Power-to-X Colombia

Fraunhofer ISE Study carried out within the Colombian-German Dialog on Re-Industrialization via Renewable Hydrogen

On behalf of

BDI The Voice of German Industry

WORLD ENERGY COUNCIL | WELTENERGIERAT DEUTSCHLAND

FRAUNHOFER INSTITUTE FOR SOLAR ENERGY SYSTEMS ISE

POWER-TO-X COLOMBIA

Fraunhofer ISE Study carried out within the Colombian-German Dialog on Re-Industrialization via Renewable Hydrogen

A study on behalf of
Federation of German Industries (BDI) and World Energy Council (WEC)

POWER-TO-X COLOMBIA

Fraunhofer ISE Study carried out within the Colombian-German Dialog on Re-Industrialization via Renewable Hydrogen

Christoph Hank
Marius Holst
Lucas Edenhofer
Christopher Hebling

Fraunhofer Institute for Solar Energy Systems ISE

September 2024

Table of Contents

List of Abbreviations

Abbreviation	Explanation
AC	Alternating current
ASU	Air separation unit
AEL	Alkaline water electrolysis
CAPEX	Capital expenditure
CEPCI	Chemical engineering plant cost index
CO_2	Carbon Dioxide
CPS	Concentrated Point Source (for CO_2)
DAC	Direct air capturing
DC	Direct current
EUR	Euro, €
FT	Fischer-Tropsch synthesis process
GH2	Gaseous Hydrogen
GIS	Geoinformation system
GW / GWh	Gigawatt / Gigawatt hours
LH_2	Liquid hydrogen
LCoPtX	Levelized cost of a specific PtX product (e.g. ammonia)
LOHC	Liquid Organic Hydrogen Carrier
LPG	Liquefied petroleum gas
MCDA	Multi-criteria decision analysis
MeOH	Methanol
MR 2	Tanker with mid-range 2 type definition
MW / MWh	Megawatt / Megawatt hours
NH_3	Ammonia
OPEX	Operational expenditure
O&M	Operation and maintenance
PEM	Polymer electrolyte membrane electrolysis
PtX / PtL	Power-to-X / Power-to-Liquid
PV	Photovoltaic
PVGIS	Photovoltaic Geographical Information System
RE	Renewable energy
SWRO	Sea water reverse osmosis
SEC	Specific energy consumption
TRL	Technology readiness level
USD	US Dollar
WACC	Weighted average cost of capital

Executive Summary

This study by Fraunhofer ISE performs a **techno-economic analysis on Power-to-X (PtX) for Colombia** to assess its potential as a future large-scale producer of green hydrogen and its derivatives. With its ambition to become a key player leader in the green hydrogen economy, Colombia stands at the cusp of a transformative opportunity. This vision is anchored in the country's rich renewable energy resources. However, this renewable potential is concentrated in specific regions, each of which has unique advantages that align with Colombia's Hydrogen Roadmap.

The northern region of **La Guajira**, with its world-class wind and solar potential, is well positioned to become a central hub for large-scale hydrogen production. With projected at-gate production costs for green hydrogen of only 3.3 EUR/kg in 2030 and down to 2.70 EUR/kg in 2040, this region is one of the most promising in the world from a techno-economic perspective. Based on the analyses, the production and transport costs of green liquid hydrogen and ammonia to Germany are estimated at around 190-195 EUR/MWh and the costs of methanol at around 228 EUR/MWh, respectively. The latter shows slightly higher costs due to the need for a CO_2 supply by means of direct air capture. By 2040, the cost of supplying liquid hydrogen, ammonia and methanol is projected to decline further due to economies of scale and the progressive maturation of technology, with prices in the range of 147-154 EUR/MWh. To unlock La Guajira's potential, coordinated efforts among government, local communities, developers, and investors are crucial. This collaboration will ensure that the green transition is not only economically viable but also socially inclusive, attracting the multibillion euro investments necessary for advancing projects to final investment decisions.

The regions of **Cartagena** and **Barranquilla** are also emerging as key sites for initial PtX projects, benefiting from existing chemical industries, refineries, and an expanding port infrastructure. It is imperative that access to offshore wind energy or baseload green power through power purchase agreements be established in order to compensate for the limited onshore renewable energy potential in these areas.

Valle del Cauca and **Cali**, despite their limited renewable energy potential, are strategically important due to their access to biogenic carbon sources and biomass, which are vital for syngas generation and sustainable aviation fuel (SAF) production.

The achievement of a decarbonized Colombian economy hinges on the significant future expansion of renewable energy and an accompanying power infrastructure. This requires substantial investments, potentially in the multibillion euro range. As much of this funding is expected to be from international sources, Colombia must establish strong financial safeguards and transparent regulations to attract these investments.

Key strategic actions include launching pilot projects to explore sustainable hydrocarbons like green methanol and sustainable aviation fuel. In less optimal regions for wind and solar, hybrid PtX concepts combining hydrogen from electrolysis and biomass-based syngas are recommended. Moreover, the substantial offshore wind potential in northern Colombia offers a viable alternative to onshore projects, and development in this region should be closely tied to the national offshore wind roadmap.

Aligning the education sector with the green energy economy is also crucial to achieving success. Actions here include updating degree programs, improving university infrastructure, and offering retraining opportunities for workers transitioning from fossil fuels to the green economy. Public awareness campaigns and enhanced participation processes in key regions such as La Guajira are essential.

Establishing a Colombian hydrogen backbone, connecting northern production hubs with demand centers, could be pivotal in decarbonizing the economy. This approach would optimize existing infrastructure, leverage regional resources for large-scale PtX applications, and put Colombia in alignment with its climate goals, while driving economic growth and job creation in renewable-rich regions at the same time.

1 Introduction

1.1 Background

The Federation of German Industries (BDI) and the World Energy Council (WEC) approached Fraunhofer ISE in mid-2023 to prepare an accompanying study focusing on the production costs of hydrogen and its derivatives in Colombia to support the 'Colombian-German Dialogue on Reindustrialization via Renewable Hydrogen'. This project report summarizes the project results.

Colombia is undeniably a country with enormous potential for renewable energies (RE). In addition to conventional hydropower on a large and small scale and the utilization of renewable biomass, parts of the country have exceptional conditions for the generation of solar and wind power. The latter both on the mainland and with extraordinary potential off the coast. Colombia's outstanding renewable energy potential was also demonstrated in last year's Fraunhofer ISE techno-economic study *Power-to-X Country Analyses*, which was prepared for the H2Global Foundation and shows the production, transport, and supply costs of key Power-to-X (PtX) products for the year 2030 for 39 globally distributed regions in developing and emerging countries. Here, locations in northern Colombia in particular stood out due to their exceptionally favorable hydrogen production costs. [1] This study ties in with these results and looks at the cost potential for Colombian green hydrogen in a more comprehensive level of detail. In addition, this study can be seen as an important addition to the previous analyses of Colombia's PtX potential. [2–4]

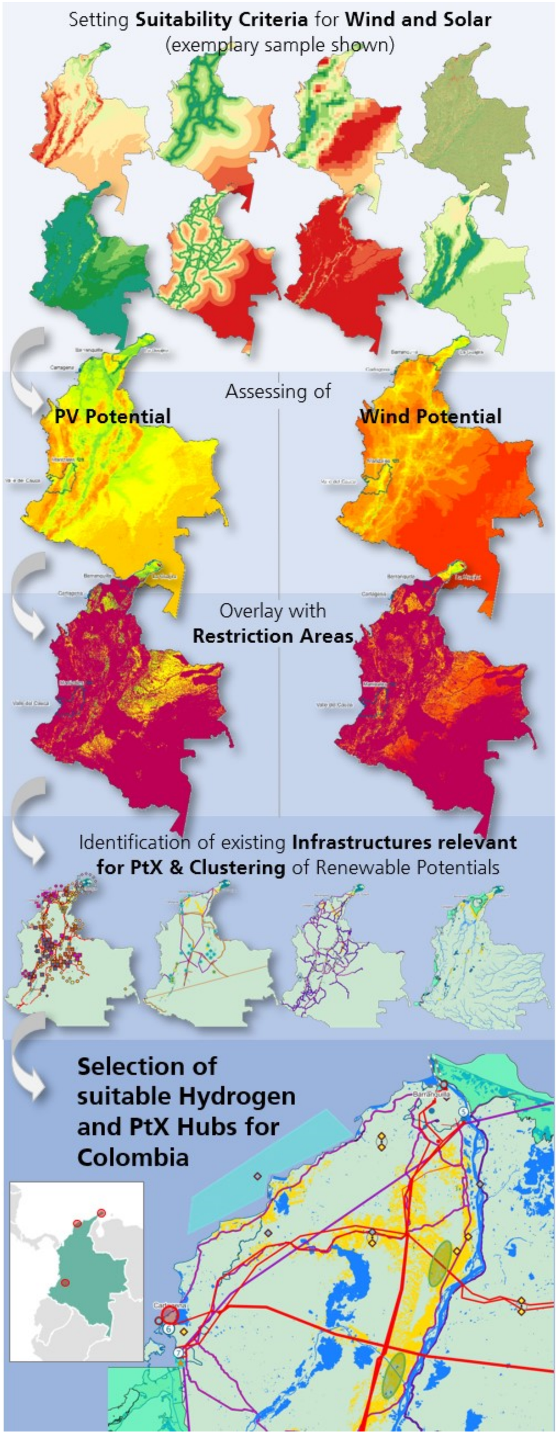


Figure 1-1: Fraunhofer ISE procedure for the assessment of the RE potential in Colombia and the selection of suitable sites for large-scale onshore wind, solar parks, hydrogen and Power-to-X hubs.

1.2 Goal and scope of the Study

This study carried out by Fraunhofer ISE focuses the techno-economic PtX analyses entirely on Colombia as a potential future large-scale producer of green hydrogen and derivatives. The procedure developed by Fraunhofer ISE for identifying potential RE and PtX sites and for determining the investment and generation costs is based on an advanced methodology that has been established in numerous previous hydrogen projects (Figure 1-1). In short, the entire country was subjected to a comprehensive analysis with regard to the potential for generating wind and solar power as well as the infrastructure relevant for hydrogen and Power-to-X. Based on this, renewable clusters were identified which are suitable for the large-scale generation of renewable electricity due to extensive defined criteria. In addition to purely technological criteria, environmentally and socially relevant criteria such as existing marine protected areas or indigenous communities were also considered. Subsequently, three locations have been selected as potential PtX hubs where the green electricity generated is to be converted into hydrogen and derivatives.
Based on the RE potential at each location, the cost-optimized system designs for electrolysis, storage systems, syntheses, and all other necessary components were determined with the help of the Fraunhofer ISE toolbox 'H2ProSim' using high resolution power production profiles. For this purpose, a detailed techno-economic simulation model of the PtX production and supply chain was used. Figure 1-2 depicts the general system layout for the analyzed PtX system, which is used to analyze the costs for **gaseous hydrogen (GH_2)**, **liquid hydrogen (LH_2)**, **ammonia (NH_3)** and **methanol (MeOH)** using CO_2 from a Direct Air Capture unit (DAC) or a concentrated point source (CPS). The systems modeled and optimized include dedicated renewable electricity production via wind and PV, and if necessary, electricity transmission and seawater desalination, followed by the production and intermediate storage of green hydrogen and its derivatives and, depending on the scenario, either their local distribution or subsequent long-distance transport to the target in Germany.

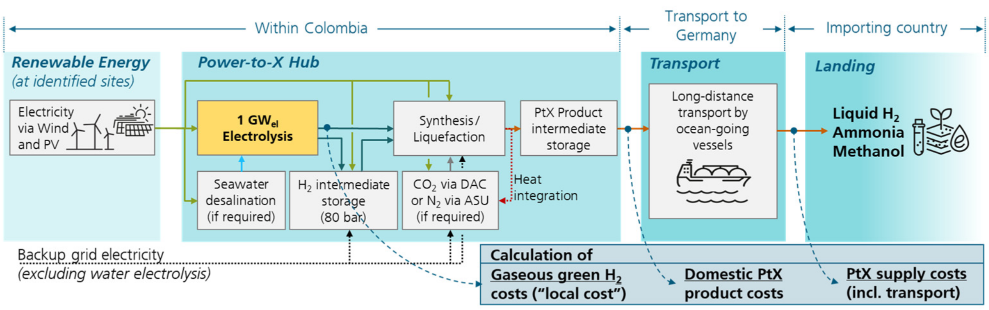


Figure 1-2: Scope of the assessed Power-to-X production and supply chains for gaseous hydrogen, liquid hydrogen, ammonia and methanol.

Colombia's electricity generation mix is already strongly dominated by hydropower, resulting in comparatively low specific emissions per kWh produced.
However, for the analysis carried out in the main part of this study, only wind and PV were considered as electricity sources, following the regulations for renewable fuels of non-biological origin (RFNBO) that are being developed in the European Union and the United States. According to these regulations, the use of grid electricity is not possible in Colombia because the specific emissions are still too high. Therefore, the following points have been taken into consideration when sourcing electricity:

- Additionality of RE plants: We assume dedicated wind and PV power plants for the analysis. Grid power is not used for hydrogen production. However, some grid power may be used for must-run capacities such as synthesis and compressors when RE power is not available.

- Local correlation: The wind and PV power plants assumed for the different locations are close to the PtX plant, as shown in the GIS analysis section. Power transmission over long distances across the country has not been considered.
- Time Correlation: Energy production profiles with a time resolution of 1 hour are used. Energy must be used as it is available. Later use of energy (by storing it in the grid) is not considered.

1.3 Structure of this Report

The report is structured into five chapters. Following the introductory chapter, which provides a comprehensive overview of the research question, the analyzed PtX pathways and products, chapter 2 outlines the methodology employed. This encompasses the methodology utilized for the GIS analysis to identify potential RE regions across Colombia, in addition to the methodology employed for the PtX cost calculation, which is presented in meticulous detail.
Chapter 3 provides a more detailed explanation of the components of the PtX production and supply chain, together with a description of the parameters that have been considered.
The findings of this study are introduced in Chapter 4, beginning with the three regions identified for RE production and subsequently followed by a comprehensive presentation of the techno-economic results. In addition to the baseline scenarios, a sensitivity analysis is presented, and a further analysis of grid power utilization is provided.
Chapter 5 presents a summary of the study's findings and conclusions. Additionally, it offers insights into the potential integration of La Guajira into a national electricity and hydrogen network.

1.4 Limitations of the Study

The methodology used in this analysis has been developed and applied by Fraunhofer ISE in several projects over the last decade. Despite this well-validated starting point, as in any study, assumptions and limitations must be taken into account, which are briefly described below.
For the site-suitability assessments publicly available data, which is already subject to specific uncertainties, was used to identify suitable RE sites. In addition, the exclusion zones and setback distances considered in the GIS analyses can never reflect all relevant aspects of spatial planning, nature conservation, species protection, or other forms of future large-scale land demand.
In case of the techno-economic modelling of the PtX pathways a model-based approach was chosen to determine the production costs of PtX. We follow the approach of a highly detailed model. However, simplifications have to be made at certain points. Simplified models often fail to capture the full complexity of real systems, leading to potentially inaccurate cost estimates. In particular, input data and parameters are subject to uncertainty. Despite detailed analysis of available literature, manufacturer data, and internal discussion of parameters (costs, efficiencies, etc.), uncertainties cannot be avoided when analyzing future scenarios and technologies. This applies, for example, to the power curves used for the considered wind turbines based on 4.5 MW. For a wind farm in 2040, significantly larger wind turbines would be conceivable and should be considered in detailed feasibility studies. In the present pre-feasibility study, the same turbine type was assumed for 2030 and 2040 for the sake of simplicity.
In addition, satellite data were used for the PV and wind time series, which show a higher uncertainty compared to local measurements.
In General, the development of real-world projects requires a much higher level of detail, which is beyond the scope of this study.

2 Methodology

This chapter first outlines the methodological approach used in the GIS-based site suitability assessment to identify renewable energy potential, promising regions, and relevant infrastructure within these regions. Furthermore, this chapter describes the methodological approach for techno economic modeling, simulation and optimization of power-to-x supply chains at the identified sites.

2.1 GIS-Based Site Suitability Assessment for Renewables and PtX Hubs

Any large-scale production of renewable hydrogen, ammonia and methanol in Colombia will require extensive renewable energy generation. Therefore, it is necessary to identify specific areas that are suitable for the large-scale implementation of ground-mounted photovoltaics and onshore wind. The objective is to identify and evaluate optimal renewable energy production sites for specified PtX supply chains with regard to economic competitiveness and project feasibility. However, the identification and selection of these sites is a complex process that requires consideration of a wide range of factors and constraints. In order to account for numerous influential factors, a multi-criteria decision analysis (MCDA) model was developed using Geographic Information System (GIS) data to assess the site suitability for renewable energy systems (RES) in Colombia.

Figure 2-1 illustrates the individual model steps which are applied for the identification of promising RES sites and PtX hub locations. All processing steps were conducted at a high resolution of 50 x 50 meters in order to maximize the information value.

In step (1), detailed exclusion zones and setbacks are considered to identify areas where ground-mounted PV and onshore wind are not viable due to legal, environmental, social, or technical constraints. The restriction areas considered include settlements, infrastructure, ecologically and culturally sensitive areas, as well as land use categories. The considered restriction area types are presented in detail in Appendix A1. The individual restriction areas are combined via a binary overlay to receive the total restriction areas for both considered RES technologies. This step is essential to comply with regulatory requirements and to avoid direct disturbance between the proposed renewable energy sites and existing settlements or infrastructure.

In step (2), Colombia is assessed for its potential to host large-scale ground-mounted PV and onshore wind parks. This allows the identification of optimal sites for renewable energy generation with low levelized costs of electricity (LCoE). Several suitability criteria have been established to reflect technical and economic conditions, as well as solar and wind resources in Colombia. These criteria have been selected following a thorough literature review and careful consideration of the unique characteristics of Colombia. The suitability criteria are divided into 11 classes, ranging from unsuitable (0%) to ideal (100%), as shown in Appendix A2. The individual suitability criteria maps for ground-mounted PV are displayed in **Figure 2-2**. The suitability criteria maps for onshore wind are presented in Appendix A3.
To establish the relevance of the individual criterion, the MCDA method Analytical Hierarchy Process (AHP) is utilized [5]. A pairwise comparison is conducted for each suitability criterion to allocate suitability criteria weights in reflection of their relevance. The pairwise comparison was conducted by the authors in line with current scientific literature. The comparative matrices resulting from these pairwise comparisons for ground-mounted PV and onshore wind can be found in Appendix A4. **Table 2-1** shows the considered suitability criteria and their resulting relevance based on

the performed AHP procedure. Based on these results, the site suitability assessment is primarily influenced by solar irradiance and wind speed, as these have a direct impact on electricity production. However, seasonal variability of wind and solar as well as the distance to transmission lines are also important factors as they affect investment in energy storage and transmission infrastructure.

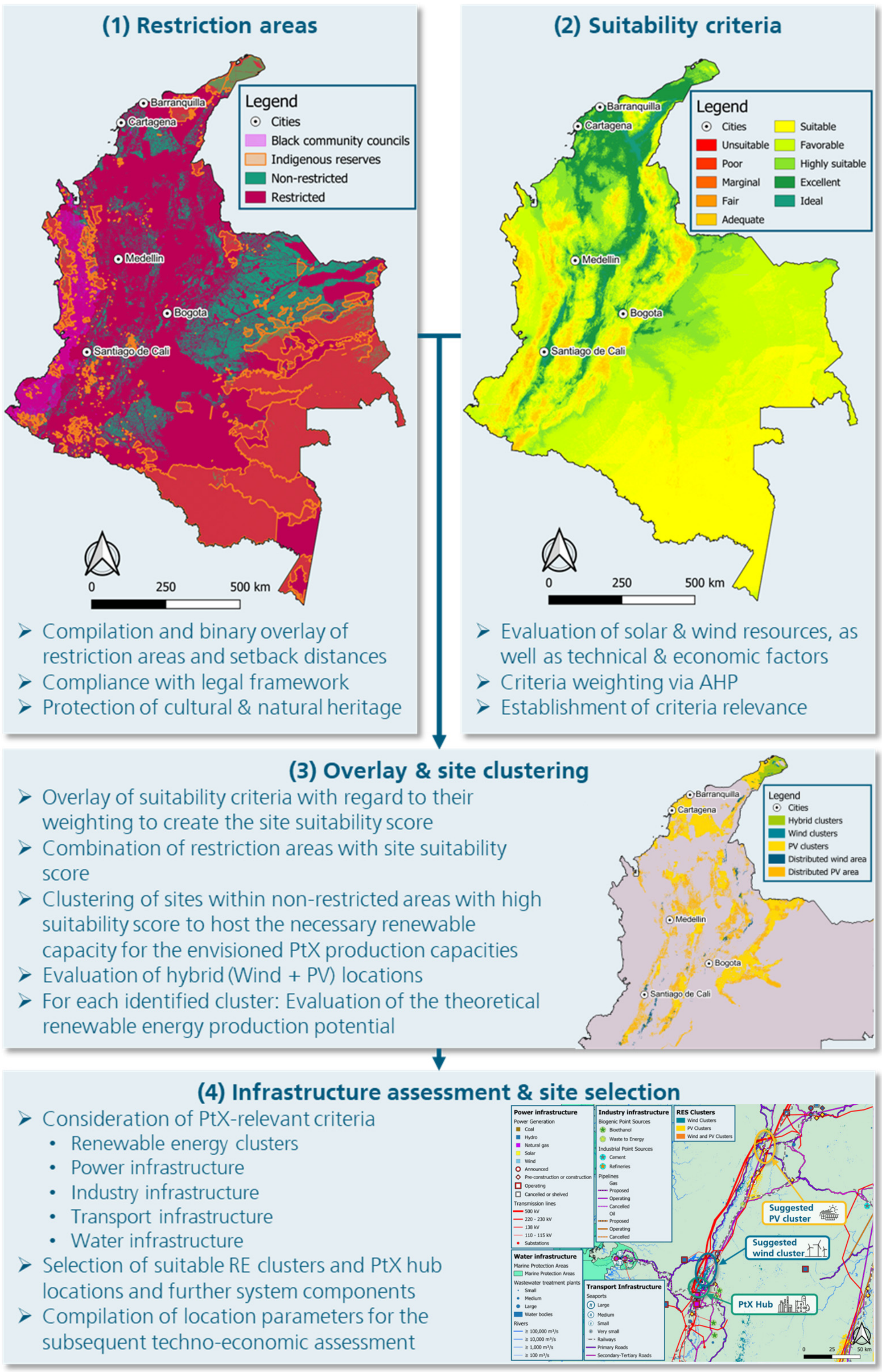


Figure 2-1: Fraunhofer ISE methodology for the GIS-based site suitability assessment for the identification of promising locations for large-scale renewables and PtX hubs.

In step (3), the restriction areas and suitability criteria are combined via a weighted overlay to generate the site suitability score and the site suitability maps for ground-mounted PV and onshore wind. Subsequently, areas with high site suitability scores are grouped in contiguous clusters. Restricted areas and areas with lower site suitability scores are not included in the clustering procedure. The cut-off site suitability score is specified with 75 % for ground-mounted PV and 60 % for onshore wind. The resulting RES clusters host sufficient area to accommodate the required RES capacities for the specified PtX plant capacities (1 GW_{el} electrolysis). This translates to minimum cluster sizes of of 50 km² (2.5 GW) for ground-mounted PV and 150 km² (2.0 GW) for onshore wind depending on the respective solar and wind resources at each location. Smaller, distributed areas with high site suitability scores are highlighted as distributed PV and wind areas.

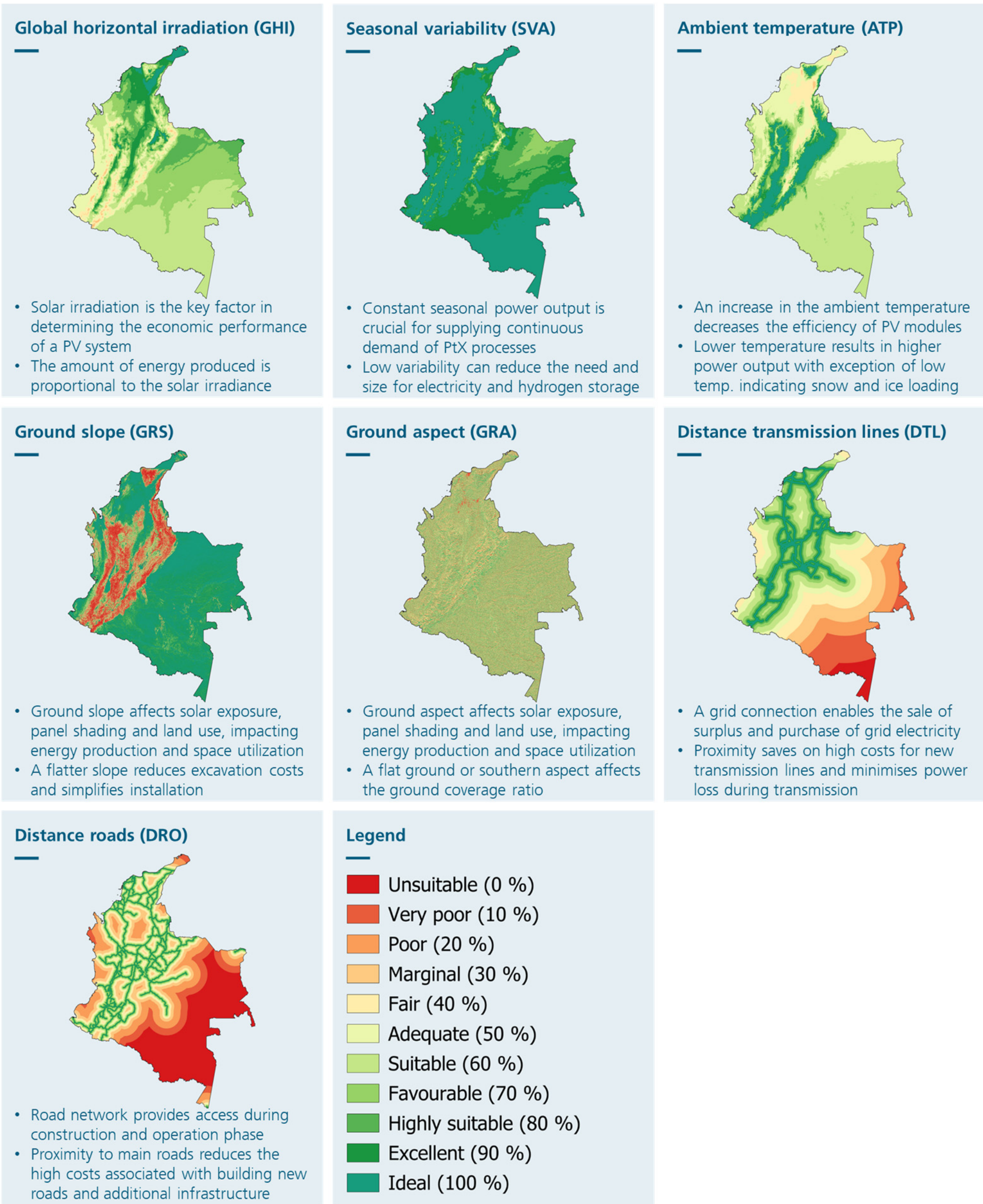


Figure 2-2: Suitability criteria for ground-mounted PV in Colombia. The suitability criteria maps for onshore wind are presented in Appendix A3.

Table 2-1: Considered suitability criteria and resulting weights based on the applied AHP methodology.

Criteria		Weight
Global horizontal irradiation	GHI	37.8%
Seasonal variability	SVA	11.4%
Ambient temperature	ATM	4.4%
Ground slope	GRS	16.6%
Ground aspect	GRA	3.4%
Distance transmission lines	DTL	16.6%
Distance roads	DRO	9.8%
Wind speed	WSP	41.8%
Seasonal variability	SVA	18.7%
Ground slope	GRS	6.1%
Ground elevation	GRE	2.9%
Distance transmission lines	DTL	18.7%
Distance roads	DRO	11.8%

In step (4), suitable RES locations and PtX hubs are selected under consideration of PtX-relevant infrastructure. This includes existing electricity, water, industry and transport infrastructure that influence and shape the PtX supply chains. The existing and planned **electricity infrastructure** enables the sale of surplus and the purchase of grid electricity via high-voltage transmission line connection. Proximity saves on the high cost of new transmission line construction and reduces power loss during transmission. The **water infrastructure** is considered to supply water for the electrolysis process and further system components. This includes unprotected coastline for seawater desalination, treated water from wastewater treatment plants and surface water. The **industrial infrastructure** can serve as potential carbon sources for the methanol synthesis via industrial or biogenic point sources. Proximity to existing industrial clusters may further enable the domestic sale of the PtX products. In addition, the utilization of or supply of waste heat, as well as the sale of oxygen may be feasible. The **transport infrastructure** enables the transport of the PtX product to local offtakers or suitable seaports for export. This includes the existing railway, pipeline and road network. The respective infrastructure maps of Colombia are presented in Appendix A5.
The selected PtX hubs and corresponding supply chains are explained in detail in Chapter 4.1.

2.2 Techno-economic simulation and optimization of PtX supply chains

For the calculation, design and optimization of the PtX production and supply chains, techno-economic models for each supply chain were created using the Fraunhofer ISE toolbox "H2ProSim" (Hydrogen Process Simulation). H2ProSim is a library of all relevant technical supply chain models implemented in Matlab/Simulink. The model structure is shown in Figure 2-3. It contains a "**technical model**" of the supply chain as well as an "**economic model**", and a "**genetic optimization algorithm**" which interact with each other. All three are explained in the following.

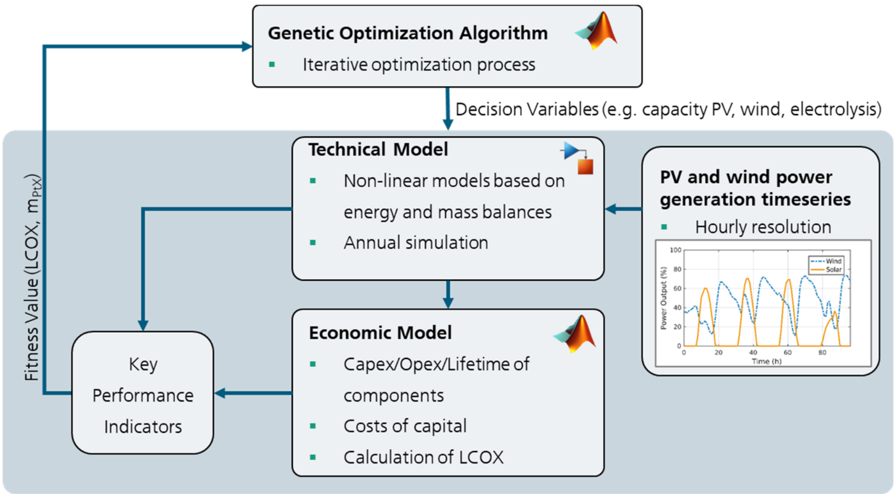


Figure 2-3: Schematic layout of the Power-to-X model structure in the Fraunhofer ISE toolbox "H2ProSim" (Hydrogen Process Simulation).

Technical Model

The technical model includes all major components relevant to the PtX supply chains, as depicted previously in Figure 1-2. The system model is used to perform annual simulations using wind and PV power generation time series for the respective sites. The time series used in this analysis are available in 1 hour increments. The individual component models are based on power curves, conversion efficiencies, and mass and energy balances, and are interconnected according to the PtX system structure. An overarching plant controller distributes the generated renewable power and ensures that the components operate within their respective operating limits.

In the case of the synthesis/liquefaction processes considered in this study, the respective minimum partial loads must be considered in each hour of the annual simulation. In particular, synthesis processes running at high temperatures and pressures cannot be operated in a dynamic range comparable to the fluctuations in renewable electricity and hydrogen production. In times of no or insufficient hydrogen production, the running synthesis process must be able to draw a defined minimum amount of hydrogen from the intermediate buffer storage. Outside the defined maintenance windows, the synthesis or liquefaction process should not be shut down due to insufficient renewable electricity and hydrogen production or operated at too high a partial load range. This would have a negative impact not only on the efficiency of the associated compressors and pumps, but also on the stability, activity and lifetime of the catalyst, and ultimately on the quality and composition of the product. The specific part load windows of the conversion processes considered are defined in section 3.3.1.

Economic Model

An economic model is used to determine the production and delivery costs of the PtX products. The economic model includes cost parameters such as specific investment costs and operating costs for all supply chain components. These values are based on literature, manufacturer information and expert knowledge. As the economic model is linked to the technical model, the results of the annual simulation of the system (e.g. component sizing, amount of PtX product produced, ship fuel demand, external power supply) are used in the economic model to calculate the economic efficiency of each PtX project. The levelized cost of the PtX product **LCoPtX** cost is calculated based on the annuity method, where the investment cost is annualized with the capital recovery factor (CRF) as follows [6]:

$$LCoPtX\left(\frac{EUR}{MWh}\right)=\sum_{i=1}\frac{CAPEX_i * CRF_i + OPEX_i}{E_{PtX}}$$

$$CRF_i=\frac{WACC * (1+WACC)^{n_i}}{(1+WACC)^{n_i}-1}$$

$\boldsymbol{CAPEX}$ stand for the necessary investment costs for each component $\boldsymbol{i}$ of the supply chain, $\boldsymbol{OPEX}$ are the respective annual operation costs (fixed and variable), $\boldsymbol{E_{PtX}}$ the total PtX energy amount (related to the lower heating value) produced / exported. The $\boldsymbol{WACC}$ is the weighted average cost of capital and $\boldsymbol{n}$ the technical lifetime specified for each component. The residual values of individual components at the end of the plant operating life are not taken into account in this study. For the present study, a Colombian WACC of 8% is assumed for the baseline scenarios in this study. In order to better assess the wide range of potential capital costs and the uncertainty associated with this key parameter, this parameter is subjected to a sensitivity analysis in Chapter 4.3.1 and varied from 6% to 10%.
The LCoPtX in this study are mainly given in costs per energy (EUR/MWh) based on the lower heating value. This ensures comparability among the different PtX carriers. The LCoPtX presented in this study are distinguished into the LCoPtX at the PtX production site - the "**PtX production cost**" - and the LCoPtX including international transport of the energy carriers to the point of import - the "**PtX supply cost**".

Genetic Optimization Algorithm
Due to different meteorological conditions at each site and different behaviors of the assessed PtX pathways, each scenario requires a specific system design to achieve optimal generation and consequently production costs. Numerous system parameters can be varied to optimize the PtX systems at each site and determine the optimal system design. In order to determine the lowest PtX production and supply costs and to find a system layout that is within the defined constraints (e.g. electrolysis capacity, no synthesis shutdown due to empty intermediate hydrogen storage), an evolutionary, "genetic" optimization algorithm is applied.
Evolutionary optimization algorithms have proven to be a powerful optimization technique for optimizing non-linear simulation models. An optimal solution is not determined by numerical linear optimization, but rather by randomized search heuristics. This approach prevents the algorithm from getting stuck in a local minimum. Improvement is achieved step by step, i.e. over many generations, by trying out possible solutions. In order to find the best solution within the given constraints, a large number of solution trials must be computed over many iterations.
he optimization algorithm can adjust selected variables, such as installed wind, PV, and synthetic capacities, with the goal of minimizing PtX production costs. An installed electrolysis capacity of 1 GW_{el} is considered as the basis for each scenario in this study. The optimization process and the system design are based on this fixed variable. In order to find the lowest cost, the following variables can be changed by the optimization algorithm:

- Installed wind capacity (MW)
- Installed PV capacity (MW)
- Volume H2 buffer Storage (m^3)
- Capacity syntheses/liquefaction (tpd)

The capacities of other components are determined based on the capacities of the variables listed above. For example, the installed capacity of the DAC unit is determined by the maximum CO_2 demand of the optimized synthesis. The capacity of a seawater desalination plant for fresh water supply is determined by the maximum hourly water demand of the electrolysis. For the determination of the PtX intermediate storage, it is assumed that the rated production of the corresponding liquefaction/synthesis can be stored for 21 days. In the case of product export, the number of transport vessels is determined using the following equation based on Reuß et al. [7], taking into account the quantity exported, the unit transport capacity and the time required for loading, unloading and sailing.

$$n_{transportShips} = \frac{m_{PtX}}{capacity_{Unit}} * \frac{trip\ duration + loading\ time + unloading\ time}{8760\ h}$$

3 Techno-economic parameters and assumptions

In this chapter, the components of the hydrogen and PtX supply chains are explained, and the selected technical and economic parameters are discussed. Additional information can be found in the Fraunhofer ISE study "Site-specific, Comparative Analysis for Suitable Power-to-X Pathways and Products in Developing and Emerging Countries" conducted by Fraunhofer ISE for the H2Global Foundation in 2023.

3.1 Power Production and Supply

3.1.1 Wind and PV

Despite the high potential for renewable energy installations in Colombia estimated to up 30 GW of wind power and 32 GW of solar PV, only 18 MW of onshore wind and 290 MW of solar PV were in operation in 2022 [8,9]. In comparison to other countries in South America (e.g. Argentina, Chile, Peru, Brazil) the installed capacity of Colombian wind and PV is significant lower so far. As a result, reliable cost data for renewable power plants in Colombia is hardly available in the literature.
Based on the latest RE generation cost report published by the International Renewable Energy Agency IRENA, investment cost for **solar PV** in Latin American countries are currently in the range between 685 EUR/kW$_p$ in Brazil and 880 EUR/kW$_p$ in Mexico. For the present analysis, cost reductions towards 2030 are assumed resulting in solar PV investment costs of 650 EUR/kW$_p$ in 2030 and 450 EUR/kW$_p$ in 2040 [10]. In the latest RE auctions in Colombia, a capacity of 4.4 GW has been awarded with almost all related to PV power projects, indicating the high interest in the technology.
For **onshore wind** IRENA reports investment costs in the range between 970 EUR/kW for Brazil and 1,375 EUR/kW for Chile and Mexico. Other South American countries are indicated with an average value of 1,200 EUR/kW. For the analysis in this report, onshore wind investment cost of 1,250 EUR/kW and 1,000 EUR/kW are assumed for 2030 and 2040, respectively. [10]
For the analysis of hydrogen production in the Cartagena region, **offshore wind** is considered, as regional onshore wind potential renders as insufficient. So far, offshore wind projects have not been realized in South America. In Colombia in the Caribbean Sea the offshore wind potential is high and an offshore wind roadmap has been published which indicates a potential of 50 GW$_{el}$ (27.2 GW$_{el}$ bottom-fixed and 21.6 GW$_{el}$ floating) [11,12].

Table 3-1: Techno economic assumptions for wind and PV technologies in Colombia.

	Onshore Wind		Offshore Wind		Solar PV	
	2030	**2040**	**2030**	**2040**	**2030**	**2040**
CAPEX (EUR/kW)	1,250	1,000	2,500	2,000	650	450
OPEX (%CAPEX/yr)	2	2	3	3	2	2
Technical Lifetime (yr)	25		25		30	

Relevant Sources: [10,11]

Meteorological data, resulting RE capacity factors and LCoE

Production timeseries for wind and photovoltaics with hourly resolution for 1-year are used which are based on satellite observations obtained from renewables.ninja [13–15]. The PV plants used are non-tracking systems with the angle and azimuth aligned for each region according to achieve the maximum yield [16]. For comparability, wind turbines of the type Enercon E112 with a nominal power of 4.5 MW are used for all sites. A lifetime of 25 years is assumed for the wind power plants. [17,18]. For solar systems, a lifetime of 30 years is assumed [18].

Table 3-2: Resulting capacity factors and levelized cost of electricity (LCoE) for the analyzed Colombian locations.

	La Guajira		Cartagena		Valle del Cauca	
	2030	**2040**	**2030**	**2040**	**2030**	**2040**
Wind: Capacity Factor (%)	63 (onshore)		49 (offshore)		Insufficient wind potential	
Wind: LCoE (EUR/MWh_{el})	36	32	100	85	Insufficient wind potential	
PV: Capacity Factor (%)	18		15		16	
PV: LCoE (EUR/MWh_{el})	42	33	42	34	40	32

3.1.2 Power transmission between RE and PtX Hub

Although the proximity of renewable energy and electrolysis was taken into account in the analyses, they are not exactly in the same location. Therefore, power transmission has been considered where necessary. Due to the high amount of power to be transmitted (> 1 GWel), it cannot be assumed that the existing transmission grid (if any) has sufficient transport capacity. Therefore, the costs of a project-specific power transmission line for connecting the RE and PtX hub are considered in a simplified manner. Table 3-3 lists the technical and economic parameters for the project-specific transmission line.

Table 3-3: Technical and economic parameters considered for power transmission between RE locations and PtX hubs via a project-specific transmission line.

Parameter	Value (2030 & 2040)	Unit
Transmission losses	1.1	%/100km
Transformer Efficiency (beginning and end of grid)	99.5	%
CAPEX	190.000	EUR/(km*GW)
OPEX	0.2	% of CAPEX/yr
Lifetime	40	Years
TRL	9	

Relevant sources:
Grid efficiency, cost, and lifetime: [19]

3.1.3 Backup power supply for must run capacities

Even during times with no or insufficient wind or PV power available, the hydrogen liquefaction or synthesis processes continue to run at partial load and are supplied with hydrogen from the buffer storage. Accordingly, these must then also be supplied with electrical power to supply compressors, pumps and other peripherals. A complete shutdown/standby, as is possible for electrolysis, is not desired here. These less flexible processes can therefore be supplied with grid electricity in times when renewable energy generation is insufficient. It should be noted that the electrolysis is never supplied with grid power in the baseline scenarios. For the two locations near Cartagena and Cali, it is assumed that grid electricity can be obtained from the grid at 200 EUR/MWh [20].
Due to the absence of an electrical transmission grid in La Guajira, here it is assumed, that the system is operated in a fully off-grid mode. Power supply for the must-run capacities is therefore supplied by the re-electrification of stored hydrogen, e.g. by a fuel cell system or a hydrogen powered power plant. Here, specific costs of 1,000 EUR/kW power capacity and an efficiency of 50 % is assumed.

3.2 Hydrogen Production and Storage

3.2.1 Water electrolysis

A central key parameter for the system optimization was a fixed design size of **1 GW_{el} for the water electrolysis**, which is treated a typical plant size for the future. This parameter applies to all assessed scenarios. The corresponding design parameters of the numerous other system components such as dedicated renewables or the syntheses, on the other hand, are specific results of the simulation and optimization process.

Polymer electrolyte membrane (PEM) electrolysis has been selected due to its high dynamic response to variable input power from wind and solar and its high-pressure production of hydrogen (30 bar), which reduces the demand for downstream compression significantly compared to atmospheric hydrogen production. However, it should be noted that the PtX concept can also be realized based on alkaline technology. With regard to the investment costs, 750 EUR/kW and 500 EUR/kW have been considered for 2030 and 2040, respectively. A fixed OPEX of 15 EUR/(kW*yr) is taken into account as well as a variable OPEX for the replacement of the electrolysis stacks after a certain operation time. The latter account for 30% of the electrolysis system costs.

Table 3-4: Technical and economic parameters considered for 1 GW_{el} PEM electrolysis.

Parameter	2030	2040	Unit
Technology	PEM electrolysis		-
Rated input power	1,000		$MW_{AC,Input}$
SEC at rated production	52	48	kWh/kg
Hydrogen production pressure	30	30	bar
Lower part load limit	10	10	%
CAPEX	750	500	EUR/kW_{AC}
OPEX	15	15	$EUR/(kW_{AC}$*yr)
System lifetime	30	30	years
Stack lifetime	85,000	100,000	Operating hours

Relevant sources:
SEC at rated production: [21,22]
Hydrogen production pressure: [23]
Lower part load limit: [24]
CAPEX: [21,23–26]
OPEX: [22,23,25,26]
Stack Lifetime: [23,25]

3.2.2 Hydrogen intermediate storage

For the production of liquid hydrogen, ammonia and methanol, intermediate hydrogen storage is required as a buffering element between electrolysis and downstream conversion. Hydrogen liquefaction and synthesis processes have only limited dynamics compared to electrolysis, which means that operation is only possible in certain load ranges and a continuous operation within these ranges requires a steady hydrogen supply. The hydrogen intermediate storage system thus acts as a buffer element and supplies the conversion steps with hydrogen even during periods without electrolytic hydrogen production.
In the present work, hydrogen storage is assumed to take the form of an underground pipe storage facility. Such facilities are commonly used for the storage of natural gas. While the use of underground pipe storage for hydrogen is also conceivable in principle, it has not yet been implemented due to the absence of a need for hydrogen storage capacities on such a large scale. Typically, pipe storages are operated at pressures of up to 100 bar [27,28]. Specific investment costs for hydrogen-capable underground pipe storage are expected to be between 250 EUR/kg and 500 EUR/kg [28,29]. In the present analysis, storage costs of 330 EUR/kg are assumed.

Table 3-5: Technical and economic parameters considered for underground pipe storage of pressurized hydrogen.

Parameter	Value (2030 & 2040)	Unit
Storage volume	Optimization Variable	m³
Max. working pressure	80	bar
Min. working pressure	10	bar
CAPEX	2,100	EUR/m³
	330	EUR/kg_{gross}
OPEX	1	% of CAPEX/yr
Lifetime	40	years
TRL (hydrogen pipe storage)	3-5	

Relevant sources:
CAPEX: industry reference; [27–29]
OPEX: own assumption
Lifetime: [25,27]

Before the storage and the liquefaction/synthesis, compressors have been taken into account, compressing the hydrogen (and nitrogen or CO_2) to the required process pressure. All required compressors in the system have been considered in the cost analysis. Further details can be found in [1].

3.2.3 Water supply via desalination

In addition to electricity, water is required to produce hydrogen. The stoichiometric water demand for the production of hydrogen is 8.9 kg H_2O/kg H_2. Due to water loss during the fine purification process to produce fully deionized water and the water contained in the saturated hydrogen and oxygen product flows after electrolysis, the initial freshwater demand is assumed to be around 15 kg H_2O/kg H_2 [30–32]. It should be noted, that the final freshwater demand depends on several factors like technology supplier and water quality.
A sustainable production of green hydrogen must also include the aspect of water supply. Negative effects of water consumption on the local population and environment should be avoided [33].
For the analysis, is it assumed, that freshwater supply is available in Cartagena and Valle del Cauca. At both location, aridity is very low and freshwater rivers are available. For the present analysis, 2 EUR/m³ H_2O have been assumed [34]. In contrast, the aridity in La Guajira is much higher and no water infrastructure is available. Therefore, seawater reverse osmosis is considered for freshwater generation. For several years, SWRO has been the dominant desalination technology thanks to its low electrical power demand and the fact that no thermal energy is required [35]. Sea water desalination is a technically mature technology. Currently, the biggest challenge is the disposal of brine, which could harm underwater habitats, so special attention should be paid to proper brine distribution in the area of discharge.

Table 3-6: Technical and economic parameters considered for sea water reverse osmosis.

Parameter	Value (2030 & 2040)	Unit
Specific energy consumption	3.6	kWh/m³
CAPEX	1,640	EUR/(m³*d)
OPEX	128	EUR/(m³*d)/yr
Lifetime	30	years
TRL	9	
Relevant sources: [36,37]		

3.3 Hydrogen Conversion

3.3.1 Liquefaction and Syntheses

The gaseous hydrogen coming from electrolysis and intermediate storage is converted in the hydrogen conversion steps to the final PtX products liquid hydrogen, ammonia, and methanol. Table 3-7 lists the technical and economic parameters for the corresponding processes. The dynamic operation of the conversion steps is dependent on the technology. For example, hydrogen liquefaction is considered to have a higher dynamic capability than the Haber-Bosch process for ammonia synthesis, which takes place at high pressure and temperature. The lower part load limit given in the table therefore refers to large-scale liquefaction and synthesis processes in 2030 and 2040, not to laboratory or pilot-scale plants.

Table 3-7: Technical and economic parameters considered for hydrogen conversion technologies.

Parameter	Value (2030 & 2040)			Unit
	Hydrogen Liquefaction	**Ammonia Synthesis**	**Methanol Synthesis (CO_2 based)**	
Rated capacity	Optimization Value			t/d
Operating pressure (inlet)	20	250	70	bar
Operating temperature (outlet)	-253	550	255	°C
SEC*	6.780	0.009	0.180	kWh_{el}/kg product
H_2 demand	1.017	0.180	0.195	kg H_2/kg product
N_2 demand	-	0.830	-	kg N_2/kg product
CO_2 demand	-	-	1.430	kg CO_2/kg product
Lower part load limit	2030: 50 2040: 25	2030: 80 2040: 60	2030: 60 2040: 40	% of rated production
CAPEX	cf. Figure 3-1			
OPEX	4	4	4	% of CAPEX/yr
Lifetime	30	30	30	years

*: In the case of synthesis, the SEC only takes into account the energy consumption of pumps and compressors within the synthesis process (e.g. recycle loop compressors). The feed compressors for H2, N2 and CO2 are considered separately.

Relevant sources:
Hydrogen Liquefaction: [25,38]
Ammonia Synthesis: [25,39,40], in-house Aspen simulation
Methanol Synthesis: [25,41–43], in-house Aspen simulation

Capacity-dependent investment costs were taken into account for the hydrogen conversion paths. Figure 3-1 shows the corresponding cost curves for hydrogen liquefaction [25,38], ammonia [25,44] and methanol synthesis [25,41–43].

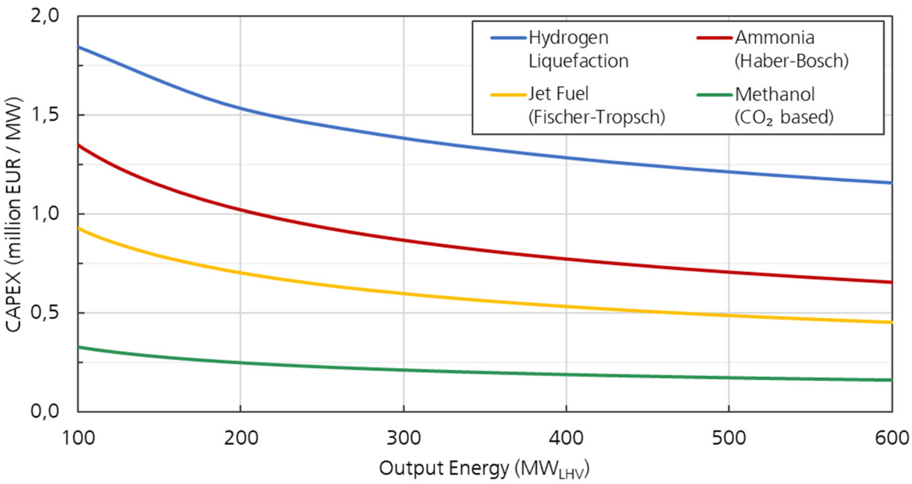


Figure 3-1: Capacity-dependent cost curves for hydrogen liquefaction, ammonia and methanol synthesis applied in this study. 'Output energy' refers to the installed capacity at each location.

3.3.2 Supply of carbon dioxide and nitrogen

Carbon sourcing: The production of methanol requires a carbon source. For the present assessment, carbon dioxide from **low-temperature DAC** is used for the production of methanol. Currently, atmospherically captured carbon dioxide and carbon from certain biogenic sources are the only carbon sources that have some likelihood of meeting the 70% greenhouse gas savings for renewable fuels of non-biological origin (RFNBO) compared to the fossil reference as defined in the last European REDII's Delegated Acts and its amendment REDIII. However, in certain cases and especially if double-counting is avoided, capturing carbon dioxide from point sources may also be possible, which in most cases allow significantly lower capture costs. DAC technology, on the other hand, still results in relatively high capture costs, but enables location independent sourcing of carbon. Moreover, together with biogenic sources, DAC is the basis for globally closed carbon cycles in the energy and fuel sectors.
In the present analysis, it is assumed that a part of the DAC thermal energy demand is covered by heat integration from the methanol synthesis [43,45]. The remaining thermal energy demand is covered by heat pumps. The techno-economic data for DAC processes are subject to high uncertainties, as no commercial plants are in operation and the technology is still under development.
For the analysis of the methanol production in Cartagena and Valle del Cauca, in addition to DAC, **concentrated carbon point sources** have been considered, as here suitable sources (e.g. from cement or ethanol plants) are available. The costs for the captured and purified CO_2 are considered at 150 EUR/ton$_{CO2}$. Other studies point to significantly lower capture costs e.g. in the range of 25-50 EUR/ton (bioethanol) and 50-125 EUR/ton (cement). However, for the integration into the methanol pathway, further CO_2 purification and conditioning is required, which should be reflected in the costs considered in this study.

Table 3-8: Technical and economic parameters of low-temperature Direct Air Capture (LT-DAC) for sourcing of carbon dioxide. The total electricity demand of the integrated DAC considers both the direct electrical energy demand (0.50 kWh$_{el}$/kg CO_2, for operation of fans etc.) as well as the thermal energy demand (during desorption). The latter is partly covered by heat integration from methanol synthesis. The remaining thermal energy demand (1.74 kWh$_{th}$/kg CO_2) is covered by a heat pump (COP: 2.51) and the corresponding electricity demand (0.69 kWh$_{el}$/kg CO_2) is added to the direct electricity demand.

Parameter	Value	Unit
Rated capacity	Based on synthesis capacity	t/d
Total electricity demand heat integrated DAC	1.19	kWh$_{el}$/kg CO_2
Specific investments costs	2030: 1000 2040: 300	EUR/(ton*yr)
Fixed operation costs	4	% of CAPEX/yr
Lifetime	25	years

Relevant sources:
General energy demand: [45]
Heat integration potential: methanol: in-house ASPEN simulation Aspen simulation
Heat pump COP: [45]
DAC costs: [46–48]

Nitrogen sourcing: To produce ammonia, nitrogen is supplied via air separation units (ASU) where atmospheric air is split into its primary components by means of a cryogenic distillation process. The location-independent ASU process is technologically mature and in use worldwide on an industrial scale (TRL 9). Therefore no alterations were made to the parameters between the years 2030 and 2040. The economic parameters for ASU are given in Table 3-9.

Table 3-9: Technical and economic parameters of air separation units (ASU) for sourcing of nitrogen.

Parameter	Value (2030 & 2040)	Unit
Rated capacity	Based on synthesis capacity	t/d
Specific energy consumption	0.56	$kWh_{el}/kg\ N_2$
Specific investments costs	129	EUR/(ton*yr)
Fixed operation costs	2	% of CAPEX/yr
Lifetime	30	years
Relevant sources: [39,49,50]		

3.3.3 Intermediate PtX Storage

The size of the storage is an optimization variable and is therefore determined for each scenario calculation. In the case of local use of the PtX product (no export), the size of the storage is based on a 21-day nominal production of the liquefaction/synthesis. Due to the high level of technical maturity, no parameter variations were made between 2030 and 2040.

Table 3-10: Economic parameters of intermediate PtX storage.

Parameter	Value (2030 & 2040)			Unit
	LH_2	NH_3	MeOH	
Storage volume	14 days of rated liquefaction/synthesis production			m^3
CAPEX	25,000	990	130	EUR/ton
Fixed OPEX	2	2	2	% CAPEX/yr
Boil-off rate	0.1	-	-	%/d
Lifetime	30	30	30	years

Relevant sources:
Liquid hydrogen: [7,25,51–54]
Ammonia:[51–53]
Methanol:[51–53]

3.4 Long-distance shipping of PtX products

The analysis of the PtX export considered only the liquid fuels LH2, NH3 and methanol. Gaseous hydrogen export was not part of the analysis. The following table lists the transport distances from the different export hubs in Colombia to Germany.

Table 3-11: Shipping transport distance from the analyzed PtX hubs to northern Germany.

PtX Hub	Shipping distance to Germany (km)
La Guajira (Puerto Bolivar)	8,550
Cartagena (Puerto Bahia)	8,990
Valle del Cauca	10,150 (from Buenaventura, passing Panama Canal)

The transportation of ammonia and methanol can be considered as state of the art, since both are traded on a global scale and transport vessels are widely available. In this study, an ammonia carrier with a transport volume of 84,000 m³ is considered. Methanol is transported by chemical tankers with a typical transport capacity of 50,000 dwt. For liquid hydrogen, only one small transport vessel is in operation for demonstration purposes. However, there are large-scale concepts that follow the principles of LNG transport. In the present study, an LH_2 carrier with a transport capacity of 10,000 dwt was considered. However, it should be noted that the availability of LH_2 carriers in 2030 is a potential bottleneck for large-scale LH_2 transport. In addition, the associated 2040 investment costs for this carrier have not been varied/reduced due to the currently still very high uncertainties.

Table 3-12: Technical and economic parameters for the considered transport vessels.

Parameter		Value (2030 & 2040)		Unit
	LH_2	NH_3	MeOH	
Vessel type	LH_2 carrier (concept)	LPG carrier	Chemical tanker	-
Transport volume	160,000	84,000	55,000	m³
Transport capacity	10,000	55,000	43,676	tons
Ship speed	16	15	15	knots
Boil-off rate	0.2	-	-	%/day
Capex	440	92	50	million EUR
Fixed opex		4		$\%_{Capex}$/yr
Lifetime		25		years

Relevant sources:
LH2: [7,25,51,54–58]
NH3: [25,51,58–61]
MeOH: [51,52,61,62]

4 Results

The main findings of this study are presented, discussed and categorized below. The results on the Colombian potential for large-scale onshore wind and PV are followed by the identified RE and PtX hub locations. Finally, the identified generation and supply costs and the associated technological parameters of the PtX hubs are discussed.

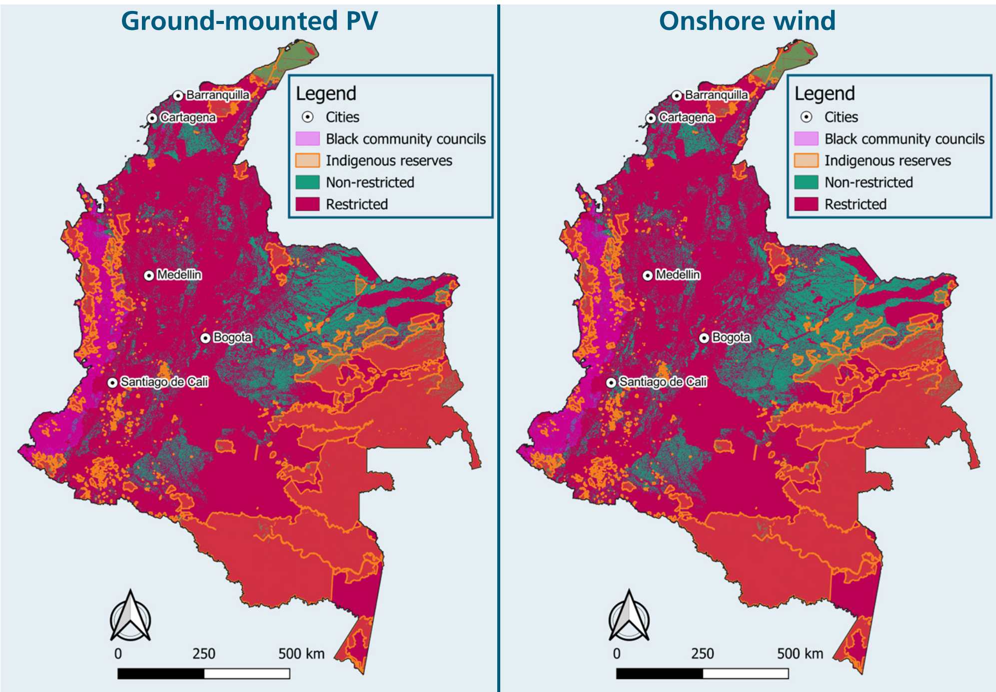
4.1 Site Suitability Results and selected PtX Hub locations

This section presents the results of the site suitability assessment and discusses the rationale behind the selected RE and PtX hub locations.

In order to identify regions that are suitable in principle for large-scale expansion of RES, the resulting restriction areas are analyzed at first. In Colombia, culturally sensitive areas, such as indigenous reserves and black community councils, are of particular importance. However, given the potential for RES in these areas, the following assessment is conducted with and without consideration of these cultural restrictions.
Figure 4-1 displays the resulting restriction areas for both technologies, PV and onshore wind, and their restriction area allocation. Furthermore, the cultural restrictions are indicated by orange and pink shading. As shown, the black community councils may pose restrictions in the western part of Colombia. The indigenous reserves are mainly present in rainforest in the south-east of the country, which are restricted for large-scale RES production. However, indigenous reserves are also present in other regions, that are otherwise non-restricted and have a high potential for RES implementation, such as La Guajira. This report recognizes the extraordinary importance of the indigenous protected areas, but also acknowledges the enormous and outstanding potential of La Guajira. For this reason, the main text and results of this report presents the assessment without consideration of these cultural restrictions, whereas further results including the cultural restrictions can be found in Appendix A6.

The Political Constitution of 1991 establishes Colombia as a democratic, participatory, and pluralistic republic that recognizes and protects ethnic and cultural diversity as a constitutional value. It further guarantees the self-determination of indigenous peoples, reaffirming Colombia as a multicultural and multiethnic state. This recognition implies that the nation accepts and safeguards the existence of diverse perspectives and forms of organization, granting ethnic and cultural identity and diversity the status of a fundamental right.
As acknowledged by the Colombian Institute of Anthropology and History (ICANH) in its document on Guidelines for the Preparation of Ethnological Studies of the Social, Political, and Cultural Organization of the Wayuu People (2024), in recent years interactions between the Wayuu people and the development of projects (including renewable energy initiatives), within their territory have intensified. As a result, the Wayuu people have broadened their approaches to dialogue and negotiation with both the State and private companies, resulting in new dynamics within their social, political, and cultural organization. However, tensions and challenges have also arisen in ensuring their constitutional rights are upheld and harmonized with the interests of project developers and governmental priorities. Issues such as the definition of authorities, organizational diversity, the concept of clan-based territory, and specific economic and political contexts pose significant challenges for institutions and companies to develop projects that both respect and preserve Wayuu culture while advancing their own development initiatives.

María Paula Moreno
Head of Social and Institutional Relationship
COLIBRI ENERGY



		Ground-mounted PV	Onshore wind
	Non-restricted	**15,4%**	**17,7%**
	Restricted	**84,6%**	**82,3%**
Settlements and infrastructure	Industrial and settlement areas	1,8%	7,6%
	Roads	0,3%	0,3%
	Railways	0,0%	0,0%
	Airports and airfields	0,0%	0,0%
	Navigational aids	-	0,2%
	Transmission lines	-	0,4%
	Existing wind turbines	0,0%	0,0%
	Existing PV parks	0,1%	0,1%
Ecology and culture	IUCN protected areas	30,3%	30,3%
	Important bird areas	-	10,6%
	Ramsar wetlands	0,2%	0,2%
	Black community councils	5,4%	5,4%
	Indigenous communities	30,6%	30,6%
Land use, natural hazards and others	Forests and vegetation	71,1%	65,1%
	Flooded vegetation	1,4%	1,4%
	Water bodies	2,4%	2,4%
	Crop land	2,3%	-
	Peasant reserve zones	1,1%	1,1%
	Mining areas	0,1%	0,1%
	Active faults	0,1%	0,1%
	Slope	4,6%	4,6%

Figure 4-1: Resulting restriction areas in Colombia and allocation of restriction types. This report acknowledges the sensitivity and distinctive nature of the land areas identified as belonging to either 'indigenous communities' (30.6%) or 'black community councils' (5.4%). Concurrently, the present analyses acknowledge the exceptional status of RE regions such as La Guajira and emphasise the sustained discourse and negotiations between affected stakeholders (including the Wayuu people), the state and private enterprises. Consequently, this map illustrates the potential of the RE area, including territories that are attributed to indigenous communities or black community councils. Further results including the cultural restrictions can be found in Appendix A6.

In the case of **ground-mounted PV**, 15.4% of Colombia (175,000 km²) is not subject to any considered restriction. The individual restricted areas account for 151.9% of the total area, with some overlap between them, resulting in 84.6% restricted area. The main causes of these restrictions are forests and dense vegetation, as well as natural protection areas and indigenous reserves. The proportion of existing settlements and infrastructure is relatively small (2.3%). Large, unrestricted contiguous areas are found mainly in the central eastern part of Colombia, as well as in the north and south-west. If indigenous reserves are not considered, also the region La Guajira hosts substantial non-restricted are for ground-mounted PV.

The non-restricted area for **onshore wind** energy development is even more extensive, accounting for 17.7% of Colombia (200,000 km²). The individual restricted areas collectively account for 160.6% of the total area, with some overlap between them, resulting in 82.3% restricted area. The primary constraints on wind energy development arise from forests and dense vegetation, as well as natural protection areas and indigenous reserves. Existing settlements and infrastructure also account for a significant proportion, covering 7.6% of the study area. Another substantial restriction is posed by Important Bird Areas (10.6%) to preserve species and biotope protection for birds.
For a simplified estimate of the theoretical PV and onshore wind potential in Colombia, an area requirement of 50 MW/km² for fix tilt PV systems and 15 MW/km² for onshore wind turbines is assumed. This results in a theoretical maximum installed capacity of 9,900 GW for open-space PV and 3,000 GW for onshore wind in Colombia. It should be noted that these are highly theoretical numbers to identify an upper technical limit. Further technical, logistical and environmental constraints are not taken into account. In particular, the non-restricted areas for onshore wind are limited by the available wind speeds and the assessment does not consider the impact of wake effects. The exclusion zones and setback distances considered can never reflect all relevant aspects of spatial planning, nature conservation, species protection or other forms of future large-scale land demand. This simplified assessment therefore tends to overestimate the potential. Nevertheless, the result shows the potential of Colombia for renewable electricity generation.

The resulting site suitability maps from the third model step are illustrated in Figure 4-2. For **ground-mounted PV** the map shows large contiguous areas with high suitability scores in La Guajira and the in the north-west near Barranquilla and Cartagena. More isolated areas with high scores appear in central Colombia, for instance in the northern part of Valle del Cauca. The highest achieved score of up to 99.5 % is achieved in the region around Bosconia and in the south of La Guajira around San Juan del Cesar. The highest site suitability score category ideal is achieved within 0.2 % of Colombia, while 2.3 % are classified as excellent. Around 0.5 - 3.0 GW of PV capacity is needed to supply a 1 GW electrolysis of depending on the respective solar and wind resources at a specific location. Based on an average space requirement of 50 MW/km² for fixed-tilt PV systems, a cluster size of 50 km² was used for the clustering procedure. As a result, 212 PV clusters with a site suitability score above 75 % and a size above 50 km² are illustrated in Figure 4-2 in yellow color. Other more distributed suitable PV area is shown in orange color.
For **onshore wind** the site suitability map shows a very heterogeneous picture. The only extensive contiguous area with high suitability scores is present in La Guajira. Other suitable non-restricted areas are limited in size for large-scale renewable energy production from onshore wind. The site suitability score category highly suitable is achieved within 0.16 % of Colombia, while 0.65 % are classified as favorable. Based on a first rough onshore wind capacity estimation to supply a 1 GW electrolysis of around 0.0 – 2.0 GW are needed. With an average space requirement of 15 MW/km² for onshore wind turbines, a cluster size of 130 km² was used for the clustering procedure. As a result, two large-scale wind clusters from within La Guajira with a total area of 4,250 km². As these locations are also suitable for large-scale PV clusters, these sites are highlighted as **hybrid** clusters in green color. Apart from these enormous wind clusters in La Guajira, further smaller distributed wind areas appear along the mountain chains of Colombia highlighted in dark blue color.

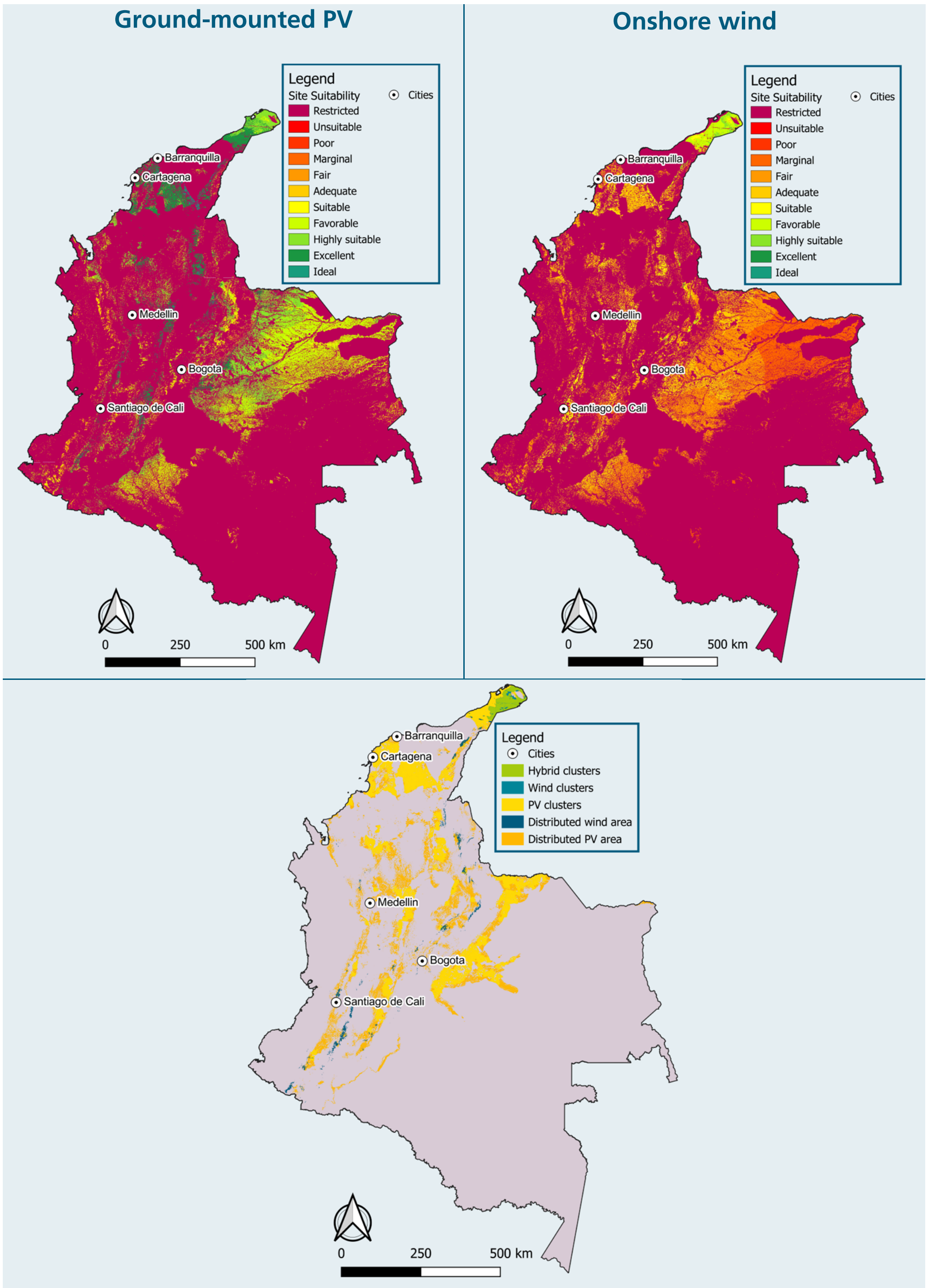


Figure 4-2: Resulting site suitability maps (top left: PV, top right: onshore wind) and resulting renewable energy clusters for potential PV, onshore wind and hybrid parks (bottom) rendering sufficient to host the necessary renewable capacities for the envisioned PtX production capacities.

4.1.1 PtX Hub 1: La Guajira

The region of La Guajira has an outstanding potential for large-scale renewable energy production via ground-mounted PV and onshore wind if cultural restrictions are not considered. As illustrated in Figure 4-2 and Figure 4-3 the peninsula hosts by far the most extensive potential renewable energy clusters within Colombia. Overall, the region is characterized by a lack of infrastructure development and one of the most pressing problems for the local population is safe access to clean drinking water and health services. In the context of a PtX hub implementation the absence of a high-voltage transmission line system and an underdeveloped rail and road system must be emphasized. The PtX hub site was selected in proximity to the existing coal-export port of Puerto Bolívar, based on the available and prospective infrastructure. The availability of free space near the harbor, combined with the region's wind and solar energy resources, makes it an ideal location from a technical point of view for large-scale wind and photovoltaic clusters with subsequent PtX production and export. This is achieved without the necessity for the lengthy transportation of electricity and water, as well as the produced PtX products. Due to the presence of an important bird area near the port, the location of the wind cluster is selected in the east of the PtX hub, which will be connected via a dedicated high-voltage transmission line. The selected photovoltaic cluster has outstanding potential with an average global horizontal irradiation of 2250 kWh/m² and enough area to host even larger production capacities. The selected onshore wind cluster has a world-class average wind speed of 13 m/s at a height of 100 meter within the 10 % windiest areas of the cluster. The focus of this PtX hub is on the export of its products, rather than on the domestic offtake, as there is currently no industry present in La Guajira. Consequently, the only carbon source for the methanol production in this region is Direct Air Capture.

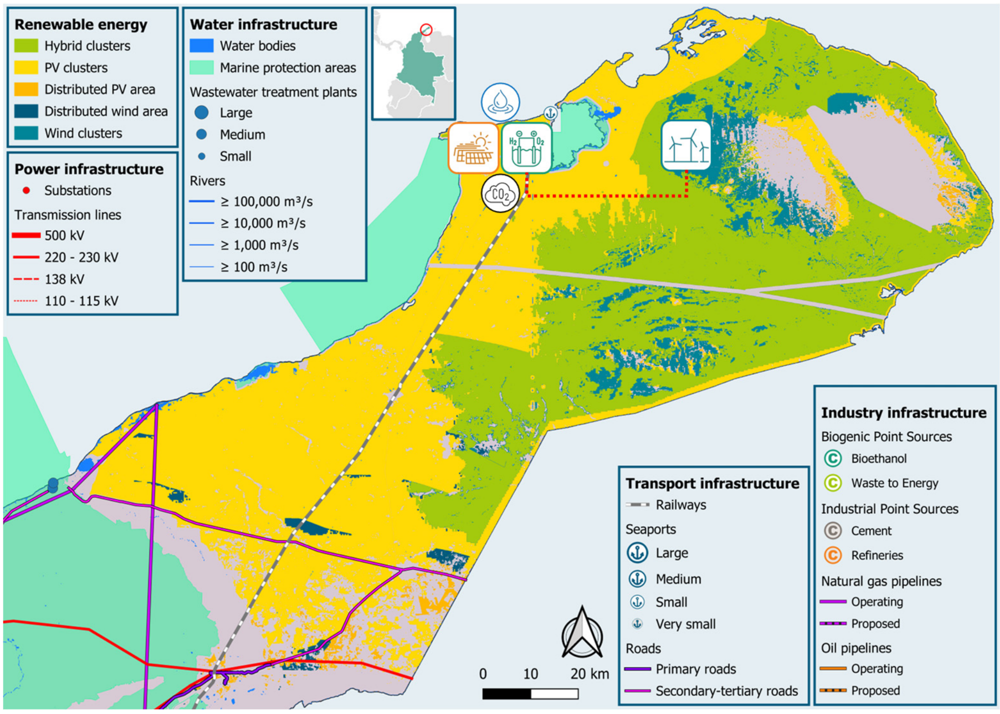


Figure 4-3: La Guajira: RE and PtX site selection based on the solar and wind potentials as well as the regional infrastructure availability.

The region's water scarcity presents a challenge and a potential benefit for the region. The primary water source assumed for electrolysis operation is seawater desalination, which is enabled by the hub's access to non-protected coastline. The oversizing of a future desalination plant could enable the usage of water for the local population and

agriculture in the region, while only adding a negligible cost addition to the PtX product costs. One challenge that would have to be overcome here would be the highly decentralized distribution of the drinking water obtained to the scattered population in the region. However, these and other aspects in connection with the socio-economic challenges in La Guajira are not part of the analyses in this technical report.
It is evident that a significant expansion of the Puerto Bolívar (1) is required in order to enable future ship transport of PtX products. Furthermore, the location of the RE and PtX facilities within indigenous reserves necessitates the identification of a mutually acceptable solution regarding the implementation and participation of all parties involved.

4.1.2 PtX Hub 2: Barranquilla and Cartagena

The region around Barranquilla and Cartagena offers a number of significant potential photovoltaic clusters, with the capacity to produce ammonia, methanol or liquid hydrogen on a large scale. The suitability of this region for extensive onshore wind development is limited by the presence of natural and marine protection areas within high wind speed areas. However, along the coastline there are potential non-floating offshore wind clusters with decent wind resources. Accordingly, this region enables the production and export of ammonia, methanol or liquid hydrogen based on standalone photovoltaic clusters or photovoltaic-offshore wind hybrid systems. Figure 4-4 displays the selected location for the renewable energy clusters and the PtX hub.

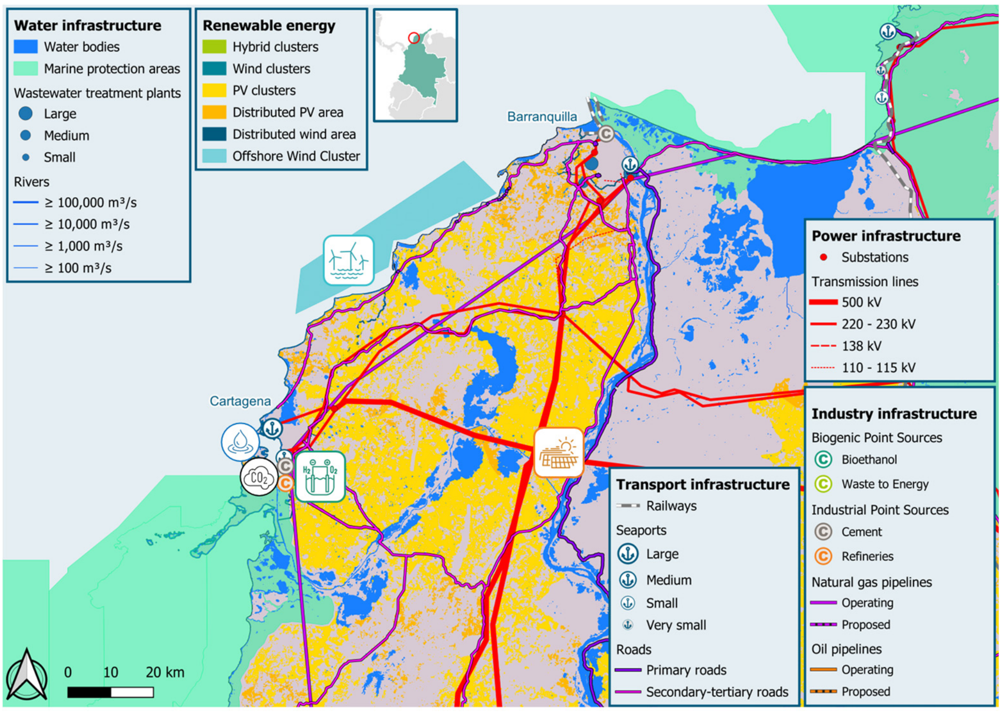


Figure 4-4: Cartagena: RE and PtX site selection based on the solar and wind potentials as well as the regional infrastructure availability.

Barranquilla and Cartagena offer a decent port infrastructure, including existing methanol and ammonia terminals. Both ports are planning to become hydrogen export facilities, partially represented in the Colombian National Development Plan. Besides the port infrastructure the cities of Barranquilla and Cartagena host several industrial complexes. Therefore, the region has several potential industrial point sources available within refinery and cement complexes to supply CO_2 for the methanol synthesis. For instance, the cement facility of Cementos Argos offers sufficient direct CO_2 emissions (~2.1 Mt_{CO2}/a) with substantial process-related share. Biogenic point sources are not

available on a relevant scale within the region. Due to the industrial infrastructure this region has the potential for domestic product offtake, besides the great export potential via the access to the Atlantic Ocean via the ports of Barranquilla and Cartagena. The potential local offtakers in Cartagena include refineries, cement and fertilizer plants (current ammonia, urea and nitric acid production). Furthermore, the availability of an excellent transmission line and natural gas pipeline system is a significant advantage of this region. In comparison to La Guajira the water supply for the electrolysis and further processing steps is not critical. Potential water sources include surface waters, treated wastewater from wastewater treatment plants or seawater desalination due to the access to unprotected coastline.
The optimal location for the PtX hub has been identified as either Puerto Bahia or within the petrochemical complex in the Mamoral/Casablanca zone. The selected photovoltaic cluster has excellent potential with an average global horizontal irradiation of 2040 kWh/m² and sufficient suitable area to host even larger production capacities. The transportation of electricity is facilitated by the utilization of dedicated grid capacities, which may be built along the existing transmission lines corridors. Any surplus electricity is injected into the transmission grid free of charge. Other nearer photovoltaic clusters, for instance in the south of Cartagena are also feasible, but have lower solar resources.

4.1.3 PtX Hub 3: Valle del Cauca

The region of Valle del Cauca (cf. Figure 4-5) northern to Cali has a number of large-scale photovoltaic clusters with isolated small-scale onshore wind sites supported by an excellent grid electricity availability (500 kV and 2 x 230 kV). The selected photovoltaic cluster has great potential with an average global horizontal irradiation of 2030 kWh/m² and sufficient suitable area to host even larger production capacities. The photovoltaic cluster further south also hosts enough suitable area, but lower global horizontal irradiance. The distributed onshore wind sites in the region of Vijes and Yumbo need an in-depth assessment of their suitability but may supplement the photovoltaic with decent wind resources above 6 m/s.

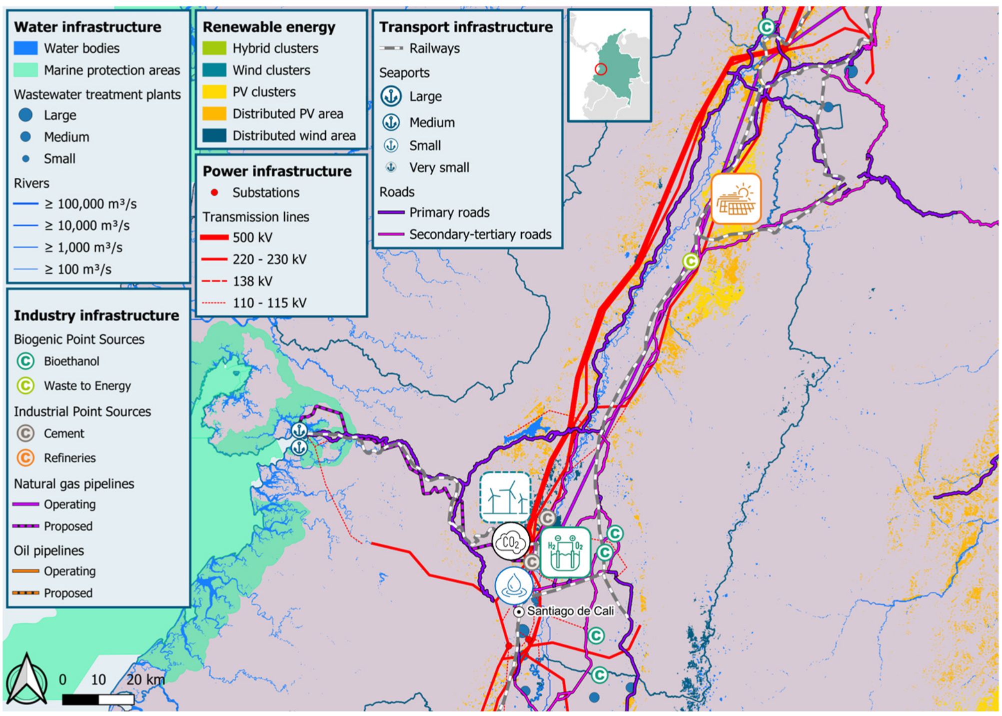


Figure 4-5: Valle del Cauca / Cali: RE and PtX site selection based on the solar potential as well as the regional infrastructure availability.

Additionally, this region is characterized by the availability of biogenic point sources in the form of bioethanol and waste-to-energy plants. Although, the potential individual biogenic point sources are too small for a large-scale methanol synthesis based on a 1 GW electrolysis, it presents a great option for medium-scale methanol plants or as a part of the product portfolio. For large-scale methanol production the cement facility Cementos San Marcos (~0.34 Mt_{CO2}/a) is suitable apart from Direct Air Capture. A location of the PtX hub is identified around 1 kilometer south of the cement plant and 25 kilometer north of Santiago de Cali. The existing natural gas pipeline may be suitable for blending, retrofitting or serve as a pipeline corridor in the future. Hydropower generation may enable the system integration of a base-load renewable energy source to a certain extent. The region benefits from water availability by the Cauca River, although it is highly polluted. Nevertheless, water availability is evaluated as uncritical and treated wastewater from the wastewater treatment plants around Santiago de Cali may represent another option. Finally, the region has two ports, Buenaventura and Aguadulce located at the Pacific Ocean, which are currently unable to accommodate large-scale liquid energy carriers. The railway connection to these ports is out of operation and recommissioning may not be feasible for the export in 2030. Therefore, this PtX cluster is centered around the production of ammonia and methanol for domestic utilization and export to north Colombia via the existing railway connection.

4.2 Techno Economic Analysis results

Based on the results of the site suitability analysis and the RE potential in the previous chapter, this chapter deals with the resulting techno-economic results for PtX production. Before the results are presented for each location, the following two summaries show the range of local hydrogen production costs and the production costs for the three end products liquid hydrogen, ammonia and methanol.

In Figure 4-6 the range of local hydrogen production costs (LCOH; at Gate, without any transport) over all analyzed locations in Colombia are depicted for 2030 and 2040. In 2030, LCOH between 3.3 EUR/kg and 5.1 EUR/kg are to be expected. Due to cost reductions for renewable energy sources and electrolysis, LCOH will fall to 2.7 EUR/kg and 3.9 EUR/kg. It should be noted, that the costs showing the LCOH without any intermediate storage or transportation of the hydrogen. As will become clear in the following sub-chapters, the main factors are the costs of renewable energies and the assumed capital costs. In particular, there is a degree of uncertainty about the extent to which cost reductions for renewable energy can be realized, especially as the time horizon increases. Corresponding sensitivity analyses for CAPEX for wind and PV as well as for WACC can be found in Chapter 4.3.1.

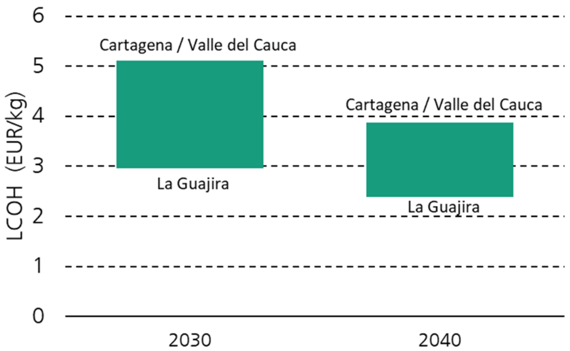


Figure 4-6: Range of local (at-Gate) hydrogen production costs over the three analyzed locations in Colombia for 2030 and 2040.

Figure 4-7 shows the corresponding results for the liquid PtX energy carries LH2, NH3 and MeOH. The bar indicates the lowest and highest local production costs determined in Colombia over all three hub locations.

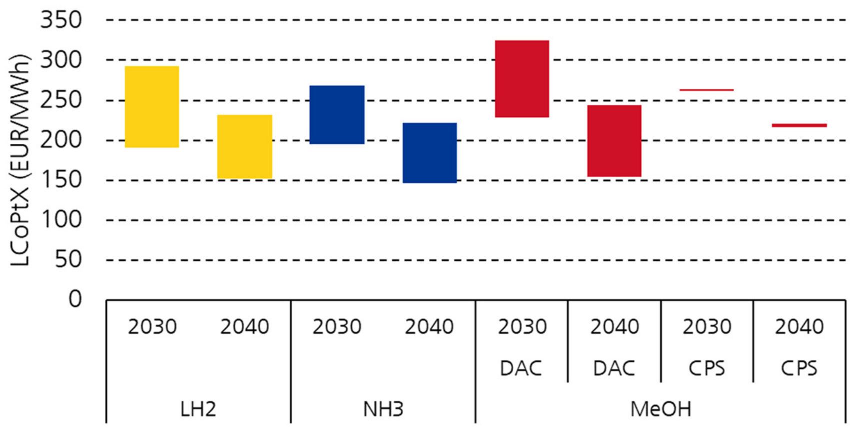


Figure 4-7: Overview of the calculated cost ranges for local (at-gate) PtX products in 2030. The respective cost ranges derive from the three identified PtX hub locations and their respective conditions. The methanol path distinguishes between carbon supply via DAC and a carbon point source (CPS). The unit EUR/MWh refers to the respective lower heating value of the end products.

4.2.1 PtX Hub 1: La Guajira

In Figure 4-8 the cost breakdowns for the three PtX export scenarios liquid hydrogen (LH2), ammonia (NH3) and methanol (MeOH-DAC) are shown. In case of the hydrocarbon methanol, CO_2 is obtained by direct air capture. In addition, the at-gate-costs for gaseous hydrogen (GH2-local) are indicated. No local costs were analyzed for the other PtX products at this location, as no large local customer could be found. The systems at this location are designed as off-grid systems that provide backup power (for synthesis, compressors, etc. - excl. electrolysis) via the reconversion of hydrogen in a fuel cell. As for all results discussed in the following, the unit EUR/MWh refers to the respective lower heating value of the end products.
In 2030, the supply costs for liquid hydrogen and for ammonia including transport to Germany are comparable, at 190 EUR/MWh (6.3 EUR/kg LH2) and 195 EUR/MWh (1010 EUR/ton NH3), respectively. The production of methanol with CO_2 capture via DAC results in supply costs of 228 EUR/MWh (1260 EUR/ton MeOH). As reference, gaseous hydrogen production costs have been determined, without any further downstream conversion nor supply constraint. For this, the resulting production costs are 98 EUR/MWh (3.3 EUR/kg) in 2030. These exceptionally low production and supply costs represent the best location in Colombia and also represent one of the best technically available locations in the world. The principal reason for this is the favorable wind and solar conditions (cf. Table 3-2), which not only exhibit high irradiation and wind speeds, but also demonstrate minimal seasonal fluctuations throughout the year.
As a consequence of ongoing technological advancement and the consequent reduction in investment and operational expenditure, a notable reduction in production and supply cost is evident across all PtX scenarios by 2040. The export costs for LH2, NH3 and MeOH exhibit only slight discrepancies. All are within the range of 147 EUR/MWh to 154 EUR/MWh. It is anticipated that the costs associated with the production of gaseous hydrogen will decline to 81 EUR/MWh (2.7 EUR/kg). The majority of the projected cost reductions can be attributed to the reduction in capital expenditure for wind and PV technologies, as well as for electrolysis systems. Additionally, the cost reduction of the direct air capture unit in the case of the methanol pathway contributes to the overall reduction in costs. From a technical perspective, enhanced electrolysis efficiency and an extended operational window for conversion processes further reduce costs.
In all four scenarios analyzed, renewable energy generation represents the highest proportion. The share of costs is dominated by onshore wind energy. The discrepancy in the installed capacities of wind and PV can be attributed to the underlying system simulation and optimization. It can be generally stated that a more dynamic operational pathway, such as the liquid hydrogen pathway, can rely on a greater proportion of wind energy than less dynamic synthesis pathways. Conversely, the ammonia pathway, which is assumed to have the least capability for dynamic operation, places a greater emphasis on solar power, which is easier to dispatch, particularly in regions closer to the equator.
The water supply via seawater desalination, which was considered for the extremely dry region, is practically not visible in the cost breakdowns for La Guajira. The cost share of this form of water supply is therefore insignificant and should in any case be used for hydrogen projects in the state of La Guajira from a techno-economic point of view. Although the selected location was chosen with the consideration that there is no marine protected area in the vicinity of the hub and the desalination plant, it is nevertheless imperative that the plant design should be chosen with the objective of minimizing the impact on the unique marine ecosystems, and that the plant should be operated in accordance with the latest technical standards in the field of seawater desalination.

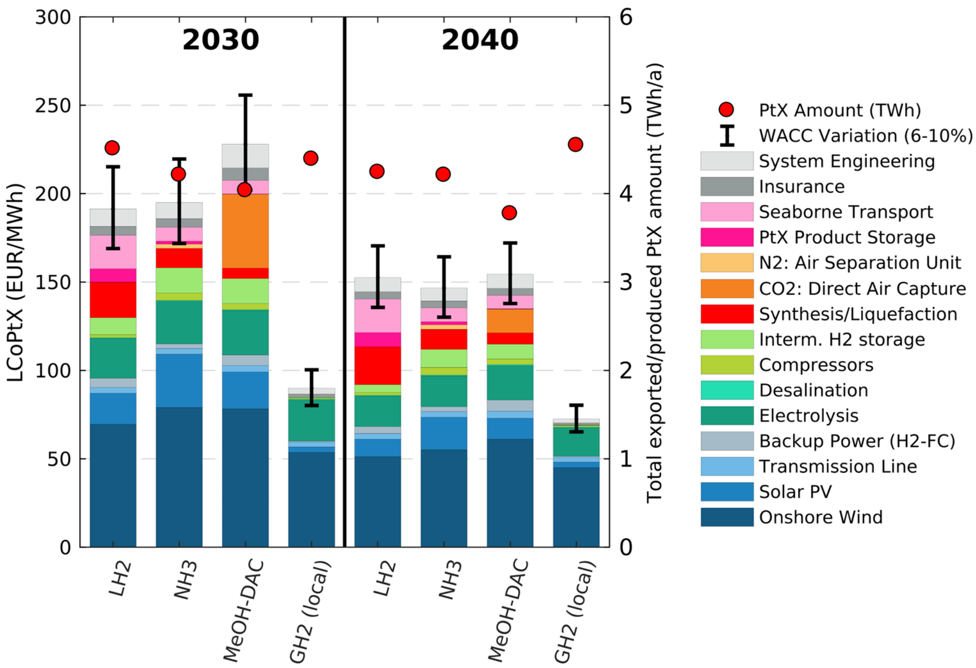


Figure 4-8: La Guajira: Cost breakdown of the analyzed PtX pathways for an off-grid PtX system located in the north-west of La Guajira. The left axis shows supply costs (including transport); the right axis shows the annual exported PtX product quantity.

For further interpretation of the cost breakdowns and techno-economic results, a selection of key performance indicators is listed in Table 4-1. With electrolysis full load hours of up to 7,272 h/yr, this wind-PV hybrid site achieves extraordinarily high electrolysis utilization at world-class level. This is also reflected in the production and supply costs.

Although the levelized cost of wind electricity (36 EUR/MWh_{el} and 32 EUR/MWh_{el}, in 2030 and 2040 respectively) is higher than that of PV electricity (42 EUR/MWh_{el} and 33 EUR/MWh_{el}, in 2030 and 2040 respectively), the overall system benefits from a higher share of wind electricity in all of the scenarios assessed. This is due to the higher system utilization resulting from a larger wind share and thus reduced PtX production costs.

In the assessed ammonia scenario the wind-PV mix is more evenly balanced, with 1.3 GW of installed wind power and 1.5 GW of installed PV capacities. Reason again is the need for dispatchable energy in the case of less-dynamic ammonia synthesis. This fact is also reflected by a lower need for cost-intensive intermediate hydrogen storage in the more dynamic liquid hydrogen pathway. Ammonia synthesis, in contrast, which allows part-load operation at only 80-100% of rated capacity (assumed in 2030), requires significantly larger intermediate hydrogen storage when run on variable renewables.

The total amount of energy exported will be between 4,035-4,509 GWh/yr in 2030 and 3,774-4,243 GWh/yr in 2040. In the case of the methanol pathway, the annual product output is reduced by the fact that some of the H_2 produced has to be reconverted into electricity in order to supply the DAC with energy even when sun and wind are not available in sufficient quantities.

The investment costs for the three export paths are estimated to be between EUR 6.1 billion and EUR 6.6 billion. The LH2 pathway is characterized by high costs associated with the H2 liquefaction process, while the methanol pathway requires a significant investment in the DAC plant. The PtX product storage and ships required for subsequent export also cause significantly higher cost shares in the liquid hydrogen pathway than in the ammonia and methanol pathway.

Table 4-1: System Parameters and techno economic KPI in the cost optimum for La Guajira in 2030 and in 2040.

La Guajira	**LH_2 Export**		**NH_3 Export**		**MeOH-DAC Export**	
Year of commissioning	**2030**	**2040**	**2030**	**2040**	**2030**	**2040**
System Parameters:						
Wind: Installed capacity (GWel)	1.6	1.2	1.7	1.3	1.6	1.3
Wind: LCoE (EUR/MWh_{el})			2030: 36	2040: 32		
PV: Installed capacity (GWel)	1.2	0.8	2.0	1.5	1.3	0.9
PV: LCoE (EUR/MWh_{el})			2030: 42	2040: 33		
Liquefaction / Synthesis Cap. (tpd)	441	443	2357	2507	2280	2281
Techno-economic KPI:						
LCoPtX (EUR/MWh)	191	153	195	147	228	154
LCoPtX (EUR/ton)	6372	5079	1010	760	1261	854
PtX Amount (GWh/yr)	4509	4243	4211	4210	4035	3774
PtX Amount (ktons)	140	132	813	813	730	682
Electrolysis: Full load hours (h/yr)	7082	6389	7272	6963	7184	6435
Unused RE (%)	18	8	34	19	18	7
Total System investment (Bn. EUR)	6.3	4.5	6.1	4.3	6.6	3.9

4.2.1 PtX Hub 2: Barranquilla and Cartagena

In Figure 4-9 shows the cost breakdowns of the least-cost optimization of the PtX production in the region of Cartagena/Barranquilla. The red markers in the figure indicate the respective local production costs, given the presence of local consumers of ammonia, methanol and hydrogen in the region.

Among the PtX energy carriers analyzed, ammonia is the most cost-effective energy carrier. Export costs of 261 EUR/MWh can be realized in 2030 and 205 EUR/MWh in 2040. Methanol production using CO_2 from a concentrated point source is in the same order of magnitude (LCoPtX of 262 EUR/MWh in 2030 and 225 EUR/MWh in 2040). Methanol produced with CO_2 from DAC is associated with higher capital expenditures for the DAC plant and an additional electricity requirement for CO2 capture. Therefore, methanol production costs are much higher in 2030 (~317 EUR/MWh). The assumed cost reduction of DAC capture and the lower LCoE in 2040 result in lower methanol costs. While the spread between the energy carriers is quite large in 2030, the costs converge in 2040.

Compared to La Guajira, the amount of PtX energy carrier is significantly lower (~ half) among all PtX energy carriers. This is due to the lack of onshore wind. Even though offshore wind would be available, it is only selected by the system optimization in the cost optimum for a few energy carriers and, if so, only a low capacity is selected. The available offshore wind has a high LCoE. In general, offshore wind is more expensive than onshore wind, and in addition, the selected offshore wind cluster has a relatively low mean wind speed. Solar PV power has much lower electricity costs. The power supply for all PtX energy sources is therefore dominated by solar PV.

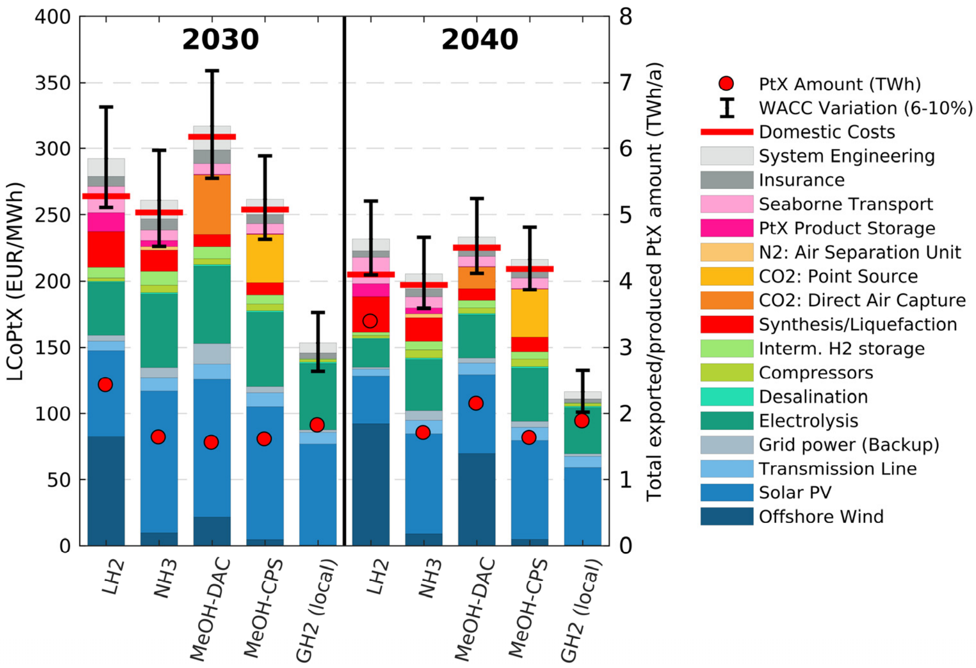


Figure 4-9: Cost breakdown of analyzed PtX production scenarios in the cost optimum of the system optimization for Cartagena/Barranquilla.

Table 4-2 lists the resulting capacities of the PtX plant in the cost optimum of the optimization and other techno-economic results. As mentioned above, the electricity supply is dominated by PV, resulting in installed PV capacities between 2.3 and 2.7 GW in all scenarios. Significant offshore wind is chosen only for LH2 in both target years and for methanol-DAC production in 2040. A maximum demand of 1.1 GW offshore wind can be observed for LH2 in 2040. Otherwise, offshore wind does not exceed 0.6 GW. The full load hours of the electrolysis system are below 3,000 flh for most scenarios. Only when offshore wind is integrated, the electrolysis full load hours increase to over 3500 flh.

Due to the absence of large capacities of wind, total investment costs are in general lower compared to the scenarios in La Guajira. However, due to the lower production quantities, the levelized production costs are higher.

Table 4-2: System Parameters and techno economic KPI in the cost optimum for Cartagena/Barranquilla in 2030 and 2040.

Cartagena	**LH_2 Export**		**NH_3 Export**		**MeOH-DAC Export**		**MeOH-CPS Export**	
Year of commissioning	**2030**	**2040**	**2030**	**2040**	**2030**	**2040**	**2030**	**2040**
System Parameters:								
Wind: Installed capacity (GWel)	0.6	1.1	0.0	0.1	0.1	0.5	0.0	0.0
Wind: LCoE (EUR/MWh$_{el}$)	(offshore) 2030: 100 2040: 85							
PV: Installed capacity (GWel)	2.4	2.3	2.7	2.5	2.5	2.4	2.5	2.3
PV: LCoE (EUR/MWh$_{el}$)	2030: 42 2040: 34							
Liquefaction / Synthesis Cap. (tpd)	287	442	938	1169	951	1560	1045	1450
Techno-economic KPI:								
LCoPtX (EUR/MWh)	292	232	261	205	317	233	262	216
LCoPtX (EUR/ton)	9733	7713	1353	1064	1752	1289	1448	1197
PtX Amount (GWh/yr)	2424	3384	1636	1702	1554	2145	1607	1628
PtX Amount (ktons)	75	105	316	329	281	388	291	294
Electrolysis: Full load hours (h/yr)	3801	5099	2814	2812	2753	3648	2847	2769
Unused RE (%)	17	17	27	22	20	18	22	20
Total System investment (Bn. EUR)	5.6	5.8	3.5	2.7	3.8	3.7	3.0	2.3

4.2.2 PtX Hub 3: Valle del Cauca

Figure 4-10 shows the cost breakdown of the least cost optimized system for Valle del Cauca. Production and export of liquid hydrogen was not analyzed for Valle del Cauca. For Valle del Cauca, only PV was considered as the only power source because no suitable large-scale areas for onshore wind could be identified.
Export costs for ammonia and methanol using CO_2 from a concentrated point source are both close together. In 2030, methanol costs of 264 EUR/MWh and ammonia costs of 268 EUR/MWh can be realized. In 2040, export cost of methanol going down to 221 EUR/MWh and export costs for ammonia to 222 EUR/MWh. In comparison of the local production costs, ammonia is slightly more cost-effective, however the transport costs of ammonia are higher compared to methanol.
Highest production and export costs can be observed for methanol using CO_2 from a DAC (325 EUR/MWh and 244 EUR/MWh in 2030 and 2040, respectively). In particular, the high cost for backup power from the grid increasing the costs. Reason for this is the power demand for the DAC, which must also be supplied when no PV power is available, as the methanol synthesis is continuously in operation.
In general, the results for Valle del Cauca are comparable to these from Cartagena/ Barranquilla. For both locations, PV power is the main power source, with slightly higher production in Valle del Cauca. However, transport costs are higher due to the longer transport distance through the Panama Canal. In Valle del Cauca, local use should be taken into the focus, as export facilities in Buenaventura must be developed.

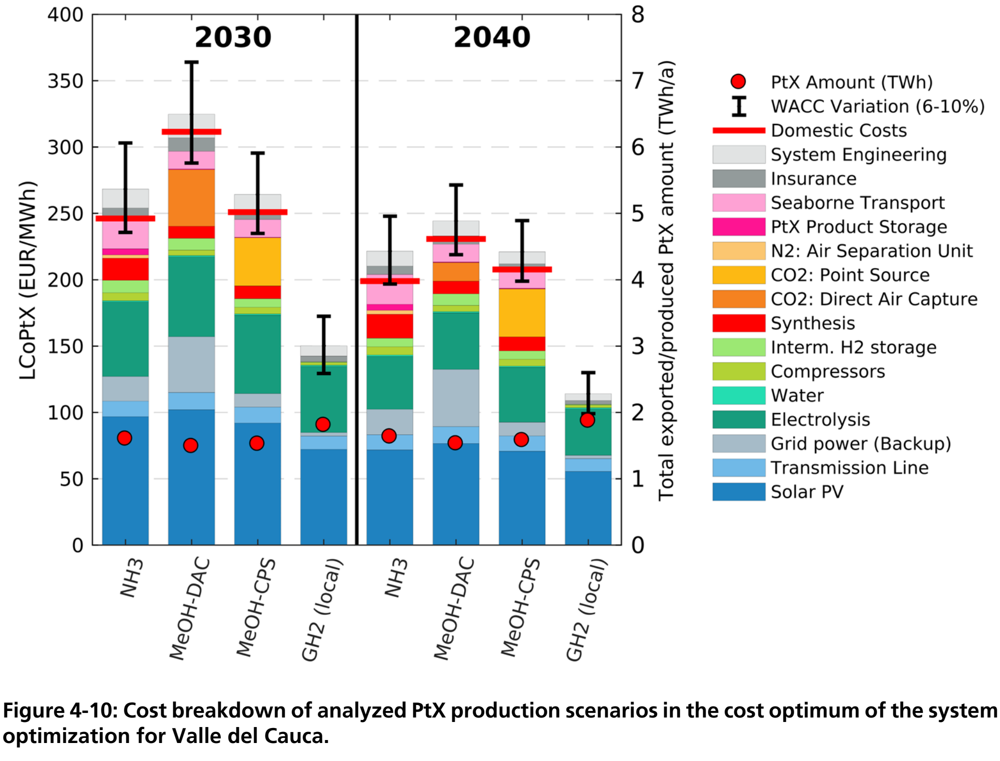


Figure 4-10: Cost breakdown of analyzed PtX production scenarios in the cost optimum of the system optimization for Valle del Cauca.

Table 4-3 lists the resulting capacities of the PtX plant in the cost optimum of the optimization and further techno-economic results. For all scenarios, the electrolysis full load hours are not exceeding 2800 flh, which is typical for PV only system. To supply the 1 GW electrolysis, between 2.1 and 2.4 GW of PV are required in the cost optimum. Due to the larger installed power, 18-20 % of the produced PV power cannot be used by the plant.

Table 4-3: System Parameters and techno economic KPI in the cost optimum for Valle del Cauca in 2030 and 2040.

Valle del Cauca (2030)	**NH_3 Export**		**MeOH-DAC Export**		**MeOH-CPS Export**	
Year of commissioning	**2030**	**2040**	**2030**	**2040**	**2030**	**2040**
System Parameters:						
Wind: Installed capacity (GWel)	0.0	0.0	0.0	0.0	0.0	0.0
PV: Installed capacity (GWel)	2.4	2.3	2.3	2.3	2.1	2.1
PV: LCoE (EUR/MWh_{el})			2030: 40	2040: 32		
Liquefaction / Synthesis Capacity (tpd)	941	1119	861	967	1002	1210
Techno-economic KPI:						
LCoPtX (EUR/MWh)	268	222	325	244	264	221
LCoPtX (EUR/ton)	1390	1148	1796	1351	1461	1222
PtX Amount (GWh/yr)	1601	1633	1490	1529	1524	1579
PtX Amount (ktons)	309	315	269	277	276	286
Electrolysis: Full load hours (h/yr)	2753	2697	2640	2604	2698	2686
Unused RE (%)	22	20	20	18	18	18
Total System investment (Bn. EUR)	3.2	2.5	3.4	2.4	2.7	2.1

4.3 Further Assessments

4.3.1 Sensitivity Analysis

Technological and economic parameters are subject to uncertainties, especially when looking further into the future. The central objective of the following sensitivity analyses is to show how strongly the PtX production and supply costs depend on individual key techno-economic parameters. A sensitivity analysis helps to identify which variables have the greatest impact on the results.
Below is a sensitivity analysis for the production of liquid hydrogen, ammonia and methanol in La Guajira in 2030 is included. Figure 4-11 shows the effect, of changing the WACC and the CAPEX from wind power plant, solar power plant and from the liquefaction/synthesis in the range between -50 % and +50 %. For methanol production, a sensitivity to the investment costs for DAC is also shown.
For all PtX energy carriers, the highest sensitivity is related to the WACC, as this value affects all components of the supply chain. For example, a 50% reduction in the WACC to a WACC of 4% reduces the PtX cost by 40-50 EUR/MWh. The second highest sensitivity of all energy sources is observed for wind power. For liquid hydrogen, the sensitivity to investment costs for solar, electrolysis and liquefaction have a comparable impact on the total cost.

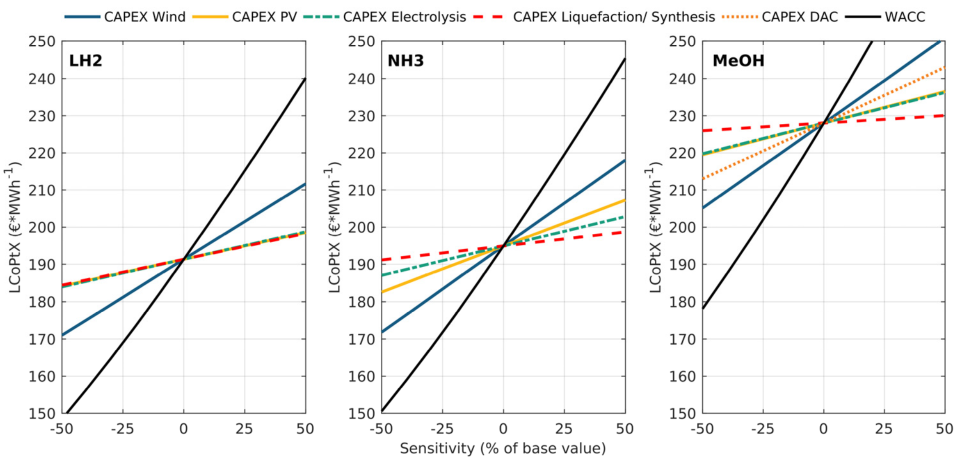


Figure 4-11: Sensitivity of selected components CAPEX and the WACC on the LCoPtX for location La Guajira in 2030.

4.3.2 Grid power for hydrogen production

In the scenarios analyzed in the main part, hydrogen production was only possible with dedicated RE power, considering the temporal and local correlation of electricity production. In this additional assessment, we consider additional grid power for hydrogen production to evaluate the potential influence on the production costs for the different PtX energy carriers.
In 2022, Colombia's electricity mix includes about 70% hydropower, resulting in a highly defossilized electricity mix. The remaining 30% is mainly generated by fossil fuels such as natural gas and coal. In the next decade, the development of large onshore wind and PV capacities should significantly increase the share of renewable electricity generation, cf. Figure 4-12 [63].

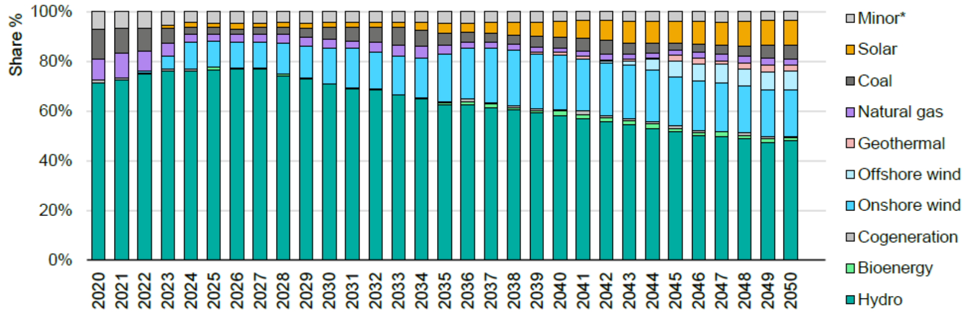


Figure 4-12: Outlook on the electricity generation share in Colombia from 2020 to 2050. [63]

Given the significant share of renewable electricity, the concept of utilizing grid electricity for hydrogen production is a logical one. Therefore, an additional analysis of the use of hydropower (grid electricity) for hydrogen production has been conducted in this chapter. It is important to recognize that the extensive use of hydropower for hydrogen production could potentially lead to an increase in fossil fuel electricity generation. While the hydrogen may be considered environmentally friendly, the carbon intensity of the Colombian electricity mix could potentially increase. Therefore, the use of existing power plants for hydrogen production is considered a critical issue [64].

The assessment has been carried out according to the Cartagena scenario. In addition to PV and offshore wind, baseload grid electricity can be used for electrolysis. To assess the impact of different electricity costs, the analysis was performed for grid electricity costs of 25, 50, 100 and 150 EUR/MWh. In addition, the amount of baseload hydropower consumed by the plant was selected as another decision variable for the optimization algorithm, allowing the algorithm to determine the extent to which baseload hydropower should be used.

Figure 4-13 illustrates the resulting PtX costs when grid electricity is used for hydrogen production. For all energy sources, the share of grid electricity is significant at low electricity costs. The capacities of solar PV are relatively modest in the cost optimum, but increase with higher grid electricity costs, as the cost of grid electricity becomes higher relative to the cost of the RE source, primarily solar PV.

In particular, the use of grid power has the effect of increasing the amount of PtX output, especially when the cost of grid power is low.

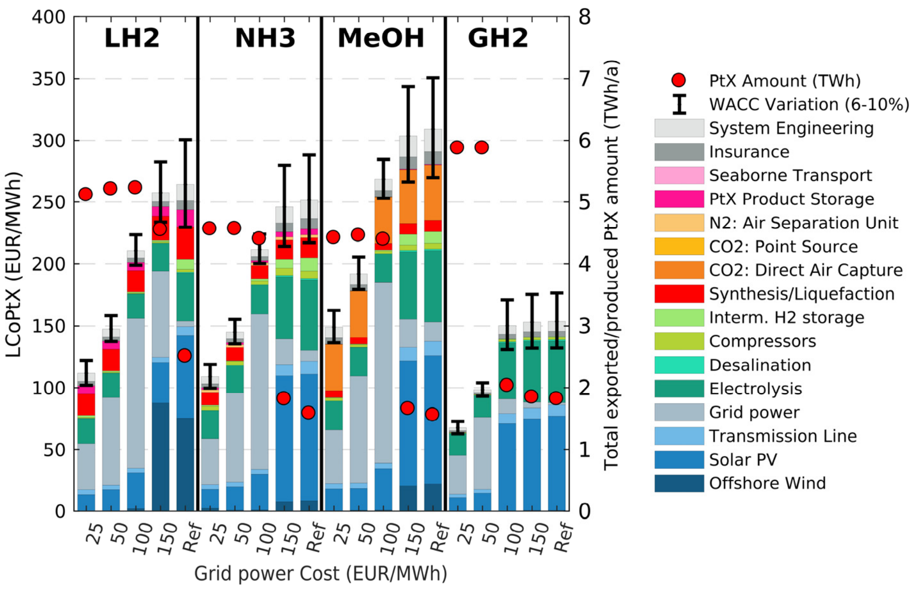


Figure 4-13: Sensitivity on additional grid power supply for the production of hydrogen for different power costs.

Assuming a direct power purchase agrrement (PPA) from a hydro power production plant, electricity costs of around 50 USD/MWh can be expected, cf. Figure 4-14 (here, referring to "Other South America") [10]. The use of low-cost hydropower can therefore have a positive effect on profitability, compared to the use of dedicated wind and PV power.

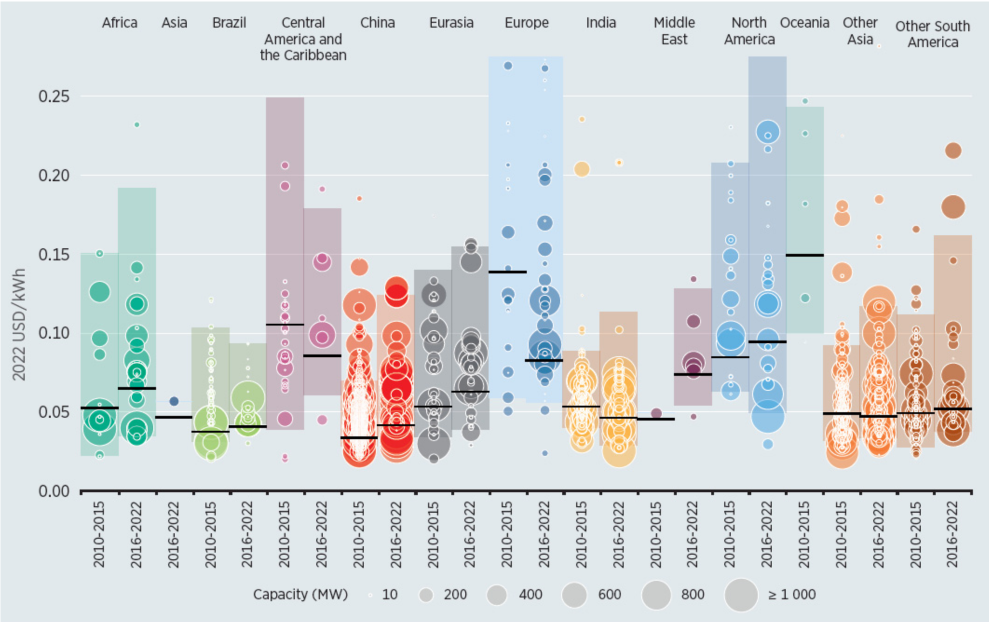


Figure 4-14: Levelized cost of electricity by Large hydropower plants based on IRENA. [10]

However, since much of the hydropower is expected to be traded on the wholesale electricity market, the electricity price for the hydropower consumed is expected to be related to the wholesale market price. Data from Climatscope (a platform of BloombergNEF) indicate electricity costs of 131 USD/MWh (~120 EUR/MWh) for Colombia in 2022 [65]. Thus, electricity prices in Colombia are in the range of the higher electricity costs analyzed, resulting in correspondingly high PtX costs.
It is questionable whether the use of grid electricity for hydrogen production is economical under current conditions.
With a current installed generation capacity of less than 20 GW, the expected electrolysis capacities of 1 GW and more for individual plants will have a significant impact on the national electricity system and the electricity market. There is therefore a real risk that this will lead to an increase in the production of electricity from fossil sources to meet the general demand for electricity in Colombia.

5 Conclusions and Recommendations

This chapter summarizes the findings from the analysis on the PtX production in Colombia. This Fraunhofer ISE study provides a comprehensive analysis of suitable production regions for wind and solar PV and of the production of Power-to-X energy carriers as gaseous and liquid hydrogen as well as ammonia and methanol. Three main hubs for the production of PtX energy carriers have been identified with the result that Colombia's ambition to become a leading producer of green hydrogen (H2) and Power-to-X (PtX) technologies is well-founded, thanks to its abundant renewable energy resources. However, this potential is concentrated in specific regions, each with unique advantages that align with the country's Hydrogen Roadmap. The PtX regions identified in this study correspond to the findings of previous work by GIZ and Fichtner, which also identified, among others, La Guajira, the region around Cartagena/Barranquilla ('Atlántico') and Valle del Cauca. [2–4]

The findings of the present study on the three PtX sites identified can be summarized as follows:

La Guajira emerges as a standout region due to its exceptional onshore and offshore wind and solar energy potential, making it ideal for large-scale hydrogen production. To capitalize on this, a collaborative effort involving the government, local communities, developers, and investors is essential. This will help ensure that the green transition is socially sustainable and that the necessary multi-billion-dollar investments reach the final investment decision (FID) stages.

Cartagena and Barranquilla are poised to become key hubs for initial PtX projects, leveraging synergies between the existing chemical industries, refineries, and expanding port infrastructure. Access to offshore wind energy and baseload green power through power purchase agreements (PPAs) is crucial to overcome the limited onshore renewable energy potential in these areas.

Valle del Cauca and Cali offer limited renewable energy potential but are strategically important due to their access to biogenic carbon sources and biomass, which are vital for syngas generation and sustainable aviation fuel (SAF) production. Buenaventura could also emerge as a significant export hub in the future.

A critical prerequisite for achieving a decarbonized Colombian economy is the substantial expansion of renewable energy and power transmission infrastructure. Large-scale renewable energy and PtX development scenarios will require extensive investments, potentially in the multi-billion-Euro range. Much of this capital is expected to come from international sources, necessitating robust funding security and a transparent regulatory framework to attract and protect these investments.
In addition to the location-specific findings, the study advises the following strategic actions:

Pilot and Demonstration Projects: The planning and execution of targeted pilot and flagship projects are recommended to explore the full range of sustainably produced hydrocarbons, including methanol, dimethyl ether (DME), e-SAF, and green ammonia.

Hybrid PtX Concepts: For regions lacking optimal wind and solar resources, the development of hybrid Power-to-X concepts is suggested. These should incorporate not only hydrogen produced via electrolysis but also syngas generated from sustainable biomass and biomass residues (such as eucalyptus, oil palm, and sugarcane, along with their by-products). This approach is particularly promising for Colombia's central and southern departments, including Valle del Cauca, Cauca, Antioquia, and Santander.

Offshore Potential in Northern Colombia: The significant offshore wind resources in northern Colombia offer a viable alternative to onshore green electricity and hydrogen production, especially if onshore projects face delays due to implementation challenges. The national offshore wind roadmap should be leveraged as a foundation for developing integrated concepts that combine offshore wind energy with green hydrogen production, either offshore or centralized on the coast.

Educational Alignment: The education sector and workforce need to be reoriented towards the emerging green energy economy. This includes updating and adapting degree programs, enhancing infrastructure and laboratories at major universities, and providing retraining opportunities for workers transitioning from traditional fossil fuel sectors, potentially through evening courses.

Awareness and Participation: Ongoing and intensified awareness campaigns are necessary to highlight the opportunities and co-benefits of renewable energy projects. Additionally, it is crucial to strengthen participation processes in key areas, particularly La Guajira, Magdalena, and Cesar.

Colombian Hydrogen Backbone (Figure 5-1): To capitalize on the vast green electricity and hydrogen potential in northern Colombia and decarbonize the broader economy, establishing a Colombian hydrogen backbone along existing gas pipeline routes is recommended. This would link production hubs, such as La Guajira, with demand centers. It would also optimize the use of existing infrastructure, such as the electricity grid, natural gas pipelines, refineries, and ports, while leveraging regional carbon sources and hydropower for large-scale PtX applications. Affordable hydrogen from the north would aid in defossilizing local industries and could also be exported. However, this vision represents a long-term scenario that must undergo more detailed evaluation and be tailored to the specific needs of neighboring departments.

The significant potential of green hydrogen production offers Colombia a unique opportunity to advance its climate and economic goals. This aligns seamlessly with the country's commitments to reduce greenhouse gas emissions by 51% by 2030 and achieve carbon neutrality by 2050. Green hydrogen supports Colombia's transition away from fossil fuels by enabling the cross-sectoral integration of renewable energy, particularly in hard-to-decarbonize industries.

Moreover, green hydrogen production can drive economic growth and job creation, especially in regions with abundant renewable resources. In the medium to long term, Colombia could become a key exporter of green hydrogen, capitalizing on the growing global demand from industrialized nations willing to pay a premium for sustainable energy. These countries are also likely to support the necessary infrastructure investments, further enhancing Colombia's position in the global energy market and aligning with its National Development Plan's focus on sustainable growth and energy security.

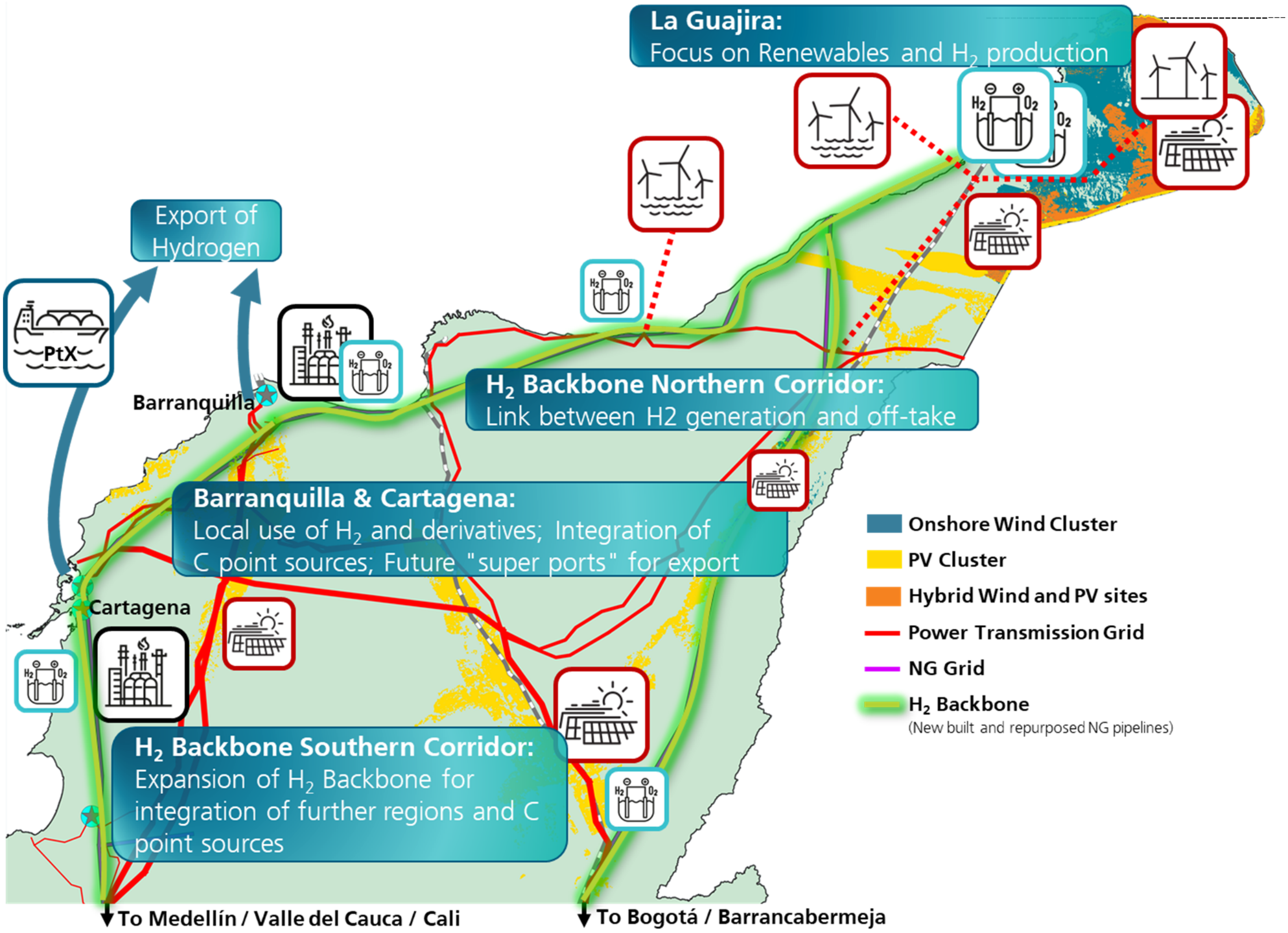


Figure 5-1: Vision for a Colombian hydrogen backbone facilitating the integration of production hubs and demand centers for optimized use of existing infrastructure, such as the electricity grid, natural gas pipelines, refineries, and ports, while leveraging regional carbon sources and hydropower for large-scale PtX applications. Source: own presentation.

6 References

[1] Christoph Hank, Marius Holst, Connor Thelen, Christoph Kost, Sven Längle, Achim Schaadt, Tom Smolinka, Site-specific, comparative analysis for suitable Power-to-X pathways and products in developing and emerging countries, 2023.

[2] Fichtner GmbH & Co. KG, Estudio técnicoeconómico para la identificación y evaluación de tecnologías PtX en Colombia, 2023.

[3] Fichtner GmbH & Co. KG, Estudio técnico, económico e identificación de hubs de hidrógeno verde en Colombia, Stuttgart, 2023.

[4] Deutsche Gesellschaft für Internationale Zusammenarbeit GmbH (GIZ), Potencial Power-to-X: En Colombia, Bogotá, 2023.

[5] R.W. Saaty, The analytic hierarchy process—what it is and how it is used, Mathematical Modelling 9 (1987) 161–176. https://doi.org/10.1016/0270-0255(87)90473-8.

[6] J. Gorre, F. Ruoss, H. Karjunen, J. Schaffert, T. Tynjälä, Cost benefits of optimizing hydrogen storage and methanation capacities for Power-to-Gas plants in dynamic operation, Applied Energy 257 (2020) 113967. https://doi.org/10.1016/j.apenergy.2019.113967.

[7] M. Reuß, T. Grube, M. Robinius, P. Preuster, P. Wasserscheid, D. Stolten, Seasonal storage and alternative carriers: A flexible hydrogen supply chain model, Applied Energy 200 (2017) 290–302. https://doi.org/10.1016/j.apenergy.2017.05.050.

[8] J. Vega Araújo, M. Muñoz Cabré, Solar and wind power in Colombia: 2022 policy overview, Stockholm Environment Institute, 2023.

[9] International Renewable Energy Agency, Renewable Energy Capacity Statistics 2023.

[10] International Renewable Energy Agency, Renewable power generation costs in 2022.

[11] Ministerio de Minas y Energía, Offshore Wind Roadmap for Colombia – Executive Summary, 2023.

[12] World Bank Group, Offshore Wind Technical Potential in Colombia, 2020.

[13] I.S. Stefan Pfenninger, Renewables.ninja, 2021. https://www.renewables.ninja/about (accessed 4 July 2021).

[14] I. Staffell, S. Pfenninger, Using bias-corrected reanalysis to simulate current and future wind power output, Energy 114 (2016) 1224–1239. https://doi.org/10.1016/j.energy.2016.08.068.

[15] I. Staffell, S. Pfenninger, Using bias-corrected reanalysis to simulate current and future wind power output, Energy 114 (2016) 1224–1239. https://doi.org/10.1016/j.energy.2016.08.068.

[16] M.Z. Jacobson, V. Jadhav, World estimates of PV optimal tilt angles and ratios of sunlight incident upon tilted and tracked PV panels relative to horizontal panels, Solar Energy 169 (2018) 55–66. https://doi.org/10.1016/j.solener.2018.04.030.

[17] International Energy Agency, Offshore Wind Outlook 2019, 2019.

[18] International Energy Agency, World Energy Outlook 2020, 2020.

[19] Anthony Wang, Jaro Jens, David Mavins, Marissa Moultak, Matthias Schimmel, Kees van der Leun, Daan Peters, Maud Buseman, Analysing future demand, supply, and transport of hydrogen, 2021.

[20] GlobalPetrolPrices.com, Electricity prices around the world. https://www.globalpetrolprices.com/electricity_prices/#hl16 (accessed 23 August 2024).

[21] Marius Holst, Stefan Aschbrenner, Tome Smolinka, Christopher Voglstätter, Gunter Grimm, Cost forecast for low temperature electrolysis - Technology driven bottom-up prognosis for PEM and alkaline water electrolysis systems, Freiburg, 2022.

[22] Clean Hydrogen Joint Undertaking, Strategic Research and Innovation Agenda 2021 – 2027: Annex to GB decision no. CleanHydrogen-GB-2022-02, 2022.

[23] Tom Smolinka, Nikolai Wiebe, Philip Sterchele, Fraunhofer-Institut für Solare Energiesysteme ISE / Freiburg – Deutschland, Franz Lehner, E4tech Sàrl / Lausanne – Schweiz, Steffen Kiemel, Robert Miehe, Sylvia Wahren, Fabian Zimmermann, Fraunhofer-Institut für Produktionstechnologie und Automatisierung IPA -Stuttgart – Deutschland, Studie IndWEDe Industrialisierung der Wasser-elektrolyse in -Deutschland: -Chancen und -Herausforderungen für nachhaltigen Wasserstoff für Verkehr, Strom und -Wärme.
[24] Hans van 't Noordende, Peter Ripson, A One-GigaWatt Green-Hydrogen Plant: Advanced Design and Total Installed-Capital Costs, 2022.
[25] International Energy Agency- IEA, The Future of Hydrogen - Assumption Annex: Seizing today's opportunities, 2019.
[26] Element Energy, Gigastack Phase 2: Pioneering UK Renewable Hydrogen, 2021.
[27] U. Bünger, J. Michalski, F. Crotogino, O. Kruck, Large-scale underground storage of hydrogen for the grid integration of renewable energy and other applications, in: Compendium of Hydrogen Energy, Elsevier, 2016, pp. 133–163.
[28] R.K. Ahluwalia, D.D. Papadias, J-K Peng, H.S. Roh, System Level Analysis of Hydrogen Storage Options, Washington, D.C, 2019.
[29] M. Reuß, Techno-ökonomische Analyse alternativer Wasserstoffinfrastruktur: Techno-Economic Analysis of Hydrogen Infrastructure Alternatives. Dissertation, Aachen, 2019.
[30] M. Newborough, G. Cooley, Green hydrogen: water use implications and opportunities, Fuel Cells Bulletin 2021 (2021) 12–15. https://doi.org/10.1016/S1464-2859(21)00658-1.
[31] H-TEC Systems, PEM Electrolyzer ME450 - Datasheet, 2023.
[32] Plug Power, The Plug EX-4250D - Datasheet.
[33] Jana Thomann, Frank Marscheider-Weidemann, Andreas Stamm, Ludger Lorych, Christoph Hank, Friedrich Weise, Lucas Edenhofer, Zarah Thiel, Hintergrundpapier zu nachhaltigem grünen Wasserstoff und Synthese-produkten: HYPAT Working Paper 01/2022, 2022.
[34] OECD, Pricing water resources and water and sanitation services, OECD, Paris, 2010.
[35] E. Jones, M. Qadir, M.T.H. van Vliet, V. Smakhtin, S.-M. Kang, The state of desalination and brine production: A global outlook, Sci. Total Environ. 657 (2019) 1343–1356. https://doi.org/10.1016/j.scitotenv.2018.12.076.
[36] U. Caldera, D. Bogdanov, C. Breyer, Local cost of seawater RO desalination based on solar PV and wind energy: A global estimate, Desalination 385 (2016) 207–216. https://doi.org/10.1016/j.desal.2016.02.004.
[37] DesalData, Desalination cost estimator, 2022. https://www.desaldata.com/ (accessed 10 February 2022).
[38] K. Stolzenburg, R. Mubbala, Integrated Design for Demonstration of Efficient Liquefaction of Hydrogen (IDEALHY): Fuel Cells and Hydrogen Joint Undertaking (FCH JU), 2013.
[39] C. Hank, A. Sternberg, N. Köppel, M. Holst, T. Smolinka, A. Schaadt, C. Hebling, H.-M. Henning, Energy efficiency and economic assessment of imported energy carriers based on renewable electricity, Sustainable Energy Fuels 4 (2020) 2256–2273. https://doi.org/10.1039/d0se00067a.
[40] O. Sekkesaeter, Evaluation of Concepts and Systems for Marine Transportation of Hydrogen. Master Thesis, 2019.
[41] F. Nestler, A.R. Schütze, M. Ouda, M.J. Hadrich, A. Schaadt, S. Bajohr, T. Kolb, Kinetic modelling of methanol synthesis over commercial catalysts: A critical assessment, Chemical Engineering Journal 394 (2020) 124881. https://doi.org/10.1016/j.cej.2020.124881.
[42] F. Mantei, R.E. Ali, C. Baensch, S. Voelker, P. Haltenort, J. Burger, R.-U. Dietrich, N. von der Assen, A. Schaadt, J. Sauer, O. Salem, Techno-economic assessment and carbon footprint of processes for the large-scale production of oxymethylene dimethyl ethers from carbon dioxide and hydrogen, Sustainable Energy Fuels 6 (2022) 528–549. https://doi.org/10.1039/D1SE01270C.

[43] S. Schemme, J.L. Breuer, M. Köller, S. Meschede, F. Walman, R.C. Samsun, R. Peters, D. Stolten, H2-based synthetic fuels: A techno-economic comparison of alcohol, ether and hydrocarbon production, International Journal of Hydrogen Energy 45 (2020) 5395–5414. https://doi.org/10.1016/j.ijhydene.2019.05.028.
[44] O. Sekkesaeter, Evaluation of Concepts and Systems for Marine Transportation of Hydrogen, Trondheim, Norway, 2019.
[45] S. Deutz, A. Bardow, Life-cycle assessment of an industrial direct air capture process based on temperature–vacuum swing adsorption, Nat Energy 6 (2021) 203–213. https://doi.org/10.1038/s41560-020-00771-9.
[46] International Energy Agency, Global Assessment of Direct Air Capture Costs: IEAGHG Technical Report 2021-05, Cheltenham, 2021.
[47] J. Young, N. McQueen, C. Charalambous, S. Foteinis, O. Hawrot, M. Ojeda, H. Pilorgé, J. Andresen, P. Psarras, P. Renforth, S. Garcia, M. van der Spek, The cost of direct air capture and storage can be reduced via strategic deployment but is unlikely to fall below stated cost targets, One Earth 6 (2023) 899–917. https://doi.org/10.1016/j.oneear.2023.06.004.
[48] M. Gutsch, J. Leker, Co-assessment of costs and environmental impacts for off-grid direct air carbon capture and storage systems, Commun Eng 3 (2024). https://doi.org/10.1038/s44172-023-00152-6.
[49] X. Liu, A. Elgowainy, M. Wang, Life cycle energy use and greenhouse gas emissions of ammonia production from renewable resources and industrial by-products, Green Chem. 22 (2020) 5751–5761. https://doi.org/10.1039/D0GC02301A.
[50] O. Osman, S. Sgouridis, A. Sleptchenko, Scaling the production of renewable ammonia: A techno-economic optimization applied in regions with high insolation, Journal of Cleaner Production 271 (2020) 121627. https://doi.org/10.1016/j.jclepro.2020.121627.
[51] Maurice Vos, Jochum Douma, Albert von den Noort, Study on the Import of Liquid Renewable Energy: Technology Cost Assessment, 2020.
[52] Christoph Stemmler, Jill Thesen, Mantė Bartusevičiūtė, HySupply: A Meta-Analysis towards a German-Australian Supply-Chain for Renewable Hydrogen: Working Paper, 2021.
[53] Lyod's Register, Techno-economic assessment of zero-carbon fuels, 2020.
[54] D. Berstad, S. Gardarsdottir, S. Roussanaly, M. Voldsund, Y. Ishimoto, P. Nekså, Liquid hydrogen as prospective energy carrier: A brief review and discussion of underlying assumptions applied in value chain analysis, Renewable and Sustainable Energy Reviews 154 (2022) 111772. https://doi.org/10.1016/j.rser.2021.111772.
[55] MAN Diesel & Turbo, Propulsion Trends in LNG Carriers Two-stroke Engines.
[56] S. Kamiya, M. Nishimura, E. Harada, Study on Introduction of CO2 Free Energy to Japan with Liquid Hydrogen, Physics Procedia 67 (2015) 11–19. https://doi.org/10.1016/j.phpro.2015.06.004.
[57] M. Raab, S. Maier, R.-U. Dietrich, Comparative techno-economic assessment of a large-scale hydrogen transport via liquid transport media, International Journal of Hydrogen Energy 46 (2021) 11956–11968. https://doi.org/10.1016/j.ijhydene.2020.12.213.
[58] IRENA, Global hydrogen trade to meet the 1.5°C climate goal: Part II – Technology review of hydrogen carriers, Abu Dhabi, 2022.
[59] Y. Seo, S. Han, Economic Evaluation of an Ammonia-Fueled Ammonia Carrier Depending on Methods of Ammonia Fuel Storage, Energies 14 (2021) 8326. https://doi.org/10.3390/en14248326.
[60] Y. Seo, J. An, E. Park, J. Kim, M. Cho, S. Han, J. Lee, Technical–Economic Analysis for Ammonia Ocean Transportation Using an Ammonia-Fueled Carrier, Sustainability 16 (2024) 827. https://doi.org/10.3390/su16020827.
[61] MAN Energy Solutions, Propulsion trends in tankers.
[62] David K. Jordan, The Shipbuilding & Secondhand Markets, 2021.
[63] International Energy Agency, Colombia 2023: Energy Policy Review, 2023.
[64] Jana Thomann, Frank Marscheider-Weidemann, Andreas Stamm, Ludger Lorych, Christoph Hank, Friedrich Weise, Lucas Edenhofer, Zarah Thiel, HYPAT Working

Paper 01/2022. Hintergrundpapier zu nachhaltigem grünen Wasserstoff und Syntheseprodukten.
[65] BloombergNEF, Climatescope 2023 | Colombia, 2024. https://www.global-climatescope.org/markets/co/ (accessed 25 April 2024).
[66] I.O. Esri, Sentinel-2 10m Land Use/Land Cover Time Series, 2024.
[67] OpenStreetMap Contributors, Map data, 2023.
[68] Airportmap, Navaids, 2023.
[69] Satlas, Renewable Energy, 2023.
[70] UNEP-WCMC and IUCN, The World Database on Protected Areas (WDPA), 2023.
[71] BirdLife International, Important Bird and Biodiversity Area (IBA) digital boundaries: September 2023 version, 2023.
[72] Ramsar Sites Information Service, Ramsar Sites and the List of Wetlands of International Importance, 2023.
[73] Portal de Datos Abiertos de la ANT, Zonas de Reserva Campesina, Resguardos Indígenas, Consejos Comunitarios, 2023.
[74] V. Maus, S. Giljum, J. Gutschlhofer, D.M. Da Silva, M. Probst, S.L.B. Gass, S. Luckeneder, M. Lieber, I. McCallum, Global-scale mining polygons (Version 1), PANGAEA, 2020.
[75] R. Styron, M. Pagani, The GEM Global Active Faults Database, Earthquake Spectra 36 (2020) 160–180. https://doi.org/10.1177/8755293020944182.
[76] P. Berry, R. Smith, J. Benveniste, Altimeter Corrected Elevations, Version 2 (ACE2), Palisades, NY: NASA Socioeconomic Data and Applications Center (SEDAC), 2018.
[77] Global Solar Atlas 2.0, A free, web-based application is developed and operated by the company Solargis s.r.o. on behalf of the World Bank Group, utilizing Solargis data, with funding provided by the Energy Sector Management Assistance Program (ESMAP), 2023.
[78] Global Wind Atlas version 3.3, A free, web-based application developed, owned and operated by the Technical University of Denmark (DTU). The Global Wind Atlas version 3.3 is released in partnership with the World Bank Group, utilizing data provided by Vortex, using funding provided by the Energy Sector Management Assistance Program (ESMAP), 2023.
[79] International Renewable Energy Agency, Global Atlas for Renewable Energy, 2024.

Appendix

A1 Restriction areas

Table 0-1: Considered restriction areas and setback distances

	Ground-mounted photovoltaics			Onshore wind		
	Restricted	Setback distance		Restricted	Setback distance	
Industrial and commercial area	Yes	+ 100 m	[66]	Yes	+ 500 m	[66]
Settlement areas	Yes	+ 100 m	[66]	Yes	+ 500 m	[66]
Highways and main roads	Yes	+ 50 m	[67]	Yes	+ 40 m	[67]
Railway	Yes	+ 50 m	[67]	Yes	+ 60 m	[67]
Airports	Yes	+ 100 m	[67]	Yes	+ 5000 m	[67]
Navigational aids	No	-	[68]	Yes	+ 3000 m	[68]
Transmission lines	Yes	+50 m	[67]	Yes	+ 150 m	[67]
Existing wind turbines	Yes	+ 500 m	[69]	Yes	+ 750 m	[69]
Existing solar parks	Yes	+ 500 m	[69]	Yes	+ 500 m	[69]
IUCN protected areas	Yes	+ 500 m	[70]	Yes	+ 500 m	[70]
Important bird areas	No	-	[71]	Yes	+ 500 m	[71]
Ramsar wetlands	Yes	+ 500 m	[72]	Yes	+ 500 m	[72]
Black community councils	Yes / No	+ 500 m	[73]	Yes / No	+ 500 m	[73]
Indigenous reserves	Yes / No	+ 500 m	[73]	Yes / No	+ 500 m	[73]
Forests and dense vegetation	Yes	+ 20 m	[66]	Yes	-	[66]
Flooded vegetation	Yes	+ 50 m	[66]	Yes	+ 50 m	[66]
Water bodies	Yes	+ 50 m	[66]	Yes	+ 50 m	[66]
Peasant reserve zones	Yes	-	[73]	Yes	-	[73]
Crop land	Yes	-	[66]	No	-	[66]
Mining areas	Yes	+ 500 m	[74]	Yes	+ 500 m	[74]
Active faults	Yes	+ 500 m	[75]	Yes	+ 500 m	[75]
Slope > 30°	Yes	-	[76]	Yes	-	[76]

A2 Suitability criteria classification

Table 0-2: Suitability criteria classification for ground-mounted PV

	Global horizontal irradiance	Seasonal variability	Ambient temperature	Ground slope	Ground aspect	Distance transmission lines	Distance roads
	GHI	SVA	ATP	GRS	GRA	DTL	DRO
	kWh/(m²*a)	$\%_{\text{Relative St. Dev.}}$	°C	°	°	km	km
Ideal (100 %)	> 2100	< 8	< 18	< 2	162 - 198	< 5	< 1
Excellent (90 %)	2000 – 2100	8 – 10	18 – 20	2 – 4	144 – 162 198 – 216	5 – 10	1 – 3
Highly suitable (80 %)	1900 – 2000	10 – 12	20 – 22	4 – 6	126 – 144 216 – 234	10 – 20	3 – 5
Favourable (70 %)	1800 – 1900	12 – 14	22 – 24	6 – 8	108 – 126 234 – 252	20 – 40	5 – 10
Suitable (60 %)	1600 – 1800	14 – 16	24 – 26	8 – 10	90 – 108 252 – 270	40 – 80	10 – 15
Adequate (50 %)	1400 – 1600	16 – 18	26 – 28	10 – 12	72 – 90 270 – 288	80 – 120	15 – 20
Fair (40 %)	1200 – 1400	18 – 20	28 – 30	12 – 14	54 – 72 288 – 306	120 – 200	20 – 30
Marginal (30 %)	1000 – 1200	20 – 25	30 – 32	14 – 16	36 – 54 306 – 324	200 – 300	30 – 50
Poor (20 %)	800 – 1000	25 – 30	32 – 34	16 – 18	18 – 36 324 – 342	300 – 400	50 – 100
Very poor (10 %)	600 – 800	30 – 35	34 – 36	18 – 20	0 – 18 342 – 360	400 – 600	100 – 150
Unsuitable (0 %)	< 600	> 35	> 36	> 20	-	> 600	> 150
Resolution [m]	250 x 250 m	250 x 250	1000 x 1000	30 x 30	30 x 30	20 x 20	20 x 20
Data source	[77]	[77]	[77]	[76]	[76]	[67]	[67]
Boundaries	217 – 2348	3.3 – 22.5	-2.4 – 31.8	0 – 68.9	0 – 360	-	-

Table 0-3: Suitability criteria classification for onshore wind

	Wind speed	Seasonal variability	Ground slope	Ground elevation	Distance transmission lines	Distance roads
	WSP	**SVA**	**GRS**	**GRE**	**DTL**	**DRO**
	m/s	$\%_{\text{Relative St. Dev.}}$	°	m	km	km
Ideal (100 %)	> 11	< 10	< 2	< 500	< 5	< 1
Excellent (90 %)	10 - 11	10 – 15	2 – 4	500 – 1000	5 – 10	1 – 3
Highly suitable (80 %)	9.0 - 10	15 – 20	4 – 6	1000 – 1250	10 – 20	3 – 5
Favourable (70 %)	8.0 – 9.0	20 – 25	6 – 8	1250 – 1500	20 – 40	5 – 10
Suitable (60 %)	7.5 – 8.0	25 – 30	8 – 10	1500 – 1750	40 – 80	10 – 15
Adequate (50 %)	7.0 – 7.5	30 – 40	10 – 12	1750 – 2000	80 – 120	15 – 20
Fair (40 %)	6.5 – 7.0	40 – 50	12 – 14	2000 – 2500	120 – 200	20 – 30
Marginal (30 %)	6.0 – 6.5	50 – 60	14 – 16	2500 – 3000	200 – 300	30 – 50
Poor (20 %)	5.5 – 6.0	60 – 70	16 – 18	3000 – 4000	300 – 400	50 – 100
Very poor (10 %)	5.0 – 5.5	70 - 80	18 – 20	4000 – 5000	400 – 600	100 – 150
Unsuitable (0 %)	< 5.0	> 80	> 20	> 5000	-	-
Resolution [m]	250 x 250 m	3000 x 3000	30 x 30	30 x 30	20 x 20	20 x 20
Data source	[78]	[79]	[76]	[76]	[67]	[67]
Boundaries	0.2 – 11.6	1.5 - 50	0 – 36.7	-38 – 5730	-	-

A3 Suitability criteria onshore wind

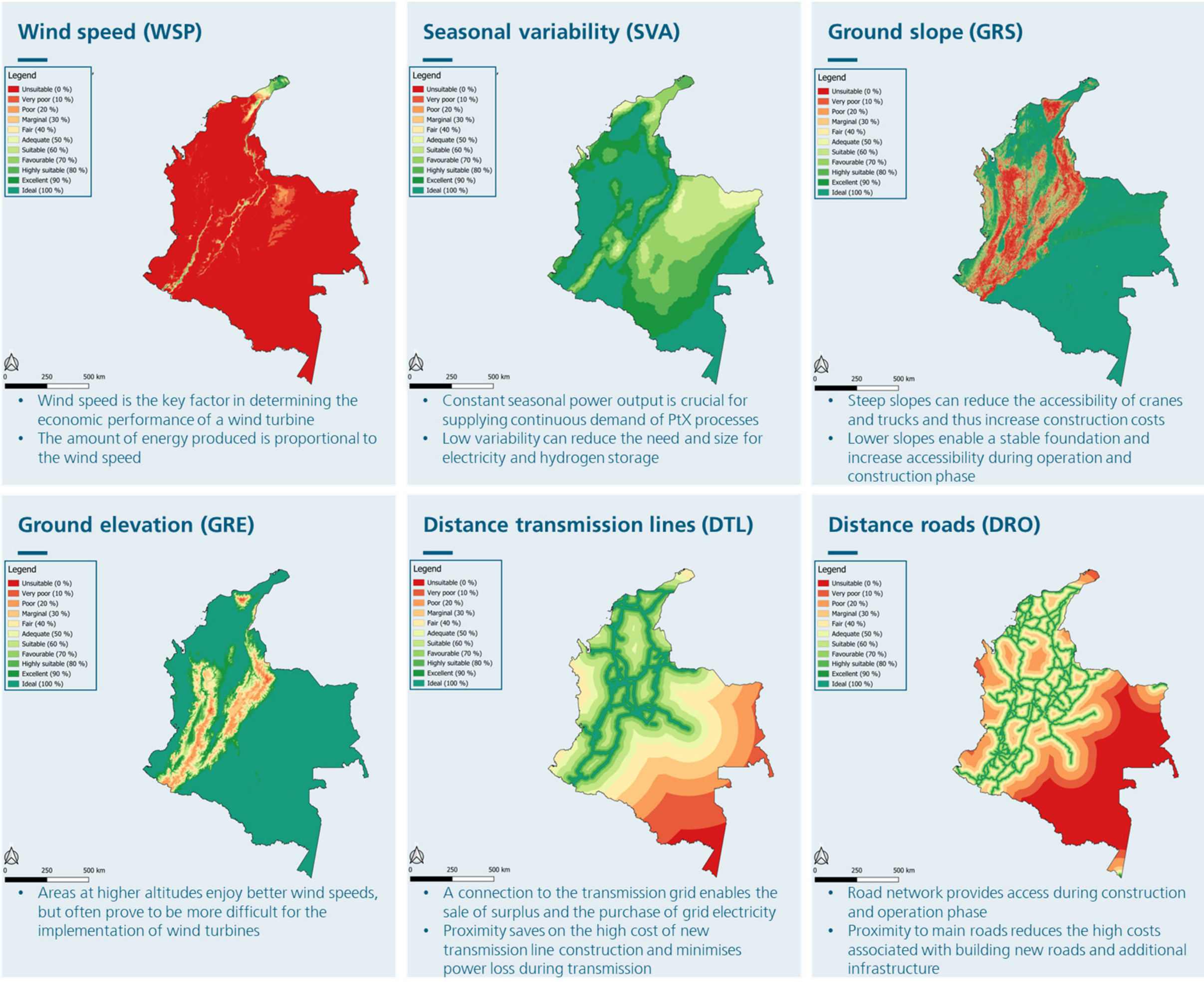


Figure 0-1: Suitability criteria onshore wind

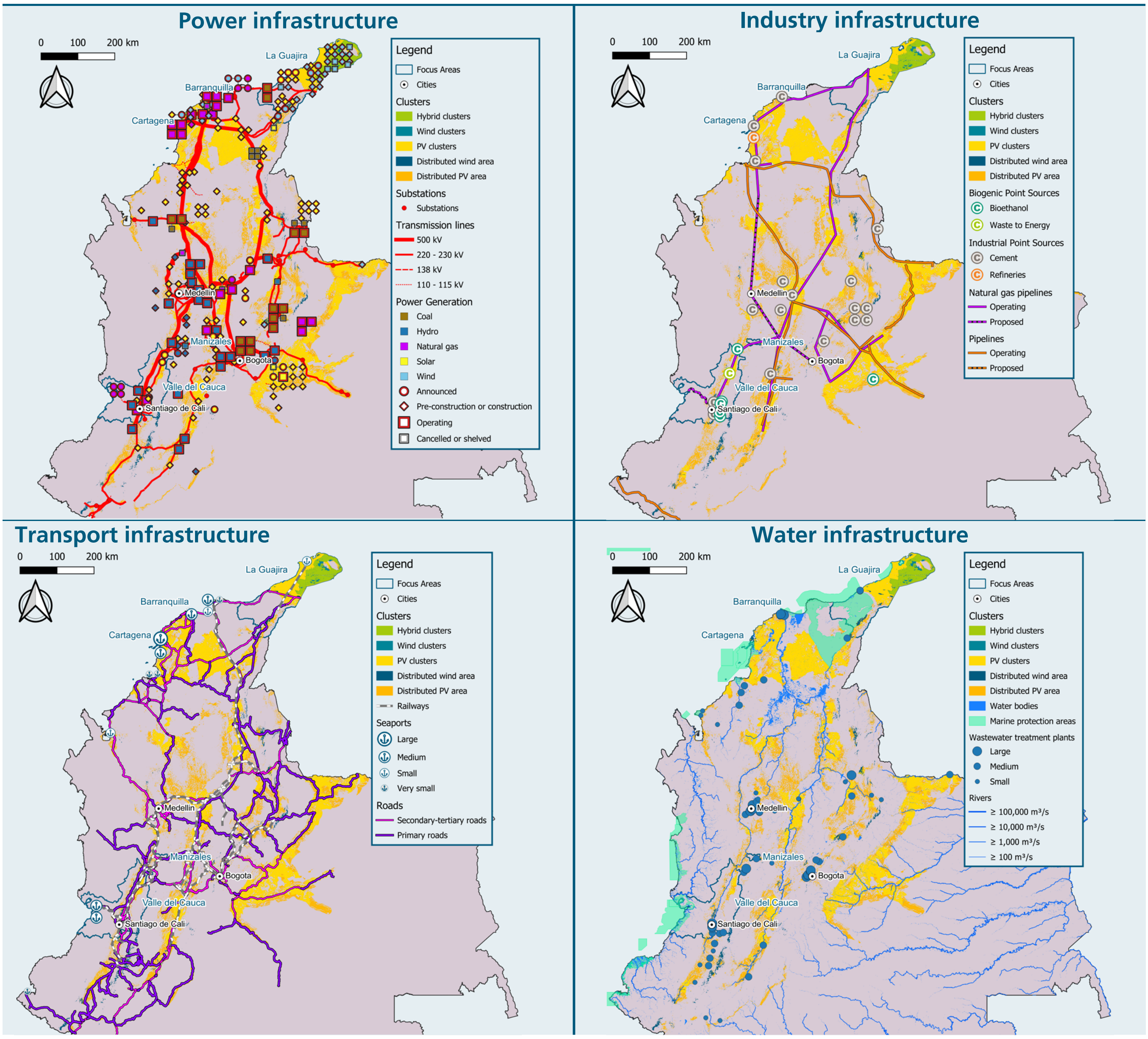
A4 Analytical Hierarchy Process

Table 0-4 Pairwise comparison of suitability criteria according to the Analytical Hierarchy Process

	Ground-mounted PV						
	GHI	SVA	ATP	GRS	GRA	DTL	DRO
GHI	1	4	6	3	7	4	5
SVA		1	4	1/2	5	1	2
ATP			1	1/4	2	1/3	1/3
GRS				1	4	2	3
GRA					1	1/3	2
DTL						1	2
DRO							1

	Onshore wind					
	WSP	SVA	GRS	GRE	DTL	DRO
WSP	1	4	3	7	3	4
SVA		1	1/2	5	1/2	1
GRS			1	4	1	2
GRE				1	1/4	1/3
DTL					1	2
DRO						1

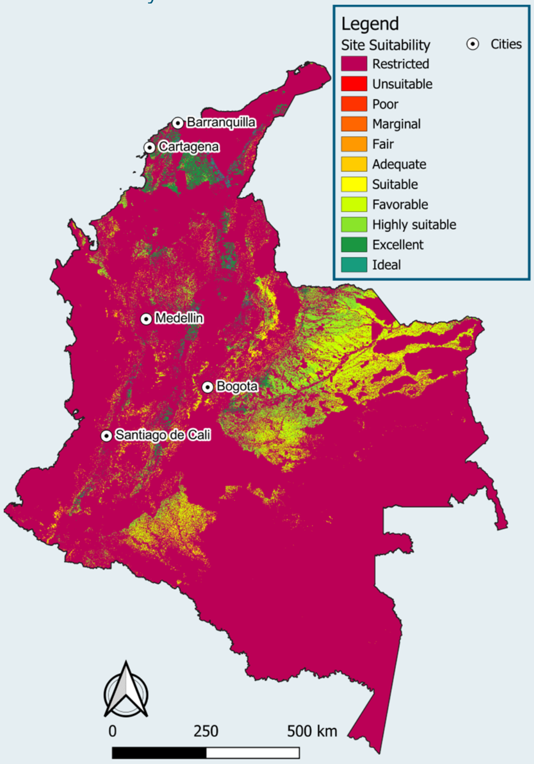
A5 PtX-relevant infrastructure



A6 Results with cultural restrictions

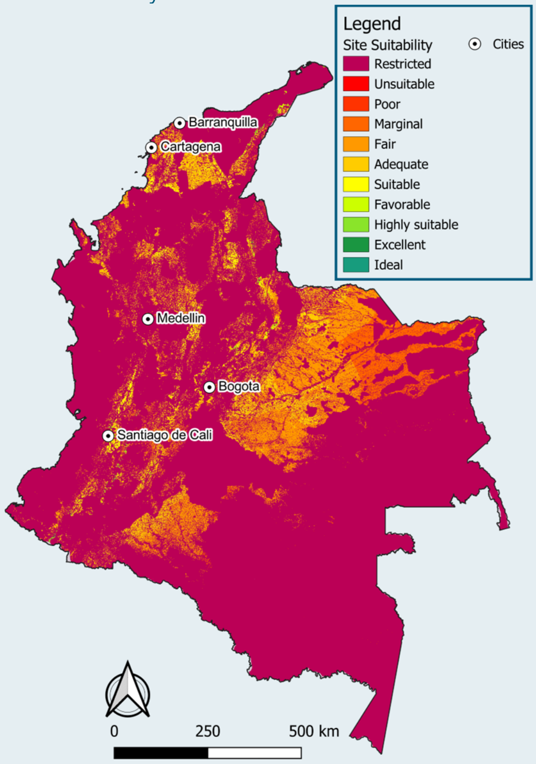
Ground-mounted PV

1. Site suitability

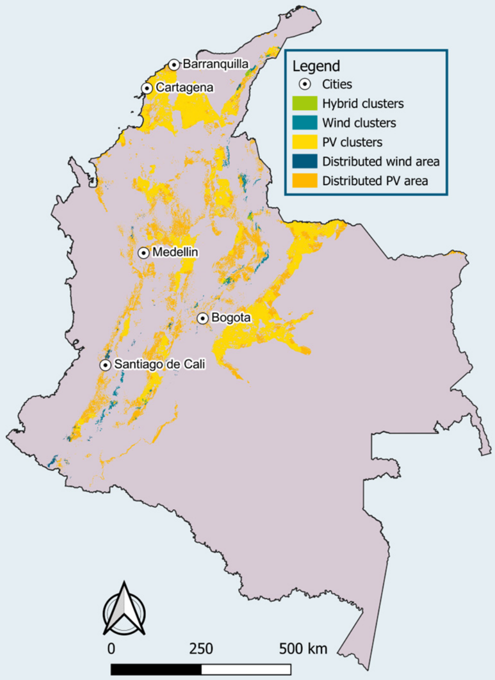


Onshore wind

1. Site suitability



2. Clusters



A7 Results for local GH2 production

Table 0-5: System Parameters and techno economic KPI in the cost optimum for gaseous hydrogen production in 2030 and 2040 for all analyzed locations

GH2 (local)	La Guajira		Cartagena/Barranquilla		Valle del Cauca	
Year of commissioning	**2030**	**2040**	**2030**	**2040**	**2030**	**2040**
System Parameters:						
Wind: Installed capacity (GWel)	1.2	1.2	0.0	0.0	0.0	0.0
PV: Installed capacity (GWel)	0.2	0.3	2.1	2.1	2.0	2.0
Techno-economic KPI:						
LCoH (EUR/MWh)	98.0	80.5	153.5	116.4	150.2	114.1
LCoH (EUR/kg)	3.2	2.6	5.1	3.8	5.0	3.8
PtX Amount (GWh/yr)	4391	4547	1817	1881	1808	1872
Product Amount (ktons)	132	137	55	56	54	56
Electrolysis: Full load hours (h/yr)	6548	6514	2709	2694	2696	2681
Unused RE (%)	2.9	2.9	15.4	15.4	14.1	14.1
Total System investment (Bn. EUR)	2.7	2.1	2.4	1.8	2.3	1.7

A8 Detailed results for PtX production (local utilization) in Cartagena/Barranquilla

Table 0-6: Detailed techno-economic results and KPI for local PtX utilization in Cartagena/Barranquilla

Cartagena	LH2 Local		NH_3 Local		MeOH-DAC Local		MeOH-CPS Local	
Year of commissioning	**2030**	**2040**	**2030**	**2040**	**2030**	**2040**	**2030**	**2040**
System Parameters:								
Wind: Installed capacity (GWel)	0.6	1.1	0.0	0.0	0.1	0.5	0.0	0.0
PV: Installed capacity (GWel)	2.6	2.3	2.5	2.5	2.5	2.4	2.4	2.5
Liquefaction / Synthesis Cap. (tpd)	289	442	919	1174	941	1545	1025	1486
Techno-economic KPI:								
LCoPtX (EUR/MWh)	264	205	252	197	309	225	254	209
LCoPtX (EUR/ton)	8795	6819	1303	1022	1708	1245	1404	1156
PtX Amount (GWh/yr)	2509	3500	1584	1703	1556	2140	1590	1663
Product Amount (ktons)	75	105	306	329	281	387	287	301
Electrolysis: Full load hours (h/yr)	3808	5096	2728	2814	2756	3640	2816	2831
Unused RE (%)	19	17	24	22	20	18	21	22
Total System investment (Bn. EUR)	5.3	5.4	3.3	2.7	3.8	3.6	2.9	2.3

A9 Detailed results for PtX production (local utilization) in Valle del Cauca

Table 0-7: Detailed techno-economic results and KPI for local PtX utilization in Valle del Cauca

Valle del Cauca	NH_3 Local		MeOH-DAC Local		MeOH-CPS Local	
Year of commissioning	**2030**	**2040**	**2030**	**2040**	**2030**	**2040**
System Parameters:						
Wind: Installed capacity (GWel)	0.0	0.0	0.0	0.0	0.0	0.0
PV: Installed capacity (GWel)	2.4	2.3	2.4	2.3	2.1	2.1
Liquefaction / Synthesis Cap. (tpd)	929	1115	865	956	1004	1189
Techno-economic KPI:						
LCoPtX (EUR/MWh)	246	199	311	231	251	208
LCoPtX (EUR/ton)	1275	1031	1723	1276	1388	1149
PtX Amount (GWh/yr)	1590	1636	1505	1540	1525	1577
Product Amount (ktons)	307	316	272	279	276	285
Electrolysis: Full load hours (h/yr)	2735	2701	2665	2620	2701	2682
Unused RE (%)	22	20	21	19	18	18
Total System investment (Bn. EUR)	3.1	2.4	3.4	2.4	2.7	2.1

Contact

Dr.-Ing. Christoph Hank
Hydrogen Technologies
Sustainable Synthesis Products
christoph.hank@ise.fraunhofer.de

Fraunhofer Institute for Solar
Energy Systems ISE
Heidenhofstraße 2
79110 Freiburg
Germany

www.ise.fraunhofer.de