Industrial development for the energy transition in latin america: Lessons learned from wind energy for green hydrogen in Argentina

Desarrollo industrial para la transición energética en américa latina: lecciones aprendidas de la energía eólica al hidrógeno verde en Argentina

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Resumen

La transición energética se ha consolidado como una tendencia global, exigiendo una profunda transformación de la matriz energética a través de la eliminación progresiva de los combustibles fósiles y la incorporación de diversas tecnologías para la generación de energía a partir de fuentes renovables. Este trabajo analiza los procesos de aprendizaje tecnológico e innovación observados durante el surgimiento y la consolidación de la industria eólica en Argentina, con el objetivo de desarrollar hipótesis sobre la interacción entre la demanda y el ciclo tecnológico en el impulso de la innovación en tecnologías de energías renovables, como la industria del hidrógeno verde, en países periféricos. A partir de una metodología de estudio de caso, nuestro análisis sugiere que las empresas basadas en la explotación de recursos naturales podrían no ser tan cruciales en el proceso de aprendizaje tecnológico, especialmente durante la fase inicial del ciclo. En cambio, los proveedores intensivos en conocimiento desempeñan un papel más relevante en el proceso de innovación que rodea la transformación de los recursos naturales vinculados a la energía. No obstante, persisten interrogantes sobre la especificidad de los recursos naturales energéticos y su potencial para generar oportunidades para el desarrollo de redes de conocimiento locales.

PALABRAS CLAVE: Energía eólica, hidrógeno verde, ciclo tecnológico, innovación, desarrollo industrial

Abstract

The energy transition has emerged as a global trend, requiring a profound transformation of the energy matrix by gradually eliminating fossil fuels and incorporating diverse technologies for power generation from renewable sources. This paper delves into the technological learning and innovation processes observed during Argentina's wind industry emergence and consolidation to develop hypotheses about the interplay between demand and the technological cycle in driving innovation around renewable energy technologies, for example the green hydrogen industry, in peripheral countries. Based on a case study methodology, our analysis suggests that natural resource-based firms may not be as critical in the technological learning process, particularly during the emergence phase of the cycle. Instead, knowledge-intensive suppliers play a more significant role in the innovation process surrounding the transformation of energy-related natural resources. However, questions remain regarding the specificity of energy-related natural resources and their potential to create opportunities for the emergence of local knowledge networks.

KEYWORDS: Wind energy, green hydrogen, Technological cycle, innovation, industrial development.

1. INTRODUCTION

For some decades now, the energy transition has emerged as a global trend that demands an active strategy from States to transform the challenges of this process into opportunities for industrial development in emerging countries. This trend requires a profound transformation of the energy matrix, which implies the gradual elimination of fossil fuels (United Nations, 2023) and the incorporation of diverse technologies for energy generation from renewable sources. These technologies are in different stages of development and, even though their adoption and diffusion may enhance the comparative advantages of the energy sector, their impact on the technological dynamism of its associated industries is unclear. For example, wind energy has a high penetration rate in South American energy markets (IRENA, 2023a) and its diffusion, within an appropriate institutional and economic framework, has facilitated the installation of factories for blade production in Brazil and tower production in Argentina. At the same time, green hydrogen is in a phase of feedback between technological development and demonstration on a global scale. Still, countries in the region continue to outline their institutional frameworks without achieving significant technological advances, except in Chile where the country's first hydrogen fuel cell vehicle was homologated (OLADE, 2023).

In the last decade, within the framework of neo-Schumpeterian and Evolutionary theories, various academic studies have suggested that the processes of learning and innovation around industries based on the exploitation of natural resources, such as those dedicated to the generation of renewable energy (RE), are relevant for economic development. These works highlight the role that natural resource-based industries have in the technological dynamism of the network of actors that supplies them with equipment, services, and knowledge and their economic and technological relevance in South American economies. However, they also point out that there are conditions that enable these processes, which are expressed in the demand configuration, the industrial organization, the technology cycle, and the institutional context (Andersen, Marín, & Simensen, 2018; Crespi, Katz, & Olivari, 2018; Katz & Pietrobelli, 2018). This work focuses on how the demand configuration and the technology cycle of the wind energy industry, in general, may have influenced the learning and innovation processes of this industry in Argentina over the past two decades. By distilling lessons from this context, we gain insights into the current opportunities and challenges for the emerging green hydrogen sector in leveraging economic development.

2. DEMAND AND TECHNOLOGICAL LIFE CYCLES: EVIDENCE FROM WIND ENERGY FOR GREEN HYDROGEN

Over the past two decades, the renewable energy industry has witnessed two significant trends: i) a scale expansion in response to countries' efforts to achieve energy security and more sustainable economic growth, and ii) increased internationalization resulting from the export of energy technologies (Kim & Kim, 2015). A prime example of these trends is China's entry into the global renewable energy market through manufacturing equipment for wind power and solar photo voltaic energy (Gandenberger & Strauch, 2018; Kim & Kim, 2015). The promotion of national wind power demand and its role as a catalyst for competitive technology development, primarily in terms of price rather than quality, explains China's active participation in the global energy market (Lin & Chen, 2019; Gandenberger & Strauch, 2018).

However, the empirical evidence regarding the impact of demand–pull policies on the development of energy technologies remains inconclusive (see review by Lin and Chen (2019)). This ambiguity may be attributed to the varying degrees of maturity reached by different energy technologies. In their comparative study of wind power and solar photovoltaic, Kim and Kim (2015) found evidence supporting a positive bidirectional relationship between domestic R&D investment and technology export. Notably, these results were more pronounced in wind power compared to solar photovoltaic, with the latter being considered a more mature technology.

These findings about the role of demand concerning the maturity of technologies have led to the Technological Life Cycle (TLC) concept to comprehend the long-term patterns of innovation and diffusion processes within the energy matrix. According to the TLC model proposed by Anderson and Tushman (1990), the cycle begins with a disruptive discovery that opens new opportunities and technological trajectories. This is followed by a fermentation stage, where technologies compete within a highly uncertain environment. Then, the third stage sees the emergence of a dominant technological design. Finally, the fourth stage involves incremental change, where the technology gradually evolves until a new technological discontinuity disrupts the trajectory and restarts the cycle. Utterback and Abernathy (1975) present a stylized representation of the TLC akin to an inverted U, which combines considerations about the type of innovation -product or process- that predominates at each stage of the cycle. Davies (1997) later differentiates technological patterns based on whether they pertain to mass-produced goods or complex products and systems.

From the perspective of the TLC, wind power is in a phase of incremental change (Huenteler, Schmidt, Ossenbrink, & Hoffmann, 2016; Kalthaus, 2020; Madvar, Ahmadi, Shirmohammadi, & Aslani, 2019), suppliers of wind energy equipment have enhanced the quality of their products (Huenteler et al., 2016) and there has been a steady decrease in wind energy prices. Drawing on the contributions of Davies (1997), the complexity of energy technologies, and thus the associated pattern of technological evolution, is determined by two key factors: i) the complexity of the product's architecture, and ii) the scale of the production process. Huenteler et al. (2016) concluded that wind power is characterized by its complexity and by incremental changes that combine product and process innovations, with the latter predominating. It's important to highlight that the trajectory of wind power technology involves a diverse range of contributors and knowledge sources. As per the findings of Kalthaus (2020) in Germany, non-specialized and unrelated knowledge played a significant role during the fermentation phase of wind power. This can be attributed to the involvement of technicians and engineers who aimed to enhance environmental conditions and offer technical alternatives to traditional energy. In subsequent phases, the amalgamation of new, specialized knowledge, as well as related knowledge gained prominence. This suggests an impending discontinuity associated with offshore wind power, marked by the participation of shipping firms in technological development. The presence of local industries engaged in turbine manufacturing, competitive on a global scale, is a positive factor for the national wind energy sector expansion and knowledge generation in this field (Zhang, Tang, Su, & Huang, 2020). This underlines the importance of a diverse knowledge base and cross-industry collaboration in advancing renewable energy technologies.

Ampah et al. (2023) demonstrate that water-based technologies for producing green hydrogen are experiencing varied stages of evolution: photolysis is in an emerging phase, thermolysis is in a growth stage, and meanwhile, electrolysis has reached maturity. Over the past five years, significant advancements have been made in areas such as cell design, electrodes, electrolytes, electrolytics, processes, and control methods. It's worth noting that while hydrogen generation through electrolyzers is a technology utilized in industrial processes, it has not yet been widely adopted for power generation due to the need for cost reduction. Consequently, the critical points in research and development in this field include the use of renewable energies (wind and solar) as a source of electrolysis, increasing efficiency, and reducing consumption and energy costs, among others. Dehghanimadvar, Shirmohammadi, Sadeghzadeh, Aslani, and Ghasempour (2020) apply the Gartner Hype Cycle model to abroad range of renewable and non-renewable technologies to explain their stage of development. They affirm these technologies are at different phases, primarily concentrated between the disillusionment stages (photo fermentation and dark fermentation), the slope of enlightenment phase (photo electrochemical, thermochemical water decomposition, and PV electrolysis), and the final productivity stage (electrolysis, fossil fuel reforming, and coal gasification). Interestingly, none of these technologies are found in the first two stages of the Gartner Hype Cycle, which are the innovation trigger and peak of inflated expectations.

Technological development in lagging economies exhibits unique characteristics derived from the local industrial trajectory, the influence of Foreign Direct Investment, the role of Global Value Chains, and restrictions arising from compliance with international regulations and standards (Crespi et al., 2018; Katz & Pietrobelli, 2018). A comparative study between Brazil and China reveals the differential strategies pursued and their impact on knowledge generation in the wind energy field. While both countries have capitalized on the influx of foreign technology, China has oriented its strategy towards learning and developing national technology, resulting in patents and national brand turbines. In contrast, Brazil still relies on Foreign Direct Investment (Gandenberger & Strauch, 2018). In Argentina, the lack of coordination between energy policies and science and technology policies, coupled with their lack of continuity, has posed a limitation to technological development in the field of wind energy (Aggio, Verre, & Gatto, 2018; Stubrin & Cretini, 2023).

3. METHODOLOGY

This study adopts a case study approach to analyze the technological learning trajectory of the domestic wind turbine industry in Argentina. The analysis centers on two domestic firms that demonstrated the capacity to develop and, to a certain extent, commercialized their wind turbine designs. While this case study does not encompass a comprehensive historical perspective, it delves into the institutional trajectory, strategies, and technological capabilities that these two key local industry players built over the years. In addition, the research explores the economic, technological, and political landscapes that underpin the emergence of a green hydrogen industry, both on a global and national scale.

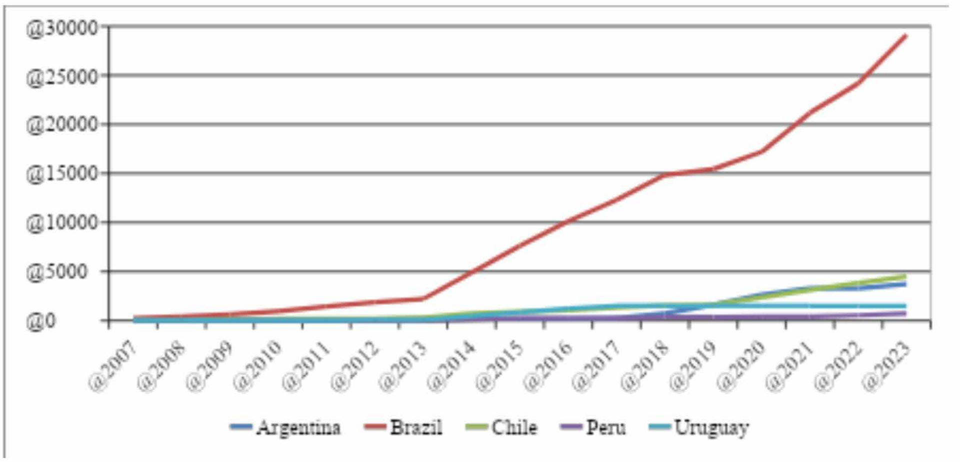
These industries were chosen due to their relevance to the energy transition agenda in South American countries and their distinct technological, market, institutional, and organizational characteristics up to the present day (Castelao Caruana et al., 2023). The analysis is based on the information collected from multiple secondary sources and semi-structured interviews with representatives from both industries.

4. WIND ENERGY TRAJECTORY

The wind energy industry emerged in the 1970s in countries like Denmark, Germany, and the United States. But it was in the late 1990s when the technology design consolidated and competition among firms began to be focused on the internationalization of technology to emerging countries (Gipe & Möllerström, 2023; Verbong, Geels, & Raven, 2008). Until then, vertical integration in wind turbine manufacturing had predominated, resulting from the organic expansion of the incumbent companies and its concentration through mergers and acquisitions (Jacobsson & Johnson, 2000). But around mid-2000, the internationalization process changed the business model giving way to the emergence of suppliers –mostly not knowledge-intensive– located in the same countries where wind farms were installed, while bigger firms continued to specialize in wind turbine design and manufacturing. So, by the decade of 2000, wind energy technology was mature, even though, as it was mentioned previously, its innovative process has remained focused on improving the product throughout its life cycle, shifting from the core sub-system to the broader range of subsystems and components that comprise wind energy (Huenteler et al., 2016). During those years, the demand for wind energy in the countries of the Southern Cone was divergent, especially in Brazil (Figure 1). Some countries, such as Argentina, Chile, Peru, and Uruguay, managed to increase their installed capacity, reaching values between 700-4,500 MW, while the rest of the countries hover around 50-60 MW, on average. The rapid increase of the wind energy installed capacity in Brazil can be attributed to the execution of national public programs specifically designed for RE, such as the PROINFA that in 2002 offered feed-in tariff schemes through 20-year contracts for wind farms, biomass, and small hydroelectric plants (Eirin, Messina, Contreras Lisperguer, & Salgado, 2022).

In Argentina, the national government implemented a program to promote electricity generation from RE sources in the late ´90 that promoted the installation of some wind farms with European technology. However, the benefits of this program were diluted with the exit from the fixed exchange rate regime called convertibility that the country went through in 2001. It was not until 2009 that the national government again promoted the installation of this type of technology with the GENREN program under the orbit of ENARSA.[1] This program tendered contracts for the electricity supply from RE sources, incorporating incentives for wind farms to develop with equipment and components produced locally. However, it had a partial impact. Even though it tendered contracts for 500 MW and obtained offers for 1,000 MW (approving 754 MW), by the beginning of 2018 only two wind farms with 130 MW had been completed, and 10 wind farms with 445 MW had started and interrupted their works. This was due to an unstable macroeconomic context that strongly conditioned access to international financing. In this context, two national wind turbine manufacturers emerged –IMPSA and NRG Patagonia – which drove the development of local suppliers.

Figure 1. Electricity Installed Capacity from Wind Energy (MW) by Country (2007-2023)



Source: own elaboration with data from IRENA (2024)

Some years later, within the framework of national Law 27.191/2016, the RenovAr program and the Renewable Energy Term Market (MATER) once again promoted the growth of wind energy demand in the country. The former was a national tender program for electricity supply contracts from ER sources that provided tax benefits associated with the incorporation of national components established by Law 27.191. The latter, also regulated by this law, is a market for electricity supply contracts from renewable sources between large users (with consumption greater than or equal to 300 KW) and generators of this type of energy participating in the Wholesale Electric Market (MEM). However, this institutional framework did not prioritize the development of domestic technology and associated local linkages (Aggio et al., 2018; Cappa, 2023), but the growth of the renewable energy sector in a complex macroeconomic context marked by energy scarcity.

1.- Energía Argentina S.A. (ENARSA) is a company owned by the national government, established in 2004 to exploit and commercialize hydrocarbons, natural gas, and electric energy.

4.1. IMPSA

At the beginning of the 2000, IMPSA (Industrias Metalúrgicas Pescarmona S.A) was a transnational company with Argentine capital[2], dedicated to developing complex hydroelectric energy projects and designing and manufacturing capital goods for these and other industries. Its advanced technological capabilities and the expansion of its production capacities beyond Latin America enabled IMPSA to access global and distant markets such as Asia, Europe and North America (Papa & Hobday, 2015). In 2003/4, with a strong commitment to innovation, IMPSA began a technological learning process for the design and manufacture of wind turbines based on its knowledge and experience in fluid mechanics and synchronous generators from the design and manufacture of hydroelectric power plants, handling of high structures and frequency conversion derived from the design and manufacture of port cranes and control systems. By 2005, when the average power of wind turbines globally was around 1.0–1.3 MW and the most consolidated European companies began to internationalize, IMPSA developed a 1.0 MW wind turbine that was tested in a wind farm in Argentine Patagonia. Although this machine did not reach a year of life due to problems in the control system, this milestone inaugurated the IMPSA Wind business unit, marking the firm's foray into the wind energy industry. However, Brazil's growing economy and dynamism of the wind market by mid-2000, compared to Argentina's economic decline and wind market halt, convinced IMPSA to shift their main wind operations and assets towards Brazil (Papa & Hobday, 2015). Given that the market was taking off in this country and that mature technologies already existed internationally, the company chose to accelerate the technological learning process by acquiring the license from Vensys, a German firm to manufacture a direct transmission wind turbine of 1.5 MW. By 2007/8 the company inaugurated its subsidiary named Wind Power and a production facility to produce wind turbines and generators in this country. Motivated by local regulations that established 60% national content, IMPSA promoted the development of local and regional suppliers that allowed the diversification of the supply chain, and the growth of the industry associated with the sector in Brazil. By 2014, IMPSA was the third producer of wind energy in this country. It was building wind farms for 480 MW and it had a contract for the manufacture, installation, and operation and maintenance of 287 generators for 574 MW for 2018. In Argentina, IMPSA developed the first wind turbine with its own technology in Latin America, called UNIPOWER® IWP-70 of 1.5 MW, which obtained international certification in 2010. This wind turbine and the subsequent ones -IWP83 and IWP-100- were manufactured in the IMPSA Argentina facilities, reaching a local content of 72 % in the IWP100 model of 2 MW. In parallel, IMPSA obtained contracts with public companies for the provision of wind turbines within the framework of the GENREN program between 2009 and 2011[3].

As in Brazil, the development of this equipment encouraged the creation of a solid network of local suppliers for the sector that included the production of towers and components of the turbines, the repair of wind blades and nacelles, the construction and protection of foundations and towers, and the manufacture of electronic controls. However, this demand was unstable over time and uncoordinated from industrial and scientific

2.- Founded in Argentina in 1907, IMPSA achieved a significant international presence, operating in 40 countries and maintaining a workforce of 3,500 employees. Subsequently, by 2021, this figure had decreased to 720, and the company is currently undergoing a process of corporate restructuring.

3.- Within the framework of this program, two 1.5 MW wind turbines were installed in El Tordillo wind farm, one designed, built, and installed by NRG Patagonia and the other by IMPSA Wind. Both were put into operation in 2009/10, but the park began operating in the MEM in 2013. Its owner was Vientos de la Patagonia I, comprised of ENARSA and the Province of Chubut. IMPSA Wind also signed two contracts with Arauco 1 Wind Farm, owned by the state energy company La Rioja SAPEM (75%) and ENARSA, to manufacture, operate, and maintain 15 IWP-83 wind turbines of 2.1 MW and 11 wind turbines of 2 MW each. This wind farm was inaugurated in 2011. In addition, in 2015 IMPSA Wind installed 4 wind turbines of 2 MW each in El Jume wind farm, owned by the public company Energía Santiago del Estero S.A. (IMPSA, 2024; (Aggio et al., 2018).

policy (Aggio et al., 2018). Despite the various improved models that the company developed to stay at the fore front of the international industry, by 2015 the power of its IWP-100 model was lagging the offer of large international companies, which, along with other barriers, made it difficult to enter the RENOVAR (Table 1). By the end of 2016, 40% of the installed power came from turbines manufactured by companies from Denmark and 23% from France, only 27% from Argentina (Aggio et al., 2018).

Due to various financial events in Argentina, Brazil, and Venezuela, IMPSA had to restructure its capital at the beginning of 2018. Currently, IMPSA is a company dedicated to the EPC of wind farms and SFV, including the production of hydrogen, the repair of large wind equipment, and the provision of operation and maintenance services, including the application of AI for preventive maintenance.

4.2. NRG Patagonia

NRG Patagonia was created in 2006 in Argentina by domestic companies in the oil and gas industry that detected the window of opportunity posed by the absence of wind turbines adapted to the winds of Patagonia at an international level. The first Wind Farms installed in this region in the 90s showed the lack of specific information about the regional wind resources (different from the predominant in Europe) and of technology adapted to its characteristics. The company then acquired the design of a Class II turbine in Germany with software from Denmark and hired German engineering to adapt it to the requirements of the winds of Patagonia (Class I), seeking that most of the parts were manufactured in Argentina. In this way, it developed internal productive capacities to manufacture, assemble, mount, and operate Class I turbines of 1.5 MW, while the rest of the components were acquired from suppliers, many of them local. One bought the license for the electric generator abroad to be able to manufacture it in the country.

As happened with IMPSA, this technology was initially installed in El Tordillo Wind Farm in 2019/10 owned by a public company to integrate a park of 3 MW, located in Comodoro Rivadavia, Province of Chubut. However, the initiative was discontinued and given the fall in projected demand and the difficulty in accessing local public and private financing, the scaling of the prototype wind turbine for Class I winds was discontinued. However, by 2014, the company embarked on the development of a Class II team in consortium with the National University of Patagonia San Juan Bosco and with economic support from Ministry of Science and Technology for about 6 million USD. The development involved the internal capacities of the firm's engineers and external specialists from Europe. Although initially this turbine was thought of as a suitable technology to generate energy with the wind resource available in other parts of the country, given the increase in the power of foreign turbines, it became a suitable team (from 1 to 2 MW) for low-scale users – electric cooperatives, municipalities and/or small and medium-sized enterprises- located in regions with not so extreme winds[4]. This segment is a niche with potential from the creation of MATER and Law 27.424/2017 of distributed generation of low interest for large multinational companies. Currently, these wind turbines have around 50% of national components from 12 local companies. In addition to this strategy, the company created ENAT in 2016, a spin-off that capitalizes on the techno-productive knowledge and market acquired in the wind market by the firm to provide knowledge services such as detection of sites with energy resources of interest, design of wind farms or pre-feasibility analysis of connection to the electrical system.

4.- In 2021, NRG Patagonia installed a 1.5 MW Wind turbine for self-consumption by the Castelli Cooperative in Buenos Aires Province.

The analysis of this sector shows several issues. First, the specificity of the NR -winds with greater load capacity and turbulence in the Patagonia region– represented an opportunity that only some companies with a trajectory in the energy sector could identify at the beginning of the ´2000 given the low level of specialized knowledge that existed in the country about this industry. Even so, the specificity of this NR did not represent a barrier to entry for foreign companies because it is an NR with similar characteristics in other parts of the world and also in those years the global wind industry was already mature and relatively concentrated – although more dispersed than at present - and under a dynamic of innovation focused on the continuous improvement of the subsystems and components that make up wind energy, which quickly closed this window of opportunity. However, in less than a decade, the national companies analyzed managed to develop the necessary technological capacities to take advantage of this opportunity through a learning process based on internal mechanisms (existing capacities) and external (license purchase) in the case of IMPSA and merely external in the case of NRG (hiring of engineering for the adaptation of an existing design to local requirements), at least in the first stage. This learning process was supported by a timid internal demand, essentially driven by public companies, but also, in the case of IMPSA, by an external, regional, and dynamic demand.

5. GREEN HYDROGEN, AN EMERGING INDUSTRY

Green hydrogen has aroused great expectations at the global level due to its potential as an energy vector for renewable energy sources, like wind and solar photovoltaic energy. Its development could complement other sources of energy and promote the decarbonization of energy-intensive industries (steel, chemicals, cement, and transport) as well as other sectors that use hydrogen in their production processes (petrochemicals, food, and electronics) (Zabaloy, Guzowski, & Didriksen, 2021). In addition, hydrogen and its derivatives have a comparative advantage in specific applications required by sectors that need to stabilize the networks supplied by a large proportion of intermittent sources, such as solar photo voltaic and wind power (IRENA, 2023b).

Green hydrogen is produced by the electrolysis of water, which requires both the availability of fresh water and a renewable energy source. In Latin America, there is a convergence of both natural resources in their potential to produce it, as auctions in Chile, Mexico, and Brazil offer the lowest prices for wind power and solar photovoltaic energy in the world, and water scarcity is not a constraint for most countries in the region. So, the development of green hydrogen in Latin America could be an advantage for potential consumers further away from the region, such as China, the European Union or the USA, as they could compensate for the distance with cheap renewable energy and less risk of geopolitical conflict than those from closer, but more politically unstable regions.

The challenge for Latin American countries is to define how to develop the energy transition for which they have the natural resources but not the capital or the technology, considering that hydrogen production is complex and requires long-term investments that allow innovation in the construction of production plants, storage, and transportation, as well as in the electrolysers production.

Electrolysis seems to be a highly modular technology with a steep learning curve. Electrolysis could be today what solar photovoltaic energy was 0 to 15 years ago, on the verge of moving from niche to mainstream technology. While this nascent sector is still developing, electrolysers made in China are 75% cheaper than those made in the West, according to Bloomberg New

Energy Finance. This is a gap that Latin American countries should close if they are to develop a competitive hydrogen ecosystem, as they have an important endowment of natural resources for low-emission hydrogen production but are still far from the technological frontier of electrolyser production.

In Argentina, the search for insertion in this ecosystem led to the emergence of some projects promoted by public and private companies (Hychico, Y-TEC), and others by foreign companies and organizations, with varying degrees of progress. Hychico has a pilot plant in Chubut that produces 120 m3 of green hydrogen per day using wind energy, currently destined for the domestic market. The project, launched in 2008, is a spin-off of the CAPEX Company with a track record in the conventional energy sector and is an example of synergy between fossil and renewable energies: two wind farms and two electrolysers at the foot of a conventional field. At the same time, Y-TEC –a technology company of YPF and Consejo Nacional de Investigaciones Científicas y Técnicas- launched a consortium for the development of the hydrogen economy in Argentina in 2020, called H2Ar, to create a collaborative workspace between local companies interested in integrating the blue or green hydrogen value chain (YPF, 2022). On the other hand, foreign entities -such as the Australian company Fortescue Future, the Fraunhofer Institute of Germany, and the MMEX Resources Corporation of the U.S.A.- have evidenced a deep interest in promoting green hydrogen production in Argentina. These external actors have focused on studying the available natural resources and their environment – wind and water sources and topography - to assess the technical and economic feasibility of installing green hydrogen production plants powered by wind energy, proposing the emergence of hydrogen hubs in the provinces of Buenos Aires, Río Negro, and Tierra del Fuego.

Despite all these actions, there are few technical and environmental studies to assess the impact of green hydrogen production and poor standards to regulate the activity. In recent years, the international context has promoted the interest of the State, both at the national and provincial levels, but there is still no broad consensus on the benefits this sector could bring to the country, on the role of government in promoting it, and on the role of hydrogen as part of industrial policy (Castelao Caruana, et al. 2023).

The first Hydrogen Promotion Act (Law 26.123) was introduced in 2006 to promote research and development of technologies to produce hydrogen from renewable and non-renewable sources (Guzowski, Zabaloy, & Ibañez Martín, 2022), expiring at the end of 2021 due to a lack of regulation. In 2023, the national government submitted a new draft law on the promotion of hydrogen production, which was strongly criticized because of the 35% national content requirement for each project (including electrolysers and power generation equipment), the duration of the promotion scheme, the requirement to contribute a percentage of the investment to a future specific allocation fund, and the multiplicity of agencies involved in hydrogen regulation. In September 2023, the National Strategy for the Development of the Hydrogen Economy presented the basis for the promotion of low-emission hydrogen, but the change of government in December put all hydrogen-related regulations (including the draft law) on hold and does not seem to have the will to move forward, at least in the short and medium term.

Table 1. Non-exhaustive mile stones on the evolution of the wind industry at different scales of analysis

Scale of analysis	´70	´90	2000-2003	2004/05	2006	2007/08	2009/10	2011	2013/14	2015/16	2018-2024
International	Wind energy industry emerged	Technology design consolidated	Vertical integration in the wind turbine industry	Mature technology. Internationalization process							
Average size of wind turbines (MW)	0.1	0.3	0.75	1.5	1.5		1.8	2	2.5	3	4-5
National level		Feed-in tariffs. First wind power projects with European technology	Technological adaptation of an European wind turbine design	Creation of ENARSA			Public program GENREN			Law 27.191: fiscal benefits, MATER. Public program RenovAr	
IMPSA				Technological development of a wind turbine designed in-house (1 MW)		Creation of IMPSA Wind. Brazil as an emergent market. Acquired an European license to manufacture wind turbines (1.5 MW)	Installation of the first wind tower designed in-house (IWP70, 1.5 MW)	In Argentina 50.4 MW of wind power in stalled. International certification of IWP-83 (2.1 MW).	In Brazil: 433 MW of wind power installed and 480 MW under construction. Closure of Wind Power Brazil	Inauguration of wind turbine production plant in Argentina (IWP-100, 2 MW)	Company restructuring. EPC for renewable energy plants. AI for O&M.
NRG					Creation of the firm with capital from companies in the O&G sector		Installation of the first wind tower designed in-house (1.5 MW)		International certification of wind turbine design	Wind turbine designed in-house Class II (1.5MW). Creation of ENAT for site detection and study of its wind resource	New domestic market: decentralized renewable energy systems.

Source: own elaboration from secondary sources

6. CONCLUSIONS

This work delves into the technological learning and innovation process observed during the emergence and consolidation of the wind industry in Argentina to develop some hypotheses about the role the inter play between demand and the technological cycle may have in driving innovation around renewable energy technologies, especially green hydrogen, in peripheral countries.

This paper focuses on the trajectory of Argentina's wind industry, analyzing the technological learning processes undertaken by IMPSA and NRG Patagonia over the last two decades. Initially, these companies designed and manufactured wind turbines tailored to the unique wind conditions of the Patagonian region. We juxtapose this evolution with global wind industry trends and internal and external demand policies that influenced these learning processes. Our findings propose hypotheses applicable to understanding learning dynamics in other emerging energy industries.

The results show that despite mature technology, there remain opportunities for technological innovation when local or regional market diffusion is limited. While the accumulated technological capabilities and the learning process play a pivotal role in the initial stages, internal demand becomes central during technology's take-off phase, especially for in-house designs. Notably, external demand from countries where the technology is not yet widespread can also drive technological development. Brazil's role in IMPSA's consolidation as a wind turbine supplier exemplifies this phenomenon.

Contrary to prevailing literature, our study suggests that natural resource-based firms may not be as critical in the technological learning process, particularly during the emergence phase of the cycle. Instead, knowledge-intensive suppliers —those involved in designing, adapting, and manufacturing technology—play a more significant role in the innovation process around the transformation of energy-related natural resources.

Doubts arise regarding the level of specificity of energy-related natural resources and their potential to open windows of opportunity for the emergence of local knowledge networks. Regardless of whether these opportunities exist, or firms seek to capitalize on those resulting from foreign technology diffusion, they must thoroughly understand the sector and develop the necessary technological and commercial capabilities to achieve technological innovation.

These observations are important for the current learning process around green hydrogen production, as there is already an international industry advancing towards its consolidation and the electrolysis technology is maturing. In Argentina, a few local companies with frontier technological capabilities are studying the process of green hydrogen production to become key players in the domestic industry, not so much in the production of electrolysers as in the provision of equipment or services to upgrade production processes. Given the lack of a supportive institutional framework and the neoliberal political context in the country, questions arise regarding the potential opportunities the external demand of green hydrogen and its by-products-this time from developed countries- may bring for technological learning and innovation in this nascent sector.

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