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Large scale hydrogen production from wind energy in the Magallanes area for consumption in the central zone of Chile

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ABSTRACT

The energy proposal of this research suggests the use of places with abundant wind resources for the production of H_2 on a large scale to be transported and used in the central zone of Chile with the purpose of diversifying the country's energy matrix in order to decrease its dependence on fossil fuels, increase its autonomy, and cover the future increases in energy demand. This research showed that the load factor of the proposed wind park reaches a value of 54.5%, putting in evidence the excellent wind conditions of the zone. This implies that the cost of the electricity produced by the wind park located in the Chilean Patagonia would have a cost of 0.0213 US\$ kWh^{-1} in the year 2030. The low prices of the electricity obtained from the park, thanks to the economy of scale and the huge wind potential, represent a very attractive scenario for the production of H_2 in the future. The study concludes that by the year 2030 the cost of the H_2 generated in Magallanes and transported to the port of Quinteros would be 18.36 US\$ $MBTU^{-1}$, while by that time the cost of oil would be about 17.241 US\$ $MBTU^{-1}$, a situation that places H_2 in a very competitive position as a fuel.

1. Introduction

Chile's power system is at great risk of undersupply in the future if no strategies and investments are made to promote sustainability. The future of the world's oil and gas reserves is uncertain, and at present there is an extensive debate on their level of exploitation, and the horizon in which production will start decreasing and causing scarcity is getting closer.

As an alternative, H_2 is a very prominent energy carrier for the future, in particular because it is clean as a fuel and high efficiency is achieved in its production. Currently H_2 is produced and distributed on a large scale in the world, reaching extremely high safety standards. In Europe and in the United States it is used commercially to move buses and generate electricity on the basis of fuel cells.

NCRE (non-conventional renewable energy) in general, and wind energy in particular, have undergone almost exponential development. Currently, demand for wind generators is growing at about 25% per year. NCRE appears as an option to diversify the energy supply system, the technologies of most of these energy sources have been tested, the resources for their operation are inexhaustible and practically free, foreign dependence for fuels is decreased, and furthermore the social and environmental benefits are rarely questionable.

The present work is a proposal to supply energy to the central zone of Chile in the long-term making use of the huge wind potential of Chile's Patagonia, using H_2 as an energy vector.

2. Methodology used

To assess the wind resources of Chile's Patagonia the research team made a trip to carry out a survey of wind information in the region. This led to standardized wind speed records from seven meteorological stations installed and administered by the Centro de los Recursos Energéticos of the Universidad de Magallanes, Chile.

To find out the volumes of H_2 that should be produced, and in the absence of a large scale market for this gas in Chile, it was decided to set up an evaluation scenario, which asssumes an established H_2 market with fixed demand. This evaluation scenario considers the displacement of oil from the Chilean energy supply system.

Once the wind resources available in the Chilean Patagonia had been quantified and the H_2 requirements of Chile's central zone had been established, we determined the sizes of all the stages of the logistics as shown in Fig. 1. For each of them the losses and efficiencies of the processes as well as the transformation cycles were quantified.

The research considers the analysis of the logistics chain created for the generation and transport of the liquefied H_2 to its port of destination, and it does not include an economic or technical analysis of the H_2 regasifying processes, and neither does it consider the logistics for the distribution of the gas on land to its final

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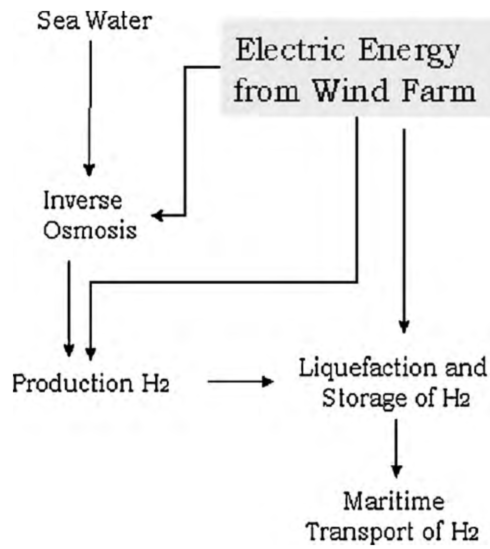

Fig. 1. Value chain of the H_2 production process.

destination. Therefore, this research provides technical guidelines and values per MBTU of H_2 delivered at a port in the central zone of Chile.

3. Wind potential analysis

3.1. Origin and characteristics of wind data

The choice of the wind site to be evaluated was based on a study made by the Centro de Estudio de los Recursos Energéticos of the Universidad de Magallanes in 2004, under the FONDEF project "Caracterización del viento en Chile" [1]. That study was carried out to evaluate the wind potential of the northern sector of the Big Island of Tierra del Fuego and part of the northern shore of the Strait of Magellan. Fig. 2 shows the sites that were studied. It was determined that the site with the highest wind potential is "Cabo Negro," located on the northwestern shore of the Strait, while the site with the highest wind potential on the island of Tierra del Fuego is "Batería 830-Cullen", hereafter "Batería 830."

Based on the above, it was decided to analyze the "Batería 830" site, since initially the energy proposal considered its development on the island of Tierra del Fuego. Furthermore, it is a very

Fig. 2. Sites considered for installing the wind park. Image provided by the Centro de Estudio de los Recursos Energéticos of the Universidad de Magallanes-Chile.

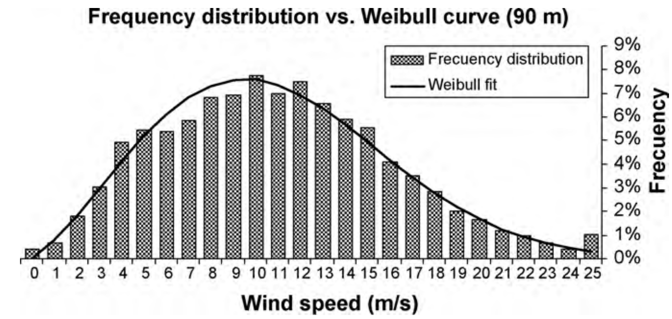

Fig. 3. Frequency distribution fitted according to Weibull.

scarcely populated sector with easy access because of its almost nil vegetation.[1]

To analyze the wind potential at the "Batería 830" site, use was made of wind data obtained by means of in situ measurements. The data came from a tower that measured wind speed at heights of 20 and 42 m above the ground, and they were taken between March 13, 2003, and March 13, 2004. The tower also had a wind vane. The wind velocity measurements correspond to averages every 10 min during the 24 h of the day, so this study involves the analysis of 52,464 velocity data at each height, equivalent to a time window of 8744 h.

3.2. Tools for calculating the wind potential

The wind data were analyzed in such a way as to extract the largest possible amount of information. This analysis in particular is based on obtaining wind information from the frequency distribution, which shows the frequency of occurrence of each wind velocity. Fig. 3 shows the frequency distribution for the year 2004 at the "Batería 830" site together with the Weibull curve, which is calculated later.

3.2.1. Land rugosity

To estimate the wind speed and energy production for the wind generators considered in this study (which have their horizontal shaft at a height of 90 m), it is necessary to establish the rugosity factor α, which can be estimated considering the wind measurements made at heights of 20 and 42 m from expression (1):

$$\frac{V(h)}{V(\mathrm{ho})} = \left[\frac{h}{\mathrm{ho}}\right]^{\alpha} \tag{1}$$

where h is the height at which the wind velocity will be estimated, $V(h)$ is the wind speed to be estimated, ho and $V(\mathrm{ho})$ are the reference height and the wind velocity at that height, respectively, and α, the rugosity factor or parameter, is calculated progressively from expression (2):

$$\alpha = \frac{\ln \nu(42) - \ln \nu(20)}{\ln\left(42/20\right)} \tag{2}$$

As a result of the application of (2) progressively to the set of data, a weighted average of 0.14090 was obtained for the rugosity factor. Since the studied site has a totally predominant norteast wind direction, the calculated rugosity factor will be considered representative and unique with respect to the wind direction.

3.2.2. Mean wind velocity

The mean wind velocity can be obtained directly from the data as well as from the frequency distribution. The wind averages that

[1] Referred to the northern sector of the island.

Table 1
Summary chart of mean spead velocities.

Height (m)	20	42	90
Velocity ($m\,s^{-1}$)	8.81	9.87	10.91

Table 2
Summary chart of the Weibull parameters.

Height (m)	20		42		90	
Parameter	A	K	A	K	A	K
Value	9.94	2.27	11.14	2.26	12.32	2.27

will be considered later for calculating the parameters of Weibull's distribution are based on the frequency distribution according to Eq. (3) [2]:

$$\bar{V} = \sum_{i=1}^{n} fi \cdot vi \tag{3}$$

where *vi* are all the intervals corresponding to each wind velocity and *fi* is the appearance frequency for each of the wind velocities.

Table 1 shows the average velocities obtained at different measuring heights, considering also the mean velocity at a hight of 90 m, obtained after calculating the rugosity parameter.

3.2.3. Weibull distribution and calculation of its parameters

Studies have shown that Weibull's probability distribution function can describe more appropriately the behavior of the wind [2]. The function is given by

$$F\,\text{Weibull} = \frac{K}{A}\left(\frac{v}{A}\right)^{k-1} \cdot \exp\left[-\left(\frac{v}{A}\right)^{K}\right] \tag{4}$$

where *K* is the shape parameter and *A* is the scale parameter.

Based on the frequency distributions built for the three different heights analyzed, the Weibull distribution parameters have been calculated. Fig. 3 shows the frequency distribution and the corresponding fit by means of the Weibull distribution at a height of 90 m.

Table 2 shows the results of the calculation of Weibull's parameters at different heights. In particular, to characterize the wind potential of the site use will be made of the Weibull distribution at a height of 20 m, while to calculate the energy production, and therefore the load factor, the distribution built at a height of 90 m will be used.

3.3. Annual energy production

With the Weibull parameters obtained at a height of 90 m we determined the annual energy production of each wind generator. This is done by the interaction of the Weibull distribution with the power curve of the wind generators considered in the research, which are 3000-kW model V-90 Vesta machines.[2] The power curve is shown in Fig. 4.

To calculate the annual energy production, each frequency of appearance of wind velocity was multiplied by its corresponding energy production value in the power curve of the wind generator, for the total hours contained in a year. Because energy production does not depend only on the available wind resource, but also on operational factors of the plant, an energy loss of 8% has been considered, composed of loss due to unavailability of the machines, loss through electric transmission, loss form turbulence, loss due to interference between machines, and loss due to the control systems of the wind ogenerators. Taking into account all the above, the energy production results are summarized in Table 3.

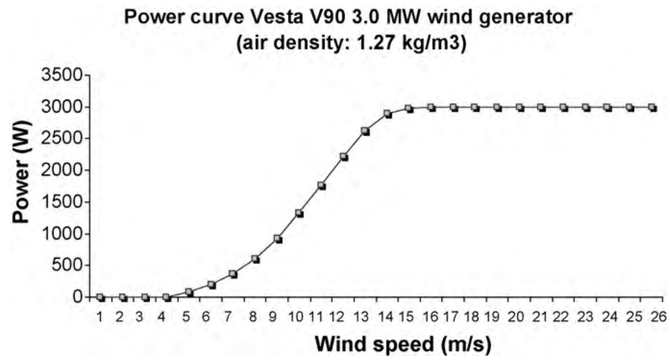

Fig. 4. Power curve of Vesta V90-3.0 MW wind generator.

Table 3
Summary chart of energy production.

Height (m)	20	42	90
Production (GWh $year^{-1}$-each machine)	11.76	13.82	15.49
Production (GWh $year^{-1}$-each machine) considering 8% loss	10.82	12.71	14.25

Table 4
Summary chart of load factors.

Height (m)	20	42	90
Load factor	44.75%	52.65%	59.26%
Load factor considering 8% loss	41.38%	48.63%	54.50%

3.4. Load factor

This factor is a percentage indicator that relates the amount of energy that will be produced theoretically, based on the local meteorological conditions in a given time, with the amount of energy that would have been obtained with the generator operating permanently during that time at its nominal power. The load factor for the "Batería 830" site based on the wind generators considered in this study is determined from Eq. (5):

$$Fc = \frac{\sum_{i-a}^{b} f(vi) \cdot P(vi)}{Pr} \tag{5}$$

where *a* is the turbine's cut-in speed, *b* is the cut-out speed, *P(vi)* is the generator's power curve, *Pr* is the generator's nominal power, and *f(vi)* represents the appearance frequency of every wind speed, obtained directly from the frequency distributions. The results obtained at different heights, with and without considering the losses, are shown in Table 4.

3.5. Considerations and observations

The main objective of the energy production calculation was to estimate the load factor at which the wind park would operate, since that would determine the size of practically all the processes involved in the energy proposal. In what follows it will be considered that the wind park will have a load factor[3] of 54.50%, which shows the region's huge wind potential.

[2] Wind generator manufacturers deliver curves for each of the most common air densities in wind settings. The power curve that corresponds to an air density of 1.27 kg/m^3 has been used.

[3] For practical purposes, the concept of load factor has been used in the same way as the concept of plant factor.

Finally, it is believed important to mention that the results of this study are quite coincident with those reported in the literature [1]. The small differences that appear between them is due to the fact that the WindPro/UASP software was used in that report to evaluate the data, while in this study we used directly the statistical and meteorological models described earlier.

4. The energy proposal

4.1. Generalities

As has been made evident in the previous section, there is a great wind potential in the zone of Magallanes, probably one of the best in the world; however, it is not being exploited because the region's energy demand is covered mainly by NG, with very low prices. The present research studies the possibility of making use of the wind resource of Magallanes transporting LH_2 by sea. Essentially, the energy proposal is based on generating electricity in a wind park located on the island of Tierra del Fuego, and using that energy to produce H_2 in the same zone by means of electrolyzers. The volume of that H_2 is reduced by liquefaction, and it is then transported by ship to the central zone, where the H_2 would be unloaded and used in energy and industrial applications.

4.2. Conceptualization of the proposal

As stated in the previous sections, this research deals with the analysis of the logistics chain set up for the generation and transport of LH_2 until the gas is unloaded at the port, so it does not consider the economic or technical analysis of the processes of regasifying the LH_2, the logistics of distribution of the gas on land, or studies on the technologies involved in the consumption of H_2. For that reason, this research will provide technical guidelines and values per MBTU of LH_2 unloaded at a port of the central zone of Chile. Fig. 5 shows the main stages of the energy proposal, which starts with the generation of H_2 by means of electrolyzers that use water and electric energy from the wind farm. Because of the physical properties of H_2, particularly in relation to its energy density, the gas must be liquefied for its efficient transport by sea. The following sections describe in detail each stage of the proposal, specifying the technologies and plant sizes.

4.3. Evaluation scenario

To determine the volume of H_2 that must be produced, and since there is no large scale market for this gas in Chile, it was decided to set up an evaluation scenario which assumes the existence of an established H_2 market with fixed demand. For the above we consider delivery at the port of Quinteros[4] of LH_2 volumes transported by ship and a displacement of 7.1% of the oil used in the energy matrix in 2006, equivalent to 33,223,417 MBTU year^{-1}. This amount of energy conditions all the sizes of the proposed plant.

4.4. Determination of plant sizes and technologies

Plant sizes will be conditioned by the amount of H_2 produced anually at the load factor of the wind park, and therefore the amounts of energy will be expressed, unless stated otherwise, in MBTU year^{-1}, and the plant sizes in m^3 day^{-1} for the water desalination plant; in kg day^{-1} for the H_2 liquefaction plant; in Nm^3 day^{-1} for the H_2 production plant; in installed MW for the wind park; and in m^3 for cryogenic storage on land and for sea transport.

[4] Located in the Fifth Region of Chile.

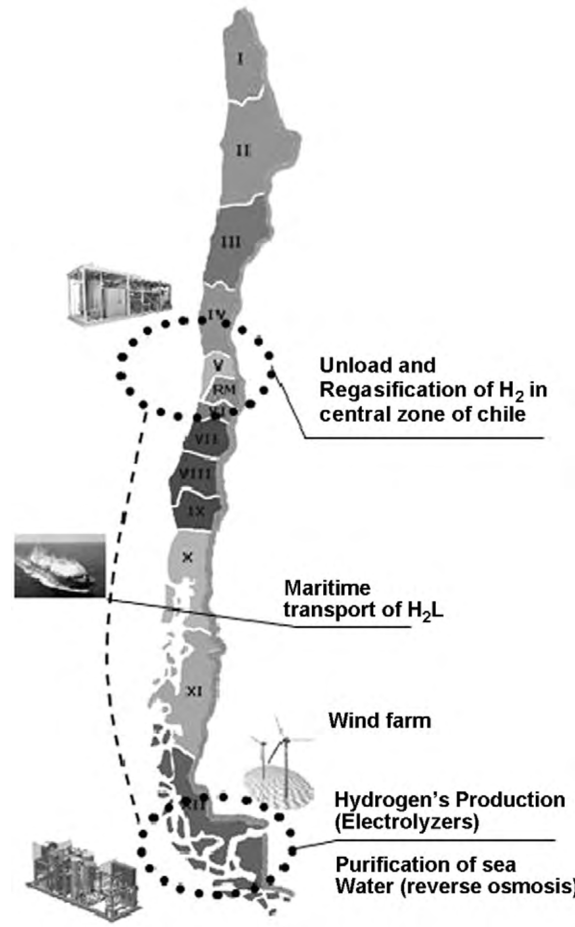

Fig. 5. Geographic scheme of the energy proposal.

For this work a particular size will not be considered for the electric transmission networks, but it will for the losses incurred in them. Due to the eventual closeness of the wind park to the H_2 production plant, it will be considered appropriate to assume 14%[5] of the investment cost of the wind park as sufficient for connecting the park with the consumption involved in the H_2 production process, therefore the cost of the networks has been included as part of the investment cost of the wind farm. The costs associated with payment for the use of a port in the zone of Magallanes,[6] and therefore also its size, have been excluded from this study.

Because of the nonexistence yet of a large scale market of H_2 for energy use, some of the plant sizes that will be specified in this work are assumptions, particularly with respect to sea transport, cryogenic storage on land, the liquefaction plant, and the H_2 production plant, although the latter is scalable in a modular way without a size limit, and so is the H_2 liquefaction plant to a smaller extent.

An aspect that is absolutely determining for the plant size associated with each process has to do with the capacity factor, which is directly related to the capacity factor of the wind park, and therefore all the processes have sizes that consider the daily and monthly fluctuations of the avilable wind resource.

[5] Corresponding to the sum of 6% for network connection and 8% for electric infrastructures.

[6] Omission of the costs associated with port duties does not involve substantial differences in the final cost of the H_2.

Table 5
Ship capacity for LH_2 and loss in transport.

	Year 2030
Transport capacity of the ship	100,000 m^3
Ships in operation	1
Approximate distance from Magallanes-Quinteros	3000 km
Average ship speed	35 km h^{-1}
Travel time of the loaded ship	3.57 days
Time between trips	10 days
Boil-off loss	0.3% day^{-1}
Total trips per year	35
Energy loss during transport	359,820 MBTU $year^{-1}$
Energy required at port in Magallanes	33,583,237 MBTU $year^{-1}$

4.4.1. Sea transport

At present no transport of LH_2 by sea takes place commercially on a large scale. Because of that, for this study it is considered that there are ships with the technological capacity to provide the service at the costs that will be specified later. It is expected that in the future the transportation of LH_2 by ship will be made under conditions very similar to those under which that of LNG is made [3]. Considering that the ship must transport annually to the port of Quinteros an LH_2 content equivalent to 33,223,417 MBTU, the following specifications are obtained (Table 5).

4.4.2. Cryogenic storage on land

No important technical barriers have been found in the available literature for the construction of cryogenic LH_2 tanks in sizes similar to those existing nowadays for storing LNG,[7] so it is assumed that they have not been built only because there is no existing market sufficiently large to justify them. Consequently, this study considers the installation of four tanks, each with a storage capacity of 50,000 m^3 of LH_2,[8] which is justified considering the capacity factor of the process, conditioned by the load factor of the wind park. For this study it will be assumed that the boil-off loss in the cryogenic storage on land is nil, because the H_2 is recovered by catchment systems and is reinjected into the liquefying plant.

4.4.3. Hydrogen liquefaction plant

In contrast with the sizes of the current NG liquefaction trains, those for the liquefaction of H_2 have been built on a medium scale, sufficient to process the volumes required by current but increasing demand for H_2.[9] This work specifies only the size of the required plant, but not the number of trains needed to process the required volumes. It should be mentioned that if the H_2 market were as big as that of NG, only one liquefaction train would be needed to process all the H_2 required by the energy proposal presented here.[10] Table 6 shows nominal conditions of the liquefaction plant, neglecting the loss by evaporation that would occur during the process.

4.4.4. Hydrogen production plant: electrolysis

Alkaline electrolyzers have been chosen because they are the most extensively developed commercially, are highly efficient, are manufactured on a large scale, and are less expensive with respect to capital cost and O&M. The plant size required for this study is feasible at present, because the electrolyzers are commercially available and the production plants are scalable in a modular way. Table 7 shows the specifications of the electrolyzers and the energy requirements. Future developments of this technology are aimed at increasing efficiency and drastically decreasing investment costs.

[7] Typical current LNG tank sizes exceed 100,000 m^3 [4].
[8] Around 1998, the world's largest cryogenic LH2 tank belonged to NASA, with a storage capacity of about 3300 m^3 of LH_2 [3].
[9] The German company LINDE KRYOTECHNIK AG currently builds liquefaction trains capable of processing aabout 16,000 Nm^3/h of H_2, while the PRAXAIR company builds trains with a capacity of 15,000 Nm^3/h of H_2.
[10] At present, liquefaction trains can process more than 800,000 Nm^3/h of NG.

Table 6
Liquefaction plant capacity and energy requirements.

	Year 2030
Plant factor[a]	54.5%
Plant size	1,249,620 kg day^{-1} of H_2
Loss by evaporation[b]	0%
Nominal plant feed flow	13,988,967 Nm^3 day^{-1} of H_2
Nominal energy requirements	6 kWh kg^{-1} [c]
Real annual energy requirements	1491 GWh $year^{-1}$
Annual energy production	33,583,237 MBTU $year^{-1}$

[a] Capacity factor dependent directly on the load factor of the wind park.
[b] Considers recovery of the loss by evaporation produced in the liquefaction process.
[c] From Ref. [5].

Table 7
Hydrogen production plant capacity.

	Year 2030
Plant factor	54.5%
Electrolyzer	Norsk Hydro
Type	Alkaline
Nominal production per electrolyzer	380,000 kg H_2 $year^{-1}$
Number of electrolyzers needed	1213
Plant size considering load factor	1,262,542 kg day^{-1} of H_2
Nominal energy requirements	44.7 kWh kg^{-1}
Loss from AC/DC conversion at electrolyzers	2%
Annual energy requirements	11,455 GWh $year^{-1}$
Annual energy production	33,583,237 MBTU $year^{-1}$

4.4.5. Purification of water as raw material

After the visit of the research team to the Big Island of Tierra del Fuego, and following an interview at the Direction General of Waters of Magallanes, it was found that fresh water resources are rather scarce in the central zone of the region of Magallanes. Tierra del Fuego has some important reserves in the extreme south of the island, while in the continental sector, near the city of Punta Arenas, the few existing important rivers and lakes are used mainly for potable water supply.

Because of the above, here we have considered the use of sea water as raw material for generating H_2 by electrolysis, desalinizing it by reverse osmosis. Although these systems are quite effective for purifying water, the electrolyzers are very sensitive to the presence of contaminants in the water, so it is quite probable that additional purification may be required. The present work will consider only desalinizing systems by reverse osmosis and will neglect additional purification systems. Table 8 specifies the size of the plant and the energyrequirements.

To determine the plant size it has been considered that the electrolyzers require 1 L of water for every Nm^3 of H_2 generated, and that the plant has the capacity for storing desalinized water economically, and therefore the plant factor does not depend on the

Table 8
Water desalinizing plant capacity.

	Year 2030
Technology	Reverse osmosis
Plant factor	97%
Conversion factor (sea water – desalinized water)	50%
Plant size (produced water)	7860 m^3 day^{-1}
Nominal energy requirements	2.5 kWh m^{-3}
Annual energy requirements	6.96 GWh $year^{-1}$

Table 9
Wind park capacity.

	Year 2030
Wind generator	VESTA V90
Nominal power	3 MW
Load factor	54.5%
Number of wind generators	923
Installed power of the park	2768 MW
Estimated annual energy production	14,322 GWh year^{-1}
Loss due to energytransport[a]	2%
Use of the surface of Tierra del Fuego[b]	0.254%

[a] The remaining losses associated with the wind park were included in the calculation of the load factor of the wind generators.
[b] This is equivalent to using an area of 97 km^2, considering that the island of Tierra del Fuego has an area of 29,484 km^2.

load factor of the wind park, but rather on the required maintenance time. On the other hand, it has been considered that the reverse osmosis technology used includes an energy recovery process[11] without which the energy requirements can vary with respect to the 10–20 kWh m^{-3} produced [6].

4.4.6. Wind park

The wind park size was based on the amount of energy required at the port of Quinteros in the form of H_2, considering the energy requirements of each of the processes and of all the losses involved in them. The nominal capacity of the wind generator chosen corresponds to an optimum use of the wind resource of the zone. All the plant factors of the processes involved in the energy proposal are conditioned by the load factor obtained from the wind park in general.

The layout of the wind park considers a distance of two rotor diameters perpendicular to the predominant wind direction between the wind generators, and five rotor diameters along the line parallel to the predominant wind direction. Table 9 shows the main characteristics of the wind park.

5. Economic analysis

5.1. Considerations

To determine the cost of each process, a capital cost of 5% has been considered and a 10% IRR has been required from each stage related to the H_2 production process. In this way the price of the products (water, electricity, H_2) and services (liquefaction) have been adjusted according to the required internal rate of return. The facilities and equipment have been depreciated in 10 years overall, not distinguishing between investment in equipment, engineering expenses, or administrative expenses in the construction of the plants, because the results after the discounted cash flow do not vary much, so the variations that occur after omission of the corresponding breakdown are considered negligible. The tax rate has been estimated at 17% per year, and the project's useful life at 20 years. The research considered carrying out discounted cash flows for each process. For this study, scale economy is a determining factor at the time of estimating the investment cost. For example, the liquefaction plant has a very high economy of scale, represented by a factor in a range of 0.6–0.7 [7], while cryogenic storage of LH_2 has a high investment cost due to the improvements in the reduction of boil-off loss, implying economy of scale with a factor close to 0.7.

[11] The energy recovery systems consider isobaric chambers.

Table 10
Background for the determination of the transportation cost of LH_2.

	Year 2009	Year 2030
Maximum transportation cost of LNG by ship[a]	1.3 US$ MBTU^{-1}	0.8 US$ MBTU^{-1}
Estimated transportation cost of LH_2 based on LNG[b]	400%	200%
Estimated transportation cost of LH_2	5.2 US$ MBTU^{-1}	1.6 US$ MBTU^{-1}

[a] From Refs. [8,9]
[b] Criterion based on Refs. [3,7–9].

Table 11
Background for determining liquefaction costs.

	Year 2009	Year 2030
Plant investment cost	650 US$ kg^{-1} day[a]	300 US$ kg^{-1} day[b]
LNG cryogenic storage investment cost	300 US$ m^{-3}-LNG	120 US$ m^{-3}-LNG
LH_2 cryogenic storage investment cost with respect to LNG[c]	140%	140%
O&M cost[d]	0.3116 US$ kg^{-1} H_2	0.1934 US$ kg^{-1} H_2
Electricity cost[e]	0.0333 US$ kWh^{-1}	0.0213 US$ kWh^{-1}

[a] From Refs. [3,11–13].
[b] Assuming a performance similar to that shown by the reference LNG liquefaction plants [3].
[c] From Refs. [3,4].
[d] From Refs. [7,12,14]. Does not include the cost of energy.
[e] These values correspond to the economic analysis made for this report in particular.

5.2. Breakdown of the costs of the processes

5.2.1. Sea transport

Since there is no market for the large scale transport of LH_2 by sea,[12] the estimation of the cost is a complex task. It is expected that the increasing development of the technologies for the transportation of LNG will promote an associated development of the technologies for the large scale transport of LH_2 due to the growth projections of the demand for H_2 at the world level. This item does not consider carrying out cash flows that consider investment and O&M costs; in place of them, transportation cost is determined on the basis of existing references and current LNG transportation costs. Table 10 shows the cost estimation.

5.2.2. Hydrogen liquefaction plant

Liquefaction is a high cost and high energy consumption process, with large economy of scale. This implies that the liquefaction of H_2 is justified mostly in centralized and large scale production centers. The investment costs of LNG plants have declined between 35 and 50% over the last ten years [3], due largely to economy of scale and improvements in design and technology [10]. The above suggests a link between the behavior of the investment cost of the LH_2 plants due to their similarity with LNG technologies and the growth of the H_2 market.

For cost purposes, we have considered cryogenic storage as an integral part of the liquefaction plant, and therefore investment cost estimations are given for this item. Table 11 shows the cost estimations associated with the liquefaction plant.

5.2.3. Hydrogen production plant

To determine the costs associated with the H_2 production plant it has been considered that the electrolyzers have electric current rectifying systems incorporated or that there is a unified conversion

[12] Not so for land transport of LH_2, a technology that is technically and commercially developed.

Table 12
Background for determining the H_2 production cost.

	Year 2009	Year 2030
Plant investment cost[a]	800 US$ kW^{-1}	360 US$ kW^{-1}
Reinvestment after 10 years of operation with respect to initial investment	30%	30%
O&M cost	0.126 US$ kg^{-1} H_2[b]	0.057 US$ kg^{-1} H_2
Water cost[c]	1.37 US$ m^{-3}	0.81 US$ m^{-3}
Electricity cost	0.0333 US$ kWh^{-1}	0.0213 US$ kWh^{-1}

[a] From [15–20]. It includes the cost of transformer, rectifier, subsystems, and assembly, the investment cost of the electrolyzer without considering these items is about 300 US$ kW^{-1} at present.
[b] From [15,21].
[c] These values correspond to the economic analysis made for this work in particular.

Table 13
Background for determining desalination cost.

	Year 2009	Year 2030
Plant investment cost	925 US$ m^{-3} day[a]	500 US$ m^{-3} day[b]
O&M cost[c]	0.589 US$ m^{-3}	0.4 US$ m^{-3}
Electricity cost	0.0333 US$ kWh^{-1}	0.0213 US$ kWh^{-1}

[a] Value obtained by averaging the information from Refs. [22–27].
[b] From Ref. [27].
[c] Value obtained by averaging the information from Refs. [23,24,28].

system to feed direct current to the electrolyzers. Determination of the H_2 production cost considers the cost of investment, O&M, desalinized water, and electricityfrom the wind park. After ten years of operation of the plant a reinvestment is considered to replace the electrolyzer mains [15]. The resultant H_2 cost is strongly linked to the cost of electricity, and there is a direct correlation between this cost and the final cost of H_2 produced by electrolysis. Table 12 summarizes the costs associated with the process.

5.2.4. Reverse osmosis

The reverse osmosis process does not consider costs for buying water or paying for water rights, because the source is sea water. The estimation of the plant's investment cost does not consider the investments needed for storing desalinized water because of the simplicity of the required technology and the low associated cost. The cost of desalinized water is strongly dependent on the price of the electric energy required to generate the pressures involved in the process, and to a smaller extent on the investment cost. Table 13 shows the investment and O&M cost.

5.2.5. Wind park

The determination of the associated costs is based on the statistics of a market that is fully established in the world, with current growth that involves an overdemand for wind generators. The economy of scale in the wind energy parks can become very strong with respect to investment costs as well as to O&M costs. Table 14 shows the wind park's investment and O&M cost estimates.

5.3. Total resultant cost of LH_2 placed at port

The final cost of H_2 placed at the port of Quinteros is subject to the costs of all the processes involved in the energy proposal. The investment amounts[13] expected for the wind park, the reverse osmosis process, the H_2 production plant, and the liquefaction and storage plant approach US$ 3,200,000,000 for the year 2030.

[13] Includes installation costs. It does not include transport and regasifying cost.

Table 14
Background for determining wind energy cost.

	Year 2009	Year 2030
Wind generator cost[a]	850 US$ kW^{-1}	500 US$ kW^{-1}
Installation cost with respect to wind generator cost	30%	30%
Investment cost	1105 US$ kW^{-1}	650 US$ kW^{-1}
O&M cost[b]	0.0040 US$ kWh^{-1}	0.0040 US$ kWh^{-1}

[a] Value obtained by averaging the information from Refs. [18,29–33]. The value corresponds to a FOB price, because of the tax and custom duty concessions of Tierra del Fuego and because no transportation costs or international insurance have been considered. The value includes the strong economy of scale present in the project.
[b] Value obtained by averaging the information from Refs. [18,29–33]. Important future variations of this item are not considered.

Table 15
H_2 distribution cost year 2030.

Process	Cost	Unit
Electricity cost	0.0213	US$ kWh^{-1}
Water cost	0.81	US$ m^{-3}
H_2 production cost	1.752	US$ kg^{-1} H_2
Liquefaction and storage cost	0.512	US$ kg^{-1} H_2
Transportation cost	0.216	US$ kg^{-1} H_2
Total	2.48	US$ kg^{-1} H_2
Total	18.36	US$ MBTU^{-1}

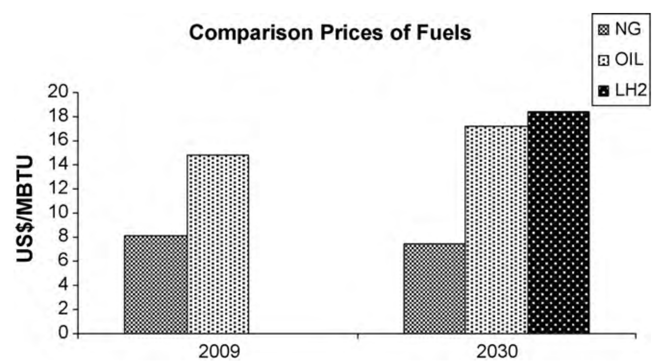

Fig. 6. Comparison of fuel prices.

5.3.1. Cost of H_2 in the year 2030

The result of the long-term cost of H_2 placed at the port of Quinteros, and its components, are shown in Table 15.

5.3.2. Cost comparison

Taking into account the results of this research and current oil prices and those projected by the EIA (Energy Information Administration) for oil[14] and NG (NYMEX for Henry Hub), it is possible to build the graph shown in Fig. 6, where present and future prices of fossil fuels and H_2 are compared.

It is important to mention that the comparison of the price of LH_2 and oil is prior to regasifying and refining, respectively, and therefore, considering that regasifying is a process that consumes less energy than oil refining, it is expected that the difference between the costs of the final products (gaseous H_2 and diesel or gasoline) would be even more favorable to H_2.

On the other hand, practically all the technologies associated with the use of oil as a fuel are subject to the laws of thermodynamics, so the thermal cycles are highly inefficient. In contrast, the technologies associated with the use of H_2 as a fuel are governed

[14] This projection indicates that in 2030 the barrel of crude will have a price of US$100, which is particularly optimistic considering the increases undergone by the fuel from 2007 to 2009.

Table 16
Cost comparison of H_2 according to different scenarios.

	H_2 cost (US\$ kg^{-1} H_2) 2030	Observations
Generation of H_2 in Magallanes	2.48	Considers the cost of liquefaction and transport, but not those of regasifying
Generation of H_2 in central zone	3.025	Does not consider cost of and transport

by electrochemical laws, which implies much higher efficiency in the conversion into electric energy.

5.3.3. Comparison between different scenarios

Alternatively, this research evaluated the resultant costs of H_2 produced from desalinized water and electric energy from a wind park installed in the central zone of Chile, operating with a typical load factor equal to 30%. This scenario does not require the liquefaction and sea transport processes. The comparison of the costs of H_2 from the energy proposal of this paper and that evaluated alternatively is shown in Table 16.

For the costs of both scenarios to be compared under equal conditions, the cost of regasifying should be added to the H_2 generated in Magallanes, a process that has a considerably lower cost than that of liquefaction. Therefore, and based on the costs of liquefaction, shown in Table 15, it can be said that the load factor obtained in Magallanes justifies making the investment in that region over a project oriented at producing the same amount of H_2, but with a load factor for the wind park equal to 30%.

6. Conclusions

The energy proposal presented in this paper shows that H_2 can achieve high competitiveness in the future with respect to the expected prices of fossil fuels. Even though at present there is no absolute development for the large scale production and distribution of H_2, it is expected that in the future this situation will change drastically, because the rates of growth of the use of H_2 are quite promising.

In particular, the energy proposal showed that the Big Island of Tierra del Fuego, and in general a large part of the region of Magallanes, has a huge potential for the production of electricity by means of wind generators. In fact, the study concludes that the load factor at a height of 90 m is equal to 54.5%, showing that the zone has one of the greatest wind potentials in the world. Because of that, and also due to the large economy of scale that exists in the energy proposal, by the year 2030 it is expected that H_2 will have a cost of 18.36 US\$ $MBTU^{-1}$, while by that time oil, in a very optimistic scenario (considering a price of US\$100 $barrel^{-1}$), would have a cost of 17.241 US\$ $MBTU^{-1}$.

On the other hand, this research shows that the load factor obtained in Magallanes justifies making the investment in that region instead of in the central zone of Chile aimed at producing the same goods, but with a typical load factor of the wind park equal to 30%.

The results obtained in this research are sufficiently open as to be extrapolated to other countries having sites with high wind potentials, but with large distant consumer centers, so they can generate H_2 on a large scale and transport it to large consumer zones.

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