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Multi-Objective Optimal Design of a Hydrogen Supply Chain Powered with Agro-Industrial Wastes from the Sugarcane Industry: A Mexican Case Study

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Abstract: This paper presents an optimization modeling approach to support strategic planning for designing hydrogen supply chain (HSC) networks. The energy source for hydrogen production is proposed to be electricity generated at Mexican sugar factories. This study considers the utilization of existing infrastructure in strategic areas of the country, which brings several advantages in terms of possible solutions. This study aims to evaluate the economic and environmental implications of using biomass wastes for energy generation, and its integration to the national energy grid, where the problem is addressed as a mixed-integer linear program (MILP), adopting maximization of annual profit, and minimization of greenhouse gas emissions as optimization criteria. Input data is provided by sugar companies and the national transport and energy information platform, and were represented by probability distributions to consider variability in key parameters. Independent solutions show similarities in terms of resource utilization, while also significant differences regarding economic and environmental indicators. Multi-objective optimization was performed by a genetic algorithm (GA). The optimal HSC network configuration is selected using a multi-criteria decision technique, i.e., TOPSIS. An uncertainty analysis is performed, and main economic indicators are estimated by investment assessment. Main results show the trade-off interactions between the HSC elements and optimization criteria. The average internal rate of return (IRR) is estimated to be 21.5% and average payback period is 5.02 years.

Keywords: sugarcane bagasse; hydrogen energy; electrolysis; MILP; multi-criteria optimization; genetic algorithm; uncertainty; Monte Carlo simulation; TOPSIS

1. Introduction

In recent years, the popularity of hydrogen as a promising sustainable energy carrier has increased significantly to contribute to clean energy transition [1]. In particular, hydrogen has a noticeable role to play in the transport sector which requires large amounts of clean energy as an enabler of deep decarbonization of this difficult to abate sector. One of the advantages of using hydrogen is the availability of different production processes [2]. The biomass contained in some agro-industrial wastes can provide enough energy to be used for hydrogen production in a variety of processes [3]. Several paths can be followed in biomass resource exploitation, among which the selection of the most appropriate conversion technology is challenging. Agro-industrial wastes are commonly known as residues that offer little benefit to their producers, so their recovery can be an option to investigate. The use of agro-industrial waste for energy production can be an alternative end-of-life for these resources by creating sustainable and renewable systems that minimize pollutant emissions. The cogeneration of electricity and thermal power could provide energy autonomy for these companies and additional income from the sale of their energy overflows, while their waste gets a second use. Applying the necessary technologies for efficient use of the energy generated from renewable resources requires a comprehensive vision that includes the assessment of several factors for decision support at different levels [4]. The objective of this work is thus to include these options in the planning and design of a hydrogen supply chain network.

The electrical energy used for hydrogen production is generated with agro-industrial wastes in 50 sugar factories located in Mexico, where steam generators are powered by burning sugar cane bagasse. The electricity generated is used for self-consumption for the sugar companies and the excess is often sold to the national grid, but is commonly wasted because of low demand; thus, an HSC network where the excess energy can be exploited may turn out to be convenient. In the proposed model, the behavior of the electricity production systems is modeled using probability distributions, among other model parameters. The major contribution of this study is the integration of a multi-objective optimization model using a genetic algorithm (GA) with a hydrogen production system generated from agro-industrial waste for mobility purposes, integrating the proposed network with already existing infrastructure from the national energy industry. The model is evaluated with energy prices and geographic information from different regions across the country. (GA). The obtained solutions offer a variety of options for setting the HSC since a multi-criteria approach is adopted to optimize economic and environmental objectives simultaneously.

The presented mathematical model is inspired on three previously built formulations, whereby Parker [5] adopts the profit maximization approach for its flexibility in terms of resource utilization, and de León Almaráz [4] considers global warming criteria, and its mathematical formulation for transport and storage in an HSC is adopted by this study. Finally, Rico Contreras [6] presents the mathematical model for generation of electricity at sugar mills available for hydrogen production; integrating these approaches contributes to the formulation of the mixed integer linear program (MILP), and significant changes were made to adapt the mathematical formulation to the case examined in this study.

The optimal HSC network configuration is selected using a multi-criteria decision-making technique (MCDM). Due to the type of problem (input data), a multi-attribute decision-making (MADM) method is adopted. This type of technique calculates the distance between each alternative and a central point. VIKOR and TOPSIS methods were considered (differing by criteria normalization procedure). Both techniques use the CP method that seeks to obtain the closest alternative from the hypothetical optimal solution. The TOPSIS method was selected since it considers the distance to the ideal solution and the distance to the non-ideal solution, while VIKOR only considers the distance to the ideal solution.

2. Literature Review

The literature review identifies the tools, technologies, resources, and other important factors to consider when designing the hydrogen supply chain (HSC) for mobility purposes. The reviewed works were selected based on similar studies with MILP models and the main scientific objective regarding the design of HSC networks. A variety of case studies were analyzed to determine the most appropriate research path given the actual conditions of the field of study. The classification of the relevant studies is based on the objective functions, agro-industrial waste, raw materials, production technologies (alkaline/ Proton Exchange Membrane (PEM) electrolysis) and the region where the methodology is implemented.

A review of the different decision levels for HSC is presented in Azzaro C. et al. [7] on the different components related to hydrogen production, transportation, and distribution.

More than 40 authors contribute to a compilation of multiple case studies, where the most recent methodologies used for modeling the HSC supply chain are presented for design, planning and operation strategies, providing diverse tools that allow the design of complex systems using mathematical models involving economic, environmental and risk criteria.

Jiyong K. et al. [8] proposed a methodology for HSC infrastructure design including production, storage, and transportation with a generic optimization-based model. The network design is formulated as a MILP to identify the optimal configuration of the supply chain from various alternatives. The goal was to consider not only cost efficiency, but safety criteria as well. Since these two aspects are contradictory, multi-objective optimization techniques were required to find practical solutions. With this approach, the effects of uncertainty in demand can also be analyzed, and deterministic and stochastic analysis methods were compared.

The pioneering work presented in A. Almansoori and N. Shah [9] emphasizes the challenges of HSC design focused on three main factors: the presence of various links in the supply chain (including local hydrogen distribution and refueling stations), the high level of interaction between the components of the supply chain and their subsystems, and the uncertainty in hydrogen demand. In this work, the growing uncertainty in the variation of hydrogen demand in the long term was integrated into an existing generic optimization model, using a scenario-based approach. For both cases, the most feasible solution involves a centralized production with small or medium-sized storage facilities and distribution through tanker trucks. The performance of the model was evaluated using sensitivity and risk analysis.

In their latest work, Güler MG et al., 2020 [10] presented a design for an HSC in Turkey for 2021–2050 using a MILP modeling approach. A mathematical optimization model was adopted to evaluate the objective functions in Turkey. The results show decentralized production as one feasible alternative to fulfill the demand, and the local production rate exhibited a significant increase from 12% to 48% by the end of the planning horizon, revealing future considerations that must be considered. The analysis revealed that almost all regions either produce or import hydrogen, but do not do both.

The work by P. Gabrielli et al., 2020 [11] concerns the optimal design of a low-carbon Swiss HSC. The infrastructure design is performed by solving an optimization problem that determines the hydrogen, biomass, and CO_2 network configuration with a focus on production technologies. A national scale case study was analyzed to derive specific guidelines concerning the design of the HSC deploying carbon capture and storage. The impact of relevant design parameters was assessed, such as the location of CO_2 storage facilities, the techno-economic characteristics of CO_2 capture technologies and network losses. The study highlights the benefits of biomass and carbon capture and storage for decarbonizing HSC networks compared to the use of electrolysis for hydrogen production due to the high carbon intensity of the electricity mix.

C. Quarton and S. Samsatli, 2020 [12] present an optimization framework to determine how carbon dioxide and hydrogen technologies could fit into existing value chains in the energy and chemicals sector, analyzing how effectively these technologies can contribute to meet the climate change goals. The first study concerning the modeling and optimization of an integrated value chain for carbon dioxide and hydrogen is performed, providing assessment of the role of carbon capture, utilization and storage (CCUS), and hydrogen technologies. The results showed opportunities for CCUS to decarbonize existing power generation capacity and emphasize the need of renewable energy and hydrogen to achieve lower cost decarbonization and flexibility in the long term. The importance of negative emissions policies to encourage investors was also discussed.

An optimization-oriented review regarding HSC design is presented by Lei Li et al., 2019 [13]. Some drawbacks and missing aspects in the literature are identified, and key components of the HSC are presented. Models are classified based on several model features. It is highlighted that profit maximization has received less attention compared to other optimization criteria, and only two of the references reported profit as the HSC performance measure.

A social cost–benefit assessment is performed by Ochoa R. et al., 2020 as post-optimal analysis for HSC design and deployment [14]. The sequential application of an optimization strategy employing genetic algorithms and a multi-criteria decision-making tool at first determine the optimal solution for the HSC network design problem. The evaluation is then performed by a social cost–benefit analysis (SCBA) to estimate the impact of hydrogen mobility deployment on social welfare. A subsidy policy scenario was implemented where results showed that CO_2 abatement dominates the externalities, while platinum was the second largest externality.

Husna I. et al., 2016 [15] present a comparative study between biomass burning and gasification techniques. It is highlighted that direct burning of biomass and co-firing with coal is most used since it is the most economic convenient decision for the biomass power plant, while little plant modifications are required. On the gasification of biomass field, some points are made highlighting the benefits of chemical recovery to produce higher process steam and electricity efficiencies, reducing capital cost compared to conventional technologies.

Loong Lam H. et al., 2013 [16] proposed a methodological framework for designing waste-to-energy supply chains that considers efficient resources management and reduction of greenhouse gas emissions. A two-stage optimization model was developed, with MILP being used in both stages. Different technologies were considered for the whole exploitation of the resources in alternative forms. It was concluded that the green strategy adopted contributes significantly to the amount of power generated in existing power plants. Further studies concerning the integration of the available infrastructure and alternative energy technologies are required to determine opportunities for a more efficient resource exploitation.

The study by Gumte K. et al., 2021 [17], presents a nationwide analysis of a supply chain network fed with bioenergy; the study looks forward to integrating a fraction of the obtained biofuels with traditional fuels during the 2018–2026 horizon. A MILP is built to handle multiple types of raw materials, products and transport alternatives, while performing the techno, economic and environmental analysis, looking forward to making optimal operational and design decisions. The main findings remark that 43% and above biomass feed is needed for the supply chain network to survive.

Goodarzian F. et al., 2021 [18] propose the design of a three-echelon green medicine supply chain network through a fuzzy bi-objective MILP model, considering multiple periods, products, and transportation modes. The study measures the environmental impacts derived from establishing pharmacies and hospitals, aiming to reduce greenhouse gas emissions and to control environmental pollutants. Meta-heuristic algorithms are used to solve the model, including two novel hybrid algorithms known as Hybrid Firefly Algorithm and Simulated Annealing (HFFA-SA) and Hybrid Firefly Algorithm and Social Engineering Optimization (HFFA-SEO).

A bi-objective optimization model approach is proposed by Abdolazimi O. et al., 2020 [19], where a comparison of exact and meta-heuristic methods is performed. The main objective of this study is to improve the inventory grouping based on ABC analysis. The objective functions seek to maximize the total net profit of the items in the central stock, and in different locations. The aim is to simultaneously optimize the number of inventory groups, the number of items to be assigned and the service level. Statistical analysis besides the AHP and VIKOR techniques is implemented to compare the applied optimization techniques in terms of efficiency. To solve the model in different dimensions, two exact methods (LP-metric and ε-constraint) and two meta-heuristic methods (NSGA-II and MOPSO) are applied.

A systematic literature review on multi-criteria decision making methods applied in different areas of supply chain management is conducted by Paul A. et al., 2021 [20]. A total of 106 published journal articles were analyzed. It is highlighted that MCDM methods are commonly used for analyzing several factors of sustainable supply chain management. In this review, it is highlighted that most of the published articles combine only two MCDM methods, and integration with other techniques, such as simultaneous optimization and simulation, are missing in the literature.

A literature review presented by Tordecilla R. et al., 2021 [21], refers to existing literature on the use of simulation techniques in the formation of resilient supply chain networks (SCNs). Research opportunities have been identified for the inclusion of three criteria (such as financial, environmental, and social) during the process of marking and the application of a multidisciplinary approach to integrating metaheuristic algorithms, simulation, and machine learning methods to integrate uncertainty and dynamic conditions.

A multi-objective novel model was developed by Hosseini S. et al., 2020 [22]. The model deals with the design/reorganization of the wheat supply network, which includes different suppliers, existing warehouses, warehouse candidate locations, flour mills, and warehouses in an uncertain environment. The purpose of the proposed model is to reduce costs, non-resiliency, and the negative effects of social responsibility. The results show that considering the cost, durability, and social impact simultaneously can greatly help improve the performance of the wheat supply chain model.

The paper presented by Gital Y. et al., 2020 [23] discusses the appropriate design and planning of a biomass supply chain network that incorporates flows from poultry farms to biogas facilities. A multi-stage novel solution methodology is designed to solve the problem of designing a biomass supply chain network. Spatial information systems, as well as hierarchy processing techniques, are used to determine the candidate location of biogas infrastructure. The aim is to determine the total amount, location, and size of biogas facilities, alongside network flow, and the electricity generated. The sensitivity analysis shows both maximum distance parameters, and purchase prices have a significant impact on decisions, as well as financial benefit.

The aim of the research conducted by Rasi R. et al., 2021 [24] is to optimize economic and environmental dimensions in a sustainable supply chain (SSC) using a MILP model to incorporate both criteria simultaneously. According to the authors, the value of the work relies on the limited alternatives regarding the design and optimization of SSC networks. The research is among the first to integrate the selection of sustainable suppliers and the optimization of performance indicators. The differences between the genetic algorithms and the MILP methods can be explained by managing the issues and their various logic alternatives.

A review regarding the development of biomass-based cogeneration energy systems in Malasia is presented by Zailan R. et al., 2021 [25]. The aim of the analysis is to report recent improvements in co-firing technology using biomass in Malaysia with the optimization modeling role. The authors address technical issues concerning the key players of the technologies and the biomass supply chain, remarking the importance of biomass utilization for energy generation in regions where agro-industrial wastes are abundant.

The study presented by Nunes L. et al., 2020 [26] reviews the status of research on biomass supply chain modelling and highlights the growing importance of biomass as a renewable alternative energy source. The review identifies modeling as a critical step in improving comprehension leading to improved supply chain performance. It is said that research using supply chain models focuses on examining specific supply chain conditions, often with the aim of reducing costs.

Seung S. et al., 2020 [27] presented a study involving the development of a hydrogen supply chain optimization model using a centralized storage approach that integrates and combines the flow of different production facilities into integrated bulk storage. The results show that a hydrogen supply chain with a central storage approach improves the phase transition of the hydrogen-producing plants, while reducing the total annual cost of the network.

A techno-economic analysis review of biomass supply chain was conducted by Yuen S. et al., 2021 [28]. The study emphasizes the growing needs of biomass caused by the increased risk of climate change. The study aims to provide an overview of the different types of methods or techniques used to assess the feasibility of biomass-based industries from a technical point of view. The study also looks forward to describing the uncertainty of the supply chain that should be included in the model test using the Malaysian case study to show the impact of this uncertainty. In total, 78% of reviewed articles chose the method of testing the mathematical model with optimization. A minority have undergone stochastic tests that include systemic uncertainty.

Rafique R. et al., 2021 [29] introduces and develops a model to design a bioenergy supply chain with the aim of minimizing the energy gap under budget and the challenges of biomass availability. The dynamic features of the model capture interactions between people, size, energy demand, biomass availability, energy consumption and the overall domestic product. The analysis highlights that the cost of further development of the bioenergy system can vary greatly during the planning horizon. Complete configuration starts as a very central system and shifts to a decentralized system divided into areas where power plants emit biofuel and provide energy locally.

Li L. et al., 2019 [30] conducted a study focusing on developing a mathematical model that encompasses the entire hydrogen supply network. The model is integrated with a hydrogen fueling station planning approach to produce a new configuration. The proposed model looks at the supply of feedstock, installation and operation facilities, the operation of transportation modes, and a system for carbon capture and storage. The proposed model can study the interactions that exist between different parts of a hydrogen supply network. Therefore, many HSC building plans are guaranteed.

From the reviewed literature, it can be concluded that further research in terms of evaluating the economic and environmental benefits of utilizing alternative energy sources and technologies in the existing energy industry infrastructure might provide the sufficient arguments to determine whether it is convenient or not to look forward to the exploitation of agricultural wastes for these means in specific regions. A summary of the literature review is presented in Table 1. We classified the relevant studies based on the adopted objective function, feedstock types (energy sources), considered hydrogen production technologies, and analyzed case studies. This study assesses the economic and environmental behavior of a power-to-hydrogen supply chain through a stochastic modelling approach, where the existing energy and biomass infrastructure is integrated on a national scale. Electricity produced by biomass combustion is already available as an energy source across the country due to the large quantities of sugarcane bagasse generated annually by agro-industrial activities and the ready-to-use infrastructure located at biomass producer facilities for energy generation and self-consumption, although a considerable part of this energy may be wasted due to the lack of synchronization of supply and demand. The results can help provide alternatives for countries that rely heavily on primary and secondary activities where biomass is widely available and where national energy autonomy is a concern.

Table 1. Summary of the reviewed literature with a supply chain optimization approach.

Reference	Objective Function	Feedstock (Energy Source)	Hydrogen Production Technology	Case Study
[8]	Total cost minimization Total relative risk minimization	NG, renewable electricity	SMR, electrolysis	South Korea
[9]	Total cost minimization	NG, oil, coal, biomass, solar power	SMR, biomass and coal gasification, electrolysis	Great Britain
[10]	Total cost minimization	NG, coal, biomass, solar, wind, hydroelectric, geothermal	SMR, coal and biomass gasification, electrolysis	Turkey
[11]	Total cost minimization GWP minimization	NG, biomass, electricity	SMR, gasification, electrolysis	Swiss

Table 1. *Cont.*

Reference	Objective Function	Feedstock (Energy Source)	Hydrogen Production Technology	Case Study
[12]	NPV maximization Emissions minimization	NG, wind power	Electrolysis	Great Britain
[14]	Total Cost minimization GWP minimization	NG, renewable electricity, nuclear power	SMR, electrolysis	France (Midi-Pyrénées)
[15]	-	Coal, biomass	Electrolysis, gasification	Malaysia
[16]	NPV maximization Transport cost minimization	Biomass	-	Malaysia

NG = Natural Gas, SMR = Steam Methane Reforming, GWP = Global Warming Potential, NPV = Net Present Value.

The objective of this study is to evaluate the economic and environmental implications of using biomass wastes from sugar factories for energy generation, opening the scope to a non-conventional application according to the state of the art, which implies the utilization of already existing infrastructure, at the time that a resource commonly considered as waste is exploited. The innovation value of this contribution relies on the proposal of a wastes exploitation scheme that can be escalated in a variety of ranges, and can be applied to other energy sources, like biomass wastes originated from other agro-industrial sectors.

3. Materials and Methods

3.1. Methodological Framework

The methodological framework applied in this study is presented in three general frames; the first one concerns the input data used in the modelThe second aspect refers to the tools used to find the optimal solution for the proposed model, which implies the mathematical formulation, solving methods and solution selection technique. The last segment shows the outputs obtained from the applied methodology and its representation form, which implies a pareto front and graphic representations of the optimal supply chain configuration (Figure 1).

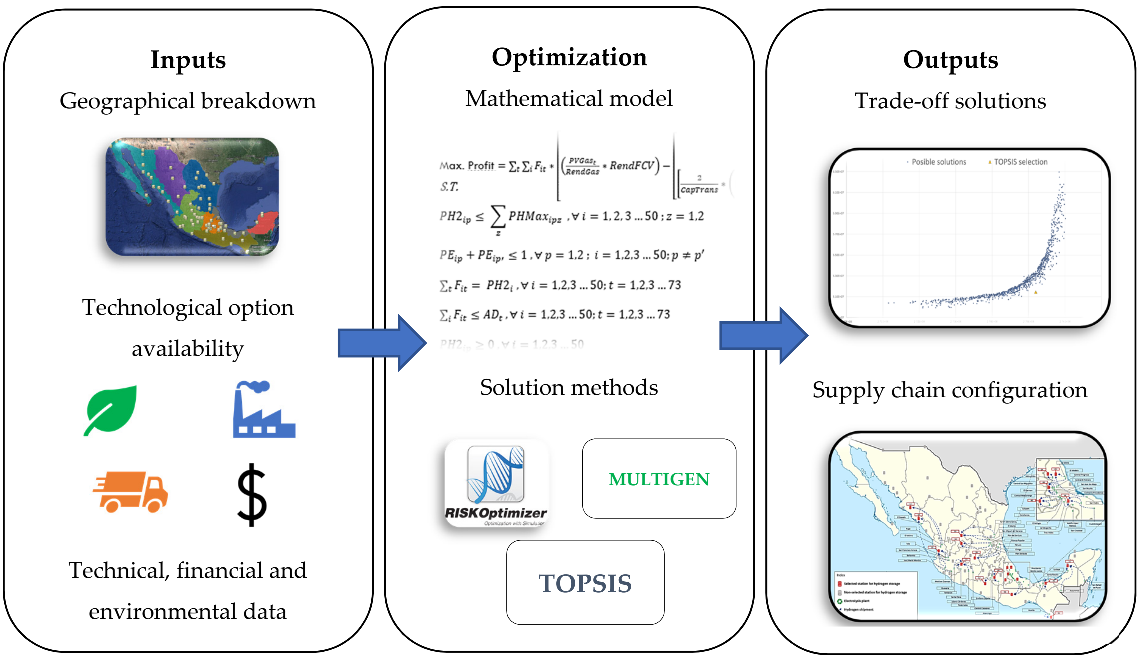


Figure 1. Methodological framework applied.

3.2. Modelling Assumptions

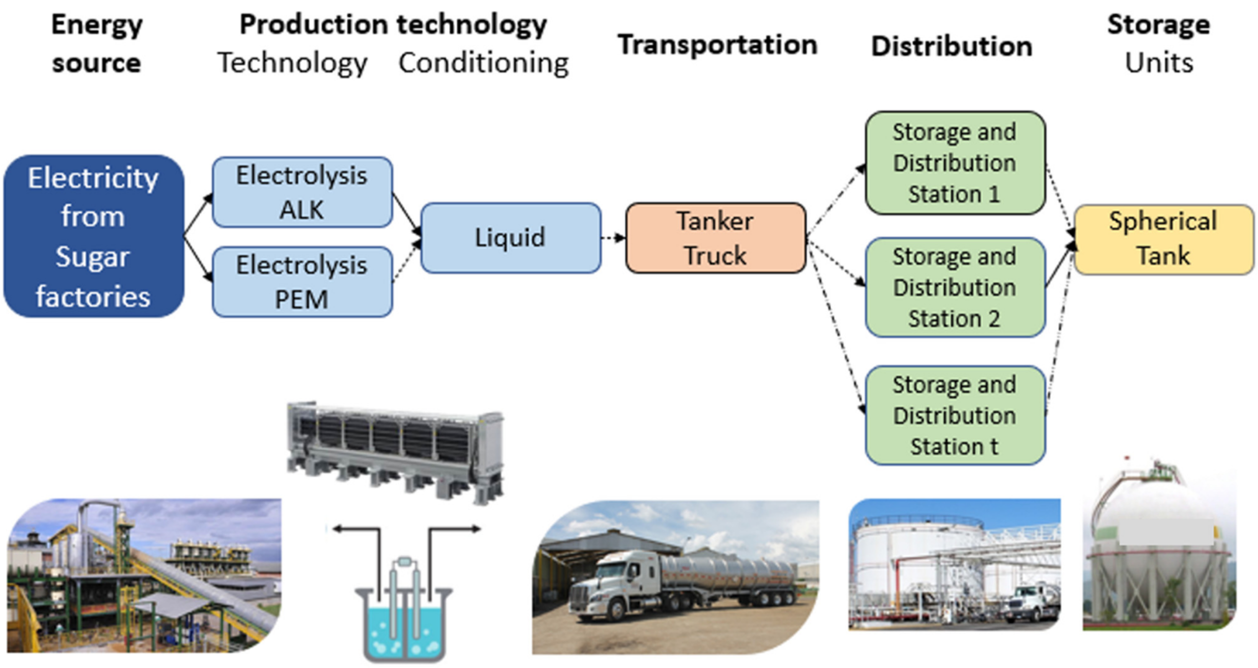
The actual model describes the optimal behavior of a hydrogen production system in the steady state, considering many aspects, such as the production, distribution, and storage operating and investment costs, the accessibility of the raw material, the selling price for hydrogen at distribution points, and the greenhouse gas emissions. The approach applied focuses on developing an optimization model that maximizes profit and minimizes greenhouse gas (GHG) emissions in a system where hydrogen is obtained using agro-industrial wastes from sugar factories in Mexico.

The model arrangement integrates several assumptions that serve as a starting point for the estimation of the economic and environmental indicators that support the decision-making process in the strategic planning of the HSC. These assumptions are as follows:

- The operating time of the system is divided into harvest and non-harvest periods, in which the behavior during the generation of electrical energy differs from one another.
- It is assumed that investments in land and construction have already been paid off. Therefore, these aspects are not considered in the required capital investment.
- Given amounts of available electric energy and storage capacities are considered as model constraints.

3.3. Optimization Model Structure

The proposed model structure is integrated through several calculation modules, which are mainly divided into the following areas: production, transport, and storage. Figure 2 shows the general structure of the model. A description of each module is presented later.



ALK = Alkaline electrolysis, PEM = Proton Exchange Membrane electrolysis

Figure 2. Hydrogen supply chain superstructure.

3.3.1. Hydrogen Production Module

The production module estimates the amount of hydrogen that is convenient to produce based on the availability of electrical energy generated in each of the sugar cane mills by burning bagasse, which is an uncertain parameter for every mill whose behavior responds through probability distributions. The major objective of these calculations is to estimate the operating and investment costs that will result from the production infrastructure. In this section of the model, the selection of the best production technology and the estimate of the amount of hydrogen to be produced by each sugar factory is evaluated (Figure 3).

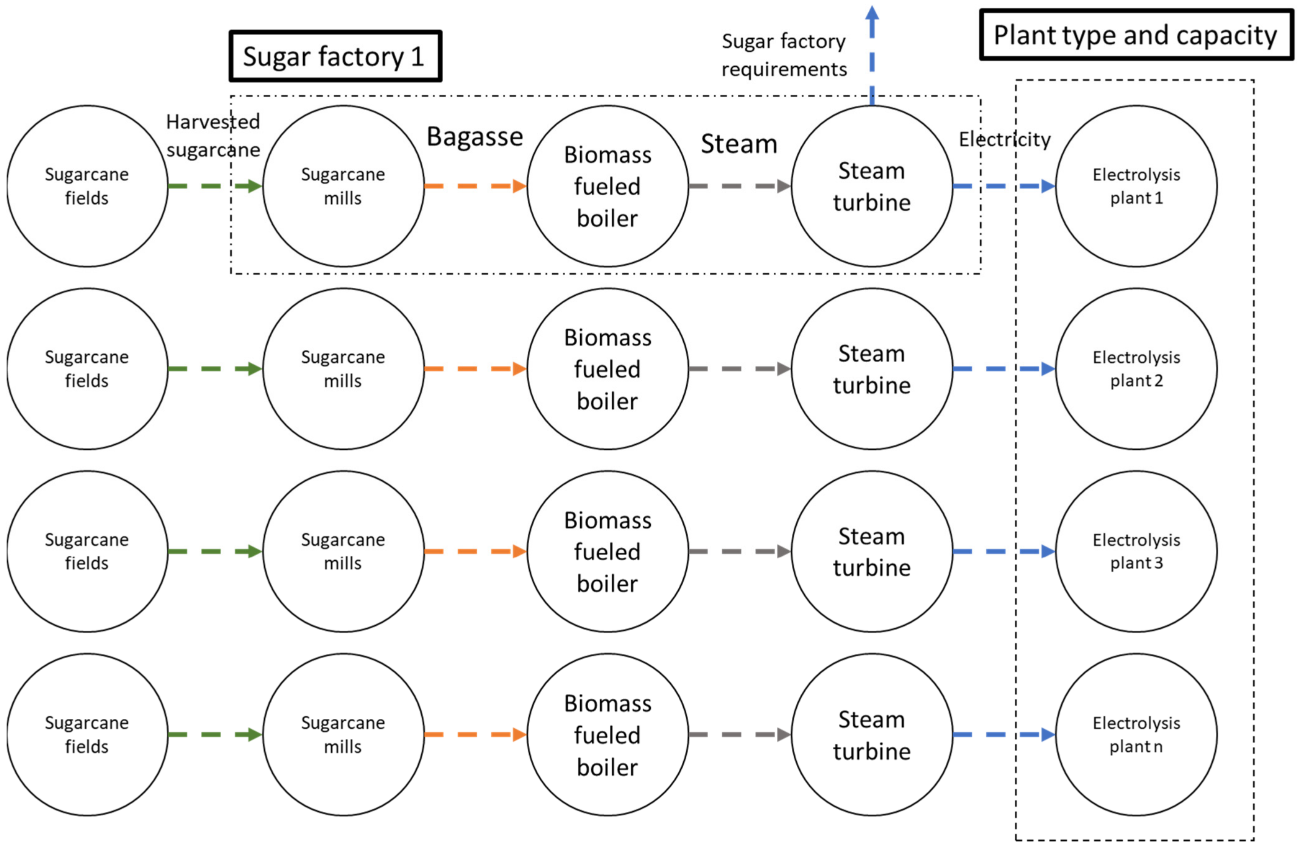


Figure 3. Hydrogen production scheme.

Hydrogen production is divided into two periods: the harvest season, when the greatest amount of H_2 is produced due to the enormous amount of electricity generated from the intensive operation of the sugar factories during this time of year; and the non-harvest season, during which mill operations are reduced due to the lack of raw sugarcane to be processed, thereby lowering the rate of electricity generation and the amount of energy available for hydrogen production. The length of each period is considered as an uncertain parameter according to probability distribution given in days per year [6].

Production cost estimations start by calculating the tons of raw sugar cane that will be processed by each mill during harvest times. The amount of bagasse obtained from sugar cane processing and the amount of moisture it contains are also measured. These values are unique for every sugar cane mill and are represented by probability distributions obtained from historical production records. Humidity measurement is used to determine bagasse energy potential [17]. The amount of bagasse that is used in each mill to generate steam in the boiler rooms during each period depends on the energy consumption behavior of the mill. The steam production dedicated to power generation in each period is estimated using the theoretical efficiencies of the boiler and the bagasse energy potential, also considering the fraction of the dead time operation. Using the amount of steam used to generate electricity, the amount of MWh generated in each period is calculated. Some of this electricity is used by the sugar factories for their daily activities, whereas the overflows are usually fed into the national electricity grid and sold to other organizations. In the proposed model, the energy overflows are used for hydrogen production, whereas their availability is different for the harvest and non-harvest periods.

Once the amount of electrical energy available for hydrogen production in each mill during each period is determined, the optimization model evaluates the most convenient means of production to convert the energy to hydrogen; the proposed technologies are alkaline water electrolysis and proton membrane exchange electrolysis, considering efficiency, investment capital and annual operating costs for each type of production facility. In addition, the variable production costs are calculated, considering the electricity and water prices for each region in which the hydrogen is produced.

3.3.2. Hydrogen Transportation Module

The hydrogen transport module focuses on estimating the capital and operating costs arising from hydrogen distribution activities throughout the supply chain, from the production facilities to the delivery of the hydrogen to the storage and dispatch stations (SDSs)—these are the endpoints where the hydrogen would be stored before they are delivered to the refueling stations (refueling stations are not considered in the actual model). In the analysis, the SDSs are considered as the final stage of the proposed supply chain design (as presented in Figure 4). The amount of greenhouse gas emissions caused by transport activities is also estimated. To achieve this, the optimization model determines the hydrogen flow in tons per year, considering the hydrogen that is generated in both harvest and non-harvest seasons. The model then evaluates the convenience of transporting the hydrogen generated in each electrolysis plant to each storage location; the most favorable network configuration relies on the active objective function. When optimizing with multiple destinations, two main factors influence this decision: the shipping distance (an aspect that has a direct impact on transport costs and equivalent CO_2 kg production), and the selling price of hydrogen at the storage locations, a value that relies on the SDSs' location selected to receive the determined amount of H_2, which has a direct impact on the income generated.

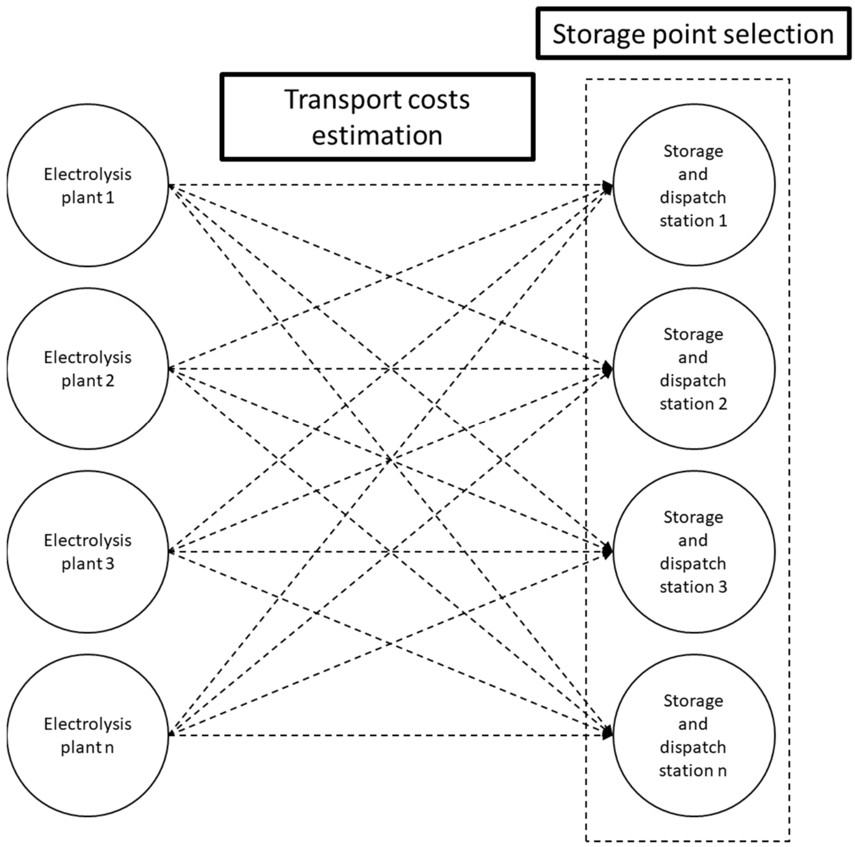


Figure 4. Hydrogen distribution scheme.

Once the annual hydrogen flow is estimated, the number of trips to be made by the transport trucks is calculated based on the vehicle's loading capacity. The time available for each transport vehicle is considered in the calculation, and the number of vehicles required for all distribution operations during the year is determined, thereby obtaining the transport investment cost. The transport operating costs are estimated considering the fuel consumption, the maintenance cost factors (whereby both costs depend directly on the travelling distance from the electrolysis plant to the SDS), the driver's wages, and the toll costs of the selected route. The distance and the toll costs of 50 sugar cane mills for each of the 73 SDSs are shown as two data fields that can be called up via the information system of the national communications and transport department. Finally, the amount of equivalent CO_2 emitted by the network is calculated.

3.3.3. Hydrogen Storage Module

Liquid hydrogen is stored at the SDS, these being the storage points selected by the model in the multiple solutions found. This module calculates the investment capital and operating costs required for the storage units. The number of storage units is determined by the model according to the maximum hydrogen inventory received at a given station during the year of operation. Within these costs, the conditioning energy required for hydrogen compression is calculated and its price depends on the region where the SDSs that have been selected for storing the hydrogen are located. Additionally, the storage costs per unit are considered, including the operating and maintenance costs of the storage unit. The above factors determine the total cost of storage, a value that is added to the cost of production and transportation to determine the final cost of hydrogen on each SDS. Moreover, the revenue generated at each station depends on the gasoline sales price at such SDS, as this price is used as a reference for establishing a competitive sales price for hydrogen, as both serve as mobility fuel for medium-sized vehicles.

3.4. Optimization Model Formulation

3.4.1. Model Notation and Decision Variables

Multiple acronyms definitions, as well as model variables and parameters are presented in Table 2.

Table 2. Glossary.

Nomenclature	Description
Alk	Alkaline electrolysis
CCUS	Carbon capture, utilization and storage
CONACYT	Consejo Nacional de Ciencia y Tecnología
CONADESUCA	Comité Nacional para el Desarrollo Sustentable de la Caña de Azúcar
FCEV	Fuel cell electric vehicle
GA	Genetic algorithm
GHG	Greenhouse gas
GWP	Global warming potential
HSC	Hydrogen supply chain
HSCN	Hydrogen supply chain network
MILP	Mixed integer linear programming
Min	Minimize
MW	Mega watt
MWh	Mega watt hour
NG	Natural gas
NPV	Net present value
O&M	Operation and maintenance
OF	Objective function
PEM	Proton exchange membrane electrolysis
SCBA	Social cost–benefit analysis
SDS	Storage and dispatch station

Table 2. *Cont.*

Nomenclature	Description
SMR	Steam methane reforming
TOPSIS	Technique for order of preference by similarity to ideal solution
Indices	
i	Sugar mills
p	Hydrogen production technology
r	Identification number for regions
t	Identification number for storage and dispatch stations
z	Production period
Decision Variables	
F_{it}	Hydrogen flow rate between sugar mill i and station t (ton/year)
PE_{ip}	Electrolysis plant type p at sugar mill i logic variable with values of 0 or 1
$PH2_{ipz}$	Hydrogen production rate during period z from plant type p at sugar mill i (ton/year)
Parameters	
AD_t	Available storage capacity at station *t* (m^3)
$AExp_t$	Total annual expenses of hydrogen stored at station *t* ($/year)
$AProf_t$	Annual profit generated at station *t* ($/year)
${AToll^C}_{it}$	Annual toll costs between sugar mill *i* and storage station *t* ($/year)
${C^{Alm}}_t$	Annual storage cost at station *t* ($/year)
$Capex_p$	Capital expenditures for electrolysis plant type *p* ($/MW)
${Cap^{Inst}}_{ip}$	Installed capacity of plant type *p* at sugar mill *i* (MW)
Cap^{Trans}	Transportation mode capacity (ton)
${C^{Comb}}_{it}$	Fuel transportation costs between sugar mill *i* and storage station *t* ($/year)
${C^{Cond}}_t$	Conditioning cost per ton of hydrogen at station *t* ($/ton)
CFP_{ip}	Annual fixed production cost for plant type *p* at sugar mill *i* ($/year)
$CFUP_{ip}$	Fixed production costs per ton of hydrogen for plant type *p* at sugar mill *i* ($/ton)
CIP_{ip}	Production investment capital ($)
${C^{Mant}}_{it}$	Maintenance expenses for transportation mode between sugar mill *i* and storage station *t* ($/year)
CMO_{it}	Annual transportation labor costs between sugar mill *i* and station *t* ($/year)
${C^{Prod}}_t$	Annual hydrogen production costs stored at station *t* ($/year)
${C^{Trans}}_{it}$	Transportation cost between sugar mill *i* and storage station *t* ($/year)
CU^{Alm}	Storage cost per ton of hydrogen at station *t* ($/ton)
${CU^P}_{ip}$	Production cost per ton of hydrogen for plant type *p* at sugar mill *i* ($/ton)
${CVU^P}_{ip}$	Variable production cost per ton of hydrogen for plant type *p* at sugar mill *i* ($/ton)
d_{it}	Distance between sugar mill *i* and storage station *t* (km)
DMT	Availability of transportation mode (days/year)
DOp_z	Operational days during period *z* (days)
EC	Fuel economy of transportation mode (km/L)
${E^{Cons}}_p$	Electricity consumption per ton of hydrogen *p* (MW/ton)
EnAc	Conditioning energy required per ton of hydrogen (MW/ton)
$FCEV^{Perf}$	FCEV performance (km/ton of hydrogen)
FP_t	Fuel price per liter at station *t* ($/L)
Gas^{Perf}	Medium size combustion vehicle performance (km/L of gasoline)
GM	Maintenance expenses of transportation mode ($/km)
GWP^{Total}	System's annual total GWP (eq kg CO_2/year)
NUT_{it}	Number of transport units between sugar mill *i* and station *t*
$Opex_p$	Annual operating expense ratio to CAPEX of plant type *p* (%)
PCG^{Alm}	Storage GWP per ton of hydrogen (kg CO_2 eq/ton)
PCG^P	Production GWP per ton of hydrogen (kg CO_2 eq/ton)
PCG^{Trans}	Transportation GWP per ton of hydrogen (kg CO_2 eq/ton)
PEE_r	Electric power price at station *t* ($/MW)
P^{GWP}	Production GWP (eq. kg CO_2/year)
$PHMax_{ipz}$	Maximum hydrogen production during period *z* from plant type *p* at sugar mill *i* (ton)
PVA_r	Water cubic meter price at region *r* ($/$m^3$)
$PVGas_t$	Reference fuel price per liter at station *t* ($/L)
$PVH2_t$	Hydrogen selling price at station *t* ($/ton)
SC	Monthly driver wage ($/month)

Table 2. *Cont.*

Nomenclature	Description
S^{GWP}	Storage GWP (eq kg CO_2/year)
TCD	Charge and discharge time of transportation mode (h/trip)
T^{GWP}	Transportation GWP (eq. kg CO_2/year)
$TollC_{it}$	Toll cost for hydrogen transportation units per trip ($)
$TotalUt_t$	Annual total utilities at station t ($/year)
$Trips_{it}$	Annual trips amount required between sugar mill i and station t (trips/year)
TUW	Transport unit weight (ton)
Vm	Average speed for transportation Unit (km/h)
$W^{Cons}{}_p$	Water consumption per ton of hydrogen at plant type p (m^3/ton)

3.4.2. Production Constraints

Hydrogen production is limited by the amount of electrical energy available from sugar mills during the periods of harvesting and non-harvesting. The optimization model determines the most suitable amount of hydrogen to be produced annually. The annual amount of hydrogen that is generated in the type p electrolysis plant in the sugar mill i ($PH2_{ip}$) must be less than or equal to the sum of the maximum amount of produced hydrogen in both z periods, as described in Equation (1).

$$PH2_{ip} \leq \sum_{z} PHMax_{ipz} \text{ , } \forall\, i = 1,\ 2,\ 3 \ldots 50\ ; z = 1,2 \tag{1}$$

The electrolysis technology is selected by binary variable PE_{ip}, which takes on the zero value if no technology is selected at all, or takes the value 1 if it is selected to generate hydrogen in the sugar mill i. Since it is not possible to select both technologies for the same point of production, a constraint must be set to limit these events from being mutually exclusive. Equation (2) describes this limitation.

$$PE_{ip} + PE_{ip'} \leq 1 \text{ , } \forall\, p = 1,2\ ;\ i = 1,2,3 \ldots 50; p \neq p' \tag{2}$$

The selection of one or the other electrolysis technology implies a difference in the conversion efficiency of electrical energy into hydrogen, both have different investment costs, annual operating, and maintenance costs.

3.4.3. Transportation Constraints

Produced hydrogen at each location should be distributed to the stations where it offers the highest economic and environmental benefits, considering the potential income, transportation costs, and CO_2 generation to make this decision. To achieve this, Equation (3) limits the flow rate of hydrogen per year distributed from sugar mill i to station t (F_{it}) to meet the amount of hydrogen transported to one or more stations with the amount produced at the supplier electrolysis plants ($PH2_i$).

$$\sum_{t} F_{it} = PH2_i \text{ , } \forall\, i = 1,2,3 \ldots 50; t = 1,2,3 \ldots 73 \tag{3}$$

3.4.4. Storage Constraints

Each SDS has a limited storage capacity, so the sum of the hydrogen flows (F_{it}) resulting from the production points i and which are to be stored in each terminal t must be limited by the available storage volume (AD_t) at this station. To achieve this, Equation (4) limits the amount of hydrogen a station can receive from one or more electrolysis plants.

$$\sum_{i} F_{it} \leq AD_t,\ \forall\, i = 1,2,3 \ldots 50; t = 1,2,3 \ldots 73 \tag{4}$$

3.4.5. Non-Negativity Constraints

All continuous, integer and binary variables must be non-negative.

$$PH2_{ip} \geq 0\ ,\ \forall\ i = 1,2,3\ldots 50 \tag{5}$$

$$PE_{ip} \geq 0,\ \forall\ i = 1,2,3\ldots 50 \tag{6}$$

$$F_{it} \geq 0,\ \forall\ i = 1,2,3\ldots 50; t = 1,2,3\ldots 73 \tag{7}$$

3.5. Profit Maximization Objective Function

The total profit of the system is calculated as the difference between the revenue obtained in the storage station and the increase in production (${C^{Prod}}_t$), transport (${C^{Trans}}_{it}$), and storage costs (${C^{Alm}}_t$) achieved in one year of operation. Equation (8) describes the calculation for this statement.

$$MAX:\ TotalProfit = \sum_t (Profit_t = incomes_t - outcomes_t),\ \forall\ t = 1,2,3,\ \ldots 73 \tag{8}$$

The income parameter results from the multiplication of the tons of hydrogen that are intended for storage in station t by the hydrogen sales price ($PVH2_t$) determined for the respective station, as shown in Equation (9).

$$Incomes_t = \sum_i F_{it} * PVH2_t,\ \forall\ i = 1,2,3\ldots 50;\ t = 1,2,3\ldots 73 \tag{9}$$

Hydrogen sales prices ($PVH2_t$) are determined based on the sales price for gasoline at each station t considering the power offered by each type of vehicle. This is achieved by Equation (10), which estimates the cost per kilometer (US$/km) it would cost to the end-user. The sales price of gasoline is divided by the average theoretical power that a gasoline engine (${Gas^{Perf}}_t$) offers for the car used as a reference in this analysis, resulting in a cost in US$/km. This value is then multiplied by the average power of a hydrogen fuel cell engine ($FCEV^{Perf}$), measured in km/kg H_2, which determines the hydrogen sales price in US$/kg at each SDS.

$$PVH2_t = \frac{PVGas_t}{Gas^{Perf}} * FCEV^{Perf},\ \forall\ t = 1,2,3\ldots 73 \tag{10}$$

when calculating the total annual costs ($AExp_t$), the operating costs for the production, transport, and storage of hydrogen from generation in the electrolysis systems to storage at the SDSs are considered. This is represented by Equation (11).

$$AExp_t = C_t^{Prod} + C_{it}^{Trans} + C_t^{Alm} \tag{11}$$

3.5.1. Production Costs

The production cost (${C^{Prod}}_t$) is calculated using Equation (12), where the hydrogen flows (F_{it}) from point i to endpoint t is multiplied by the production cost per unit (${CU^P}_{ip}$) produced in sugar mill i.

$$C_t^{Prod} = \sum_i (F_{it} * CU_{ip}^P)\ ;\ \forall\ i;\ t \tag{12}$$

The estimate of the production costs in each electrolysis plant is determined by the sum of the variable production costs per unit (${CVU^P}_{ip}$), which relates to the consumption of water and electricity in the process, and the fixed unit production costs ($CFUP_{ip}$), including the cost of operating and maintaining the production facilities as expressed in Equation (13).

$$CU_{ip}^P = CVU_{IP}^P + CFUP_{ip},\ \forall\ i \tag{13}$$

$CVU^P{}_{ip}$ (Equation (14)) results from costs of electricity and water volume required hydrogen production per ton. These costs vary depending on the prices of these resources (PEE_r and PVA_r) in each region r. The power consumption depends on the electrolysis technology selected at each point i, since each type of plant has a different transformation performance (Equation (14)).

$$CVU^P_{pr} = (PEE_r * E^{Cons}_p) + \left(PVA_r * W^{Cons}_p\right), \forall\, r,\ p \tag{14}$$

The fixed production costs (CFP_{ip}) comprise the operating and maintenance costs ($Opex_p$) in the production facilities, which are expressed as a percentage (%) of the investment capital and refer to an annual cost. Both the production investment capital (CIP_{ip}) and the operating and maintenance costs depend on the hydrolysis technology selected. The cost of capital estimate is based on the installed capacity ($Cap^{Inst}{}_{ip}$) of energy processing converted into hydrogen at point i (where an additional gap of 20% is considered to compensate for possible fluctuations in the electricity supply) multiplied by the cost of the capital per installed MW ($Capex_p$). The maximum electricity conversion capacity is estimated using the maximum amount of electricity per hour that will be achieved during the harvest season. This is shown in Equations (15)–(17).

$$Cap^{Inst}_{ip} = \frac{PH2_{ipz}}{OpD_z * 24} *\ E^{Cons}_P * 1.2;\ z = 1,\ \forall\, i, p \tag{15}$$

$$CIP_{ip} = Capex_p\ *\ CapInst_{ip},\ \forall\, i,\ p \tag{16}$$

$$CFP_{ip} = CIP_{ip} *\ Opex_p,\ \forall\, i,\ p \tag{17}$$

The fixed unit production cost ($CFUP_{ip}$) is estimated by dividing the annual cost by the annual production (Equation (18)) during harvest and non-harvest periods.

$$CFUP_{ip} = \frac{CFP_{ip}}{PH2_{ipz} + PH2_{ipz\prime}},\ \forall\, i,\ p,\ z \tag{18}$$

3.5.2. Transportation Costs

The transportation costs ($C^{Trans}{}_{it}$) consider the fuel consumption ($C^{Comb}{}_{it}$), the labor costs (CMO_{it}), and the maintenance costs ($C^{Mant}{}_{it}$) of the transport units, as well as the toll costs ($TollC_{it}$), the values of which are specific for the transport of the hydrogen produced in each plant location i and delivered to the stations t during the entire operating days. Equation (19) is used to illustrate these calculations.

$$C^{Trans}_{it} = \sum_i (C^{comb}_{it} + CMO_{it} + C^{Mant}_{it} + TollC_{it});\ \forall\, i,\ t \tag{19}$$

First, the estimate of the number of trips required to distribute the hydrogen flow allocated from facilities i to stations t is obtained, dividing the annual hydrogen flow by the capacity of the transport units (Cap^{Trans}), as shown in Equation (20).

$$Trips_{it} = \frac{F_{it}}{Cap^{Trans}}\ ;\ \forall\, i,\ t \tag{20}$$

The fuel cost ($C^{Comb}{}_{it}$) used by the transport units to distribute the hydrogen is obtained by multiplying the estimated number of trips by twice the distance from point i to point t (d_{it}). This value is then multiplied by the fuel price ($PComb_t$) and divided by the fuel consumption (EC) in km/L. This concept is illustrated in Equation (21).

$$C^{comb}_{it} = \frac{PComb_t}{EC} * (2 * d_{it}) *\ Trips_{it};\ \forall\, i,\ t \tag{21}$$

The labor cost is calculated using the number of transport units required for hydrogen distribution for all the days of operation. The number of transport units is estimated using Equation (22), where *Vm* relates to the average speed of the unit, *TCD* to the loading and unloading time, and *DMT* to the available time that the transport units consider disposed of. Both values are expressed in hours/year.

$$NUT_{it} = Trips_{it} * \left(\frac{2d_{it}}{Vm} + TCD\right) * \frac{1}{DMT}; \forall\, i,\ t \tag{22}$$

The NUT_{it} parameter is multiplied by the driver's monthly salary (*SC*) and multiplied by 12 (months per year) to calculate the annual labor cost (CMO_{it}), as shown in Equation (23).

$$CMO_{it} = NUT_{it} * SC * 12;\ \forall\, i, t \tag{23}$$

The maintenance cost of the transport unit is calculated by multiplying the maintenance cost (*GM*) by the total distance in all working days. This is expressed in Equation (24).

$$CMant_{it} = GM * (2d_{it}) * Trips_{it};\ \forall\, i,\ t \tag{24}$$

Finally, the annual toll costs (${AToll^C}_{it}$) that must be covered to use the routes selected by the model for hydrogen distribution are calculated. This is achieved by considering the number of trips multiplied by the toll price ($TollP_{it}$), which is specific to each route, as shown in Equation (25).

$$AToll^C_{it} = Trips_{it} * TollP_{it};\ \forall\, i,\ t \tag{25}$$

3.5.3. Storage Costs

The total storage costs comprise the storage costs per unit (CU^{Alm}), considering the O&M costs of the storage units and hydrogen conditioning cost per unit (${C^{Cond}}_t$), a value that is a function of the electrical power required to liquefy the hydrogen (*EnAc*) to the desired conditions prevailing in the region in which the SDS is located. With this assumption, the conditioning cost per unit is calculated using Equation (26), while the total storage cost is calculated using Equation (27).

$$C_t^{Cond} = EnAc *\ PEE_r;\ \forall\, r,\ t \tag{26}$$

$$C_t^{Alm} = \sum_i F_{it} * \left(CU^{Alm} + C_t^{Cond}\right);\ \forall\, i,\ t \tag{27}$$

3.6. GWP Objective Function

The *GWP* parameter considered in this model includes the greenhouse gas emissions from hydrogen storage (S^{GWP}), and transport (T^{GWP}), which are generated during an entire year of system operation. Equation (28) is used to calculate the total amount of equivalent CO_2 kilograms for the entire operation.

$$Min\ GWP^{Total} = P^{GWP} + S^{GWP} + T^{GWP} \tag{28}$$

3.6.1. Production GWP

The greenhouse gas emissions from hydrogen production are determined by multiplying the total hydrogen produced in the year of operation by the amount of CO_2 produced per kilogram of hydrogen (PCG^P), as shown in Equation (29).

$$P^{GWP} = \sum_i PH2_i * PCG^P;\ \forall\, i \tag{29}$$

3.6.2. Transportation GWP

Hydrogen transport is a major contributor to emissions from the CO_2 and heavily depends on the distances between the production points and the storage stations selected by the model to store hydrogen. Equation (30) is used to estimate the calculation of the kilograms of equivalent CO_2 produced by transportation. These calculations start with the distances traveled in the year of operation of the system, with the number of trips made multiplied by twice the distance from the production site to the SDS. The resulting value is multiplied by the eq- CO_2 kg (PCG^{Trans}), and the weight of the transport unit (*WeightUT*) is also considered when estimating this parameter.

$$T^{GWP} = \sum_{it}(2 * d_{it} * Trips_{it}) * PCG^{Trans} * WeightUT \ ; \ \forall \ i, \ t \quad (30)$$

3.6.3. Storage GWP

The storage of hydrogen also generates a significant amount of equivalent CO_2, mainly related to energy conditioning and the operation of storage units. The estimate of the carbon dioxide emissions generated by the storage of hydrogen is determined using Equation (31), which uses the variable PCG^{Alm}, which refers to the equivalent CO_2 kg/ton of hydrogen, and which is multiplied by the total hydrogen tons accumulated in each terminal for the entire year of operation.

$$S^{GWP} = \sum_{it} F_{it} * PCG^{Alm} \ ; \ \forall \ i, \ t \quad (31)$$

3.7. Solution Methods

For solving MILP problems, the use of genetic algorithms appears to be one of the most effective methods to find a wide range of feasible solutions when solving similar mathematical problems according to the literature. For selecting the multi-objective optimization method, several alternatives were considered. The selected approach was a meta-heuristic technique, using MULTIGEN software which is a GA used by the research team in previous studies. In addition, multi-objective simulated annealing and multi-objective tabu search techniques were evaluated. At first, a mono-objective optimization method was applied to identify the behavior of the model concerning the optimal solutions for each objective function (to identify antagonism), then multi-criteria optimization was performed. MULTIGEN turned out to be convenient in terms of efficiency and convergence time. MULTIGEN has been applied by the research team in previous studies concerning multi-objective optimization of the HSC [14,31]. The optimization approach was performed in two stages. The first one focuses on the single optimization of each objective function. The second one is aimed to obtain a range of feasible solutions when both optimization criteria are considered simultaneously. For selecting the mid-point solution from the obtained pareto front, the multi-criteria decision-making technique TOPSIS was applied. The assignment of weights for each criterion was performed along the organization interested in the study, assigning equivalent weights for both criteria, since the company decided that both aspects were equally relevant in the decision making.

The GA applied for solving the mathematical model was built using the user interface, generated by the optimization software. The GA parameters were defined based on an iterative procedure, where different combinations were evaluated, selecting those with the smallest solving times. The TOPSIS method was applied using a spreadsheet that allows evaluation of the 1000 possible solutions.

3.8. Mathematical Model Optimization Framework

The mathematical model optimization was carried out with two GA's, the first regarding the independent optimization of each target using the Evolver optimization software in version 7.6 developed by PALISADE, obtaining the best value for each objective function. The second GA is a multi-objective optimization tool that implements a variant of NSGA II developed in the Chemical Engineering Laboratory at the Institut National Polytechnique de Toulouse (INPT). The MULTIGEN algorithm was set to optimize the optimization criteria at the same time. The optimization algorithms were calculated using an 8-core AMD Ryzen 7 2700X processor at 3.7 GHz.

3.8.1. Mono-Objective Optimization

The individual criteria optimization is carried out using the GA interface, which is integrated into the Evolver optimization software. With this software, the user can easily define an optimization model, prioritizing that the logic of the decision variables and the constraints correspond to the mathematical formulation.

The performance of a GA for finding optimal solutions can be influenced by its parameter configuration. Therefore, a sensitivity analysis was performed to define these elements and look for those that would give the best results in finding the optimal solution. These parameters are listed in Table 3 along with the stopping conditions considered for the mono-objective optimization, which were defined to obtain workable solutions until a significant improvement is found over a certain number of iterations.

Table 3. Genetic algorithm parameters and stopping conditions for mono-objective optimization.

Parameter	Value
Population	30,000
Crossing rate	0.5
Mutation rate	0.1
Solution method	Order
Stopping conditions	
Max. Change	0.005%
Max. Iterations without improvement	20,000

3.8.2. Multi-Objective Optimization

The multi-criteria optimization phase is carried out by MULTIGEN optimization software. The model formulation is introduced by generating the optimization interface in which the GA parameters, such as population size or the number of generations, can be defined. The selected configuration of the GA is shown in Table 4. These values are determined by a sensitivity analysis, from which the best configuration for the selected algorithm could be determined.

Table 4. Multi-objective genetic algorithm configuration.

Parameter	Value
Population	36,500
Number of generations	73,000
Crossing rate	0.9
Mutation rate	0.5

Different parameters were used in both algorithms since each of them responds differently to the parameter values. Several values were tried before finding the optimal configuration for each GA. When optimizing multiple objectives simultaneously, a Pareto front is generated with a set of different feasible solutions; then, the alternative that better meets both optimization criteria is selected using a decision-making technique (TOPSIS).

4. Case Study

4.1. Mexican Sugarcane Industry

Sugar cane is mainly used in Mexico to make refined sugar by extracting syrups from its stems. In the 2018/2019 harvest season, the National Committee for the Sustainable Development of Sugar Cane (CONADESUCA) reported a harvested area of 805.5 thousand hectares, around 57,036,700 tons of gross base cane and 6.4 million tons of sugar. The average yield per hectare at the national level is estimated at 70.81 tons in the industrialized acreage dedicated to grinding in the sugar mills [32,33].

The main activities of the sugar mills are divided into two periods: harvest or grinding period. This is when the harvested cane is processed for sugar production and the maintenance period, which coincides with the rainy season when farmers devote themselves to growing sugar cane. In the second phase, production in the mill is stopped to take over the dismantling, repair, and improvement of the factory to prepare for the next grinding period. The 2018/2019 harvest took place over 179 days with 50 sugar mills operating, mainly located in the west, the Gulf, and the south of the country.

Sugarcane Bagasse Generation and Characteristics

In this study, information of 50 sugar mills is taken from the sixth statistical report of the agro-industrial sugar cane sector in Mexico [34] by CONADESUCA, which provides data from the harvest period 2006/2007 to 2018/2019. The amount of bagasse available is modeled as a percentage of the tons of raw cane milled annually. Acting as model inputs, the amount of ground raw cane, the remaining bagasse fraction, and the moisture contained in the bagasse are considered as uncertain parameters and modeled using probability distribution. The mathematic formulation for calculating the fraction of bagasse that is available in the HSC for power generation is extracted from the work previously carried out by Rico Contreras, among the calculations for converting the bagasse into electricity [6]. This information is presented in Appendixes A and B.

4.2. Hydrogen in Mexico

4.2.1. Hydrogen Demand

The estimated hydrogen demand for mobility purposes has been determined based on the available capacity of each of the 76 SDSs, which are spread across Mexican territory and are currently used for fossil fuel storage and subsequent distribution at petrol stations for sale to the public [35].

4.2.2. Hydrogen Production

The proposed model considers two primary means of hydrogen production: alkaline electrolysis and the proton exchange membrane [36]. They are mainly considered due to their technological maturity and their availability in the international market. Each technology has different properties that can have a significant impact on the cost of hydrogen production [37]. These are shown in Table 5. Electricity and water prices were modeled using probability distributions, as listed in Appendix C.

Table 5. Production parameters.

Parameter	Alkaline	PEM	Reference
E^{Cons} (kWh/kgH_2)	49	52	[36]
Performance (HHV) (%)	71	64	
CAPEX ($/kW)	507.8	740.5	
Opex (%CAPEX/year)	3	2	
Lifetime (years)	20	20	
W^{Cons} (m^3/ton H_2)	9		

The variable cost of hydrogen produced by electrolysis is heavily influenced by the electricity and water prices of the region in which it is produced. Information on these prices has been compiled for each region considered in the study.

4.2.3. Hydrogen Storage

Capital costs of the storage units, the storage unit costs, and the parameters to produce greenhouse gases are presented in Table 6. Information concerning the storage capacity and availability for each SDS is presented in Appendix D.

Table 6. Hydrogen storage parameters.

Parameter	Storage Unit	
Minimum Capacity (kg)	500	[7,9]
Maximum capacity (kg)	10,000	
Investment capital ($)	5,542,595	
C^{Alm} ($/kg H_2)	0.722	
Lifetime (years)	20	
S^{GWP} (kg CO_2 per ton H_2)	704	
Maximum storage time (days)	10	Assumption

4.2.4. Hydrogen Transportation

This study uses real geographic information from the communications and transportation department to determine the shipping distances and toll costs of the selected routes and to find the optimal route configuration. The proposed transportation mode to be used in the hydrogen shipment are tanker trucks, as this is the transportation mode of fossil fuels currently used in Mexico [35]. The toll costs of the selected routes for the hydrogen distribution considers the type of truck used, which are 6-axis vehicles. The distances between each mill and the SDSs considered are collected as well [38]. To calculate the transport costs, these values must be multiplied by two to get the round-trip flight costs. The hydrogen transport parameters are listed in Table 7. Data sets used for distance and transportation costs calculations are listed in Appendix E.

Table 7. Hydrogen transportation parameters.

Parameter	Value	Scale	Reference
TUW	40	Ton	[9]
SC	736	$/month	[35]
EC	2.3	km/L	[7]
FP	-	-	Appendix D
TCD	2	Hours per trip	[7]
C^{Mant}	2.42	$/km	[7]
Vm	67	km/h	
DMT	18	Hours/day	Assumption
T^{GWP}	62	g CO_2 per ton-km	[4]
Cap^{Trans}	3.5	Ton	
$Trans^{Capex}$	293,756	$	[7]

4.2.5. Hydrogen Selling Price

The information for estimating the hydrogen sales price is given in Table 8. The annual distance traveled by a medium-sized private vehicle is also established to be used in the calculation of the hydrogen selling price.

Table 8. Hydrogen selling price parameters.

Parameter	Value
$FCEV^{Perf}$	0.98 kg H_2/100 km
Annual average distance traveled for medium size vehicles	15,000 km/year

5. Results and Discussion

5.1. Mono-Objective Optimization Results

Both objective functions were initially optimized independently of one another. With these results, it is possible to create a comparison table showing the resulting values from both selected criteria optimizations, as shown in Table 9.

Table 9. Mono-objective optimization results.

Parameter	Profit O.F.	GWP O.F.
Number of production units	50 ALK	50 ALK
Number of transport units	73	55
Number of storage units	275	286
Investment capital costs		
Production capital cost	$373,654,974	$373,654,974
Transport capital cost	$5,402,025	$4,070,019
Storage capital cost	$1,524,213,622	$1,585,182,167
Total capital cost	$1,903,270,621	$1,962,907,160
Operating costs		
Production	$188,692,213	$188,692,213
Transport	$5,682,987	$2,242,429
Storage	$27,354,603	$28,880,026
Total Outcome	$221,729,804	$219,815,777
Average cost per unit ($/kg H_2)	$3962	$3928
Profit estimation		
Total hydrogen production (ton/year)	55,965	55,965
Average selling price ($/ton)	$8938	$8782
Total income	$500,220,813	$491,490,525
Annual profit	$278,491,009	$271,675,857
Net profit margin	55.67%	44.72%
GWP (kg eq. CO_2)		
Production	-	-
Transport	39,399,360	39,399,360
Storage	19,783,361	7,015,414
Total GWP (kg eq.CO_2)	59,182,721	46,414,774
GWP per unit (kg eq. CO_2/ton H_2)	1057	829
Optimization time (s)	17,388	21,728

Based on the resulting values, it is determined that it is possible to produce hydrogen at the 50 locations of the sugar mill, which allows the system to produce 55,965 tons of hydrogen per year.

From the profit maximization O.F. obtained solution, 73 transportation units and 275 storage units are required to ensure the logistics demand of hydrogen. In contrast, in the GWP O.F. solution, only 55 transport units and 286 storage units are needed. Additionally, the capital expenditures for each element of the supply chain were estimated, resulting in US$1,903,270,621 for the first O.F., and US$1,962,907,160 for the second one. The obtained solutions put the annual operating cost of the entire system at US$221,729,804 and US$219,815,777 for each O.F., respectively. The production cost obtained in the first O.F. optimization contributes 85% to the final cost of hydrogen (Figure 5), while transportation and storage give 3% and 12%, respectively.

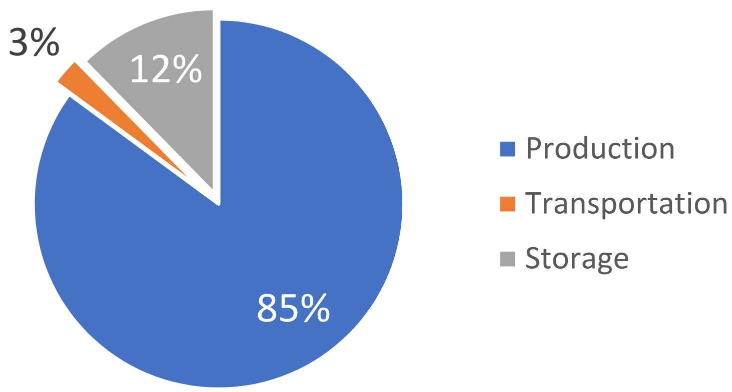


Figure 5. Pie chart of the hydrogen total cost composition obtained from Profit O.F.

In Figure 6, a pie chart shows the composition of the total cost of hydrogen obtained from the GWP O.F. optimization. It can be observed that the transportation costs reduced their participation on the total cost of hydrogen in the optimization of the second O.F. from 3% to 1%. This is expected since the GWP optimization looks mainly to deliver the hydrogen to the closet SDS to reduce the gases emitted by the network. The production and storage cost participation increased due to the previous statement.

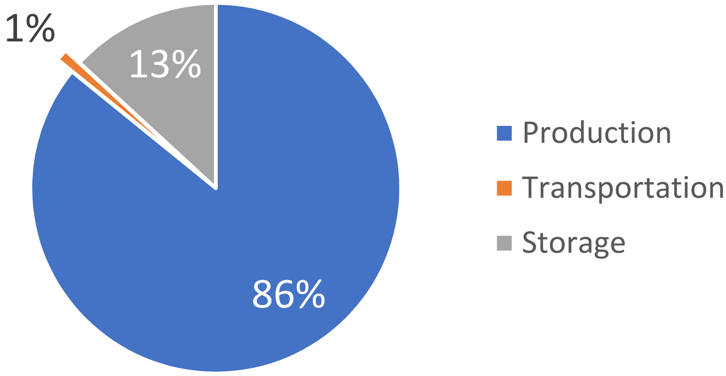


Figure 6. Pie chart of the hydrogen total cost composition obtained from GWP O.F.

Another clear difference is the average selling price of hydrogen which goes from US$8938/ton in the profit optimization to US$8782/ton in the GWP optimization, which was expected since the selling price of hydrogen is a critical factor for a SDS to be selected in the profit O.F. The annual profit of the system is estimated at US$278,491,009, which equates to a net profit margin of 55.67% for the first objective function and US$271,675,857 with a profit margin of 44.72% for the second O.F. Occupancy in the SDS's refers to the percentage of storage volume at the selected station in which hydrogen is stored, whereby a ratio of 4.49% is achieved.

A detailed economic report is shown in Table 10. In the first column are the names of the sugar factories where the electrolysis plants were located. The second column shows the names of the storage and dispatch stations where the hydrogen is stored, which are the locations for the storage units. In the rest of the columns, the information of the hydrogen flow from the PE to the storage location, the costs of production, transportation, and storage per unit are shown separately at first, then the total cost of hydrogen and the selling price per unit at each SDS. A profit estimation calculated from the difference of selling revenues and total cost is displayed.

Table 10. Profit O.F. detailed economic report.

E.P. Location	SDS	Hydrogen Flow (Ton/Year)	Production Cost ($/Ton)	Transportation Cost ($/Ton)	Storage Cost ($/Ton)	Total Cost per Unit ($/Ton)	Selling Price ($/Ton)	Profit ($/Year)
El Molino	Guamúchil	880	1984.82	265.82	290.91	2541.55	9198.38	5,858,008
Puga		1414	1984.82	266.11	290.91	2541.85	9198.38	9,412,337
El Dorado	Culiacán	479	1984.82	35.71	290.91	2311.44	9163.75	3,282,257
Quesería		1292	3269.16	367.73	290.91	3927.80	9163.75	6,764,828
Ameca	Tepic	1050	3269.16	81.73	290.91	3641.80	9085.17	5,715,544
Bellavista		641	3269.16	97.94	290.91	3658.01	9085.17	3,478,795
José Ma Morelos		648	3269.16	151.03	290.91	3711.10	9085.17	3,482,392
Melchor Ocampo		1162	3269.16	138.41	290.91	3698.48	9085.17	6,259,316
Tala		1714	3269.16	82.71	290.91	3642.83	9085.17	9,328,207
Aarón Sáenz	Zacatecas	1104	3456.53	171.07	500.74	4128.34	9030.35	5,411,801
El Mante		976	3456.53	172.05	500.74	4129.32	9030.35	4,783,390
San Miguel del Naranjo		1980	3456.53	163.51	500.74	4120.78	9030.35	9,720,987
Alianza Popular	Aguascalientes	1216	3456.53	161.64	500.79	4118.96	9032.66	5,975,092
Plan de Sal Luis		1400	3456.53	225.29	500.79	4182.61	9032.66	6,790,102

Table 10. *Cont.*

E.P. Location	SDS	Hydrogen Flow (Ton/Year)	Production Cost ($/Ton)	Transportation Cost ($/Ton)	Storage Cost ($/Ton)	Total Cost per Unit ($/Ton)	Selling Price ($/Ton)	Profit ($/Year)
Lázaro Cárdenas	Zamora	273	3269.16	81.68	500.79	3851.62	9078.54	1,426,943
Pedernales		436	3269.16	106.04	500.79	3875.98	9078.54	2,268,306
Santa Clara		655	3269.16	38.51	500.79	3808.45	9078.54	3,451,896
Tamazula		1566	3269.16	59.58	500.79	3829.52	9078.54	8,219,934
Plan de Ayala	Celaya	1325	3456.53	201.18	500.79	4158.50	9013.80	6,433,280
El Higo		1957	3436.98	182.47	500.79	4120.24	9013.80	9,576,710
Pánuco		1918	3436.98	254.86	500.79	4192.63	9013.80	9,247,004
Atencingo	Cuautla	1827	3617.09	25.44	557.81	4200.34	8944.01	8,666,645
Casasano		645	3617.09	19.30	557.81	4194.20	8944.01	3,063,613
Calipam	Tehuacán	233	3617.14	53.49	557.81	4228.44	8872.10	1,081,978
El refugio		475	3616.80	76.18	557.81	4250.79	8872.10	2,195,132
Constancia		886	3436.98	64.24	557.81	4059.04	8872.10	4,264,358
Motzorongo		1341	3436.98	58.99	557.81	4053.78	8872.10	6,461,356
Emiliano Zapata	Iguala	1187	3617.09	50.39	557.81	4225.29	8998.92	5,666,304
López Mateos	Oaxaca	1607	3616.80	76.47	557.81	4251.08	8933.10	7,523,971
Tres Valles		2396	3436.98	86.00	557.81	4080.80	8933.10	11,626,096
Huixtla	Tapachula	1202	3616.80	25.98	557.81	4200.59	8927.95	5,682,255
El Modelo	Perote	1079	3436.98	44.20	528.29	4009.48	8845.38	5,217,947
Mahuixtlán		436	3436.98	48.72	528.29	4014.00	8845.38	2,106,469
La Gloria	Xalapa	1581	3436.98	29.91	528.29	3995.19	8816.01	7,621,740
San Pedro		1273	3436.98	82.86	528.29	4048.13	8816.01	6,069,513
El Carmen	Escamela	577	3436.98	19.79	528.29	3985.07	8797.40	2,776,722
El Potrero		1707	3436.98	21.91	528.29	3987.18	8797.40	8,211,057
La providencia		811	3436.98	30.11	528.29	3995.38	8797.40	3,894,444
Progreso		913	3436.98	48.23	528.29	4013.51	8797.40	4,367,711
San Cristobal		560	3436.98	18.81	528.29	3984.09	8797.40	2,695,459
San Miguelito		525	3436.98	55.60	528.29	4020.87	8797.40	2,507,675
San Nicolas		1103	3436.98	23.48	528.29	3988.75	8797.40	5,303,941
La margarita	Tierra Blanca	1226	3616.80	17.04	528.29	4162.13	8773.28	5,653,241
Cuatotolapan		835	3436.98	60.31	528.29	4025.59	8773.28	3,964,315
San Cristobal		2584	3436.98	28.68	528.29	3993.96	8773.28	12,349,672
Benito Juárez	Villahermosa	1438	3436.98	26.18	528.29	3991.45	8733.89	6,819,600
Santa Rosalia		781	3436.98	27.31	528.29	3992.58	8733.89	3,702,945
Azsuremex	Campeche	223	3436.98	166.31	547.35	4150.69	8760.07	1,027,891
La Joya		826	3553.49	32.12	547.35	4132.96	8760.07	3,821,972
Pucte		1602	3553.49	103.05	547.35	4203.88	8760.07	7,298,984
-	Total	55,965	-	-	-	-	-	278,491,009
-	Average	1119	3352.11	94.50	486.00	3961.94	8938.11	5,569,820

It is possible to see significant differences in the contribution of the various elements of the supply chain to costs. For example, hydrogen from the El Molino and Puga generation points makes a higher contribution to the transport costs than the rest, as the reported production costs in these facilities are exceptionally low (US$1984.82/ton of H_2) compared with other facilities. It is possible to distribute hydrogen over greater distances to stations with higher sales prices.

The hydrogen distribution for this solution is a decision that is heavily influenced by the selling price at the SDS for which it is intended. However, a SDS an extremely large distance from the electrolysis plant that supplies it would cause higher transport costs. Therefore, the model carries out an assessment and determines to which of the storage stations the hydrogen produced should be distributed.

The GWP for supply chain operations was then calculated. The electrical energy from the emissions balance of bagasse production is regarded as neutral due to its agricultural origin, so that the estimate of greenhouse gas emissions is limited to the transport and storage factors, the second one contributes majorly with a share of 67% of greenhouse gas emissions. On this basis, it is estimated that this configuration of the HCS generates 59,182,721 kg of equivalent CO_2, or 1057 kg of CO_2/ton of distributed and stored hydrogen.

The HSC configuration obtained from the profit objective function optimization is presented in Figure 7.

Figure 7. HSC configuration obtained by profit O.F. optimization.

Concerning the optimization of the GWP objective function, considerable differences can be observed compared to the profit optimization function. First, the number of transport units has been significantly reduced to 55, so the investment capital is also reduced. However, this configuration requires 286 storage units, a higher number than previous results, and while this is the factor that has the greatest impact on the capital cost. Thanks to this, the investment required to deploy the supply chain increases to US$1,962,907,160.

The production makes the largest contribution to operating costs but remained constant for both OFs. Besides, the operating costs for the transport are reduced by 60%, which is a consequence of the fact that the algorithm in this OF mainly focuses on the selection of the shortest distances from the hydrogen production points to the SDS and requires fewer transport units to carry out the distribution. As a result, the unit cost of hydrogen will be significantly reduced to an average of US$3928 per ton.

With respect to profit, the average selling price is US$8782/ton of hydrogen. Because of this, there are fewer economic benefits compared to the solution shown above, which in this case is US$271,675,857, resulting in a profit margin of 44.72%.

Table 11 shows the key results of the economic indicators for each station selected by the model for hydrogen storage and shows the unit cost of supply chain operations and the selling price at each SDS. In this case, the average final cost of hydrogen is reduced compared to the previous solution, assuming a value of US$3908/ton and an average sales price of US$8804/ton.

Table 11. GWP O.F. detailed economic report.

E.P. Location	SDS	Hydrogen Flow (Ton/Year)	Production Cost ($/Ton)	Transportation Cost ($/Ton)	Storage Cost ($/Ton)	Total Cost per Unit ($/Ton)	Selling Price ($/Ton)	Profit ($/Year)
El Dorado	Culiacán	479	1984.82	35.71	290.91	2311.44	9163.75	3,282,247
El Molino	Tepic	880	1984.82	12.03	290.91	2287.82	9085.17	5,981,676
Puga		1414	1984.82	12.18	290.91	2287.92	9085.17	9,611,305
Aarón Sáenz	Cd. Victoria	1104	3456.58	41.85	531.24	4029.67	8841.90	5,312,714
Alianza Popular		1216	3456.58	102.55	531.24	4090.37	8841.90	5,777,865
San Miguel del Naranjo		1562	3456.58	63.65	531.24	4051.47	8841.90	7,482,657
Pánuco		1918	3436.98	94.70	531.24	4062.92	8841.90	9,166,055
El Mante	Cd. Mante	976	3456.58	10.36	531.24	3998.18	8783.10	4,670,094
San Miguel del Naranjo		418	3456.58	39.24	531.24	4027.06	8783.10	1,988,030
Plan de Ayala	Cd. Valles	1325	3456.58	7.66	531.24	3995.48	8809.97	6,379,213
Plan de SL		1400	3456.58	19.55	531.24	4007.37	8809.97	6,723,660
El Higo		1957	3436.98	37.03	531.24	4005.26	8809.97	9,402,801
Ameca	Zapopan	1050	3269.16	30.40	500.79	3800.34	8990.47	5,449,620
Bellavista		641	3269.16	28.83	500.79	3798.77	8990.47	3,327,871
Tala		1714	3269.16	15.08	500.79	3785.02	8990.47	8,922,122
Santa Clara	Zamora	655	3269.16	38.56	500.79	3808.50	9078.54	3,451,876
Lázaro Cárdenas	Uruapan	273	3269.16	39.15	500.79	3809.09	9000.49	1,417,253
Pedernales		436	3269.16	69.30	500.79	3839.24	9000.49	2,250,304
Quesería	Colima	1292	3269.16	17.34	500.79	3787.28	8927.31	6,640,918
Tamazula		1566	3269.16	43.32	500.79	3813.26	8927.31	8,008,598
José María Morelos	Manzanillo	648	3269.16	90.77	500.79	3860.71	8667.29	3,114,665
Melchor Ocampo		1162	3269.16	98.62	500.79	3868.57	8667.29	5,576,116
Atencingo	Cuautla	1827	3617.14	25.44	557.81	4200.39	8944.01	8,666,588
Casasano		645	3617.14	19.30	557.81	4194.25	8944.01	3,063,593
Calipam	Tehuacán	233	3617.14	53.44	557.81	4228.39	8872.10	1,081,986
Emiliano Zapata	Cuernavaca	1187	3617.14	22.74	557.81	4197.69	8915.18	5,599,657
Huixtla	Tapachula	1202	3616.80	25.98	557.81	4200.59	8927.90	5,682,213
Mahuixtlán	Xalapa	436	3436.98	27.31	528.29	3992.58	8816.01	2,103,009
El Carmen	Escamela	577	3436.98	19.74	528.29	3985.02	8797.40	2,776,734
El Potrero		1707	3436.98	21.91	528.29	3987.18	8797.40	8,211,016
La Providencia		811	3436.98	31.58	528.29	3996.86	8797.40	3,893,227
Progreso		913	3436.98	48.23	528.29	4013.51	8797.40	4,367,679
San José de Abajo		560	3436.98	33.79	528.29	3999.07	8797.40	2,687,057
San Miguelito		525	3436.98	55.60	528.29	4020.87	8797.40	2,507,667
Adolfo López Mateos	Veracruz	1607	3616.80	62.97	528.29	4208.06	8522.45	6,933,222
El Modelo		1079	3436.98	28.44	528.29	3993.71	8522.45	4,886,503
La Gloria		1581	3436.98	29.32	528.29	3994.60	8522.45	7,158,529
Motzorongo		1341	3436.98	50.34	528.29	4015.62	8522.45	6,043,655
San Cristobal		2584	3436.98	68.22	528.29	4033.50	8522.45	11,599,444
San Nicolás		1103	3436.98	55.80	528.29	4021.07	8522.45	4,965,017
San Pedro		1273	3436.98	44.25	528.29	4009.53	8522.45	5,744,944
El Refugio	Tierra Blanca	475	3616.80	33.74	528.29	4178.83	8773.23	2,182,339
La Margarita		1226	3616.80	17.04	528.29	4162.13	8773.23	5,653,206
Constancia		886	3436.98	26.62	528.29	3991.90	8773.23	4,236,264
Tres Valles		2396	3436.98	12.13	528.29	3977.41	8773.23	11,490,797
Cuatotolapam	Minatitlán	835	3436.98	44.94	528.29	4010.22	8623.23	3,851,868
Azsuremex	Villahermosa	223	3436.98	109.48	528.29	4074.75	8733.89	1,038,987
Benito Juárez		1438	3436.98	26.18	528.29	3991.45	8733.89	6,819,623
Santa Rosalía		781	3436.98	27.31	528.29	3992.58	8733.89	3,702,960
La Joya	Campeche	826	3553.49	32.12	547.35	4132.96	8760.07	3,822,004
San Rafel Pucté	Yucatán	1602	3553.49	74.71	547.35	4175.54	8524.36	6,966,830
-	Total	55,965	-	-	-	-	-	271,675,857
-	Average	1097	3354	40.72	513.11	3907.96	8803.93	5,433,517

Finally, a significant decrease in the equivalent CO_2 tons emitted by the system can be observed, which corresponds to a reduced travel distance for the hydrogen distribution. As a result, the amount of CO_2 emitted per ton of hydrogen is significantly reduced, assuming values of 829 kg equivalent CO_2/ton of H_2, which corresponds to 78.42% of the value obtained in the previous solution. For this configuration, it was found that the contribution from transport to CO_2 emissions decreased from 33% to 15%.

The HSC configuration obtained from the optimization of the GWP objective function is shown in Figure 8. The model in this case is mainly committed to storing the hydrogen in the nearest SDSs from the production facilities, the major reason for the significant decrease in CO_2 emissions generated by the system.

Figure 8. HSC configuration obtained by GWP O.F. optimization.

5.2. Multi-Objective Optimization Results

The simultaneous optimization of both objective functions carried out with the MULTI-GEN optimization software, through which it is possible to obtain a Pareto front with a set of 1000 possible solutions, the one that fulfills both criteria most satisfactorily. Figure 9 shows a Pareto front diagram and the solution chosen by the TOPSIS.

In most cases, the hydrogen storage terminals where higher profits would be made are not close to the points where hydrogen production takes place. However, at some point, the increase in profit is no longer proportional to the increase in emissions, which indicates that there are solutions whose emissions are considerably high ($<5.70 \times 10^7$) and whose contribution to profit is not as significant compared to other solutions found for the model.

The solution selected using the TOPSIS method that best meets both optimization criteria is highlighted in the diagram. With this configuration, a profit of US$275,197,557/year is achieved, and 51,443,692 kg of equivalent CO_2 is emitted annually. Next, the HSC design based on this configuration is presented, in which important performance indicators were estimated.

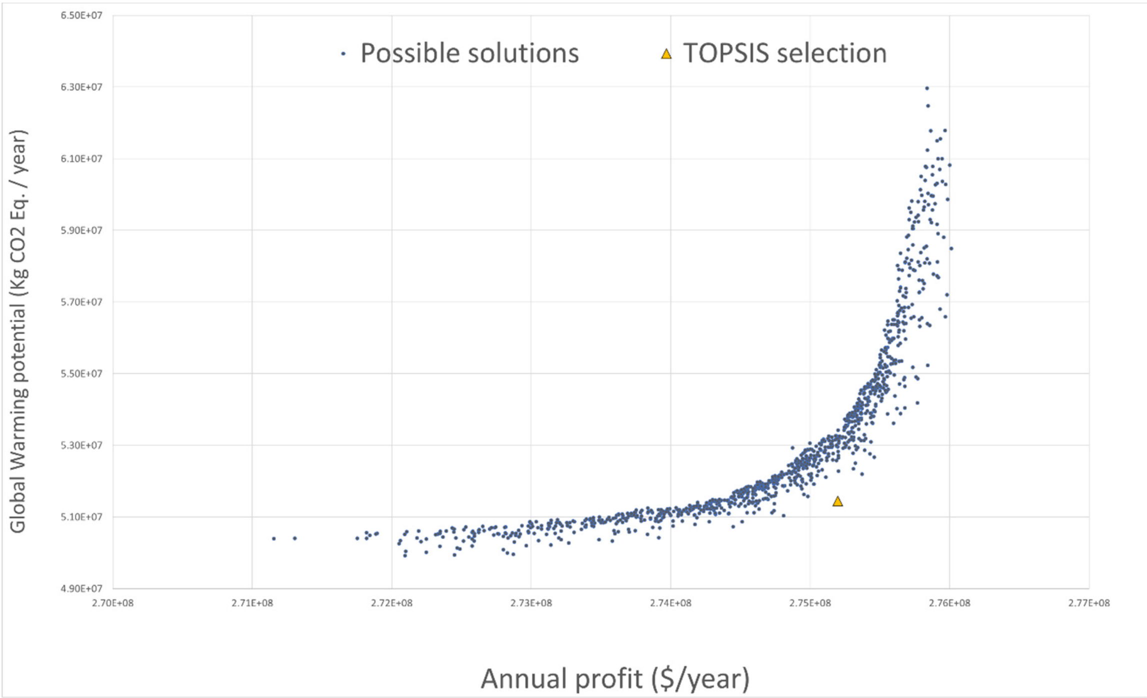


Figure 9. Pareto front chart and TOPSIS selected solution.

5.3. Optimal Hydrogen Supply Chain Configuration

Table 12 shows the results of the general economic and environmental system indicators for the optimal solution that TOPSIS selected from the Pareto front.

Table 12. Multi-objective optimization results.

Parameter	Values
Number of production units	50 ALK
Number of transport units	59
Number of storage units	279
Investment capital costs	
Production capital cost	$373,654,974
Transport capital cost	$4,366,020
Storage capital cost	$1,546,384,002
Total capital cost	$1,924,404,997
Operating costs	
Production	$188,692,213
Transport	$3,550,495
Storage	$29,250,926
Total outcome	$275,197,558
Average cost per unit ($/kg H_2)	$3958
Profit estimation	
Total hydrogen production (ton/year)	55,965
Average selling price ($/ton)	$8875
Total income	$496,691,192
Annual profit	$275,226,444
Net profit margin	55.40%
GWP (kg CO_2 eq.)	
Production	0
Transport	39,399,360
Storage	12,044,332
Total GWP (kg CO_2 eq.)	51,443,692
GWP per unit (kg CO_2/ton H_2)	919
Optimization time (s)	19,879

The average contribution of each element in the supply chain to the final cost of hydrogen in the storage station can be determined. The cost of hydrogen production adds an average of 85% to the total cost of the product in the supply chain. In this case, the transport costs add (on average) 2% to the total costs of hydrogen. Table 13 lists the economic details within the HSC, listing the SDSs selected for hydrogen storage and their supplier production points.

Table 13. Multi-objective optimal solution detailed economic report.

E.P. Location	SDS	Hydrogen Flow (Ton/Year)	Production Cost ($/Ton)	Transportation Cost ($/Ton)	Storage Cost ($/Ton)	Total Cost Per Unit ($/Ton)	Selling Price ($/Ton)	Profit ($/Year)
El Dorado	Culiacán	479	1984.82	35.71	290.91	2311.44	9163.75	3,282,247
El Molino	Tepic	880	1984.82	12.03	290.91	2287.82	9085.17	5,981,676
Puga		1414	1984.82	12.18	290.91	2287.92	9085.17	9,611,305
San Miguel del Naranjo	Matehuala	1980	3456.58	86.84	531.24	4074.66	8982.42	9,717,387
Aarón Sáenz	Cd. Victoria	1104	3456.58	41.85	531.24	4029.67	8841.90	5,312,714
Pánuco		1918	3436.98	94.70	531.24	4062.92	8841.90	9,166,055
El Mante	Cd. Mante	976	3456.58	10.36	531.24	3998.18	8783.10	4,670,094
Plan de Ayala	Cd. Valles	1325	3456.58	7.17	531.24	3994.99	8809.97	6,379,864
Alianza Popular		1216	3456.58	26.96	531.24	4014.78	8809.97	5,830,960
El Higo		1957	3436.98	37.03	531.24	4005.26	8809.97	9,402,801
Plan de SL	S.L.P.	1400	3456.58	126.67	531.24	4114.49	8835.66	6,609,652
Ameca	Zapopan	1050	3269.16	30.40	500.79	3800.34	8990.47	5,449,620
Bellavista		641	3269.16	28.83	500.79	3798.77	8990.47	3,327,871
José María Morelos		648	3269.16	84.53	500.79	3854.47	8990.47	3,328,129
Melchor Ocampo		1162	3269.16	64.73	500.79	3834.68	8990.47	5,991,035
Tala		1714	3269.16	15.08	500.79	3785.02	8990.47	8,922,122
Quesería	Zamora	1292	3269.16	124.41	500.79	3894.35	9078.54	6,697,967
Santa Clara		655	3269.16	38.56	500.79	3808.50	9078.54	3,451,876
Tamazula		1566	3269.16	59.58	500.79	3829.52	9078.54	8,219,962
Pedernales	Irapuato	436	3269.16	122.64	500.79	3892.58	9016.65	2,234,093
Lázaro Cárdenas	Uruapan	273	3269.16	39.15	500.79	3809.09	9000.49	1,417,253
Calipam	Tehuacán	233	3617.14	53.44	557.81	4228.39	8872.10	1,081,986
Constancia		886	3436.98	64.24	557.81	4059.04	8872.10	4,264,375
Motzorongo		1341	3436.98	58.99	557.81	4053.78	8872.10	6,461,367
Atencingo	Cuernavaca	1827	3617.14	44.01	557.81	4218.96	8915.23	8,580,084
Casasano		645	3617.14	24.66	557.81	4199.61	8915.23	3,041,575
Emiliano Zapata		1187	3617.14	22.74	557.81	4197.69	8915.23	5,599,716
Mahuixtlán	Toluca	436	3436.98	188.75	557.81	4183.55	8927.21	2,068,232
El Refugio	Azcapotzalco	475	3616.80	194.60	557.81	4369.20	8856.19	2,131,316
La Margarita		1226	3616.80	195.83	557.81	4370.43	8856.19	5,499,534
El Potrero	Añil	1707	3436.98	167.39	557.81	4162.18	8904.42	8,094,980
Progreso		913	3436.98	188.65	557.81	4183.45	8904.42	4,310,236
Adolfo López Mateos	Oaxaca	1607	3616.80	76.47	557.81	4251.08	8933.10	7,524,008
Tres Valles		2396	3436.98	86.00	557.81	4080.80	8933.10	11,626,131
Benito Juárez	Tuxtla Gutiérrez	1438	3436.98	79.47	557.81	4074.26	8781.48	6,768,982
Huixtla	Tapachula	1202	3616.80	25.98	557.81	4200.59	8927.95	5,682,272
El Modelo	Xalapa	1079	3436.98	29.96	528.29	3995.24	8816.01	5,201,617
La Gloria		1581	3436.98	29.91	528.29	3995.19	8816.01	7,621,725
El Carmen	Escamela	577	3436.98	19.79	528.29	3985.07	8797.40	2,776,706
La Providencia		811	3436.98	30.11	528.29	3995.38	8797.40	3,894,422
San José de Abajo		560	3436.98	33.79	528.29	3999.07	8797.40	2,687,057
San Miguelito		525	3436.98	55.60	528.29	4020.87	8797.40	2,507,667
San Nicolás		1103	3436.98	23.48	528.29	3988.75	8797.40	5,303,935
San Cristobal	Tierra Blanca	2584	3436.98	28.68	528.29	3993.96	8773.28	12,349,769
San Pedro		1273	3436.98	63.21	528.29	4028.49	8773.28	6,040,122
Cuatotolapam	Minatitlán	835	3436.98	44.94	528.29	4010.22	8623.23	3,851,868
Santa Rosalía	Villahermosa	781	3436.98	27.31	528.29	3992.58	8733.89	3,702,960
Azsuremex	Mérida	223	3436.98	208.10	547.35	4192.44	8524.41	966,030
La Joya		826	3553.49	79.57	547.35	4180.40	8524.41	3,588,160
San Rafel Pucté		1602	3553.49	74.71	547.35	4175.54	8524.41	6,966,908
-	Total	55,965	-	-	-	-	-	275,198,425
-	Average	1119	3352.11	66.40	519.01	3937.52	8874.71	5,503,968

The CO_2 emissions from transport and storage were estimated at 51,443,692 kg equivalent carbon dioxide per year, with transport processes contributing 23%. The optimal design of the HSC network is shown in Figure 10. The hydrogen produced is distributed across a larger number of storage terminals compared with the solution that minimized the GWP. On the other hand, it can also be observed that the distribution distances are usually shorter compared to the solution found, which maximizes the benefits of the system and reaches a central point from both limits.

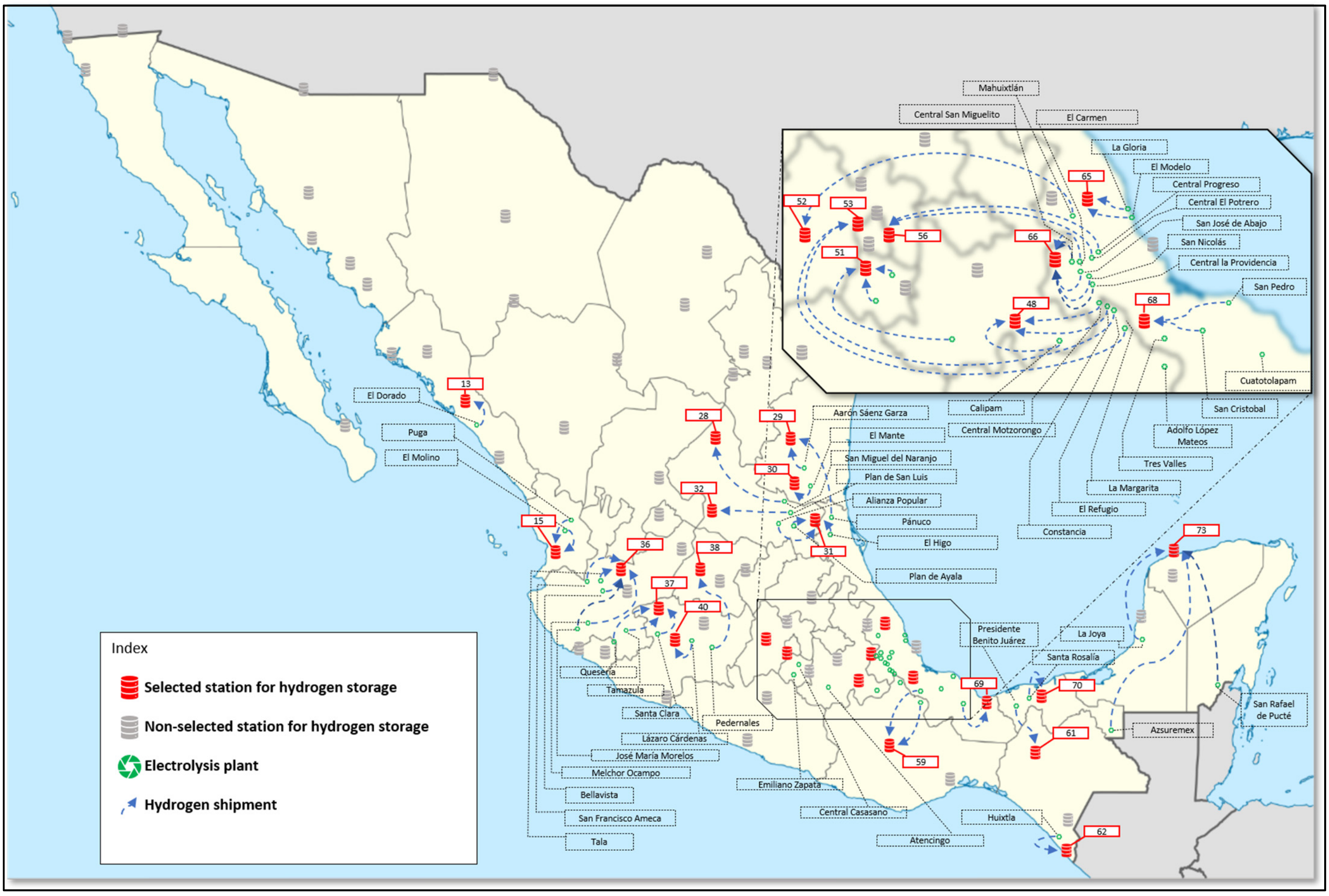


Figure 10. Optimal design for hydrogen supply chain network.

Investment Assessment and Uncertainty Analysis

An investment assessment within a horizon of 10 years was performed to estimate the internal rate of return (IRR) and payback period, using probability distributions for modeling the uncertain behavior within model inputs. The uncertainty analysis was performed using the Monte Carlo simulation methodology. In Figure 11, IRR ranges are estimated for each hydrogen receiving SDS, where it can be observed that Tepic's HSC is the most profitable case with an average of 28.90%, with minimum and maximum values oof about 15.10% and 34.20%, respectively, while Toluca's HSC is the least profitable one, with an average IRR of 15.80%, and minimum and maximum values of about 7.10% and 21%, respectively. The average IRR for all SDS is 21.50%, which is considered an acceptable value in terms of this study.

In terms of payback period, the average value for all SDS is 5.02 years. As expected, and according to the IRR, the case with the shortest payback period is Tepic, with an average value of 3.94 years, and minimum/maximum values about 3.45 and 6.11 years, respectively. In the case of the largest payback period, Toluca presented 6.12 years on average, and minimum/maximum values of 4.97 and 9.01 years, respectively. This information is presented in Figure 12.

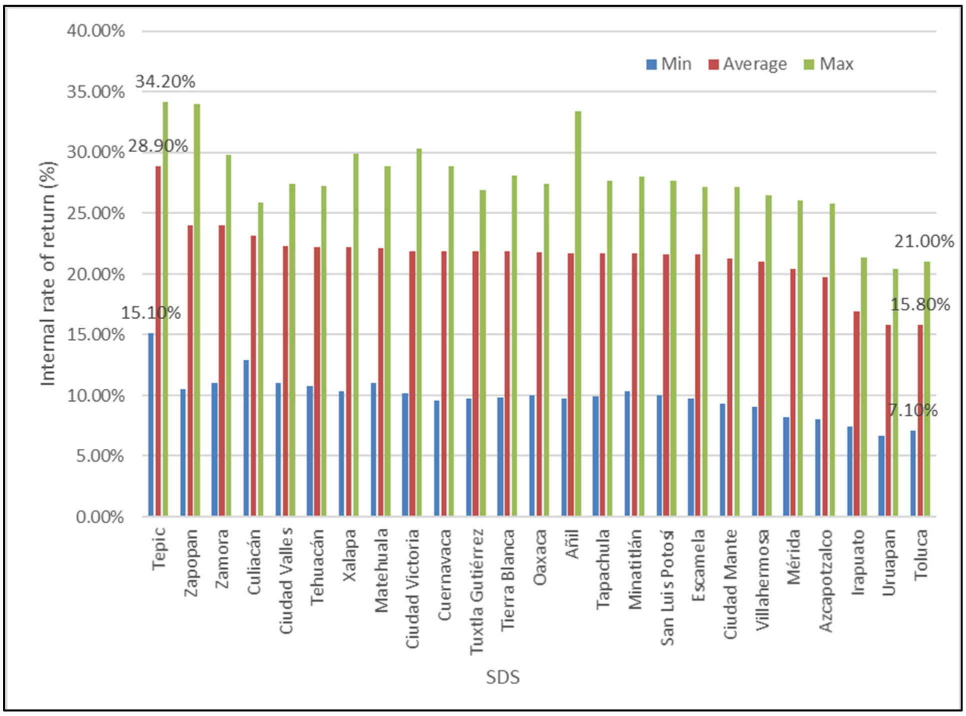


Figure 11. IRR for each SDS case.

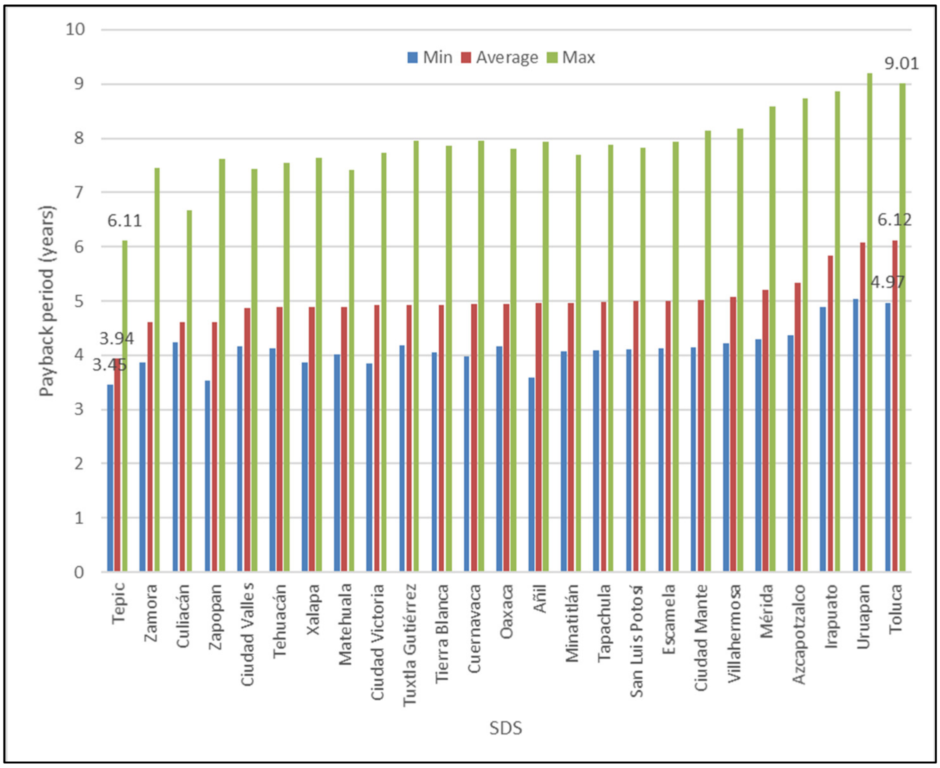


Figure 12. Payback period for each SDS Case.

From the uncertainty analysis it can be concluded that, in most cases, the HSC's deployment might turn out convenient in economic term, due to their acceptable IRR and short payback periods. There are some cases like Tepic's where the case is extremely convenient and others like Toluca's where economic indicators are not that favorable. The main reason why there are big differences between cases is the wide range of water, electricity, and fuel prices across the country, along with differences in raw sugar cane availability and quality.

6. Conclusions

The information gathered was used to develop a mathematical optimization model that estimates the main economic and environmental indicators of the HSC network operation; the optimization criteria are defined as the annual profits and GWP. The latter refers to the generation of equivalent carbon dioxide that comes from the HSC activities.

Once the optimization criteria were established, it was possible to find the optimal values of the mathematical model using the artificial intelligence tool known as GA, which was used as a first approximation under a single criteria approach to know the limits of the model and obtain the maximum and minimum values of the relevant parameters. Subsequently, both optimization criteria were optimized at the same time, so that many feasible solutions could be generated, from which the one that best met the specified criteria was selected. This optimal configuration selection was made using the TOPSIS multi-criteria decision technique. Based on these results, it was possible to observe the different configurations that the hydrogen supply chain can take, as well as the advantages and disadvantages associated with each solution. In addition, the proportion of the contribution of the many elements of the system to investment capital and operating costs, as well as their contribution to the equivalent CO_2 emissions, could be defined. The obtained results show that it turns out to be economically convenient to produce hydrogen in each of the 50 proposed production points for all the scenarios, the storage infrastructure layout distributed across strategic parts of the country exposes several advantages in terms of resource utilization, since the closeness of multiple storage points from each production plant location brings a wide scope of possible solution alternatives. Several differences can be observed between the solutions: in the profit maximization function the profit ratio of 55.67% and 1057 kg of CO_2 per ton of hydrogen is achieved, while the GWP minimization function offers an average profit ratio of 44.72% and 829 kg of CO_2 emitted due to direct hydrogen transportation and storage activities. An evaluation to quantify the economic benefits of using the available electric energy and the utilization of already existing infrastructure for hydrogen production, storage and transportation can be exposed as a starting point for considering the integration of hydrogen as an energy carrier in developing countries, with the infrastructure deployment being the most capital-intensive phase of the energy transition to a hydrogen economy.

The impact of the study relies on putting into perspective the economic and environmental benefits obtained from non-conventional energy sources, and its integration to the national energy grid, directing such energy to sectors with higher demand, like the transportation sector. The knowledge acquired supports the decision-making process during the exploration of new alternatives in the search for supplying the energy deficit in a specific region—Mexico, in this case. This paradigm opens the scope of research to new possibilities for considering economically and environmentally convenient solutions, under resource constraints and the uncertainty contained in the system. The proposed model was validated in a case study of the Mexican sugarcane industry.

Further research is recommended by adding refueling station location capabilities to the model to complete the final HSC echelon. It is also recommended to evaluate social risk by quantifying possible hazards and optimizing the risk criteria along the economic and environmental objective functions. It can be highlighted from the reviewed literature that there are few studies that integrate biomass waste utilization and hydrogen production, and even less studies using electrolysis in a biomass to power to hydrogen configuration using existing infrastructure in all the HSC echelons. As far as we know, this is the only study that considers this type of hydrogen production scheme applied to Mexican territory.

Some model limitations include that it was designed for evaluating an operation year that is divided in two periods. Moreover, the model was built for considering only the electrolysis process for hydrogen production, and existing storage infrastructure, which restricts the possibilities of the model in terms of specific location of such facilities.

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Appendix A. Calculations for Estimating Model Inputs

In Equation (A1), the bagasse availability is calculated in tons for each sugar mill i using the quantity of raw sugarcane and the mass fraction of bagasse, both represented by probability distributions.

$$AvBag_i = tCane_i * \%BagInCane_i, \ \ \forall\, i = 1 \dots 50 \tag{A1}$$

In Equation (A2) Operation hours parameter for each period z is calculated considering the number of operation days in each period z (modeled using probability distributions) and the downtime during operation.

$$OpHrs_z = (DOp_z * 24) * (100\% - \%Downtime)\ ,\ \forall\, 1,\ 2 \tag{A2}$$

The quantity of bagasse per hour combusted in the boilers of each sugar mill i is calculated using Equation (A3).

$$BagBrn_{iz} = \frac{AvBag_i}{OpHrs_z}\ ,\ \forall\, z = 1,\ 2\,; i = 1 \dots 50 \tag{A3}$$

The lower bagasse energy content in cal/ton is estimated using Equation (A4) extracted from [32], where bagasse humidity ($BagHum_i$) is an uncertain parameter, modeled by probability distributions for each mill i.

$$BagECont_i = 17{,}799.3 - 20{,}305.98 * BagHum_i \; \forall \; i = 1 \ldots 50 \quad \text{(A4)}$$

Equation (A5) calculates the bagasse energy flow per hour.

$$BagEFlow_{iz} = BagBrn_{iz} * BagECont_i \;, \forall \; i = 1 \ldots 50 \quad \text{(A5)}$$

Steam production in tons at each sugar mill i is calculated using Equation (A6).

$$Steam_{iz} = \frac{BagEFlow_i \left(\frac{BoilerEf}{DEnthalpy} \right)}{1000}, \; \forall \; i = 1 \ldots 50 \quad \text{(A6)}$$

Electric power generation in MWh at each mill i is estimated using Equation (A7).

$$ElecPwr_{iz} = \frac{Steam_i - (\%SelfCons * Steam_i)}{GenPerf}, \; \forall \; i = 1 \ldots 50 \quad \text{(A7)}$$

Table A1. Complementary calculations glossary.

Variable	Description
%Downtime	Fraction of inactivity time (%)
%SteamSelfCons	Percentage of steam consumption (%)
$AvBag_i$	Available bagasse at each sugar mill i (tons)
$BagBrn_{iz}$	Bagasse burning flow at mill i during period z (tons/hour)
$BagECont_i$	Bagasse energy content at mill i (kcal/ton)
$BagEFlow_{iz}$	Bagasse energy content flow at mill i (kcal/hour)
$BagHum_i$	Mass fraction of humidity content at mill i (%)
$BagInCane_i$	Mass fraction of bagasse in sugar cane at each sugar mill i (bagasse tons/sugarcane tons)
BoilerEf	Boiler efficiency (%)
DEnthalpy	Steam delta enthalpy (kcal/cm^2)
$ElecPwr_{iz}$	Electric power generation at mill i during period z (MWh)
GenPerf	Electric generator turbine performance (steam tons/MWh)
DOp_z	Operation days during period z (days)
$OpHrs_z$	Operation hours during period z (hours)
$Steam_{iz}$	Steam production at mill i during period z (tons/hour)
$tCane_i$	Sugar cane available at each sugar mill i (tons)

Appendix B

Table A2. Probability distributions for bagasse availability modelling.

Sugar Mill	tCane (Tons)	BagInCane	BagHum (%)
Aaron Sáenz	RiskLaplace (1,062,951, 162,684.8)	RiskExtvalueMin (0.28208, 0.0052635)	RiskPareto (45.277, 50.01)
Alianza popular	RiskPareto (15.534, 1,091,755)	RiskPareto (17.647, 0.24674)	RiskUniform (42.853, 54.287)
Ameca	RiskUniform (1,032,772, 1,314,071)	RiskExtvalueMin (0.24318, 0.007397)	RiskPareto (47.183, 49.841)
Atencingo	RiskUniform (1,539,709, 1,931,089)	RiskExtvalueMin (0.28181, 0.0017849)	RiskPareto (227.42, 50.64)
Azsuremex	RiskUniform (111,320, 236,294)	RiskExtvalueMin (0.35416, 0.024192)	RiskExtvalueMin (51.1982, 0.88002)

Table A2. *Cont.*

Sugar Mill	tCane (Tons)	BagInCane	BagHum (%)
Bellavista	RiskUniform (544,556, 767,230)	RiskLaplace (0.26549, 0.0042446)	RiskExtvalueMin (51.7613, 0.39862)
Benito Juárez	RiskUniform (915,567, 1,669,420)	RiskExtvalueMin (0.29877, 0.0024705)	RiskExtvalueMin (51.2247, 0.46764)
Calipam	RiskLaplace (185,777.6667, 24,246.0872)	RiskPareto (17.107, 0.31175)	RiskExtvalueMin (50.8465, 0.70592)
Casasano La abeja	RiskPareto (17.203, 581,923)	RiskPareto (34.074, 0.25738)	RiskKumaraswamy (0.075606,0.18032, 46.1,51.18)
Constancia	RiskPareto (10.619, 751,826)	RiskLaplace (0.27543, 0.010389)	RiskPareto (98.361, 49.106)
Cuatolapam	RiskPareto (8.3168, 669,112)	RiskExtvalue (0.283955, 0.016257)	RiskUniform (49.9225, 51.9875)
El Carmen	RiskExtvalueMin (565,173.2923, 110,856.4894)	RiskExtvalueMin (0.323, 0.010938)	RiskKumaraswamy (0.078411, 0.19166, 50.629, 53.053)
El Higo	RiskNormal (1,758,914, 89,388)	RiskNormal (0.3233037, 0.0076643)	RiskUniform (51.7425, 56.0475)
El Mante	RiskUniform (606,942, 1,101,350)	RiskKumaraswamy (0.076156, 0.18217, 0.296446, 0.314114)	RiskLaplace (51.1, 0.44173)
El Modelo	RiskExtvalueMin (1,059,250.2819, 96,686.0013)	RiskPareto (25.15, 0.26806)	RiskTriang (48.7756, 50.41, 50.41)
El Molino	RiskPareto (5.0488, 681,227)	RiskPareto (77.099, 0.27102)	RiskPareto (135.6, 50.25)
El Potrero	RiskNormal (1,629,870, 78,703)	RiskPareto (66.285, 0.2666)	RiskTriang (47.8444, 50.61, 50.61)
El Refugio	RiskExtvalueMin (460,201.2784, 48,913.5247)	RiskPareto (145.56, 0.28926)	RiskPareto (63.715, 49.85)
El Dorado	RiskNormal (451,622, 124,580)	RiskPareto (20.357, 0.26842)	RiskTriang (48.5712, 51.865, 51.865)
Emiliano Zapata	RiskUniform (1,001,194, 1,241,654)	RiskPareto (12.091, 0.26608)	RiskKumaraswamy (0.079838, 0.18665, 48.426, 54.43)
Huixtla	RiskUniform (865,578, 1,386,963)	RiskLaplace (0.27892, 0.016637)	RiskLaplace (50.12, 0.52322)
José Ma Morelos	RiskLaplace (573,662, 97,203.5759)	RiskLaplace (0.30045, 0.0091253)	RiskTriang (48.274, 52.01, 52.01)
La Gloria	RiskExtvalue (1,387,788, 128,254)	RiskLaplace (0.27426, 0.0057259)	RiskKumaraswamy (0.073444, 0.19034, 47.59, 50.08)
La Joya	RiskPareto (6.2914, 662,566)	RiskUniform (0.260448, 0.28558)	RiskPareto (25.533, 48.01)
La Margarita	RiskExtvalueMin (1,114,659.5247, 65,442.6361)	RiskPareto (69.982, 0.29615)	RiskKumaraswamy (0.081137, 0.18753, 48.63, 51.85)
La providencia	RiskUniform (622,858, 921,585)	RiskPareto (20.115, 0.25945)	RiskKumaraswamy (0.074596, 0.18167, 47.5, 51.71)
Lázaro Cárdenas	RiskUniform (220,651, 420,987)	RiskPareto (25.779, 0.21863)	RiskKumaraswamy (0.074316, 0.18577, 49.732, 51.932)
López Mateos	RiskLaplace (1,552,596, 164,296.2606)	RiskExtvalue (0.2769587, 0.004824)	RiskPareto (51.682, 50.35)
Mahuixtlan	RiskUniform (345,480, 488,480)	RiskExtvalueMin (0.27271, 0.0014487)	RiskLaplace (49.9522, 0.10657)
Melchor Ocampo	RiskLaplace (1,110,585, 54,862.1928)	RiskLaplace (0.28742, 0.0042788)	RiskKumaraswamy (0.075628, 0.18143, 50.36, 53.11)
Motzorongo	RiskLaplace (1,301,433, 203,462.3613)	RiskPareto (24.532, 0.25684)	RiskLaplace (49.89, 0.33796)
Panuco	RiskUniform (1,299,749, 1,906,185)	RiskPareto (48.802, 0.31117)	RiskExtvalue (50.1014, 1.0208)

Table A3. Probability distributions for operation days and bagasse utilization.

Variable	Probability Distribution	Unit
OpDays during harvesting period (z = 1)	Pert (155,160,179)	Days
OpDays during non-harvesting season (z = 2)	Pert (30,32.82,35.65)	Days
AvBag for energy production (z = 1)	Pert (52%,52.42%,52.848%)	% de Bagazo
AvBag for energy production (z = 2)	Pert (7%,7.33%,7.68%)	% de Bagazo

Appendix C

Table A4. Probability distributions for electricity and water prices modelling.

Region (r)	Electricity Price ($/MW)	Water Price ($/m^3)
Northwest	Pert (26.23, 35.23, 44.19)	Pert (0.18, 0.40, 0.56)
North	Pert (26.23, 35.23, 44.19)	Pert (0.18, 0.40, 0.56)
Northeast	Pert (41.06, 64.33, 79.26)	Pert (0.07, 0.24, 0.73)
West	Pert (37.21, 60.66, 76.98)	Pert (0.13, 0.23, 0.44)
Center	Pert (42.99, 67.58, 86.21)	Pert (0.038, 0.11, 0.238)
South	Pert (42.99, 67.58, 86.21)	Pert (0.025, 0.093, 0.159)
Gulf	Pert (41.23, 64, 81.47)	Pert (0.105, 0.236, 0.236)
Southeast	Pert (42.42, 66.28, 81)	Pert (0.0951, 0.190, 0.190)

Appendix D

Table A5. Storage availability and probability distributions for fuel prices modelling.

Region	State	ID (t)	Name	Design Capacity (Barrels)	Utilization Rate	Fuel Price (MX$)
Northwest	B.C. Norte	1	ROSARITO	1,393,000	0.73	RiskLogistic (19.20514, 0.18998)
	B.C. Norte	2	ENSENADA	135,000	0.74	RiskLogistic (19.39158, 0.18992)
	B.C. Norte	3	MEXICALI	155,000	0.76	RiskLogistic (19.45041, 0.19028)
	Sonora	4	NOGALES	45,000	0.77	RiskLaplace (19.6776, 0.30941)
	Sonora	5	MAGDALENA	40,000	0.67	RiskLaplace (19.6675, 0.32126)
	Sonora	6	HERMOSILLO	125,000	0.69	RiskLaplace (19.3266, 0.32346)
	Sonora	7	GUAYMAS	750,000	0.71	RiskLaplace (19.1096, 0.32513)
	Sonora	8	CIUDAD OBREGÓN	170,000	0.66	RiskLaplace (19.3257, 0.32251)
	Sonora	9	NAVOJOA	35,000	0.72	RiskLoglogistic (15.3836, 4.3047, 24.893)
	B.C. Sur	10	LA PAZ	230,000	0.7	RiskExtvalueMin (19.6679, 0.37766)
	Sinaloa	11	TOPOLOBAMPO	760,000	0.71	RiskTriang (17.9917, 19.7924, 20.1903)
	Sinaloa	12	GUAMÚCHIL	105,000	0.71	RiskTriang (18.7036, 20.2588, 20.8076)
	Sinaloa	13	CULIACÁN	115,000	0.74	RiskTriang (18.8595, 20.0375, 20.6478)
	Sinaloa	14	MAZATLÁN	620,000	0.75	RiskWeibull (5.175, 1.5556)
	Nayarit	15	TEPIC	95,000	0.7	RiskLaplace (19.6781, 0.27458)
North	Chihuahua	16	CIUDAD JUÁREZ	245,000	0.75	RiskLaplace (18.6858, 0.32223)
	Chihuahua	17	CHIHUAHUA	420,000	0.8	RiskLaplace (19.1491, 0.30599)
	Durango	18	DURANGO	75,000	0.69	RiskLaplace (19.6863, 0.27829)
	Chihuahua	19	PARRAL	55,000	0.73	RiskLaplace (19.6639, 0.3026)
	Durango	20	GÓMEZ PALACIO	475,000	0.72	RiskLaplace (19.5364, 0.30492)
Northeast	Coahuila	21	SABINAS	100,000	0.73	RiskLaplace (19.5153, 0.319)
	Coahuila	22	MONCLOVA	235,000	0.77	RiskLaplace (19.4711, 0.33153)
	Tamaulipas	23	NUEVO LAREDO	75,000	0.78	RiskLaplace (19.34, 0.3101)
	Tamaulipas	24	REYNOSA	23,500	0.62	RiskLaplace (19.3046, 0.33903)
	Nuevo León	25	SANTA CATARINA	850,000	0.69	RiskLoglogistic (18.23, 1.0127, 6.1548)
	Nuevo León	26	SALTILLO	151,000	0.78	RiskLaplace (19.4162, 0.33261)
	Nuevo León	27	CADEREYTA	100,000	0.75	RiskLoglogistic (17.4049, 1.7244, 10.6)
	SLP	28	MATEHUALA	33,000	0.74	RiskLoglogistic (18.1427, 1.272, 7.2404)
	Tamaulipas	29	CIUDAD VICTORIA	195,000	0.75	RiskLoglogistic (17.8593, 1.2518, 7.2491)
	Tamaulipas	30	CIUDAD MANTE	21,000	0.71	RiskLaplace (19.0238, 0.35456)
	SLP	31	CIUDAD VALLES	75,000	0.74	RiskLoglogistic (17.792, 1.2502, 7.2677)
	SLP	32	SAN LUIS POTOSÍ	100,000	0.69	RiskLaplace (19.1377, 0.34971)

Table A5. *Cont.*

Region	State	ID (t)	Name	Design Capacity (Barrels)	Utilization Rate	Fuel Price (MX$)
West	Zacatecas	33	ZACATECAS	85,000	0.68	RiskLaplace (19.5594, 0.3408)
	Aguascalientes	34	AGUASCALIENTES	105,000	0.65	RiskLaplace (19.5644, 0.33496)
	Guanajuato	35	LEÓN	110,000	0.73	RiskLaplace (19.5183, 0.32495)
	Jalisco	36	ZAPOPAN	390,000	0.72	RiskLoglogistic (18.47193, 0.94869, 5.5621)
	Michoacán	37	ZAMORA	90,000	0.71	RiskLaplace (19.6637, 0.32359)
	Guanajuato	38	IRAPUATO	430,000	0.73	RiskLaplace (19.5297, 0.31447)
	Guanajuato	39	CELAYA	180,000	0.72	RiskLaplace (19.5235, 0.32444)
	Michoacán	40	URUAPAN	130,000	0.79	RiskLoglogistic (18.1592, 1.2971, 7.5307)
	Colima	41	COLIMA	55,000	0.79	RiskLoglogistic (18.1186, 1.1784, 7.112)
	Michoacán	43	MORELIA	135,000	0.73	RiskLaplace (19.5371, 0.30931)
	Jalisco	44	EL CASTILLO	345,000	0.64	RiskLoglogistic (18.52751, 0.91876, 5.1437)
	Michoacán	45	LÁZARO CÁRDENAS	830,000	0.73	RiskLaplace (18.7947, 0.33233)
	Colima	46	MANZANILLO	465,000	0.71	RiskLaplace (18.773, 0.31928)
Center	Morelos	47	CUAUTLA	60,000	0.75	RiskLaplace (19.3723, 0.31474)
	Puebla	48	PUEBLA	425,000	0.71	RiskLaplace (19.2147, 0.31217)
	Puebla	49	TEHUACÁN	45,000	0.72	RiskLaplace (19.2166, 0.32322)
	Querétaro	50	QUERÉTARO	230,000	0.72	RiskLaplace (19.4604, 0.31185)
	Edo. De México	51	SAN JUAN IXHUATEPEC	225,000	0.62	RiskLoglogistic (18.26004, 0.9894, 5.5995)
	Morelos	52	CUERNAVACA	135,000	0.76	RiskLoglogistic (18.0638, 1.2074, 7.239)
	Edo. De México	53	TOLUCA	195,000	0.69	RiskLoglogistic (17.5463, 1.7658, 11.077)
	CDMX	54	AZCAPOTZALCO	1,500,000	0.74	RiskLoglogistic (18.0401, 1.1, 6.6497)
	Hidalgo	55	PACHUCA	170,000	0.71	RiskLoglogistic (18.0877, 1.0409, 6.3148)
	CDMX	56	BARRANCA DEL MUERTO	125,000	0.73	RiskLoglogistic (18.26353, 0.99106, 5.6165)
	CDMX	57	AÑIL	235,000	0.67	RiskLoglogistic (18.24477, 0.99028, 5.7233)
South	Guerrero	58	IGUALA	60,000	0.7	RiskLaplace (19.4913, 0.30988)
	Guerrero	59	ACAPULCO	235,000	0.62	RiskLaplace (19.1366, 0.31701)
	Oaxaca	60	OAXACA	110,000	0.76	RiskLaplace (19.3487, 0.31066)
	Oaxaca	61	SALINA CRUZ*	1,479,000	0.76	RiskLogistic (18.86307, 0.18242)
	Oaxaca	62	SALINA CRUZ	205,000	0.75	RiskLogistic (18.86307, 0.18242)
	Chiapas	63	TUXTLA GUTIÉRREZ	105,000	0.71	RiskLogistic (19.02036, 0.17406)
	Chiapas	64	TAPACHULA*	24,500	0.62	RiskLaplace (19.3375, 0.30994)
	Chiapas	65	TAPACHULA II	65,000	0.78	RiskLaplace (19.3375, 0.30994)
Gulf	Veracruz	66	POZA RICA	55,000	0.7	RiskLaplace (18.8571, 0.31891)
	Veracruz	67	PEROTE	25,000	0.74	RiskLoglogistic (17.8551, 1.265, 7.42)
	Veracruz	68	XALAPA	45,000	0.6	RiskLoglogistic (17.8126, 1.2419, 7.1738)
	Veracruz	69	ESCAMELA	98,000	0.72	RiskLaplace (19.0548, 0.32629)
	Veracruz	70	VERACRUZ	536,000	0.66	RiskLaplace (18.4593, 0.32756)
	Veracruz	71	TIERRA BLANCA	71,000	0.69	RiskLaplace (19.0025, 0.31694)
	Veracruz	72	MINATITLÁN	10,000	0.59	RiskLogistic (18.67753, 0.18353)
	Tabasco	73	VILLAHERMOSA	328,500	0.72	RiskLaplace (18.9172, 0.31921)
Southeast	Yucatán	74	PROGRESO	280,500	0.71	RiskLaplace (18.4223, 0.32023)
	Campeche	75	CAMPECHE	265,000	0.79	RiskLaplace (18.9739, 0.31608)
	Yucatán	76	MÉRIDA	148,000	0.77	RiskLaplace (18.4635, 0.31978)

Appendix E

Distance Matrix (km)		Northwest (BC, BCS, Sonora, Sinaloa, Nayarit)															North (Chihuahua, Durango)				
		ROSARITO	ENSENADA	MEXICALI	NOGALES	MAGDALENA	HERMOSILLO	GUAYMAS	CIUDAD OBREGÓN	NAVOJOA	LA PAZ	TOPOLOBAMPO	GUAMÚCHIL	CULIACÁN	MAZATLÁN	TEPIC	CD JUAREZ	CHIHUAHUA	DURANGO	PARRAL	GOMEZ PALACIO
Northwest	El Molino	2052	2070	1873	1430	1343	1150	1021	903	824	913	694	583	474	271	6.5	1449	1145	481	895	707
	El Dorado	1633	1652	1455	1012	924	732	603	484	405	495	275	168	55.5	175	448	1400	1058	432	847	658
	Puga	2059	2244	1880	1437	1350	1157	1028	909	830	920	700	590	481	278	19.2	1455	1152	488	902	713
Northeast	Aaron Saenz	2688	2753	2488	1989	1946	2155	2031	1905	1838	4119	1557	1444	1344	1131	862	1586	1184	774	1069	735
	Alianza Popular	2727	2792	2527	2219	2129	1940	1816	1690	1623	4189	1488	1374	1274	1061	793	1637	1268	709	1153	842
	El Mante	2714	2780	2515	2003	1960	2169	2045	1919	1852	4146	1545	1432	1332	1119	850	1581	1212	771	1097	764
	Plan de Ayala	2773	2839	2574	2265	2176	1987	1862	1737	1669	4235	1534	1421	1321	1108	839	1682	1313	755	1198	865
	Plan de SL	2682	2683	2710	2012	1973	1933	1803	1685	1610	1716	1475	1381	1257	1050	847	1628	1257	787	1129	807
	San Miguel	2876	2647	2674	1976	1937	1875	1746	1627	1552	1658	1418	1323	1199	992	789	1592	1221	729	1093	771
West	Ameca	2253	2272	2074	1629	1544	1351	1223	1104	1025	1115	895	783	676	473	192	2089	1237	702	1097	799
	Bellavista	2279	2279	2100	1655	1570	1377	1248	1129	1050	1140	920	810	701	498	226	1572	1203	667	1088	764
	Jose Ma Morelos	2442	2477	2278	1832	1747	1554	1425	1306	1231	1318	1097	1002	878	673	398	1758	1387	851	1259	949
	Lazaro Cardenas	2524	2560	2360	1914	1829	1636	1507	1388	1313	1400	1179	1084	960	756	480	1721	1350	814	1222	913
	Melchor Ocampo	2398	2434	2234	1788	1703	1511	1381	1262	1187	1274	1053	958	834	630	354	1714	1343	808	1215	906
	Pedernales	2632	2668	2468	2022	1937	1744	1615	1496	1421	1508	1287	1192	1068	864	588	1739	1368	832	1240	930
	Quesería	2383	2419	2219	1773	1688	1495	1366	1247	1172	1259	1038	943	819	615	339	1699	1328	793	1200	891
	Santa Clara	2442	2477	2278	1832	1747	1554	1425	1306	1231	1318	1097	1002	878	673	398	1677	1308	772	1179	870
	Tala	2232	2268	2068	1622	1538	1345	1215	1097	1022	1108	887	793	668	464	189	1567	1198	662	1083	759
	Tamazula	2374	2410	2211	1765	1680	1487	1358	1239	1164	1251	1029	935	811	606	331	1685	1316	781	1202	878
Center	Atencingo	2922	2988	2722	2307	2218	2029	1905	1779	1712	4353	1576	1463	1363	1150	881	1981	1612	1077	1498	1174
	Calipam	3021	3087	2822	2407	2317	2128	2004	1878	1811	4453	1676	1562	1463	1250	981	2067	1698	1163	1584	1260
	Casasano	2858	2923	2658	2243	2154	1965	1840	1715	1647	4289	1512	1399	1299	1086	817	1883	1514	979	1399	1076
	Emiliano Zapata	2878	2944	2679	2264	2174	1985	1861	1735	1668	4310	1533	1420	1320	1107	838	1909	1540	1005	1426	1102
South	El refugio	3114	3179	2914	2499	2410	2221	2096	1971	1903	4545	1768	1655	1555	1342	1073	2115	1764	1232	1622	1318
	Huixtla	3873	3939	3674	3259	3169	2980	2856	2730	2663	5305	2528	2414	2315	2102	1833	2875	2523	1991	2392	2077
	La margarita	3158	3223	2958	2543	2454	2265	2140	2015	1947	4589	1812	1699	1599	1386	1117	2158	1764	1232	1622	1318
	López Mateos	3210	3275	3010	2595	2506	2317	2192	2067	1999	4641	1864	1751	1651	1438	1169	2274	1922	1328	1781	1414
Gulf	Azsuremex	3733	3799	3534	3119	3029	2840	2716	2590	2523	5165	2388	2274	2174	1961	1693	2735	2383	1851	2242	1937
	Benito Juárez	3471	3537	3272	2857	2767	2578	2454	2328	2261	4903	2126	2012	1912	1699	1431	2473	2121	1589	1980	1675
	Constancia	3114	3179	2914	2499	2410	2221	2096	1971	1903	4545	1768	1655	1555	1342	1073	2115	1764	1232	1622	1318
	Cuatotolapan	3292	3357	3092	2677	2588	2399	2274	2149	2081	4723	1946	1833	1733	1520	1251	2293	1942	1410	1800	1496
	El Carmen	3038	3104	2839	2424	2334	2145	2021	1895	1828	4470	1693	1579	1479	1267	998	2040	1688	1156	1547	1242
	El Higo	2965	3030	2765	2350	2261	2072	1947	1822	1754	4396	1619	1506	1406	1193	924	1754	1402	870	1261	956
	El Modelo	3156	3222	2957	2542	2452	2263	2139	2013	1946	4588	1811	1697	1597	1384	1115	2136	1785	1253	1643	1339
	El Potrero	3064	3129	2864	2449	2360	2171	2046	1921	1853	4495	1718	1605	1505	1292	1023	2065	1714	1182	1572	1268
	La Gloria	3156	3222	2957	2542	2452	2263	2139	2013	1946	4588	1811	1697	1597	1384	1115	2136	1785	1253	1643	1339
	La providencia	3091	3156	2891	2476	2387	2198	2073	1948	1880	4522	1745	1632	1532	1319	1050	2092	1741	1209	1599	1295
	Mahuixtlán	3092	3157	2892	2477	2388	2198	2074	1949	1881	4523	1746	1633	1533	1320	1051	2072	1721	1188	1579	1275
	Motzorongo	3103	3168	2903	2488	2399	2210	2085	1960	1892	4534	1757	1644	1544	1331	1062	2104	1753	1221	1611	1307
	Panuco	2998	3063	2798	2383	2294	2105	1980	1855	1787	4429	1652	1539	1439	1226	957	1787	1435	903	1294	989
	Progreso	3278	3343	3078	2663	2574	2385	2260	2135	2067	4709	1932	1819	1719	1506	1237	2279	1928	1396	1786	1482
	San Cristobal	3212	3277	3012	2597	2508	2319	2194	2069	2001	4643	1866	1753	1653	1440	1171	2213	1862	1330	1720	1416
	San José de Abajo	3077	3142	2877	2462	2373	2184	2059	1934	1866	4508	1731	1618	1518	1305	1036	2078	1727	1195	1585	1281
	San Miguelito	3064	3129	3064	3129	2864	2449	2360	2171	2046	1921	1853	4495	1718	1605	1505	1292	1023	2065	1714	1182
	San Nicolas	3064	3129	3064	3129	2864	2449	2360	2171	2046	1921	1853	4495	1718	1605	1505	1292	1023	2065	1714	1182
	San Pedro	3278	3343	3078	2663	2574	2385	2260	2135	2067	4709	1932	1819	1719	1506	1237	2279	1928	1396	1786	1482
	Santa Rosalia	3471	3537	3272	2857	2767	2578	2454	2328	2261	4903	2126	2012	1912	1699	1431	2473	2121	1589	1980	1675
	Tres Valles	3153	3218	2953	2538	2449	2260	2135	2010	1942	4584	1807	1694	1594	1381	1112	2154	1803	1271	1661	1357
Southeast	La Joya	3838	3094	3639	3224	3134	2945	2821	2695	2628	5270	2493	2379	2280	2067	1798	2840	2488	1956	2347	2042
	Pucte	4105	4276	4011	3596	3506	3317	3193	3067	3000	5642	2865	2751	2651	2438	2169	3212	2860	2328	2719	2414

		Northeast (NL, Tam, SLP, Coa)												West (Zacatecas, Aguascalientes, Jalisco, Colima, Michoacán y Gto)												
		SABINAS	MONCLOVA	NUEVO LAREDO	REYNOSA	SANTA CATARINA	SALTILLO	CADEREYTA	MATEHUALA	CIUDAD VICTORIA	CIUDAD MANTE	CIUDAD VALLES	SAN LUIS POTOSÍ	ZACATECAS	AGUASCALIENTES	LEÓN	ZAPOPAN	ZAMORA	IRAPUATO	CELAYA	URUAPAN	COLIMA	MORELIA	EL CASTILLO	LÁZARO CÁRDENAS	MANZANILLO
Northwest	El Molino	1103	991	1268	1274	1047	978	1096	737	872	850	839	561	527	412	417	191	356	488	538	467	380	471	229	702	460
	El Dorado	1104	992	1270	1276	1049	979	1098	1219	1354	1332	1321	1042	733	850	856	630	795	892	976	906	819	910	668	1141	898
	Puga	1103	991	1268	1274	1047	978	1096	737	872	850	839	561	539	423	429	203	368	500	549	479	392	483	241	714	471
Northeast	Aaron Saenz	748	602	627	437	412	471	381	304	112	31.1	125	311	483	475	498	653	651	503	548	721	848	679	645	942	927
	Alianza Popular	844	738	837	610	606	561	554	306	276	146	50	246	418	410	428	588	573	438	483	656	783	542	580	877	862
	El Mante	737	630	655	465	440	499	409	301	132	4.4	99	308	480	472	495	650	636	500	545	718	845	604	642	939	924
	Plan de Ayala	890	784	752	562	536	607	505	352	229	97	1.6	291	460	550	420	635	619	487	498	702	823	587	621	918	908
	Plan de SL	830	724	746	567	540	546	512	291	231	99	44	318	488	584	501	663	647	514	526	730	851	615	649	946	935
	San Miguel	794	688	707	528	501	510	473	255	192	60	84	260	430	426	444	605	589	456	498	672	793	557	591	888	878
West	Ameca	1089	1089	1087	1072	1072	792	921	610	739	721	703	416	414	293	299	72	239	337	417	349	234	352	110	580	318
	Bellavista	1054	948	1053	1037	821	757	887	576	705	688	669	382	381	259	265	49	202	299	383	312	176	315	66	500	260
	Jose Ma Morelos	1241	1134	1232	1221	1008	944	1069	757	886	896	850	563	562	440	446	231	383	481	565	493	222	496	247	476	131
	Lazaro Cardenas	1150	1043	1137	1075	911	866	972	611	740	723	704	428	525	403	297	296	140	228	234	18	32	132	282	214	565
	Melchor Ocampo	1197	1091	1189	1177	965	901	1025	713	842	825	806	519	518	396	402	187	339	437	521	449	176	453	203	499	179
	Pedernales	1168	1061	1155	1092	929	884	990	629	758	740	722	446	543	421	315	404	268	246	252	133	589	150	390	277	673
	Quesería	1182	1076	1174	1161	949	889	1010	698	827	810	791	504	503	381	387	172	324	422	506	270	34.5	438	188	407	119
	Santa Clara	1145	1038	1132	1069	906	861	967	606	735	717	699	423	482	360	236	214	81	225	275	82	219	226	200	313	303
	Tala	1049	943	1046	1033	822	758	882	570	699	682	663	376	383	253	259	32.5	199	297	378	310	214	313	70.7	541	299
	Tamazula	1168	1062	1165	1153	941	877	1001	690	819	801	783	496	503	373	379	206	175	287	336	213	88.4	309	180	398	173
Center	Atencingo	1328	1222	1315	1075	1090	1045	1151	789	918	741	669	607	789	681	575	757	621	509	456	604	897	489	743	685	982
	Calipam	1417	1311	1404	1131	1179	1133	1240	870	862	789	718	687	870	762	656	838	702	590	537	684	1024	570	825	901	1115
	Casasano	1231	1124	1217	1032	992	947	1053	691	821	699	784	509	692	584	478	640	503	412	359	486	824	371	626	702	908
	Emiliano Zapata	1257	1151	1244	1086	1116	974	1080	718	847	752	811	536	718	611	504	663	526	438	386	509	847	394	649	592	931
South	El refugio	1460	1348	1444	1113	1223	1173	1272	914	878	769	684	737	928	820	713	896	759	647	595	742	1080	627	882	958	1164
	Huixtla	2220	2108	2204	1792	1983	1933	2032	1674	1557	1448	1363	1497	1687	1584	1478	1661	1524	1412	1359	1507	1845	1392	1646	1723	1929
	La margarita	1504	1392	1488	1077	1267	1217	1316	958	841	732	648	781	945	837	731	913	777	665	612	759	1098	645	899	976	1182
	López Mateos	1556	1444	1540	1129	1319	1269	1368	1010	893	784	700	833	1018	910	803	986	849	737	685	832	1170	717	972	1048	1254
Gulf	Azsuremex	2079	1973	2066	1641	1841	1795	1642	1540	1379	1307	1245	1357	1581	1455	1333	1500	1376	1266	1213	1363	1680	1254	1491	1605	1785
	Benito Juárez	1812	1705	1799	1373	1573	1528	1375	1273	1112	1039	1039	1090	1319	1193	1071	1238	1114	1004	951	1101	1418	992	1229	1343	1523
	Constancia	1456	1349	1443	1065	1217	1172	1278	917	804	731	730	734	928	820	713	896	759	647	595	742	1080	627	882	958	1164
	Cuatotolapan	1625	1519	1612	1186	1350	1341	1188	1086	925	853	852	903	1139	1014	891	1059	934	825	771	922	1239	813	1050	1163	1344
	El Carmen	1392	1285	1379	1106	1153	1108	1214	853	982	772	700	670	886	760	638	805	681	571	518	668	985	559	796	910	1090
	El Higo	973	867	820	601	613	689	585	434	313	182	108	371	568	568	574	732	707	559	436	820	912	711	723	1062	1017
	El Modelo	1450	1148	1166	930	960	1167	932	911	669	596	595	729	1004	857	734	923	798	668	614	786	1082	677	914	1028	1187
	El Potrero	1422	1315	1409	1057	1183	1152	1244	883	796	723	722	700	911	786	663	831	706	597	543	694	1011	585	822	935	1116
	La Gloria	1450	1144	1162	926	956	1189	928	920	665	592	591	737	1004	857	734	923	798	668	614	786	1082	677	914	1028	1187
	La providencia	1430	1324	1417	1062	1192	1146	1252	891	801	728	591	708	938	813	690	858	733	624	570	721	1038	612	849	962	1143
	Mahuixtlán	1400	1294	1202	945	975	1116	947	861	684	612	611	678	939	793	670	858	734	603	550	722	1018	613	849	963	1123
	Motzorongo	1450	1343	1436	1071	1211	1166	1073	911	810	737	737	728	3103	3103	3103	3103	3103	3103	3103	3103	3103	3103	3103	3103	3103
	Panuco	871	764	783	543	576	636	548	476	264	184	149	413	601	601	607	765	740	592	647	846	945	737	756	1088	1050
	Progreso	1436	1329	1422	1034	1197	1152	1036	896	773	184	699	714	1125	1000	877	1045	920	811	757	908	1225	799	1036	1149	1330
	San Cristobal	1551	1444	1369	1112	1312	1267	1114	1012	851	779	778	829	1059	934	811	979	854	745	691	842	1159	733	970	1083	1264
	San José de Abajo	1426	1320	1413	1059	1188	1142	1248	887	798	725	725	704	924	799	676	844	719	610	556	707	1024	598	835	948	1129
	San Miguelito	1572	1268	1397	1067	1172	1127	1233	871	806	734	733	689	911	786	663	831	706	597	543	694	1011	585	822	935	1116
	San Nicolas	1418	1311	1404	1077	1179	1134	1240	878	817	744	743	696	911	786	663	831	706	597	543	694	1011	585	822	935	1116
	San Pedro	1594	1488	1324	1066	1096	1310	1068	1055	805	733	732	872	1125	1000	877	1045	920	811	757	908	1225	799	1036	1149	1330
	Santa Rosalia	1833	1727	1820	1394	1595	1549	1396	1294	1133	1061	999	1111	1319	1193	1071	1238	1114	1004	951	1101	1418	992	1229	1343	1523
	Tres Valles	1525	1419	1512	1087	1287	1242	1089	986	826	753	752	804	1000	875	752	920	795	686	632	783	1100	674	911	1024	1205
Southeast	La Joya	2185	2073	2169	1757	1948	1898	1997	1639	1522	1413	1328	1462	1686	1561	1438	1605	1481	1371	1318	1469	1785	1359	1596	1710	1890
	Pucte	2557	2445	2541	2129	2320	2270	2369	2010	1894	1785	1700	1833	2058	1932	1810	1977	1852	1743	1689	1840	2157	1731	1968	2082	2262

Figure A1. *Cont.*

Center (Morelos, Pue, Qro, Edo.MX, CDMX, Hid, Tlaxc)											South (Chiapas, Guerrero, Oaxaca)							
CUAUTLA	PUEBLA	TEHUACÁN*	QUERÉTARO	SAN JUAN IXHUATEPEC	CUERNAVACA	TOLUCA	AZCAPOTZALCO	PACHUCA	BARRANCA DEL MUERTO	AÑIL	IGUALA*	ACAPULCO	OAXACA	SALINA CRUZ*	SALINA CRUZ	TUXTLA GUTIÉRREZ	TAPACHULA	TAPACHULA II
832	859	981	561	721	786	667	742	755	742	742	861	1102	1198	1531	1531	1569	1875	1875
1314	1341	1463	1043	1203	1268	1149	1224	1237	1224	1224	1343	1583	1680	2013	2013	2051	2357	2357
832	859	981	561	721	786	667	742	755	742	742	861	1102	1198	1531	1531	1569	1875	1875
711	663	751	496	698	794	691	695	552	706	709	877	1091	1040	1169	1169	1207	1513	1513
749	757	877	430	633	729	626	629	650	641	644	807	1022	987	1117	1117	1155	1460	1460
711	663	751	493	614	791	688	692	553	703	630	865	1038	1017	1146	1146	1184	1490	1490
795	579	676	476	679	774	669	673	353	687	692	854	1068	932	1062	1062	1100	1405	1405
734	619	716	504	706	801	696	701	508	714	720	903	1091	931	1151	1151	1199	1550	1550
765	771	900	446	649	744	638	643	669	657	662	845	1033	1116	1174	1174	1223	1574	1574
723	746	875	471	624	696	557	618	641	611	622	748	665	1047	1296	1296	1401	1752	1752
686	709	838	401	587	659	520	581	606	574	585	711	948	1053	1302	1302	1408	1758	1758
867	890	1019	618	768	840	701	762	788	755	766	892	1130	1234	1484	1484	1589	1939	1939
502	525	654	298	404	476	336	398	423	390	402	528	481	870	1119	1119	1224	1575	1575
823	846	975	539	724	796	657	719	744	711	723	848	1086	1191	1440	1440	1545	1896	1896
537	543	673	317	421	493	354	416	441	408	420	546	544	889	1137	1137	1242	1593	1593
808	831	960	524	709	781	642	704	729	696	708	833	674	1176	1425	1425	1530	1881	1881
614	619	740	327	497	569	430	492	517	484	496	622	580	964	1213	1213	1318	1669	1669
701	706	835	431	584	656	517	579	604	571	583	709	946	1051	1300	1300	1405	1756	1756
697	702	832	388	581	653	513	575	600	567	579	705	665	1047	1296	1296	1401	1752	1752
67.7	112	229	422	196	129	224	194	224	180	180	191	354	444	694	694	799	1149	1149
281	171	51	511	317	342	357	315	313	309	288	405	559	220	469	469	710	904	904
18.4	134	251	325	121	35.9	151	120	181	107	107	157	303	467	716	716	821	1172	1172
97.8	182	299	352	145	40.3	174	143	226	130	130	110	262	515	764	764	869	1220	1220
330	220	173	561	367	391	406	364	362	358	345	454	616	412	476	476	525	876	876
1095	985	937	1325	1132	1156	1171	1129	1127	1123	1110	1219	1063	628	416	416	326	61.2	61.2
348	238	190	578	385	409	424	382	380	376	363	471	634	430	480	480	529	879	879
420	310	263	651	457	481	496	454	452	533	435	544	706	215	320	320	460	650	650
943	833	785	1173	979	1004	1019	977	975	971	958	1066	1229	1025	677	677	448	1066	1066
676	566	518	906	709	736	751	709	707	703	691	799	962	757	409	409	217	568	568
320	210	162	550	353	380	395	353	351	347	335	443	606	401	477	477	526	876	876
489	379	331	719	525	550	565	523	520	516	504	612	775	571	292	292	341	692	692
256	146	98	486	317	316	331	289	287	283	271	379	542	337	500	500	548	899	899
527	482	579	557	435	542	501	452	371	456	453	643	831	795	953	953	1002	1353	1353
345	235	255	544	375	406	420	378	346	372	360	468	631	494	525	525	574	925	925
286	176	128	516	319	346	361	378	317	313	301	409	572	367	472	472	521	872	872
353	243	267	553	384	414	429	387	354	381	369	477	639	506	537	537	586	937	937
294	184	136	524	328	355	370	328	325	321	309	417	580	376	470	470	519	870	870
294	184	218	494	325	355	370	343	296	322	310	418	580	458	604	604	653	1004	1004
314	204	156	544	350	374	389	347	345	341	329	437	599	395	483	483	532	882	882
592	547	645	598	500	607	566	514	436	521	518	766	897	860	1009	1009	1058	1409	1409
299	189	142	530	336	360	375	333	331	327	315	423	585	381	486	486	535	885	885
415	305	257	645	451	476	490	449	446	443	430	538	701	496	360	360	409	760	760
290	180	132	520	326	351	366	324	321	317	305	413	576	372	474	474	523	874	874
274	164	117	504	311	335	350	308	306	302	290	398	560	356	483	483	535	882	882
281	171	124	512	318	342	357	315	313	309	297	405	567	363	493	493	542	892	892
458	348	300	688	494	519	534	492	489	4585	473	581	744	540	401	401	450	800	800
697	587	539	927	733	758	773	731	728	724	712	820	983	779	430	430	205	556	556
389	279	231	619	450	450	465	423	421	417	404	513	675	246	351	351	454	805	805
1043	944	864	1267	1130	1086	1135	1068	1081	1068	1068	1182	1373	1128	803	803	569	875	875
1415	1315	1235	1639	1502	1458	1507	1439	1452	1439	1439	1554	1745	1500	1175	1175	941	1247	1247

Gulf (Ver, Tab)								Southeast (Yuc, Camp, Q.Roo)		
POZA RICA	PEROTE	XALAPA	ESCAMELA	VERACRUZ	TIERRA BLANCA	MINATITLÁN	VILLAHERMOSA	PROGRESO	CAMPECHE	MÉRIDA
935	1002	1051	998	1135	1112	1308	1480	2052	1862	2020
1417	1483	1533	1479	1617	1594	1790	1961	2534	2344	9580
935	1002	1051	998	1135	1112	1308	1480	2052	1862	2020
551	585	770	634	728	926	1092	1688	1690	1500	1658
347	514	555	896	597	691	889	1056	1638	1448	1606
394	551	592	770	634	728	927	1093	1667	1477	1635
309	537	578	655	558	721	919	1084	1583	1393	1551
349	577	557	695	598	760	959	1124	1716	1514	1677
449	607	642	795	689	790	989	1154	1739	1538	1701
833	835	875	896	1025	1006	1204	1369	1930	1740	1899
796	797	838	859	945	968	1167	1332	2052	1862	2020
958	1025	1074	1021	1159	1136	1332	1503	2075	1885	2044
604	671	720	667	804	781	977	1148	1721	1531	1689
911	978	1027	974	1112	1089	1285	1456	2028	1838	1997
600	666	716	662	800	777	973	1144	1717	1527	1685
902	950	997	964	1102	1079	1275	1446	2019	1829	1987
682	749	798	745	882	859	1055	1227	1799	1609	1767
783	850	900	846	984	941	1157	1328	1900	1710	1869
770	837	886	833	971	948	1144	1315	1887	1697	1856
589	220	260	250	367	360	558	723	1228	1038	1196
446	216	261	169	290	270	469	634	1118	928	1086
347	242	283	272	390	382	580	746	1298	1108	1266
400	290	331	320	438	430	628	794	1348	1158	1316
359	254	207	83.4	109	50.4	284	450	1057	867	1025
1087	982	935	848	937	765	543	526	1087	897	1055
363	257	210	101	112	32.7	288	453	1020	830	989
413	307	260	173	162	59.3	219	385	941	751	910
935	829	783	696	685	612	391	220	590	389	552
668	562	515	429	417	345	123	67	659	457	620
360	254	207	72.7	109	55.3	285	450	1042	840	1003
481	375	328	242	231	158	100	266	857	656	819
420	164	141	5.1	129	109	308	473	1064	863	1026
213	380	420	559	461	563	761	926	1518	1317	1479
225	119	72.1	166	33.7	135	334	499	1090	889	1052
352	194	199	38.6	101	82	280	445	1037	836	998
221	128	80.7	147	45.6	147	345	511	1102	901	1064
357	202	204	46.8	106	75.4	278	444	1035	834	997
240	68.8	23.3	128	112	214	412	577	1169	968	1131
366	222	213	66.5	115	61.5	291	456	1048	846	1009
278	436	477	624	518	619	818	983	1574	1373	1536
329	223	176	52.4	91.5	95.6	294	459	1051	849	1012
407	301	254	168	156	84.2	168	333	925	724	886
354	198	201	42.9	103	84.2	282	448	1039	838	1001
362	183	210	112	92.4	281	456	362	1048	846	1009
373	190	220	34.3	122	103	301	466	1058	857	1019
361	255	208	211	111	180	209	374	966	764	927
689	583	536	450	439	366	144	53.3	645	444	606
381	276	229	142	131	28.1	214	379	970	769	932
1063	957	910	823	812	740	518	346	253	52	215
1312	1206	1159	1073	1062	989	767	689	257	307	217

Figure A1. Distance matrix for hydrogen transportation.

Toll Cost / trip		Northwest (BC, BCS, Sonora, Sinaloa, Nayarit)															North (Chihuahua, Durango)				
		ROSARITO	ENSENADA	MEXICALI	NOGALES	MAGDALENA	HERMOSILLO	GUAYMAS	CIUDAD OBREGÓN	NAVOJOA	LA PAZ	TOPOLOBAMPO	GUAMÚCHIL	CULIACÁN	MAZATLÁN	TEPIC	CD JUAREZ	CHIHUAHUA	DURANGO	PARRAL	GOMEZ PALACIO
Northwest	El Molino	243	248	189	177	173	163	158	147	137	248	117	108	96	69	0	420	369	192	319	283
	El Dorado	143	149	90	77	74	64	58	48	38	149	18	0	0	27	96	378	327	150	277	241
	Puga	243	248	189	177	173	163	158	147	137	248	117	108	96	69	0	420	369	192	319	283
Northeast	Aaron Saenz	232	238	179	159	159	345	339	329	319	214	225	216	204	177	108	175	123	23	73	28
	Alianza Popular	244	249	190	293	290	280	274	264	254	334	234	225	213	186	117	207	156	32	105	49
	El Mante	223	229	170	159	159	345	339	329	319	229	225	216	204	177	108	175	123	23	73	28
	Plan de Ayala	254	260	201	304	300	290	285	274	264	344	244	235	223	196	127	217	166	42	116	59
	Plan de SL	254	260	201	304	300	290	285	274	264	344	244	235	223	196	127	217	166	42	116	59
	San Miguel	254	260	201	304	300	290	285	274	264	344	244	235	223	196	127	217	166	42	116	59
West	Ameca	267	272	213	201	197	187	182	171	161	272	141	132	120	93	24	444	393	216	343	307
	Bellavista	267	272	213	201	197	187	182	171	161	272	141	132	120	93	24	444	393	216	343	307
	Jose Ma Morelos	267	272	213	201	197	187	182	171	161	272	141	132	120	93	24	444	393	216	343	307
	Lazaro Cardenas	312	317	258	246	242	232	227	216	206	317	186	177	165	138	69	282	231	107	181	145
	Melchor Ocampo	267	272	213	201	197	187	182	171	161	272	141	132	120	93	24	444	393	216	343	307
	Pedernales	306	312	253	240	237	227	221	211	201	312	181	172	160	133	63	266	215	91	165	129
	Quesería	303	309	250	237	234	224	218	208	198	309	178	169	157	130	60	284	233	109	183	147
	Santa Clara	299	304	245	233	229	219	213	203	193	304	173	164	152	111	56	224	172	48	122	86
	Tala	267	272	213	201	197	187	182	171	161	272	141	132	120	93	24	444	393	216	343	307
	Tamazula	285	291	232	219	216	205	200	190	179	291	159	151	139	111	42	266	215	234	165	129
Center	Atencingo	431	437	378	365	362	351	346	336	325	437	305	297	285	257	188	279	228	104	178	142
	Calipam	458	463	404	392	388	378	373	362	352	463	332	323	311	284	215	306	254	131	204	168
	Casasano	400	406	347	335	331	321	315	305	295	406	275	266	254	227	158	271	267	95	169	133
	Emiliano Zapata	396	402	343	331	327	317	311	301	291	402	271	262	250	223	154	265	213	89	163	127
South	El refugio	496	501	442	430	426	416	410	400	390	501	370	361	349	322	253	344	292	168	242	206
	Huixtla	596	602	543	530	527	517	511	501	491	602	471	462	450	422	353	444	393	269	343	307
	La margarita	506	511	452	440	436	426	420	410	400	511	380	371	359	332	263	344	292	168	242	230
	López Mateos	512	518	459	446	443	432	427	417	406	518	386	378	366	338	269	306	254	185	204	223
Gulf	Aszuremex	566	572	513	501	497	487	481	471	461	572	441	432	420	393	324	415	363	239	313	277
	Benito Juárez	560	566	507	494	491	480	475	465	454	566	434	425	414	386	317	408	357	233	307	271
	Constancia	496	501	442	430	426	416	410	400	390	501	370	361	349	322	253	344	292	168	242	206
	Cuatotolapan	526	531	472	460	456	446	440	430	420	531	400	391	379	352	283	374	322	198	272	236
	El Carmen	487	493	434	421	418	407	402	392	381	493	361	353	341	313	244	335	284	160	234	198
	El Higo	370	375	316	304	300	290	285	274	264	375	244	235	223	196	127	217	166	42	116	80
	El Modelo	493	498	439	427	423	413	408	397	387	498	367	358	346	319	250	348	296	172	246	210
	El Potrero	496	501	442	430	426	416	410	400	390	501	370	361	349	322	253	344	292	168	242	206
	La Gloria	493	498	439	427	423	413	408	397	387	498	367	358	346	319	250	348	296	172	246	210
	La providencia	496	501	442	430	426	416	410	400	390	501	370	361	349	322	253	344	292	168	242	206
	Mahuixtlán	466	471	412	400	396	386	381	370	360	471	340	331	319	292	223	321	269	145	219	183
	Motzorongo	496	501	442	430	426	416	410	400	390	501	370	361	349	322	253	344	292	168	242	206
	Panuco	375	381	322	309	306	296	290	280	270	381	250	241	229	201	132	223	171	48	121	85
	Progreso	526	531	472	460	456	446	440	430	420	531	400	391	379	352	283	374	322	198	272	236
	San Cristobal	522	527	468	456	452	442	437	426	416	527	396	387	375	348	279	370	318	195	268	232
	San José de Abajo	496	501	442	430	426	416	410	400	390	501	370	361	349	322	253	344	292	168	242	206
	San Miguelito	493	498	439	427	423	413	408	397	387	498	367	358	346	319	250	348	296	172	246	210
	San Nicolas	493	498	439	427	423	413	408	397	387	498	367	358	346	319	250	348	296	172	246	210
	San Pedro	526	531	472	460	456	446	440	430	420	531	400	391	379	352	283	374	322	198	272	236
	Santa Rosalia	560	566	507	494	491	480	475	465	454	566	434	425	414	386	317	408	357	233	307	271
	Tres Valles	506	511	452	440	436	426	420	410	400	511	380	371	359	332	263	344	292	168	242	230
Southeast	La Joya	593	598	539	527	523	513	508	497	487	598	467	458	446	419	350	441	389	266	339	303
	Pucte	603	608	549	537	533	523	517	507	497	608	477	468	456	429	360	451	399	275	349	313

Northeast (NL, Tam, SLP, Coa)												West (Zacatecas, Aguascalientes, Jalisco, Colima, Michoacán y Gto)												
SABINAS	MONCLOVA	NUEVO LAREDO	REYNOSA	SANTA CATARINA	SALTILLO	CADEREYTA	MATEHUALA	CIUDAD VICTORIA	CIUDAD MANTE	CIUDAD VALLES	SAN LUIS POTOSÍ	ZACATECAS	AGUASCALIENTES	LEÓN	ZAPOPAN	ZAMORA	IRAPUATO	CELAYA	URUAPAN	COLIMA	MORELIA	EL CASTILLO	LÁZARO CÁRDENAS	MANZANILLO
289	289	135	136	111	320	113	96	108	108	127	89	85	80	79	24	56	56	78	56	60	80	24	114	88
248	248	302	303	278	278	280	192	204	204	223	185	161	176	175	120	152	152	175	152	157	177	120	210	185
289	289	135	136	111	320	113	96	108	108	127	89	85	80	79	24	56	56	78	56	60	80	24	114	88
25	2	25	0	0	0	0	0	0	0	0	11	11	27	43	84	28	19	40	67	120	53	84	116	148
36	36	59	8	36	36	37	20	8	8	8	20	20	36	52	93	37	28	49	76	129	62	36	125	157
25	2	25	0	0	0	0	0	0	0	0	11	11	27	43	84	28	19	40	67	120	53	84	116	148
46	46	25	0	0	0	0	0	0	0	0	31	31	46	66	103	52	38	60	86	140	73	103	136	167
46	46	25	0	0	0	0	0	0	0	0	31	31	46	66	103	52	38	60	86	140	73	103	136	167
46	46	25	0	0	0	0	0	0	0	0	31	31	46	66	103	52	38	60	86	140	73	103	136	167
87	87	111	112	87	87	89	72	84	84	103	65	61	56	55	0	32	32	54	32	36	56	0	36	64
87	87	111	112	87	87	89	72	84	84	103	65	61	56	55	0	32	32	54	32	36	56	0	36	64
87	87	111	112	87	87	89	72	84	84	103	65	61	56	55	0	32	32	54	32	36	56	0	36	64
84	84	107	109	84	84	85	68	80	80	99	61	95	90	61	45	11	61	69	2	81	16	45	47	109
87	87	111	112	87	87	89	72	84	84	103	65	61	56	55	0	32	32	54	32	36	56	0	36	64
68	68	91	93	68	68	70	53	64	64	84	45	80	75	45	39	5	45	53	14	76	0	39	63	104
124	124	147	149	124	124	125	109	120	120	140	101	98	93	92	36	18	68	91	18	0	93	36	0	28
32	32	55	57	32	32	34	17	28	28	48	9	37	32	9	32	0	0	22	0	18	25	32	35	46
87	87	111	112	87	87	89	72	84	84	103	65	61	56	55	0	32	32	54	32	36	56	0	36	64
106	106	129	131	106	106	107	90	102	102	121	83	80	74	73	18	0	9	31	0	18	34	18	18	46
115	115	139	102	115	115	117	100	111	102	88	93	167	161	164	164	132	132	110	121	201	108	164	171	229
142	142	165	120	142	142	144	127	138	120	107	119	193	188	159	191	159	159	136	148	170	135	191	198	198
107	107	130	132	107	107	108	92	103	89	122	84	158	153	123	134	102	123	101	91	170	77	134	62	198
101	101	124	126	101	101	102	86	97	97	116	78	152	147	117	130	98	117	95	87	166	73	130	55	194
180	180	203	74	180	180	181	165	74	74	60	157	231	226	197	229	197	197	174	186	265	172	229	235	265
280	280	304	158	280	280	282	265	158	158	144	258	332	327	297	329	298	297	275	286	366	273	329	336	366
190	190	213	67	190	190	191	175	67	67	53	167	231	226	197	229	197	197	174	186	265	172	229	235	265
196	196	220	73	196	196	198	181	73	73	60	173	247	242	159	245	213	159	136	202	282	189	245	252	282
251	251	131	128	251	251	252	235	128	128	114	228	302	297	267	300	268	267	245	257	336	243	300	306	364
244	244	125	122	244	244	246	229	122	122	108	222	296	290	261	293	261	261	239	250	330	237	293	300	358
180	180	203	74	180	180	181	165	74	74	60	157	231	226	197	229	197	197	174	186	265	172	229	235	265
210	210	233	65	210	210	65	195	65	65	51	187	261	256	227	259	227	227	204	216	295	202	259	265	323
176	176	200	77	176	176	178	161	77	77	63	153	227	222	193	225	193	193	170	182	262	169	225	232	289
46	46	25	0	0	0	0	0	0	0	0	31	31	46	66	103	52	38	60	86	140	73	103	136	167
67	67	60	34	34	67	34	51	34	34	21	65	228	230	201	226	194	201	178	183	269	170	226	233	297
180	180	203	77	180	180	181	165	77	77	63	157	231	226	197	229	197	197	174	186	265	172	229	235	265
67	67	60	34	34	67	34	51	34	34	21	65	228	230	201	226	194	201	178	183	269	170	226	233	297
180	180	203	74	180	180	181	165	74	74	60	157	231	226	197	229	197	197	174	186	265	172	229	235	265
157	157	173	34	150	157	152	135	34	34	21	127	201	203	174	199	167	174	151	156	242	143	199	206	270
180	180	203	74	180	180	181	165	74	74	60	157	231	226	197	229	197	197	174	186	265	172	229	235	265
35	12	35	10	10	51	10	36	10	10	5	36	36	52	68	108	53	44	65	151	145	138	108	201	173
210	210	233	65	210	210	65	195	65	65	51	187	261	256	227	259	227	227	204	216	295	202	259	265	323
206	206	229	83	206	206	208	191	83	83	69	183	257	252	223	255	223	223	200	212	291	199	255	262	319
180	180	203	74	180	180	181	165	74	74	60	157	231	226	197	229	197	197	174	186	265	172	229	235	265
180	180	203	77	180	180	181	165	77	77	63	157	228	230	201	226	194	201	178	183	269	170	226	233	297
180	180	203	77	180	180	181	165	77	77	63	157	228	230	201	226	194	201	178	183	269	170	226	233	297
210	210	233	65	210	210	65	195	65	65	51	187	261	256	227	259	227	227	204	216	295	202	259	265	323
244	244	125	122	244	244	246	229	122	122	108	222	296	290	261	293	261	261	239	250	330	237	293	300	358
190	190	213	67	190	239	191	175	67	67	53	167	231	226	197	229	197	197	174	186	265	172	229	235	265
277	277	300	154	277	277	279	262	154	154	140	254	328	323	294	326	294	294	271	283	362	270	326	333	390
287	287	310	164	287	287	288	272	164	164	150	264	338	333	304	336	304	304	281	293	372	279	336	342	400

Figure A2. *Cont.*

Center (Morelos, Pue, Qro, Edo.MX, CDMX, Hid, Tlaxc)											South (Chiapas, Guerrero, Oaxaca)							
CUAUTLA	PUEBLA	TEHUACÁN*	QUERÉTARO	SAN JUAN IXHUATEPEC	CUERNAVACA	TOLUCA	AZCAPOTZALCO	PACHUCA	BARRANCA DEL MUERTO	AÑIL	IGUALA*	ACAPULCO	OAXACA	SALINA CRUZ*	SALINA CRUZ	TUXTLA GUTIÉRREZ	TAPACHULA	TAPACHULA II
173	188	72	100	152	149	127	160	146	160	160	178	220	251	314	314	335	353	353
269	285	311	196	248	245	233	256	243	256	256	275	316	348	410	410	432	450	450
173	188	72	100	152	149	127	160	146	160	160	178	220	251	314	314	335	353	353
89	94	120	19	75	92	42	102	79	102	102	93	156	178	118	118	140	158	158
105	88	114	28	84	101	51	92	79	92	92	102	165	172	112	112	134	152	152
89	94	120	19	75	92	42	102	79	102	102	93	186	178	118	118	140	158	158
116	80	107	38	102	111	61	102	0	102	59	113	176	164	104	104	126	144	144
116	80	107	38	102	111	61	102	0	102	59	113	176	164	104	104	126	144	144
116	80	107	38	102	111	61	102	0	102	59	113	176	164	104	104	126	144	144
149	164	191	76	128	125	103	136	122	136	136	154	196	227	290	290	311	329	329
149	164	191	76	128	125	103	136	122	136	136	154	196	227	290	290	311	329	329
149	164	191	76	128	125	103	136	122	136	136	154	196	227	290	290	311	329	329
108	123	150	90	87	84	62	95	82	95	95	114	45	186	249	249	271	289	289
149	164	191	76	128	125	103	136	122	136	136	154	196	227	290	290	311	329	329
93	108	135	75	71	68	46	79	66	79	79	98	61	171	233	233	255	273	273
185	201	227	112	178	161	139	172	159	172	172	191	12	264	326	326	348	366	366
117	132	159	44	96	93	71	104	91	104	104	123	33	195	258	258	280	298	298
149	164	191	76	128	125	103	136	122	136	136	154	196	227	290	290	311	329	329
126	141	168	53	105	102	80	113	100	113	113	132	56	204	267	267	288	307	307
0	8	34	88	58	0	23	47	35	47	47	23	64	71	133	133	155	173	173
68	27	0	115	85	68	86	74	62	74	74	91	132	36	69	69	91	109	109
0	41	68	78	26	0	23	26	37	26	26	23	64	104	166	166	188	206	206
0	41	68	74	22	5	18	22	42	22	22	16	57	104	166	166	188	206	206
106	65	9	153	123	106	124	111	100	111	111	129	170	93	57	57	79	97	97
206	165	109	253	223	206	225	212	201	212	212	229	19	13	19	19	18	0	0
106	65	9	153	123	106	124	111	100	111	111	129	170	93	57	57	79	97	97
122	81	25	169	139	122	140	128	116	128	128	91	132	0	19	19	63	81	81
176	135	79	224	193	176	195	182	171	182	182	200	241	164	49	49	20	38	38
170	129	64	217	187	170	188	176	164	176	176	193	234	158	42	42	14	32	32
106	65	9	153	123	106	124	111	100	111	111	129	170	93	57	57	79	97	97
136	95	39	183	152	136	154	141	130	141	141	159	200	123	19	19	41	59	59
102	61	5	149	119	102	120	108	96	108	108	125	166	89	61	61	82	101	101
116	80	107	38	102	111	61	102	0	102	59	113	176	164	104	104	126	144	144
78	36	29	61	31	78	59	83	8	83	83	81	123	65	77	77	99	117	117
106	65	9	153	123	106	124	111	100	111	111	129	170	93	61	61	82	101	101
78	36	29	61	31	78	59	83	8	83	83	81	123	65	77	77	99	117	117
106	65	9	153	123	106	124	111	100	111	111	129	170	93	57	57	79	97	97
83	42	46	130	93	83	94	88	77	88	88	99	140	83	76	76	97	115	115
106	65	9	153	123	106	124	111	100	111	111	129	170	93	57	57	79	97	97
121	57	49	0	88	108	116	88	65	88	88	131	173	86	104	104	126	144	144
136	95	39	183	152	136	154	141	130	141	141	159	200	123	19	19	41	59	59
132	91	35	179	149	132	150	138	126	138	138	155	196	119	35	35	56	74	74
106	65	9	153	123	106	124	111	100	111	111	129	170	93	57	57	79	97	97
106	65	9	153	123	106	124	111	100	111	111	129	170	93	61	61	82	101	101
106	65	9	153	123	106	124	111	100	111	111	129	170	93	61	61	82	101	101
136	95	39	183	152	136	154	141	130	141	141	159	200	123	19	19	41	59	59
170	129	64	217	187	170	188	176	164	176	176	193	234	158	42	42	14	32	32
116	75	19	163	132	116	134	121	110	121	121	139	180	6	35	35	56	74	74
203	162	106	250	220	203	221	209	197	209	209	226	267	190	75	75	47	65	65
213	172	116	260	230	213	231	218	207	218	209	236	277	200	85	85	57	75	75

Gulf (Ver, Tab)								Southeast (Yuc, Camp, Q.Roo)		
POZA RICA	PEROTE	XALAPA	ESCAMELA	VERACRUZ	TIERRA BLANCA	MINATITLÁN	VILLAHERMOSA	PROGRESO	CAMPECHE	MÉRIDA
161	205	223	244	273	263	302	317	360	360	360
257	302	319	341	369	359	399	414	456	456	456
161	205	223	244	273	263	302	317	360	360	360
28	34	34	86	58	67	107	122	164	164	164
17	24	26	43	28	33	42	50	158	158	158
28	34	34	86	58	67	107	122	164	164	164
14	21	21	72	44	53	93	108	150	150	150
14	21	21	72	44	53	93	108	150	150	150
14	21	21	72	44	53	93	108	150	150	150
137	181	199	220	249	239	278	293	336	336	336
161	205	223	244	273	263	302	317	360	360	360
137	181	199	220	249	239	278	293	336	336	336
96	141	158	179	208	198	237	252	295	295	295
137	181	199	220	249	239	278	293	336	336	336
81	125	143	164	193	182	222	237	279	279	279
174	229	242	257	286	275	315	330	372	372	372
105	150	167	188	217	207	246	261	304	304	304
137	181	199	220	249	239	278	293	336	336	336
114	159	176	197	226	216	255	270	313	313	313
44	36	49	64	93	82	122	137	179	179	179
29	29	46	0	29	19	58	73	116	116	116
64	70	83	97	126	116	155	170	213	213	213
56	70	83	97	126	116	155	170	213	213	213
44	28	31	9	17	0	17	61	104	104	104
128	150	115	109	101	74	51	101	75	75	75
44	28	31	9	17	0	17	61	97	97	97
44	66	31	25	17	6	30	45	87	87	87
98	121	86	79	71	45	21	6	10	16	10
92	114	79	73	65	38	15	0	43	43	43
44	28	31	9	17	0	17	61	104	104	104
35	57	22	39	8	4	8	23	66	66	66
47	24	35	5	20	10	49	64	107	107	107
14	21	21	72	44	53	93	108	150	150	150
0	0	0	45	18	26	66	81	123	123	123
47	28	35	9	20	10	49	64	107	107	107
0	0	0	45	18	26	66	81	123	123	123
44	28	31	9	17	0	17	61	104	104	104
0	13	0	43	16	25	64	79	122	122	122
44	28	31	9	17	0	17	61	104	104	104
14	21	21	72	44	53	93	108	150	150	150
35	57	22	39	8	4	8	23	66	66	66
54	76	41	35	26	0	23	38	81	81	81
44	28	31	9	17	0	17	61	104	104	104
47	28	35	9	20	10	49	64	107	107	107
47	28	35	9	20	10	49	64	107	107	107
35	57	22	39	8	4	8	23	66	66	66
92	114	79	73	65	38	15	0	43	43	43
38	60	25	19	10	0	23	38	81	81	81
125	147	112	106	97	71	48	33	10	10	10
135	157	122	116	55	81	58	43	0	0	0

Figure A2. Toll cost matrix for hydrogen transportation.

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