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The energy transition towards hydrogen utilization for green life and sustainable human development in Patagonia

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HIGHLIGHTS

- Green energy transitions associated with hydrogen.
- Renewable energy in Patagonia.
- New legislation for renewables.
- Large-scale energy storage options.
- Patagonia energy trading.

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ABSTRACT

Energy transitions towards cleaner and transparent systems in Patagonia are examined, considering energy data for hydrogen utilization to store variable renewable energy. The interrelated sectors – power, heating, cooling and transport – demand large amounts of energy and power. Wind transformation and distributed energy management can achieve synergies towards a new energy paradigm. Fossil fuels should be replaced by a system capable of storing massive amounts of electricity and fuels. Full energy services are not affordable employing only rechargeable batteries or air and water pumping. We analyze wind resources, electricity grids, and hydrogen developments carried out in Argentina, and the perspective of large wind-hydrogen facilities for export. We verify the current demand of natural gas and electricity, and propose the start of distributed production, management and utilization of hydrogen in Patagonia and to supply the most populated areas reaching Buenos Aires. Hydrogen sea transportation from South Patagonia to Rio de la Plata could be feasible. "The whole process would help the training of qualified human resources and also encourage the establishment of companies dedicated to renewable and hydrogen technology activities."

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Introduction

"Towards a hydrogen civilization"

This work is inspired by the need to contribute to a hydrogen civilization, initially introduced by T. N. Veziroglu, V. A. Goltsov and V. L. Goltsova in 2001 [1]. In 2006 the same authors introduced a more detailed scope of this same concept [2]. In their corresponding abstract, they wrote:

"For the first time it is noted that the HyCi-conception includes two constituent, mutually conditioned parts: humanitarian—cultural part and environmental—industrial one. The most important possible stages of the transition to the HyCi have been indicated, including the important role of the world hydrogen movement, general public, international and regional organizations, parliaments and governments of the world countries. It has been emphasized that these global changes in humankind's life need a long period of time, humanitarian—cultural and legislative—economical self-regulation of the life of people and countries."

Other reference guidelines to which we want to contribute to are expressed in the title of this work, and has been manifested in the G20 meetings as well as in the United Nations Sustainable Development Goals [3,4].

Global energy and environmental challenges. G20 summit Argentina 2018 – Japan 2019

The potential agendas and issues for G20 Osaka include under the heading "Greater provision of international public goods and resilience", a chapter dedicated to climate change and energy [5,6]. It claims that "the international community needs to make advancements in terms of emissions reduction and the concretion of a low-carbon society, in order to address climate change as a global issue. Such efforts should not be regarded as negative for economic growth and, on the contrary, they can even promote growth as private-sector-driven green industries can emerge as a result of these measures. In fact, the invigoration of green businesses involved in energy transition and de-carbonization can be an engine that drives world economic growth. The G20 has 1) committed to building open and transparent energy markets; 2) stressed the need for continued investment in energy projects; and 3) reaffirmed the importance of collaboration towards a cleaner energy future and sustainable energy security. Furthermore, it is important to support developing countries in improving universal energy access. Thus, the G20 leaders are encouraged to cooperate towards the implementation of the Paris Agreement and the realization of a circular, green economy, and achieve a complete de-carbonization, so that the international community overall can move towards achieving the 2° goal. Developed countries with advanced technologies can support de-carbonization in the developing world. Furthermore, for steady implementation of the Paris Agreement, long-term strategies not bound by previous conventional wisdom will be needed to instigate a virtuous cycle for the environment and growth and encourage business-led technological innovation" [7,8]. We strongly believe that hydrogen can play a relevant role.

Patagonia – description, natural resources and population

Patagonia is a remote region of the world located in the southernmost part of the American continent and extends from 37° S to 56° South latitude. The region reaches the southern tip of the continent and was tectonically connected to the Antarctic Peninsula until the South American-Antarctica land bridge split apart by a tectonic plate (Scotia Plate) between the two continents [9]. Its limits are somewhat diffuse, but naturally they range from the Colorado River and the Barrancas River in Argentina to Cape Horn and between the Atlantic and Pacific Oceans. For this reason, it comprises administratively the provinces of Neuquén, part of La Pampa, part of Buenos Aires, Río Negro, Chubut, Santa Cruz and the province of Tierra del Fuego, Antártida e Islas del Atlántico Sur in Argentina. In the Chilean side it covers the administrative regions XI (Aysén Region) and XII (Region of Magallanes) and part of Region X (Region of the Lakes). The total area of Patagonia comprises 1.05 million square kilometers of which 90% are in Argentina (see the map on Fig. 1) (see Fig. 2).

The spine of this region is undoubtedly the Andes Mountain Range that runs throughout the continent and serves as a natural boundary between the two countries. The Andes of South America is the longest mountain range in the world, stretching for an estimated distance of 7000 km. In that territory we can observe the dominion of the South Pacific Anticyclone on the South Atlantic Anticyclone which strongly marks the climate on both sides of the mountain range with abundant rainfall to the West and on both sides of the mountains, resulting in a dry climate and strong - almost permanent - winds that dominate the mythical Patagonian steppe. In a few words, the climate is arid, dominated by masses of air and high intensity winds that come from the Pacific Ocean. These absolutely extraordinary conditions - together with the vast territory - are the causes that generate fierce winds and energy generation potential which cannot be compared to any other place in the world. The extreme south of Argentina has extremely favorable conditions for the use of wind energy as well as many neighboring regions to the maritime coast of the Province of Buenos Aires and the River Plate where there is an ancient tradition of using the wind resource through the use of mills in "estancias" and rural establishments of the Pampas, which has forged the base of the agricultural and livestock wealth of Argentina over the last 150 years. Patagonia is immense and mysterious, and has great cultural diversity [10]. The population density of Patagonia is very low, due to the severity of the climate and living conditions and the great extension of the territory, which is reflected with rates that do not exceed two inhabitants per square kilometer and in many areas are lower than 0.5. The extension of its territory represents a third of the country, but it is inhabited by less than 5% of the total population. More than seventy percent of its population is located in just 20% of

Fig. 1 — Patagonia region map.

its territory. Patagonia has become renowned as one of the few surviving regions of the world designated as an "Eden" or region where pristine nature still exists. Fisheries exploitation is very important as well, and is very advantageous due to the wide surface of the continental shelf [11].

Finally, renewable energy generation is a growing activity because wind resources are abundant. Most of the area has an average annual wind speed above 10 m/s. Established wind parks demonstrate a load factor of 50% and in some cases 60% during the windy months.

Aspects to take into account

Renewable energies are the unique solution to a sustainable global energy system: they are clean, inexhaustible, and

Fig. 2 – Satellite photograph of Patagonia from Southwest.

available at different intensities everywhere in the world. Intermittent and at times unpredictable renewable energies must link to another variable condition: the energy services menu. In a practical manner, natural resources are transformed into electricity. Direct "injection" into the electrical grid is limited by its stability and capacity. Temporary electricity storage is also limited by means of electric rechargeable batteries, capacitors, mechanical devices, air compression, and also – at a higher level – water pumping. Electricity converted into hydrogen – as a pure element – or combined with carbon, produces synthetic fuels. Stored hydrogen supplies a flexible means that caters for steady secure electricity, heat and a sustainable fuel for industry, transportation, and any other energy requirement. Hydrogen allows energy storage in the widest range of power and energy scale. Wind and solar power are Variable Renewable Energies (VRE) that fluctuate within a relatively short period of time, therefore, they need additional technologies able to convert surplus electricity into hydrogen or hydrogen compounds. Those technologies are generally known as Power-to-Fuel (P2F) and convert renewable electricity into hydrogen gas, methane or liquid fuels like methanol or ammonia for example.

Global phenomena like climate change must be tackled and avoided at a higher rate than the way it is being done today. This is claimed and well-explained in the text "Laudato Si' Encíclica 2015" from Pope Francisco [12].

The Argentine law promotes renewable energy with the compromise to reach 20% of electricity generation for 2025 [13]. The current consumption and projected increase show that 14,000 MW – mostly from solar and wind power – should be installed. At a national level, the distributed generation and the hydrogen promotion laws should be taken into consideration because to make the energy transition possible, political leadership and governmental help are needed as Argentina demonstrated during the preparatory work of the G20 Summit in Buenos Aires [14,15]. Regarding to the Energy chapter, in the vision of the Argentina Sherpa Track we can ask ourselves: Why Energy Transitions? Because the term "transitions" – in plural – emphasizes that each G20 member can follow its own path towards a cleaner, more flexible and transparent energy future. This view reflects the fact that each G20 member has a unique energy mix as starting point, different geographies, cultures and development stages. It also emphasizes that energy sources are diverse around the world, with differences in natural resources, technologies, capital and national circumstances. Moreover, diverse transition processes imply the coexistence of country-specific goals, such as promoting economic growth, improving access to energy for all citizens, providing energy security, mitigating climate change, meeting climate or sustainable development commitments or simply reducing emissions [16].

The electricity sector that comprises power generation and use, is changing to renewable sources in many countries but the transformation of the heating, cooling and cooking areas are not going in the same paved road suffering many different problems, including no change at all. Accomplishing the target set in the Paris agreement is not an easy task if renewables are considered only for the power sector, instead of considering the total picture that should include transportation, heating and cooling among other sectors. We should remember the words of Rana Adib, Executive Secretary of REN21: "Equating 'electricity' with 'energy' is leading to complacency," who also said "Maybe we are a step ahead on the way towards a future based on 100% renewable electricity, but when it comes to heating, cooling and transport, we are advancing as if we had all the time in the world. Unfortunately that is not the case".

Modern renewable energy met around 10% of worldwide heating and cooling demand in 2016, but its growth in the sector continues to be minor. Even though heating and cooling accounted for around half of total final energy demand, policy attention in this area is still lacking [17]. However, Argentina is among the countries that are imposing regulatory policies at national level to enhance energy utilization and efficiency for heating, air cooling and energy isolation in the sector of building in residential and also in public buildings [18,19].

A similar situation can be seen in the transport sector in terms of renewable energy penetration, except for the fact that electrification, the use of public transportation and penetration of biofuels are increasing in Argentina, where liquid biofuels as biodiesel dominate the renewables contribution [20].

In 2018, the global energy demand increased an estimated 2.3%, the greatest rise in a decade. This was due to strong global economic growth (3.7%) and to higher heating and cooling demand in some regions. China, the United States and India together accounted for almost 70% of the total increase in demand while Argentina accounted for 1% of the global demand [21]. In 2016, the main energy producers in the non-OECD Americas were Brazil, Venezuela, Colombia, Argentina, Trinidad and Tobago and Ecuador. Together, these countries produced 89% of the region's total energy production. Due to a rise in fossil fuel consumption, global energy related carbon dioxide (CO2) emissions grew an estimated 1.7% during the year. As of 2017, renewable energy accounted for an estimated 18.1% of total final energy consumption

(TFEC). Modern renewables supplied 10.6% of TFEC, with an estimated 4.4% growth in demand compared to 2016 [22].

Renewable energy. National program RenovAr

The sanction and enactment of Law 27.191, National Promotion Regime for the use of Renewable Energy Sources was carried out in 2015 [23]. The purpose of this law is to incorporate 20% of renewable electricity by the year 2025.134 projects - totalling 4700 MW with an investment exceeding 7 billion USD - were awarded up until the beginning of year 2019. The RenovAr program is based on bidding rounds, having completed rounds 1, 1.5 and 2 to date, which have received offers for 147 projects, most of which include wind energy, followed by solar-photovoltaic, small hydraulic uses, biomass, biogas, and landfill biogas [24]. To meet the goals of renewable generation by 2025, more than 15,000 MW of electric power should be installed, depending on the proportion which involves the five sectors mentioned and their corresponding load factors.

The electricity generation in the SADI (Argentine Interconnection System) amounts to approximately 130,000 GWh. In certain months, renewable generation has reached 3.1% of the total corresponding amount. For example, taking into account the month of September 2018, the following amounts were reached by using renewable energy sources [25]: Wind energy: 150 GWh - Small hydroelectric plants: 120 GWh - Biomass: 32 GWh - Biogas: 12.5 GWh - Solar-photovoltaic: 11.5 GWh.

RenovAr - Round 3–2019 is underway, corresponding to the so-called Mini Renewable, which seeks to add 400 MW of renewable energy in the regional electricity distribution systems. Each project can reach a power of up to 10 MW, which are injected into the low voltage power grid, from 13.2 to 33 kW. Regarding the Patagonian region, there is a power of only 30 MW for the provinces of Chubut and Santa Cruz, and also a small power – similar estimated value to the previous one - for the provinces of Rio Negro and Neuquén.

Seeking to increase a greater use of renewable energies, the government launched in 2018 the so-called MATER (a particular market with a specific regulation). This market was created with its own rules, since renewable energies, in all their phases and stages, have special characteristics that require a specific framework. The MATER's objective is to regulate a mechanism for the purchase of electric power, which allows the acquisition by free agreement between the parties, for the large users of the wholesale electricity market (MEM) with power demands equal to or greater than 300 kW.

Up until June 2019, MATER has added 44 electricity generation projects from renewable sources, with dispatch priority (grid electricity injection), which was assigned by CAMMESA (Argentinian Electricity Wholesale Market Company). This corresponds to 1080 MW of installed power that will be injected to the grid to supply energy to industries and businesses through private contracts [26]. For the second half of the year, the national government will launch a new bidding process - round 4 - which will include investments in high voltage electricity transmission infrastructure. To achieve a significant increase in electricity generation with direct injection to the SADI (Argentine Interconnection System), the construction of 5000 km of power lines is required. A map showing the high and medium voltage electrical system for the entire Argentine Republic appears in a figure following a link in the literature [27].

We found that enormous areas in the Patagonian region are not connected to the high-tension lines or are connected to weak ones [28]. A partial solution would be the installation of new lines of electrical transmission. However, a solution that could guarantee a firm, clean and safe electric service, in addition to having locally produced fuel - taking advantage of the high quality of renewable energies, especially wind power - is by means of hydrogen.

RenovAr Program (2016–2020), Solar-photovoltaic energy parks are located in the north-west of Argentina while Wind energy parks with powers up to 100 MW are located on the Atlantic border of Buenos Aires province as well as the Atlantic border of north and south Chubut and northern regions of Santa Cruz province [29].

The total amount of wind power which is possible to inject into the National Electric Grid – Patagonia - is only up to 1 GW. Unfortunately, nowadays this is a limited amount if we want to take advantage of the strong full wind potential available in South Patagonia. Fundamentally, due to the long distances and low regional consumption, it is necessary "to export" that energy to the centers where there is greater consumption, such as the central average regions of the country, especially Buenos Aires. Even in this case, the use of this abundant clean cheap energy can only be viable through mass storage and handling. This is only possible with hydrogen as carrier or energy vector. An increase in the use of wind energy in Patagonia - through the incorporation of new electric transmission lines - will contribute another minimum amount.

To map the projects that are operational, under construction or awarded in the auctions of the RenovAr Program, the National Government developed an interactive dynamic map that shows the geographical location of each of the projects [30].

The RenovAr program (in its bidding rounds 1, 1.5 and 2) awarded 147 projects in 21 provinces for a total of 4466.5 MW. Respectively, there are 41 solar projects, 34 wind projects, 18 of Biomass, 14 Small Hydroelectric Projects, 36 of Biogas and 4 of Landfill Biogas. The development of renewable energies in Argentina is a reality that transforms the way in which energy is generated and consumed, creating new markets and actors, with both economic, environmental and social benefits.

The success of the RenovAr Program and the boost experienced by MATER are clear examples of the national wealth in terms of energy resources, the strength and credibility of the regulatory framework and the potential contribution of renewable sources in the diversification of the energy matrix and the mitigation of climate change.

Another Law "Distributed Electricity Generation" has recently been approved (National Law number 27.424) and establishes the "Regime for the promotion of distributed generation of renewable energy integrated into the public electricity grid". The law declares of national interest the distributed generation of electrical energy from renewable energy sources for self-consumption and the injection of surplus electric power into the distribution network. The

Argentine Government published in November 2018 Decree 986/2018 that regulates the aforementioned national law allowing users to inject clean energy into the distribution network. The legal document categorizes the users-generators, establishes the technical requirements, the connection procedures, the aspects of billing and all the details for the operation of the new regime [31].

Variable power & energy demand. Argentine scenario

Natural gas variation for industry, utilities, commercial and residential, GNC for transportation

The graphs and trends presented in this section are based on public information provided by official entities [32–34]. and [35].

The monthly variation is greater between the summer and the end of autumn, close to 6000 MW, between January–February and April–May, and then it grows again significantly in the winter, reaching more than 5000 MW over the last years (Fig. 3).

In the case of natural gas (shown in Fig. 4), a similar situation occurs, with seasonal variation greater than 20 Million NM^3/day. In both cases, there is greater electricity demand which is mostly required by the utilities that employ natural gas. The residential use of air conditioning (cooling) and heating – currently generated mainly by natural gas - are also responsible for producing this behavior. During the last decade is observed, in Argentina, a constant increase of the use of natural gas for electricity generation reaching almost 40% of the consumption.

Towards the winter, the highest consumption - both electric and natural gas - is influenced by the heating sector while during summer the increased use of air conditioners is the main responsible of the peaks. These consumption characteristics show that, for a greater penetration of renewable energies in the energy matrix and, consequently, a reduction of greenhouse gases (GHG), a massive energy storage system is inevitably required together with high capacity power.

The analysis of the daily regular and peak demand - winter & summer season - shows a growing difference between the typical curve and the maximum demand due to the use of different electric appliances, especially electric heating.

Future trends for wind and solar energies

Considering the potential industrial growth following the promotion laws, and according to the Energy National Secretary, Renewable Energy Sub-Secretary, the country trends which involve renewables show an additional 20% of the total energy production for the year 2025. Data are presented in Tables 1 and 2.

Technically, to be able to directly inject and/or dispatch electric power, it is required to extend the high voltage transmission lines in a 5000-km range. This, in turn, requires a very significant economic investment.

The vast geography in Argentina, characterized by its strong winds, especially Patagonia Austral, is located between 1500 and 2500 km from the high consumption area, south-north, from Chubut & Santa Cruz to Buenos Aires. The west-east lines (north Patagonia) between Neuquén & Rio Negro and Buenos Aires range between 1200 and 1500 km. The system is fundamentally radial, which imposes restrictions regarding the stability of the electrical transmission system and its optimization with the use of the region's abundant wind energy.

To harmonize and to extend the use of renewable energies in Patagonia, a high-capacity energy storage system is

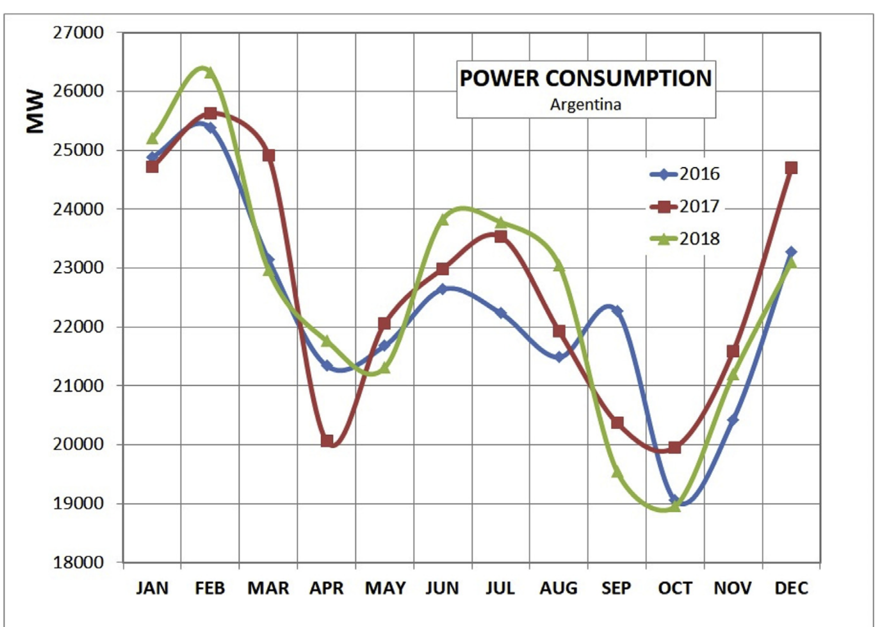

Fig. 3 – Power consumption - Argentina.

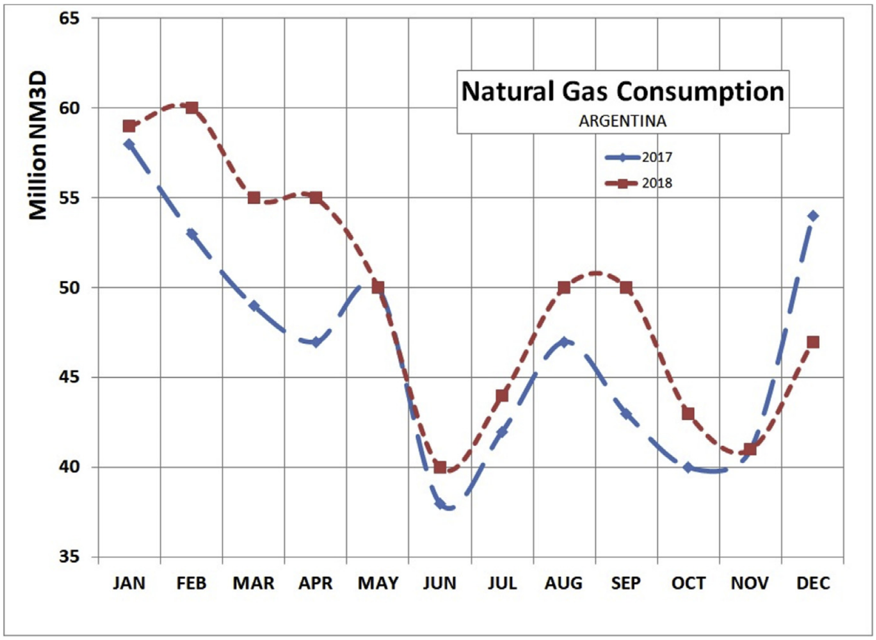

Fig. 4 — Natural gas consumption in Argentina.

required. This is hydrogen, which would allow to increase and maximize the use factor of the mentioned electrical networks, while establishing another link from its source to the high consumption cities, Rio de la Plata region, either transporting hydrogen by pipeline, or by sea taking advantage of the nearby areas adjacent to the Atlantic Ocean.

Table 2 shows the participation of renewable sources – 20% of the total Argentine electricity projected for 2025. These would involve 60% wind; 30% solar; 10% small hydro & biomass & biogas. As indicated in Table 1 TWh of annual electric energy should be reached. The set adds a total power ranging 10,000 MW.

Table 1 – Future trends for renewable energies - These include: wind, solar, small hydro, biomass and biogas.

Total electric energy trends in Argentina
Share of renewable energy in percentages and in TWh

Year	Total Projected Electricity Demand	Percentage	Share of Renewable Energy
2019	135	12%	16.2
2021	143	16%	23.0
2023	149	18%	26.8
2025	155	20%	31.0

Source: Argentina Energy National Secretary

Requirements for massive energy storage

Rechargeable batteries

Lithium-ion batteries will help to increase renewable installations applied to stationary and mobility. However, 0.3 kg of lithium is required for each kWh of battery electricity storage, which is rather a small range capacity [36].

The use of battery energy storage systems (BESS) for large-scale is increasing but it certainly has many restrictions and challenges despite the cost and lifetime and, of course, it depends on lithium availability. Let us examine some figures:

The global production of lithium in year 2015 was 37,000 tons/year. Projection for year 2030 is 80,000 tons/year. In addition, the global demand for lithium metal is projected to rise 9% per year through 2019, to 49,500 metric tons.

Some other applications also need part of the lithium reserves due to the growing demand. In fact, lithium can be

Table 2 – Participation of renewable sources to meet the goal of 20% electricity generation by the year 2025.

Total electric energy trends in Argentina (TWh)
Share of renewable energy in percentages and in TWh

Source	Percentage	Electric Energy	Average Load Factor	Power
	%	Total: 31 TWh		MW
Wind	60%	18.6	40	5251
Solar	30%	9.3	25	4246
Small hydro/biomass/biogas	10%	3.1	60	589

Source: Argentina Energy National Secretary alloyed with aluminum, copper, manganese, and cadmium to make high-performance alloys for aircraft.

Available for batteries (2030): 60,000 tons/year.

Equivalent to store: 200,000 MWh.

Electricity/Emissions – Argentina (0.7% world level – potentially 1400 MWh storage capacity added per year).

Ten-year durability implies a maximum estimated of 14,000 MWh, which is equivalent to 1-h energy storage of Argentine SIN (National Interconnected System for Electricity).

The integration of large-scale battery storage of renewable energy for the electric grid is a growing alternative technology, but it is certainly not the solution to massive energy storage today.

Water dams & water pumping

A larger-scale storage system constitutes water dams
A quantitative analysis was carried out to evaluate the energy storage capacity of Comahue Hydro Electricity dams, which include water reservoirs such as El Chocon, Piedra del Aguila, Alicurá, Barrales and Planicie Banderita. These represent a possible 4-6-day storage capacity of electric current required in the Argentine networking system (See Fig. 5).

Potential energy by water dams storage
The analysis we conducted is based on the main dams in terms of energy accumulation. The main characteristics of the dams and final results of energy accumulation are presented in Table 3.

TOTAL: 533 * 10 exp 12 kgf-m = 1450 GW- hour.

The average power for Argentina SIN is 15,000 MW.

The total energy storage is equivalent to almost 100 h or 4 days of electricity in SIN Argentina.

Analyzing the results, it can be observed that the accumulation is important but it is only for four days, which leads to the consideration of hydrogen for large-scale storage system.

Hydrogen

The production of hydrogen by renewable energies to store and distribute massive quantities of energy seems to be the best transition way for a greener and sustainable future. Moreover, solar-driven water splitting is an additional visionary strategy if we consider the artificial photosynthesis to generate bio hydrogen.

Hydrogen developments accomplished. Argentine pilot projects

Pico Truncado

The Pico Truncado hydrogen experimental plant includes two installed electrolyzers - the first one provided by the Hydrogen Laboratory of the University of Quebec A Trois Rivieres, with the capacity to produce 1 Nm^3 of hydrogen per hour. The plant

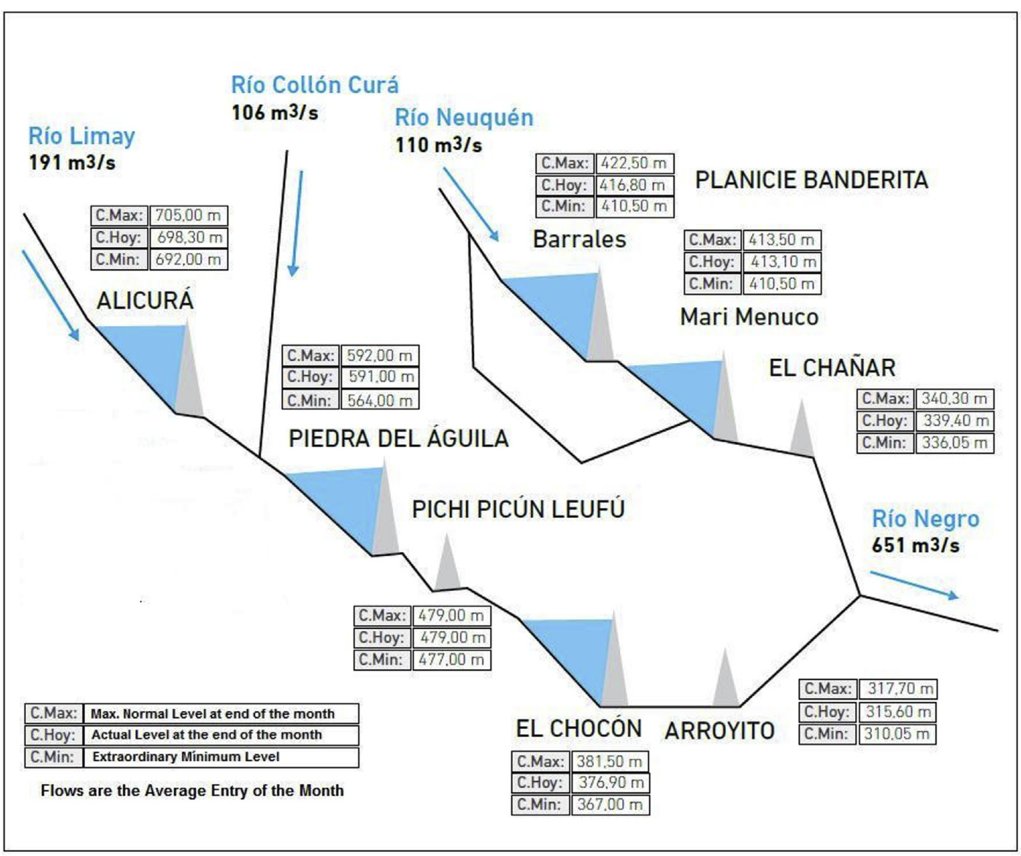

Fig. 5 – Comahue hydro electricity dams level map. - Credits from CAMMESA (Argentinian Electricity Wholesale Market Company)

Table 3 – Comahue hydro electricity data.

Characteristics of Comahue Hydro Electricity main dams					
Comahue Dam	Measurement (m) Max/min	Power (MW)	Dam Capacity (hm^3)	Height (m)	Available Energy Accumulation (kgf-m x 10exp12)
Alicura	705.00 692.00	1000	3215	135	43
Piedra del Aguila	592.00 564.00	1400	12,400	172	213
El Chocón	381.50 367.00	1200	20,600	86	177
Barrales	422.50 410.50	450	28,162	35.50	100

Only main reservoirs are considered for the analysis

has been operative since 2005 to gain experience and to perform laboratory tests with hydrogen produced on site [37]. The second electrolyzer was built in Argentina under an agreement with the Technological Institute of Buenos Aires (ITBA) from 2011 to 2013. With the prospect of increasing hydrogen production capacity and experimenting with larger equipment, a more powerful electrolyzer was acquired from a Swiss company and installed in 2014. The experimental plant also consists of a laboratory room where small-scale experiments have been carried out in the fields of hydrogen hydrides, catalytic burners, ovens for domestic use, small fuel cells, etc. Another experimental area is intended for the preparation of internal combustion engines to work with hydrogen or mixtures with natural gas (H2CNG). Other facilities within the premises include a classroom, offices, a library and administrative services in order to provide education on subjects related with hydrogen and renewable energies. There are also facilities for fueling road vehicles that work with hydrogen or with gas mix - natural gas plus H2 at 20% concentration. Figs. 6 and 7 respectively show a general view of the facilities and the fuelling station with the compressor's area.

This demonstration station allowed Argentina to appear on the map of southern hemisphere hydrogen service stations for the first time in 2005. The gas compressors for hydrogen and blends were developed and also built in Argentina. The cooling water integrates a subsystem of hot water up to 80° Celsius that, by means of heat exchangers, dissipate and provide adequate and controlled environmental conditions in installed greenhouse floors to achieve synergy and more efficient use of energy, greater exergy [38]. This translates into the production of fresh food that, together with the management of controlled salinity water, allows greater productivity in greenhouses, the availability of water, and the possibility of obtaining clean fuel through hydrogen. This is an initial model that we believe is very convenient to apply in different places, especially in areas of low population density, so that each community produces these basic elements for life: clean energy, fresh food and drinking water. In Patagonia, thanks to the strong winds, and in the extensive semi-arid zones south, center and north of the country, similar kinds of facilities can be installed to enhance the living standard.

MAEL

The module known as "MAEL" (Argentine module of clean energy) is one of the products conceived at the experimental hydrogen plant of Pico Truncado, Santa Cruz Province, and installed at the Esperanza Research Station, Antarctica, in December 2008. It forms an integral energy chain from the Wind Park, water electrolyzer, oxygen and hydrogen storage system and final applications such as laboratory fuel cells, generator set, welding machine, cooker and ovens [39]. The general goal for the station was to reduce 50% of the fossil fuel consumption of the research station over a 15-year period.

Fig. 6 – General view of the facilities at the Pico Truncado Plant.

Fig. 7 – Fuelling station at the Pico Truncado plant.

All the components of the MAEL project were first presented in partnership in April 2008, then tested in the laboratories at the Pico Truncado Experimental Plant and finally transferred for permanent use to the National Directorate of the Antarctic (DNA) in December 2008.

The electrolyzer designed by ITBA produces by electrolytic decomposition of water up to 0.7 Nm^3/h of hydrogen and 0.35 Nm^3/h of oxygen gas at a maximum pressure of 30 Bar. The gases produced are conducted through stainless steel lines out of the module to feed the storage tanks. These buffers are comprised of a battery of several hydrogen cylinders while the oxygen is sent to the storage cylinders located in a separated area. Fig. 8 shows the MAEL during summer.

Hydrogen developments in progress

Hychico

The Diadema Wind Park, comprising seven 0.9-MW Enercon E–44 wind turbines and a total installed capacity of 6.3 MW, is located approximately 20 km (12.43 miles) northwest of Comodoro Rivadavia City, Chubut Province, Argentina (Fig. 9). The hydrogen plant, which was commissioned in December 2008 has two electrolyzers with a total capacity of 120 Nm3/h of hydrogen and 60 Nm3/h of oxygen. The capacity factor, that is the ratio of the actual energy generated in a given period and the theoretical energy that could be generated running full time at rated power, was 54.9% net for the Hychico Wind Park during the year 2017 [40].

Underground hydrogen storage: Storing large quantities of hydrogen is one of the critical aspects of integrating hydrogen into the energy matrix and developing a hydrogen economy. Given the proximity of the hydrogen plant to some depleted oil and gas reservoirs, the possibility of underground hydrogen storage in one of them was put under consideration as a pilot project in 2010. Such a Pilot Project intends to test the reservoir's capacity, tightness and behavior to acquire experience in hydrogen storage. The main results and perspectives can be consulted in literature [41]. A possible application is to use a mix of hydrogen and natural gas as fuel to feed equipment between 10 and 30 MW and supply electric power to the

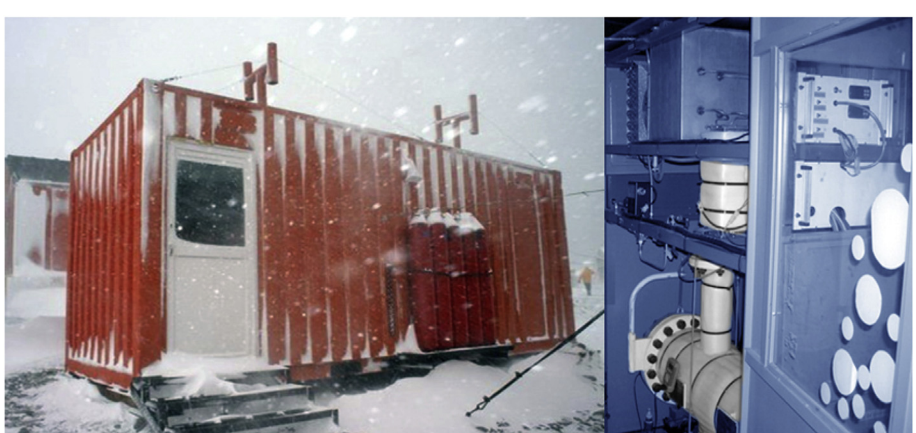

Fig. 8 – MAEL during Antarctic summer.

Fig. 9 – Hychico wind park & hydrogen plant.

Wholesale Electricity Market at times of peak demand. The pilot test is devised in stages involving cycles of natural gas and hydrogen injection and production at different pressures and concentrations. Fig. 10 shows the surface layout of the facilities. Hychico's long-term goal is to provide future regional and international markets with "green hydrogen", produced from Renewable Energies, and also with "green methane", by using hydrogen as raw material and a sustainable source of carbon dioxide [42].

Feasible local & regional hydrogen applications in Patagonia. Distributed Energy management, firm electricity and renewable hydrogen

POWER to POWER and HEAT, POWER to MOBILITY, POWER to INDUSTRY

The large territories and low populated regions in Patagonia are crossed by strong – almost permanent - winds which could produce all the energy that inhabitants consume and, progressively, by means of hydrogen, increasing that production capacity and by moving to areas in Argentina with high population density as it happens in Buenos Aires and Rio de la Plata. This infrastructure would pave the way to the start of exportation to countries such as Japan or eventually the European Union by 2030.

As we can observe on the map showing high voltage power grids and gas pipelines in Patagonia (Figs. 11 and 12), they only interconnect a small strip of that region. In the SADI (Argentine Interconnection System) the electric network has a maximum capacity of 1 GW. Its expansion could increase in a similar capacity. However, the high quality wind resource would allow the installation of wind farms with power ranging several hundred GW. This would only be profitable taking advantage of the low cost of the electricity that can be obtained and, consequently, of the abundant green hydrogen at a very competitive cost.

We are thinking of an "energy model" with parks to be installed in each city, town or village, or also in the nearby regions of a wind farm, looking for human settlements that could have firm electricity available by means of hydrogen.

The remarkable thing is that, if we think of each wind farm, not only in the case of Power-to-Power, a part of the electric generation would be injected into networks of high, medium and low voltage in the distribution sector, with an important fraction that would also be destined to the production of electrolytic hydrogen with its corresponding storage system. This, where geology allows it, could be done as underground storage, for example, in depleted oil and gas reservoirs and would require a compression process [41,43,44]. In the case of the Power-to-Power, an important heat release occurs in a local environment by means of fuel cells or reciprocating engines and/or hydrogen gas turbines.

This "energy model" became a project which began at the Hydrogen Experimental Plant in Pico Truncado, taking into account that 20%–30% of energy in the form of heat is lost in the electrolyzer, 10% is lost in the compression of hydrogen, 50% in the case of the fuel cells and, in engines or turbines, depending on the power, between 50% and 70% of energy is

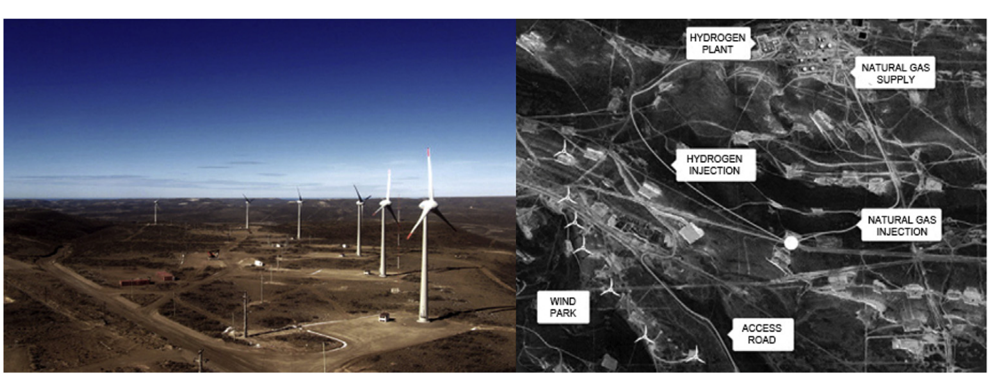

Fig. 10 – Surface layout of Hychico Plant.

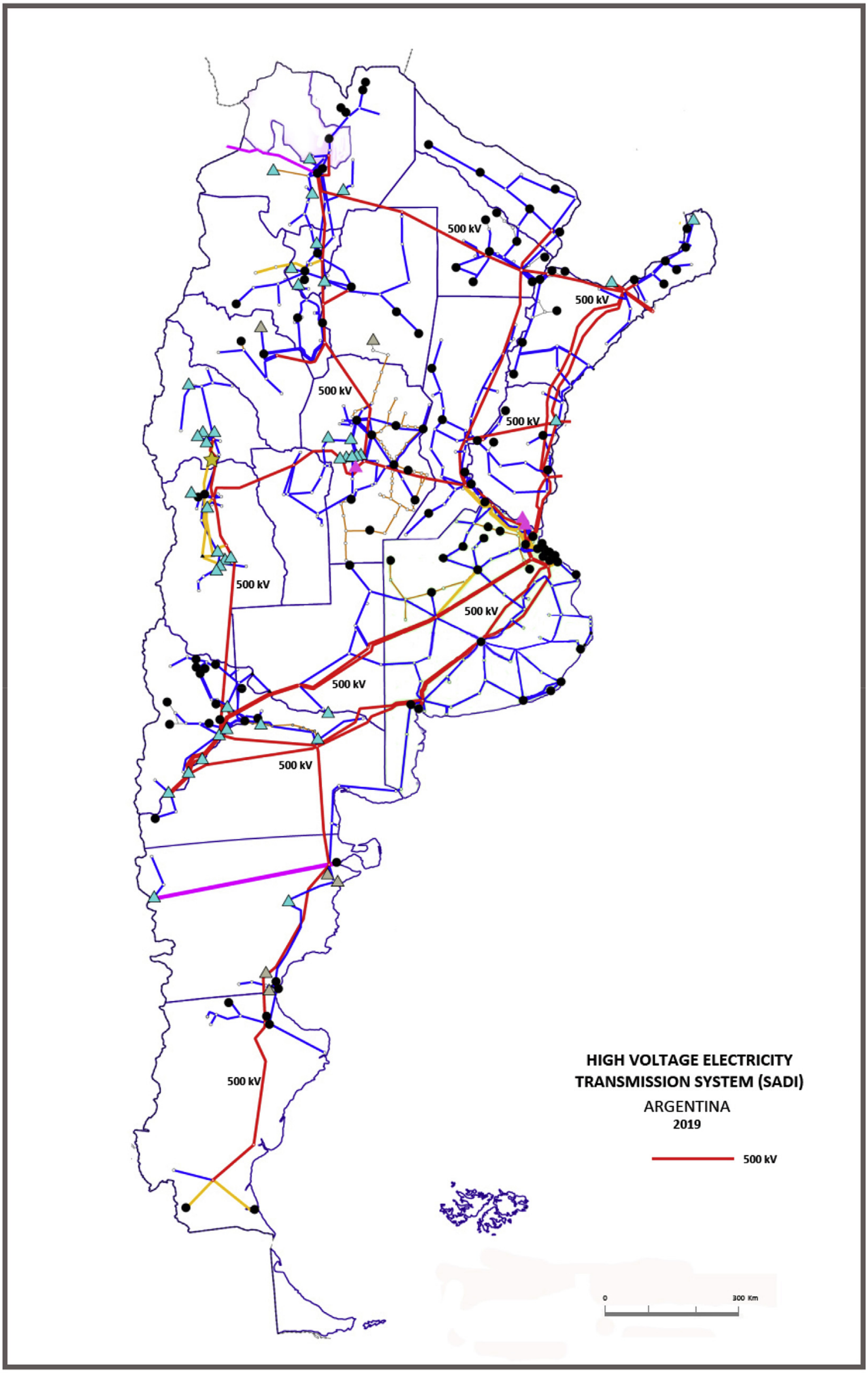

Fig. 11 – High voltage power grids Map of Argentina.

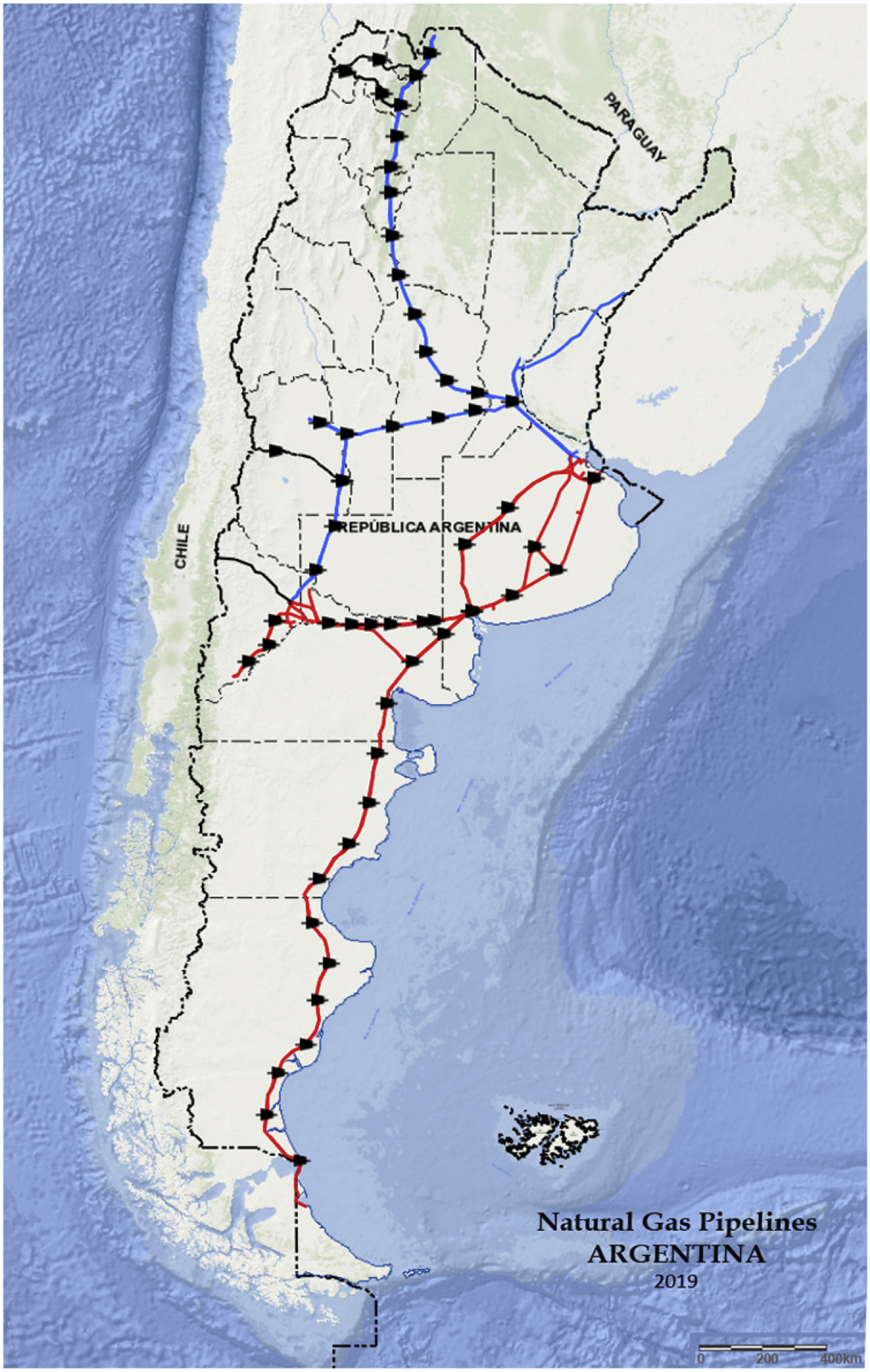

Fig. 12 – Main natural gas pipelines in Argentina.

lost in the form of low temperature heat. These heat flows can easily be collected in the form of hot water, which - to a large extent - can be used in residential/domestic uses, including heating. An important fraction of this energy could be used for the production of fresh food in different greenhouses. As a reference value, regarding heating, an improvement in exergy and energy efficiency could be attained.

For a 10 GW wind electricity Power-to-Power, we estimate that one third of the energy could be converted into heat. For a load factor of 40% (electrolysis and compression) and 90% for electricity reconversion, minus small amounts of energy loss, a total of 30 GWh per day could be converted into hot water with temperatures lower than 100 Celsius degrees. The average heat required for one typical household is 60 kWh/day. This results in the fact that half a million houses could be heated if we took an average of 4 inhabitants per household. Thus, roughly speaking, we can estimate that two million people can get this service. This correlates with the current number of inhabitants in Patagonia and is in agreement with the proposal REN 21, concerning the relevant participation of heating and cooling in the energy matrix [18].

Another application could be Power-to-Mobility. Nowadays, we have witnessed a rapid development of fuel cell trains and buses [45]. A few railways have been installed from the Andes mountain Range to the Atlantic border. For example, connecting Bariloche to Viedma, with a length of 820 km. A remarkable influx of both local and international tourists - around a million per year - arrive in the "seven lake's area", Bariloche and its surrounding areas, many of whom could do so on a comfortable sustainable train trip in order to visit this wonderful region and to admire the magnificence of north Patagonia, reaching the area adjacent to Chile, of equally majestic beauty. Another line in the center of Patagonia connects Comodoro Rivadavia, Diadema and Colonia Sarmiento - and another one is located between Puerto Deseado, Pico Truncado and Las Heras. Towards the south end, another railway is located between Río Turbio and Rio Gallegos, close to the Magallanes strait and, there, another train running across the neighboring Ushuaia, Tierra del Fuego. In some cases, hydrogen could re-start the train services that are currently out of order: for example, the ones covering the extreme south and mid-Patagonia and, those running periodically - employing diesel - could be replaced by hydrogen fuel-cell trains. The production and loading of hydrogen could be carried out in the towns that are established near the railways.

By having many production settings and hydrogen loading capacity, the loading of the mentioned means of transport would be facilitated in the medium term. The same could be applied to cars that run on hydrogen. In locations near the coast, we consider it important to develop projects to apply hydrogen in maritime uses also in the medium-term, such as cargo transport from Patagonian ports to Rio de la Plata, covering distances from 1000 to 3000 km, e.g. from San Antonio Oeste in Rio Negro to Ushuaia in Tierra del Fuego. As well as this, promoting and making the fishing industry more competitive would contribute significantly to the environment and sustainable human development.

Another application is Power-to-Industry. Mining has become an activity of great interest to many people in Patagonia, with most of the deposits located far from the crowded centers. Currently, diesel fuel is being used or, in some cases, liquefied natural gas, LNG, or liquefied petroleum gas (LPG). Hydrogen local production and substitution could provide more security when supplying, and would in turn improve the environmental equation.

Among other considerations and benefits regarding the handling of hydrogen, having the electrical networks as a complementary aid, makes the transportation by pipeline a safer procedure, especially in winter time, with less visual impact of the overhead electrical lines. All the above mentioned factors would undoubtedly improve the quality of life and sustainable human development in Patagonia.

However it's important to note that some disadvantages and/or barrier to the proposed hydrogen economy should be eliminated. In that sense, to remove or mitigate barriers to the commercialization of hydrogen energy, especially for promotion of new technologies and taxation, an important effort is made at federal level to have the pieces of legislation needed to help for that purpose. Moreover, it was identified by the action of the Argentine Hydrogen Association that continuous education outreach is the main tool to deal positively with social acceptation and sustainability values. Additionally government action is needed to overcome high infrastructure barriers. Finally, the task of standardization at local level (IRAM Argentine Standardization Institute) and international (ISO/TC 197) are important factors to overcome safety and regulatory issues.

Other options

Considering that in some places of Patagonia there exist huge deposits of lignite, a synergistic Hydrogen production approach could be done employing the oxygen coming out from the electrolysis of the Wind-Water process [46]. Partial oxidation in situ avoids conventional mining, giving a cleaner supply of Hydrogen from coal [47]. However the greenhouse gases emissions should be evaluated. Additionally, the coal deposits in Rio Turbio, extreme west south, are far away (about 800–1000 Kilometers) of the places in mid Patagonia which are considered for the first large scale wind-hydrogen installations, north of Santa Cruz and south of Chubut provinces.

Another synergy could occur with biomass combined with electrolytic hydrogen and oxygen. However, the biomass of the native flora in Patagonia is scarce. Because biodiversity would be limited by the extraction of this biomass for energy purposes, this option is not considered within the scope of this article. In the same way, agricultural developments are not analyzed due to the great fragility of the ecosystems. Only locally restricted areas could be considered in other studies.

Power to ammonia - Arroyito P2A

The ammonia molecule has about twice the energy density by volume as liquid hydrogen and, for that reason, it is a firm candidate to play the role of hydrogen storage chemical and, therefore, an energy storage media in the near future. Moreover, it is easier to ship and distribute in many ways.

In Patagonia, another interesting possibility that we analyze here - to store renewable energies produced by wind power - is to convert power to ammonia in order to make a hydrogen storing compound by combining electrolytic hydrogen from water and nitrogen separated from air. Then, ammonia can be stored as gas or as liquid in tanks, and their molecules can be converted back into electricity when burned in a turbine according to demand or dissociated by catalytic cracking into nitrogen and hydrogen again. Finally, the hydrogen vector can be used directly, for instance, in hydrogen fuel cells to power road vehicles or in stationary fuel cells to close the cycle. In Arroyito, Neuquén Province, there is a facility that still applies the Haber-Bosch process to produce ammonia that is used as an isotope carrier in a heavy water plant (Arroyito HWP). The reactors that support the reaction to combine hydrogen with nitrogen to make ammonia efficiently can be converted to be fed with renewable hydrogen instead of natural gas. Therefore, if wind turbines are installed in combination with water electrolyzers, the process can be turned into a new green ally so as to cut dramatically the total CO_2 emissions from the entire process when it is compared with the classical option which uses steam reforming.

The industrial plant in the town of Arroyito has two large-scale synthesis loops for the manufacture of 4000 tons per day (TPD) of ammonia. Fig. 13 shows the synthesis loops containing radial flow ammonia converters rated at 2150 TPD each, making these one of the largest in the world. The "key" of this conversion technology lies in taking advantage of the installed capacity for the production of ammonia from the Arroyito HWP by opening its loops to the injection of hydrogen gas generated in new electrolyzer units and then processing

Fig. 13 – Ammonia loops at Arroyito HWP.

that ammonia for the production of "green urea" in an international-scale industrial plant (until 1 million annual tons capacity) or using "green ammonia" as an energy carrier as it was mentioned before. This means that the conversion of one production line is carried out first and then, according to the convenience, the second line could be converted. Some more research and economic analysis is needed to move forward.

Potential energy trading link between Patagonia and Japan based on CO2 free hydrogen

The idea of exporting Wind-Hydrogen at a large scale from Patagonia was introduced by Prof. Veziroglu, Ing. Magallanes and Ing. Spinadel in the 90s, discussed in several conferences during the 12th WHEC 98, Buenos Aires, Argentina [48,49] and presented at the 2004 Bonn Renewable Energy Conference by Mr. Enrique Goetz from Capsa-Capex, mother company of Hychico, Argentine Energy Company [50].

In 2003 a collaboration document was signed by HESS – Hydrogen Energy Systems Society from Japan - and AAH – Asociación Argentina del Hidrógeno. They started with the careful evaluation of Patagonian wind resources employing high altitude towers with cup anemometers and ultrasonic equipment to measure the wind characteristics. Initially, this work started at the Hydrogen Experimental Plant in Pico Truncado, and currently continues together with Hychico in Diadema, Comodoro Rivadavia [51]. Continuous evaluation of data is being performed and some previous evaluation concerning technical and economic assessments were presented by Ken-Ichiro Ota in the meeting of the Partnership for Advancing the Transition to Hydrogen (PATH) celebrated during the 19th WHEC in Toronto (2012), [52].

More recently (May 2019) D. Stolten et al. published a "Techno-economic analysis of a potential energy trading link between Patagonia and Japan based on CO2 free hydrogen".

"Our analysis reveals that approximately 25% of the total land area in Patagonia would be eligible. Approx. 33,000 turbines with a minimum number of 4500 full-load hours with an overall capacity of about 115 GW can be positioned. Taking into consideration the related average number of 4750 full-load hours and an electrolysis efficiency of 0.7, this leads to a potential production of about 11.5 million tons/year of hydrogen. So the wind power potential of Patagonia would theoretically be sufficient for the assumed Japanese hydrogen demand of 8.83 million tons/year. The total hydrogen pretax cost would amount to approx. 4.40 €/kg_{H2} at a liquid state at the harbor of Yokohama. Hence, the final specific costs of hydrogen in Japan depend on the expansion of wind power in Patagonia and therefore hydrogen based on wind energy can be cost-competitive to conventional fuels" [53].

"Taking into account the processes such as electrolysis, compression and pipeline transportation, a cost for in situ, inland or close to the Hydrogen production plant would be ranging 2.20–2.74 €/kg of Hydrogen (see Figs. 14 and 15) where LCOH is defined as the levelized cost of hydrogen."

A sensitivity or range cost analysis, according to our experience in Argentina, info from hydrogen equipment suppliers and literature, indicates that as a first approximation it is concluded that:

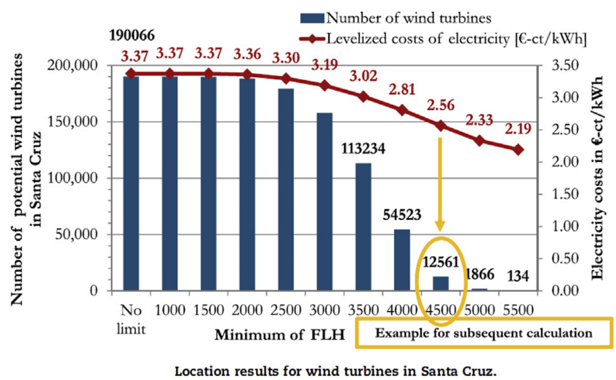

Fig. 14 – Location results for wind turbines in Santa Cruz. Credits from the original Fig. 6 - IJHE paper by Detlef Stolten et al.

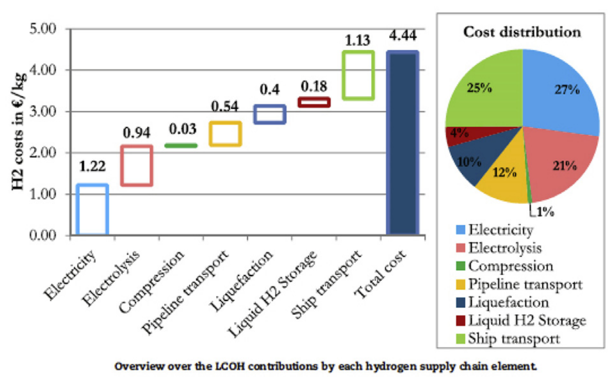

Fig. 15 – Overview over the LCOH contributions by each hydrogen supply chain element. Credits from the original Fig. 7 - IJHE paper by Detlef Stolten et al.

- Electricity proportionally represents the largest component in the total in situ costs.

Wind electricity cost could range, for large wind parks in Patagonia, between 20 and 30 €/MWh and 50 kWh are required to produce one Kg H_2 from electrolysis. This gives a cost between 1.0 and 1.5 €/KgH_2, which are in the range of Stolten results.

- Compression of Hydrogen, between 20 and 200 bar, requires 2 to 4 kWh which will add (0.04–0.08) €/KgH_2 for the lower electricity cost to (0.06–0.12) €/Kg H_2 for the higher cost. These results are higher than those reported by Stolten.
- Electrolysis amortization, 20 years, for CAPEX (capital expenditures) ranging (0.6–1.2) x 10^6 €/MW, load plant factor of 50% in Patagonia and OPEX (operating expenditures) of 5% results in (0.6–1.2) €/Kg H_2, which is in agreement with Stolten.
- Concerning piping, we assume for the first stage of wind-Hydrogen large production facilities, to be located close to the Atlantic ports. A hydrogen pipeline transmission system in a 2000 Km^2 area for the transportation of 360 TonsH_2/hour is a complex net that would require a CAPEX estimated in 6000 million €. Standard local cost for Natural Gas pipelines, as a reference, is estimated at 45 €/inch-Kilometer.

Together with underground hydrogen storage, buffer, which will allow a continuous interconnecting H2 pumping net, its conditioning facilities to produce Liquid Hydrogen (LH2), Ammonia (NH3) or Liquid Organic Hydrogen Carriers (LOHC) will operate during 8000 h/year. The infrastructure amortization and operation would imply a cost between (0.3–0.4) €/Kg H_2.

The costs for liquefaction process or other storage concepts like NH3 or LOHC, as well as their respective storage facilities and ship transportation technologies are a matter for future analysis.

For overseas trading it would be necessary to include hydrogen liquefaction, liquid hydrogen storage, and ship transportation. Projecting Japan as a possible first market, a distance across the Atlantic ocean is of about 21,000 Kilometers, Comodoro Rivadavia-Yokoyama ports, and could be transported during 27 days. However, an alternative to making this H2 from Patagonia to Japan cheaper and more competitive would be the exportation through Chile in the Pacific Ocean. From the port of Puerto Aysen, the distance would be reduced to 17,000 km.

It is Japan's goal to reduce CO2 emissions by 26% by the year 2030. To do so, the Japanese government strives for an emission free H2 society, for which H2 will be the primary energy medium. The estimated H2 market for Japan is of 11.5 millon tons/year of hydrogen [54].

In the case of taking the European market as another possible demand scenario, the distance to Rotterdam port is of 13,000 km from Comodoro Rivadavia in Chubut province.

Some other studies presented interesting data based on different method of production [55] and sustainable options [56] to produce hydrogen, including economic analysis of grid connected water electrolysis systems [57,58].

Patagonia, lying in the southern extreme hemisphere, between the Atlantic and Pacific Oceans, will constitute an outstanding link towards "The hydrogen civilization" [1,2]. It will also be necessary to deeply impact on "The second solar civilization" (C. J. Winter 2000) [59], to move towards a truly sustainable human natural way of living, and "To live in harmony with nature and to accept each other" as stated many times by T. K. Bose, WHEC 1998 held in Buenos Aires, Montreal 2002 in Canada, at the 2007 WHTC in Montecatini Terme, Italy and in Yokohama during the 15th WHEC [60,61].

Conclusions

1. It is high time for us to establish the use of hydrogen in Patagonia, managing the maintenance of a pristine environment and improving the quality of life of its inhabitants.
2. It is high time we accelerated the process and our involvement in more work on Renewable Energies & Hydrogen in Patagonia, with the vision of exporting hydrogen in the medium and long term.
3. It is time to develop mass storage and transportation systems in Argentina that allow the use of wind energy from Patagonia in highly populated areas such as Buenos Aires capital city as well as other adjacent regions on the

Rio de la Plata, taking advantage of the maritime transport and/or employing the natural gas pipelines.

4. We need to comply with the statements in the cited documents of the United Nations Program for Sustainable Development, the G20 Governmental Organization, the three religious messages (2015) stated in the Encyclical Laudato Si' from Pope Francisco; the Islamic Declaration on global Climate change; The Rabbinic Letter on the Climate Change, in order to establish a true Hydrogen Civilization (this latter idea introduced by Prof. T. N. Veziroglu).
5. We need to promote and allow the full use of renewable energies, removing "the roof" for its development, only considering electrical networks, "looking up at the sky" and betting on hydrogen.
6. We must establish intelligent, efficient networks that encourage the responsible use of energy, taking advantage of the maximum capacity of renewable energies and applying them to any sector in demand and energy services.
7. With a large-scale industry devoted to the production of hydrogen, we should aim at achieving very competitive costs: from electricity at 26 €/MWh or less, from the wind in Patagonia to hydrogen local cost of 2.6 €/kg or less and, regarding exportation, 4.35 €/kg or less, taking Japan as an example destination.
8. Experiences gained in Argentina along with international collaboration will allow us to take advantage of and manage large volumes of clean energy, always respecting the environment.
9. The development of technologies for massive hydrogen storage – e.g. underground storage – will allow us to have a strategic reserve to address the variable need in sectors such as electricity generation, and especially in heating and cooling applications.
10. From the wind energy and its transformation into hydrogen, we should take advantage of the process transformation heat – e.g. electrolysis, compression and electricity reconversion by means of fuel cells or by combustion, to pick up the released heat as hot water, to be partially stored and used for domestic purposes, heating and in greenhouses in Patagonia.
11. We must improve the local economy, promoting social inclusion and providing sustainable jobs.
12. We should be able to integrate the synergy of wind parks for firm energy management - close to each village, town and city within Patagonia - by means of electricity and hydrogen, extended to the local production of fresh food in greenhouses, and to the consumption of potable water for both human and animal uses as well as for irrigation.

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