Optimization of the distribution of a hydrogen refueling network in Uruguay

Optimización de la distribución de una red de repostaje de hidrógeno en Uruguay

Otimização da distribuição de uma rede de abastecimento de hidrogênio no Uruguai

Carlos Pita [1] (*), Daniel Jurburg [2], María Jesús Álvarez [3], Florencia Villalba [4]

Recibido: 14/03/2026 Aceptado: 22/06/2026

Summary. - In the context of the global commitment to mitigate climate change, as reflected in the Paris Agreement, and amid a growing trend towards more sustainable transportation systems, the development of infrastructure for hydrogen production and distribution emerges as a crucial component of the energy transition. In this regard, Uruguay, recognized for its dedication to renewable energies, presents itself as a favorable environment for implementing innovative technologies in the transportation sector. Therefore, the primary objective of this article is to design an algorithm for the strategic planning of an optimal network of hydrogen stations in Uruguay. This initiative aims to catalyze the adoption of these emerging technologies and promote progress towards a more sustainable mobility, leveraging the opportunities provided by the Uruguayan context.

Keywords: *Sustainability; Hydrogen; Transport; Decarbonization; Logistics.*

(*) Corresponding author.

[1] Alumni, Universidad de Navarra (Spain), cpitamanzan@alumni.unav.es, ORCID iD: https://orcid.org/0009-0002-5361-4498

[2] Director of Centro de Innovación en Organización Industrial (CINOI), Universidad de Montevideo (Uruguay), djurburg1@um.edu.uy, ORCID iD: https://orcid.org/0000-0001-9226-1520

[3] Researcher of Centro de Innovación en Organización Industrial (CINOI), Universidad de Montevideo (Uruguay), f.villalba@um.edu.uy, ORCID iD: https://orcid.org/0009-0001-5142-9902

[4] Full Professor, Universidad de Navarra (Spain), mjalvarez@tecnun.es, ORCID iD: https://orcid.org/0000-0002-0099-4848

Memoria Investigaciones en Ingeniería, núm. 30 (2026). pp. 266-281
https://doi.org/10.36561/ING.30.18
ISSN 2301-1092 • ISSN (en línea) 2301-1106 – Universidad de Montevideo, Uruguay

Resumen. - *En el contexto del compromiso global para mitigar el cambio climático, destacado por el Acuerdo de París, y en medio de un impulso creciente hacia sistemas de transporte más sostenibles, el desarrollo de infraestructura para la producción y distribución de hidrógeno se erige como un componente esencial para la transición energética. En este contexto, Uruguay, reconocido por su compromiso con las energías renovables, emerge como un escenario propicio para la implementación de tecnologías innovadoras en el sector del transporte. Por lo tanto, el objetivo primordial de este artículo es idear un algoritmo para la planificación estratégica de una red óptima de estaciones de hidrógeno en Uruguay. Esta iniciativa busca fomentar la adopción de estas tecnologías emergentes y propiciar el avance hacia una movilidad más sostenible, capitalizando las oportunidades que ofrece el entorno uruguayo.*

Palabras clave: *Sostenibilidad; Hidrógeno; Transporte; Descarbonización; Logística.*

***Resumo*. -** *No contexto do compromisso global de mitigar as mudanças climáticas, refletido no Acordo de Paris, e diante de uma crescente tendência em direção a sistemas de transporte mais sustentáveis, o desenvolvimento de infraestrutura para a produção e distribuição de hidrogênio surge como um componente crucial da transição energética. Nesse sentido, o Uruguai, reconhecido por seu compromisso com as energias renováveis, apresenta-se como um ambiente favorável para a implementação de tecnologias inovadoras no setor de transporte. Portanto, o principal objetivo deste artigo é projetar um algoritmo para o planejamento estratégico de uma rede ótima de estações de hidrogênio no Uruguai. Essa iniciativa visa catalisar a adoção dessas tecnologias emergentes e promover o avanço em direção a uma mobilidade mais sustentável, aproveitando as oportunidades oferecidas pelo contexto uruguaio.*

Palavras-chave: *Sustentabilidade; Hidrogênio; Transporte; Descarbonização; Logística.*

1. Introduction. - In the context of the ongoing energy transition, the transportation sector has become one of the most critical areas for in-depth analysis. As the leading contributor to greenhouse gas emissions—accounting for 27% of total emissions in Spain—the sector represents a key focus for institutions, governments, and private actors seeking to promote sustainable mobility [1]. This situation is even more pronounced in Uruguay, where the transportation sector is responsible for approximately 60% of national greenhouse gas emissions [2].

Within the broader framework of transport decarbonization, two main technological pathways have emerged: battery electric vehicles and hydrogen fuel cell vehicles. Although numerous studies compare the performance and viability of both alternatives, this work focuses on hydrogen fuel cell technology due to its particular suitability for heavy-duty transport applications. Heavy vehicles—such as buses, light, medium, and heavy trucks—play a central role in the transportation sector. Notably, medium and heavy trucks, defined as vehicles with a payload capacity exceeding 3.5 tons, account for 62% of emissions within this group while representing only 30% of the fleet [3]. In other words, a relatively small number of vehicles is responsible for the majority of emissions. Consequently, when addressing emissions reduction in the freight transport sector, it is essential to adopt decarbonization technologies that are well suited to heavy-duty vehicles.

One of the main advantages of hydrogen fuel cell technology for heavy-duty trucks lies in the characteristics of hydrogen storage systems. Compared to lithium-ion batteries, hydrogen tanks are lighter and take up less space, allowing for greater payload capacity and more efficient use of vehicle volume [4]. Refueling time is another decisive factor favoring hydrogen. As shown by J. Kenny and S. Breske [5], hydrogen fuel cell truck fleets require between 3% and 10% fewer vehicles than battery electric fleets to meet the same transport demand, primarily due to shorter refueling times. In practice, refueling a hydrogen-powered truck typically takes between 3 and 8 minutes, whereas charging the batteries of an electric truck generally requires at least one hour [6]. Furthermore, hydrogen exhibits a high gravimetric energy density of 39.39 kWh/kg [7], which exceeds that of most commercially available battery technologies used in electric trucks.

Taken together, these factors result in greater operational autonomy for hydrogen-powered trucks compared to battery electric alternatives, reinforcing hydrogen's potential as a viable energy carrier for the decarbonization of heavy-duty road transport.

Nevertheless, the transition toward hydrogen mobility faces a significant barrier commonly referred to as the "chicken-and-egg" problem [8]. End users are unlikely to adopt alternative fuel vehicles without access to adequate refueling infrastructure; manufacturers are reluctant to scale production in the absence of sufficient demand; and infrastructure providers are hesitant to deploy hydrogen refueling stations without an established customer base. Therefore, the objective of this study is to design an optimal hydrogen refueling station network that supports the transition toward sustainable mobility while simultaneously incentivizing adoption from the user perspective.

The structure of this paper is the following: section 2 includes a literature review about optimization models for the deployment of hydrogen refueling station networks, section 3 presents Uruguay as a case study, section 4 introduces the methodology used for this study, section 5 describes the process used to obtain the data required to parameterize the optimization problems addressed in this study, section 6 describes the different models generated during the study and the algorithms used for the optimization of the models, section 7 shows the main results, and section 8 presents the conclusion, together with some limitations of the study and future lines of research.

2. Review of existing models in literature. - The existing literature is reviewed in order to analyze and compare the application of optimization models for the deployment of hydrogen refueling station networks across different regions. The work by A. Saha and I. Nithin [12] provides a comprehensive overview of optimization strategies for locating hydrogen infrastructure, emphasizing that the choice of model strongly depends on the objective of the problem. When the goal is to minimize travel distance, classical location models such as the p-median, p-center, and flow-interception models are commonly employed.

The p-median model aims to minimize the total distance traveled between demand nodes and refueling stations by optimizing both station locations and demand assignment, and it is the most widely used approach in hydrogen refueling station location studies. In contrast, the p-center model focuses on minimizing the maximum distance between demand points and stations, ensuring that all users remain within a bounded distance from a refueling facility. Flow-interception models seek to maximize the amount of traffic captured by refueling stations along predefined routes, incorporating variables such as vehicle range and demonstrating that fewer stations are required for vehicles with greater autonomy. When multiple objectives are considered—such as cost, risk, and distance—more complex approaches are adopted, including agent-based models and price-based models.

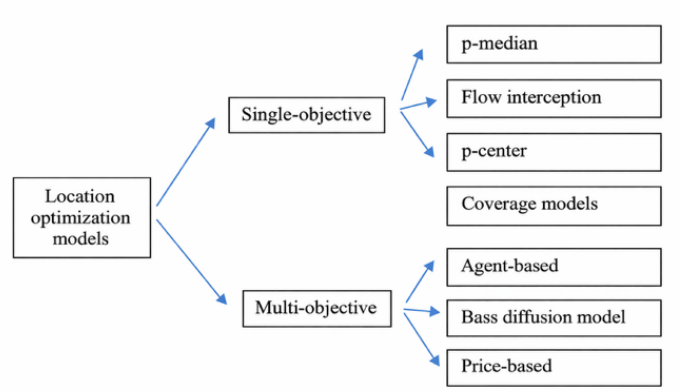

Figure I. Classification of optimization models for refueling station location. Source: [12]

Rodríguez Puerta, Brey Sánchez, and Fernández Carazo [13] analyze the optimal deployment of hydrogen refueling stations in the Andalusia region. Using a multicriteria analysis combined with a *p-median* mathematical model, the authors identify suitable zones for infrastructure implementation and define hydrogen corridors between urban centers. The model seeks to minimize the number of required stations while incorporating constraints related to the proximity of municipalities in order to avoid redundancy. However, these models do not explicitly address whether hydrogen production should be performed on-site at refueling stations or centralized in external production plants—an aspect that is explicitly considered in the present work. P. Rose [14] develops a hydrogen refueling station network model to supply fuel cell trucks in Germany under a projected 2050 scenario. Using a Flow-Refueling Location Model, the study optimizes the network by minimizing the number of stations while ensuring coverage of traffic demand. Additionally, the article evaluates two cost-reduction strategies: centralized hydrogen production with subsequent distribution, and on-site production using grid-connected electrolyzers. While centralized production reduces hydrogen generation costs, on-site electrolysis—despite higher initial investment—can offset expenses by lowering long-term energy generation and distribution costs.

B. Hernández et al. [15] propose a hydrogen infrastructure planning model for fuel cell vehicles in California using geospatial information systems (GIS). The model determines both the optimal number and locations of refueling stations and evaluates alternative hydrogen production sources, including on-site solar-powered electrolysis and external supply. The study highlights that approximately 45% of refueling stations would rely on on-site hydrogen production, particularly in areas with sufficient space for photovoltaic installations. In contrast, S.D. Stephens-Romero and T.M. Brown [16] employ a geographic planning tool known as STREET rather than mathematical optimization models, concluding that the transition from internal combustion vehicles to hydrogen vehicles could reduce greenhouse gas emissions by up to 80% and overall energy demand by 42%. Their analysis estimates that only 830 refueling stations would be required in Southern California—significantly fewer than the number of conventional gasoline stations currently operating in the region.

In summary, optimization models for hydrogen refueling infrastructure deployment vary widely depending on project objectives and regional characteristics, ranging from classical location models such as *p-median* and *p-center* to more dynamic approaches based on traffic flow interception. Case studies conducted in Andalusia, California, and Germany provide valuable insights into the technical feasibility, cost structure, and efficiency of hydrogen refueling networks. Nevertheless, key challenges remain, particularly regarding hydrogen production location and supply strategies, which must be carefully addressed to optimize infrastructure networks in accordance with local conditions.

3. Case Study. Uruguay. - This study selects Uruguay as the case study for the development of an optimal hydrogen refueling station network, given its strong potential to lead the transition toward sustainable mobility in Latin America. Uruguay stands out for its electricity generation mix (see Figure II), with approximately 97% of its electricity produced from renewable sources, making it a highly favorable setting for the production of green hydrogen [9]. In addition, the country's location within the La Plata Basin and the availability of abundant water resources—particularly from the Uruguay River—facilitate hydrogen production through electrolysis, enabling the efficient use of local hydrological assets.

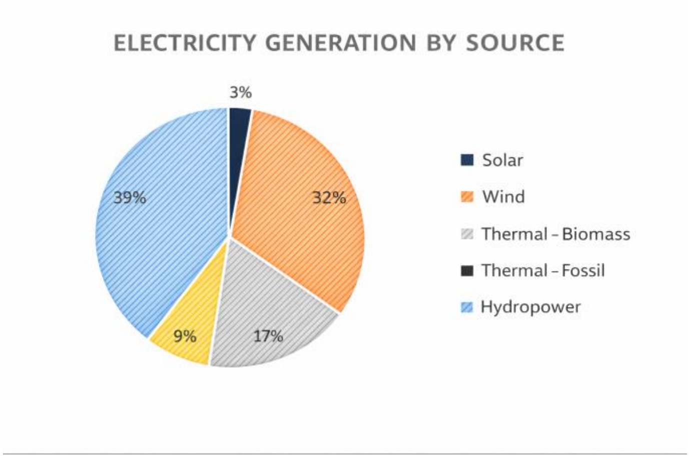

Figure II. Uruguay's electricity generation mix. Source: Authors' own elaboration.

Institutional support constitutes another key enabling factor. The Ministry of Industry, Energy and Mining of Uruguay has developed a national hydrogen roadmap [10] that establishes medium- and long-term objectives, supported by regulatory frameworks such as Article 150 of Law No. 19,996 (2021), which sets standards for hydrogen production and transportation. From an international perspective, Uruguay has signed strategic agreements with Germany and the Netherlands aimed at knowledge exchange and cooperation in green hydrogen projects.

Furthermore, the country exhibits a high density of conventional service stations compared to the Latin American average, creating an opportunity to partially repurpose this existing infrastructure into hydrogen refueling stations and thereby facilitate the transition toward sustainable mobility. In addition, Uruguay represents an attractive destination for foreign investment due to its sociopolitical stability, advanced public-sector digitalization, and institutional transparency.

Regarding ongoing initiatives, H24U represented the first green hydrogen project in Uruguay, primarily aimed at decarbonizing the transport sector, particularly within the forestry industry. However, the project currently holding the greatest relevance is Kahiros. Developed by Ventus, Fraylog, Fidocar–Hyundai, and Banco Santander, the initiative seeks to establish the country's first operational green hydrogen plant. With commissioning planned for November 2026, Kahiros constitutes a tangible milestone in Uruguay's national decarbonization pathway.

Another major initiative is the Paysandú plant [11], conceived at a significantly larger scale, with an estimated production capacity of up to 100,000 tons of H_2 per year, compared to the approximately 70 tons projected for Kahiros. This project aims to produce synthetic fuels through the combination of green hydrogen and biogenic CO_2 and has already secured offtake commitments from European countries. Nevertheless, the focus of the present study is on the domestic utilization of locally produced green hydrogen to promote sustainable mobility within Uruguay.

In summary, Uruguay possesses the potential to become a central hub in Latin America's energy transition, leading the adoption of green hydrogen both domestically and regionally. Beyond designing an optimal hydrogen refueling network, this study seeks to demonstrate the technical and strategic viability of green hydrogen as a transport fuel, thereby laying the groundwork for future infrastructure development across the region.

4. Methodology. - A methodological framework is defined in which, based on the geographical distribution of existing service stations within a given region, a subset is selected to be converted into hydrogen refueling stations. In particular, the approach determines which stations will incorporate on-site hydrogen production and which will operate as storage facilities supplied by truck delivery, thereby configuring an optimal hydrogen refueling network. Although Uruguay is selected as the case study in this work, the methodology is fully transferable to other geographical contexts.

The process begins with data collection, compiling the complete list of operational service stations in the country, along with their geographical coordinates and corresponding department. In parallel, a shapefile obtained from the OpenStreetMap platform is used to represent the geometry of Uruguay's road network.

Using these inputs, Program 1 is developed to generate the road network map and geolocate all service stations, each assigned a unique numerical identifier. Based on the resulting map, the nearest interconnections between service stations are examined. Two stations are considered connected if a direct primary-road connection exists between them without any intermediate station located along the route. These connections are recorded in a text file specifying, for each station, the list of other stations to which it is directly connected.

Once all connections have been defined, Program 2 converts this file into an adjacency matrix in an Excel format. Program 3 then uses both this matrix and the geographical coordinates of each service station to perform two tasks: first, to verify whether any node contains self-connections; and second, to generate a graphical representation of the network. Nodes are displayed according to their geographical position and labeled with their corresponding numerical identifier, approximately replicating the structure of the road network map. Also, weights are assigned to the edges based on the distance between nodes.

At this stage, a graph is obtained representing the country's service stations and the road segments linking them. Since the objective of the study is to analyze hydrogen demand by state and determine the location of hydrogen refueling stations within each state, the connections file is subsequently partitioned by state using Program 5. Program 6 then generates the corresponding adjacency matrix for each state, and Program 7 produces its associated graph. In other words, the initial steps of the methodology are replicated at the state level.

To determine the optimal number of production-based and storage-based hydrogen refueling stations required in each state, Program 8 is employed. This program solves Model 1 (described further in Section 6) using the economic, production, and demand parameters (detailed in Section 5). Since the graph structures generated in the previous steps are not required for this optimization stage, the problem can be solved independently and executed in parallel with the network construction process.

To identify the optimal locations of both types of hydrogen refueling stations within the graph, Program 9 is implemented. This program solves Model 2 (described further in Section 6) through a heuristic approach based on geospatial criteria, enabling the identification of suitable candidate nodes among the existing service stations for both production and storage facilities. The algorithm operates on the graph structures obtained in the earlier steps and produces a final set of potential locations for each type of station.

By combining the candidate nodes identified through Program 9 with the optimal number of stations determined by Program 8, the problem is fully resolved, yielding the optimal hydrogen refueling network configuration for each state and, consequently, for Uruguay as a whole.

The complete repository, including the source code and documentation for each program, is available at: https://github.com/carlospitamanza/Optimizaci-n-de-la-distribuci-n-de-una-red-de-hidrogeneras-en-Uruguay.

5. Data Acquisition- This section describes the process used to obtain the data required to parameterize the optimization problems addressed in this study. Although the analysis focuses on the case study of Uruguay, the methodology used to determine the necessary parameters is applicable to any country or region.

In order to solve the proposed optimization problems, the following information is required:

a. Production capacity of the hydrogen production plant.
b. Production and storage capacities of both types of hydrogen refueling stations.
c. Installation costs associated with each type of hydrogen refueling station.
d. Hydrogen demand for each state

5.1 Production Plant. - As mentioned in the introduction, there is an advanced project for the construction of a green hydrogen production plant in Paysandú. Its primary objective is the production of synthetic fuels derived from green hydrogen and captured CO_2. However, the focus of this study is on using the hydrogen produced as a final energy carrier, meaning that the hydrogen obtained directly from the electrolyzer is considered the final product.

According to the information provided in the interview [17], the plant has a maximum production capacity of 100000 tons of hydrogen per year. Since the primary purpose of the facility is the production of synthetic fuels, a scenario is considered in which part of this production is allocated to supply hydrogen refueling stations. It is therefore assumed that 40% of the total hydrogen production is used as fuel for transport applications. In addition, because the reported value corresponds to the maximum production capacity, it is assumed that the plant operates at an average annual capacity factor of 70%. These assumptions are reflected in Equation (1).

$$H_2\ transport\ \text{prod.}\ = Max\ plant\ prod. \cdot Plant\ capacity\ factor \cdot Transport\ H_2\ fraction \qquad (1)$$

Therefore, the Paysandú plant is assumed to supply 28000 tons of hydrogen per year to hydrogen refueling stations without on-site electrolysis.

5.2 Hydrogen refueling stations and service stations. - The current locations of conventional service stations are considered potential candidates to be converted into hydrogen refueling stations, either with on-site production or storage facilities, as suggested in [13]. It is assumed that the existing distribution of service stations is the result of a long process of infrastructure development and optimization. Moreover, given the similar driving ranges of hydrogen and gasoline vehicles, it is reasonable to assume that the future locations of hydrogen refueling stations will largely coincide with those of the current service stations.

The complete list of operational service stations in the country is obtained from the website of the Regulatory Unit for Energy and Water Services of the Oriental Republic of Uruguay [18], which provides the locations of all stations distributed across the 19 states. In addition, it is necessary to determine the production and storage capacities of the potential hydrogen refueling stations. Hydrogen Refueling Solutions (HRS) is a French manufacturer of hydrogen refueling stations for vehicles and is considered one of the leading companies in the sector. After evaluating several alternatives, the HRS40 model was selected for this study [19].

This model includes two dispensers operating at 350 and 700 bar and allows simultaneous refueling. Category A vehicles typically use hydrogen storage at 700 bar, while heavy-duty trucks commonly operate at either 350 or 700 bar. Therefore, providing both pressure levels is necessary in order to avoid limiting the range of vehicles that can be served by the infrastructure.

With regard to production capacity, the compressor of the HRS40 model is capable of supplying up to 40 kg per hour. Assuming that the refueling station operates 24 hours per day and 365 days per year, and considering a production rate of 63%, an annual hydrogen production of approximately 220 tons is obtained. In addition, the supplier indicates that the selected refueling station model is capable of storing 35 kg of hydrogen in its tanks, with the possibility of expanding this capacity depending on operational needs. Based on this information, the storage capacity of a storage-type hydrogen refueling station is estimated at 100 tons per year. These values are therefore adopted as the production and storage parameters used in the optimization problem.

Regarding installation costs, different sources were consulted. On the one hand, Hydrogen Refueling Solutions provides an approximate budget of 2.33 million dollars for the installation of the HRS40 model. However, this configuration does not allow the exclusion of the electrolyzer, and therefore it is not possible to directly estimate the cost of a hydrogen refueling station that only stores hydrogen supplied externally. On the other hand, the California-based organization The Hydrogen Fuel Cell Partnership [20] provides cost estimates of 2.33 million dollars for stations supplied by external hydrogen production facilities and 3.72 million dollars for stations with on-site hydrogen production.

Based on the comparison of these sources, the installation cost of the HRS40 model is estimated at 3.72 million dollars for stations with an electrolyzer and 2.33 million dollars for stations without an electrolyzer.

5.3 Hydrogen Demand. - To estimate the hydrogen demand required by the country, the current number of vehicles circulating in Uruguay is taken into account. The list of registered vehicles by state is obtained from the Economic Studies and Evaluation Division, within the Concessions subdivision of the National Directorate of Transport. In addition, it is necessary to determine the hydrogen consumption of both vehicle categories in order to estimate demand. Since the Toyota Mirai is currently the best-selling hydrogen vehicle, its consumption is used as a reference for Category A vehicles. For Category B vehicles, the sector is still less developed and has limited market presence. The most advanced project in this segment is the Hyundai Xcient Fuel Cell truck, and therefore its consumption is used as the reference value.

In the scenario considered in this study, it is assumed that hydrogen vehicles will reach a market penetration of 12.24%. This value can vary depending on the scenario considered and is taken from the study by Coulibaly et al. [21]. Furthermore, it is necessary to estimate the annual distances traveled by vehicles in Uruguay. For trucks, the CINOI report [3] estimates an average of 77960 kilometers traveled per truck per year. For passenger cars, an average value of 15000 kilometers per year is assumed, which is widely accepted in the literature.

Based on these parameters, Equation (2) is formulated to estimate the hydrogen demand required to meet the transport demand of each state and for each vehicle category.

$$Statal\ demand\ (tonnes) = \frac{N^{o}\ vehicles \cdot H_2\ \text{Consumption}\left(\frac{kg}{km}\right) \cdot Distance\left(\frac{km}{year}\right) \cdot Penetration\ rate\ (\%)}{1000} \quad (2)$$

With this approach, the total hydrogen demand for each state is obtained, resulting in a total annual hydrogen demand for Uruguay of 58275,193 tons.

With the parameters of available production capacity, refueling station production and storage capacities, installation costs, and hydrogen demand by state, the dataset required to formally formulate the optimization models presented in the following section is fully defined.

6. Models. - In this section, the program is divided into two branches. On the one hand, the optimal number of hydrogen refueling stations (both with on-site production and off-site supply) is determined. This problem is mathematically formulated in Model 1, and its resolution is implemented through Program 8.

On the other hand, Model 2 describes the heuristic used to identify candidate locations for both types of hydrogen refueling stations based on specific geospatial criteria. The pseudocode included in this section outlines the method applied step by step.

6.1. Model 1. - The objective function is to minimize the total cost of the transformation considered in this study. To achieve this, the model minimizes the sum of the installation costs of hydrogen refueling stations with on-site production and the costs of constructing stations that store hydrogen supplied from external sources.

$$Min\ Z = \sum_i (C_{H_i} \cdot H_i + C_{A_i} \cdot A_i)$$

$s.to$

$$\sum_i^N (Q_{H_i} \cdot H_i + Q_{A_i} \cdot A_i) \geq D_j \qquad j \in \{1,2...19\} \qquad (5)$$

$$H_i + A_i \leq 1 \qquad i \in \{1,2...N\} \qquad (6)$$

$$H_i, A_i, C_{H_i}, C_{A_i} \geq 0 \qquad i \in \{1,2...N\} \qquad (7)$$

The variables H_i and A_i, represent the number of hydrogen refueling stations with on-site production and storage stations, respectively, for each state. These are integer decision variables. Regarding the parameters, C_{H_i} and C_{A_i}represent the installation costs of a hydrogen refueling station with on-site production and of a storage station, respectively. Similarly, Q_{H_i} and Q_{A_i} denote the hydrogen production capacity and storage capacity per state.

Regarding the constraints, constraint (5) ensures that the total demand of each state is satisfied, allowing the supply to exceed the demand if necessary. This is achieved by adding the annual production of each on-site hydrogen refueling station and the storage capacity of each storage station, and requiring that this sum be greater than or equal to the total demand. Constraint (6) establishes that at most one type of hydrogen refueling station can be installed at each node, either a storage station or a station with on-site production.

6.2 Model 2. - This model aims to determine the optimal locations of hydrogen refueling stations, both with on-site production and storage, among the N candidate sites corresponding to the existing service stations. The model is implemented through Program 9 in the code repository, and its pseudocode is presented below.

The objective is to obtain a set of production and storage hydrogen refueling stations that satisfy specific location requirements. To achieve this, a heuristic approach is developed, consisting of a sequence of systematic steps designed to solve a specific problem: the location of hydrogen refueling stations with production and storage functions. The pseudocode presented in this section clearly describes the steps followed in the algorithm. All algorithms are implemented in Python. This heuristic is divided into three independent components which, when executed sequentially, solve the problem under consideration.

6.2.1 Algorithm 1. Avoid production refueling stations near the plant. - The objective of this first algorithm is to ensure that hydrogen refueling stations with on-site production are not located too close to the main production plant, thereby avoiding the presence of two nearby production sources.

The algorithm is applied to the graph generated in Program 7 of the repository, where the nodes represent the existing service stations in Uruguay and the edges represent the connections between them. Node W corresponds to the location of the hydrogen production plant.

The inputs of the algorithm are:

- Graph with N nodes representing the existing service stations in Uruguay and their corresponding edges.
- Special node W, representing the production plant.
- Distance threshold u, which defines the minimum distance from the plant beyond which a node is considered eligible for a production hydrogen refueling station.

1. An empty dictionary {d} is initialized to store the distances between each node and the plant.

2. For each node i in the graph (except W):
    a. The minimum distance d_i between node i and node W is calculated.
    b. The value d_i is stored in the dictionary {d}.

3. Two empty sets {A} and {B} are created.
4. For each node i contained in the dictionary {d}
    a. If $d_i >$ u, add i to set {A}.
    b. If $d_i \leq$ u, add i to set {B}.
5. Return the sets {A} and {B}.

Outputs:

- Set {A}: nodes eligible for hydrogen refueling stations with on-site production.
- Set {B}: nodes not eligible for production stations but that remain potential candidates for hydrogen storage stations.

In this way, the algorithm defines a set {A} of candidate locations for hydrogen refueling stations with on-site production, as these nodes are located at a distance from the plant greater than the threshold u. The set {B} is excluded as a possible location for production stations due to its proximity to the plant, although it remains a set of potential locations for hydrogen storage stations.

6.2.2 Algorithm 2. Ensuring adequate distance between production hydrogen refueling stations. - The objective of this second algorithm is to ensure that the selected hydrogen refueling stations with on-site production are not concentrated within the same area by imposing a minimum separation criterion between them. The algorithm is applied to the set of candidate nodes {A} obtained from Algorithm 1 and uses the road network graph to evaluate the distances between possible locations for production hydrogen refueling stations.

Inputs:

- Set {A} obtained from Algorithm 1.
- Graph with N nodes representing the existing service stations in Uruguay and their corresponding edges.
- V, minimum distance threshold between production hydrogen refueling stations.

1. An empty dictionary D_A is initialized.
2. All distances between pairs of nodes belonging exclusively to set {A} are calculated and stored in the dictionary D_A.
3. An empty set {H} is created to store the nodes selected as production hydrogen refueling stations.
4. For each node N_j in set {A}:
a. the distances separating it from the remaining candidate production nodes are evaluated.
b. if the minimum distance between N_j and any other production node in set {A} is greater than threshold V, node N_j is added to set {H}.
    c. otherwise, the node is discarded as a viable location for a production hydrogen refueling station.
5. Return set {H}.

Outputs:
- Set {H}: nodes selected for production hydrogen refueling stations.
- Set {R}: complement of {H} within set {A}, defined as {R} = {A} \ {H}, which groups the nodes discarded as production hydrogen refueling stations and which are considered in Algorithm 3.

Through this algorithm, a set {H} of locations is obtained that satisfies a minimum separation criterion between production hydrogen refueling stations according to the threshold V, thereby avoiding excessive concentration of production capacity.

6.2.3 Algorithm 3. Location of storage hydrogen refueling stations relative to production stations and the plant. - This third algorithm aims to restrict the candidate locations for storage hydrogen refueling stations by selecting only those nodes that, without having been chosen as production hydrogen refueling stations, are located at an operationally viable distance from both the production plant and the hydrogen refueling stations with on-site production. The objective is to avoid isolated or logistically inefficient storage stations whose supply would require excessive transportation distances.

The algorithm builds on the results of the previous algorithms and uses the distances previously calculated on the road network graph to evaluate the logistical feasibility of each candidate node.

Inputs:
- Sets {H}, {R} and {B} obtained from previous algorithms.
- Distances d_i and D_{AB}.
- Threshold z, representing the maximum admissible distance for supplying a storage hydrogen refueling station.

```
1. Define the set {S}={R}∪{B}, which groups the nodes that are candidates for storage hydrogen refueling stations.
2. From the set of distances $d_i$, exclude those involving nodes belonging to set{H}.
3. From the set of distances $D_{AB}$, retain only those distances that connect nodes in set {H} with nodes in set {S}.
4. Store the resulting distances in set {F}.
5. Create an empty list {a}.
6. For each element in set {F}:
        a. if the associated distance is less than the threshold z, add said element to list {a}.
7. Create an empty set {T}.
8. For each node associated with the elements in list {a}:
        a. if the node belongs to set {S}, does not belong to set {H} and does not coincide with node W, add it to set {T}.
9. Return set {T}.
```

Outputs:
- Set {T}: eligible nodes for storage hydrogen refueling stations.

Through this algorithm, a set {T} of viable locations for storage hydrogen refueling stations is obtained that satisfy logistical proximity criteria with respect to both the production plant and the production hydrogen refueling stations. Together with the set {H}, defined in the previous algorithms, the final locations of production and storage hydrogen refueling stations within the network are determined.

7. Results. - Using the demand data for each state, together with the costs and production and storage parameters of both types of hydrogen refueling stations, Program 8 is executed to solve the optimization problem described in Model 1. The results indicate that 137 hydrogen refueling stations with on-site production and 10 stations supplied through off-site production are required to meet the hydrogen demand of the transport sector across the 19 states of Uruguay under the scenario considered. In addition, the total cost of the deployment amounts to 539,8 million dollars. Table I presents the detailed results for each state with HRS standing for hydrogen refueling station.

State	Existing stations	On-site prod. HRS	Storage HRS	Total cost (M €)
Artigas	7	2	1	8,9
Canelones	67	24	0	76,8
Cerro Largo	9	4	0	12,8
Colonia	39	10	0	32
Durazno	12	2	1	8,9
Flores	7	7	0	22,4
Florida	14	4	0	12,8
Lavalleja	12	2	1	8,9
Maldonado	27	12	1	40,9
Montevideo	144	31	1	101,7
Paysandú	20	5	0	16
Rio Negro	13	3	1	12,1
Rivera	8	3	1	12,1
Rocha	15	2	0	6,4
Salto	14	4	1	15,3
San José	23	10	1	34,5
Soriano	18	6	0	19,2
Tacuarembó	12	4	1	15,3
Treinta y Tres	7	2	0	6,4

Table I. Number of hydrogen refueling stations (HRS) per state.

Once the number of hydrogens refueling stations of each type has been determined for every state, the next objective is to identify their locations among the 468 existing service stations that serve as potential candidates. As discussed in the previous section, Model 2 was designed, consisting of three algorithms that, by imposing specific constraints, reduce the number of candidates and provide a selection for both types of hydrogen refueling stations. When Program 9 is executed, the thresholds defined in the code are specified and the problem is solved. The threshold u defines the radius around the plant (represented by node W) within which a production hydrogen refueling station cannot be located. The threshold U establishes the minimum distance required between two production hydrogen refueling stations. Finally, the threshold z represents the minimum distance that storage hydrogen refueling stations must maintain with respect to the plant W and the production hydrogen refueling stations in order for truck-based supply to be feasible.

For the first iteration, the following arbitrary values, expressed in kilometers, are established and the results are analyzed:

- u=50, production hydrogen refueling stations cannot be located within 50 km of the production plant.
- U=1, a minimum distance of 1 km must be maintained between production hydrogen refueling stations.
- z=200, storage hydrogen refueling stations must be located at a maximum distance of 200 km from either the production plant or a production hydrogen refueling station.

With the selected threshold values, the proposed algorithm identifies 300 existing service stations as possible locations for hydrogen refueling stations with on-site production. In addition, 168 service stations are identified as possible locations for storage hydrogen refueling stations. Given that there are 468 service stations in the country, these values do not sufficiently constrain the problem and would require the use of additional strategies to select hydrogen refueling stations within such a broad range.

The main limitation of the first iteration is that the same threshold values are applied to all states, despite the fact that their geographical conditions and connectivity differ substantially. For this reason, a second iteration is proposed in which only parameter U is considered, since this parameter is the one that effectively constrains the number of hydrogens refueling stations. Thus, in order to determine the set of production hydrogen refueling stations for each state, only the minimum separation distance between them, given by parameter U, is taken into account. This procedure is implemented in Program 10. By adapting the minimum separation distance between hydrogen refueling stations to each state, demand can be satisfied and, in most cases, the decision space is fully reduced, yielding a fixed set of nodes for the selection of production hydrogen refueling stations. The resulting nodes selected as production hydrogen refueling stations according to parameter U are presented in Table II. Since the number of storage hydrogen refueling stations is very small, more subjective criteria can be used for their selection, as discussed below.

State	Required on-site prod. HRS	U (km)	Nodes
Artigas	2	21	{4,5}
Canelones	24	2.1	{ 9, 10, 11, 12, 15, 20, 23, 28, 33, 34, 38, 39, 40, 44, 54, 55, 56, 60, 61, 64, 65, 66, 72, 73, 74}
Cerro Largo	4	2.69	{76, 77, 78, 79}
Colonia	10	1.58	{96, 97, 104, 105, 106, 107, 108, 116, 120, 94, 95}
Durazno	2	26.1	{128, 133}
Flores	7	0.079	{136, 137, 138, 139, 140, 141, 142}
Florida	4	14.5	{145, 155, 156, 151}
Lavalleja	2	58.1	{160, 157}
Maldonado	12	1.26	{192, 169, 170, 171, 172, 176, 179, 180, 181, 185, 187, 188, 189}
Montevideo	31	0.775	{276, 280, 283, 284, 285, 288, 289, 293, 300, 301, 302, 303, 304, 305, 307, 308, 318, 329, 202, 331, 204, 334, 225, 226, 227, 228, 235, 236, 237, 241, 242, 247}
Paysandú	5	23.9	{358, 359, 342, 343, 344, 345}
Rivera	3	11.73	{380, 373, 374}
Río Negro	3	23	{360, 361, 370, 371}
Rocha	2	40	{389, 390}
Salto	4	1.82	{408, 409, 396, 405}
San José	10	1.5	{419, 424, 426, 427, 431, 432, 411, 413, 414, 415}
Soriano	6	10.4	{448, 449, 450, 433, 435, 447}
Tacuarembó	4	40.5	{462, 460, 461, 454}
Treinta Y Tres	2	32.1	{465, 466}

Table II. Production hydrogen refueling stations as a function of parameter U.

Figure III shows the resulting hydrogen refueling station network for Montevideo. The red nodes represent production hydrogen refueling stations, most of which are located along the outer ring of the city. Since the algorithm in Model 2 seeks to maximize the distances between hydrogen refueling stations in order to constrain the problem, stations located in the central area, where service stations are closer to each other, are not selected. For this reason, the storage hydrogen refueling station is chosen from the inner cluster.

Node 264 is selected, located on Boulevard Artigas, one of the city's main arteries that runs from north to south, at its intersection with Avenida José Garibaldi, another highly trafficked avenue. In addition to being a strategic and easily accessible location for refueling from any part of the city, it also allows efficient supply by trucks, since they can circulate through wide avenues rather than narrow streets. Moreover, Boulevard Artigas connects at its northern end with Avenida General Flores, one of the main routes leading out of the city.

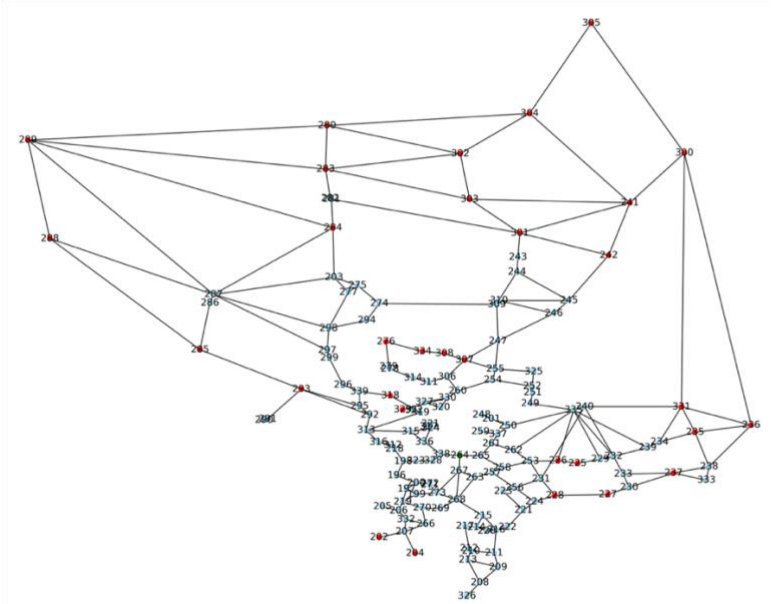

Figure III. Proposed hydrogen refueling station network for Montevideo.

The complete network for Uruguay consists of 137 hydrogen refueling stations with on-site production and 10 stations supplied through off-site production, with a total deployment cost of 539,8 million dollars. Based on these results, and assuming an average production of 220 tons of H_2 per year per production hydrogen refueling station, the installed stations collectively produce 30140 tons of hydrogen annually. This value is obtained by multiplying the annual production per station by the 137-production hydrogen refueling stations. This production is added to the hydrogen supplied by the main plant. The resulting network is illustrated in Figure IV, where the red nodes represent production hydrogen refueling stations and the green nodes represent storage hydrogen refueling stations.

Figure IV. Proposed hydrogen refueling station network for Uruguay.

8. Conclusions. - The objective of this study was to design a network of hydrogen refueling stations, both with on-site production and off-site supply, capable of supporting the transition toward sustainable mobility in Uruguay. Based on an analysis of the vehicle fleet by state and a projected market penetration of hydrogen vehicles, the future hydrogen demand in the transport sector was estimated. These data served as the basis for the formulation of optimization models aimed at determining both the required scale and the location of the necessary infrastructure.

The methodology was based on a linear programming approach to determine the optimal number of hydrogens refueling stations of each type for every state. Subsequently, a location algorithm was applied to select existing service stations that could potentially be converted into hydrogen refueling stations. Due to the geographical diversity of the country, it was necessary to adjust the coverage thresholds for each state which made it possible to obtain more realistic and constrained solutions. The separation of the original problem into two stages (sizing and location) also significantly reduced computational execution times, thereby improving the efficiency of the model.

The resulting design consists of a network of 147 hydrogen refueling stations strategically distributed across the country, with an estimated total cost of 539 million dollars. This estimate is based on technical and economic parameters provided by companies specialized in the installation of hydrogen refueling stations, which strengthens the reliability of the cost estimation. Compared with international projects, the proposed budget falls within reasonable margins considering the scale and ambition of the proposed system. Moreover, given that this investment represents approximately 0,699% of Uruguay's GDP, it can be considered consistent with typical investment levels for strategic energy transition infrastructure. For instance, the Pampa Wind Farm project represented an investment equivalent to approximately 0,48% of the national GDP.

One of the main limitations identified concerns the representation of distances between nodes in the geospatial model. Although a simulated road network based on OpenStreetMap data was used, the calculated distances do not correspond to actual road routes. For future developments, the incorporation of the Google Maps API is proposed, which would allow road distances to be calculated more accurately. In addition, future work should extend the model to include variables related to hydrogen transportation, which would provide a more comprehensive logistical and economic analysis of the system.

Finally, it should be emphasized that both the algorithms and the models developed in this study are fully reproducible and adaptable to other geographical contexts. The modular structure of the approach allows it to be applied to different countries or regions, provided that basic data on demand, road networks, and infrastructure availability are accessible. Overall, this work represents a relevant contribution to the strategic planning of hydrogen infrastructure in Uruguay and may serve as a methodological reference for the design of similar networks in other Mercosur countries.

References

[1] "Inventario Nacional de Emisiones a la Atmósfera," Ministerio para la Transición Ecológica y el Reto Demográfico, 2022.

[2] "Uruguay lanza estrategia ambiental para lograr su descarbonización hacia 2050," La Vanguardia, 8 August 2020.

[3] D. Jurburg, M. Tanco, M. Levy, S. Rossi and M. S. Cavalleri, "Transporte eléctrico de carga: análisis de los desafíos para su introducción en Uruguay. Análisis comparativo de emisiones de contaminantes," Montevideo, 2021.

[4] D. Jurburg, M. Tanco and M. D. L. N. Camacho, "Hydrogen fuel cell heavy-duty trucks: Review of main research topics," International Journal of Hydrogen Energy, vol. 47, pp. 29505–29525, 2022.

[5] J. Kenny, S. Breske and N. Singstock, "Hydrogen-powered vehicles for autonomous ridehailing fleets," International Journal of Hydrogen Energy, vol. 47, pp. 9422–9427, 2022.

[6] F. Unterlohner, "Comparison of hydrogen and battery electric trucks," 2020.

[7] Y. Manoharan and S. E. Hosseini, "Hydrogen Fuel Cell Vehicles: Current Status and Future Prospect," Applied Sciences, vol. 9, 2019.

[8] R. Brey Sánchez, J. J. Brey Sánchez, A. Fernández Carazo and I. Rodríguez Puerta, "Planificación del despliegue de las estaciones de servicio de hidrógeno necesarias para facilitar el uso de este gas como combustible en Andalucía," Agencia de Innovación y Desarrollo de Andalucía IDEA, Sevilla, 2015.

[9] "H2U. Hoja de ruta del hidrógeno verde en Uruguay," 2022. Available: https://www.gub.uy/ministerio-industria-energia-mineria/sites/ministerio-industria-energiamineria/files/documentos/noticias/H2_final_14jul22_digital.pdf Accessed: 5 November 2023.

[10] Ministerio de Industria, Energía y Minería, "H2U. Hoja de ruta del hidrógeno verde en Uruguay," 2021. Available: https://www.gub.uy/ministerio-industria-energia-mineria/sites/ministerio-industria-energiamineria/files/documentos/noticias/H2_final_14jul22_digital.pdf

[11] Uruguay XXI, "Compañía chilena concretará millonaria inversión en Uruguay para producir e-combustibles a partir de hidrógeno verde," 9 June 2023. Available: https://www.uruguayxxi.gub.uy/es/noticias/articulo/compania-chilena-concretara-millonaria-inversion-en-uruguay-para-producir-ecombustibles-a-partir-de-hidrogeno-verde/ . Accessed: 5 November 2023.

[12] A. A. Saha and I. Nithin, "A Review of the Optimization Strategies and Methods Used to Locate Hydrogen Fuel Refueling Stations," Energies, vol. 16, no. 2171, 2023.

[13] I. Rodríguez Puerta, R. Brey Sánchez, J. J. Brey Sánchez and A. Fernández Carazo, "Planificación del despliegue de las estaciones de servicio de hidrógeno necesarias para facilitar el uso de este gas como combustible en Andalucía," Asociación Española del Hidrógeno, Sevilla, 2015.

[14] P. Rose, "Modeling a potential hydrogen refueling station network for fuel cell heavy-duty vehicles in Germany in 2050," Karlsruher Institut für Technologie, Karlsruhe, 2020.

[15] B. Hernandez, E. Azar, A. Alkayas and A. Mayyas, "Mathematical Model for the Placement of Hydrogen Refueling Stations to Support Future Fuel Cell Trucks," IEEE Access, vol. 9, 2021.

[16] S. D. Stephens-Romero and T. M. Brown, "Projecting full build-out environmental impacts and roll-out strategies associated with viable hydrogen fueling infrastructure strategies," International Journal of Hydrogen Energy, vol. 36, 2011.

[17] A. Stipanicic, interviewee, "Proyecto de hidrógeno verde y combustibles sintéticos en Paysandú: ¿Cómo es? ¿Qué plazos maneja?", interview, 14 June 2023.

[18] "Listado Estaciones de Servicio Activas," Unidad Reguladora de Servicios de Energía y Agua, 13 May 2022. Available: https://www.gub.uy/unidad-reguladora-servicios-energia-agua/sites/unidad-reguladora-servicios-energia-agua/files/202205/Listado%20Estaciones%20de%20Servicio%20Activas.pdf

[19] Hydrogen Refueling Solutions (HRS), "HRS40 Product Sheet." Available: https://www.hydrogen-refuelingsolutions.fr/wp-content/uploads/HRS40_fiche_produit-202311.pdf Accessed: January 2024.

[20] Hydrogen Fuel Cell Partnership. Available: https://h2stationmaps.com/costs-and-financing Accessed: 3 January 2024.

[21] A. R. K. T. Y. Coulibaly, S. Managi and Zulfhazli, "Analysis of prospective demand for hydrogen in the road transportation sector: Evidence from 14 countries," International Journal of Hydrogen Energy, vol. 56, pp. 853–863, 2024.

Author contribution:
1. Conception and design of the study
2. Data acquisition
3. Data analysis
4. Discussion of the results
5. Writing of the manuscript
6. Approval of the last version of the manuscript

C.P. has contributed to 1, 2, 3, 4, 5 and 6.
D.J. has contributed to 1, 2, 3, 4, 5 and 6.
M.J.A. has contributed to 1, 2, 3, 4, 5 and 6.
F.V. has contributed to 1, 2, 3, 4, 5 and 6.

Acceptance Note: This article was approved by the journal editors Dr. Rafael Sotelo and Mag. Ing. Fernando A. Hernández Gobertti.