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Design of a regional hydrogen supply chain framework: A case study for Central America

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ABSTRACT

This study presents a comprehensive framework for establishing a hydrogen supply chain network in Central America, encompassing Costa Rica, El Salvador, Guatemala, Honduras, Nicaragua, and Panama, in alignment with global decarbonization efforts. Utilizing Mixed Integer Linear Programming, the research assesses the techno-economic feasibility of hydrogen integration, focusing on its role in freight transportation and regional electricity supply. The findings highlight alkaline electrolysis as the preferred production method, with liquefied hydrogen and ammonia identified as optimal carriers. Costa Rica and Nicaragua emerge as key production hubs, supplying hydrogen to neighboring countries via sea transport. The estimated levelized cost of hydrogen is 10.84 USD/kg, largely driven by electricity prices, with projections indicating a reduction to 5.16 USD/kg by 2050. A comparative analysis suggests that under specific conditions, hydrogen could achieve cost parity with diesel by 2050. While acknowledging data limitations and socio-economic uncertainties, this study provides critical insights into hydrogen's potential role in Central America's energy transition, serving as a foundation for future research and policy development.

1. Introduction

Governments worldwide are increasingly dedicating resources and revising policies to achieve sustainability, particularly through decarbonization and circular economy frameworks. Hydrogen is an energy vector that aids in decarbonizing sectors such as industrial manufacturing and transport, and can also serve as a storage medium to counter the intermittency of renewable energy [1]. From a logistics perspective, hydrogen is notable for its versatility, as it can be transported in multiple forms (compressed, liquefied, as ammonia or liquid organic hydrogen carriers) and through various transport modes (truck, pipeline, ships) [2]. Recent studies have underscored hydrogen's potential applications, ranging from electricity generation and energy storage to fuel for transport and feedstock for chemical production [3]. The use of natural gas and liquefied petroleum gas at household level has also been identified as potentially replaceable through hydrogen integration, delivering socio-economic and environmental benefits in countries that rely on gas distribution networks [4]. With the increasing growth of renewable energy, applications in power systems, transportation, and the chemical industry have the potential to be supplied at competitive costs compared to conventional fossil-based processes [5], although recent global assessments highlight that outcomes remain sensitive to electricity prices, resource availability, and infrastructure assumptions [6].

Recent literature has examined hydrogen's role across multiple energy applications with increasing analytical depth, particularly in the context of regional disparities in renewable energy availability [7]. As an emerging energy vector, the concept of a hydrogen supply chain remains broad, as different technologies, carriers and transport options generate multiple system configurations that affect cost, energy efficiency, safety, and environmental performance. Nevertheless, several pilot projects worldwide are already testing these concepts in practice. For instance, the HyDeploy project at Keele University in England demonstrated how hydrogen blended with natural gas at a 20 mol% can be safely used in domestic appliances without modification [8]. Although blending is not a long-term decarbonization strategy, it provides a transitional pathway to evaluate regulatory requirements, safety standards, and consumer acceptance for hydrogen integration into existing networks [9]. In Japan, the Fukushima Hydrogen Energy

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Nomenclature

List of abbreviations

APAC	Asia Pacific
BOE	Barrel of Oil Equivalent
CAPEX	Capital Expenditure
CCS	Carbon Capture and Storage
ECLAC	Economic Commission for Latin America and the Caribbean
EV	Electric Vehicle
FCV	Fuel Cell Vehicle
GDP	Gross Domestic Product
GW	Gigawatt
GWh	Gigawatt-hour
HSC	Hydrogen Supply Chain
IEA	International Energy Agency
IRENA	International Renewable Energy Agency
LCOH	Levelized Cost of Hydrogen
LCOE	Levelized Cost of Electricity
LHV	Lower Heating Value
LPG	Liquefied Petroleum Gas
MILP	Mixed Integer Linear Programming
MJ	Megajoule
MW	Megawatt
NG	Natural Gas
NDCs	National Determined Contributions
OPEX	Operational Expenditures
PV	Photovoltaic
SMR	Steam Methane Reformation
TEU	Twenty-foot Equivalent Units
TWh	Terawatt-hour

Notation of variables and parameters for mathematical model

Hydrogen production

CAPEXEi	Capital cost of electrolyzer *i* (USD/kW) [Parameter]
CCost	Capital and operational expenditure costs of hydrogen production (USD/a) [Variable]
ECFi	Electrolyzer (*i*) facility capacity factor (%) [Parameter]
effei	Electrolyzer efficiency (%) [Parameter]
EHCost	Cost of electricity for hydrogen production (USD/a) [Variable]
EPj	Electricity cost (USD/MWh) [Parameter]
HyProdij	Hydrogen produced through electrolyzer *i* in country *j* (kg/a) [Variable]
interval	Number of hours in a year (hr/a) [Parameter]
LHV	Lower heating values of hydrogen (kWh/kg H_2) [Parameter]
mei	Mass efficiency of electrolyzer *i* (kWh/kg H) [Parameter]
PC	Hydrogen production cost (USD/a) [Variable]
PMTFj	Annuity factor in country *j* (1/a) [Parameter]
OPEXF	Operational expenditure factor (%) [Parameter]

Hydrogen carrier production

CaCost	Capital and operational expenditure costs of carrier production (USD/a)[variable]
CAPEXCk	Capital cost of carrier *k* (USD/kW) [Parameter]
Camm	Cost of producing ammonia (USD/a) [Variable]
CEk	Conversion efficiency of technology for carrier *k* (kWh/kg H2) [Parameter]
CC	Carrier production cost (USD/a) [Variable]
Ccomp	Cost of producing compressed hydrogen (USD/a) [Variable]
Cliq	Cost of producing liquefied hydrogen (USD/a) [Variable]
ECaCost	Cost of electricity for carrier production (USD/a) [Variable]
ECFk	Carrier (*k*) facility capacity factor (%) [Parameter]
EEk	Equipment efficiency for carrier *k* (kWh/kWh) [Parameter]
HCEk	Hydrogen consumption efficiency for ammonia (kg NH_3/kg H_2) [Parameter]
HyCarrijk	Hydrogen produced by electrolyzer *i* in country *j* and carrier *k* (kg/a) [Variable]

Transportation

TC	Transportation cost (USD/a) [Variable]
TCj,jp,k,l	Transportation capital cost from country *j* to country *jp* with carrier *k* and transport mode *l*

Storage

SC	Storage cost (USD/a) [Variable]
SCost	Storage capital cost (USD/a) [Variable]
SEcost	Storage energy cost (USD/a) [Variable]
SCk	Storage capital cost of carrier *k* (USD/kg) [Parameter]
SD	Storage days (days) [Parameter]
SCOk	Storage energy consumption of carrier *k* (kWh/(kg-day)) [Parameter]

Demand and electricity availability

AEj	Available electricity in country *j* (kWh/a) [Parameter]
HyDemandj	Hydrogen demand in country *j* (kg/a) [Parameter]

Research Field (FH2R) project has established one of the world's largest renewable-powered electrolysis facilities, producing hydrogen for fuel-cell power generation, transport, and industrial use [10]. The GET H2 Nukleus project in Germany plans to build a 300 MW electrolysis facility, with the first 100 MW expected to start operation in 2025. The project aims to supply green hydrogen to industrial consumers within Germany and later expand deliveries to the Netherlands, Belgium, and France [11].

Regions that are unable to deploy large-scale renewable energy projects may therefore need to rely on energy imports mediated through hydrogen as an energy carrier. Gerard, et al. [12] illustrate this dynamic by positioning Africa as a green hydrogen export hub for Europe, particularly for France. Using a multicriteria decision-making approach, their study demonstrates that the viability of hydrogen supply chains is shaped not only by techno-economic performance but also by policy, governance, and institutional factors. Extending this perspective, Sgarbossa, et al. [13] emphasize the role of stakeholders and external drivers in hydrogen supply chain development, showing how these factors evolve as markets progress through different stages of maturity. Their analysis highlights that the "which comes first" supply–demand paradox constitutes a key barrier in early market phases and must be addressed through coordinated scaling strategies. Zhang [14] further reinforces the human side of hydrogen supply chains, underlining that policies also need to support the development of human capital through education to build resilient hydrogen economies.

Complementing these governance and market perspectives, Ganter, et al. [15] show that the spatial scale at which hydrogen supply chains are designed has a determining impact on the estimation of infrastructure requirements. Their analysis highlights how spatial resolution influences both hydrogen transport infrastructure and upstream input logistics, which ultimately affect hydrogen's effectiveness as a decarbonization pathway. Shao, et al. [16] further demonstrate that incorporating regional feedstock cost differences into design optimization significantly affects hydrogen supply chain viability. Their work emphasizes that detailed intra-country data availability is critical for models to generate reliable results.

Riera, et al. [17] identify optimization as an essential tool for hydrogen systems development, while noting that much of the existing literature prioritizes regional production systems with established infrastructure rather than international supply chain configurations. They further caution that demand projections limited to a single end-use, such as fuel cell vehicles, can constrain system design outcomes. Zubairu, et al. [18] similarly recognize the potential of a hydrogen economy but emphasize that effective integration into the energy markets requires country-specific characteristics to be explicitly considered. These findings motivate a closer examination of hydrogen supply chains and their logistical configurations, as the design of production, conversion, storage, and transport systems ultimately determines hydrogen's feasibility across different regional and market contexts.

1.1. Hydrogen supply chains modelling and optimization literature

Recent literature has focused on hydrogen supply chain modeling from techno-economic, organizational, and system-integration perspectives. Bozzolo Lueckel, et al. [19] reviewed the modeling of hydrogen supply chains at the energy system scale, emphasizing on integration into existing energy networks as a key aspect to build wholistic models. Their findings emphasize that hydrogen systems must be analyzed as interconnected components of broader systems rather than standalone structures.

While Johnston, et al. [20] explored the cost structure of hydrogen transport from Australia to potential import regions, demonstrating that shipping distance and carrier choice are dominant cost drivers whose relative importance varies across assumptions, Hasankhani, et al. [21] shift the attention to the integration of hydrogen into the Dutch context, uncovering the organizational complexities that accompany technical and policy transitions. Rasool, et al. [22] examined the potential for exporting renewables-based hydrogen from a high-renewable energy country (Australia) to nations committed to achieving net-zero emissions, such as Japan, Germany, and Singapore. Their study identified what are the best production-carrier combinations by evaluating multiple factors, including electricity prices, transport distance, and capital cost. Villalba-Herreros, et al. [23] explored how the gap between origin and destination electricity prices defines the cost-effectiveness of hydrogen production onsite or overseas, highlighting liquid hydrogen as an optimal carrier. Systems that allow the integration of renewable electricity and hydrogen production paired with low-cost storage and transmission of hydrogen provide a solid infrastructure for low-carbon hydrogen networks [24].

Although electrolysis is the main production method being frequently discussed, due to the focus on low-emission hydrogen, there are studies focusing on the production via biomass gasification that, even though the emissions compared to renewable electrolysis are higher, with the appropriate network configuration can achieve not only cost-effective systems but also such with considerably lower emissions than traditional methods like steam methane reformation [25]. The intermittency of renewable energies has encouraged studies that focus on building hydrogen supply chains that are resilient through strategic development and novel applications of game theory [26].

These studies collectively showcase that hydrogen supply chain development involves not only techno-economic assessments but also socio-political dimensions. Despite these advances, existing hydrogen supply chain studies predominantly focus on developed regions with mature energy markets, established port infrastructure, and well-defined hydrogen demand projections. As a result, the structural feasibility, cost drivers, and logistical constraints of hydrogen supply chains in developing regions with high renewable potential remain insufficiently explored. In particular, there is limited quantitative assessment of how infrastructure limitations, transport distances, and carrier choices shape optimal supply chain configurations in such contexts.

2. Research gap and contribution

Much of the current research focuses on developed countries and regions where hydrogen strategies are in place - supported by dedicated policies, infrastructure, and demonstration projects. In contrast, developing regions such as Central America remain largely absent from the global hydrogen trends. This study aims to address this research gap by developing a conceptual framework for a Central American hydrogen supply chain, showcasing how production, conversion, storage, and transport could be structured in alignment with regional resources. Insights from conceptual and practical worldwide applications are used to outline the potential configurations and logistical pathways that could enable a feasible hydrogen economy in Central America. This study therefore seeks to address two key questions: how hydrogen supply chains could be structured in developing regions, such as Central America, and what logistical and economic factors shape their feasibility under alternative assumptions regarding renewable energy availability, energy prices, and hydrogen demand. While the modeling approach is general and transferable, Central America is used as a case study to demonstrate the application of the framework in a region that has not yet established a hydrogen strategy. The hypothesis and methodological contribution therefore, remain broader than the region itself, positing that systematic MILP-based evaluation of renewable resource availability, transport infrastructure, and hydrogen carrier options can identify feasible and cost-competitive hydrogen supply chain configurations even in regions with limited data and infrastructure.

3. Materials and methods

This section introduces the concept of hydrogen supply chain (HSC) networks through a review of existing publications throughout the world. The existing technologies for production and potential applications are summarized to better understand what the available application streams for hydrogen as an energy vector are. The mathematical models used in HSC design are analyzed, and a tailored model will be developed to align with the objectives of this study.

3.1. Hydrogen supply chain networks

Although hydrogen supply chain networks are not a reality yet, the number of studies on the topic are rapidly growing and diverse. Table 1 summarizes some of these studies by country and the approach of the networks designed by their authors.

Table 1
Hydrogen supply chain designs around the world.

Country	Description	Source
USA	Biomass (wastewater biogas, food waste, crop residue, municipal waste, etc.) generated hydrogen through steam methane reformation (SMR) is considered specifically to displace the use of fossil fuels in the transportation sector. Both compressed and pipeline were considered to transport hydrogen to final refuelling stations.	[27]
Canada	Production of hydrogen through SMR of natural gas including carbon and capture storage (CCS). The hydrogen produced is intended to be used within Canada or the USA via pipeline or to be exported to Japan and Korea by liquefying the hydrogen.	[28]
Australia	Electrolysis produced hydrogen to supply local and international markets in the APAC region. The government is focused on introducing hydrogen to the entire economy's supply chain through the development of policies that aim to encourage the adoption of this energy source.	[29]
Germany	Analysis of multiple sources for hydrogen production in 2030 and 2050 scenarios to replace the use of fossil fuels in the transportation sector. Both coal and "green" scenarios were executed to determine the location of production facilities within the 16 federal states of Germany.	[30]

The development of HSCs encompasses not only mathematical optimization models but also external factors which have an impact in the result of these models. Suarez, et al. [27] focus on identifying hydrogen supply chains in Latin America, rather than network designs, highlighting key relationships between the region and European countries as major investors in green hydrogen development. Li, et al. [28] introduce a decision-making model for the development of HSCs, designed to assist decision-makers in the hydrogen industry by considering supply, demand, and temporal planning perspectives. The majority of research done on HSCs focuses on optimization of cost or environmental impact; nonetheless, there are other factors such as energy efficiency, social benefits, and uncertainty [29], which need to be considered as well to build more comprehensive models.

3.2. Hydrogen applications

According to the International Renewable Energy Agency (IRENA) [30] the current uses of hydrogen are focused on oil refining, chemical production, iron and steel production, and high-temperature heat applications. These industries are not a relevant part of the Central American economy but the application of green hydrogen as a decarbonizing medium will increase demand in these industries and could eventually represent a potential market for hydrogen produced in the region.

On the one hand, hydrogen has potential uses in the transport, building, and electricity generation sectors [31]. The main application in buildings is heat generation. The Central American Region has no gas infrastructure. Given its location near the tropics, the necessity of building calefaction is not present. LPG is used in households as a medium for cooking but is mainly used through gas canisters. Hythane is a mixture of natural gas and hydrogen at different concentrations. As concluded by [32], Hythane has potential for energy production and domestic applications, but further research is needed, and its adoption and market diffusion will require several changes made to the gas supply chain, including storage materials used and specialized transport.

Hydrogen as a carrier provides the flexibility to store energy for future uses. Makaryan et al. [32] mention the use of ammonia (hydrogen carrier) as a co-firing element in coal plants and the use of hydrogen in fuel cells as backup systems. Transport is the most popular discussion topic regarding the various applications of hydrogen. The adoption of this fuel in the transport industry is being studied for all types of transport modes (i.e., maritime, aviation, road), but research is still ongoing regarding which hydrogen carrier is the most suitable for each application. The growth of electric vehicle (EV) adoption is another factor that influences the adoption of hydrogen as a fuel for road transport through fuel cell vehicles (FCV). For this paper, the use of hydrogen in road transport has been selected as the main use for the hydrogen produced in the proposed HSC. The intended use would be for freight transport trucks near port areas, as these areas are selected as production nodes for the proposed supply chain scenario.

Aside from costs, the comparison between hydrogen carriers should also consider other dimensions such as safety, infrastructure and environmental impacts. For compressed hydrogen, high pressure, reinforced and specialized materials are required. Given the nature of hydrogen of being odorless and colorless, strict leak detection measures are required. Liquefied hydrogen requires cryogenic temperatures (below −253 °C) which translates into additional energy requirements and specialized insulated storage containers. Ustolin, et al. [33] highlight how infrastructure and infrastructure suppliers influence equipment availability and other technical limitations for liquid hydrogen, while noting that these challenges are not insurmountable. Ammonia, with different chemical properties compared to pure hydrogen, comes with other types of issues such as toxicity, and vapor leaks; nonetheless, the current bulk shipping marine infrastructure already handles this type of cargo. Although toxicity is a concern, Zhai, et al. [34] describe how ammonia leaks are easier to detect by both human, robotic and automatic sensors, without reaching recommended exposure levels. Based on the current development of catalyzers, reactors and materials, it is suggested that ammonia is a suitable option for the scalable use of hydrogen [34]. From an environmental perspective, all carriers require additional energy to change state or to reconvert in the case of ammonia, which comes with embedded emissions. The additional infrastructure such as storage specialized vessels are also a source of upstream emissions for the transport of hydrogen. The lifecycle assessment executed by [35] indicates that pipeline and ship transport, along with compressed and liquefied hydrogen, respectively, are the options with the least environmental impact for the specific European scenario in their case study. There is no universally optimal hydrogen carrier, as each involves trade-offs; however, this study focuses on broader system-level considerations rather than the detailed optimization of carrier selection.

Table 2 highlights the differences in energy, cost, and losses among the three mentioned hydrogen carriers. Compressed hydrogen has relatively low conversion energy, resulting in the lowest energy penalty (8–22% of LHV) and moderate CAPEX, but its low volumetric energy density limits transport efficiency over long distances. Liquefied hydrogen achieves higher volumetric energy density, making it more compact for transport, but at the cost of significant liquefaction energy (34–40% of LHV) and higher storage CAPEX. Ammonia offers the lowest gravimetric hydrogen content and the highest energy penalties due to synthesis and reconversion (151–303% of LHV), but its higher volumetric density and moderate transport costs make it advantageous for long-distance shipping. Aggregation of the environmental footprint lifecycle impact results in a single-score indicator (mPt/kg H_2 delivered), indicating that compressed hydrogen has the lowest overall environmental impact (36–37 mPt), followed by ammonia (44–46 mPt), while liquid hydrogen exhibits the highest impact (49–50 mPt) [36]. The total score is largely driven by energy-related impacts, particularly climate change and fossil resource use, with differences between carriers primarily reflecting the additional energy requirements associated with liquefaction and chemical synthesis compared to compression.

Table 2
Hydrogen carrier metric comparison.

Metric	Compressed H_2	Liquefied H_2	Ammonia
LHV (MJ/kg)	120	120	18.6
Volumetric energy density (MJ/l)	4.712 (700 bar)[1]	8.506 (−253 °C)[1]	12.700 (10 bar, −34 °C)[1]
Gravimetric hydrogen content (% weight)	100%	100%	17.6%
Conversion/ reconversion energy (MJ/kg)	10–26[2]	41 – 48.2[3]	28.1 – 56.4[3]
Energy penalty (% of LHV)	8 – 22%	34 – 40%	151 – 303%
Carrier formation CAPEX (USD/ kW H_2)	2.6[8]	1300—1900[4]	670[4]
Storage CAPEX (USD/kg)	0.19 – 0.70[5]	4.5 – 5.6[5]	2.6 – 2.8[5]
Transport cost (USD/kg)	−20 inch diameter pipeline: 0.2–4.2 USD/kg (100 to 2000 km)[5] −Truck 3–5 USD/ kg (100 km)[5]	−Tanker: 4.2 – 5 USD/kg (100 to 2000 km)[5]	−Tanker: 1.43 – 4.13 USD/kg (100 to 2000 km)[5]
Boil off/losses (%)	≈ 0	0.05 – 0.25% per day[6]	0.1% per day[7]
Environmental impact (mPt/kg H_2)	36.3 – 36.9[9]	48.6 – 50.4[9]	44.5 – 45.7[9]

1 Extracted from [40], 2 extracted from [41], 3 extracted from [42], 4 adapted from [43] @ 0.62 USD/NZD, 5 data extracted from [44], 6 data extracted from [45], 7 data extracted from [46], 8 adapted from [47], 9 adapted from [48] with factors from [49].

These differences directly influence the optimization models. Carriers with low energy penalties and high gravimetric content, such as compressed hydrogen, are favored for short-distance or high-demand scenarios due to lower operational energy and cost. Conversely, carriers with high volumetric density, like ammonia, can become preferable in long-distance transport scenarios despite higher upstream energy requirements.

3.3. Hydrogen supply chain optimization framework

Optimization through linear and non-linear programming is a common tool to analyze the potential of HSCs in different regions and different sources. Table 3 presents some of the supply chains that have been analyzed in different countries. The table specifies what type of optimization was applied and the objective of the developed mathematical model. The energy sources and proposed state of aggregation can also be found in Table 3.

For this study, a mixed-integer linear programming (MILP) approach has been selected to analyze the production of hydrogen and the development of an HSC network in the Central American Region. The objective of the model is to minimize the total cost of the network which includes the cost of producing hydrogen and its carriers, transportation, and storage. Fig. 1 is a visual representation of the decision model on which the mathematical model will be based. More details on the mathematical formulation of the model are provided next.

3.4. Mathematical model formulation

This section focuses on developing the mathematical model, defining its objective, constraints, and governing equations, as well as the individual components within these equations. The subsections are organized to describe in detail the different stages of the hydrogen supply chain, including hydrogen production, carrier production, transport, and storage.

3.4.1. Objective function

The main objective of the mathematical model is to minimize the total cost of the HSC network in the region under the assumption mentioned in the previous section. The total cost is composed by the production of hydrogen, production of carriers, as well as carriers' transportation and storage. The total cost function to be minimized is represented by:

$$HSC\ Total\ Cost = PC + CC + TC + SC, \quad (1)$$

where *PC* stands for production cost, *CC* for carrier cost, *TC* for transport cost, and *SC* for storage cost. For further reference on the abbreviations used in the equations throughout this document refer to the notation of variables section. The model was solved using MATLAB, by applying this software's options for mixed integer linear programming.

3.4.2. Hydrogen production cost

The production cost of hydrogen can be divided into two main components: the capital and operational expenditures as well as the cost of the main input, which in this case is electricity. The production cost (*PC*) is subdivided and represented by

$$PC = CCost + EHCost \quad (2)$$

where *CCost* takes into account the cost of the electrolyzer facility and its operation. According to the decision tree in Fig. 1, this facility can be of two types of electrolyzers: Alkaline electrolyzer ($i = 1$) and PEM electrolyzer ($i = 2$). This cost is further detailed by:

$$CCost = \sum_{i,j}\left(CAPEXE_i \times \left(\frac{HyProd_{i,j} \times me_i}{ECF_i \times Interval}\right) \times PMTF_j\right) \times OPEXF \quad (3)$$

CAPEXEi represents the facility's capital cost which depends on the electrolyzer type *i*. $HyProduction_{ij}$ represents the amount of hydrogen to be produced through facility *i* in country *j*. LHV is the lower heating value of hydrogen, $effe_i$ represents the efficiency of electrolyzer *i*, and ECF_i is the capacity factor of electrolyzer *i*. The *interval* is the number of hours in the time frame of the analysis which is one year. $PMTF_j$ is the annuity factor which depends on the discount rate for each country *j*. *OPEXF* represents a percentage of the capital cost that the operational expenditure represents. Taking this into account, Equation (4) introduces the no-production constraint at the sink nodes.

$$HyProd_{i,j} = 0, \text{ for } i = 2, 3, 4, 6 \quad (4)$$

The cost of electricity (*EHCost)* to produce hydrogen can be obtained through:

$$EHCost = \sum_{i,j}\left(HyProd_{i,j} \times me_i \times EP_j\right) \quad (5)$$

where me_i represents the mass efficiency of the electrolyzer *i* (electric requirement for production in kWh/kg H_2) and EP*j* denotes the electricity price in country *j*.

The production of hydrogen and its carriers is assumed to be maximized at supplier nodes, thus utilizing all the available excess electricity. This introduces a constraint for production related to the usage maxi-

Table 3
Hydrogen supply chain optimization approaches and details.

Country	Optimization Approach	Objective	Energy Source	State of Aggregation	Reference
France	Multiobjective-Mixed-Integer Linear Programming	Total Cost Minimization Total Global Warming Potential Minimization Total Inherent Risk Index	Biomass, solar, wind and hydro.	Liquid	[50]
Great Britain	Mixed-Integer Linear Programming	Total Cost Minimization	NG-SMR, oil, coal, biomass and solar.	– Liquid – Gaseous	[51]
Mexico	Multiobjective-Mixed-Integer Linear Programming	Profit Maximization	Biomass.	– Liquid	[52]
Mongolia	Multiobjective-Mixed-Integer Linear Programming	Total Cost Minimization Total Global Warming Potential Minimization	NG-SMR, electricity (no origin specified), coal and biomass.	–Liquid –Gaseous	[53]
Switzerland	Multiobjective-Mixed-Integer Linear Programming	Total cost Minimization Total Global Warming Potential Minimization	NG-SMR, electricity (no origin specified) and biomass	– Liquid – Gaseous	[54]
South Korea	Multiobjective-Mixed-Integer Linear Programming	Total cost Minimization Relative risk minimization	NG-SMR and electricity (no origin specified).	– Liquid – Gaseous	[55]
Turkey	Multiperiod-Mixed-Integer Non-Linear Programming	Total cost Minimization	NG-SMR, coal, biomass, solar, wind, geothermal and hydro.	– Liquid	[56]

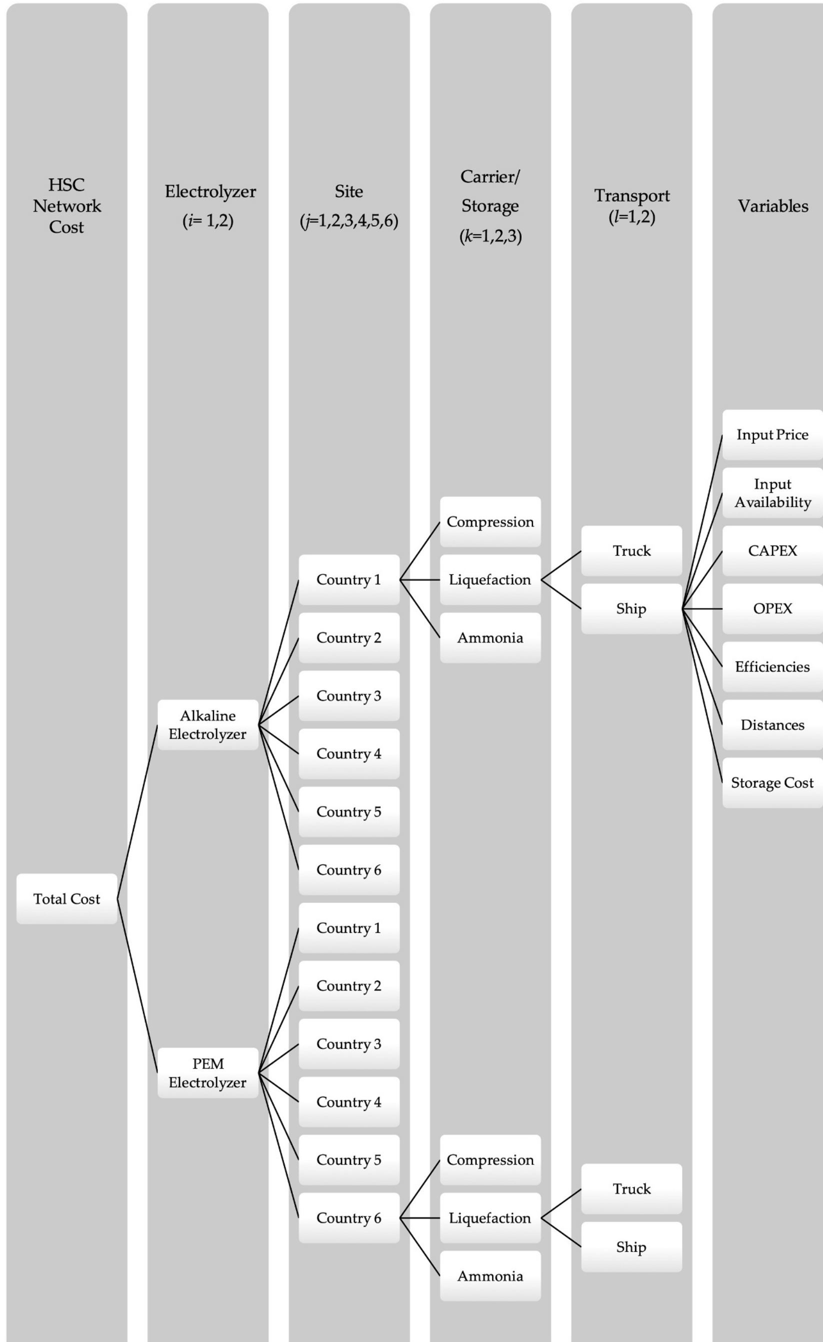

Fig. 1. Decision model for HSC.

mization of the available energy, which is represented by

$$\sum_{i,j}\left(HyProd_{i,j} \times me_i\right) + \sum_{i,j,k=1}\left(HyCarr_{i,j,k} \times \frac{CE_k}{EE_k}\right) + \sum_{i,j,k=2}\left(HyCarr_{i,j,k} \times CE_k\right) + \sum_{i,j,k=3}\left(HyCarr_{i,j,k} \times HCE_k \times CE_k\right) = AE_j \tag{6}$$

where $HyCarr_{ijk}$ represents the amount of hydrogen to be produced through facility i in country j and carrier k. CE_k represents the conversion efficiency for the technology of carrier k, HCE_k is the hydrogen consumption efficiency for ammonia, and AE_j stands for the available energy at country j.

3.4.3. *Carrier production cost*

Similar to hydrogen production, the production of its carriers can be divided in two parts. Again, the first subcategory is the capital and operational expenditure costs, whereas the second one is the cost of energy to produce the carrier. The carrier production cost (*CC*) as the second subcategory is represented by:

$$CC = CaCost + ECaCost \tag{7}$$

where *CaCost* takes into account the cost of the carrier production facility and its operation. According to the decision tree in figure 12, this facility can be of three types: compressed hydrogen ($k = 1$), liquefied hydrogen ($k = 2$), and ammonia ($k = 3$). *CaCost* is further detailed through Equation (10) as follows:

$$CaCost = Ccomp + Cliq + Camm \tag{8}$$

where *Ccomp* is denoted by:

$$Ccomp = \sum_{i,j,k=1}\left(\left(CAPEXC_k \times \left(\frac{HyCarr_{i,j,k} \times \frac{CE_k}{EE_k}}{ECF_k \times Interval}\right) \times PMTF_j\right) \times OPEXF(\%)\right). \tag{9}$$

Here, $CAPEXC_k$ represents the facility capital cost which depends on carrier type k. $HyCarr_{ijk}$ represents the amount of hydrogen to be produced through facility i in country j and carrier k. CE_k is the conversion efficiency of carrier k and EE_k the equipment efficiency in this case of the compressor. ECF_k is the capacity factor of carrier facility k. Equations (10) and (11) are similar to Equation (9) but adapted to its corresponding carrier. *Cliq* and *Camm* are represented by Equations (10) and (1) as follows:

$$Cliq = \sum_{i,j,k=2}\left(\left(CAPEXC_k \times \left(\frac{HyCarr_{i,j,k} \times CE_k}{ECF_k \times Interval}\right) \times PMTF_j\right) \times OPEXF\right) \tag{10}$$

$$Camm = \sum_{i,j,k=3}\left(\left(CAPEXC_k \times \left(\frac{HyCarr_{i,j,k} \times HCE_k}{ECF_k \times Interval}\right)\right) \times OPEXF(\%)\right) \tag{11}$$

where ECF_k is the electricity capacity factor of the equipment for carrier k. The production of carriers $HyCarr_{ijk}$ must not exceed the total production of hydrogen $HyProd_{ij}$ in supplier nodes. This new constraint is introduced through Equation (12):

$$\sum_i HyProd_{i,j} = \sum_{i,j,k} HyCarr_{i,j,k} \text{ for all } j \tag{12}$$

Finally, the cost of energy for carrier production (*ECaCost*) is detailed by:

$$ECaCost = \sum_{i,j,k=1}\left(HyCarr_{i,j,k} \times \frac{CE_k}{EE_k} \times EP_j\right) + \sum_{i,j,k=2}\left(HyCarr_{i,j,k} \times CE_k \times EP_j\right) + \sum_{i,j,k=3}\left(HyCarr_{i,j,k} \times HCE_k \times CE_k \times EP_j\right) \tag{13}$$

3.4.4. Transportation cost

Transportation cost (*TC*) is defined by the transportation mode which according to Fig. 1 has been reduced to land (truck $l = 1$) and sea (ship $l = 2$) transportation. This cost is defined by:

$$TC = \sum_{j,jp,l,k}\left(HyFlow_{j,jp,l,k} \times TC_{j,jp,l,k}\right), \ j \neq j_p, \tag{14}$$

where $HyFlow_{j,jp,k,l}$ is the hydrogen flow from country j to country jp using transportation mode l and carrier k. $TC_{j,jp,k,l}$ represents the cost of transporting a kilogram of hydrogen from country j to country jp using transportation mode l and carrier k. The data collected for $TC_{j,jp,k,l}$ (transportation total cost from country j to country jp with carrier k and transport mode l) includes the capital cost of the equipment. This term is represented by using route-specific mass-based coefficients (USD/kg) derived from literature and cost estimates that can be referred to in Table S4 in the Supplementary Material. These coefficients aggregate distance-dependent transport costs with typical loading and unloading charges. The model focuses on economic optimization and does not simulate operational constraints such as port handling throughput, vessel availability, or equipment fleets, which fall outside the scope of a static supply-chain cost formulation.

For supply nodes, the available hydrogen to be exported cannot exceed the available hydrogen which will be the excess hydrogen produced. In contrast, the imported hydrogen in sink nodes cannot exceed the amount that has been established as demand. This constraint is defined by Equations (15) and (16) as follows:

$$\sum_{j,jp,l,k} HyFlow_{j,jp,l,k} = \sum_{i,j} HyProd_{i,j} + HyDemand_j, \text{ for } j = \{1, 5\} \tag{15}$$

$$\sum_{j,jp,l,k} HyFlow_{j,jp,l,k} \leq HyDemand_j, \text{ for } j = \{2, 3, 5, 6\} \tag{16}$$

where $HyDemand_j$ represents the demand in country j. The constraint for no flow from sink nodes is defined by Equation (17) and the no-flow condition from the supplier-to-supplier node is introduced by Equation (18).

$$\sum_{j,jp,l,k} HyFlow_{j,jp,l,k} = 0, \text{ for } j = \{2,3,5,6\} \tag{17}$$

$$\sum_{i,j,k} HyFlow_{j,jp,l,k} = 0, \text{ for } j = \{1,5\} \text{ and } jp = \{1,5\}. \tag{18}$$

The overall hydrogen flow of a specific carrier k from a production node cannot exceed the total amount of that carrier produced in node j. This constraint is introduced by Equation (19).

$$\sum_{j,jp,l} HyFlow_{j,jp,l,k} = \sum_{j,jp,l} HyCarr_{i,j,k}, \text{ for } j = \{1,5\} \text{ and for all } k \tag{19}$$

3.4.5. Storage cost

The storage mode will depend on the carrier as they all need different modes of storage given the intrinsic properties of the carrier. The storage cost is defined by Equation (20) as follows:

$$SC = SCost + SECost, \tag{20}$$

which is divided into two terms. The first one (*SCost*) encompasses the capital cost of the storage equipment, whereas the second one (*SECost*) refers to the energy consumption of the storage devices. *SCost* is defined by Equation (21),

$$ECost = \sum_{i,j,k}\left(HyCarr_{i,j,k} \times \frac{SD}{365} \times SC_k \times PMTF_j\right) \tag{21}$$

where SD represents the number of days that the hydrogen is being planned to be stored and SC_k is the capital cost of storage for carrier k. This component estimates storage capital cost using a unit cost expressed in USD/kg (refer to Table S1 on the Supplementary Material), scaled by the mass stored and the assumed storage duration. Given that the required storage volume is derived directly from the modeled carrier flows, the formulation does not impose an explicit upper capacity limit. Storage is therefore treated as a scalable component. While this is appropriate for a system-level analysis, real-world facilities have discrete and site-specific capacity constraints. These are acknowledged as limitations of the current model and can be incorporated in future refinements.

SECost is defined by Equation (22) as:

$$SECost = \sum_{i,j,k}\left(HyCarr_{i,j,k} \times SD \times SCO_k \times EP_j\right) \tag{22}$$

where *SCOk* denotes the storage energy consumption for carrier k.

4. Energy overview of Central America

The Central American Region (Fig. 2) is no exception in this respect and actions towards these objectives can be observed [37]. The region is composed of six countries (Costa Rica, El Salvador, Guatemala,

Fig. 2. Central American region as part of the continent of America.

Honduras, Nicaragua, and Panama) and all of them, at some point, have submitted their National Determined Contributions (NDCs) with strategies to mitigate their greenhouse gas levels. Nevertheless, aside from increasing their shares of renewable energies and the reduction of fossil fuel consumption, no other actions are being declared. Costa Rica is the exception in this last fact as it has, to some extent, mentioned the inclusion of hydrogen in their energy system. According to Gischler, et al. [38], El Salvador and Panama as well are developing laws that regulate hydrogen.

In 2023, the Inter-American Development Bank (IDB) along with the Latin American Energy Organization (OLADE) launched an initiative named CertHiLAC which aims to develop a certification system for low-emission hydrogen production in the region [39]. Although not solely focused on Central America, the International Energy Agency (IEA) [40] identifies low-carbon hydrogen as a key element for Latin America's transition to clean energy. Among the discussed applications for hydrogen, road transport and shipping are identified as potential opportunities to aid the region towards decarbonization [40]. Regional hydrogen hubs are identified as the first step towards lower production and transport costs through economies of scale [6].

To meet the emission reduction objectives, countries must focus efforts on diversifying their energy systems (production, storage and distribution) by using energy vectors. An energy vector is defined as an "… energy carrier which can be primary or produced from other energies, and is transportable with lead and lag time…" [41]. The terms "lead" and "lag" are of crucial importance as they introduce flexibility to an energy system which is exactly what the region is lacking at the moment.

Fig. 3a shows the population of the Central American region since the year 1958. In 2023, the population was estimated to be around 52 million (precisely 51,777,300) [42], representing a more than fourfold increase over 75 years. Fig. 3b presents the population distribution by country, expressed as a percentage of the regional total. This breakdown is derived from the national population data to highlight the relative weight of each country within the region. The resulting distribution provides a clearer basis for comparing the scale at which national demand nodes may influence supply chain configurations. Note that these demographic indicators do not necessarily align with renewable energy shares or energy production, which reinforces the need of designing supply chains that explicitly decouple demand from resource availability.

Fig. 4 details the GDP values per country for the year 2022. The total GDP for the region for 2022 was 295,051 billion USD [42] with a GDP per capita of 5,768 USD per person. Presenting these indicators jointly enables a comparison of economic scale and purchasing power across countries, which are relevant for understanding differences in energy demand and investment capacity. However, GDP levels do not reflect renewable energy potential, highlighting mismatches between economic activity, population distribution, and energy resource availability that motivate the development of regional supply chains.

The region's electricity generation is dominated by renewable energy sources. According to the Economic Commission for Latin America and the Caribbean [43], in 2020, the whole region's renewable electricity share was 81.8%, which was 5.0% more than in 2017. Fig. 5 represents electricity generation in the region from 2017 to 2022 (available data in

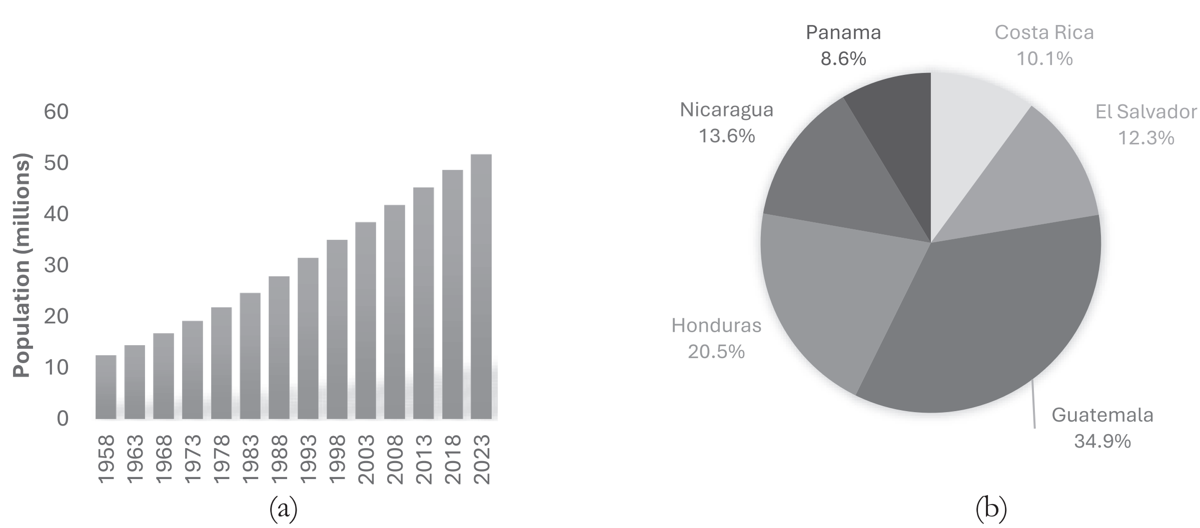

Fig. 3. (a) Population of the Central American region; (b) Percentage of total population by country (data).
Source: [62]

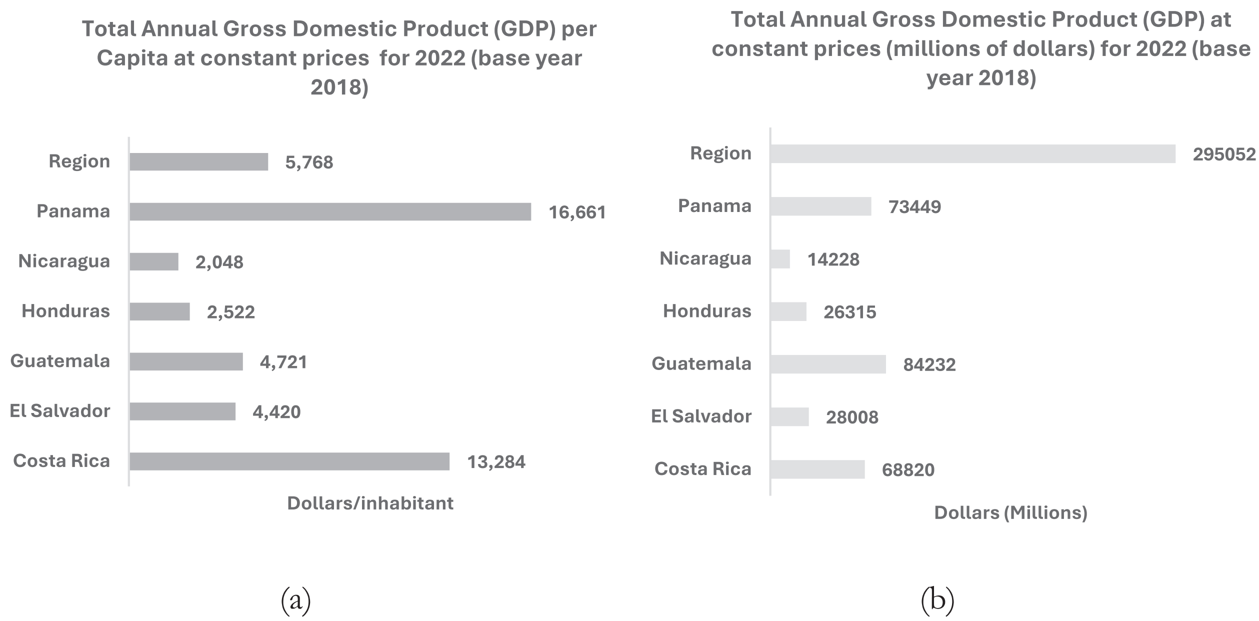

Fig. 4. GDP of Central American countries: (a) National value in million USD, and (b) Per capita values (data).
Source: [63]

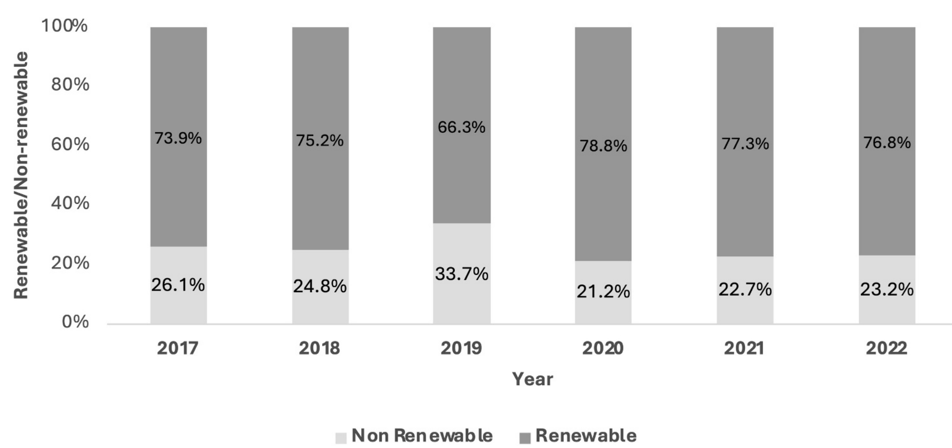

Fig. 5. Renewable vs non-renewable electricity generation for the Central American region (Data source: [63]).

[43]), a period during which slight increases took place in its renewable share.

It is important to highlight that Costa Rica has managed to sustain its renewable electricity generation share at above 98% between 2017 and 2022 [43]. With the data available for 2021, Guatemala and Honduras have increased their share by 2.9% and 6.6%, respectively, since 2017. Hydro, wind, geothermal, and solar are the main renewable energy sources. Fig. 6 shows the generation distribution among the sources mentioned before. It is important to highlight that the thermal category in Fig. 6 includes both renewable and non-renewable thermal sources, which could not be further broken down due to a lack of information on this specific source. The non-renewable thermal sources are mainly fossil fuels (oil and natural gas). The percentage of renewable energy sources for each country varies within the region, given the availability of resources (natural and economic) and policies (political and economic).

Table 4 summarizes total electricity consumption compared to total renewable energy production. This data is relevant to analyzing a country's potential capacity to produce green hydrogen. A positive value indicates a net positive renewable generation compared to national electricity demand, while a negative value implies that the electricity demand is higher than the renewable energy generation.

From the data reported in Table 3, it is possible to observe that the region is not producing more renewable electricity than its electricity consumption, with the exception of Costa Rica. Electricity imports and exports (Fig. 7) showcase the dynamics of international electricity trading in the region, which is one of the reasons that drives countries such as Costa Rica to produce beyond the local demand. This local demand is what drives countries to further develop their energy sources.

Nevertheless, from the data reported in Table 3, it can be seen that the gap between demand and renewable energy availability has a stable trend (with the exception of 2019), which can be seen in Fig. 8.

The electricity prices in the region can be observed in Fig. 9. Nicaragua, Guatemala and Costa Rica show relative stability or only small changes in their prices. In contrast, Honduras, El Salvador and Panama have suffered significant increases.

Given the fact that the region already has a high percentage of renewable energy in its electricity grid, it is clear what the objective should be regarding electricity generation, which would be to keep increasing the renewable energy share. If the region intends to achieve its greenhouse gas emissions reduction objectives, it is of high importance to focus not only on the electricity sector alone but also on other

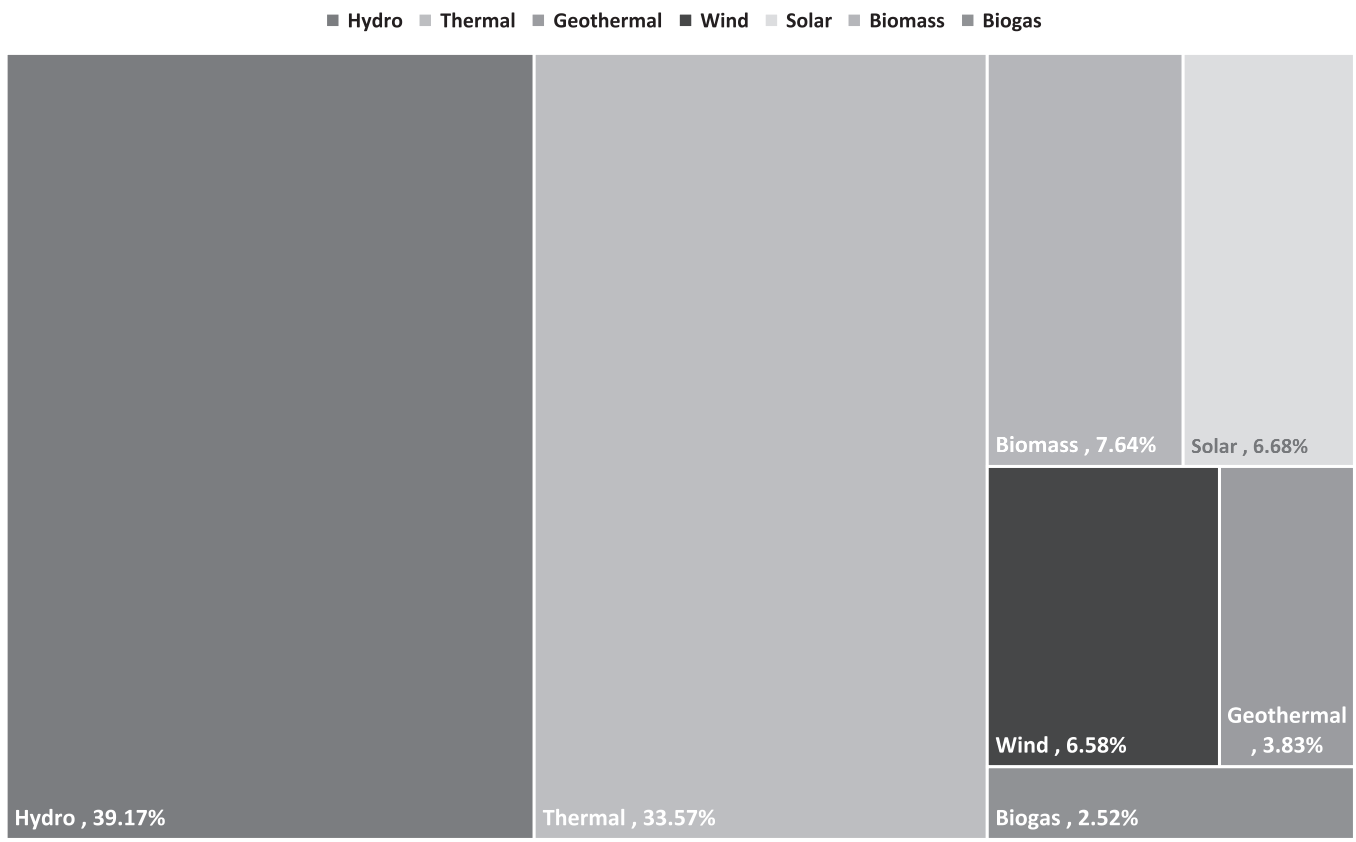

Fig. 6. Electricity generation percentage shares by energy source (Data source: [64]).

Table 4
Electricity Demand vs Renewable Electricity Supply (GWh) by Country (2017–2022) (data).

Country	Indicator	2017	2018	2019	2020	2021	2022
Costa Rica	Electricity Consumption	9914	10,008	10,182	9897	9907	10,509
	Renewable Electricity Generation	11,173	11,197	11,217	11,511	12,537	12,500
	Surplus	1259	1189	1035	1614	2630	1991
El Salvador	Electricity Consumption	6155	6225	6346	5990	6488	6740
	Renewable Electricity Generation	4121	4207	4319	5213	5120	5534
	Surplus	−2035	−2018	−2027	−777	−1368	−1206
Guatemala	Electricity Consumption	9594	10,220	10,660	10,381	11,760	11,252
	Renewable Electricity Generation	7870	7696	7093	8373	8524	9403
	Surplus	−1724	−2524	−3567	−2009	−3237	−1848
Honduras	Electricity Consumption	6640	6824	7252	6630	7757	7605
	Renewable Electricity Generation	5317	5902	5091	5151	6346	6182
	Surplus	−1323	−922	−2161	−1479	−1411	1423
Nicaragua	Electricity Consumption	3753	3731	3769	3653	3903	3999
	Renewable Electricity Generation	2533	2739	2601	3647	2911	2812
	Surplus	−1220	−992	−1168	−5	−992	−1186
Panama	Electricity Consumption	9095	9339	11,065	11,024	12,158	12,655
	Renewable Electricity Generation	7910	8693	6136	8133	9678	9555
	Surplus	−1185	−646	−4929	−2891	−2480	−3100

Source: [63]

sectors, such as transport, also due to sector coupling. Fig. 10 shows the CO_{2e} emissions for the 2020 electricity and transport sectors. Evidently, transport emission exceeds those of electricity generation, thus making it a priority to focus policy efforts in this sector.

The Central American Region's electricity system is interconnected by landlines that belong to the Electricity Interconnection System of the Central American Countries (SIEPAC in Spanish). This system is composed of 1830 km of 230 kV lines, connected to 15 substations within the countries, and has a capacity of transporting 300 MW [44]. The Regional Electricity Market (MER in Spanish) is the entity through which all the electricity transactions within the mentioned circuit are executed. The existence of this network shows that there is an administrative infrastructure that could serve as a starting point to build other energy networks across the region. Fig. 11 describes the SIEPAC line along the region and some details regarding the composition of the transmission circuit.

As discussed in [45], for the 2020–2030 decade, the region is planning to add a minimum of 1000 MW of solar-based energy, 847 MW of wind-based energy and 800 MW of hydro-electric power. As of 2023, the estimated percentage levels of utilization were 31.6% for the hydro potential, 19.8% for geothermal, and 53.7% for wind-based energy [45]. In this case, levels of utilization refer to how much of the identified

Table 5
Estimated electricity availability per country in 2050.

Country	Source	Potential (MW)	Potential (GW)	Utilization (%)	Capacity Factor (%)	Availability (GWh)	Total (GWh)
Costa Rica	Geothermal	865.00	0.87	30.3	80	1836.76	25,596.49
	Hydroelectric	6500.00	6.50	77.7	51	22,563.61	
	Solar[1]	5.40	0.01	100.0	16.90	7.99	
	Wind	600.00	0.60	68.5	33	1188.12	
El Salvador	Geothermal	333.00	0.33	61.3	80	1430.54	5283.80
	Hydroelectric	2165.00	2.17	31.5	51	3046.79	
	Solar[1]	474.46	0.47	100.0	16.90	702.40	
	Wind	36.00	0.04	100.0	33	104.07	
Guatemala	Geothermal	1000.00	1.00	61.3	80	4295.90	12,261.39
	Hydroelectric	5000.00	5.00	31.5	51	7036.47	
	Solar[1]	92.50	0.09	100.0	16.90	136.94	
	Wind	400.00	0.40	68.5	33	792.08	
Honduras	Geothermal	120.00	0.12	61.3	80	515.51	8776.39
	Hydroelectric	5000.00	5.00	31.5	51	7036.47	
	Solar1	512.73	0.51	100.0	16.90	759.07	
	Wind	235.00	0.24	68.5	33	465.35	
Nicaragua	Geothermal	1200.00	1.20	30.3	80	2548.11	9869.98
	Hydroelectric	1760.00	1.76	77.7	51	6109.53	
	Solar[1]	16.36	0.02	100.0	16.90	24.22	
	Wind	600.00	0.60	68.5	33	1188.12	
Panama	Geothermal	0.00	0.00	0.0	0	0.00	9233.79
	Hydroelectric	2341.00	2.34	77.7	51	8126.37	
	Solar[1]	213.00	0.21	100.0	16.90	315.33	
	Wind	400.00	0.40	68.5	33	792.08	

1 Extracted from [64].

Table 6
Estimated electricity prices by country, 2050.

Country	2050 Estimated Prices (USD/MWh)
Costa Rica	62.26
El Salvador	58.74
Guatemala	61.38
Honduras	61.52
Nicaragua	63.89
Panama	63.59

potential is being exploited. In the analysis of different scenarios in [46], the decarbonizing scenario showcases how the region can reach a nearly 100% renewable electricity target by generating around 200 TWh through bioenergy, hydropower, geothermal, solar PV, solar CSP, and wind power by 2050. This allows to infer that there are opportunities available for the renewable energies sector to keep growing.

Taken together, the regional energy statistics presented in this section provide the empirical basis for the modeling assumptions applied in Section 3.1. The current fuel consumption levels for road transport (Table 8) across Central American countries inform the scenario-based demand estimates for transport-sector hydrogen substitution. Differences in national energy mixes and renewable resource availability (Tables 4 and 6) further justify the identification of Costa Rica and Nicaragua as candidate production locations. Aligning these regional characteristics with the model parameters ensures that the optimization reflects not only theoretical supply chain structures but also the practical constraints and opportunities inherent to the Central American energy landscape.

This paper aims to establish a foundational framework for the future of hydrogen supply chains in the region by addressing questions related to production and application. It investigates the most suitable type of hydrogen carriers to produce, assesses the potential regional applications and determines which are the optimal production countries based on renewable energy availability, economic conditions, and geographical locations. Additionally, this paper analyzes the costs of the entire supply chain from production all the way to delivery in consumer countries. This research provides original insights, based on available

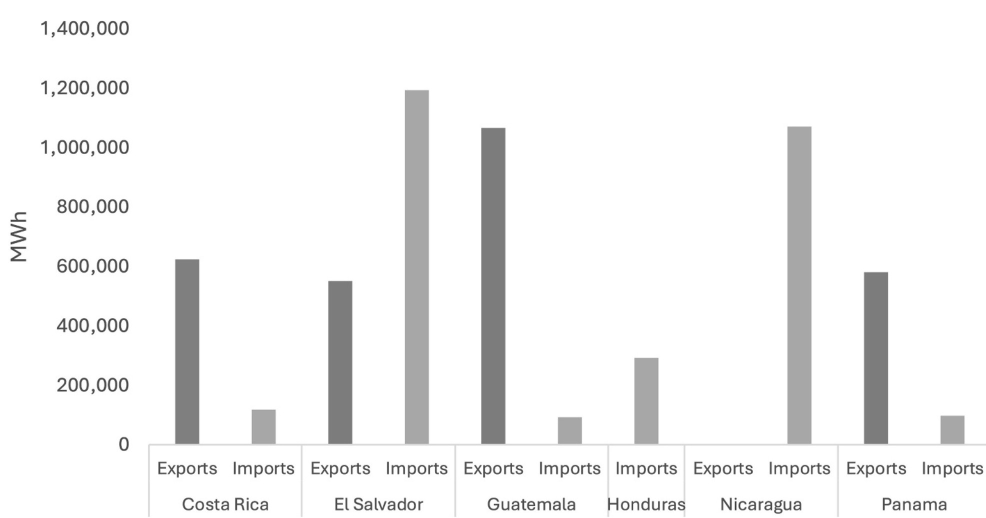

Fig. 7. Electricity imports and exports in 2020 (Cross-national trade among the showcased countries only). Data source: [62].

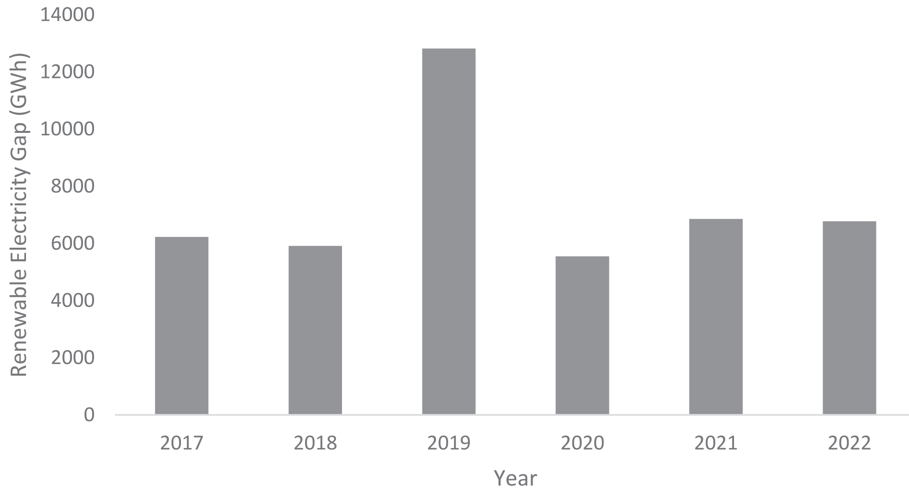

Fig. 8. Difference between electricity consumption and renewable electricity availability for the Central American region (GWh), based on data from [63].

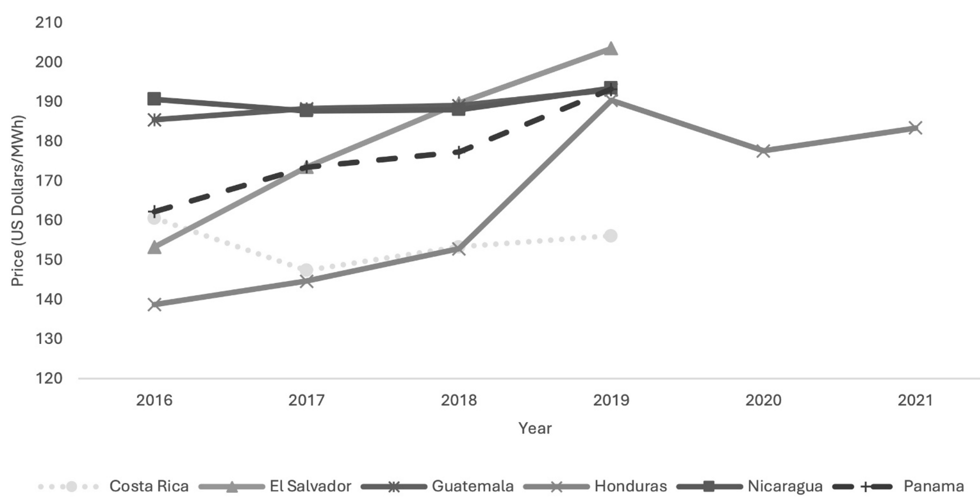

Fig. 9. Electricity prices in the Central American region 2016–2021 (USD/MWh), based on data from [63].

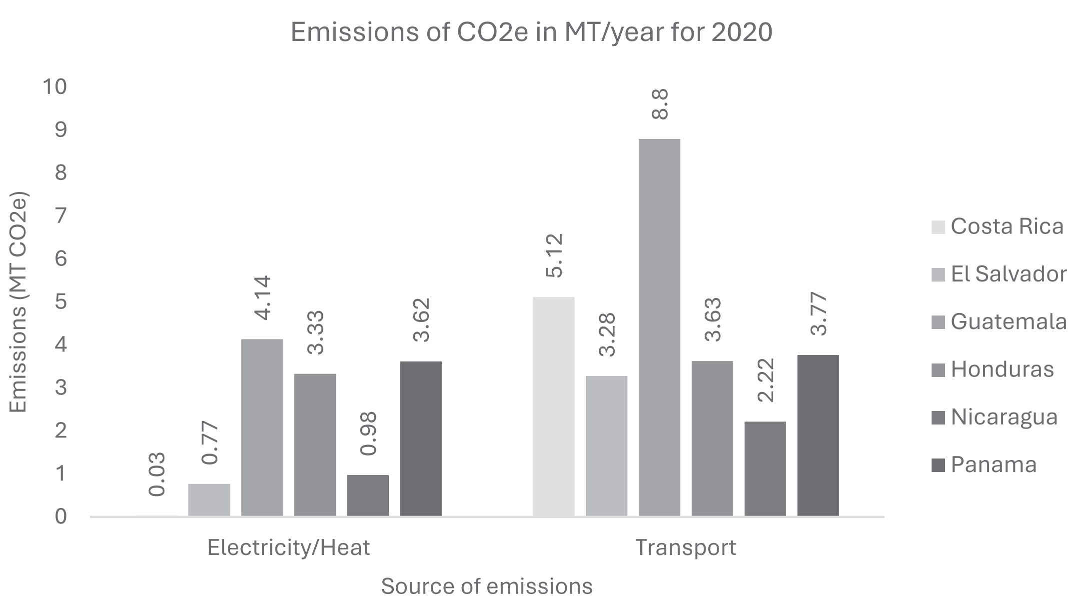

Fig. 10. CO_{2e} emissions of the transport and electricity sectors in 2020 for the Central American region, Source: based on [65].

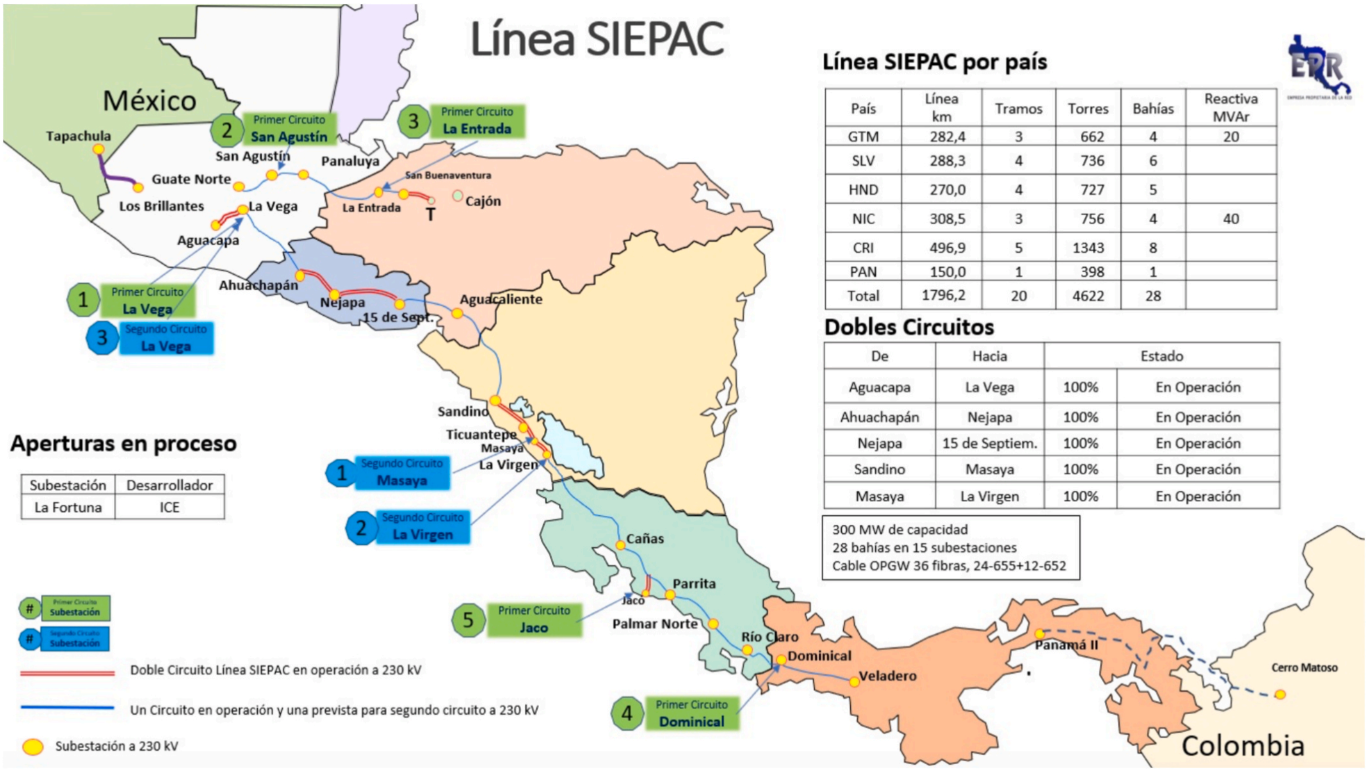

Fig. 11. SIEPAC Transmission Line Circuit. Source: Figure extracted from EPR [67].

Table 7
Population and electricity consumption by country, 2020 and estimates for 2050.

Country	Population 2020 (thousands)	Electricity Consumption (GWh/1000 inhabitants)	Population 2050 (thousands)	Electricity Consumption (GWh)
Costa Rica	5123.1	1.95	5702.5	11,119.7
El Salvador	6292.7	0.95	6636.9	6316.7
Guatemala	17,362.7	0.60	24,600.7	14,700.3
Honduras	10,121.8	0.66	14,258.5	9339.9
Nicaragua	6755.9	0.54	9094.6	4946.1
Panama	4294.4	2.15	5736.1	12,331.3

Note: Based on data from [62].

Table 8
Estimated electricity consumption and available renewable electricity in proposed scenario (2050).

Country	Electricity Consumption (GWh)	Renewable Electricity Generation (GWh)	Difference (GWh)
Costa Rica	11,120	25,596	+14,477
El Salvador	6317	5284	−1033
Guatemala	14,700	12,261	−2439
Honduras	9340	8776	−563
Nicaragua	4946	9870	+4924
Panama	12,331	9234	−3098

Note: Based on data from Tables 5 and 7.

data, to build a framework that can be utilized as a preliminary decision-making tool for the development of hydrogen in the region. It is important to note that the regional focus serves solely as an applied example of the broader analytical framework proposed in this paper. The purpose of this section is not to formulate a region-specific hypothesis, but to contextualize the case study through which the general modeling approach is demonstrated.

4.1. Scenario and assumptions for mixed-integer linear programming model

Even though there is no current excess of renewable energy in the Central American Region there is significant potential for the further development of this energy source. As there is no accurate information from official sources in these countries, the following scenario related to renewable energies is proposed:

The potential of various renewable sources of energy and its current utilization by country were determined in [45]. To forecast the availability of energy in a 2050 scenario the assumptions described in the following were taken into consideration.

The level of utilization of certain renewable energy sources for each country, described by Equation (23), was assumed as an upper-bound scenario to be equal to the maximum level (2020) of the countries which share a border for 2020. For example, for the hydroelectrical level of utilization, Nicaragua shares a border with Costa Rica (Level: 77.7%), and Honduras (14.5%). The level of utilization for Nicaragua was set as 77.7%. This of course is an optimistic scenario which does not account for the willingness of governments to pursue these levels of energy production. The renewable energy penetration levels projected for 2050 are derived from the highest shares achieved by neighboring countries and should be interpreted as indicative upper bounds reflecting data limitations rather than precise forecasts. Following the modeling practices discussed by Yu, et al. [47], scenario-based frameworks are frequently used to explore optimistic and conservative limits under uncertainty and limited data availability.

The assumed level of utilization was then multiplied by the capacity factor of each technology to obtain a value for production of energy. Table 5 summarizes the data obtained from this assumption. Equations (1) and (2) describe how the figures in Table 4 were obtained. As an additional remark, the solar energy level of utilization was set to 100%, given that the available data is only about installed capacity rather than potential capacity. The level of utilization is given by

$$\mathit{Level\ of\ Utilization} = \frac{\mathit{Installed\ Capacity}}{\mathit{Potential\ Capacity}} \tag{23}$$

$$\mathit{Electricity\ Production}\ 2050 = \mathit{Potential\ Capacity} \times \mathit{Level\ of\ Utilization} \times \mathit{Capacity\ Factor}. \tag{24}$$

Based on the energy mix shown in Table 5, electricity prices for 2050 were estimated using the levelized cost of electricity (LCOE) of each generation source. This provides a transparent approximation of future electricity costs in the absence of detailed long-term market projections for Central America. Recent assessments indicate that the LCOE from new utility-scale renewables projects is decreasing and in some cases reaching 40–80 USD/MWh [48]. The estimated 2050 electricity prices used in this study (Table 6) therefore lie within the plausible lower-cost range for high-renewable systems, while retaining a conservative premium to reflect regional conditions.

National electricity consumption was estimated through the electricity consumption per capita of 2020 and the population by 2050 for each country. The results for this estimation are presented in Table 7.

Utilizing the data from Tables 5 and 7, the availability of electricity by 2050 under the aforementioned assumptions can be observed in Table 8. From this table, it can be inferred that there is excess energy available in two countries (Costa Rica and Nicaragua). Based on the numbers provided, these two countries have been selected as production nodes while the rest are going to be considered as sink nodes. In terms of the mathematical model, Costa Rica ($j = 1$) and Nicaragua ($j = 5$) are considered as supply nodes and the rest of them as sink nodes (consumer nodes $j = \{2,3,4,6\}$).

In this study, the term excess renewable electricity refers to the portion of renewable power generation that remains after meeting domestic electricity demand under the scenario assumptions. Equation (8) allocates this excess to hydrogen production as a modeling boundary condition. This does not imply that all surplus electricity could realistically be captured for hydrogen production, but instead represents an upper-bound estimate under idealized conditions. Due to the lack of robust long-term renewable energy forecasts and limited publicly available data on future generation profiles in Central America, this simplifying assumption provides a transparent and internally consistent way to approximate the renewable energy that could potentially be available for hydrogen production.

Hydrogen is proposed as an alternative fuel for the transport sector. The main assumption regarding demand is to replace 10% of fossil fuel consumption (diesel, fuel oil, and gasoline, based on 2021 consumption) by country by 2050. This assumption is not intended as a forecast but rather as a scenario boundary condition, representing an early-stage adoption trajectory consistent with the S-curve technology diffusion typically observed for new energy carriers [49] and with scenario-based approaches adopted in recent hydrogen system studies [47]. Data on fuel cell vehicle penetration and hydrogen use in Central America are currently limited or nearly nonexistent. For reference, in 2023 approximately 4 Mt were produced in the region, of nearly which 90% was used in the oil refining business [6]. Given the lack of regional data, a scenario-based approach was therefore selected to establish a consistent analytical boundary. While hydrogen demand may evolve over time across multiple sectors, the current transport energy consumption provides a practical baseline for estimating potential substitution levels. It is further assumed that hydrogen production and consumption occur primarily at or near port areas, where transport applications and related infrastructure are concentrated; therefore, inland transport is excluded from this scenario.

Table 9 summarizes the consumption of these mentioned fuels for 2021 by country. The table includes the equivalent energy demand from hydrogen and its corresponding hydrogen weight requirement, providing a clear reference for energy-to-mass conversion in the context of hydrogen utilization.

It is important to remark that this scenario and its corresponding assumptions do not take into account the willingness of regional governments to execute such a proposal. A comprehensive overview of the key assumptions employed in the model is provided in Table 10. This table consolidates the main technical, economic, and scenario-specific parameters, and core assumptions behind the 2050 estimations.

4.2. Selected production technology pathway

Among the main hydrogen production pathways discussed in the literature are coal and biomass gasification, steam methane reformation (SMR) of natural gas, and water electrolysis. However, the relevance of these pathways in highly context dependent. Central America is not a major producer of coal or natural gas, and both energy carriers are imported and used within the transport or electricity generation sectors. Fig. 12 presents the regional consumption of natural gas and coal, showing that only Guatemala and Panama report non-negligible use. This evidence supports the exclusion of coal gasification and SMR from the present analysis, as these pathways would rely on imported fossil fuels and would not align with the decarbonization objectives that this study adopts as a framework for the development of a hydrogen supply chain. In particular, expanding coal use for hydrogen production would directly conflict with the emission reduction goals motivating hydrogen development.

The current low availability of natural gas makes the SMR process something to analyze in the future if new sources of this energy vector arise. The gasification of biomass is a process that could be feasible in a local context. Biomass can be stored for prolonged periods of time, and without specialized storage technologies; nevertheless, biomass would require significant amounts of low-value resources to be transported. This last fact likely implies the use of fossil fuels to transport it. Still, diesel and oil are the main fuels used for transportation in the region, with the introduction of less carbon-intensive means of transport, biomass has the potential to become a hydrogen source for a regional supply chain.

Taking advantage of the fact that there is an existing electricity network within the region, the electrolysis process is selected as the studied process. Given that there is an infrastructure to deliver electricity between the countries, it is possible that the proposed HSC can be supported by this infrastructure in the future when there is enough surplus electricity.

5. Results

Regarding the cost of producing one kilogram of hydrogen and the resulting HSC network, two scenarios related to electricity prices are presented. In the first scenario, the electricity prices for 2019 are used to generate results, while in the second situation (green scenario), an estimated price based on the energy composition in Table 5 is applied. The values used for elements in the mathematical model can be found in Tables S1-S5 on the Supplementary Material. The results from each scenario are discussed in the following.

Table 9
Fuel consumption and estimated hydrogen demand by country.

Country	Diesel oil (BOE thousands)	Fuel oil (BOE thousands)	Gasoline/alcohol (BOE thousands)	Total (BOE thousands)	Equivalent in GWh	10% Replacement (GWh)	H_2 Demand (t)
Costa Rica	7760.9	744.1	7249.8	15,754.8	26,773.8	2677.4	81,132.8
El Salvador	5517.1	1690.1	5995.1	13,202.3	22,436.1	2243.6	67,988.2
Guatemala	14,700.5	1652.7	14,543.2	30,896.5	52,505.8	5250.6	159,108.5
Honduras	7000.8	4912.5	6107.3	18,020.7	30,624.5	3062.4	92,801.4
Nicaragua	4206.7	2371.4	N/A	6578.0	11,178.8	1117.9	33,875.1
Panama	5649.8	342.4	N/A	5992.2	10,183.3	1018.3	30,858.4

Note: Based on data from [62].

Table 10
Key assumptions and parameters.

Assumption	Details
Hydrogen demand	Demand is estimated as a 10% replacement of fossil fuel consumption (Table 8) at a country level.
Electricity availability for production	Excess renewable energy at designated production nodes based on results of Table 7.
Electricity prices	Estimated from the energy mix presented in Table 4 and LCOE of energy sources.
Discount rates	Lending rates were used as discount rates and converted into annuity factors for 30 years. Please refer to Table S2 in the Supplementary Material.
Capital and operational costs	Refer to Table S3 in the Supplementary Material for specific data and sources.
Capacity factors	Refer to Table S3 in the Supplementary Material for specific data and sources.
Facilities lifetime	30 years
Transport costs and distances	Transport costs were estimated at route-specific level between countries. Refer to Table S4 in the Supplementary Material.

5.1. Scenario 1: 2019 electricity prices

The results from the MILP model show that the alkaline electrolyzer is preferred in both supplier nodes. Ammonia is the resulting optimal carrier and ship transportation by sea is the preferred method of transportation. Table 11 summarizes the general output of the defined mathematical model. Costa Rica covers its 10% substitution of fossil fuels and becomes a supplier of hydrogen as ammonia to three countries in the region. Costa Rica manages to supply 100% of the demand to El Salvador, 46.1% to Guatemala, and 100% to Panama. Ammonia is preferred as a carrier for local consumption in Costa Rica.

Nicaragua produces all its required hydrogen through ammonia and ships ammonia by sea to Guatemala to cover 35.4% of its demand. Fig. 13 is a visual representation of the resulting HSC network of this optimization problem.

5.2. Scenario 2 (green scenario): Forecasted electricity prices

The results from the MILP model have a slight change given the

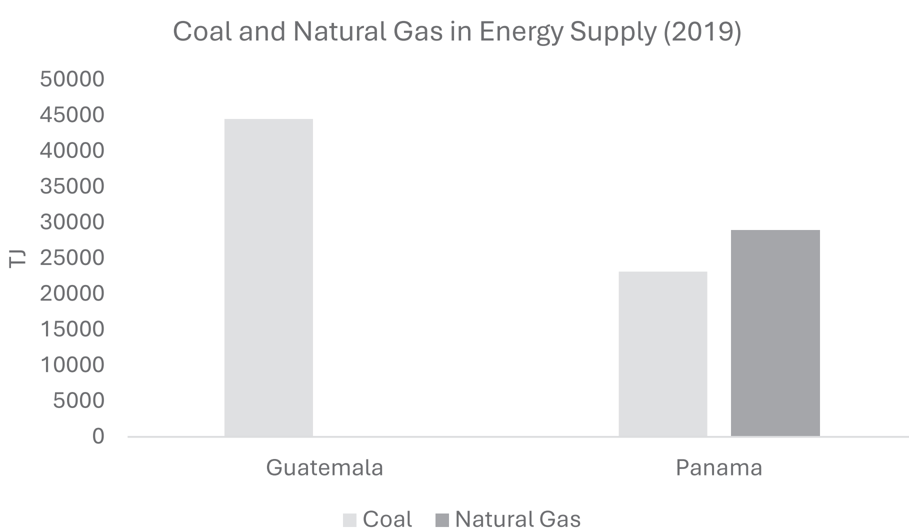

Fig. 12. Coal and natural gas energy supply in the Central American region (data: [2]).

Table 11
MILP model results - Scenario 1.

Production Country	Electrolyzer	Production (t/a)	Carrier	Carrier (t/a)	Transport	Import Country	Flow (t/a)
Costa Rica	Alkaline	251,090	Ammonia	251,090	Ship	El Salvador	67,376
					Ship	Guatemala	72,736
					Ship	Panama	30,580
			Ammonia	80,402	Local Consumption	Costa Rica	80,402
	Total	251,090		251,090			251,094
Nicaragua	Alkaline	85,403	Ammonia	85,403	Ship	Guatemala	51,834
					Local Consumption	Nicaragua	33,570
	Total	85,403		85,403			85,404

* Note: Unmatching total amounts originates from rounding differences.

Fig. 13. HSC network result from MILP model - Scenario 1.

change in price of the main input. Alkaline electrolyzer is still the preferred option in both supplier nodes. Liquid hydrogen is now produced, and ammonia continues to be selected as a carrier. Ship transportation by sea is the preferred method of transportation. The main change in the results can be observed in the number of energy carriers produced. In this scenario, Nicaragua produces ammonia to export to El Salvador instead of producing ammonia to be shipped to Guatemala. Table 12 summarizes the results of this scenario, and Fig. 14 depicts the HSC network under this scenario. In this new scenario, Costa Rica supplies 23.1% of El Salvador's forecasted demand, 68.3% of Guatemala's, and 100% of Panama's. Nicaragua supplies the remaining 76.9% of El Salvador's unmet demand.

6. Discussion

The objective of the proposed network was to minimize the total cost of the HSC network. From this analysis, the levelized cost of hydrogen can be obtained as well. Table 13 presents the total cost of the hydrogen network (in million dollars) and the cost per kilogram of hydrogen. In scenario 1, the cost of hydrogen is 10.84 USD/kg while in the scenario where electricity prices drop, the cost of hydrogen is 5.16 USD/kg as a region.

Diesel is the main fossil fuel utilized in the region's transport sector. Thus, it is going to be used as a comparative base for the LCOH. The average price for diesel in the region for 2021 was 3.18 USD/[Gal] (0.84 USD/l) [62]. The comparison can be done from two perspectives: based on weight or based on energy content. Table 14 presents this comparison between the price of diesel and the price of hydrogen for the two scenarios analyzed. In the scenario with current prices, hydrogen is far from being competitive compared to diesel, which has a cost that is 992% higher on a weight basis and 291% higher on an energetic perspective.

In scenario 2, the comparison has a more optimistic outlook having a cost that is 420% higher on a weight basis and 86% from an energetic perspective. By optimistic, it means that the use of hydrogen would be more plausible at this price under the right conditions, such as subsidies. Presenting this analysis from two perspectives delves into a topic that was not considered throughout this paper: the feasibility of implementation and adoption of hydrogen fuel cell vehicles in the region. Nonetheless, this topic will be addressed in the limitations section further below. It is important to highlight that the producing countries export hydrogen to Honduras under none of the scenarios considered. This is directly related to the transport distance by sea to Honduras' most important port, Puerto Cortés. In the case of Honduras, although the country has a port with access to the Pacific Ocean, its activity is significantly lower than that of Puerto Cortés, which accounts for 41.5% of imports and 62.8% of exports for 2023 [72]. El Salvador (single port), Guatemala, and Nicaragua have the country's most important ports on the Pacific side, and hence ports in the Pacific were prioritized. Details on transportation distances and costs are provided in Table S4 of the Supplementary Material. Table 15 provides a direct numerical

Table 12
MILP model results - Scenario 2 (Green Scenario).

Production Country	Electrolyzer	Production (t/a)	Carrier	Carrier (t/a)	Transport	Import Country	Flow (t/a)
Costa Rica	Alkaline	234,170	Liquid	153,770	Ship	El Salvador	15,542
					Ship	Guatemala	107,650
					Ship	Panama	30,580
			Ammonia	80,402	Local Consumption	Costa Rica	80,402
	Total	234,170		234,172			234,174
Nicaragua	Alkaline	85,403	Ammonia	85,403	Ship	El Salvador	51,834
					Local Consumption	Nicaragua	33,570
	Total	85,403		85,403			85,404

* Note: Unmatching total amounts originates from rounding quantities.

Fig. 14. HSC network result from MILP model - Scenario 2 (Green Scenario).

Table 13
Network and hydrogen costs by scenario.

Scenario	Network Cost (billion USD/a)	LCOH (USD/kg)
1	3.65	10.8
2	1.65	5.2

Table 14
Cost comparison hydrogen vs fossil fuel (diesel).

	Diesel	H2 (Scenario 1)	H2 (Scenario 2)
Cost (USD/kg)	0.99	10.843	5.16
Comparison	–	992%	420%
Cost (USD/kWh)	0.08	0.33	0.16
Comparison	–	291%	86%

Note: This table is built on the results of this paper and partially based on data from [62].

comparison of shipping distance, transport cost, and port activity across candidate export routes. Honduras is consistently disadvantaged: sea routes to Puerto Cortés involve distances of 2,100 – 2,700 km, compared with 300 – 1,300 km for competing destinations, resulting in transport costs that are roughly two to four times higher across all hydrogen carriers (e.g., liquefied hydrogen: 0.19 – 0.24 USD/kg versus 0.03 – 0.12 USD/kg). Although Puerto Cortés exhibits moderate port activity (0.74 million TEU), this remains well below Panama's Balboa port (2.63 million TEU), which also benefits from shorter distances and lower costs. As a result, Honduras is dominated by alternative routes and is consistently excluded from the cost-optimal solutions.

The cost range found in this study (USD 5.16—–10.84) is comparable to some results in existing literature. IRENA [74] states that green hydrogen can be produced at 4–6 USD/kg but does not specify within which part of the supply chain. Ochoa and Zondervan [30] determined under a green scenario a cost range of between 9.57–9.69 USD/kg. Moreno et al. [75] analyzed that the cost of hydrogen from renewable sources can vary from 6 − 14 USD/kg.

While the comparison between hydrogen and diesel in this study focuses on levelized cost metrics, broader policy and market factors also influence practical competitiveness. Currently, Central American countries do not provide subsidies or fiscal incentives for green hydrogen deployment, and fuel cell vehicle penetration remains low. Nevertheless, several countries in the region have estimated a social cost of carbon—approximately 40 USD/tCO_2 in Costa Rica and Honduras, and 162 USD/tCO_2 in Nicaragua [76]. Applying these values to standard diesel emission factors (3.15 kg CO_2/kg diesel) results in an implied carbon cost of 0.13–0.51 USD/kg of diesel. Although modest, this uplift improves the relative cost position of low-carbon hydrogen but indicates that complementary policy measures may still be required for full competitiveness. Furthermore, international developments, such as emerging export markets and cross-border policy alignment, may further affect competitiveness.

The cost per supply chain stage for each of the scenarios is presented in Fig. 15. It can be appreciated how most of the cost is allocated at the hydrogen production cost stage (>88%). This cost includes the capital and operational cost of the electrolyzer facility, and the electricity used in the electrolysis process. The carrier production, transportation and storage represent the remaining fraction, the carrier production being the most significant of these three. These stages can be further analyzed to comprehend what contributes towards their results.

Fig. 16 showcases the cost breakdown of the stages to be able to visualize how these are compounded. In both scenarios, the cost of electricity (hydrogen production and carrier production) remains the most influential input which determines the cost of hydrogen. The CAPEX and OPEX cost of the electrolyzer facility follow electricity in terms of cost in second place.

As mentioned before, the price of electricity has a high influence over the price of hydrogen. Based on both producing countries and considering actual and forecasted electricity prices, a weighted average electricity price reduction of 61.9% led to a 52.41% decrease in hydrogen prices. For every percentage unit the electricity price changes, the price

Table 15
Transport cost comparison by port.

Mode	Origin	Destination Port	Port Activity (million TEU)[1]	Distance (km)	Transport Costs (USD/kg)		
					Compressed	Liquefied	Ammonia
Sea	**Puerto Caldera, Costa Rica**	Puerto Acajutla, El Salvador	0.25	982	0.51	0.09	0.03
		Puerto Quetzal, Guatemala	0.70	1078	0.56	0.10	0.03
		Puerto Cortés, Honduras	0.74	2102	1.09	0.19	0.06
		Balboa, Panama	2.63	719	0.37	0.06	0.02
	Puerto Corinto, Nicaragua	Puerto Acajutla, El Salvador	0.25	326	0.17	0.03	0.01
		Puerto Quetzal, Guatemala	0.70	430	0.22	0.04	0.01
		Puerto Cortés, Honduras	0.74	2717	1.41	0.24	0.08
		Balboa, Panama	2.63	1333	0.69	0.12	0.04
Land	**Puerto Caldera, Costa Rica**	Puerto Acajutla, El Salvador	0.25	925	2.16	0.85	0.31
		Puerto Quetzal, Guatemala	0.70	1112	2.59	1.02	0.37
		Puerto Cortés, Honduras	0.74	971	2.26	0.89	0.32
		Balboa, Panama	2.63	862	2.01	0.79	0.28
	Puerto Corinto, Nicaragua	Puerto Acajutla, El Salvador	0.25	506	1.18	0.47	0.17
		Puerto Quetzal, Guatemala	0.70	693	1.61	0.64	0.23
		Puerto Cortés, Honduras	0.74	552	1.29	0.51	0.18
		Balboa, Panama	2.63	1346	3.14	1.24	0.44

1 Data extracted from [73], in thousand twenty-foot equivalent units (TEU).

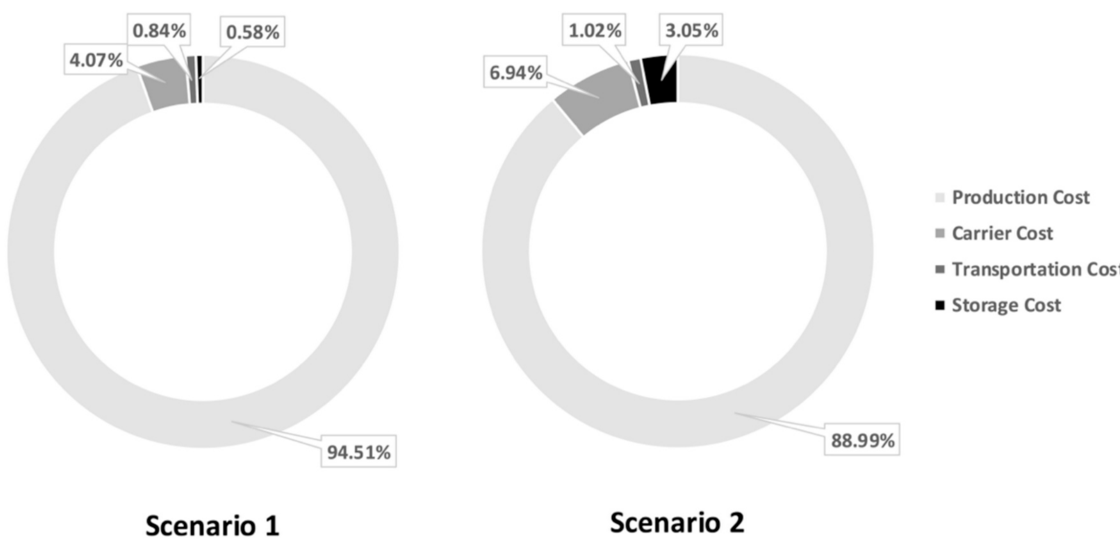

Fig. 15. Hydrogen Cost by Supply Chain Stage (%).

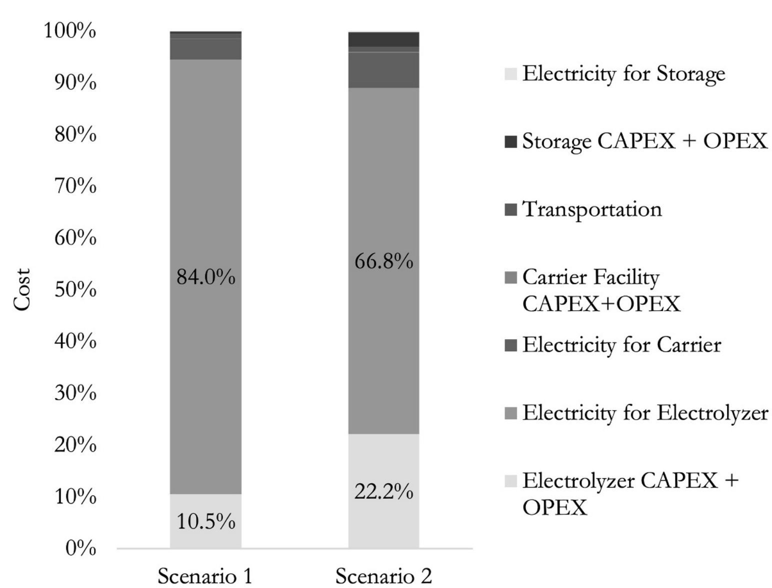

Fig. 16. Hydrogen Supply Chain Cost Breakdown (%).

of hydrogen changes by approximately 0.84%. Fig. 17 presents the sensitivity analysis for the hydrogen price for this supply chain network with regard to several key variables which were varied by ± 10% and particularly 10- and 20-year lifetime for facilities.

The relative influence of each parameter is shown in Fig. 18, which presents the elasticity of the LCOH with respect to the variables included in the sensitivity analysis. In this context, elasticity indicates the percentage change in LCOH resulting from a 1% change in a given parameter. Electrolyzer efficiency and electricity price exhibit the highest elasticities (0.94 and 0.88, respectively), indicating that small variations in these inputs lead to proportionally large shifts in the LCOH. In contrast, discount rate and facility lifetime show substantially lower elasticities, reflecting a comparatively weaker influence on the overall cost outcome.

The production cost (including the carrier cost) is presented in Table 16 for each producing country. This table reveals how the electrolyzer facility and its inputs are the main factors contributing to the production of hydrogen in each production country.

As Costa Rica and Nicaragua emerge as the primary hydrogen production nodes in the modeled scenarios, it is important to acknowledge that such a configuration carries implications beyond technical feasibility. Although the two countries share geographic proximity, their political and economic contexts differ substantially. Costa Rica has historically emphasized environmental sustainability and maintains relatively stable governance structures, while Nicaragua faces more constrained institutional capacity and slower progress in renewable energy development. These differences, combined with notable differences in GDP per capita and investment capability, may influence each country's ability to develop large-scale hydrogen infrastructure and could shape future regional cooperation, financing strategies, and risk-sharing mechanisms. While a full geopolitical assessment is beyond the scope of this study, recognizing these contextual factors provides a more comprehensive understanding of the practical feasibility of the proposed supply chain configuration.

Based on the energy outlook for Latin America [77], ranges for electricity availability, hydrogen demand, and LCOE were defined to construct pessimistic, baseline, and optimistic variants of the proposed green scenario (Table 17). The scenario analysis demonstrates that the main structural outcomes of the model remain stable across pessimistic, baseline, and optimistic assumptions. In all cases, sea transport dominates, accounting for 100% of international hydrogen flows, indicating that transport mode selection is robust to changes in demand, electricity prices, and renewable energy availability. Liquid hydrogen and ammonia consistently emerge as the preferred export carriers, while compressed hydrogen is not selected in any scenario. Costa Rica remains the principal exporter of liquid hydrogen across all scenarios, supplying mainly Guatemala, Panama, and El Salvador, whereas ammonia exports are supplied by Costa Rica or Nicaragua depending on electricity availability and demand levels. Although the LCOH decreases from 5.85 to 4.40 USD/kg between the pessimistic and optimistic scenarios, relative carrier shares and export hubs remain largely unchanged, supporting the robustness of the model's conclusions under alternative

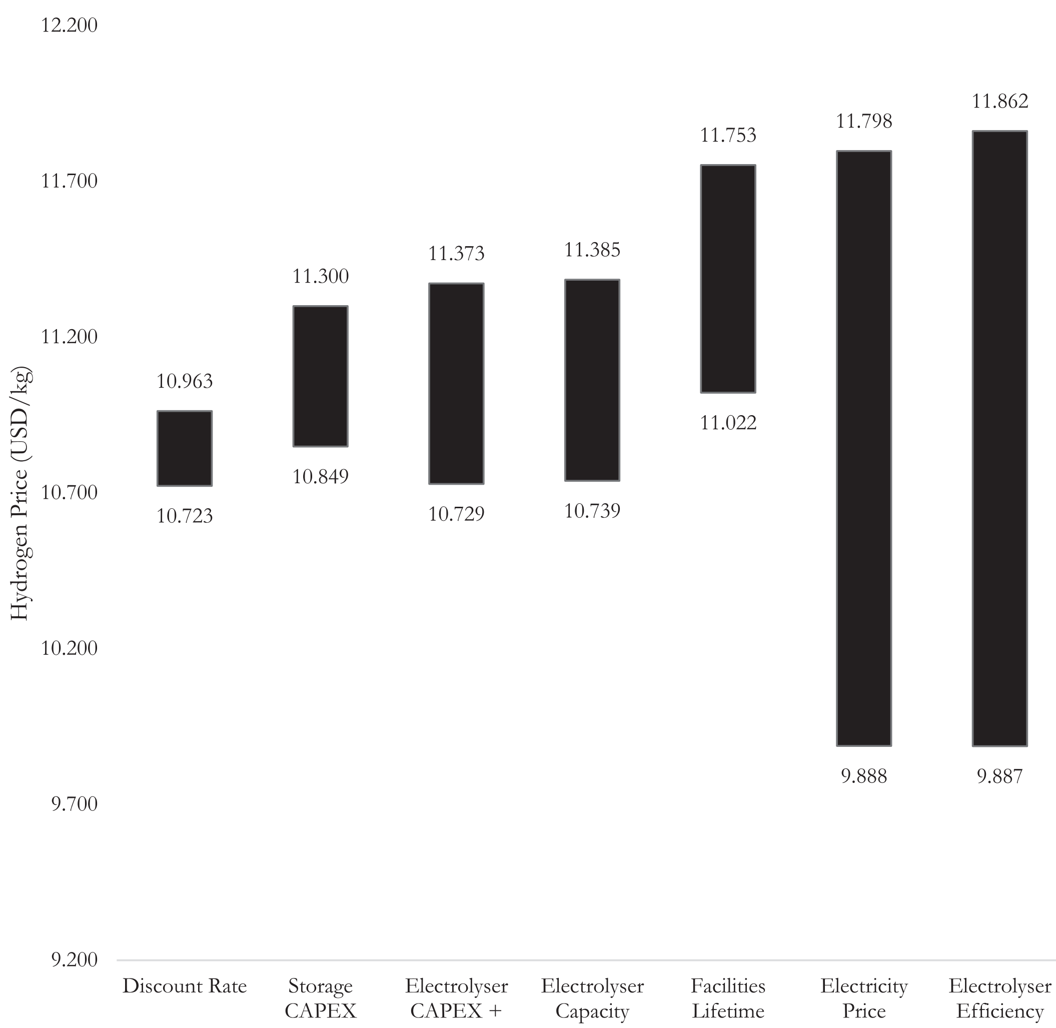

Fig. 17. Hydrogen price sensitivity analysis.

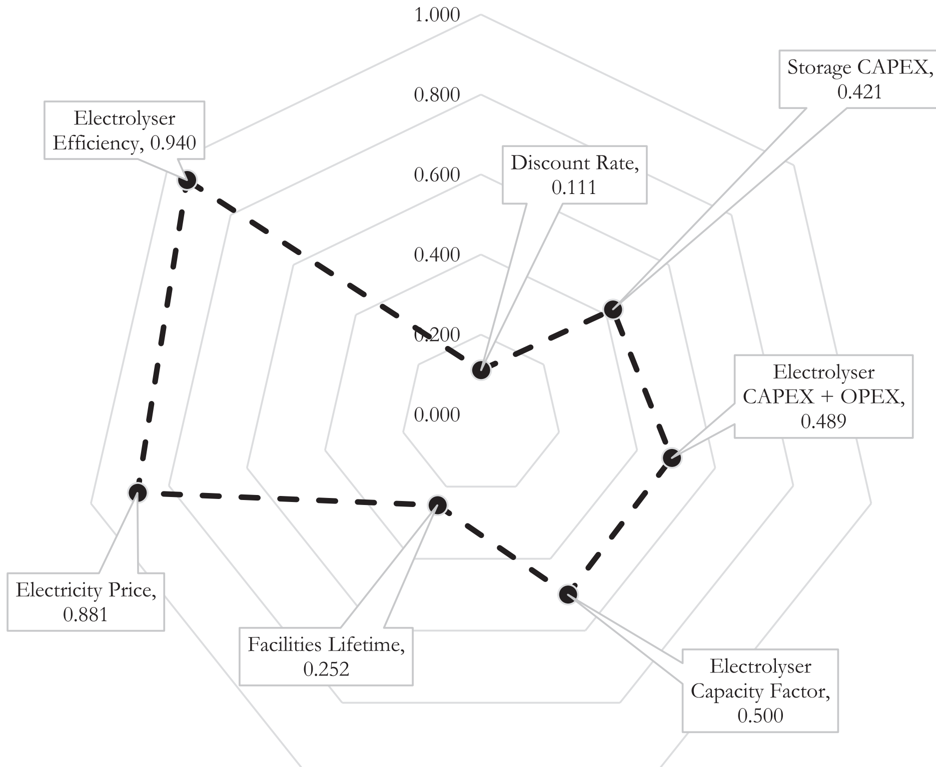

Fig. 18. LCOH elasticity based on sensitivity analysis.

Table 16
Production cost (including carrier) at each producing country (USD/kg).

	Scenario 1		Scenario 2	
Cost	Costa Rica	Nicaragua	Costa Rica	Nicaragua
Electrolyzer CAPEX + OPEX	1.09	1.29	1.09	1.29
Electrolyzer Electricity	8.58	10.64	3.42	3.51
Carrier CAPEX + OPEX	0.002	0.002	0.002	0.002
Carrier Electricity	0.415	0.514	0.425	0.170
Production Cost (Including Carrier)	10.09	12.45	4.94	4.97

future assumptions.

6.1. Limitations and future works

The lack of up-to-date information was one of the main challenges for the development of this paper. Most information was only available for the years 2020 and 2021. Given that the development of renewable energy has taken up momentum over the last couple of years, the most recent information can be relevant for future analysis. In contrast, the availability of information related to the subject is still very limited, as no considerable developments or studies have been executed at a local level. This paper has not considered socio-political or socio-economic aspects of the countries studied. Aspects such as governmental willingness to support this kind of initiatives and the availability of capital can have great control over the development of projects of this magnitude, and thus the results are subject to change if these aspects are considered.

The estimation of hydrogen demand in this study is based on a simplified scenario in which hydrogen replaces 10% of current fossil fuel consumption in the transport sector by 2050, with production and use concentrated near port areas. This assumption provides a boundary condition to explore early-stage hydrogen adoption in a region with limited data availability. However, actual demand development may differ depending on the pace of vehicle electrification, industrial hydrogen applications, or its use in power systems. Future research could refine these estimates using sector-specific data and multiple scenario pathways.

Several modeling simplifications should be kept in mind. The

Table 17
Scenario analysis.

Scenario	Electricity availability	Hydrogen demand	LCOE	LCOH	Transport mode	Carriers export	Exporters	Importers (% of carrier flow)
Pessimistic	80%	70%	120%	5.846	Sea (100%)	LH_2 37.2%	Costa Rica	El Salvador – 25.6% Guatemala – 74.4%
						NH_3 62.8%	Costa Rica Nicaragua	Panama – 43.6% Panama – 56.4%
Baseline (Green Scenario)	100%	100%	100%	5.160	Sea (100%)	LH_2 48.1%	Costa Rica	El Salvador – 10.1% Guatemala – 70.0% Panama – 19.9%
						NH_3 51.9%	Nicaragua	El Salvador – 100%
Optimistic	120%	130%	80%	4.403	Sea (100%)	LH_2 48.6%	Costa Rica	El Salvador – 5.5% Guatemala – 75.8% Panama – 18.7% of
						NH_3 51.4%	Nicaragua	El Salvador – 100%

allocation of excess renewable electricity to hydrogen production is treated as an upper-bound assumption given that long-term renewable generation forecasts are limited. In reality, only part of this surplus would be available once factors, such as balancing needs and grid constraints, are accounted for. Transport costs are represented through route-specific mass-based coefficients without modeling operational bottlenecks such as port handling capacity, vessel availability, or equipment limitations. As a result, the formulation reflects economic feasibility rather than actual physical throughput. Storage costs are applied as scalable unit values (USD/kg) without explicit upper capacity limits, even though real installations depend on discrete tank sizes and site-specific constraints. Incorporating more detailed transport and storage capacity limitations would strengthen future analyses as regional data become available. The current model focuses solely on economic cost minimization as an initial framework for hydrogen supply chains in the region. Multi-objective considerations, such as carbon emission minimization, are not included in this initial analysis. Incorporating environmental objectives and exploring cost–emission trade-offs represent a natural extension for future work as the framework is refined.

Future research on HSC networks in the region should prioritize forecasting models that accurately predict renewable electricity availability across different countries. This would enable a more targeted analysis of specific energy sources, such as solar or wind, optimizing their potential for hydrogen production and supply chain efficiency. Another aspect to be further explored is the penetration of fuel cell vehicles in each country to provide a finer prediction of hydrogen demand. The integration of the current shared electricity network within the countries presents a prospective channel to maximize the output of hydrogen, and its incorporation to an HSC should be an object of study. There are other supply chain stages that have not been explored, such as the sufficient availability of water which is a fundamental resource for electrolysis. Climate change can impose pressure over this resource as natural phenomena can reduce its production. Aside from its procurement, the cost of water treatment is a matter of study for future works.

7. Conclusions

The Central American region has a high potential for the development of renewable energy resources, which can contribute towards the region's decarbonization aims. Nonetheless, the seasonality and variability to which renewable energy sources are subject to create the necessity of finding energy vectors that are able to provide a medium transportability and storability for these resources. Hydrogen and its different carriers are able to channel renewable energies beyond their traditional applications. With the current electricity prices in the region, the cost of producing hydrogen and its carriers is between 10.1 and 12.5 USD/kg (transport and storage not included) in Costa Rica and Nicaragua, respectively, which however is not competitive with current fossil fuels price such as diesel. The price of hydrogen is particularly determined by the electricity prices (88–94%). Thus, fast development of new renewable electricity prices should allow for this price to drop considerably in the coming years. In Scenario 2 proposed in this paper, where energy cost is around 61.9% lower than in Scenario 1, the range for both countries drops to 4.9 to 5.0 USD/kg which portrays a better scenario for the adoption of hydrogen as an energy source for transportation. The continuous research and development of electrolyzer technology will allow for the capital cost of these facilities to decrease, which will consequentially have an impact in the final cost of hydrogen. This research has established a framework for the development of a hydrogen supply chain network in the Central American Region, which can aid in meeting emissions objectives in countries' agendas and decrease the region's dependency on fossil fuels.

CRediT authorship contribution statement

Mario Montalvan: Writing – review & editing, Writing – original draft, Conceptualization. **Kaveh Khalilpour:** Writing – review & editing, Supervision. **Reinhard Madlener:** Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary material

Supplementary material to this article can be found online at https://doi.org/10.1016/j.enconman.2026.121172.

Data availability

Data will be made available on request.

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