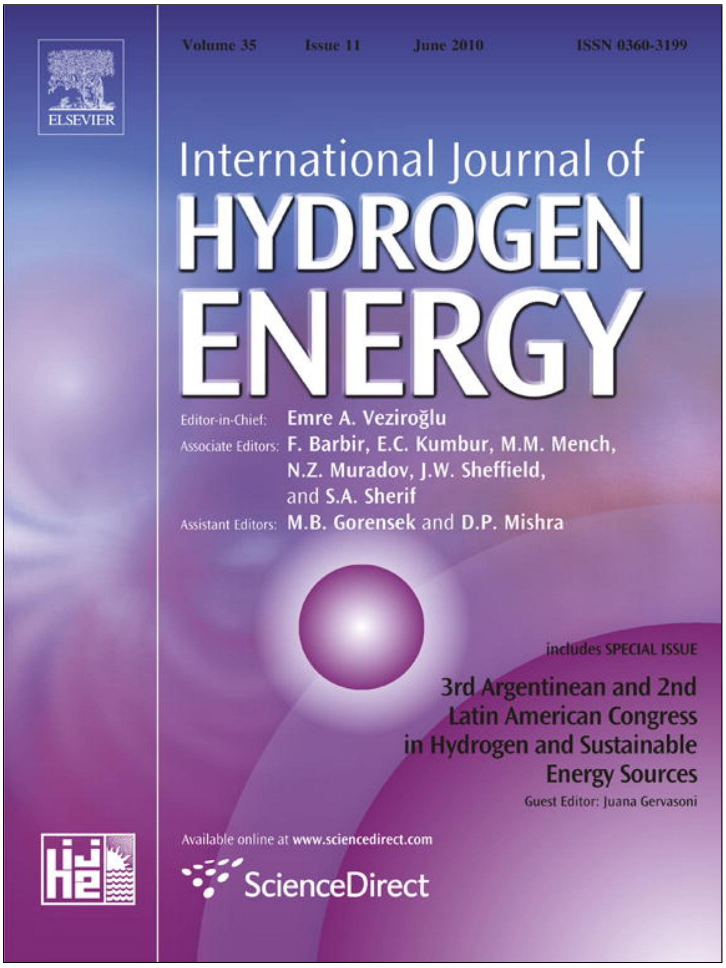
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Analysis of the potential for hydrogen production in the province of Córdoba, Argentina, from wind resources

C.R. Rodríguez [a,*], M. Riso [b], G. Jiménez Yob [b], R. Ottogalli [b], R. Santa Cruz [a], S. Aisa [a], G. Jeandrevin [c], E.P.M. Leiva [d]

[a] Universidad Empresarial Siglo 21, Monseñor Pablo Cabrera s/n calle, 5000 Córdoba, Argentina

[b] Subsecretaría de Infraestructuras y Programas, Ministerio de Obras y Servicios Públicos del Gobierno de la Provincia de Córdoba, Av. Poeta Lugones 12, 2do. Piso, 5000 Córdoba, Argentina

[c] Instituto Universitario Aeronáutico, Avenida Fuerza Aérea km 6 ½ , 5022 Córdoba, Argentina

[d] INFIQC, Unidad de Matemática y Física, Facultad de Ciencias Químicas, Universidad Nacional de Córdoba, Haya de la Torre s/n, 5010 Córdoba, Argentina

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ABSTRACT

The potential for hydrogen production from wind resources in the province of Córdoba, second consumer of fossil fuels for transportation in Argentina, is analyzed. Three aspects of the problem are considered: the evaluation of the hydrogen resource from wind power, the analysis of the production costs via electrolysis and the annual requirements of wind energy to generate hydrogen to fuel the vehicular transport of the province. Different scenarios were considered, including pure hydrogen as well as the so-called CNG plus, where hydrogen is mixed with compressed natural gas in a 20% V/V dilution of the former. The potential for hydrogen production from wind resources is analyzed for each department of the province, excluding those regions not suited for wind farms. The analysis takes into account the efficiency of the electrolyzer and the capacity factor of the wind power system. It is concluded that the automotive transportation could be supplied by hydrogen stemming from wind resources via electrolysis.

1. Introduction

1.1. *Motivation*

The generation of hydrogen from renewable resources has been appointed as a key issue to address in the way towards a clean hydrogen economy [9]. In this respect, wind energy may be employed to provide clean energy to electrolyzers and generate hydrogen. In this way, such a procedure may provide a way for the use of domestic renewable energy resources that contribute directly to the reduction of the greenhouse effect and the replacement of fossil fuels. High purity hydrogen, as required for example for the use in fuel cells, may be produced by means of electricity flow across a set of electrodes in an aqueous solution or a membrane, with the concomitant water splitting through the reaction $H_2O \rightarrow \frac{1}{2}\ O_2 + H_2$.

Three aspects of the system must be considered to assert the potential for the production of hydrogen from wind resources:

1 Evaluation of the wind resource.
2 Analysis of the hydrogen production cost via water electrolysis.
3 Annual energy requirement for hydrogen production.

* Corresponding author.
E-mail addresses: ramiro246@gmail.com (C.R. Rodríguez), ricardo.ottogalli@cba.gov.ar (R. Ottogalli), rsantacruz@uesiglo21.edu.ar (R. Santa Cruz), saisa@uesiglo21.edu.ar (S. Aisa), gjeandrevin@iua.edu.ar (G. Jeandrevin), eleiva@fcq.unc.edu.ar (E.P.M. Leiva).

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For the current costs in Argentina of liquid fuel for vehicles (ca. 1 USD per liter) and taking into account that 1 kg of hydrogen is energetically equivalent to ca. 4 l of gasoline, we can conclude in a first approximation that hydrogen production in Argentina would turn to be competitive if the hydrogen cost would locate between 3.2 and 4.2 USD/kg. With the additional consideration that a relatively efficient electrolyzer consumes ca. 52.5 kWh/kg [1], we arrive at the conclusion that the electricity cost should be of the order of 0.06–0.08 USD/kWh. Taking into account that in July 2009 the price of the kWh in Córdoba for industrial purposes is 0.03 USD [2], we find a favorable scenario. A further reason to consider Córdoba for the present analysis is that this province, consuming 1,878,165 m^3 of liquid fuels for transportation per year [8], is the second consumer in Argentina after Buenos Aires. Located in the geographical heart of Argentina with a surface territory of 165,321 km^2, this province connects several strategic commercial points in our country, powering the insertion of the country in the MERCOSUR. Its capital city, also denominated Córdoba, is the second largest city in the country. The province is divided into 26 departments (A department is a local level of government below the province).

Since the former crude estimation presents optimistic facets, the problem to tackle is to consider whether in the province of Córdoba there are enough wind resources so as to generate the quantity of hydrogen required to mobilize the vehicular transportation of the province. The next points to consider are the identification of the economical and technical systems necessary to provide the renewable energy to the refueling stations. The latter point is not trivial, since the liquid fuel consumption in the province of Córdoba is equivalent to ca. 500,000 tons of hydrogen (which require in turn 26,250 GWh to be generated). This is certainly not a negligible amount, since this value is about 1/300 of the annual USA gasoline consumption in the year 2006 (140,000,000,000 gallons, [6]).

2. Technical approach

2.1. *Evaluation of the resource*

The Regional Center of Eolic Energy (CREE, Chubut, Argentina) together with the Infrastructure and Programs Subsecretary, Public Service and Works Ministry of the province of Córdoba designed and developed the wind map whose information will be employed for the present estimations. Such a map provides information on the wind power available in the different sites of Argentina. As mentioned in Section 1, the energy E_{annual} that may be obtained annually at a given location can be calculated from:

$$E_{annual} = N_0 \int_{u=V_i}^{u=V} P(u) f(u) du \quad (1)$$

where N_0 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 [4]. The integration is performed between the wind speed limits where the wind turbine is operative. For the present calculation purposes, the present estimations were performed considering capacity factors of a V90, 2 MW wind turbine VESTAS (95 m hub height), with a nominal installed power density of 5 MW/km^2. Taking this generator as a reference, we estimated the annual energy generation per turbine E^i_{annual}. The areas (A_i) with the same power density within each department were calculated and multiplied by the previous quantity E^i_{annual}.

According to the previous statements, each equipotential region within each department generates the energy amount $E(A_i)$ given by:

$$E(A_i) = E^i_{annual} A_i \times 2.50 \quad (2)$$

where the factor 2.50 occurs because of the power density reported above. As mentioned in Section 1, the province of Córdoba is divided into departments. Thus, the annual energy generated in a given department will be given by:

$$E_{depto} = \sum_i E(A_i) \quad (3)$$

where the sum index runs over all the types of equipotential area defined in the department. For the calculation of the areas, natural conservation areas and regions with slopes larger than 20%, not adequate for the installation of wind turbines were subtracted.

2.2. *Fuel consumption in the province of Córdoba vs wind hydrogen generation*

On the basis of information provided by the Secretary of Energy of Argentina and the natural gas enterprise Enargas, we estimated the annual energy consumed in the province of Córdoba for vehicular transportation, performing its conversion into kg of hydrogen equivalent for that purpose. This information is shown in Table 1. This data indicates that 5.25×10^8 kg of hydrogen would be necessary to propel all the vehicles in the province of Córdoba during one year. Considering an electrolyzer with an efficiency of 75%, we are led to the conclusion that 27,600 GWh should be generated during this period. Assuming a capacity factor of 0.39, typical for class 4 winds, like those typically found in the south of Córdoba with a 2 MW (class 2) generation turbine, it would be necessary to count with an installed power of 8074 MW. With a density of turbines like that

Table 1 – Estimation of the energy consumed in the province of Córdoba for vehicular transportation, and its equivalent in kg of hydrogen.

Fossil fuel	Gasoline	CNG	Gas oil
Amount [m^3]	514,807	3.32×10^8	1,363,363
Energy equivalent [kcal]	4.19×10^{12}	3.09×10^{12}	1.05×10^{13}
Mass equivalent [kg of H_2]	1.24×10^8	9.12×10^7	3.10×10^8

reported above, we conclude that a surface of 1614 km^2 (ca. 40 km × 40 km) could provide the annual energy required for transportation.

3. Results and discussion

3.1. *Analysis of the wind resource*

The results obtained from the analysis described in Section 2.1 are shown in Fig. 1. They show that considerable potential wind resources, amounting 100 millions of MWh/year or more, are available in ten departments: Gral. San Martín, Tercero Arriba, General Roca, Roque Saenz Peña, Unión, Marcos Juárez, Juárez Celman, San Justo, Río Primero and Río Cuarto. The latter is the department with the highest annual energy available: 3.9×10^8 MWh/year.

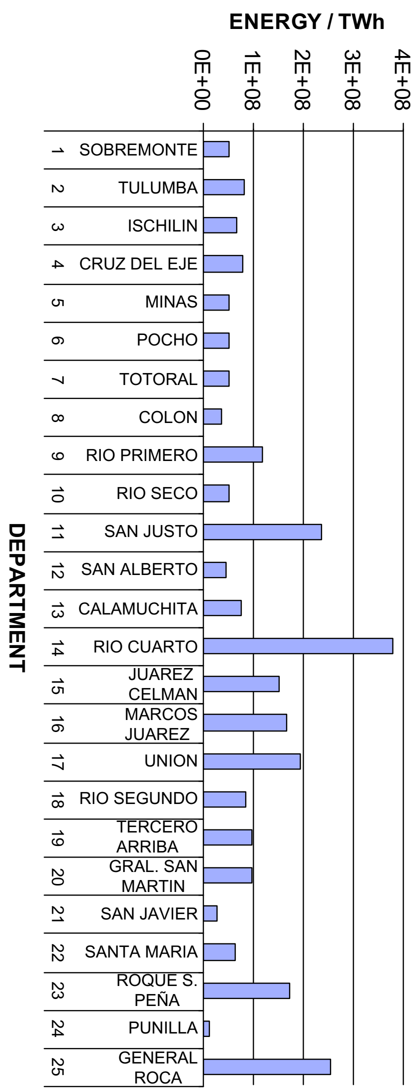

Fig. 1 – Potential of wind energy generation per year in the different departments of the province of Córdoba, Argentina.

3.2. *Analysis of hydrogen generation*

On the basis of the energy results shown in Fig. 1, we analyze now its conversion into hydrogen for the ten departments with the highest energy score. These results, shown in Table 2, indicate that the single department of RÍo Cuarto has by itself the potential to generate **ten times** the amount of energy required for transportation in the province of Córdoba. On the basis of these estimations, we propose that the gas mixture known as CNG plus, where hydrogen is provided in a 20% mixture with CNG, could be a viable alternative as a fuel towards the transition of the use of pure hydrogen in vehicular transportation. The changes in the current CNG infrastructure would be minimal, taking into account that modular transportation is already available, without the need of extra gas pipelines in those regions where distance and demand do not justify such an investment, as is currently the case in some locations in the south of the province of Córdoba [3].

3.3. *Discounted cash flow analysis*

As stated in Section 1, the electricity cost seems to play a fundamental role in determining the hydrogen prices. In order to make a more quantitative statement, we used the U.S. Department of Energy Hydrogen Analysis (H2A) Central Modeling Tool [5], designed for cost analysis of central hydrogen production. Some of the key parameters of this model are shown in Table 3. The parameters not included there are the same as those given by Ivy Levene et al. [1].

With values for the other parameters fixed, the price of electricity determines the hydrogen cost in the analysis performed with the H2A tool. In order to perform a realistic estimation, we applied previously the Clean Energy Project Analysis Software RETScreen® [7], which is a decision support tool, developed to evaluate energy production and savings, costs, emission reductions, financial viability and risk for various types of renewable energy. With the aid of this program, we determined the threshold price of the

Table 2 – Potential for hydrogen generation in the different departments of the province of Córdoba, Argentina. An efficiency of 75% was assumed for the electrolysis process.

Department	Energy per department [TWh/year]	Hydrogen production [millions of tons/year]
Río Primero	124	2.35
San Justo	248	4.73
Río Cuarto	398	7.57
Juarez Celman	161	3.06
Marcos Juarez	175	3.34
Unión	203	3.86
Tercero Arriba	101	1.92
Gral. San Martín	102	1.94
Roque S. Peña	182	3.46
General Roca	268	5.11

Table 3 – Parameters used in the discounted cash flow analysis with the H2A program of hydrogen generation via electrolysis.

Parameters	Assumptions
Process parameters	
Primary feedstock	Electricity and water
Electricity used	Industrial electricity
Conversion energy	Electrolysis
Hydrogen purity (%)	99.8
Process electricity consumption (kWh/kg)	52.5
Financial parameters	
Start-up year	2009
Plan design capacity (kg/day)	1050
Replacement capital parameters	
Electrolyzer cell stack lifetime	10
Non-depreciable capital parameters	
Land ($/acre) 1 acre = 0.405 ha	2000
Operation and maintenance parameters	
Burdened labor ($/h)	10
Overhead (% of labor costs)	20
Property tax and insurance rate (% of depreciable capital costs)	2

eolic MWh (null net present value) that makes the eolic farm profitable. This corresponded to 22.34 [USD/MWh]. The financial parameters used in this model are shown in Table 4. Table 5 shows the results of analysis performed with the two programs described above. While the first line denotes the threshold value for the cost of hydrogen required to grant profitability of the wind farm, the following lines denote the hydrogen prices obtained with the increasing energy costs assumed in the first column. The cost of hydrogen is reported per kg and also in the equivalent of 1 l of gasoline. Keeping in mind our previous statement that hydrogen generation would turn to be competitive with prices between 3.2 and 4.2 USD/kg, we can conclude from the figures of Table 5 that this situation would be feasible with electricity costs of below 50 USD/MWh.

Table 4 – Parameters used in RETScreen program for the wind power project devoted to generate electricity to feed hydrogen production.

Parameters	Assumptions
Energy parameters	
Eolic Park capacity	60 MW
Turbine model	VESTAS V90-2.0 MW – 95 m
Capacity factor	42%
Wind turbine cost	2200 USD/kW (installed)
Financial parameters	
Inflation rate	18%
Discount rate	18%
Debt interest rate	6%
Project life	25 years
Debt ratio	100%
Debt term	25 years

Table 5 – Estimated hydrogen prices as a function of the electricity costs. The electricity cost in the first line corresponds to the threshold value that would make a wind farm enterprise profitable, as calculated using the RETscreen software [7]. The remaining values were calculated using the H2A program [5]. The third column reports the price of a hydrogen amount that is equivalent to 1 l of gasoline.

Electricity costs (wind) [USD/MWh]	H_2 price [USD/kg]	Price of the equivalent in 1 l gasoline [USD/l]
27.59	3.10	0.818
40.00	3.80	1.003
60.00	4.94	1.304
80.00	6.08	1.605
100.00	7.21	1.904

4. Conclusions

The present analysis relative to the potential for hydrogen generation existing in the province of Córdoba, Argentina, was based on three different aspects of the problem: availability of the wind resource, cost analysis and annual energy requirements. Each analysis was useful to define the challenges and opportunities for an important aspect of hydrogen economy in our province: the potential use of hydrogen for vehicular transportation. The present estimation indicates that an important part of the vehicular transportation in our province could by powered by hydrogen generated in the province. The estimated costs of wind electricity, as compared with the conventional electricity and consequently the comparison between hydrogen and gasoline costs indicate that both clean alternatives can be envisaged as competitive with the conventional ones. As a highlight, it can be remarked that wind energy gained in a single Department (Río Cuarto) could provide ten times the hydrogen amount required to power the whole vehicular transportation in the province.

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