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A New Geographic Information System (GIS) Tool for Hydrogen Value Chain Planning Optimization: Application to Italian Highways

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Abstract: Optimizing the hydrogen value chain is essential to ensure hydrogen market uptake in replacing traditional fossil fuel energy and to achieve energy system decarbonization in the next years. The design of new plants and infrastructures will be the first step. However, wrong decisions would result in temporal, economic losses and, in the worst case, failures. Because huge investments are expected, decision makers have to be assisted for its success. Because no tools are available for the optimum design and geographical location of power to gas (P2G) and power to hydrogen (P2H) plants, the geographic information system (GIS) and mathematical optimization approaches were combined into a new tool developed by CNR-ITAE and the University of Bologna in the SuperP2G project, aiming to support the interested stakeholders in the investigation and selection of the optimum size, location, and operations of P2H and P2G industrial plants while minimizing the levelized cost of hydrogen (LCOH). In the present study, the tool has been applied to hydrogen mobility, specifically to investigate the conversion of the existing refuelling stations on Italian highways to hydrogen refuelling stations (HRSs). Middle-term (2030) and long-term (2050) scenarios were investigated. In 2030, a potential demand of between 7000 and 10,000 tons/year was estimated in Italy, increasing to between 32,600 and 72,500 tons/year in 2050. The optimum P2H plant configuration to supply the HRS was calculated in different scenarios. Despite the optimization, even if the levelized cost of hydrogen (LCOH) reduces from 7.0–7.5 €/kg in 2030 to 5.6–6.2 €/kg in 2050, the results demonstrate that the replacement of the traditional fuels, i.e., gasoline, diesel, and liquefied petroleum gases (LPGs), will be disadvantaged without incentives or any other economic supporting schemes.

Keywords: power to hydrogen (P2H); P2H industrial plants; mobility; geographic information system; optimization; operations

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Citation: Guzzini, A.; Brunaccini, G.; Aloisio, D.; Pellegrini, M.; Saccani, C.; Sergi, F. A New Geographic Information System (GIS) Tool for Hydrogen Value Chain Planning Optimization: Application to Italian Highways. *Sustainability* **2023**, *15*, 2080. https://doi.org/10.3390/su15032080

Academic Editors: Antonella Meneghetti and Patrizia Simeoni

Received: 23 December 2022
Revised: 15 January 2023
Accepted: 16 January 2023
Published: 21 January 2023

1. Introduction

Hydrogen is one of the alternative solutions for mobility decarbonization even if its supply chain is still missing. Several targets were defined to cover the gap. The Alternative Fuels Infrastructure Regulation (AFIR) recommends one hydrogen refuelling station (HRS) every 100 km along the Trans-European Transport Network (TEN-T) Core and Comprehensive Network by 2027, reducing the previous target of every 150 km [1]. More than 800 HRSs are expected across Europe. It will be a preliminary step to cover part of the demand for a total fleet of more than two million vehicles by 2030 [2]. However, to date, 685 HRS have been installed worldwide. More than 50% of them are in Asia, and only 30% are in Europe [3]. Germany accounts for almost 100 HRSs, while only three were in service by 2021 in Italy. The goal is still so far away.

Research is still working on different topics on hydrogen mobility to speed up the transition. First of all was safety: preventive and protective countermeasures, safety distances, and standards were discussed [4–10]. Second was the HRS plants' design: the H2Mobility proposed four standardized sizes in terms of the maximum daily throughout, e.g., small (200 kg/day), medium (500 kg/day), large (1000 kg/day), and extralarge (4000 kg/day). Regarding the refuelling technologies, different solutions were proposed: a 350 bar of compressed gaseous hydrogen (CGH) HRS, a 700 bar of CGH HRS, and the subcooled liquid hydrogen (sLH^2) and the cryo-compressed (CcH^2) configurations [11].

Third was the economic aspects. Hydrogen supply chain (HSC) optimization aims to minimize the levelized cost of hydrogen (LCOH) [12–15]. As reviewed by Dagdougui, three approaches have been applied to HSC optimization [16]: the mathematical optimization models, the GIS-based approaches, and the transition models. The mathematical formulation was prevalently applied to find the best configuration, i.e., the type, the numbers, the location, and the capacity of HSC components. While most researchers considered cost minimization a criterion, a limited number of them also applied other criteria, such as safety or environmental impact. On the other hand, Dagdougui found that the GIS-based approach often takes into account only the geographic data without coupling them to mathematical models. However, the advantages and potentials resulting from the integration of the two approaches have already been demonstrated in other research fields, such as energy systems [17–21], biomass [22,23], energy storage [24], district heating [25–28], and wind and photovoltaic energy [29–33].

Focusing on HSC, Ball et al. proposed a new model, called MOREHyS (model of regional hydrogen supply) for the highways project [34]. A mixed-integer linear optimization model defined the most cost-effective solution in terms of electricity, heat, and hydrogen production according to the time period, technology type and area, required investment, and reduced emissions. GIS was used only on the clustering of the population density, but no efforts were made to investigate the transport cost between production and consumption sites. Strachan et al. integrated GIS-based data in the MARKAL model, i.e., a linear programming energy systems optimization model, to investigate different hydrogen supply scenarios for the UK [35]. However, limited supply and demand locations were investigated owing to the significant computational efforts required. Samsatli developed the value web model to optimize heat decarbonization by using green hydrogen [36]. Specifically, the GIS was used to investigate the areas' suitability for the installation of offshore and onshore wind turbines and to calculate the distances. Zhou et al. investigated the layout of a hydrogen refuelling station (HRS) in Weifang City of Shandong Province by applying a two-stage location and optimization model where GIS was used to investigate the potential locations [37]. Similarly, Lin et al. applied a multihybrid algorithm driven by GIS data to investigate an HRS in Beijing with respect to driving distance, but production sites were not considered in the analysis [38]. Nicholas et al. investigated the optimization of an HRS through a GIS-based method to minimize the average driven time from home to the refuelling station. For this purpose, the model created a composite map of potential sites using GIS, by using a mesh of 200 m^2 grid cells. Once the potential locations have been identified, the model calculates the driving times from the population centroid to each refuelling station and selects the ones that minimize it [39]. The optimum strategy to deploy hydrogen-compliant infrastructures was investigated by Johnson and Ogden [40]. An answer to the questions about refuelling technology and the size of the HRS that minimizes the levelized cost of hydrogen (LCOH) can be obtained by the model proposed by Li et al. [41]. For this purpose, they modelled the hydrogen-fuelling demand flow network by including 31 cities as nodes. The hydrogen production and transmission (HyPAT) model, i.e., a network optimization tool for identifying the lowest cost centralized production and pipeline transmission infrastructure based on a MILP approach, was developed and applied to a case study in the United States. Specifically, the model minimizes the total cost of hydrogen production and transportation on the basis of three geographical inputs introduced in GIS, i.e., the location of hydrogen demands, the potential hydrogen production facilities, and the route of hydrogen pipelines. However, the locations of the hydrogen production facilities were limited to 13 locations where existing cofired plants operated. A similar problem regarding the planning of a hydrogen pipeline infrastructure to supply HRS in Germany was investigated by Baufumé et al. [42]. In the study, GIS data on the distribution of vehicle fleets and existing refuelling stations were used to localize the potential hydrogen demand, while production sites were considered the barycentre of the 16 German states or the onshore connection points, respectively, for the electrolysers that are power supplied by onshore and offshore wind turbines. Soha and Hartmann investigated the planning of power to gas (P2G) plants connected to anaerobic digesters for the conversion of carbon dioxide [43]. Locations for green PV power–supplied hydrogen production plants in Malaysia were studied by Ali et al.; they developed an integrated GIS and AHP model in which technical, economic, and environmental parameters were used for the ranking process even if hydrogen demand locations were not considered in the investigation [44]. The green hydrogen HSC in 10 Malaysian districts was also optimized by Mah et al., who calculated the LCOH by using a GIS-MILP-integrated model [45]. The authors located GIS data in single representative points within each district, resulting in 10 nodes in total, and evaluated cases that differed for the available storage volume.

However, the authors found no GIS tool for the optimum design and planning of power to hydrogen (P2H) plants. For this purpose, a web-based geographical information system (GIS) tool was developed and applied by CNR-ITAE and the University of Bologna within the "synergies utilizing renewable power regionally by means of power to gas" (SuperP2G) project [46].

This paper aims to show the potentialities of the tool by investigating a case study relating to hydrogen mobility that focuses on the revamping of existing refuelling stations on Italian highways to HRSs. This paper is structured as follows: Section 2 is divided into two parts. In the first one, the SuperP2G-Italy tool is described. In the second one, the method applied for the estimation of the hydrogen demand in the HRS installed on the Italian highways is described. In the Sections 3 and 4, the results obtained by applying the tool to Italian highways in the middle- and long-term scenarios, i.e., 2030 and 2050, are shown and discussed. Concluding remarks and further research activities are reported in the final section.

2. Materials and Methods

2.1. The SuperP2G-Italy Tool

2.1.1. Overview: The Code and the Structure

SuperP2G-Italy is a GIS-based planning and optimization tool to determine the optimal HSC configuration that minimizes the LCOH. On the basis of a set of Python libraries, called modules, the tool processes raw input data for mathematical optimization, based on the well-known "transhipment problem" formulation, to meet supply and demand while minimizing the relative costs [47].

Because it is based on a geographic information system (GIS) approach, high spatial flexibility is possible, making it possible for users to analyse data within specific areas. In fact, since the first appearances were reviewed by Green et al. in 1985 [48], many other functionalities have been developed. The tool allows the user to localize the required information in the exact position of the space on the basis of the geographical coordinates, i.e., latitude and longitude, defined in the WGS84 (EPSG_4326) coordinate reference system. Therefore, the tool has no limitations on the geographical scale, allowing the users to optimize the solution to specific local areas. On the other hand, the temporal analysis is limited to an annual resolution.

The cost optimization model gives, as a result, the location, size, and number of P2G plants, to cover the hydrogen demand in the investigated territory, guaranteeing that energy balances and hydrogen demand constraints will be satisfied.

The core structure of the model is preliminarily shown in Figure 1. As shown, different calculation steps occur. First, input data are uploaded to the database (Sections 2.1.1 and 2.1.2).

Data are managed and elaborated in specific modules (Section 2.1.3) for the mathematical optimization (Section 2.1.4). Once the optimization has completed, the results are saved in the database and web visualization is realized (Section 2.1.5).

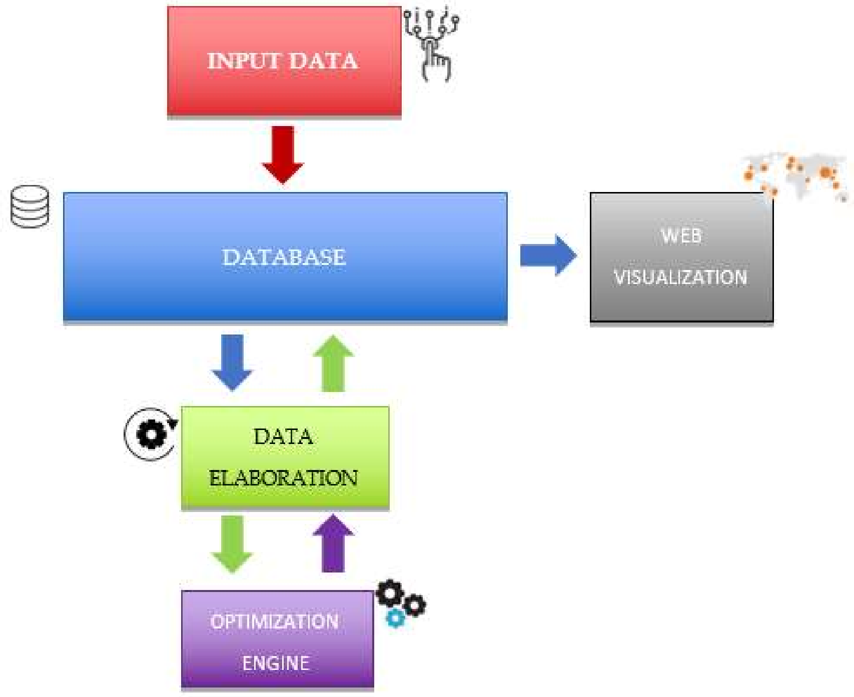

Figure 1. The simplified structure of the under developing SuperP2G-Italy tool.

2.1.2. Input Data

The SuperP2G-Italy tool requires users to input data. Specifically, the end user has to quantify and localize the annual hydrogen demand in the investigated area. Other data are already included and periodically updated in the SuperP2G-Italy tool by the developers. Among these are the location and the annual energy production of the renewable energy sources, the path of the existing energy infrastructure (power and gas networks), and the transportation infrastructure (the roads, railways). In addition, technoeconomic values such as predefined P2G plant efficiency, the CAPEX and OPEX, and hydrogen transport costs by pipeline or trucks are already included. A detailed description of the input data used in the investigated case study is reported in the Appendix A.

2.1.3. The Database

The database has been designed to manage inputs in the form of a shape file or a raster file. Based on PostgreSQL [49], more precisely through the spatial database extender PostGIS [50], the database is structured to gather data from different and heterogeneous sources. Because different public and private companies are responsible for the collection, the data are usually available in files of different formats, or they are downloaded through an application programming interface (API). For the tool, the database is structured using two layers to divide between mobility and power flows. In Figure 2, a schematic representation of the database with the included layers is shown. In each layer, information is grouped in an entities-based architecture, resulting in the possibility to simulate, for example, the possibility that an end user is connected to more than one electric cabin, such as the possibility that a renewable plant supplies more than one customer.

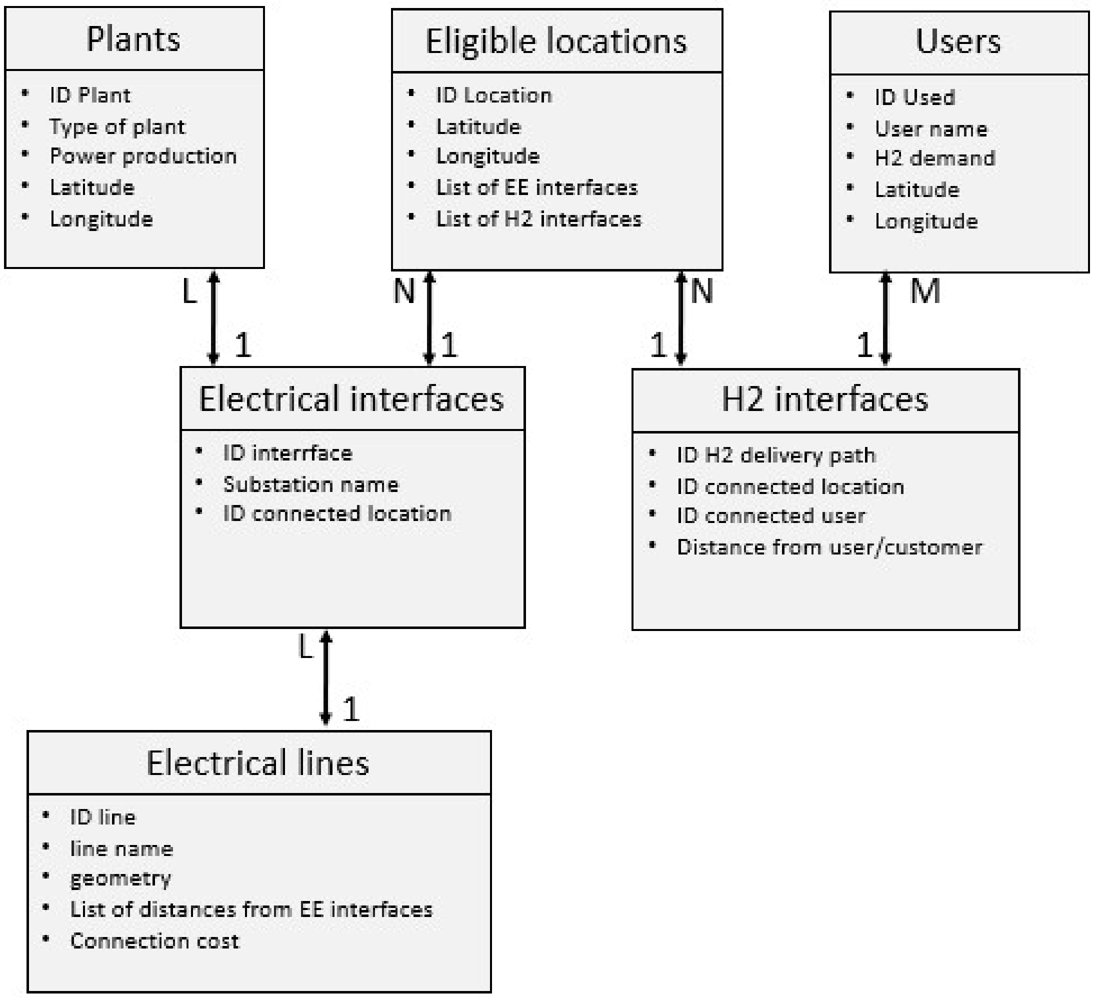

Figure 2. Conceptual model representation of the implemented database (relations between entities).

The implementation was done in a structured query language (SQL), ensuring high flexibility regarding data management (i.e., insertion, deletion, extraction, and modification) by using the open-source PostgreSQL, with its PostGIS extension, to manipulate geometric/georeferenced data.

2.1.4. Data Elaboration

Several steps are required to make the raw input data suitable for mathematical optimization:

- Thanks to the high number of renewable plants, clustering techniques are applied to aggregate renewable power plants.
- Territorial meshing is performed to have homogeneous data for distance/costs computation and demand aggregation (only in specific use cases).
- Power and gas/fuel network geometry is manipulated.
- Other preprocessing operations assemble data from different sources (national open databases, administrative/statistical territorial information collections, GIS server for mapping, national infrastructure database).

At the end of this first part, geodesic or routing distances are evaluated to approach the edges–costs correspondences (for estimating electrical and gas connections costs). Although the calculation of the shortest path between two locations in the space using commercial and free datasets is a well-known problem, as investigated by Zielstra and Hochmar and by Debnath [51,52] (such as the quality of these datasets, as investigated for developing countries by Mahabir et al. [53]), a simplified approach was applied in this first version of the SuperP2G-Italy tool for computational costs reasons.

The computational time and accuracy of the above-described procedures are affected by the following parameters:

- The clustering technique (density based, distance based, K-means) used for unsupervised learning.
- The mesh granularity to represent the analysed territory through a set of eligible P2G positions, one among which is selected as the best subset to minimize LCOH.
- The number of selected electrical networks to calculate distances for P2G connections (the presence of different nominal voltage/capacity networks may result in different costs).
- The technique to evaluate the distance from P2G plants to consumers (e.g., geodesic, routing), even if they can be adjusted to simplify calculations.

Once the nodes have been defined (generation points, eligible positions for P2G plants, and hydrogen consumers positions), the second part of the procedure is the formulation of the mathematical problem.

2.1.5. The Mathematical Optimization Model

The SuperP2G-Italy tool minimizes the total costs. The problem is defined by an objective function involving all the considered costs whose sum has to be minimized. Specifically, the cost function Fc includes three terms, as shown in Equation (1). The first considers the transportation of hydrogen to the user. The second is the cost of the P2H plant's connection to the electrical grid or to the renewable plant. The third term includes the P2H plant's CAPEX and OPEX. A detailed explanation of the three costs and of the main assumptions applied in this study is included in the Appendix A. The cost function Fc can be written as in Equation (1):

$$F_c = \sum_{j \in D} \sum_{i \in F} d_j c_{ij} x_{ij} + \sum_{k \in R} \sum_{i \in F} o_k c\prime_{ik} x\prime_{ik} + \sum_{i \in F} f_i(s_i) y_i \tag{1}$$

where d_j is the consumer demand that is defined as ≥ 0 with j ϵ D (set of consumers); c_{ij} is the unit cost to serve the jth consumer from the ith P2G plant (also in this case, it is required that $c_{ij} \geq 0$); x_{ij} is the demand fraction of the jth consumer that is supplied from the ith P2G plant, and the range that can be assumed by the parameter is between 0 (the jth consumer is not supplied by the ith P2G plant) and 1 (the jth consumer is supplied only from the ith P2G plant); o_k is the renewable production source that is considered ≥ 0 with k ϵ R (a set of production sources); c'_{ik} is the unit cost to supply power to the ith P2G plant from the kth production source; s_i is the capacity of the P2G plant; x'_{ik} is the capacity fraction of the ith P2G plant served from the kth production source, and the range that can be assumed by the parameter is between 0 (the ith P2G plant is not supplied by the kth source) and 1 (the i-th plant is supplied only from the kth source); f_i is the cost ≥ 0 to realize and to operate the ith P2G plant; y_i is the open factor for the ith P2G plant, and the only two values that can be assumed by the parameter y are, on the one hand, $y_i = 0$ if there is no P2G plant located in the ith point and, on the other, $y_i = 1$.

2.1.6. The Optimization Solver

Regarding the solver selection, there are plenty of open-source and commercial solvers that may be exploited to find the optimal solution. Depending on the complexity of the objective function and constraints, the selection may be limited, owing to, for instance, the nonlinearity of the objective function or constraint formulation or the discreteness of the P2G power/capacity set. In this work, thanks to its high flexibility for problem description within a Python code, wide solver support (including specific options), and free availability, the "Pyomo" library was used [54,55]. This choice allowed for flexible methods and options to describe the problem parameters (distances, costs, and P2G capacity values in terms of existence domains) with specific initialization functions from the precalculated georeferenced data. Moreover, this package offers the possibility to select different solvers for problem optimization (with even specific options such as the termination conditions and iterative approach). Thus, it was possible to compare the benefits and the drawbacks of a bunch of solvers on simplified formulations (to reduce the computation time) and then correctly select the final choice.

2.1.7. SuperP2G-Italy Limitations

The SuperP2G-Italy tool has completed a first development phase, and new functionalities will be developed to reduce the impact on calculation accuracy by the existing limits:

- Approximation of continuous variables—the current version of the tool elaborates the data in a mesh in which size can be decided by the users. Therefore, a very fine mesh could be selected to resolve the problem. However, as for other nondeterministic class problems, the computational time increases, rapidly diminishing the size of the mesh.
- Geographical boundary conditions—in the current version, the tool calculated the best position for the plant without taking into account of any potential boundary constraints, such as hydrogeological ones, fire and earthquake risks, and reserve areas or forbidden areas.
- Complex cost models—the estimation of the P2H plants' capital expenditure (CAPEX) and operational expenditure (OPEX) requires a complex cost function that depends on many parameters and boundary conditions, first of all the size. However, the introduction of too many restrictive constraints or complex cost models could determine an "infeasible" condition using (currently available) deterministic mathematical solvers requiring a simplified estimation.

2.2. Hydrogen Demand on Italian Highways

2.2.1. Italian Highways: Overview

The most updated reports [56,57] show that Italian highways currently cover almost 7000 km. More than 84.7 billion km of vehicles annually move through the 75 routes, of which 64 are given in concession to private organizations. To supply fuel to the vehicles, 440 refuelling stations were installed along the infrastructure in 2019, when 242.9, 136.4, and 975.2 million litres of gasoline, liquefied petroleum gas, and diesel, respectively, were sold. No information is available regarding the methane amount.

The trends of vehicles and litres sold on Italian highways between 1980 and 2020 are shown in Figure 3. As shown, few data are available between 1980 and 2000, while a higher sampling frequency is available in the following period. Discarding the data for 2020, where the COVID-19 pandemic strongly affected people's everyday lives because of lockdowns and other limitations, a continuous increase in Italian traffic appears except for the period between 2010–2013, which is probably connected to the increase in fuel selling prices. The symbol "X" is used to indicate 2020, i.e., the year affected by the COVID-19 pandemic lockdown. The amount of fuel purchased shows a different trend of increasing until 2001, when a maximum of 4181 million litres were sold. A decreasing trend appears in the following years, down to 1355 million litres in 2019, resulting in a reduction in the specific amount for each refuelling station from 10.2 million litres in 2001 to less than 3.4 million litres in 2019 owing to not only the price gaps between highways and other roads but also improvements in vehicle efficiencies.

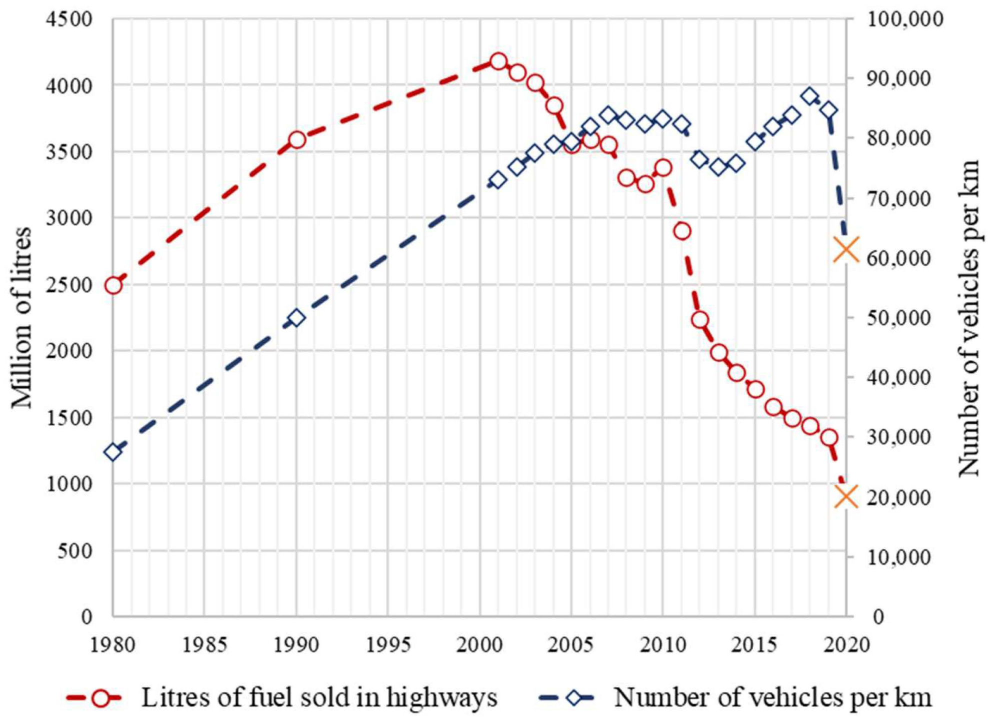

Figure 3. Trend of litres of fuel sold on Italian highways (red) and trends of traffic (blue).

2.2.2. Hydrogen Demand Estimation

Because no hydrogen is currently consumed in the Italian mobility sector, two temporal scenarios are considered: 2030 and 2050. For both scenarios, the potential hydrogen amount [ton/year] is calculated by Equation (2):

$$H_{2,n} = \alpha_j \times \frac{\sum_{i=1}^{3} V_{l,n} \times LHV_l}{1000 \times LHV_{H2}} \tag{2}$$

where

- l = 1, 2, 3. Specifically, l = 1 for gasoline, l = 2 for diesel, and l = 3 for LPG.
- n = 1, 2. Specifically, n = 1 for 2030 and n = 2 for 2050.
- α_n is the hydrogen penetration in the mobility sector assumed equal to 2% in 2030 and 15% in 2050 in accordance with [50].
- V_l is the annual amount of the lth fuel sold on Italian highways in 2030 and in 2050 [L/year].
- LHV is the low heating value of the fuel, and it is assumed equal to 31.8 MJ/L, 36.1 MJ/L, 25.5 MJ/L, and 120 MJ/kg, respectively, for gasoline, diesel, LPG, and hydrogen.

The amount of fuel sold in the two future scenarios has to be calculated, considering the expected traffic volumes and vehicles' specific fuel consumption. Regarding the traffic, no data dedicated to Italy are available, resulting necessary to take some assumptions. In accordance with the International Transport Forum [58], two cases are considered, e.g., a baseline and an optimized one. As shown in Figure 4, vehicle traffic doubles in the baseline scenario, while the number of vehicles per kilometre is reduced to 60% in the optimized scenario.

More-complex analysis is required concerning the amount of fuel sold on Italian highways. In fact, in addition to vehicle efficiency improvements, thanks to measures such as the ones proposed in [59], including better engine tuning, driving styles, use of more-efficient aftermarket replacement parts, reduction in vehicle weight, reduction in congestion, also the price gap between highways and other roads contribute to reducing the volume of fuels sold on the highways. According to the data referring to the amount of gasoline, diesel and liquefied petroleum gases sold in Italian highways between 2001 and 2020, shown in Figure 5, asymptotic values seem to have been reached by gasoline and LPG: 0.025 for gasoline and 0.014 for LPG. According to the forecasted EU future demand for fossil fuels in 2030 and 2050, reductions of 10% and 55% are preliminary assumed for diesel, while 5% and 62.5% are assumed for gasoline and LPG, respectively, in 2020.

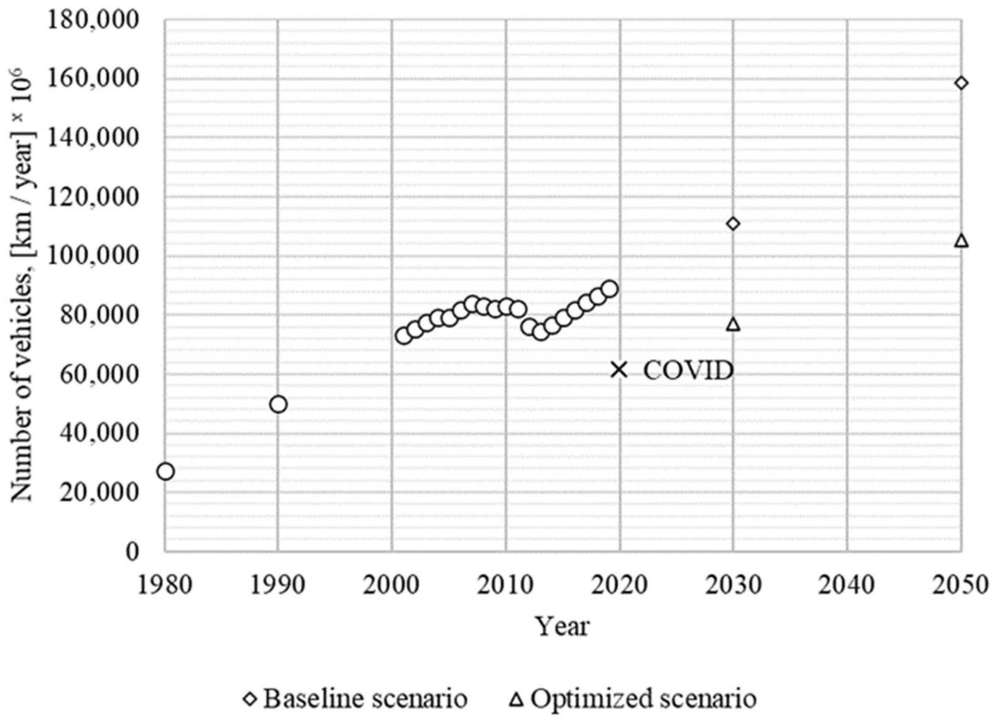

Figure 4. Number of vehicles in the baseline scenario and in the optimized scenario.

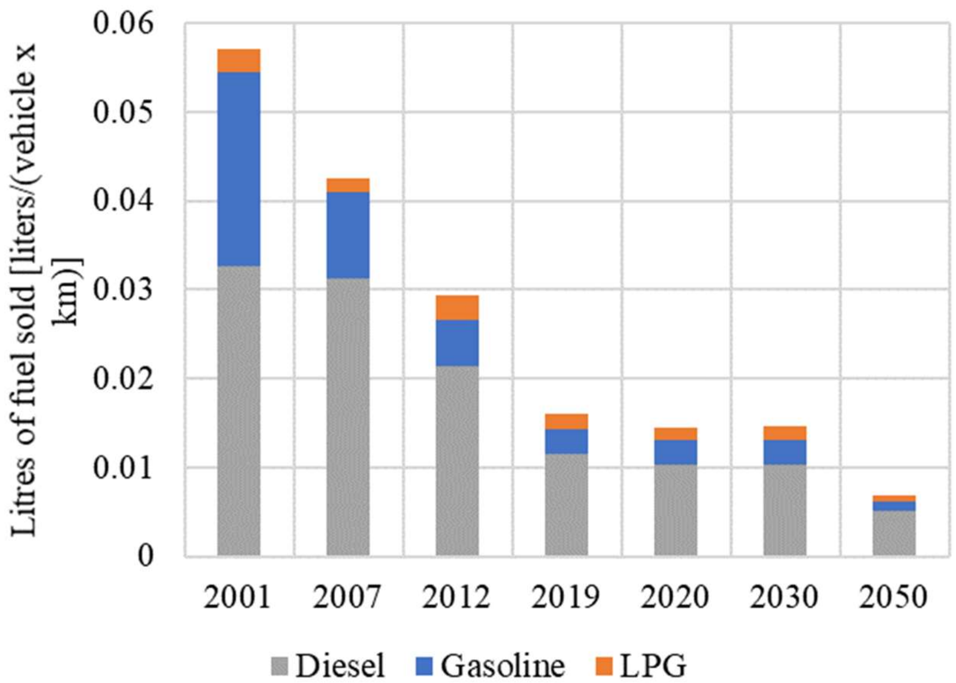

Figure 5. Amount of fuel sold on the Italian highways.

An assumption has to be made concerning the geographical location of hydrogen demand. The information on the fuel sold in each Italian refuelling station is not available, while it is the total amount in the route. Hydrogen demand $H_{2,j,o,p}$ in the oth refuelling station in the pth Italian route is estimated on the basis of Equation (3):

$$H_{2,j,o,p} = \frac{H_{2,n,p}}{N_{n,p}} \tag{3}$$

where

- k = 1, 2, . . . ,75 is the number of Italian highways' routes.
- $H_{2,n,p}$ is the estimated hydrogen demand in the kth route.
- $N_{n,p}$ is the number of refuelling stations in the kth route that will be converted to hydrogen.

2.2.3. Scenario Definitions

Four scenarios were investigated by the SuperP2G-Italy tool to check the effect of any variations in the baseline scenario. The parameters used to characterize the other scenarios are shown Table 1:

- Hydrogen penetration—the parameters will depend on H^2 penetration in the mobility market. As shown, in 2030 and 2050, a maximum penetration of 2% and 15%, respectively, is assumed.
- P2H plant nominal size—because there is a lower specific cost from increasing the nominal size, different plant sizes are investigated by the tool. As a preliminary assumption, a maximum P2H plant nominal size of 10 MW is considered for similar applications in 2030, while a high threshold and a low threshold, specifically 20 MW and 30 MW, respectively, are assumed for 2050.
- Baseline and optimized scenarios were investigated following the process from the previous section.
- A maximum daily distance covered by a truck was assumed to be equal to 200 km and 500 km.

Table 1. Parameters used for the scenarios' analysis.

#sim	Temporal Frame	P2H Plant Nominal Size [kW]	H^2 [%]	Scenario	truck_km
1	Middle Term (2030)	(100, 300, 1000, 3000, 5000, 10,000)	2	base	200
2			2	opt	
3			2	base	500
4			2	opt	
5	Long Term (2050)	(500, 1000, 3000, 5000, 10,000, 20,000, 30,000)	15	base	200
6			15	opt	
7			15	base	500
8			15	opt	

3. Results

3.1. Hydrogen Demand on Italian Highways in 2030 and 2050

Only a fraction of all vehicles will be converted to hydrogen. For example, assuming 2% and 15% as realistic conversion factors for 2030 and 2050, the annual demand in the baseline scenario is calculated equal to 10,000 ton/year and 72,500 ton/year in the baseline, i.e., more or less than 1.8% and 12.9% of the current total Italian hydrogen demand [60]. The demand is reduced to 7000 ton/year and 32,600 ton/year in the optimized case. Therefore, 230–330 GWh/year and 1100–2400 GWh/year of hydrogen have to be produced to supply the demand of the refuelling stations installed on the Italian highways in the middle and long-term scenarios, respectively.

Concerning the geographical distribution, Figures 6 and 7 show hydrogen demand in 2030 and 2050 at the NUTS-3 level, i.e., including 109 provinces. Excluding 34 provinces where no demand will be present, 50% of the total demand is in 17 provinces that are passed through as the highest-traffic Italian highways. As shown, the higher concentration is near big cities interconnected by different routes, such as Rome, Milan, Florence, and Bologna, which cover more than 20% of the total demand. Owing to the limited development of highways, a smaller demand is expected in the South of Italy and the islands, even with the great potential for local renewable energy.

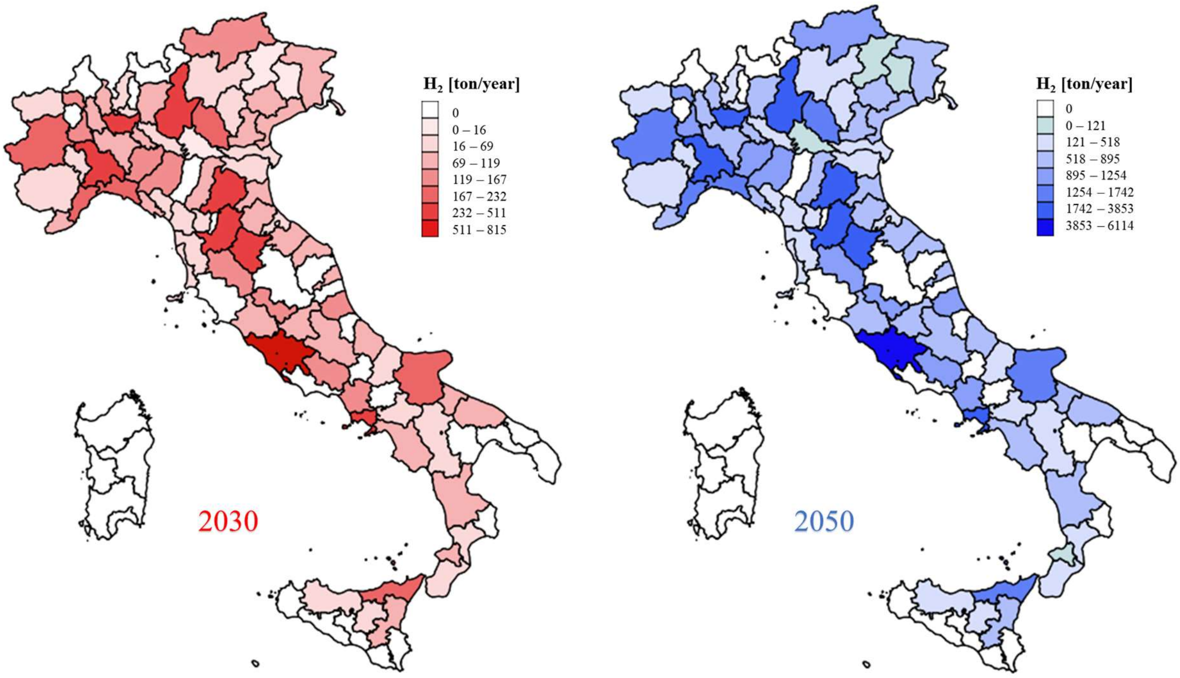

Figure 6. Forecasted hydrogen demand in 2030 and 2050 for each Italian province.

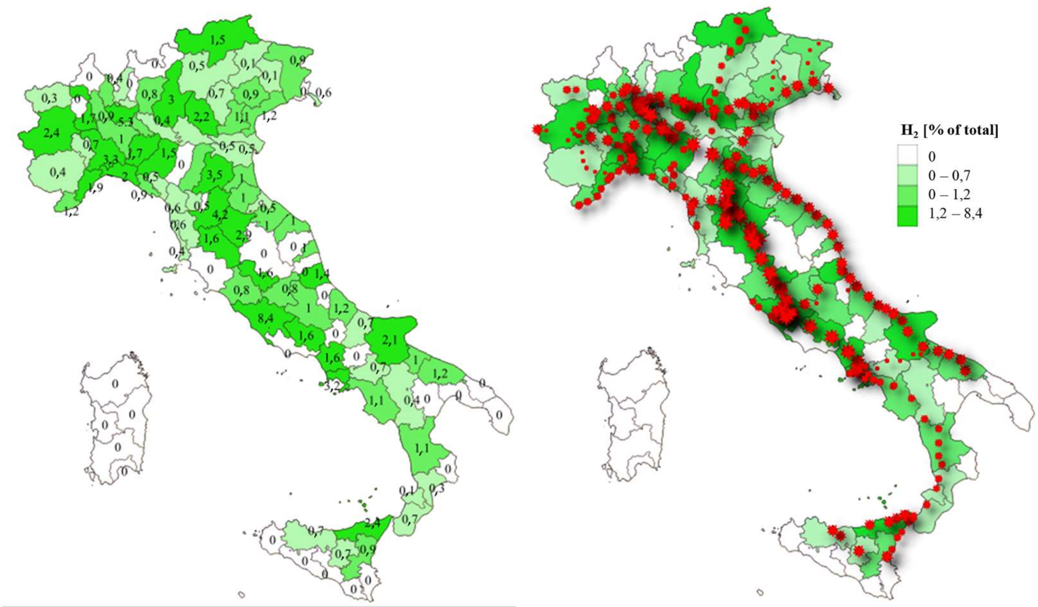

Figure 7. Percentage of hydrogen demand for each Italian province (**left**) and distribution of refuelling stations (**right**).

3.2. Scenario Analysis: 2030

The results of the scenario of 2030 are summarized in Table 2 and in Figure 8. As indicated, LCOH ranges from 6.93 €/kg to 7.46 €/kg. The number of plants substantially differs, changing the truck autonomy from 200 km to 500 km. As shown, keeping the hydrogen demand constant and increasing the truck autonomy reduces the number of plants. Fewer plants but better nominal plants result in Cases 3 and 4. P2H plants with a nominal size smaller than 3 MW are not considered in the optimum solution in Case 4, while they represent only 22% in Case 3. In Cases 1 and 2, on the other hand, smaller sizes are not disregarded. Owing to truck range limitations, a plant supplies less demand in the territory. Therefore, increasing the size signifies an increase in the percentage of partial load operations, reducing the positive effect that the increase in the size would have on investment.

Table 2. Summary of the 2030 scenarios.

Case	P2H Nominal Power [MW]	Number of Plants [-]	LCOH [€/kg]
1	293.6	105	7.46
2	208.0	83	7.98
3	295.7	81	7.02
4	205.0	52	6.93

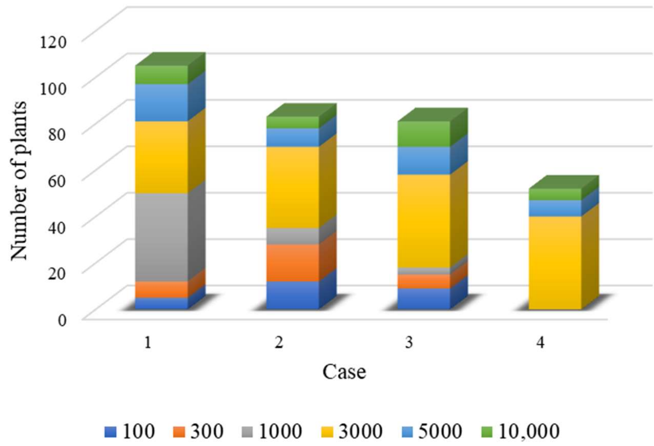

Figure 8. Number of plants as a function of the nominal size in [MW] for the four cases for 2030.

The LCOH of the four scenarios is also shown in Figure 9, where the contribution of the P2H plants' CAPEX and OPEX, the connection to the electric grid, and the H^2 transport are highlighted. As expected, the main contribution is due to plants' investments and operations, which are responsible for more than 90% of the costs in all the scenarios.

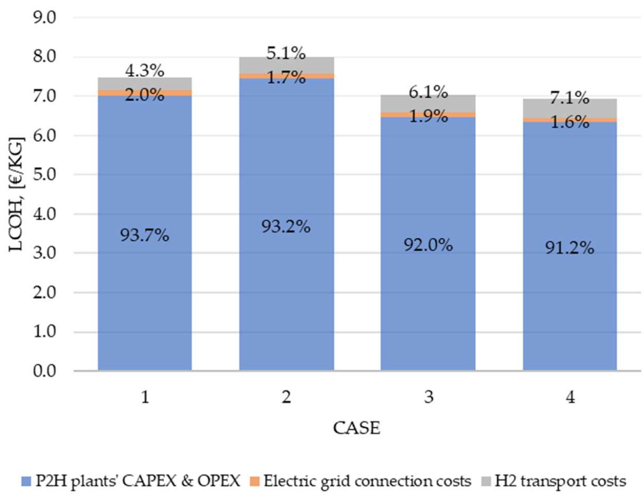

Figure 9. LCOH for the four investigated scenarios at 2030.

Regarding the location of the P2H plants, a GIS representation of the results of the four cases is shown in Figure 10. Three colours are used to indicate the following: P2H plants (black dots), renewable energy plant clusters (blue dots), and HRSs (red dots). As shown, P2H plants are mainly near the HRSs characterized by the greatest demand, particularly in those provinces characterized by the greatest demand, as investigated in Section 3.1.

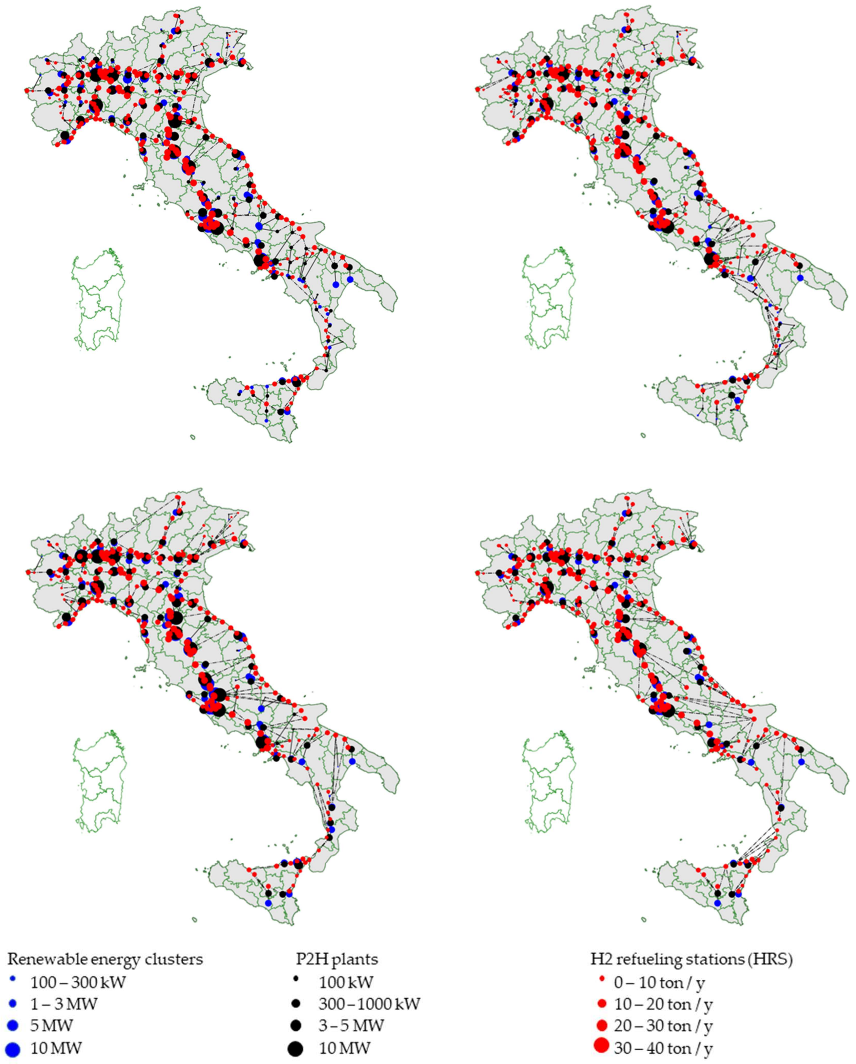

Figure 10. Geographical location of P2H plants, HRSs, and renewable energy clusters. Case 1—upper left; Case 2—upper right; Case 3—bottom left; Case 4—bottom right.

3.3. Scenario Analysis: 2050

The results of the scenario for 2050 are summarized in Table 3 and in Figure 11. As indicated, LCOH ranges from 5.62 €/kg to 6.12 €/kg. Differently from the previous case, the LCOH of the defined baseline case is smaller than that of the optimized case. The scale effect on the investment cost of the P2H plants can explain this result. Figure 11 shows the nominal size for each analysed case. As shown, because of the higher demand, the mean size of the plants installed increases, discounting for a better economy-of-scale effect. Differently from the 2030 scenario, increasing truck autonomy results in an increase in the LCOH. Although the average plants' nominal size increases with truck autonomy, the economy-of-scale positive effect is reduced by the partial load operations that increase with the plants' nominal size, especially at a high value (20 MW and 30 MW). For example, the installed plants in Cases 6 and 8 produce 98% and 90% of their potential, respectively, resulting in higher specific investment for the unit of hydrogen production.

Table 3. Summary of the 2030 scenarios.

Case	P2H Nominal Power [MW]	Number of Plants [-]	LCOH [€/kg]
5	2277.0	111	5.62
6	991.0	101	5.69
7	2231.5	100	5.63
8	1084.0	101	6.12

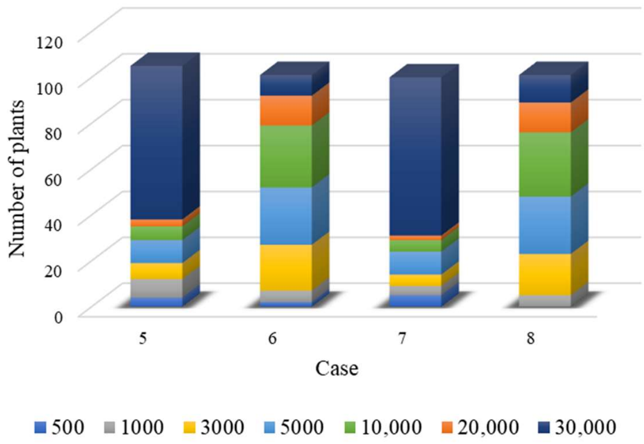

Figure 11. Number of plants as a function of the nominal size in [MW] for the four cases for 2050.

As for the 2030 scenario, the LCOH of the remaining scenarios is shown in Figure 12. Like 2030, the P2H plants' cost is the main contribution. However, hydrogen transport cost slightly increases, reaching almost the 10% in Case 7.

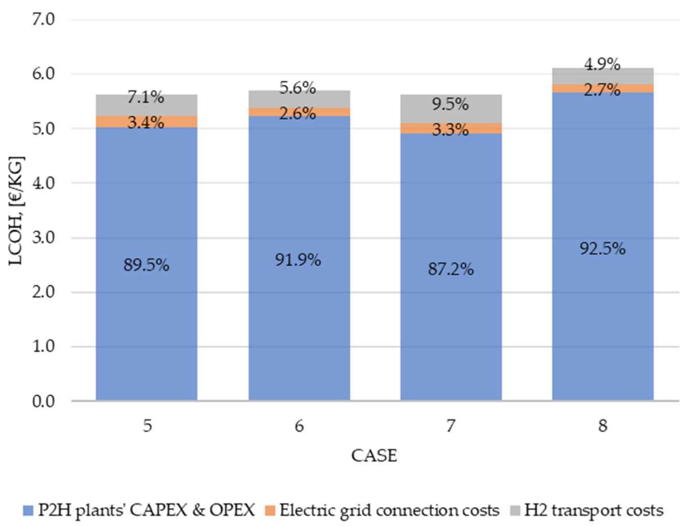

Figure 12. LCOH for the four investigated scenarios for 2050.

Regarding the location of the P2H plants, the results are shown in Figure 13. Compared with the previous case, baseline and optimized cases radically differ in the size and location of the plants in the territory. Specifically, because there is a greater demand in 2050 than in 2030, high nominal power plants are uniformly located in the Italian territory in the baseline cases. In the optimized case, the plants of the highest capacity are mainly near the high-demand HRSs. From the performed analyses, a noticeable result is shown by Case 7 (and highlighted in the related map), where two points show relevant effects:

- The impact of CAPEX's share on the total investment cost over 20 years (already shown in Figures 9 and 12),

- The granularity of the P2G plants' availability (i.e., the set of available nominal power/capacity values in the scale production).

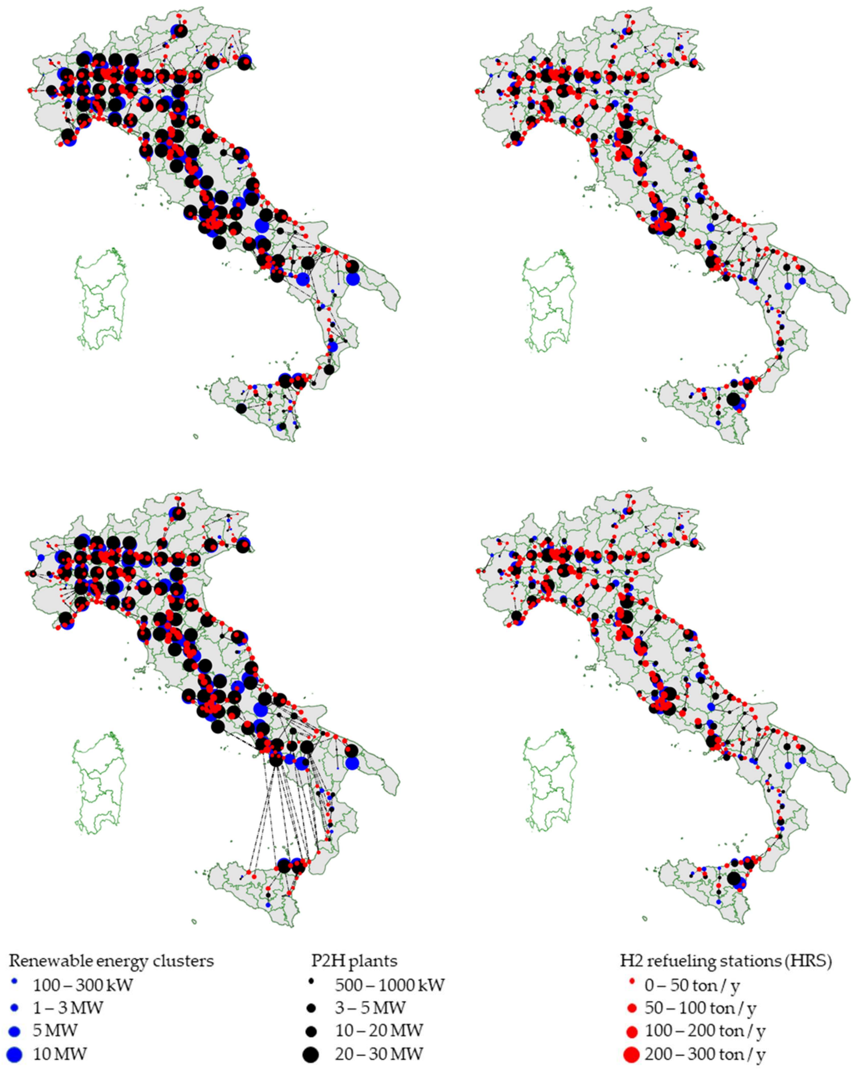

Figure 13. Geographical location of P2H plants, HRSs, and renewable energy clusters. Case 5—upper left; Case 6—upper right; Case 7—bottom left; Case 8—bottom right.

In Southern Italy (in particular to deliver hydrogen to some users in western Sicily), those factors determine the advantage of the (apparently sea-crossing) long-range (about 500 km) truck journeys, instead of using (by far) larger converters in their proximity. First of all, owing to the high impact of CAPEX (in particular for small capacity values), a new P2H plant would cause an overall increment in the costs, and even more, it could be operated at a low usage percentage. Second, owing to the chosen granularity of the nominal power, using the next greater value would result in a cost increment (to serve few small users) that could not be compensated by the hydrogen delivery cost reduction by the shorter range of truck journeys.

4. Discussion

The first important consideration concerns hydrogen mobility sustainability. As estimated, a large amount of hydrogen would be required in the HRSs on the Italian highways to achieve the expected penetration for 2030 and 2050. Although the existing Italian hydrogen demand, i.e., more or less 460 kton/year, is higher, the potential conversion of traditional cars to hydrogen has to be carefully evaluated. First, assuming the target alkaline electrolysers' efficiency defined by the Clean Hydrogen Partnership (i.e., 48 kWh/kg), 336–480 GWh/year of electricity results for 2030 [61]. Although it represents less than the 0.2% of the total Italian electricity demand, to produce green hydrogen, only renewable electricity has to be considered. According to the target set by PNIEC (in Italian "*Piano Nazionale Integrato per l'Energia e il Clima*"), 95.2 GW of renewable plants are expected to be in operation by 2030, ensuring an annual energy production of up to 186.8 TWh/year [62] even if higher targets could be necessary to achieve "Fit for 55" goals [63]. According to the Italian hydrogen strategy, 5 GW of P2H plants would be operated in 2030 for the production of green hydrogen. Therefore, P2H for hydrogen mobility on highways would represent 6% of the total, resulting in a first step for mobility decarbonization.

The second emerging reflection concerns the economic feasibility. The calculated LCOH is well aligned with the literature. For example, Minutillo et al. calculated a value of 12.48 €/kg for an onsite plant in Naples, even if the refuelling station cost were included in the analysis [15]. An LCOH in the range of 4.07 to 12.69 €/kg was calculated by Caponi et al. [64]. Onsite plants, different sizes, and electricity purchase costs were considered in their study. The range of 5.19 to 15.34 €/kg was instead calculated for decentralized production, depending on the distance from the HRS and the retail cost of hydrogen.

According to the value calculated by the SuperP2G-Italy tool with an electricity purchase cost of 75 €/MWh (pre-crisis values) and given the same energy content, an LCOH between 5 and 8 €/kg causes hydrogen to be more convenient than gasoline, diesel, and LPG only if their purchase costs exceed 1.34–2.13, 1.52–2.42, and 1.07–1.71 €/L, respectively. Even if the energy and oil crises were responsible for approaching these thresholds, appropriate measures have to be considered to ensure the competitiveness of hydrogen mobility and to make it real. The first condition for hydrogen mobility success is that the H^2 car owner is advantaged by its use. From an economic point of view, the investment and the operative costs should justify the purchase.

For example, hydrogen and diesel cars have different costs. To date, the hydrogen Toyota Mirai costs 67 k€. The Audi A4 (diesel) costs 45.8 k€. The advantages of selecting one of the two alternatives depend on many factors. Factoring in only the fuel cost and assuming an annual distance of 11,000 km [65], the diesel should cost more than 4.6 €/L to make profitable the hydrogen car over a lifetime of 10 years. By doubling the travelled kilometres, a cost of 2.9 €/L would be necessary. With these conditions, no way is feasible for the success of H^2 vehicles without any intervention. Two approaches are possible. Cost reduction is the first point to be targeted. As shown, the CAPEX is affected by a scale effect. Standardizing P2H plants would be beneficial because the design of the components will be performed a single time and then repeated, avoiding engineering costs. According to the obtained results for the two temporal scenarios, the 1 MW and 3 MW plants should be standardized in the middle term, while the 5, 10, 20, and 30 MW in the long term. Standardizing the plants would reduce costs and installation time because all those activities linked with the engineering phase could be easily repeated. A typical example would be authoritative procedures reviewed by [66], which are still unexplored in the P2H sector.

According to OPEX, electricity constitutes the main source of costs. Two strategies have to be stressed for its reduction. First of all, investments in research and development activities could be a decisive factor for decreasing the current costs. Specifically, research activities should be encouraged to propose and develop new disruptive and potentially winning technologies in electrolysis. Second, P2H plants should be considered for remuneration while ensuring grid-balancing services. However, these could be insufficient, requiring a direct intervention from policymakers supporting car owners in purchasing ecofriendly mobility solutions. Incentives have typically been proposed in several ways in the past, such as in the electrical mobility sector. However, particular attention should be paid to avoid the speculation effect or any distortion of the market that would negatively affect the entire sector. Other solutions, such as a discount on the selling price, should be examined. On the other hand, increasing the taxes on traditional fossil fuels to achieve the previous values could negatively affect the current economy and, consequently, the general public's perception regarding the support schemes for ecofriendly mobility solutions.

5. Conclusions

The SuperP2G-Italy tool was developed by CNR-ITAE and the Department of Industrial Engineering of the University of Bologna during the SuperP2G project, aiming to give interested stakeholders help in planning P2H projects investments. To show the potentialities, a case study regarding hydrogen mobility was investigated in the middle term and long term.

The main conclusions of the study are reported below:

- An LCOH in the range from 5 to 8 €/kg, i.e., 0.042 to 0.067 €/MJ, was calculated for the eight scenarios. Therefore, according to the present purchase costs without incentives or other supporting strategies, hydrogen mobility would be less convenient than a traditional one, resulting in a barrier to market uptake.
- Several plants must cover the entire hydrogen demand in all the investigated scenarios. While the plants' design would be not so critical, authorization procedures have to be lightened, reducing the complexity and the time required to complete a project. Additionally, efforts should be taken to improve the public's understanding of hydrogen, increasing social acceptance and avoiding phenomena such as NIMBYism that could stop projects and increase the expected costs.
- To increase the competitiveness of hydrogen mobility, efforts should be performed in R&D to reduce the cost of plants and improve efficiency. In the first case, standardized modules with a predefined size should be designed, and the plant configuration should be optimized to minimize investment costs. To date, this market is more characterized by customization that increases the total cost. In the second case, research should address increases in efficiency or the use of low-grade energy. New designs of traditional electrolysers, the use of different materials, or the direct exploitation of solar irradiation are some of the potential actions that can be taken.

As demonstrated, the SuperP2G-Italy tool is an effective instrument for investment decision planning, helping stakeholders to select the best size and location and also to easily perform sensitivity analysis while changing the interested parameters. However, some limitations still exist. They will be covered in future research. Some examples are listed below:

- The possibility to use continuous values of P2H plants' nominal capacity rather than a discrete set of values.
- While in the existing version, the geodesic distance is used to approximate the length of the path between two locations, the exact road distance will be implemented, increasing the accuracy of the results.
- The possibility for users to design their plant configuration, deriving expected CAPEX and OPEX.

Author Contributions: Conceptualization, methodology, data curation, and formal analysis: G.B. and A.G.; software: G.B. and D.A.; supervision: F.S. and C.S.; writing—original draft: A.G.; writing—review and editing: G.B., M.P., C.S. and F.S. All authors have read and agreed to the published version of the manuscript.

Funding: This project has received funding in the framework of the joint programming initiative ERA-Net Smart Energy Systems' focus initiative integrated, Regional Energy Systems, with support from the European Union's Horizon 2020 research and innovation programme under agreement no. 775970.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data presented in this study are openly available.

Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Appendix A.1. Hydrogen Transport Cost

For the selected case study, it is assumed that the P2G plant is installed away from the refuelling station and that the produced hydrogen is transported by trucks in a gaseous state. Transport by pipeline is not considered because a massive investment would be required to install new pipelines to connect all refuelling stations considered in the study. The hydrogen transport cost is calculated by the model proposed by [67]. Because the model was developed for Germany, different values are applied in the Italian framework. Specifically, the diesel cost value is for the last-updated value available in September 2022. Table A1 reports the values, while Equation (A1) is the correlation applied:

$$c_{ij} = 0.0109 \times D_{i,j} \tag{A1}$$

where

- c_{ij} is the transport cost between the jth consumer and the ith P2G plant.
- $D_{i,j}$ is the distance between the jth consumer and the ith P2G plant, in km.

Table A1. Assumptions for the calculation of the transportation costs.

Source of cost	Value
CAPEX (truck + trailer)	0.835 M€ (= 0.185 + 0.65)
O and M	12% CAPEX truck + 2% CAPEX trailer
H^2 conveyed by a truck	300 kg
Fuel consumption	34.5 km/L
Diesel cost	1.4 €/L
Personnel cost	3185 €/month
Daily operation	8 h/day
WACC	8%

Appendix A.2. P2G Plant's Electrical Connection Costs

The P2G plant's electrical connection is calculated as the connection of a renewable plant to the national grid. Specifically, the criterion of Equation (A2) was applied in accordance with [68]:

$$c\prime_{ij} = \min\begin{cases} 35 \times P_i + 90 \times P_i \times D_{ik} + 100 \\ 4 \times P_i + 7.5 \times P_i \times D''_{ik} + 6000 \end{cases} \tag{A2}$$

where

- P_i is the P2G electrical power, kW.
- D_{ik} is the geodetic distance between the P2G plant and the nearest medium/low-voltage electric cabinet.
- D''_{ik} is the geodetic distance between the P2G plant and the nearest high voltage transformation cabinet.

Appendix A.3. P2G Plant's CAPEX and OPEX

The preliminary design of the plant is sufficient for the SuperP2G-Italy tool. Specifically, the following plant sections were considered for the CAPEX estimation:

- Water electrolysis section—hydrogen is produced in this section by electrolysers. For the calculation, the PEM technology was assumed to be based on its greater flexibility with respect to the alkaline technology, even its higher CAPEX.

- Compression section—hydrogen is compressed up to 250 barg from a suction pressure of up to 30 barg. Two compressors are considered in the simplified configuration to maximize the availability of the plant.
- Storage section—hydrogen is assumed to be stored in AISI 316L Type I storage vessels.
- Refilling—hydrogen is filled in the truck in this section.

Based on the configuration, Equation (A3) was applied for the calculation of the P2G plant's CAPEX:

$$\mathrm{CAPEX} = \mathrm{CAPEX_{EL}} + \mathrm{CAPEX_{COMP}} + \mathrm{CAPEX_{STORAGE}} + \mathrm{CAPEX_{FILLING}} + \mathrm{OTHER} \quad \text{(A3)}$$

where

- $\mathrm{CAPEX_{EL}}$ is the CAPEX of the electrolysis section [€].
- $\mathrm{CAPEX_{COMP}}$ is the CAPEX of the compression section [€].
- $\mathrm{CAPEX_{STORAGE}}$ is the CAPEX of the storage section [€].
- $\mathrm{CAPEX_{FILLING}}$ is the CAPEX of the filling section [€].
- OTHER includes nonequipment and civil work costs that are required for the realization of the plant [€]. Particularly, nonequipment costs include (i) engineering costs, (ii) distributed control system (DCS) and energy management unit (EMU) installation costs, and (iii) interconnection, commissioning, and start-up costs.

Concerning the OPEX, Equation (A4) was applied:

$$\mathrm{OPEX} = \mathrm{OPEX_{EL}} + \mathrm{OPEX_{COMP}} + \mathrm{OPEX_{STORAGE}} + \mathrm{OPEX_{FILLING}} + \mathrm{OTHER} \quad \text{(A4)}$$

where

- $\mathrm{OPEX_{EL}}$ includes the following source of costs: electricity, O and M, water, and stack replacement.
- $\mathrm{OPEX_{COMP}}$ includes electricity and O and M.
- $\mathrm{OPEX_{STORAGE}}$ includes O and M costs.
- $\mathrm{OPEX_{FILLING}}$ includes electricity and O and M.
- OTHER includes the P2G plant's general O and M costs.

The main assumptions are reported in Table A2, and the values are taken in accordance with [69].

Table A2. Assumptions for the CAPEX and OPEX of the P2H plant.

Source of Cost	Value
$\mathrm{CAPEX_{EL}}$	$\mathrm{P_{el}} < 700$ kW: $C_O \times (P_{el}/P_{el,0})^n$ $\mathrm{P_{el}} \geq 700$ kW and $\mathrm{P_{el}} < 2000$ kW: $C_O \times (P_{el}/P_{el,0})^n \times (P_{el},1/P_{el})^a$ $\mathrm{P_{el}} \geq 700$ kW: $\mathrm{C_{0,1}}$ where $\mathrm{C_0}$: 4000 €/kW; $\mathrm{C_{0,1}}$: 1000 €/kW; $\mathrm{P_{el,0}}$: 100 kW; $\mathrm{P_{el,1}}$: 700 kW; n = −0.37; a: 0.7
$\mathrm{CAPEX_{COMP}}$ $\mathrm{CAPEX_{FILLING\text{-}GASEOUS}}$	$A\left(\frac{Q}{Q_{ref}}\right)^a + B\left(\frac{Q}{Q_{ref}}\right)^b \times \left(\frac{\frac{p_{disc}}{p_{in}}}{p_{ref}}\right)^c \times \left(\frac{p_{disc}}{p_{ref}}\right)^d \times 1.099$ A: 100 [€], B: 300 [€], a: 0.66; b: 0.66; c: 0.25; d: 0.25—COMP A: 500 [€], B: 300 [€], a: 0.66; b: 0.66; c: 0.25; d: 0.25—COMP Q is the nominal flowrate [kg/h]; $\mathrm{Q_{ref}}$ is the reference flowrate equal to 50 kg/h; $\mathrm{p_{disc}}$ is the discharge pressure [bar], $\mathrm{p_{in}}$ is the inlet pressure [bar], and $\mathrm{p_{ref}}$ is the reference pressure equal to 50 barg and 200 barg; and inflation and depreciation from 2017 are taken into account.
$\mathrm{CAPEX_{STORAGE}}$	300
$\mathrm{C_{other}}$	$10\%\left(\frac{2.5}{P_{el}}\right) + 35\%$
Electricity price	75 €/MWh
OPEX	Electrolyser: 2%, 3%, or 4% of the CAPEX for, respectively, $\mathrm{P_{el}} < 1000$ kW, $1000 \leq \mathrm{Pel} < 5000$, and $\mathrm{P_{el}} > 5000$ kW Compressors, storage; filling stations: 2% of CAPEX
Electricity cost	75 €/MWh

Note: The value of the storage was conservatively assumed because it is the average value with respect to those reported in the literature. The value was also verified by means of an offer received by the authors for bundles of 50 L.

Appendix A.4. Assumed Constraints

In addition to the objective function, a set of constraints was defined according to three main principles:

- Energy and mass conservation balances
    - For each user/customer, the sum of the x_{ij} fractions must be 1;
    - For each generator, the sum of x'_{ik} must be lower than 1;
    - The sum of hydrogen flows leaving each P2G plant must be lower than the plant capacity;
    - The sum of the electrical power supply for each P2G plant must be lower than the plant capacity;
    - The sum of hydrogen flows cannot be higher than the energy supplied (net of conversion efficiency coefficient).
- Market orientation/exploitation
    - The P2G capacity nominal value belongs to a discrete set (to simulate a standardization of the plants for mass adoption/scaling economy).
- Distance and positioning limitations
    - Each grid mesh centroid out of the considered territory was discarded as an eligible P2G position;
    - As an option of the tool, the eligible P2G plant positions too far away from adequate (in terms of nominal voltage) electrical lines were neglected, owing to the hypothesis of relevant electrical connection costs;
    - The case of hydrogen delivery by trucks was (for the sake of the completeness of the analysis) customized with the (optional) possibility to limit the trucks' autonomy (i.e., routing distance).

Given the large territory considered, to reduce the computation time, the (square) meshing procedure was performed in two steps. The former (rough meshing) identify a large portion of territory to discard all the centroids lying out of the territory (this avoids calculating, geometrical intersections with administrative borders and lands as well as distances from power networks, and routing or gas network connection distances for the immediately excluded points). The latter operates only on the not previously excluded rough.

Appendix A.5. Other Assumptions

Simulations were performed with different input parameters to identify a trade-off between an approximation of the problem description and optimization performance (i.e., objective function minimization).

In particular, the iterations differed one another from the following variables:

- Meshing resolution—40 km^2 mesh was adopted for the case study;
- P2G plant capacity sets—to estimate the importance of developing high-capacity electrolysers in the future (i.e., reduction of highest values of the set);
- Variable percentage of the aggregated fuel demand replaced with hydrogen equivalent;
- Maximum truck autonomy to reach users from P2G plants.

To use freely available data (both for reproducibility purposes and to rapidly test the algorithm), the mobility case of the analysis was carried out by assuming the following:

- Renewable energy generation—the overall PV production at NUTS-3 granularity (*provincia* in Italian). This is to exploit the current scenarios predicting continuous increments of RES plant penetration that can supply (along and beside the participation to the energy market) the conversion systems with a surplus (e.g., net of the possible consumption by priority loads) in production;
- On the demand side—the georeferenced information (position, fuel demand, association to specific motorways) of the refuelling devices on the Italian motorway network.

The visual representation of the investigated problem was synthesized through a pair of graphs (structures consisting of nodes and connecting edges): the former from generators to P2H plants and the latter from P2H plants to refuelling stations. In particular, the generation point variables (positions, nominal power, availability fraction of the day) and hydrogen distribution network characterized the nodes, and on the other hand, connection distance and costs (from nodes to the meshing grid centroids, and vice versa) to model characterized the edges of the graphs. In the adopted representation, the main approximation to build the overall graph was the technique to determine the distances. In detail, it was assumed that because the PV generators are (obviously) distributed on the NUTS-3-level territories, they were considered as aggregated in the position of the territorial geometric centroid, so that the distance from the power network (for each NUTS-3-level zone) was averaged to the 220 kV electrical line closest to the centroid.

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