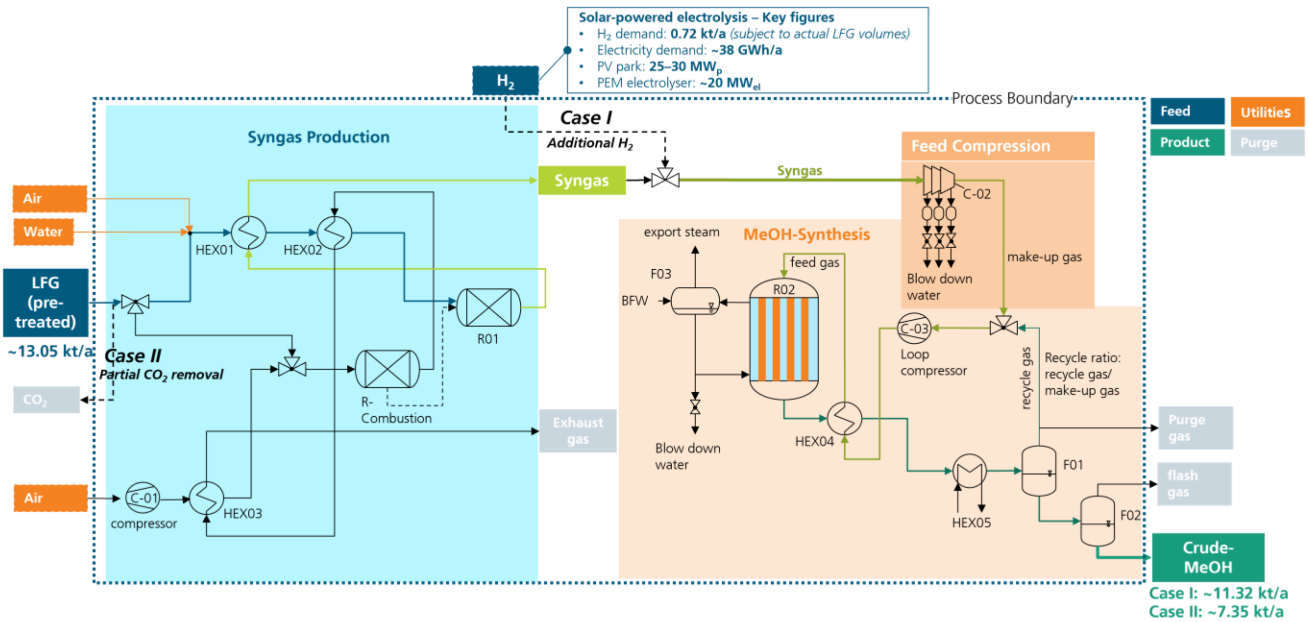


Figure 11: Process flow diagram for Case I syngas production based on reforming of landfill gas and subsequent methanol synthesis.

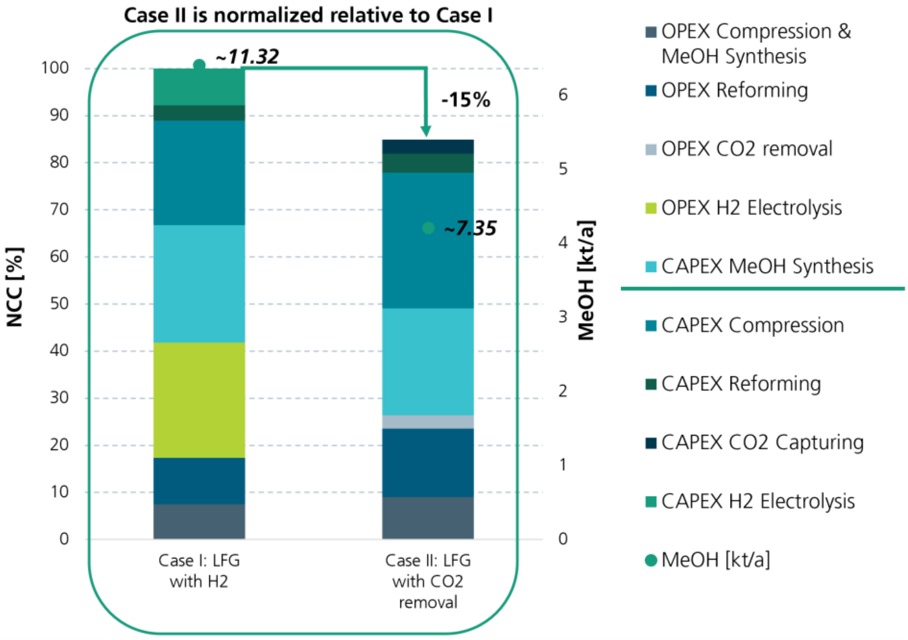


Figure 12: Case I and case II normalized net conversion costs (NCC) of methanol production (NCC = solely investment and operational cost associated with reforming, electrolysis, synthesis and purification process steps, i.e. without feedstock costs)

Although Case I achieves higher methanol output, this benefit is offset by higher NCC values, primarily due to the additional capital and operating costs of electrolysis. In contrast, Case II reduces the normalized conversion cost by approximately 15% relative to Case I, indicating that the preferred configuration depends on whether the project prioritizes maximum methanol production and carbon utilization or lower conversion costs through a simpler system configuration. The figure therefore illustrates a clear trade-off between production capacity and economics.

From a regulatory perspective, the underlying landfill gas stream is predominantly classified as advanced biofuel feedstock with a minor recycled-carbon fraction under EU RED III, providing a comparatively robust basis for compliance-grade methanol, provided that the overall system design and certification route are aligned with advanced-biofuel rules.

Technology maturity

Most sub-processes of the landfill-gas-to-methanol concept are based on commercially proven technologies. Landfill-gas pretreatment, syngas compression, conventional $Cu/ZnO/Al_2O_3$ methanol synthesis, product purification, storage, and the use of solar PV and PEM electrolysis as standalone units are all at high technology readiness levels. The main technological challenge lies in the multi-reforming step, where real landfill-gas composition and variability must be accommodated without compromising syngas quality. The more critical issue overall is system integration: combining reforming, syngas adjustment, and stable methanol synthesis under fluctuating landfill-gas conditions while maintaining reliable plant performance and emissions compliance.

Key risks

The concept is exposed to several specific risks. Feedstock quantity and quality may change over time, both at the shortlisted landfills in the Cartagena area, affecting plant utilization and syngas quality. In Case I, economic performance is highly sensitive to the cost of renewable hydrogen and associated electricity, which can erode the advantage of higher methanol output. In both cases, the project requires a robust certification and offtake pathway in a context where there is no strong domestic methanol mandate, making market access reliant on export and niche applications. Overall, the concept remains a promising first-mover opportunity, provided that feedstock validation, process integration, and market access are de-risked in a coordinated manner. A detailed breakdown of technological readiness level and integration risks for the individual process steps is presented in Appendix A2.

Next steps

Immediate next steps should focus on three areas: (1) detailed feedstock characterization and long-term supply assessment at at the shortlisted landfills in the Cartagena area; (2) process simulation work on multi-reforming and syngas control under real landfill-gas conditions, including Case I/Case II comparison; and (3) early engagement with potential offtakers and certification bodies to define credible export, bunkering, and sustainability pathways for landfill-gas-based methanol.

4.2 Valle del Cauca Concept: SAF from Bioethanol and Residues

Department overview

Valle del Cauca provides highly favorable conditions for biomass- and SAF-oriented PtX development due to the strong concentration of sugarcane industry assets in the Cauca River valley. As depicted in Figure 13, the department comprises several sugar mills, including five sites with co-located bioethanol production, and therefore offers access to substantial volumes of bagasse, sugarcane harvest residues, and high-purity fermentation CO_2. This biogenic resource base is complemented by extensive hydropower availability, existing high-voltage grid infrastructure, and Pacific export access through Buenaventura and Puerto Industrial de Aguadulce. Although the region has less heavy-industry demand than the Caribbean coast, its industrial structure is particularly compatible with SAF production pathways based on ethanol and residues.

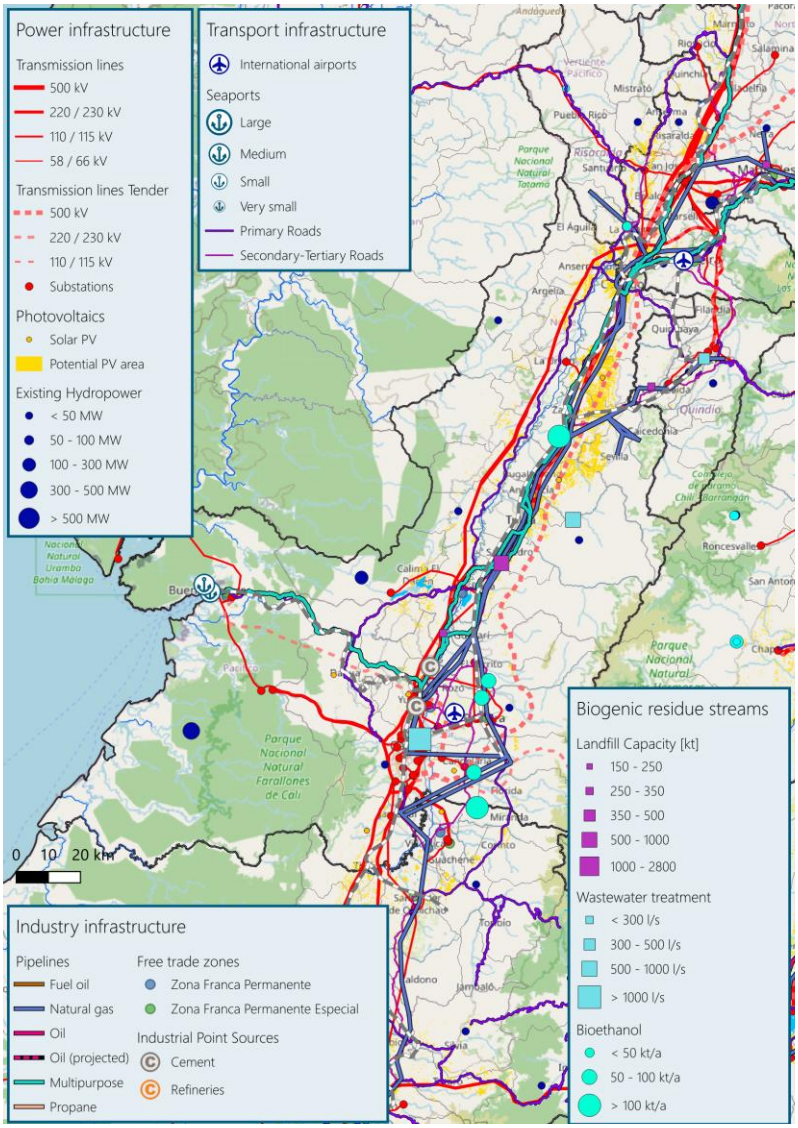


Figure 13: Department-level PtX/PBtX overview for Valle del Cauca, showing renewable resources, biogenic feedstocks, infrastructure and key offtake anchors

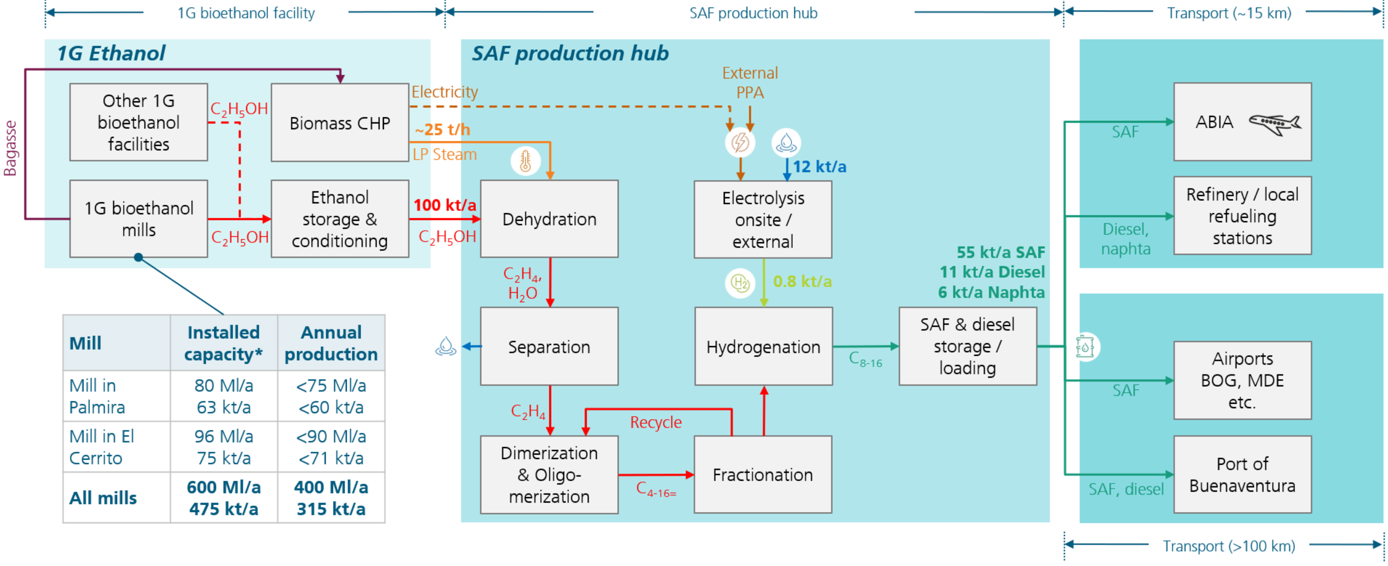
Project development in Valle del Cauca is shaped by a different constraint profile than in Atlántico or Bolívar. Solar PV deployment is comparatively constrained by land-use and grid conditions along the Cauca corridor, while socio-environmental restrictions, zoning complexity, and water availability from the Río Cauca constitute the main structural challenges. These constraints may be further intensified during El Niño-related drought periods and should therefore be treated as central design and bankability considerations from the outset.

Against this backdrop, the Valle del Cauca screening revealed a broader portfolio of potential first-mover concepts beyond the selected ATJ-based SAF pathway. These included SAF from sugarcane residues via gasification and Fischer–Tropsch synthesis, e-methanol from biogenic fermentation CO_2 and renewable hydrogen, methanol from landfill gas, biomethane from landfill gas, and biochar-based fertilizers from sugarcane residues. Taken together, these options underline that Valle del Cauca is not only a strong location for one specific SAF concept, but a wider PtX/PBtX opportunity space built around the region's sugarcane cluster, biogenic carbon availability, existing CHP and industrial infrastructure, and export access via Buenaventura.

Selected project concept

The selected concept for Valle del Cauca is sustainable aviation fuel (SAF) production via Alcohol-to-Jet (ATJ) conversion of first-generation (1G) bioethanol from sugar mills, with a phased pathway toward a second-generation (2G) extension using bagasse and sugarcane harvest residues (RAC) as lignocellulosic feedstock. In the initial phase, the ATJ route converts bioethanol into SAF through dehydration, oligomerization, hydrogenation, and fractionation, delivering an ATJ synthetic paraffinic kerosene

(ATJ-SPK) blend that complies with ASTM D7566 Annex 5 and is compatible with existing jet fuel infrastructure.



Mill	Installed capacity*	Annual production
Mill in Palmira	80 Ml/a 63 kt/a	<75 Ml/a <60 kt/a
Mill in El Cerrito	96 Ml/a 75 kt/a	<90 Ml/a <71 kt/a
All mills	**600 Ml/a** **475 kt/a**	**400 Ml/a** **315 kt/a**

Figure 14: System layout for 1G-ATJ plant in Valle del Cauca

The 2G phase is designed to build on this platform by integrating lignocellulosic feedstock supply chains and expanding SAF volumes while moving into advanced-biofuel territory under EU RED III. The system layout for the 1G plant is visualized in Figure 14.

The preferred technology licensor for the ATJ conversion step is LanzaJet, whose Freedom Pines Fuels facility in Georgia represents the world's first commercial-scale ethanol-to-SAF plant and provides a fully operational reference for ethanol-based ATJ technology. Topsoe's ATJet™ solution and Axens/IFP Energies Nouvelles' ATJ offerings are considered as competing technology options and provide an additional benchmark for process design and performance. On the feedstock side, primary partners are the local sugar mills in Palmira and El Cerrito, both ISCC-certified bioethanol producers located in the Cauca River valley and strategically positioned as co-location hosts for the ATJ conversion facility. Their integration potential, combined with the region's hydropower and biomass CHP base, makes Valle del Cauca a particularly suitable location for a sugarcane-based SAF hub.

Highlight: Site selection

The site-selection analysis for the Valle del Cauca ATJ concept in Figure 15 compares a dual-mill configuration at the southern sugar mill with a single-site option in the northern part of the valley. The southern cluster offers two ISCC-certified mills with 130–150 kt/a combined 1G ethanol output, direct access to sugarcane residues for future 2G expansion, and strong CHP synergies, as well as the

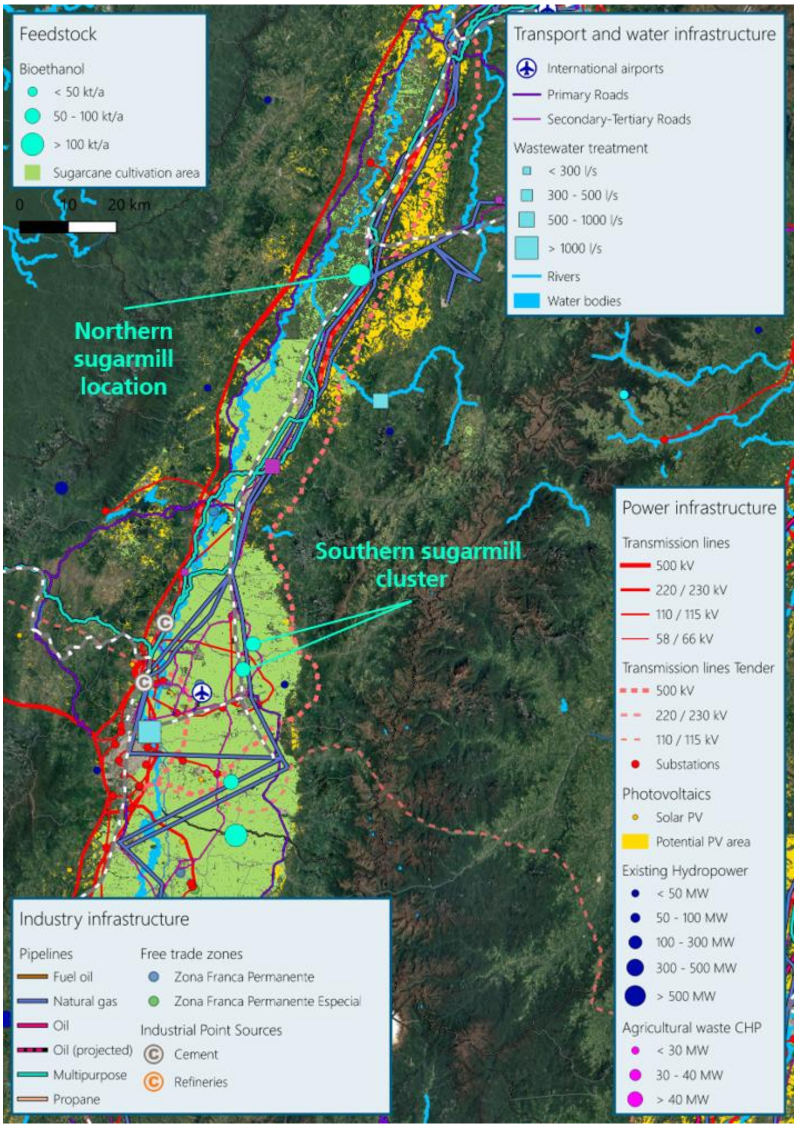


Figure 15: GIS-based site selection map for the Valle del Cauca ATJ SAF concept around selected sugar mill locations in Valle del Cauca.

shortest tanker route to Alfonso Bonilla Aragón Airport for initial SAF offtake. The northern sugar-mill location, by contrast, provides closer proximity to the Cauca River and the multipurpose pipeline corridor, which could enable low-cost SAF distribution at scale to Bogotá and other demand centers via pipeline tie-in, but relies on a single large ethanol source and longer export distances to Buenaventura. Overall, Table 1 concludes that the southern cluster constitutes the preferred first-mover site due to feedstock redundancy, proven CHP integration and airport access, while the northern sugarmill location remains a viable alternative if pipeline-based SAF distribution to major refineries and airports becomes the dominant offtake route.

Table 1: Site selection comparison for the Valle del Cauca ATJ SAF concept (Southern cluster versus northern location)

	Southern sugarmill cluster	Northern sugarmill location
Feedstock availability	• Two ISCC-certified mills: combined ~130–150 kt/a 1G ethanol • Dual-mill redundancy reduces supply concentration risk • Located within the sugarcane cultivation belt → direct RAC/bagasse access for 2G extension	• Single largest mill with significant ethanol output • Lower combined 1G volume for a large ATJ plant • Northern belt fringe → longer 2G residue logistics from southern cultivation areas
Water availability	• River Cauca is the primary source; CORPOCAUCA permit pathway • Treated wastewater (Cali WWTP) available as backup • Slightly longer distance to Cauca vs. Riopaila	• Closer proximity to River Cauca → shorter intake conveyance • Same CORPOCAUCA permitting requirements and El Niño drought risk apply • Relevant advantage in distance
Transport & offtake infrastructure	• ~15 km road tanker to ABIA for initial anchor volumes • Road tanker distribution to broader domestic jet fuel network or export via Buenaventura (~100 km) • No direct pipeline in proximity (~17 km) for large-volume, low-cost SAF distribution to major demand centers	• Adjacent to the multipurpose pipeline corridor connecting refineries to major airports including Bogotá El Dorado • A short pipeline tie-in (~1–2 km) could enable batch injection of SAF into the existing jet fuel distribution system without dedicated trucking • Port of Buenaventura (~170 km) available for export
Renewable energy & utility synergies	• Onsite biomass CHP at both mills (LP steam directly usable for ATJ dehydration/distillation) → avoids dedicated process boiler • Grid-connected; Small-scale PV areas available along Cauca corridor with land-use constraints	• Comparable biomass CHP at cogeneration complex • Better access to potential large-scale flat PV areas → RE availability for onsite electrolysis • PV advantage is secondary for ATJ (H_2 demand limited to hydrogenation step)
Summary	✅ Dual feedstock redundancy, shortest path to ABIA, 2G extension feedstock proximity, and proven CHP integration make this the **preferred first-mover site**. However, full-scale offtake beyond ABIA requires road-based distribution or export logistics, as no pipeline access exists for cost-efficient delivery to major airports	⚠️ **Viable alternative** due to pipeline proximity enabling low-cost SAF delivery at scale to Colombia's largest aviation demand centers. Becomes the preferred site if SAF volumes exceed ABIA absorption capacity or if pipeline tie-in can be developed easily. However, the 2G logistics may provide a feasibility bottleneck

Economics

The economics of the Valle del Cauca SAF concept are dominated by ethanol supply cost, which accounts for roughly 75–80% of total operating expenditure in the 1G ATJ configuration. At an optimistic ethanol price of around 1,000 USD/t, indicative levelized SAF production costs remain below 2,000 USD/t_{SAF}; if ethanol prices increase to approximately 1,200 USD/t, SAF costs move toward 2,500 USD/t_{SAF}. Capital expenditure for a first-of-kind ATJ project in Colombia is expected to exceed 100 MUSD, covering the ATJ conversion unit, hydrogen supply, storage, utilities, and contingencies. Long-term ethanol supply contracts with partner mills at prices below 1,000 USD/t therefore represent the single most important lever for economic viability.

Regulatory market positioning

The 1G sugarcane-ethanol ATJ pathway may provide an initial route into Colombian, CORSIA-eligible and voluntary SAF markets, subject to the applicable sustainability and certification requirements. It cannot, however, count toward the ReFuelEU Aviation SAF mandate because aviation fuels produced from food and feed crops, including sugar crops, are excluded from the mandate calculation. The recommended strategy is therefore to treat the 1G facility as an initial non-ReFuelEU market platform and to develop a subsequent 2G pathway based on qualifying bagasse and sugarcane harvest residues, which may access the ReFuelEU compliance market as an advanced-biofuel pathway subject to certification and lifecycle-GHG compliance.

Book & Claim could become an important future option, but it should not be treated as the core route to market at this stage. The European Commission is assessing the feasibility of further flexibility mechanisms, but the timing, design and eligibility conditions of any future Book & Claim mechanism remain uncertain. The business case should therefore not rely on its introduction. Until an applicable mechanism is formally established, Colombian SAF intended to contribute to the ReFuelEU Aviation mandate must be physically supplied to, and uplifted at, Union airports in accordance with the Regulation's requirements.

The 2G extension is therefore the decisive step for a long-term EU compliance-market strategy. It should be developed in parallel with the 1G concept, including early confirmation of residue availability, sustainability certification, traceability, lifecycle-GHG performance, technology integration and offtake arrangements.

Key risks

The concept faces four main risk clusters. First, ethanol price volatility driven by global sugar markets and domestic blending policy directly affects SAF production costs and margin. Second, land-use and zoning constraints around mills can slow or restrict siting of ATJ facilities, making early engagement with municipalities and communities essential. Third, the exclusion of food- and feed-crop-based aviation fuels from the ReFuelEU Aviation mandate prevents 1G sugarcane-ethanol ATJ from serving the mandated EU SAF market and makes development of a qualifying 2G pathway important for accessing regulated EU demand. Fourth, there is dependency on the selected technology licensor and limited local operational experience with ATJ technology, which together introduce implementation and ramp-up risk. A detailed breakdown of technological readiness level and integration risks for the individual process steps is presented in Appendix A2.

Next steps

Immediate next steps should concentrate on four tightly coordinated workstreams. First, structure long-term ethanol supply agreements with priority mills at target price levels, explicitly incorporating scalable options for 2G feedstock and product integration over time. Second, move siting and permitting forward early through targeted zoning, water, and socio-environmental assessments, so that land-use and community constraints are resolved before major CAPEX commitments. Third, refine the 1G/2G phasing strategy in light of evolving EU RED III and CORSIA rules, coupling this with detailed offtake negotiations with domestic and EU airlines to secure bankable SAF volume, tenor, and premium structures. Fourth, negotiate technology licensing and technical-support packages that de-risk first-of-a-kind ATJ deployment and systematically build local operating, maintenance, and certification capability along the full SAF value chain.

4.3 Atlántico Concept: Renewable Ammonia for Local Fertilizers

Department overview

Barranquilla is characterized by a comparatively favorable infrastructure base for early PtX deployment. The department benefits from a dense natural gas pipeline network, a spatially-developed 220 kV transmission grid with ongoing expansion tenders, established chemical and fertilizer logistics through the Port of Barranquilla, and the presence of an established fertiliser-production complex as a potential industrial anchor with existing downstream demand for ammonia-based products. Solar PV represents the primary renewable energy source, while offshore wind could provide a medium-term complement after 2032 following the 425 MW offshore award in December 2024. By contrast, the regional biogenic feedstock base is relatively narrow and mainly comprises two local landfills, the Barranquilla wastewater treatment plant, biodiesel glycerol residues, and paper-mill residues. At the same time, renewable power cost and grid congestion remain the key structural constraints for project realization.

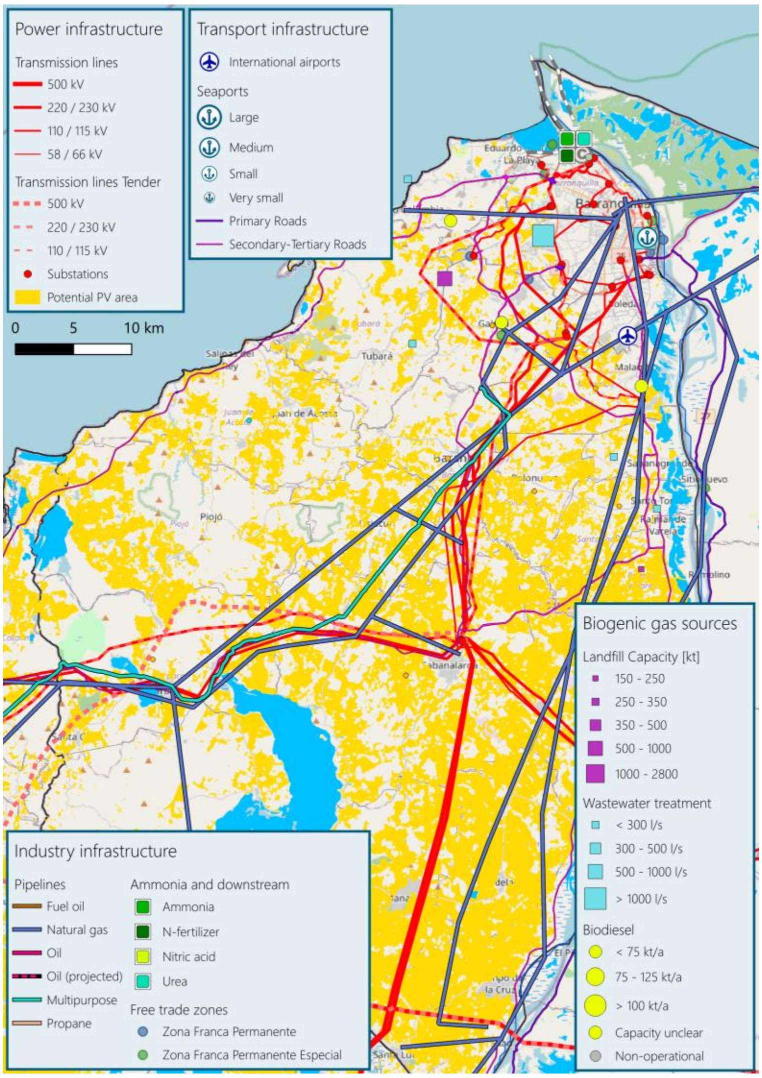


Figure 16: Department-level PtX/PBtX overview for Atlántico, showing renewable resources, biogenic feedstocks, infrastructure and key offtake anchors

Colombia currently imports the large majority of its ammonia demand, and the local fertiliser complex itself relies heavily on imported fossil ammonia to supply its downstream fertilizer and nitrogen-chemical production, exposing the country to global ammonia price volatility and foreign-exchange risk. This existing fossil import dependency is a central strategic rationale for the selected concept, since a domestically produced renewable ammonia stream can directly displace imported volumes.

In line with these conditions, the Atlántico screening identified a broader set of project concepts beyond the selected renewable ammonia pathway. These included methanol and biomethane from wastewater-based biogenic gas at Barranquilla treatment sites, methanol from captured landfill gas, and methanol from biodiesel glycerol residues in the Galapa area. Taken together, these concepts show that Atlántico's opportunity space is not limited to large-scale PtX ammonia, but also includes smaller hybrid BtX/PtX options linked to existing waste and by-product streams, even if their scale and economics are generally less favorable than the ammonia concept selected for deeper assessment.

Selected project concept

The selected first-mover concept is a large-scale renewable ammonia facility targeting approximately 100 kt/a of green ammonia, with approximately 60 kt/a replacing current fossil ammonia imports at the local fertiliser complex and approximately 40 kt/a designated for export or maritime bunkering. The system layout in Figure 18 combines a co-located solar PV and battery energy storage system (BESS) park, hybrid PEM/alkaline electrolysis, a flexible Haber–Bosch synthesis loop (three-stage feed compression, three adiabatic reactor beds with intercooling operating at 150–200 bar and 350–400 °C reactor inlet temperature), and a cryogenic air separation unit, delivering liquid ammonia at −33 °C and 99.98 mol% purity. The concept could leverage existing on-site ammonia storage, port loading infrastructure, and downstream fertilizer logistics, reducing market-entry barriers versus a greenfield development. The indicative new-build plant footprint outside the renewable electricity supply is estimated at 8–12 hectares, dominated by electrolysis and safety/logistics buffer areas, and highly dependent on final power supply and hydrogen storage sizing.

Economics and key levers

Establishing an offshore wind and PV-driven green ammonia production chain results in costs in the range of approximately 1,200–1,300 EUR/t, against a grey ammonia import benchmark of approximately 530–660 EUR/t. Four priority levers were identified to reduce the cost gap: (1) mass-balance-based production split applying RFNBO-compliant rules to the export share and Colombian grid-balancing to the domestic share (as highlighted in Figure 17); (2) a hybrid alkaline + PEM electrolyzer configuration to improve full-load hours while maintaining flexibility; (3) a flexible Haber–Bosch synthesis with wide operational window to reduce intermediate hydrogen storage requirements and renewable electricity curtailment; and (4) joint optimization of PV, BESS, grid access, electrolyzer sizing, and hydrogen storage using Fraunhofer ISE's H2ProSim or an equivalent hourly-resolved simulation and optimization tool.

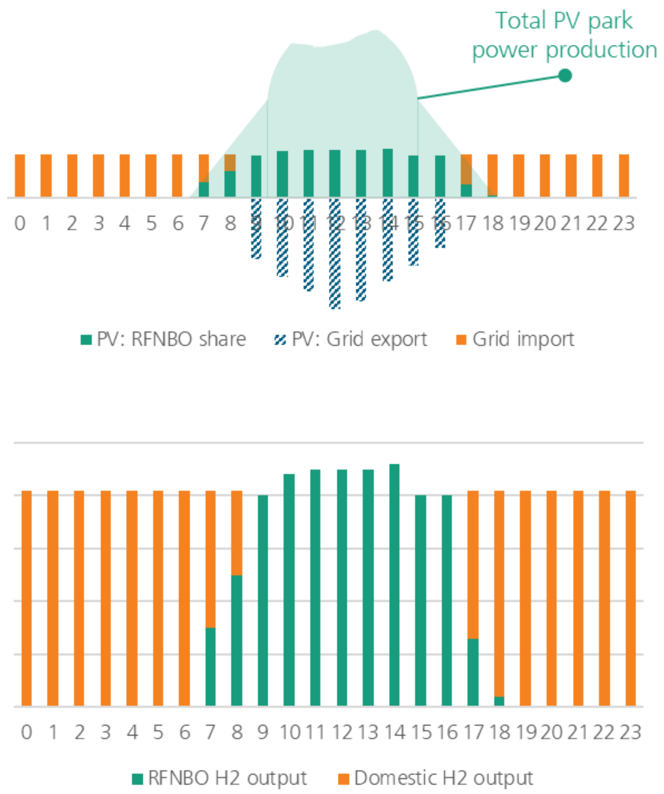


Figure 17: Simplified daily production split without battery / PPA / congestion for power shares (top) and corresponding hydrogen shares (bottom)

Technology maturity

The sub-process technology risk assessment confirms that solar PV, alkaline electrolysis, ASU, ammonia storage, and HVAC transmission are all at TRL 9 and fully commercial. Flexible Haber–Bosch is at TRL 7–8 in 2026, reaching TRL 8–9 by 2030, with the first commercial-scale flexible green ammonia plants beginning operation globally. The fully integrated Power-to-Ammonia system (PV/Wind → BESS → HVAC → Electrolyzer → Flexible HB → Storage) is at TRL 7–8 overall, with primary risks related to low-cost renewable electricity access, system integration, regulatory uncertainty, and bankability of the full chain. A detailed breakdown of technological readiness level and integration risks for the individual process steps is presented in Appendix A2.

Key risks

The Atlántico ammonia concept is exposed to four principal risks. First, renewable electricity cost and overall power-system competitiveness remain the central economic challenge, as green ammonia production continues to be significantly more expensive than grey ammonia imports and therefore requires a highly optimized system design. Second, timely delivery of the required grid and water infrastructure is uncertain, particularly because key transmission upgrades lie outside the direct control of the project developers. Third, the concept is closely linked to a single fertiliser complex as potential industrial partner and anchor offtaker, creating dependencies related to cooperation, ownership structure, and offtake concentration. Fourth, regulatory and certification uncertainty persists. Although Resolution 0900 of 2026 has established a national low-emission-hydrogen threshold of 3.6 kg CO_2e per kg H_2 on a cradle-to-production-gate basis, a fully operational certification and chain-of-custody system aligned with EU requirements remains to be established; the export share would also need to comply with the detailed EU RFNBO qualification rules.

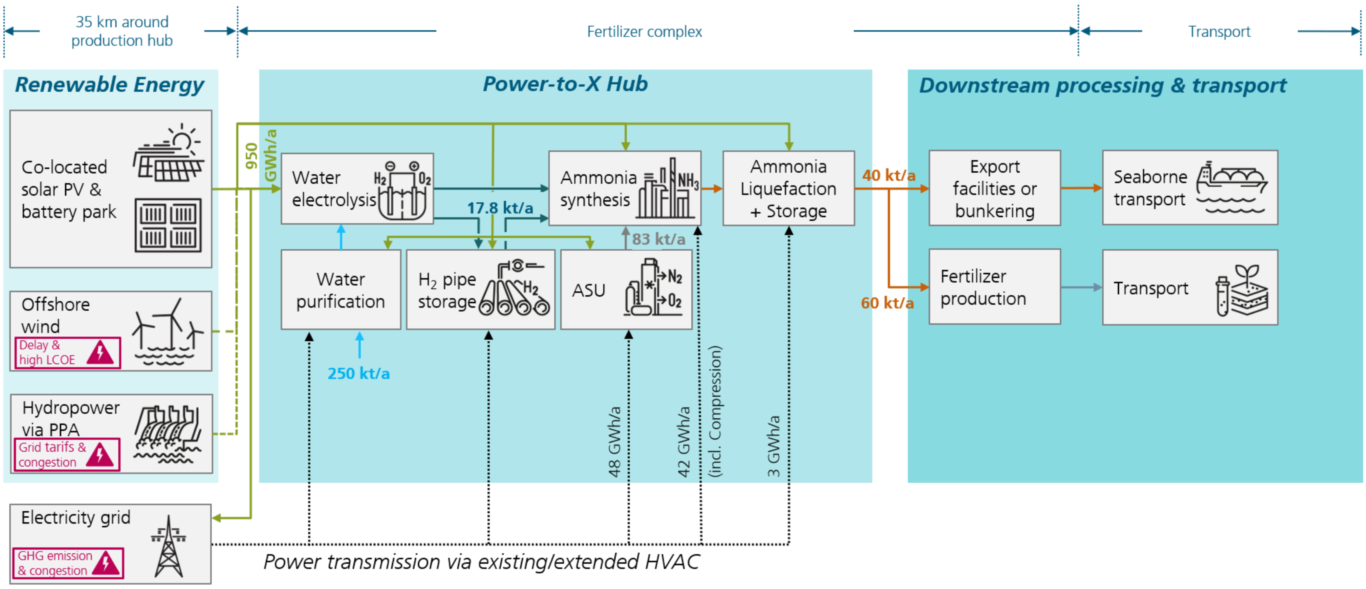


Figure 18: System layout for the Atlántico concept

Next steps

To advance the concept toward a bankable next phase, several immediate actions are recommended. These include establishing an alignment workshop with the relevant stakeholders, and rebaselining the power-supply concept in order to define the most suitable solar PV and battery energy storage configuration. In parallel, a detailed H2ProSim simulation should be carried out to optimize the domestic/export production split and the overall system configuration. On this basis, the project should move into a formal feasibility study and pre-FEED definition phase.

5 Findings and Recommendations

Power-to-X Colombia 2.0 demonstrates that Colombia's path to becoming a significant PtX exporter runs through two parallel tracks that reinforce rather than compete with each other. The large-scale, wind-and-solar-driven export model from La Guajira established in PtX Colombia 1.0 remains globally competitive but requires major infrastructure commitment and long-term political will. The hybrid PBtX first-mover approach developed in PtX-COL 2.0 offers a more immediately bankable entry point, grounded in existing industrial assets, proven technology routes, and a biogenic feedstock base that is unique in the global PtX landscape.

The regulatory environment has evolved materially in Colombia's favour. EU mandates for SAF and maritime fuels create growing compliance-driven demand for sustainable fuels, while Colombia's incentives for non-conventional renewable energy can support project economics. In 2026, Colombia closed two important policy gaps: Resolution 0900 established a maximum lifecycle-GHG intensity of 3.6 kg CO_2e per kg H_2 for hydrogen to be classified as low-emission, and CONPES 4210 established the country's first dedicated National Hydrogen Policy and an intersectoral roadmap through 2031. Further action is nevertheless required to accelerate transmission-grid expansion in the three focus departments, establish a fully operational certification and chain-of-custody system aligned with target-market requirements, and support early projects through bankable long-term offtake structures and targeted CAPEX support. For EU RFNBO markets, the transitional additionality exemption for installations commissioned before 1 January 2028 may benefit early projects until 2038, but temporal, geographical and lifecycle-GHG requirements still apply. Colombia stands at the beginning of a multi-decade transformation of its energy sector. The first-mover projects conceptualized in this study are the entry points to that transformation.

The results of PtX-COL 2.0 were presented to Colombian and European industry, investor, and policymaker stakeholders during the second project webinar on 14 July 2026. The resulting responses provide indicative stakeholder feedback on the perceived attractiveness of the concepts but should not be interpreted as a representative market survey or independent validation of technical or commercial feasibility. Among participating organizations, 48% ranked the Atlántico renewable ammonia concept as the most promising opportunity, followed by 34% for the Bolívar landfill-gas-to-methanol concept and 14% for the Valle del Cauca SAF concept. Stakeholders appear to weigh the existing fertiliser-demand anchor and Atlántico's more mature infrastructure base as decisive for near-term bankability.

For a potential Phase III, 62% of respondents identified a full feasibility study on a single selected concept as the most valuable next step, compared with 19% favoring the securing of stakeholder and offtake agreements and 15% favoring a smaller-scale pilot or demonstration project. Among webinar respondents, these results indicate a preference for advancing one selected concept into a feasibility study rather than distributing the next phase across all three concepts. In addition, 65% of respondent organizations indicated they are ready to engage as a Phase III partner immediately, while 18% would require additional information and 12% classify themselves as observers without near-term readiness to participate. Overall, the feedback points to strong industry appetite for continuation of the work, a preference for concentrating resources on one bankable concept rather than spreading effort across all three, and a realistic pool of potential partners for a future Phase III scoping phase.

Building on these conceptualizations and the stakeholder feedback, the logical next steps for a targeted Phase III of the project are:

1. **Decide what to advance:**
   Select the most promising first-mover concept, site, and target market.
2. **De-risk the critical assumptions:**
   Confirm feedstock, power, water, logistics, certification, and offtake conditions.
3. **Optimize the concept to bankability:**
   Refine design, run sensitivities, validate techno-economic levers.
4. **Build the Phase III implementation package:**
   Feasibility/pre-FEED, partner-engagement plan, funding roadmap.

Taken together, these steps would move one selected PtX-COL 2.0 concept from screening-level conceptualisation toward feasibility-grade definition and investment readiness. A Phase III should seek to confirm site, feedstock, utility, certification and offtake conditions; optimise the design and economics; and develop a feasibility/pre-FEED package, partner-engagement plan and funding roadmap. Investment approval and binding partner commitments would remain subject to the results of that work. By concentrating resources on a single, well-prepared concept while keeping the wider departmental option space in view, Colombia can demonstrate early success, build regulatory and institutional learning, and create a replicable blueprint for subsequent PtX and PBtX projects across the country.

6 References

[1] Fraunhofer ISE, "Power-to-X Colombia: Fraunhofer ISE Study carried out within the Colombian-German Dialog on Re-Industrialization via Renewable Hydrogen," 2024. [Online]. Available: https://www.ise.fraunhofer.de/content/dam/ise/en/documents/publications/studies/24_en_ISE_Study_Power-to-X_Colombia.pdf

[2] Ministerio de Minas y Energía de Colombia, *Hoja de Ruta del Hidrógeno en Colombia*, 2021. [Online]. Available: https://www.minenergia.gov.co/documents/5862/Colombias_Hydrogen_Roadmap_2810.pdf

[3] UPME, "Geoportal Sectorial: Geoportal Sectorial," 2026. [Online]. Available: https://sig.upme.gov.co/portal/apps/sites/#/geoportal-sectorial-gps

[4] IEA. "Hydrogen Tracker: Project-level data on low-emissions hydrogen production worldwide based on data and analysis from the Global Hydrogen Review." [Online]. Available: https://www.iea.org/data-and-statistics/data-tools/hydrogen-tracker

[5] *Commission Delegated Regulation (EU) 2023/1184 (RFNBO production methodology)*, 2023. [Online]. Available: https://eur-lex.europa.eu/eli/reg_del/2023/1184/oj/eng

[6] *Commission Delegated Regulation (EU) 2023/1185 (GHG methodology for RFNBO and recycled carbon fuels)*, 2023. [Online]. Available: https://eur-lex.europa.eu/eli/reg_del/2023/1185/oj/eng

[7] *Commission Delegated Regulation (EU) 2025/2359*, 2025. [Online]. Available: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=OJ%3AL_202502359

[8] *Regulation (EU) 2023/1805 of the European Parliament and of the Council of 13 September 2023 on the use of renewable and low-carbon fuels in maritime transport, and amending Directive 2009/16/EC*, 2023. [Online]. Available: https://eur-lex.europa.eu/eli/reg/2023/1805/oj/eng

[9] Regulation (EU) 2023/2405 of the European Parliament and of the Council of 18 October 2023 on ensuring a level playing field for sustainable air transport (ReFuelEU Aviation), (n.d.). [Online]. Available: https://eur-lex.europa.eu/eli/reg/2023/2405/oj/eng

[10] *Regulation (EU) 2023/956 of the European Parliament and of the Council of 10 May 2023 establishing a carbon border adjustment mechanism*, 2023. [Online]. Available: https://eur-lex.europa.eu/eli/reg/2023/956/oj/eng

[11] *Regulation (EU) 2023/1804 of the European Parliament and of the Council of 13 September 2023 on the deployment of alternative fuels infrastructure, repealing Directive 2014/94/EU (AFIR)*, 2023. [Online]. Available: https://eur-lex.europa.eu/eli/reg/2023/1804/oj/eng

[12] *Directive (EU) 2024/1788 of the European Parliament and of the Council of 13 June 2024 on common rules for the internal markets for renewable gas, natural gas and hydrogen, amending Directive (EU) 2023/1791 and repealing Directive 2009/73/EC (recast)*, 2024. [Online]. Available: https://eur-lex.europa.eu/eli/dir/2024/1788/oj/eng

[13] *Regulation (EU) 2024/1789 of the European Parliament and of the Council of 13 June 2024 on the internal markets for renewable gas, natural gas and hydrogen*, 2024. [Online]. Available: https://eur-lex.europa.eu/eli/reg/2024/1789/oj/eng

[14] Ministerio de Ambiente y Desarrollo Sostenible, Ed., "Resolución 900 del 17 de julio de 2026," 2026. [Online]. Available: https://www.minambiente.gov.co/documento-normativa/resolucion-900-del-17-de-julio-de-2026/

[15] Consejo Nacional de Política Económica y Social (CONPES), Departamento Nacional de Planeación (DNP), Ed., "Política Nacional de Hidrógeno," 2026. [Online]. Available: https://www.valoraanalitik.com/wp-content/uploads/2026/08/2026-07-16-Documento-CONPES-Politica-Nacional-de-Hidrogeno_VAprobacion.pdf

[16] International Energy Agency (IEA), Ed., "Colombia – Energy mix," 2026. [Online]. Available: https://www.iea.org/countries/colombia/energy-mix

[17] Riviera Maritime, Ed., "Copenhagen Infrastructure Partners awarded Latin America's first offshore wind lease," 2025. [Online]. Available: https://www.rivieramm.com/news-content-hub/copenhagen-infrastructure-partners-awarded-south-americas-first-offshore-wind-lease-87197

[18] IRENA, Ed., "Renewable energy statistics," 2025. [Online]. Available: https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2025/Jul/IRENA_DAT_RE_Statistics_2025.pdf

[19] Superintendencia de Servicios Públicos Domiciliarios (SSPD), Ed., "Informe Nacional de Disposición Final de Residuos Sólidos en Colombia," 2025. [Online]. Available: https://www.superservicios.gov.co/sites/default/files/2025-12/Informe-Nacional-de-Disposicion-Final-de-Residuos-Solidos-en-Combia-2024.pdf

[20] Superintendencia de Servicios Públicos Domiciliarios (SSPD), Ed., "Informe Sectorial de los Servicios Públicos Domiciliarios de Acueducto y Alcantarillado," 2025. [Online]. Available: https://www.superservicios.gov.co/sites/default/files/2025-12/Informe-Sectorial-de-los-Servicios-Publicos-Domiciliarios-de-Acueducto-y-Alcantarillado-2024.pdf

[21] Asociación de Cultivadores de Caña de Azúcar de Colombia (Asocaña), Ed., "Informe Anual 2024–2025," 2025. [Online]. Available: https://www.asocana.org/documentos/2362025-582E725C-00FF00,000A000,878787,C3C3C3,0F0F0F,B4B4B4,FF00FF,FFFFFF,2D2D2D,A3C4B5.pdf

[22] *Atlas del potencial energético de la biomasa residual en Colombia*. Bogotá, 2010.

[23] ACLED, Ed., "Event data," 2025. [Online]. Available: https://acleddata.com/

[24] X. Zhao *et al.,* "Conversion of landfill gas to liquid fuels through a TriFTS (tri-reforming and Fischer–Tropsch synthesis) process: a feasibility study," *Sustainable Energy Fuels*, vol. 3, no. 2, pp. 539–549, 2019, doi: 10.1039/C8SE00344K.

[25] A. C. Elwell, N. H. Elsayed, J. N. Kuhn, and B. Joseph, "Design and analysis of siloxanes removal by adsorption from landfill gas for waste-to-energy processes," *Waste management (New York, N.Y.)*, vol. 73, pp. 189–196, 2018, doi: 10.1016/j.wasman.2017.12.021.

[26] F. Nestler *et al.,* "A novel approach for kinetic measurements in exothermic fixed bed reactors: advancements in non-isothermal bed conditions demonstrated for methanol synthesis," *React. Chem. Eng.*, vol. 6, no. 6, pp. 1092–1107, 2021, doi: 10.1039/D1RE00071C.

[27] F. Nestler *et al.,* "Experimental Validation of Methanol Synthesis from Steel Mill Gases Using a Miniplant Setup," *Chemie Ingenieur Technik*, vol. 94, no. 10, pp. 1466–1475, 2022, doi: 10.1002/cite.202200022.

[28] Peters et al., "Plant design and economics for chemical engineers," 2003.

Appendix

A1 Agricultural and livestock residues in Colombia

Table 2: Biomass and energy potential of agricultural and livestock residues in Atlántico, Bolívar and Valle del Cauca, relative to Colombia [22]

			Atlántico	Bolívar	Valle del Cauca	Colombia
Basic data	Area	Value [km^2]	3,316	25,798	22,140	1,141,748
		Percentage	0.3%	2.3%	1.9%	100%
	Population	Value [Mio.]	2.7	2.2	4.5	50.4
		Percentage	5.4%	4.3%	9.0%	100%
Agricultural residues	Rice	Residue mass [t/a]	0	319,388	102,079	6,282,409
		Energy potential [TJ/a]	0	1,415	452	27,836
		Percentage	0%	5.1%	1.6%	100%
		Department rank	-	7	11	-
	Banana (banano)	Residue mass [t/a]	0	0	399,844	11,550,891
		Energy potential [TJ/a]	0	0	228	6,596
		Percentage	0%	0%	3.5%	100%
		Department rank	-	-	3	-
	Cafe	Residue mass [t/a]	0	2,849	340,509	5,051,246
		Energy potential [TJ/a]	0	28	3,310	49,107
		Percentage	0%	0.1%	6.7%	100%
		Department rank	-	20	7	-
	Sugar cane (caña de azúcar)	Residue mass [t/a]	0	0	12,667,620	15,534,591
		Energy potential [TJ/a]	0	0	96,695	118,579
		Percentage	0%	0%	81.5%	100%
		Department rank	-	-	1	-
	Sugar cane (caña de panela)	Residue mass [t/a]	0	47,885	221,234	9,513,429
		Energy potential [TJ/a]	0	408	1,885	81,055
		Percentage	0%	0.5%	2.3%	100%
		Department rank	-	16	11	-
	Corn	Residue mass [t/a]	28,091	218,782	223,472	1,936,189
		Energy potential [TJ/a]	302	2,349	2,400	20,793
		Percentage	1.5%	11.3%	11.5%	100%
		Department rank	17	3	2	-
	Oil palm	Residue mass [t/a]	0	30,365	0	1,660,074
		Energy potential [TJ/a]	0	293	0	16,014
		Percentage	0%	1.8%	0%	100%
		Department rank	-	8	-	-
	Banana (residual de plátano)	Residue mass [t/a]	10,670	200,256	904,497	20,414,042
		Energy potential [TJ/a]	6	114	517	11,657
		Percentage	0.1%	1.0%	4.4%	100%
		Department rank	28	20	8	-
Livestock residues	Poultry	Manure mass [t/a]	119,535	36,678	570,494	3,446,345
		Energy potential [TJ/a]	650	16	3,662	29,183
		Percentage	2.2%	0.1%	12.5%	100%
		Department rank	9	21	3	-
	Cattle	Manure mass [t/a]	1,118,254	3,939,728	2,331,423	99,168,609
		Energy potential [TJ/a]	1,024	3,609	1,936	83,075
		Percentage	1.2%	4.3%	2.3%	100%
		Department rank	20	9	15	-
	Pigs	Manure mass [t/a]	25,515	19,185	251,332	2,803,110
		Energy potential [TJ/a]	30	22	358	4,308
		Percentage	0.7%	0.5%	8.3%	100%
		Department rank	21	24	3	-

A2 Technological maturity and integration risk

Table 3: Technological maturity and integration risk for Bolívar concept

Sub-process	Technology / Configuration	TRL (2026)	TRL (2030)	Project risk
Power supply				
Solar PV	Multi-hundred MW ground-mounted 1-axis tracking PV park	9	9	Low – mature, competitive LCOE in Colombia; strong local irradiation and potential fast, staged build-out
Power storage and transmission				
Battery storage (BESS)	Li-Ion utility-scale co-located with PV	9	9	Low – fully commercial; rapidly falling costs; active deployments in Latin America
HVAC power transmission	High-voltage AC line 115–500 kV	9	9	Medium-High – standard infrastructure; Colombia grid expansion ongoing, but delay and execution risk
Water and utilities				
Water purification / supply	Industrial demineralised water treatment	9	9	Medium – standard industrial process; water availability in Cartagena manageable, but dedicated strategy needed
Low-pressure steam generation	Low-pressure steam (~6 bar) for Methanol synthesis and distillation, and heat integration	9	9	Low – Standard utility at industrial chemical sites; EcoPetrol operates steam infrastructure on site
Electrolysis				
Alkaline electrolysis	Multi-MW to GW stacks; baseload operation	9	9	Low — fully commercial; preferred for baseload; strong supplier base
PEM electrolysis	Dynamic variable-load stacks; fast response	9	9	Low — fully commercial; suited for variable solar input; strong supplier base
Intermediates				
Compressed H_2 buffer storage	Compressed underground pipe storage, 10–80 bar	8-9	9	Low — no large-scale global roll-out; commercial for industrial scale; optimal sizing is an engineering task
Methanol from landfill gas (& renewable H_2) and storage				
Feed supply	Landfill gas collection	9	9	Low — mature source if landfill gas flow is stable; key risk is long-term gas quality and capture efficiency
Gas Pretreatment	Moisture, H_2S, Siloxanes, etc.	9	9	Low — Standard landfill gas upgrading step; contaminant management is essential.
CO_2 removal	PSA-based CO_2 removal	8-9	9	Medium — technically mature, but integration and CO_2 recovery depend on feed composition and capture rate
Syngas generation	Multi-reforming	5-7	7-9	Medium — The overall technology is based on proven industrial processes. However, feedstock variability and heat integration adds design challenges. While SMR, ATR, and POX are fully mature commercial technologies (TRL 9), multi-reforming that includes dry reforming is less mature (TRL 5-7) as dry reforming is still under development and not yet widely established at commercial scale.
Methanol synthesis	$Cu/ZnO/Al_2O_3$	9	9	Low — fully commercial process technology
Methanol purification and storage	Distillation and storage tanks	9	9	Low — standard downstream methanol handling
System integration				
Full integrated BtX/ PtX hybridsystem	**Case I:** PV → Electrolyzer → Landfill gas → Gas Pretreatment → Multi-reforming → Methanol synthesis → Storage **Case II:** Landfill gas → Gas Pretreatment → CO_2 separation → Multi-reforming → Methanol synthesis → Storage	7–8	8–9	Medium-High — Hybrid carbon and power integration is conceptually proven but first-of-a-kind at project scale; main risks are feed variability, syngas conditioning, dynamic operation, regulations, permitting and bankability.

Table 4: Technological maturity and integration risk for Valle del Cauca concept

Sub-process	Technology / Configuration	TRL (2026)	TRL (2030)	Key risks
Feedstock				
1G bioethanol supply chain	Supply of 1G bioethanol via identified mills	9	9	Medium – Existing commercial operations, but SAF-dedicated offtake contract needed
Renewable hydrogen delivery	External hydrogen supply for hydrogenation step (e.g. Celsia)	9	9	Medium – Introduces external project dependencies, but simplifies onsite supply chain
Renewable electricity + PEM electrolysis	Internal hydrogen supply via Multi-MW PV park / biomass CHP	9	9	Medium – mature, siting complexity and constraints, elevated LCOH due to project scale
AtJ				
Ethanol dehydration	Catalytic dehydration of ethanol to ethylene in fixed-bed reactor	9	9	Low – Commercially proven globally; novel in Colombia; requires licensor partnership
Gas-phase ethylene separation	Cooling/condensation plus gas purification to polymer-grade ethylene	9	9	Low – Standard industrial process
Olefin oligomerisation (AtJ)	Catalytic oligomerisation of ethylene/light olefins to jet-range olefins using licensor process	8	8-9	Low-Medium – Commercial scale at Freedom Pines; Colombian first-mover; proprietary know-how from specific licensors
Distillation / fractionation	Fractionation of oligomer product into jet-range cut, lighter naphtha/gasoline fraction, and recycle streams	9	9	Low – Standard petrochemical unit; familiar to Ecopetrol supply chain
Hydrogenation (ATJ-SPK)	Catalytic hydrogenation / hydroprocessing of jet-range olefins to ATJ-SPK using renewable H_2	8-9	9	Low-Medium – Commercial scale at Freedom Pines; Colombian first-mover; Hydrogen supply chain needs to be established
Storage and logistics				
Storage tanks	Storage units for ethanol, jet fuel and diesel	9	9	Low – Commercially proven globally, siting constraints
SAF blending logistics to ABIA	Truck-based SAF delivery to ABIA, airport-side blending/storage, and coordination with existing fuel supplier	7	8-9	Medium – No dedicated SAF logistics; requires UAEAC/Terpel coordination
2G bioethanol extension				
Residue collection & logistics	Bagasse diversion and RAC collection, densification, storage, and transport to the 2G ethanol unit	4-6	6-8	Medium-High – RAC supply chain not yet established; seasonal availability, moisture & collection costs are critical
2G pretreatment & hydrolysis	Lignocellulosic pretreatment and enzymatic hydrolysis of bagasse/RAC to fermentable sugars	6-7	7-8	Medium-High – Technically proven but first-of-kind in Colombia;feedstock heterogeneity &process integration risk
2G fermentation & distillation	Fermentation of sugar streams and downstream ethanol distillation	7	8	Medium – Mature unit operations, but yield stability and integration remain key challenges
2G wastewater / lignin handling	Wastewater treatment plus lignin/residue handling for steam, CHP, or internal energy recovery	6-7	8	Medium – Energy integration is essential to economics; wastewater load, solids handling & stable lignin valorization
Certification				
ATJ-SPK ASTM D7566 Annex 5	Fuel specs	9	9	Low – Already approved for up to 50% blend; no new certification needed
ISCC/RSB SAF-specific chain-of-custody	Sustainability certification / traceability	6-7	8	Medium – Existing ISCC-certified ethanol supply chains reduce the entry barrier, but SAF-specific chain-of-custody extension, product certification scope, and end-to-end traceability for aviation claims still need project-specific implementation
System integration				
Full integrated 1G BtX system	-	8	8-9	Low – Core subsystems are already commercially mature and the Phase 1 concept mainly combines proven ethanol supply, ATJ conversion, hydrogenation, utilities, and mill integration into one site-specific configuration; remaining work is project execution and local integration rather than basic technology validation
Full integrated BtX system with 2G extension	-	6	7-8	Medium-High – The staged 2G extension is technically credible, but integration risk rises because pretreatment, lignocellulosic ethanol production, residue logistics, lignin/energy handling, and staged coupling to the 1G hub are not yet demonstrated in this configuration

Table 5: Technological maturity and integration risk for Atlántico concept

Sub-process	Technology / Configuration	TRL (2026)	TRL (2030)	Project risks
Power supply				
Solar PV	Multi-hundred MW ground-mounted 1-axis tracking PV park	9	9	Low – mature, competitive LCOE in Colombia; strong local irradiation and potential fast, staged build-out
Offshore wind – fixed-bottom	Fix-bottom turbines (<60 m depth)	9	9	Medium-High – TRL 9 globally; no Caribbean fix-bottom precedent; local O&M supply chain, port infrastructure and permitting immature
Power storage and transmission				
Battery storage (BESS)	Li-Ion utility-scale co-located with PV	9	9	Low – fully commercial; rapidly falling costs; active deployments in Latin America
HVAC power transmission	High-voltage AC line 115–500 kV	9	9	Medium-High – standard infrastructure; Colombia grid expansion ongoing, but delay and execution risk
Water and utilities				
Water purification / supply	Industrial demineralised water treatment	9	9	Medium – standard industrial process; water availability in Barranquilla manageable, but dedicated strategy needed
Cryogenic air separation (ASU)	N_2 production for Haber-Bosch loop	9	9	Low – well-established industrial standard; multiple qualified EPC suppliers
Low-pressure steam generation	Low-pressure steam (~3–6 bar) for ASU, and HB loop heat integration	9	9	Low – Standard utility at industrial chemical sites; Fertilizer hub already operates steam infrastructure on site
Electrolysis				
Alkaline electrolysis	Multi-MW to GW stacks; baseload operation	9	9	Low — fully commercial; preferred for baseload; strong supplier base
PEM electrolysis	Dynamic variable-load stacks; fast response	9	9	Low — fully commercial; suited for variable solar input; strong supplier base
Alkaline / PEM split	Combined electrolysis technologies with shared interface	7-8	8-9	Medium — Integrated operation, control & safety interface with energy managment system becomes feasible
AEM electrolysis	Lower-cost flexible stacks; MW-scale pilots	7	8-9	Medium — smaller stack and system sizes; bankability not yet confirmed at MW scale
Intermediates				
Compressed H_2 buffer storage	Compressed underground pipe storage, 10–80 bar	8-9	9	Low — no large-scale global roll-out; commercial for industrial scale; optimal sizing is an engineering task
Ammonia synthesis and storage				
Conventional Haber-Bosch	Fixed-load fossil-grade synthesis loop	9	9	Low — mature and fully commercial; strong supplier base
Flexible Haber-Bosch	Load-flexible synthesis reactor	7-8	8-9	Medium — first commercial-scale flexible green NH_3 plants are starting operation; licensor selection and long-term performance guarantees are key risk
Ammonia storage	Refrigerated liquid NH_3 tanks at −33°C	9	9	Low — standard >100 years of use; existing Monómeros infrastructure may be partially reusable
System integration				
Full integrated PtX system	PV/Wind → BESS → HVAC → Electrolyzer → Flexible HB → Storage	7–8	8–9	Medium — first commercial-scale fully integrated Power-to-Ammonia system are becoming operational; numerous large-scale projects in advanced development stages; access to low-cost and large-scale renewable electricity, system integration, regulatory uncertainty and bankability of full chain are the primary project risks

Contact

Dr.-Ing. Christoph Hank
Hydrogen Technologies
Hydrogen System Analysis

Fraunhofer Institute for Solar Energy Systems ISE
Heidenhofstraße 2
79110 Freiburg. Germany
www.ise.fraunhofer.de

mobile +49 162 1013 909
phone +49 761 4588 2247
christoph.hank@ise.fraunhofer.de