INTERNATIONAL JOURNAL OF HYDROGEN ENERGY 40 (2015) 4413–4425

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Study of the natural resource and economic feasibility of the production and delivery of wind hydrogen in the province of Córdoba, Argentina

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ARTICLE INFO

Article history:
Received 15 September 2014
Received in revised form
19 January 2015
Accepted 25 January 2015
Available online 27 February 2015

Keywords:
Wind energy
Hydrogen
GIS
Hydrogen delivery
Cost estimation
VRP

ABSTRACT

The wind map of the province of Córdoba, Argentina is improved starting from new wind measurements of ten meteorological stations installed in the province, whose equipment meets international standards for wind measurements. This correction is made on the basis of GIS *Ordinary Cokriging* interpolation method along with other wind global data basis. From the new wind GIS, a map of potential for annual production of electrolytic hydrogen from wind energy is performed and the required demand for generating mixtures of hydrogen to 20% V/V with natural gas, within CNG stations, is calculated. This clean alternative fuel is proposed as a hybrid technology for progressive transition to a hydrogen economy in Córdoba, and in Argentina. Hydrogen delivery costs are estimated considering gas modules transported by trucks taking into account optimization of routes solving numerically the capacitated vehicle routing problem. The total cost for hydrogen including production and delivery is estimated to be 9.41 USD/kg H_2.

Introduction

Since the implementation of the Replacement of Liquid Fuels National Plan given in Argentina in 1983, the country has become a leader in the use of Natural Gas (NG). This is evidenced by the participation of about 50% of this fossil fuel in the mix of primary energy production. About 7% of this fuel is used as Compressed Natural Gas (CNG) in the transport sector, supplying a fleet nearby to 2 million vehicles, while 33% is intended to electricity generation in thermal plants. Regarding CNG, this situation has led to a strong infrastructure development and technologies associated with its use, such that the country has firmly positioned in this area to

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http://dx.doi.org/10.1016/j.ijhydene.2015.01.149

levels of exports in the international market. In particular, the province of Córdoba follows the national trend in the growth and implementation of CNG. Thus this province, the second biggest in population in Argentina, is representative of the development of the CNG industry nationwide [1].

However, in recent years the production of natural gas in Argentina has declined sharply having direct impact on the electricity system. This growing deficit has been covered by imports of NG from Bolivia and LNG from different sources in bigger amounts than those imported by USA [2]. In this context, the role of energy public policies is essential to promote the expansion of the renewable energy development in the country [3].

These circumstances, coupled with the immense potential of exploitable renewable resources in Argentina, poses an interesting opportunity to initiate a process of gradual transition to a renewable hydrogen economy in the country, by mixing CNG with this energy carrier [4]. Another interesting intermediate case before an all-hydrogen fuel economy may be that of the Hydrogen-gasoline internal combustion engine vehicle (HGICV) [5], which is not considered in this study.

There are numerous studies that highlight the benefits of adding 20% V/V of H_2 to CNG under appropriate conditions. First HCNG allows for an initial use of hydrogen while taking advantage of the current CNG infrastructure. Hydrogen is characterized by a rapid combustion speed, a wider combustion limit and low ignition energy. The advantages are twofold: on the one hand this hybrid fuel increases the fuel economy, the thermal efficiency and the energy production of internal combustion engines and, on the other hand, it reduces the exhaust emission of greenhouse gases such as CO, CO_2 and unburned hydrocarbons in the combustion [6–13].

In previous work [14], we analyzed the cost of electrolytic hydrogen production from wind. One of these results indicates that the annual consumption of fossil fuel for transportation could be replaced by hydrogen produced in a wind park of about 800 MW. In the present work we extend this analysis evaluating the cost of hydrogen delivery from a wind central production park located in the best wind potential region of the province. Furthermore, this study considers the amount of hydrogen needed to make cuts of 20% V/V on CNG, as preliminary steps for the gradual transition to a hydrogen economy.

The cost of production of wind electrolytic hydrogen depends proportionally on the cost of electricity generated from this primary energy source. Additionally, the power that can be extracted from this source is very sensitive to the average wind speed since the power of the wind in a given site, passing perpendicularly through a circular area is theoretically proportional to a third power of the speed. Nevertheless, the energy E_{annual} that may be obtained annually at a given location, depends in a convoluted way on the wind turbine type and the wind distribution function, and can be calculated from Ref. [14]:

$$E_{annual} = N_o \int_{u=v_o}^{v} P(u) f(u) du$$

where N_o is the number of hours in a year (8765), $P(u)$ is the power function of the wind turbine employed and $f(u)$ is the wind speed distribution function, that may be approximated by the Weibull distribution function. As a result, the precise determination of this variable in each specific site is essential both for the goals outlined in this work, as well as for its intrinsic value for wind development. For this reason, a semi-empirical method is proposed here to combine and update information of existing digital databases in conjunction with data from field measurements of wind. All available information was processed by the GIS software ArcGIS® 9.3, from which a set of weighted database was organized and the corresponding mappings were developed obtaining new wind speed maps for the province.

From this new wind map updated with data of wind measurements from available meteorological stations, we determine more accurately the potential for wind hydrogen production and then we estimate the delivery costs of hydrogen from a central plant of production to all CNG service stations in the province, in order to produce the alternative hybrid fuel CNG + H_2.

Wind assessment by databases and field measurements

Argentina has one of the highest wind potentials in the world, estimated in over 2000 GW [15]. It is very well known that Patagonia is the most windy region of the country, but also in the central region of Argentina, in particular in the provinces of Buenos Aires and Córdoba, there is a good potential for wind energy production using small and medium wind turbines [16].

Geographic Information Systems (GIS) have become an indispensable tool for decision making and planning of various projects. These actions can be framed in scientific, technological or political developments and are ideal for a wide variety of enterprises. In wind studies performed to determine a suitable place to install wind turbines and predict their energy performance, there should be enough meteorological stations providing field measurements. If they are not available, then the necessary data can be obtained from reanalysis of wind data available from other sources, and its subsequent processing and modeling. In addition, estimates of economic viability, and therefore the investment decision of many projects, are based on information provided by GIS. For this reason, the analysis concerning the methods used and the reliability of data provided are essential for correct decision-making for energy resource management.

Global information is available in the wind database compiled by New et al. [17]. This data set has a spatial resolution of 10′ lat/lon, and was interpolated from a data set of station means for the period centered on 1961 to 1990. They were based on earlier work which resulted in a 30′ lat/lon data set, included additional station data in some data-sparse areas, and made use of an improved topographic data set.

In Argentina, a wind GIS (National SIGE-Wind Map) is also available, as prepared by the Ministry of Federal Planning, Public Investment and Services and the Regional Centre for Wind Energy (CREE) in the province of Chubut [18]. This GIS provides information about wind speed and wind potential for generation of any wind turbine anywhere in the country.

To carry out the model, data from global digital elevation G-TOPO 30 were used. The calculation of terrain roughness was performed by image processing provided by SAC-C satellites and Global Land Cover Characterization by the U.S. Geological Survey. Finally, using a reanalysis of data coming from the last five years of meteorological stations of our country, most of which belong to the National Weather Service (SMN), interpolated wind data was obtained.

The mentioned wind GIS provides a first approximation of the above information, together with the identification of supposed areas of high wind potential in which it would be convenient to perform field measurements for energy purposes. However, the weather stations used in the confection of the wind GIS, were not installed in order to evaluate the wind resource with the aim of electricity generation using wind turbines, since they measured wind speed near the surface level, at heights less than or equal to 10 m above the ground. Thus, only data extrapolation provides the speed profile with height.

Besides, since the determination of the wind potential at a given site (and thus the calculation of annual energy production and the cost of energy generated), are very sensitive to the value of the measured wind speed, there are specific recommendations for the measurement of this later physical quantity [19]. Some of these specifications prescribed: to collect an average data of each physical quantity of interest every 10 min and measuring at least two or three levels, depending on simple or complex land surveying, respectively.

In the particular case of the construction of the wind map for the province of Córdoba, twenty meteorological stations of SMN were used. That distribution is shown in Fig. 1, along with the digital models of topography and roughness mentioned above. Since the province has an area of 165,321 km^2, the density of stations would be 8266 km^2 by station, assuming a homogeneous distribution of the same. However, as seen in Fig. 1, the distribution is heterogeneous, whereby the information available is even more skewed.

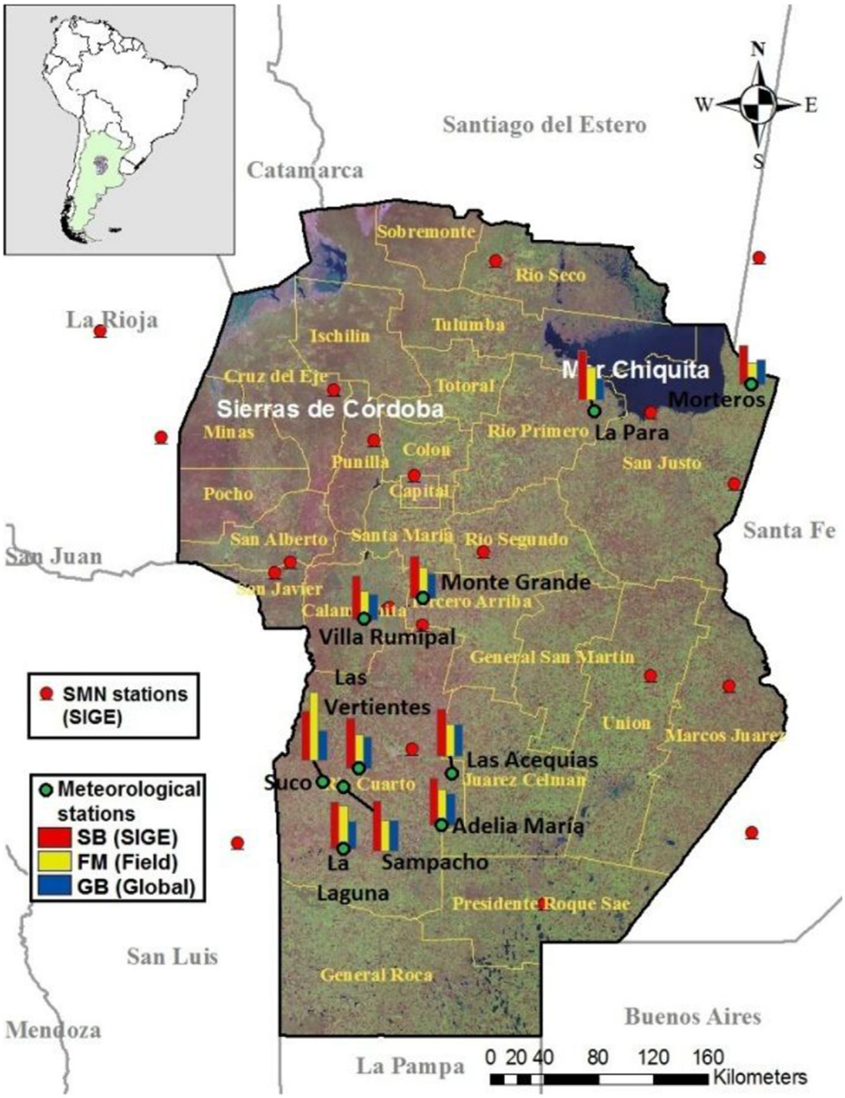


Fig. 1 – Location of the stations of the National Meteorological Service (SMN) used for confection of SIGE and comparison between wind speed values predicted by SB, GB and FM.

Table 1 – Databases used in this study.

Database	Notation	Spatial resolution	Measurements interval	Authors
Global Climatological Database	GB	10′	1961–1990	New et al.
Wind National GIS Database	SB	10′	1997–2007	CREE
Field measurements	FM		Indicated in Table A1	GCSA

Field measurements and databases

The area under study is shown in Fig. 1. It represents the province of Córdoba, in central Argentina, between latitudes 29°30′11.9556″ S and 34°59′55.4424″ S, and between longitudes 65°46′41,732″ W and 61°46′39.6192″ W.

In order to update the wind map of the province of Córdoba, and due to the sensitive dependence of economic parameters on the wind speed already discussed, we used base information of ten meteorological stations, whose equipment meet international standards for wind measurements. Details of the geographical coordinates of the sites where stations were installed are shown in Appendix A as well as the annual average wind speeds, the predominant wind directions obtained at each station and the start date of the measurements.

The field measurements (FM) from these stations, jointly with the other databases listed in Table 1 (GB and SB), were used to create, in a first step, a new wind database that we will denominated weighted database (WB). With this purpose, we contrast the information provided by these three data sources at each station location and calculate the mean square error of the deviation of the SB and GB bases compared with FM. Fig. 1 highlights this comparison and Fig. 2 shows that SB overestimates the velocity values measured at the stations, with a root mean square error of ~1.72 m/s. Meanwhile GB generally underestimates the field data, with a root mean square error of ~0.8 m/s. Considering this situation, we built the new reference database by the weighted average of the two bases, so that the weights minimize the mean square error between the weighted basis and field data.

Thus we have:

$$PB = aSB + bGB, \quad a + b = 1$$

The weighting factors a and b that minimize the mean square error between predictions database WB and measured values are given by:

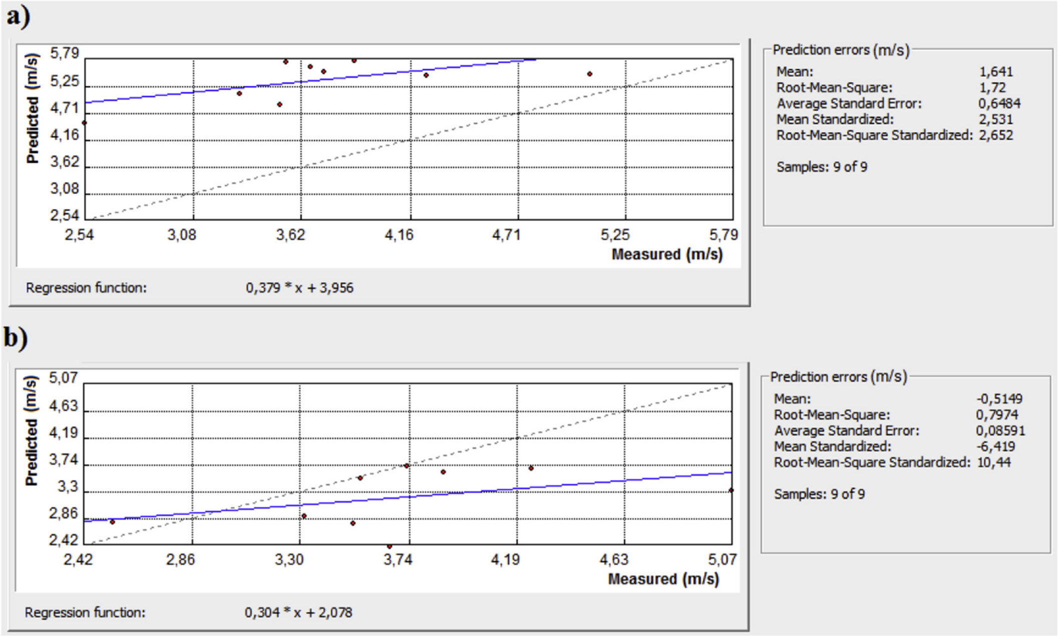
$a = 0.26$; $b = 0.74$

In this way, a minimum root mean square error of ~0.56 m/s is obtained for WB when compared to FM, as shown in Fig. 3.

Vertical extrapolation and interpolation methods

Vertical extrapolation

With the aim to homologate all data from different databases with the field measurements at 10 m above ground level, it was necessary to use a vertical extrapolation tool. We used the exponential Hellmann law, which is a suitable approach for our purpose: $\frac{v_2}{v_1} = \left(\frac{H_2}{H_1}\right)^{\alpha}$, where: v_2 is the wind speed at height H_2, v_1 is the wind speed at height H_1 and α is the Hellmann



a)

Regression function: 0,379 * x + 3,956

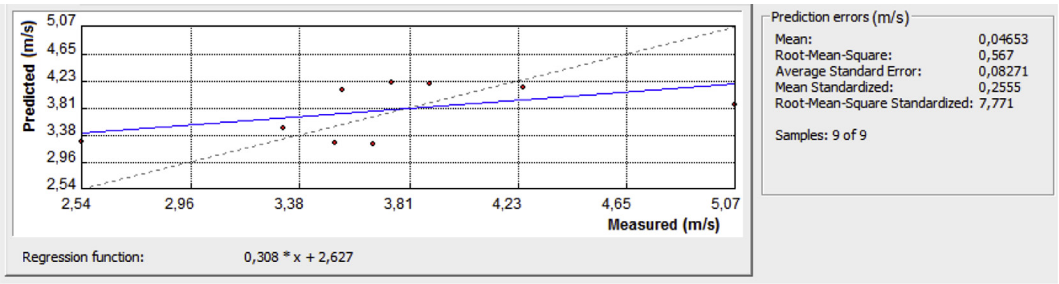
Prediction errors (m/s)
Mean: 1,641
Root-Mean-Square: 1,72
Average Standard Error: 0,6484
Mean Standardized: 2,531
Root-Mean-Square Standardized: 2,652
Samples: 9 of 9

b)

Regression function: 0,304 * x + 2,078

Prediction errors (m/s)
Mean: -0,5149
Root-Mean-Square: 0,7974
Average Standard Error: 0,08591
Mean Standardized: -6,419
Root-Mean-Square Standardized: 10,44
Samples: 9 of 9

Fig. 2 – a) Comparison and root mean square error between data predicted by National SIGE Database and field measurements (SB vs FM, see acronym in the text); b) Comparison and root mean square error between data predicted by Global Database and field measurements (GB vs FM).



Prediction errors (m/s)

Mean: 0,04653

Root-Mean-Square: 0,567

Average Standard Error: 0,08271

Mean Standardized: 0,2555

Root-Mean-Square Standardized: 7,771

Samples: 9 of 9

Regression function: 0,308 * x + 2,627

Fig. 3 – Comparison and root mean square error between data predicted by the new Weighted Database and field measurements (WB vs FM).

friction coefficient (see more details of this coefficient in Appendix A).

Interpolation method

In a second stage, having already the reference wind database WB, we use the interpolation method Ordinary Cokriging – as an extension to the normal Ordinary Kriging method-in order to build a new wind speed map for the province. A spherical approximation to the variogram model associated with the method is used, together with the property of anisotropy and fifteen (15) lags.

The FM data were inserted into WB base and, in order to give a relatively greater weight to the latter data, a radius (corresponding to the search of near neighbors, chosen by the interpolation process) around those ones, was established. Then, those grid points falling within its domain were

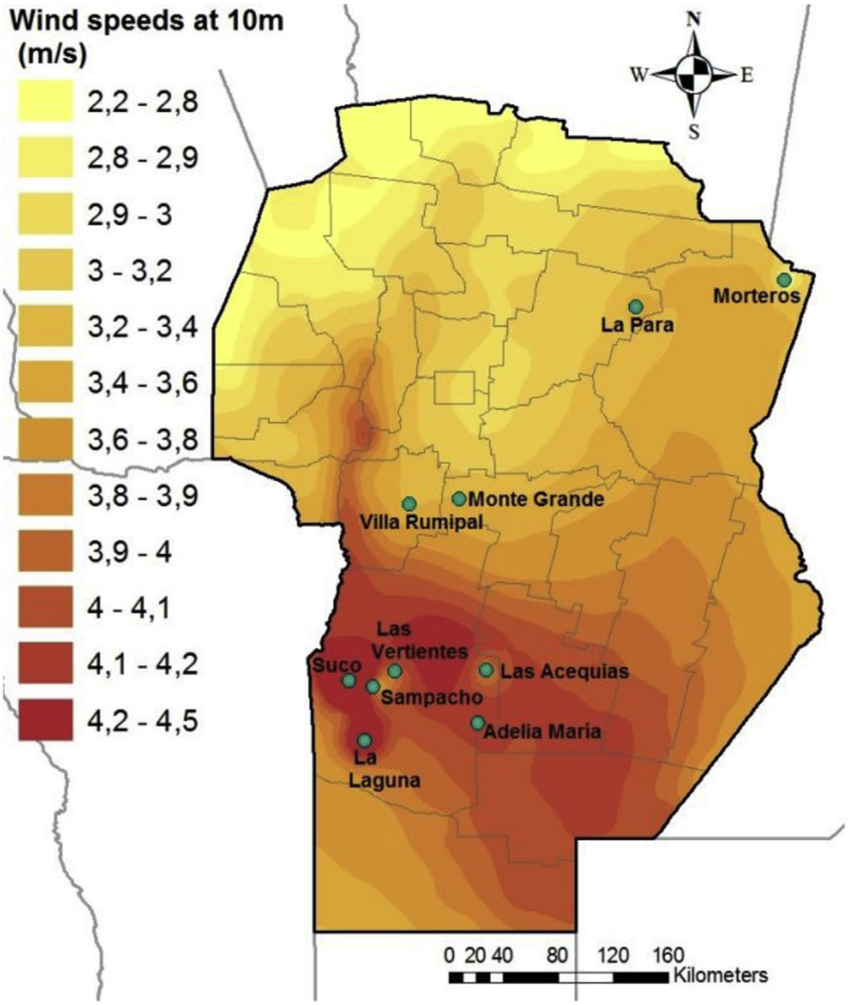


Fig. 4 – Wind speeds map UM, performed from Ordinary Cokriging Interpolation, using WB and FM.

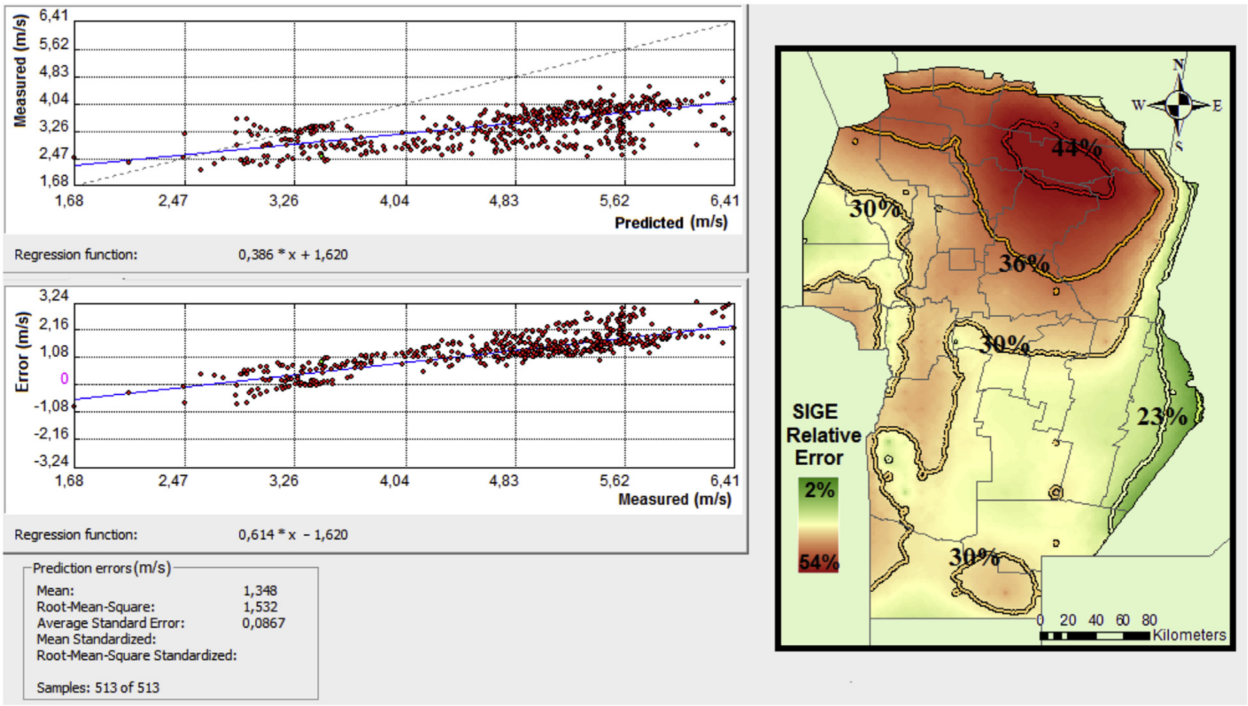


Fig. 5 – Differences map (DM), obtained by comparison between UB and SB.

removed from WB. Based on this interpolation method and including FM on WB, an updated database (UB) was obtained, yielding the adjusted and updated wind speeds map (UM) shown in Fig. 4.

By comparison of UB with SB, the difference map DM is obtained, as shown in Fig. 5.

Environmental and land-use exclusions for wind sites included lands with a specific designation such as protected areas, parks, conservation areas, urban areas, water bodies, special landforms and slopes greater than 20%, as calculated on a Digital Elevation Model (DEM) with 90 m resolution, were considered. The procedure, performed with the two available and the FM-obtained databases, is shown schematically in Fig. 6.

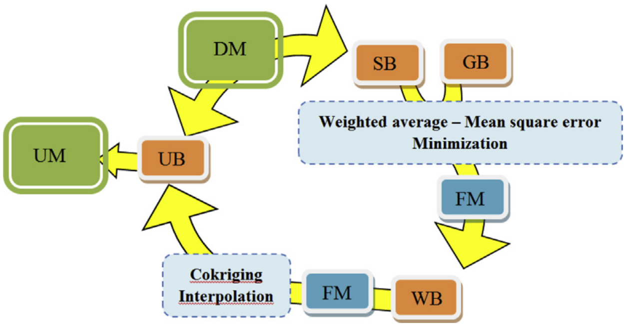


Fig. 6 – Scheme of the iterative process of combining and updating existing digital data with field measurements. Processes and maps emerging interpolation are outlined, where UM: Updated Map; DM: Differences Map; UB: Updated Database; SB: SIGE Database; GB: Global Database; WB: Weighted Database; FM: Field Measurements.

Wind hydrogen. Potential for production and delivery costs

Hydrogen production

Once the annually produced wind energy is known, in the way explained previously, the hydrogen production rate can be estimated. To asses E_{annual}, an IMPSA wind turbine, model UNIPOWER® IWP-83, of 2.1 MW nominal power (as those one installed in Wind Park Arauco at La Rioja, Argentina [20]) with an energy density of 5 MW of wind turbines installed on each square kilometer, was considered. After that, assuming an electrolytic production rate of 52.5 kWh/kg of hydrogen (near 75% efficiency) [21], we calculate the annual potential for wind hydrogen production per wind generator using the new map of winds obtained above. The units of potential for hydrogen production are tons of H_2/km^2/year.

Hydrogen delivery

In a recent work, Ogden and Yang [22] compare compressed gas trucks, cryogenic liquid trucks and gas pipelines as hydrogen delivery modes for different geographic and market characteristics. By models that estimates costs and characterize distances of transportation, they could determine the most cost effective delivery way for each particular case. These studies consider parameters like population, population density, size of the city, number of available CNG refueling stations that could be adapted for hydrogen dispatch and the energy demand for CNG transportation. Based on the assumptions of Ogden and Yang it appears, as will be discussed

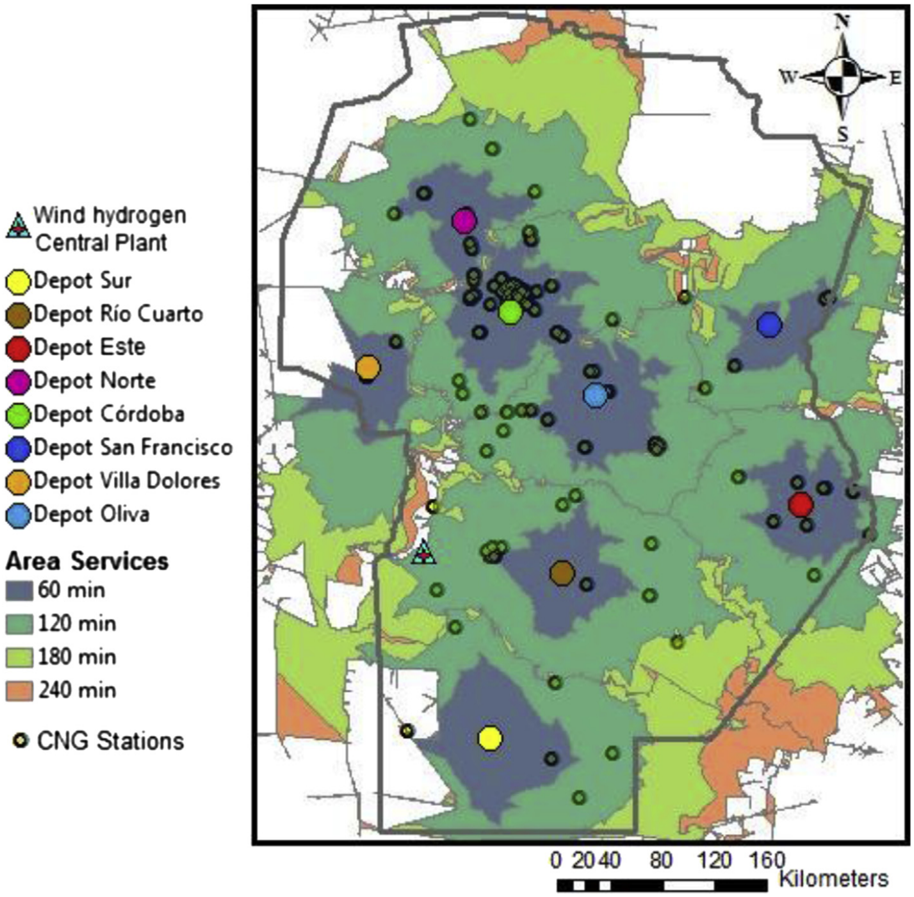


Fig. 7 – Location of Depots, Central Plant of Wind Hydrogen Production and CNG Refueling Stations. The map shows the Service Areas for each Depot, and its scopes in units of travel time.

below, that Córdoba's case matches well to gas trucks mode as the most cost effective delivery method.

As an illustrative example these authors investigate the case of San Jose city, whose radius (modeled as an ideal spherical city) is 15 km, with an area of 462 km^2, a density population of 2300 inhab./km^2 and a population of 1.5 million people. This data are comparable with those of the capital city of the Province of Córdoba, Córdoba city. The latter is the largest in the province with 576 km^2, an ideal radius of 13.5 km, 2308 inhab./km^2 and 1.4 million inhabitants.

Following [22], we took into account the transmission and distribution through virtual pipelines to estimate costs of hydrogen delivery in the province, i.e. we choose the delivery mode of compressed hydrogen gas in truck transportable modules.

As a first delivery step, we consider the transport from a central plant of wind hydrogen production (detailed specifications in the previous item), located in the region of greatest potential for the province to eight depots strategically located throughout the provincial territory. In a second delivery step, we consider the distribution from these depots to the existing CNG refueling stations. The amount and location of the depots, the location of the central plant (which were also parameters in optimizing the delivery routes) and the CNG stations are presented in Fig. 7. This figure also shows the calculated service areas for each depot.

According to the Secretary of Energy of Argentina [23], approximately 332 million m^3 of CNG are consumed annually in the province of Córdoba, for transport purposes. We can estimate now the hydrogen mass required to produce mixtures at 20% V/V with natural gas to satisfy this demand. First, we note that the corresponding hydrogen volume will be 66.4 million m^3. Second, considering the state equation of ideal gases with standard temperature and pressure (STP) as established by International Union of Pure and Applied Chemistry (IUPAC), we can evaluate that the corresponding mass will be 5900 Tons of H_2 per year. Since there are 246 CNG stations in the province, each one should dispense on average 65 kg H_2/day.

For route optimization, a numerical solution of the well-known problem called VRP (Vehicle Routing Problem) was applied [24,25]. In particular, we used the CVRP (capacitated Vehicle Routing Problem) implemented in the software ArcGIS® 9.3.

For the network topology of route and street tranches with directions and types of track, we used the databases extracted, for the entire province, from OpenStreetMap (OSM) [26]. A traversal average speed was assigned to each road segment according to the type classification of the latter, in order to calculate average time costs depending on road's distances. Table 2 shows this street classification.

The VRP solver initiates generating an origin-destination matrix of shortest-path costs along the network, between

Table 2 – Streets classification for time cost estimates in routing optimization.

Type	Average speed (km/h)
Bridleway	0
Byway	0
Construction	0
Cycleway	0
Footway	0
Ford	0
Living_street	30
Motorway	70
Motorway_link	50
Path	30
Pedestrian	0
Platform	30
Primary	70
Primary_link	50
Raceway	70
Residential	30
Road	30
Secondary	50
Secondary_link	30
Service	20
Steps	20
Tertiary	50
Tertiary_link	30
Track	30
Trunk	70
Trunk_link	50
Unclassified	30
Yes	30

depots and stores (CNG stations in our case) locations. All the routing solvers within the software used are based on the Dijkstra's algorithm [27] for finding shortest paths, and on a hierarchical path solver for faster performance. The resequencing iteration process uses an heuristic based on the Tabu Search metaheuristic method [28–30]. Table 3 provides details on parameters and assumptions that were used in the routing optimization.

Table 3 – Assumptions and parameters used in routing optimization for costs estimation of hydrogen delivery.

Amount of hydrogen dispensed in each CNG station	65 kg H_2/day
Number of trucks	25 – two daily shifts (50 routes total)
Truck capacity	325 kg H_2 (high pressure, $P_{max} = 200$ bar and low pressure $P_{min} = 30$ bar, in the truck tubes of compressed gas)
Distance cost (fuel)	11.20 $/liter of gasoline (For comparison with USA study by Ogden and Yang: 0.53 USD/liter of gasoline)
Time cost (truck driver wage)	0.61 $/min (For comparison with USA study by Ogden and Yang: 0.48 USD/min)
Hydrogen loading time	60 min
All vehicles start and end their routes in their corresponding Depots	

Note: $ is the Argentine Currency, USD is dollar.

Results and discussion

Wind speed map

Fig. 4 shows the wind speed distribution map. It can be noticed that those areas of strongest winds and therefore of better eolic potential are located at the southwest of the province. Those zones include the departments of Río Cuarto, Juárez Celman and Presidente Roque Sáenz Peña. This region presents wind speeds exceeding 4 m/s (at 10 m height). The wind gradient, normal to the contour lines of Fig. 4, is in the NE–SW direction.

Fig. 5 shows a DM map of the differences between SB and UB. It can be seen as a general trend that SB overestimates all wind speed values in the province. This overestimation follows a linear trend, as shown in the left part of Fig. 5, giving larger differences the larger the wind speeds. Two different areas on the chart are identified, one that goes up to 4 m/s and another one for values greater than this speed. In the first zone, between 1.68 and 4 m/s, the differences between the two bases are smaller than 1 m/s, and for many values the error is close to zero. In the second zone, between 4 and 6.41 m/s, the SB overestimates the wind speed values in amounts between 1 m/s and 3 m/s. The root mean square error calculated over all values is 1.53 m/s, which gives an idea of the global SIGE (SB) overestimation, representing a relative error of ca. 35%.

Fig. 5 shows on the right the distribution of differences between UB and SB. It is observed that the overestimation of SB is higher in the northeast of the province, particularly on the Mar Chiquita lagoon and its surroundings. The wind speed differences in these areas are between 2 and 2.5 m/s (ca. 36–44% relative error) around the lagoon, and from 2.5 to 2.7 m/s (ca. 44–54% relative error) over it. These differences may be understood by the following analysis. By construction, the SB takes into account three general inputs: topology, surface roughness and wind measurements. The relatively low spatial density of meteorological stations in the region of the lagoon reduces the contribution of the third input to the construction of the SB map, resulting in the overestimation found due to the overemphasis of the two other factors.

Potential for wind hydrogen production

Fig. 8 shows the results of the potential for hydrogen production from wind energy in the province of Córdoba. It can be seen that the greatest potential for wind hydrogen production is located in the Department of Río Cuarto, at the southwest of the province, with a potential of 120 Tons of H_2 per year per wind turbine installed. Given the hydrogen demand stated above of about 5900 Tons of H_2 per year for transportation, it would require a farm with 50 IWP-83 wind turbines to supply it, with a total installed wind power capacity of 105 MW. It is also worth noting from Fig. 8 that the regions able to produce more than 95 tons of H_2 per year per wind turbine are about 13% of the surface of the province.

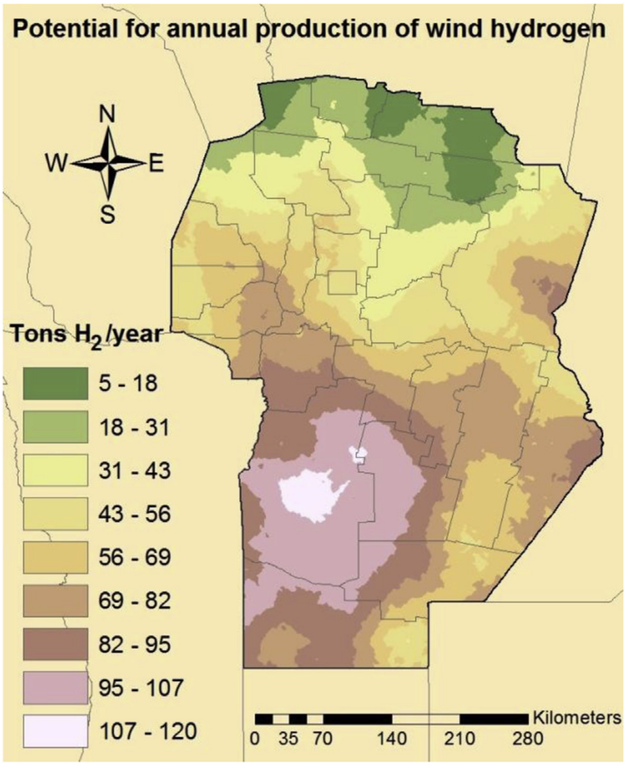


Fig. 8 – Map of the potential for annual production of wind hydrogen in the province in Tons of H_2/(year·turbine).

Estimation of costs for hydrogen delivery

Distribution

As a first analysis, it is worth noting that the city of Córdoba, a typical city of radial growth, would be well suited to the idealized spherical city distribution model and homogeneous arrangement of CNG refueling stations, proposed by Ogden and Yang in their study [22]. This correspondence is illustrated on the right of Fig. 9, wherein a backbone road which crosses the heart of the city is stand out, and from there, the different path lines are deployed to reach all the CNG stations, just as proposed in the idealized model of Ogden and Yang, shown in the inset of the figure.

For this reason, in order to compare and validate our assessment and results with those reported in reference [22], we consider first the items of Fuel and O&M assumed for the cost estimation of hydrogen distribution according to these authors, which amount 27% of total distribution cost. In the following, we denote this fraction of the total distribution cost as F-O&M costs. Taking into account, as we mentioned before, that the city of Cordoba is very similar to the city of San Jose, CA, United States, we would be led to the conclusion that the F-O&M costs for Cordoba city is about 0.37 USD/kg H_2. The corresponding cost analysis using route optimization, according to the methodology described in section 2.2, using the same fuel cost and truck driver wage employed by the previous authors (see Table 3) yields a result of 0.40 USD/kg H_2. This very good agreement represents a significant validation of the methodology employed, applied to a more realistic situation. The optimized routes are shown on the left of Fig. 9.

The VRP numerical solution for the province, whose routes are given in Fig. 10, yields a result of 0.36 USD/kg H_2 on the

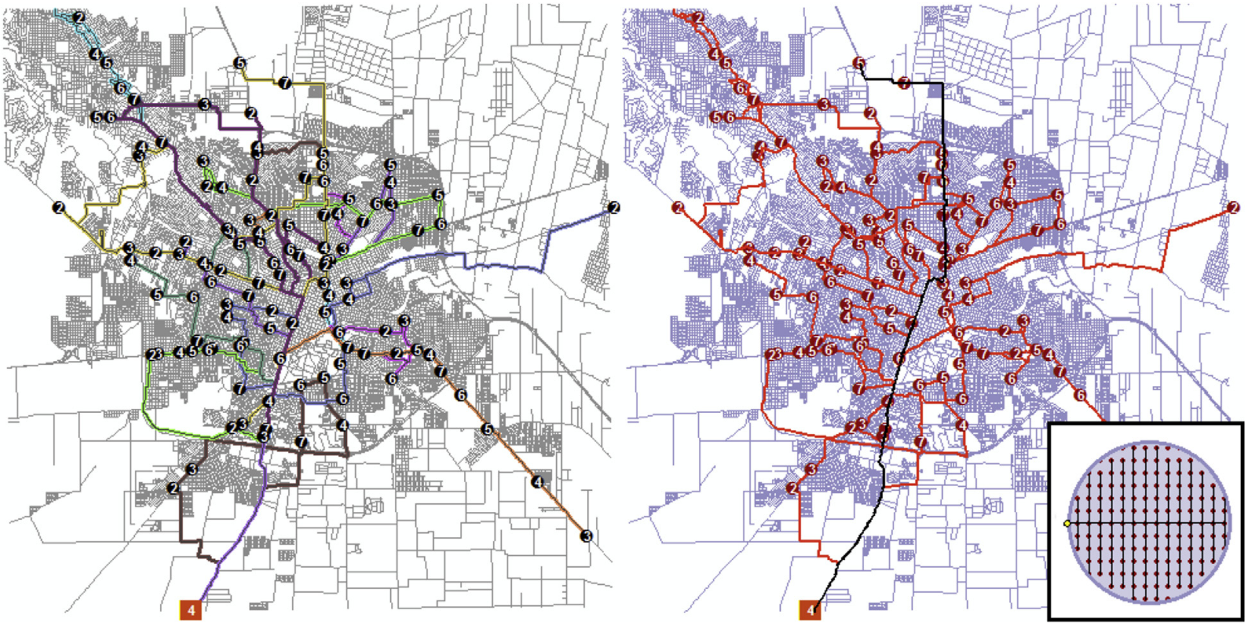


Fig. 9 – Left: Optimized routes for hydrogen distribution in the city of Córdoba, highlighted in different colors. The numbers along each route indicate the sequence of stations run along this route. Number 1 is omitted and coincides with the location of the depot. Right: Comparison with the idealized model of circular cities of Ogden and Yang [22] for distribution cost estimates. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

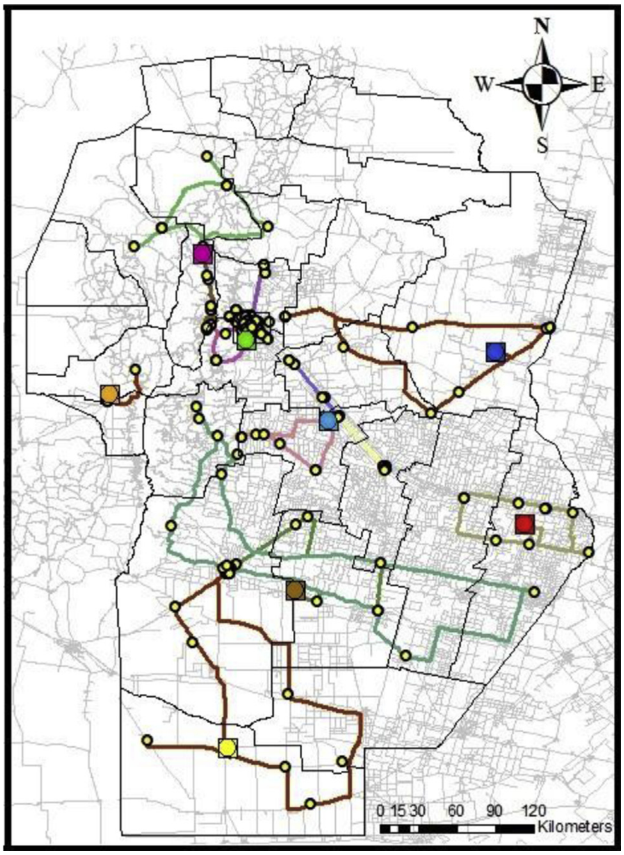


Fig. 10 – Optimized depot sites (marqued with squares) and routes for hydrogen distribution in the province of Córdoba. The optimization was carried out using the CVRPTW model as implemented in the software ArcGIS® 9.3. The different colors correspond to routes leading to different depots and their assignation was described in Fig. 7. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

average for distribution from all depots. This result is again computed taking into account the distance and time costs used by Ogden and Yang. Considering the argentine costs to march 2014, detailed in Table 3, the F-O&M costs would be 0.09 USD/kg H_2, i.e. 4 times cheaper than in USA.

Transmission

Transportation, i.e. transmission of hydrogen from the central plant to all the depots, involves driving 21,395 km/day, with a F-O&M cost of 0.22 USD/kg H_2. Again, Argentina presents a cost almost three times cheaper than USA for this item.

Table 4 shows time and roundtrip distance from the central plant to each depot, total time and total transportation distance, the number of CNG stations assigned to each depot and the corresponding amount of hydrogen dispensed per day. For comparison, in the last columns of Table 4, our F-O&M costs are contrasted with those corresponding to the estimated transmission cost according to Ogden and Yang. An excellent agreement is observed between our results and their

Table 4 – Routing optimization results for hydrogen transmission from Wind Central Plant to the Depots. Comparison with Ogden and Yang results [22]. The location of the different depots are marked in Fig. 7.

Depot Name	Roundtrip Time (minutes)	Roundtrip Distance (km)	Number of CNG Stations assigned	Amount of H_2 dispensed (kg)	Total time (minutes)	Total distance (km)	Total Cost calculated according Ogden and Yang [22] (USD/kg H_2)	F-O&M (27% Total Cost) according Ogden and Yang [22] (USD/kg H_2)	F-O&M calculated (USD/kg H_2)
Córdoba	399	445	157	10,205	12,364	13,809	2.41	0.65	0.63
Este	522	591	8	520	1043	1182	3.09	0.83	1.05
Norte	554	623	15	975	1662	1869	3.24	0.87	0.89
Oliva	360	417	24	1560	1802	2086	2.28	0.62	0.61
Río Cuarto	195	210	25	1625	975	1049	1.32	0.36	0.31
San Francisco	550	630	5	325	550	630	3.27	0.88	0.89
Sur	337	382	5	325	337	382	2.12	0.57	0.54
Villa Dolores	337	387	4	260	337	387	2.14	0.58	0.68

Table 5 – Assumptions and parameters used for calculation of delivery of hydrogen.

Compressor size	1500 kW
Compressor power	2.2 kWh/kg
Compressor capital cost (taken from $C_x = C_0\left(\frac{1500\ \mathrm{kW}}{10\ \mathrm{kW}}\right)^{0.9}$ where C_0 is the capital cost of a 10 kW compressor [22])	U$S 1,350,000
O&M Costs (fraction of compressor capital costs)	5%
Central plant storage capital (own estimation)	U$S 5,650,000
Storage capacity	16,164 kg/day
Electricity cost	0.05 USD/kWh
Truck capital cost	0.40 USD/kg

calculations. There is also an outstanding agreement with the results in a study of the NREL [31].

Delivery

Taking into account the assumptions and parameters shown in Table 5 and the F-O&M costs calculated above (considering argentine driver wage and fuel costs), the total estimated cost of hydrogen delivery for the province of Córdoba results 1.63 USD/kg H_2. The final cost of hydrogen production and delivery for different wind electricity costs can be estimated considering the wind hydrogen production costs performed in a previous study in the same area for wind potential of Córdoba [14]. Table 6 summarizes the results. As can be seen, with the current argentine cost of 110 USD/wind MWh, hydrogen would cost 9.41 USD/kg H_2, i.e., almost twice as expensive as the equivalent cost of liquid fuels to March 2014 (2.48 USD/eq. liter of gasoline VS. 1.43 USD/actual liter of gasoline). At 40 USD/MWh for wind power, hydrogen would be competitively priced.

HCNG mixture

In this paragraph we analyze the cost of HCNG, considering that NG is composed only of methane.

Assuming the cost of CNG as 0.54 USD/Nm^3, the cost of HCNG is shown in the last column of Table 6. We can see that the wind electricity cost has relatively little incidence in the final HCNG cost, so that the cost for introducing electrolytic wind hydrogen into transportation in this way is rather reduced, even in geographic regions where wind resources are modest.

Conclusions

In order to analyze the opportunities of implementing a future Hydrogen economy in Argentina, we have considered the costs items of hydrogen production and distribution in the province of Córdoba. Considering the great development of CNG infrastructure in the province, the present study estimated the amount of hydrogen needed to make cuts of 20% V/V on CNG, as preliminary steps for a gradual transition to a hydrogen economy. Then, we estimated the delivery cost of the hydrogen produced from a wind central plant settled in the best wind potential zone of the province.

An improved wind hydrogen map was used to dimension the wind central plant and to establish its optimal installed capacity able to produce the required amount of hydrogen stated above, making it possible to generate the HCNG mixture for the province and the hydrogen delivery costs were estimated considering virtual pipelines.

The potential for wind hydrogen annual production in the best zone of the province, the Rio Cuarto department, is 120 Tons of H_2 per 2.1 MW wind turbine per year. To supply hypothetical future mixtures of HCNG at 20% V/V of hydrogen at CNG stations, the hydrogen demand would be about 5900 Tons of H_2 per year in the whole province. This amount could be provided by a farm having 50 IWP-83 wind turbines, with a total installed wind power capacity of 105 MW.

While the estimated cost of hydrogen delivery for the province of Córdoba resulted 1.15 USD/kg H_2, the total cost hydrogen cost (including production) was estimated to be 9.41 USD/kg H_2, i.e., almost twice as expensive as the equivalent cost of liquid fuels (2.48 USD/eq. liter of gasoline vs. 1.42 USD/actual liter of gasoline).

The cost of the HCNG mixture appears as almost independent of wind electricity cost, since its cost ranges between 0.53 and 0.60 USD/Nm^3 for the extremes values of that cost.

Acknowledgments

We are grateful to Secretaría de Ciencia y Tecnología, Universidad Nacional de Córdoba (SeCyT – UNC) and Consejo Nacional de Investigaciones Científicas y Técnicas (CONICET), for financial assistance and facilities used in this investigation. A. Sigal also acknowledges SeCyT UNC for a fellowship.

Table 6 – Estimated hydrogen costs considering production and delivery, based in different electricity costs. The lasts two columns represents the hydrogen cost of an amount equivalent to 1 L of gasoline and the cost of 1 Nm3 of HCNG, respectively.

Wind electricity cost [USD/MWh]	H_2 cost – production [USD/kg]	H_2 cost – transport [USD/kg]	H_2 cost – distribution [USD/kg]	H_2 cost – production and delivery [USD/kg]	Cost of 1 equivalent liter of gasoline [USD/liter]	HCNG cost [USD/Nm^3]
40.00	3.80	1.16	0.47	5.43	1.43	0.53
60.00	4.94	1.16	0.47	6.57	1.73	0.55
80.00	6.08	1.16	0.47	7.71	2.03	0.57
100.00	7.21	1.16	0.47	8.84	2.33	0.59
110.00	7.78	1.16	0.47	9.41	2.48	0.60

Appendix A. Fields measurements and Hellmann coefficient

The present Appendix briefly reports information relative to the wind measurements that were relevant to perform the estimations for wind-energy generation, from which the wind map was constructed.

Table A1 shows the coordinates, the annual average wind speeds, the predominant wind directions obtained at each station and the start date of the measurements.

Table A2 – Friction coefficient α for a variety of landscapes.

Landscape type	Friction coefficient α
Lakes, ocean and smooth hard ground	0.10
Grassland (ground level)	0.15
Tall crops, hedges and shrubs	0.20
Heavily forested land	0.25
Small town with some trees and shrubs	0.30
City areas with high rise buildings	0.40

Table A1 – Meteorological Stations data, installed by the Company Generadora Córdoba S.A [36].

Station	Longitude	Latitude	Anemometers heights (m)				Annual average wind speed (m/s)[a]	Annual directions modes	Starting date of measurements
			H1	H2	H3	H4			
La Para	−62° 59′ 48.5088″	−30° 53′ 41.949″	12	42	–	–	3.67	NE	Jul 2011
Las Acequias	−63° 58′ 41.9478″	−33° 16′ 53.3604″	12	42	–	–	3.74	NNE	Jul 2011
Sampacho	−64° 43′ 22.1808″	−33° 23′ 2.7312″	12	39	–	–	3.55	N	Aug 2011
Suco	−64° 52′ 51.3582″	−33° 20′ 46.1508″	10	20	–	–	7.67	NE	Sep 2011
Monte Grande	−64° 9′ 11.8764″	−32° 9′ 18.1008″	12	22	43	–	3.52	NNE	Sep 2009
Morteros	−62° 1′ 14.6382″	−30° 42′ 51.9078″	10	34	52	72	2.54	ENE	Jun 2010
Las Vertientes	−64° 34′ 41.0016″	−33° 16′ 58.0008″	20	40	60	–	3.89	NNE	Mar 2009
La Laguna	−64° 46′ 32.9988″	−33° 44′ 19.7982″	12	42	–	–	5.07	NNE	Aug 2007
Villa Rumipal	−64° 28′ 46.9488″	−32° 11′ 24.63″	12	22	34	–	3.32	N	Mar 2011
Adelia María	−64° 1′ 59.9982″	−33° 37′ 32.0016″	15	55	75	–	4.25	NE	Mar 2011

[a] All annual average wind speed corresponding to 10 m above ground level measurements, or are vertically extrapolated to this point.

Table A2 shows the variation of the friction coefficients α for different types of landscapes, taken from the literature. This information shows that the Hellmann coefficient (α) depends mostly on terrain roughness, height over ground level and temperature [32–34].

Concerning the present data, Fig. A1 shows two representative examples of the hourly variation of mean values of α along the day. The cases considered are those of La Para (with two anemometers at different heights) and Monte Grande (with three anemometers at different heights). The Weibull parameters (shape and scale factors) were k: 1.56; 2.45 and A: 4.25; 6.22 m/s, for these sites, respectively.

The variation of Hellmann coefficient over the heliophany hours is shown at the top Fig. A1. Typically, it is found that α decreases when the average temperature rises. We can try to understand this behavior in term of the expression used to calculate α:

$$\alpha = \frac{\ln v_2 - \ln v_1}{\ln H_2 - \ln H_1}$$

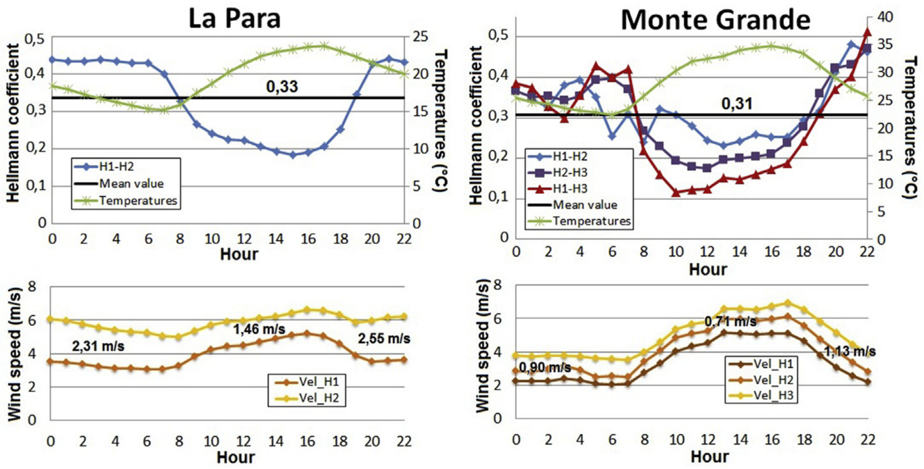


Fig. A1 – Typical hourly variation and mean value Hellmann coefficient for two representative stations: a) La Para; and b) Monte Grande.

The latter equation indicates that, for a given height difference, α decreases when the speed values v_2 and v_1 are close to each other. Comparison with the α values of Table A2 indicate that the present situation corresponds to a place which important terrain irregularities, generating turbulences, i.e., the wind gradient is dependent on the temperature gradient, among other factors, according to the Taylor theory of turbulence [35].

The mean values α shown in Fig. A1 were used to extrapolate wind speeds to 10 m height, which is the distance at which the wind map was constructed.

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