



Strategic management of patents on electrochemical conversion fuel cells and batteries in Latin America as a mechanism for moving towards energy sustainability

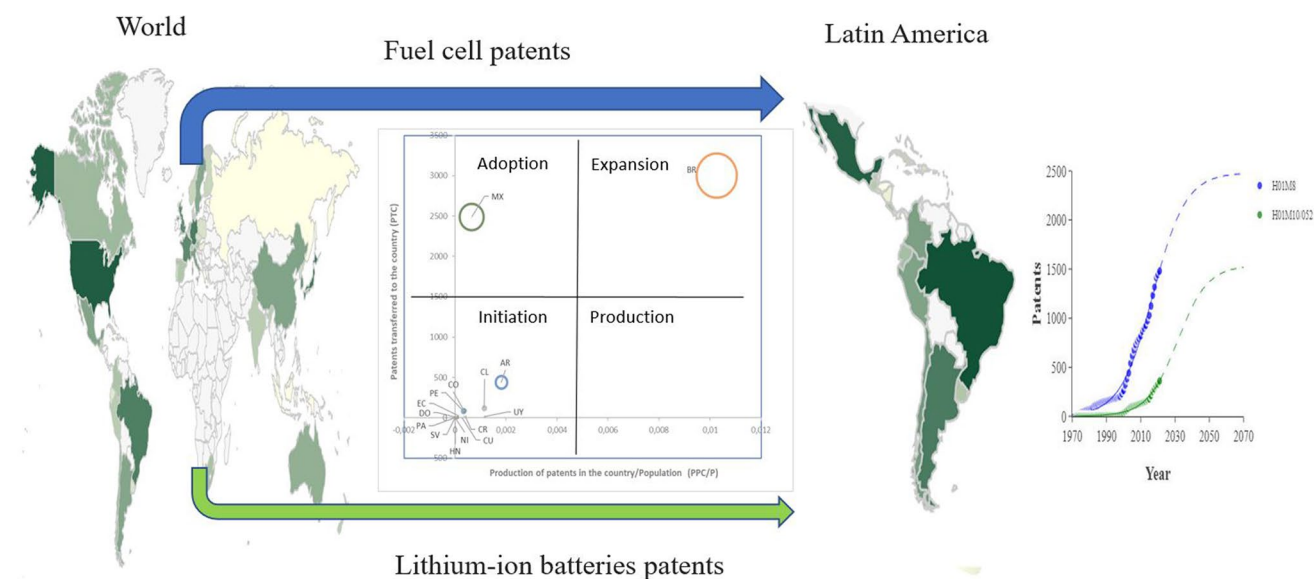
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Abstract

Electrochemical conversion batteries (ECBs), especially fuel cells and lithium-ion batteries (LIBs), are the focus of attention of the scientific community due to their potential contribution to the decarbonization of the economy. In this context, the objective is to analyze patent publication flows on LIBs in Latin America (LATAM) by proposing a technology adoption matrix, a Patents friendly to sustainable technologies (PFST) indicator, and the use of technology s-curves. Data collection and analysis were carried out using the PatSeer knowledge base, Gephi, VantagePoint, and Loglet Lab software. The results show the leadership of Brazil, Mexico, and Argentina, with high dependence on the United States, Japan, and Germany. The PFST indicates that 79.3% of the published patents address climate change mitigation. In general, there is a low rate of publication of ECB patents in LATAM, marked by a technological lag in the evolution of key technologies. Patents on fuel cells are more published than those related to LIB. Under this scenario, it is unlikely that LATAM will achieve the necessary competitiveness to produce complex technologies in this field. In this regard, it follows that to reverse the position of traditional exporters of low value-added commodities, these countries should formulate strategies that allow the development of the innovation ecosystem, promoting open and applied innovation mechanisms, subsidized adoption, greater integration of universities and, at the same time, strengthening technological integration with countries that currently lead the transfer and others with great potential such as China and South Korea.

Graphical abstract



Extended author information available on the last page of the article

Keywords Fuel cells · Lithium-ion batteries · Technology adoption matrix · Analysis of patent information · Sustainable · s-Curve

1 Introduction

In response to environmental and energy challenges, there is a group of technologies that seek to become widespread to reduce Greenhouse Gas (GHG) emissions. Among these are the different battery systems (cells, batteries) that are called to play a fundamental role in the energy transition processes undertaken by different countries [1]. Batteries are already essential for the operation of many of the goods or systems aimed at providing society with greater comforts. Their importance is growing as fuel cell electric vehicle (FCEV), electric vehicle (EV), and stationary electricity storage system technologies become more widespread [2].

On the one hand, several countries have bet on the development of green hydrogen (H_2) as the energy carrier of the future [3]. To this end, these nations have to develop the chain of production and use of H_2 , which can be structured in four phases: (i) the selection of the type of renewable energy to produce H_2 [4]; (ii) the electrolytic separation where H_2 is obtained [5, 6]; (iii) the storage and distribution of H_2 [7]; and (iv) the form of H_2 use (consumption) [1]. Each of these phases has become a major challenge for the scientific community. In the case of the form of use, one of the solutions developed for H_2 consumption is the “hydrogen fuel cell,” which have high conversion efficiency and do not emit pollutants into the atmosphere [8]. These cells are powered by H_2 , converting its chemical energy into electrical energy, which is used to power the electrical elements used in different types of electric propulsion means of transportation, heating systems, and other industrial systems.

There are different types of fuel cells. Among the most collaboratively addressed by researchers are H_2 fuel cells, direct methanol, microbial, solid oxide, molten carbonate, proton electrolyte membrane, and phosphoric acid fuel cells [9]. The function of these cells is to provide electrical energy to a system (motor or other), for which they depend on the supply of chemical energy provided by an energy carrier (such as, for example, methanol, ammonia, H_2 , or fuel sources). These fuel cells, especially H_2 fuel cells, have enabled the development of FCEV. Thanks to the incorporation of these fuel cells, these vehicles have become one of the main candidates for providing society with clean, economical, and efficient means of transportation [10, 11]. The fuel cell system converts hydrogen into the electrical energy needed to power the electric motor of the FCEV propulsion system [12].

On the other hand, the other technology anticipated to achieve the decarbonization of the economy are the EVs, which depend on power from an external electric power source, and therefore a high dependence on charging stations. Nonetheless, these vehicles currently command a greater presence in the markets. Their success is based mostly on the incorporation of lithium-ion batteries (LIB) that have allowed them to improve their autonomy and charging times [13]. However, autonomy, charging times, and safety remain important challenges to be improved by researchers and stakeholders in general [13].

Fuel cells and LIB play an essential role in the development of EVs and FCEVs as evidenced by their high dynamism from the point of view of patent generation and indexed scientific articles [14, 15]. In particular, different data on patents associated with these types of technologies are a valuable input for assessing the links between environmental policies and technological change [16, 17].

In this field of knowledge, as in other scientific topics, there are leading nations and others lagging in terms of the production of scientific papers and/or patents. However, given the commitment made by nations in the context of the Paris agreement and the Sustainable Development Goals (SDGs), (specifically goal 7), the technologies that arise in response to climate change (as is the case) must advance significantly in all countries. Therefore, technologies that emerge in response to climate change (as is the case) need to advance significantly. Accordingly, it is fundamental to generate studies that describe the existing gaps in the adoption of these technologies, especially in less developed countries [18, 19], as is the case of Latin America (LATAM).

According to a report by the United Nations Development Program (UNDP), (2021), there is a lag in annual per capita economic growth in the LATAM region compared to the rest of the world. This places LATAM below countries in East Asia and slightly above those in Africa [20]. Despite this, some of these nations have made significant progress in their aspirations to become developed countries: implementing strategies that have allowed them to join important global development groups, such as the Organization for Economic Cooperation and Development (OECD), a forum that brings together developed and other countries with the greatest potential for development. These governments work to promote solutions to member countries' problems; identify best practices and coordinate domestic and international policies [21]. LATAM

countries are also part of the main global agreements to minimize the effects of climate change, such as the SDGs and the Paris Agreement [18].

Energy transition to clean energy in LATAM is gaining momentum. This is evidenced by the publication of ambitious strategies in the field of green H₂ production [3]. There is no doubt about the region's enormous potential for renewable energy production [22]. But do LATAM countries have the inventive skills to enable them to address the major challenges posed by this transition?

1.1 Patents analysis background

Patents are considered as active forms of disclosure of protected knowledge to other parties in exchange for a monopoly for a limited period of time [23]. Patents provide a rich source of practical technical information and in recent years there has been a significant increase in the number of studies using patent data to capture technological information from different industrial areas [24]. Detailed patent classification systems make it possible to identify advances in technological fields. Moreover, since inventors can apply for patents in several countries, the diffusion of technologies between countries can also be tracked [17].

In particular, a patent registration contains relevant technological information which can be used to monitor competitors, evaluate technologies, manage the R&D portfolio, and track and assess potential sources for external generation of technological knowledge [25]. Patent counts are therefore an important metric for assessing technologies and the innovative and technological capacity of companies and countries [17, 26]. In recent times, they have become an indicator of progress towards a green economy [27] and low-carbon technologies [28].

There are studies that have addressed important environmental issues using patent analysis. For example, Lanjouw and Mody [29] used patent data from the United States (US), Japan, Germany, and 14 low- and middle-income countries to assess environmental innovation. They concluded that environmentally friendly innovation increases as spending to reduce pollution increases. The authors showed that in developed countries most of these patents are domestic. In contrast, developing countries adopt patents from foreign countries, which highlights the importance of diffusion for less developed countries [29].

1.2 Patent classification systems

A key aspect of patent analysis research is data collection and processing. The definition of search parameters is a determining factor in research results. Particularly in the case of patents, it is common to use keywords for searches on specific topics. However, for certain topics the construction

of the search syntax can be complex. It is possible to find some patent studies in the energy field based on the use of keywords. The study by Pu et al. [30] used the keywords “lithium-ion battery” and “battery and lithium-ion” to study the evolution of the industry–university–research cooperation network in the field of energy storage technology in China. The paper from Leu et al. [31] focuses on the keywords “biofuels and biohydrogen” to analyze the technological trends in that energy field.

Another alternative as regards patent analysis research is based on the use of the codes or classification systems that index the different topics. These codes are described by main world organizations in charge of regulating patents and used to group the statistical information of the different patent families [32, 33].

In 1979, the Strasbourg Agreement Concerning the International Patent Classification (IPC) was established [34]. The IPC defines the classification of patents and utility models according to the different technological areas to which they belong [35]. Patents are divided into eight sections, from “A” to “H,” which in turn are subdivided into classes, subclasses, groups, and subgroups, making it possible to classify and search all patent-related information [35]. Particularly within section H (electricity), we find subclass H01M which covers primary or secondary galvanic cells or batteries, fuel cells or cells (see detailed description in Sect. 2).

For its part, Cooperative Patent Classification (CPC) is an extension of the IPC and is jointly administered by the European Patent Office (EPO) and the U.S. Patent and Trademark Office (USPTO). In addition to the existing sections (in the IPC), a new “Y” section has been added. This new section covers general labeling of new technological developments, general labeling of cross-cutting technologies covering several sections of the IPC. Y02, in particular, refers to climate change mitigation or adaptation technologies or applications [36]. This classification is used in a cross-cutting manner to label documents that are already classified or indexed in another code [33]. For example, a patent labeled within a technology area “H01M” that presents attributes that mitigate climate change can also be labeled with Y02. Mueller et al. [36] provide a broad description of technology classes related to battery types for energy storage, the authors indicate that batteries are grouped in the “H” and “Y” sections of the CPC classification. In their study, they underline that patent related to regenerative fuel cells doubled during the period 2009 to 2011. At the same time, they highlight that LIB continue to produce the best performance [36].

In the field of electrochemical conversion batteries (ECB), the use of IPC and CPC codes to obtain research data is more frequent. For example, Tsang et al. [37] studied emerging fuel cell technologies using data from the USPTO for the period 1976 to 2011 for codes H01M 008/00–H01M

008/24, focusing on patent survival, i.e., renewal over time. Alvarez-Meaza et al. [14] used the CPC code Y02T90/34 to study fuel cell powered electric vehicles. In order to identify and compare the patent landscape of solid-state batteries (SSB) with that of LIB, Block and Song [38] used the CPC codes H01M0010052 OR H01M00100525 OR Y02E0060122 OR Y02T00107011 employing the Derwent Innovations Index (DII) database. On the other hand, Shen et al. [39] used H01M 2/-, H01M 4/-, H01M 10/- to analyze the factors influencing the performance of EV technology in China. In this study, the authors underline the importance that the Chinese government's support from has had on the country's outstanding performance in that field [39].

Another practice used is data retrieval by combining keywords and IPC/CPC classifications. Such is the case of Stephan et al. [40] who analyzed the development and diffusion of LIB knowledge in Japan by obtaining patent information related to main components, peripheral components, cell system, and battery integration. In the study by Albino et al. [28], a recovery of codes is observed through the use of the IPC green inventory. This makes it possible to identify patents that contribute to the development of low-carbon energy sources [28].

For its part, the International Energy Agency & the European Patent Office [2] carried out wide-ranging research on electrical energy storage technologies. Although the study had a worldwide scope, the results focus on certain Asian and European countries, and USA. This research reveals important contributions from the point of view of the methodology used for patent retrieval, incorporating the participation of experts to determine the

relevant technologies in the field of ECBs [2]. As stated by Ma et al. [41], determining the words is a rigorous task, which may include working with experts and/or a thorough review of the literature covering the subject matter.

1.3 Main highlights of patent studies in the battery field

Table 1 shows a summary of the main reflections regarding the most studied and highlighted countries, methodological tools, and results. These were obtained by reviewing the main literature related to published patents in the field of battery technologies.

Despite abundant research focused on analyzing patents on ECB (i.e., fuel cells, LIB, among others), we have not identified relevant studies on the subject that focus on developing countries, especially LATAM. In this context, the objective of this research is to analyze the status of patent publications on ECB technologies, especially fuel cells and LIB, in the LATAM region. For this purpose, the use of a model based on the application of a Technology adoption matrix (TAM) and a Sustainable Co-occurrence indicator is proposed to analyze the implications of BCEs in the Y02 technological field (i.e., technologies to mitigate climate change), as well as launching an analysis of technological evolution and forecasting.

For the development of this article, the following structure is followed: Sect. 2 presents the methodology proposed to achieve the objectives; Sect. 3 gives the results; Sect. 4 is dedicated to the discussion and, finally, Sect. 5 provides the conclusions.

Table 1 Highlights of main publications related to patents of battery technologies

Highlights	Sources
China, Japan, Germany, the United States, South Korea, and other European countries are the focus of patent studies in the field of batteries. China and Japan lead the way in patent production in this field	[2, 42, 43]
The main forms of patent data retrieval in the field of batteries are the use of IPC and CPC classification codes	[37, 38, 44]
The CPC Y02 technology fields and the IPC green inventory allow climate change mitigation and/or carbon emission reduction technologies to be monitored	[14, 36]
Interdisciplinary patents play a key role in the future trajectory of electric vehicle development. Therefore, new patents in the various related fields need to be further developed	[41, 42]
Network analysis with centrality indicators stands out among the methodologies used for patent analysis	[41, 45, 46]
Governments play an essential role in the development and maintenance of patents in the battery field, especially those aimed at reducing carbon emissions	[28, 39, 47]
In general, patents related to LIB technologies are the most prominent worldwide. Asian manufacturers dominate the patent space	[36, 38, 44]
Universities play a secondary role in the production of battery patents	[30]
Fuel cells as well as LIB are increasing significantly within the context of global energy transformation	[11, 12, 42, 48]
Sustainable recycling of LIBs is essential to achieve a sustainable energy transition	[42, 45]

Source Own authors

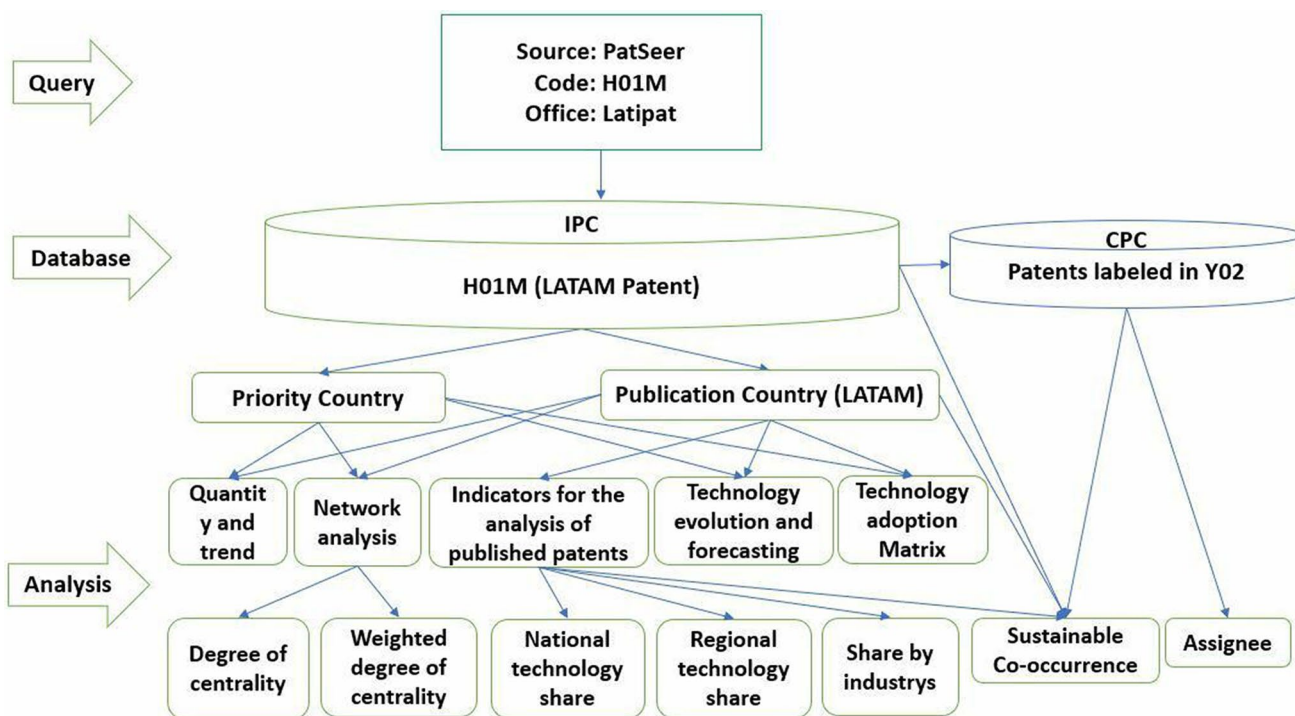


Fig. 1 Structure of research methodology. Source Own authors

2 Methodology

The methodology proposed to analyze the status of patent publications on ECB technologies, especially fuel cells and LIB, in the LATAM region, is summarized in the scheme provided in Fig. 1. First, key aspects of data retrieval are indicated (see Sect. 2.1 for a complete description). This results in a database obtained according to the CPI classification and its corresponding equivalence in the CPC. In the latter, only the information specific to code Y02 is retrieved. As a first step in the level of analysis, a quantitative analysis of priority countries and countries of publication is indicated (see Sect. 2.2 for a complete description). This is followed by a network analysis based on the centrality indicator to visualize the transfer flows between priority countries and recipient countries in LATAM (see Sect. 2.3 for a full description). Subsequently, the proposal of indicators to analyze patents published in LATAM is shown (see Sect. 2.4 for a complete description). Within this section, the degree of co-occurrence of BCEs with the Y02 classification (i.e., the one that identifies climate change mitigation technologies according to the CPC) is evaluated (see Sect. 2.4.2). Finally, the state of adoption of ECBs by LATAM countries is analyzed, proposing a TAM (i.e., a matrix relating the production of priority patents and the number of patents extended from other countries) (see Sect. 2.5 for a complete description).

2.1 Data recovery

As explained, a key aspect of patent analysis research is data collection and processing. In our case, we mainly used the data indexed under code H01M, which “covers primary or secondary galvanic cells or batteries, fuel cells or batteries” [32]. This code belongs to the International Patent Classification (IPC), described by the World Intellectual Property Organization (WIPO). The H01M code includes fuel cells (H01M 008/00 to H01M 008/24) and LIB (H01M 10/052). Although the present study focuses on the aforementioned batteries/cells, the analysis has adopted a broader perspective by analyzing the general context in which they are developed within the ECB subclass. On the one hand, this perspective allows us to better understand their relative importance or representativeness and, on the other hand, to determine whether or not there is a favorable innovation ecosystem for the transition to new technologies (LIB and fuel cells) based on the existing knowledge of related technologies. This analysis from a broader perspective also offers an input for future studies on battery patents. Accordingly, and to facilitate an understanding of the ECB subclass grouping, Fig. 2 shows the classification structure defined by WIPO for the H01M code [32], which is composed of eight groups, explained below:

- Electrodes (H01M 4/00) “when classifying the electrodes of hybrid cells, the individual half-cells of the hybrid cell

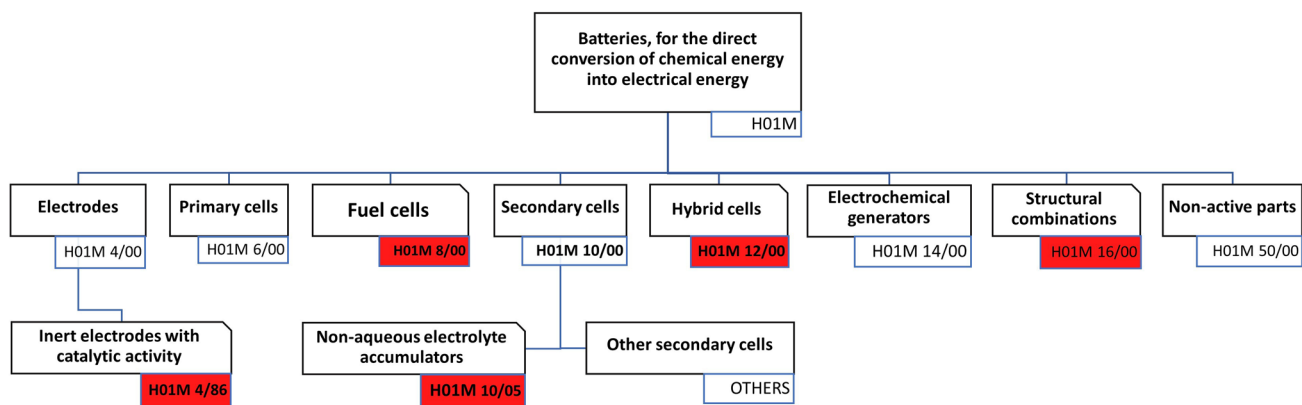


Fig. 2 Classification structure for electrochemical conversion batteries (ECB). *Source* Own authors

are considered separately.” Specifically, the code H01M 4/86 “inert electrodes with catalytic activity” is associated with fuel cells [32].

- Primary cells (H01M 6/00) “are electrochemical generators in which the energy of the cell is present in chemical form and is not regenerated” [32]. This type of battery has traditionally been used in calculators, watches, medical equipment, toys, etc. [49].
- Fuel cells (H01M 8/00) are “electrochemical generators in which the reagents are supplied from the outside” [32]. These would allow the massive exploitation of hydrogen through fuel cell EVs, contributing to sustainable mobility [50].
- Secondary cells (H01M 10/00) are one of the most diverse codes, defined as “accumulators receiving and supplying electrical energy by reversible electrochemical reactions” [32]. This group includes the most dynamic and promising battery systems, including batteries with non-aqueous electrolyte and, within this subgroup, LIB (H01M 10/052). The latter have been key in the current development of EVs [13].
- Hybrid cells (H01M 12/00) are “electrochemical generators having two different types of half-cells, the half-cell being a combination of electrode and electrolyte of a primary, secondary or fuel cell” [32]. These batteries

are particularly promising because they combine features of different technologies to achieve better results [51].

- Electrochemical generators (H01M 14/00), this group includes generators other than those provided for in groups H01M 6/00–H01M 12/00 [32].
- Structural combinations (H01M 16/00), as the name suggests, cover structural combinations such as “fuel cells with rechargeable batteries” [32]. This code may also be of interest for the analysis of fuel-battery-related technologies.
- And finally “construction details or manufacturing processes of non-active parts of electrochemical cells” (H01M 50/00), excluding those related to fuel cells [32]. This code is equivalent to H01M 2/00.

The data obtained were filtered for the Latipat office, which allowed access to all the results from LATAM, obtaining 6742 patents over the time period 1973 to 24-06-2021. The PatSeer Pro web application was used, with an option called Quick stats, which make it possible to obtain useful information for the analysis, similar to other studies that used this tool [52, 53]. Subsequently, the patents transferred to the LATAM region were characterized by using VantagePoint text mining tools, considering the definitions and scope of Table 2.

Table 2 Definitions and scope of methodological parameters

Parameter	Definition and scope	Results
H01M	Processes Or Means, E.G., Batteries, For The Direct Conversion Of Chemical Energy Into Electrical Energy	6742
Timespan	No time restriction, downloaded: 24–06–2021	1973–2021
Priority Country	It is the country where the patent was first registered	57
Publication Country	Country where the patent was extended, in this case the LATAM countries	13
Edge	Number of patents extended from Priority Country to Publication Country	141

Source Own authors, based on (PatSeer and WIPO 2021)

The geographical assignment of authorship of a patent is fundamental, as it may influence the interpretation of the research results. There are several ways to assign authorship of a patent to a country. One option is the first inventor's country of residence. Another way is to assign it to each participating inventors' country [27]. These two options can be confusing. Should it be assigned using the first option, the weight of the other participants is underestimated. Conversely, when assigned to all inventors, there are records that create duplicity of information. In this case, one solution proposed has been to assign a fraction to each inventor's country [2, 42], which can be cumbersome from an information processing perspective. Another option, the one chosen for this study, is to assign it by the priority country field. We consider that country-specific conditions attract patent priority. These conditions could be given by the attractiveness and needs of industry, as well as by aspects such as nationality or residence. Another approach could be to use the geographic location of the owner or assignee of the patent. Since the inventor or inventors are generally under an obligation to assign their patent rights to the company or institution where they are employed, the location of the inventor or inventor's employer is generally equivalent.

2.2 Quantitative description

First, a quantitative analysis was carried out to characterize priority countries and countries of publication. In the case of publication countries, an analysis of the evolution of the trend in the number of patent publications over time was performed.

2.3 Network analysis

To relate the priority countries and publication countries, a network was created using Gephi software, which allows a user-friendly representation of the nodes and destinations, as well as the relationship between them [54, 55]. In this case, the relationship between the countries is reflected in the number of industrial property registrations (patents) received by the country of publication from the priority countries. The degree of centrality (DC) was used for network analysis. This indicator describes the number of nodes connected to a specific network node [30]. The Gephi software allows us to obtain the DC and weighted degree of centrality (WDC). The latter incorporates the number of links between one node and another [56].

2.4 Indicators for the analysis of published patents

Three indicators were used to characterize the patents transferred to the LATAM region. The National/Regional technological share indicator and the "Patents friendly to

sustainable technologies" indicator. In addition, the analysis of patents included a count of the number of patents by industrial sector.

2.4.1 Indicators for technological share

Based on the National technology share (NTS) indicator described in Baumann et al. (2021), we derived two types of technology share analysis. The first at the national level, in this case, the relative frequency of participation by country in each of the 20 main technology subgroups was represented. The second was adapted to calculate (Eq. 1) the Regional technology share (RTS) indicator for the different technological groups according to the classification shown in Fig. 2. This measures the relevance of technology groups for the region.

$$\text{RTS} = \frac{P_G}{\sum P_G} * 100 \quad (1)$$

RTS: Regional technological share, P_G : Number of patents belonging to a specific group, for example, H01M2, H01M4..., $\sum P_G$: Sum of the patent number classified in each group of subclass H01M.

2.4.2 "Patents friendly to sustainable technologies" indicator

In order to determine the degree of association or relationship of ECB with climate change mitigation technologies, the Patents friendly to sustainable technologies (PFST) indicator is proposed. It is important to note that a patent may present attributes that allow it to be indexed in different codes. In particular, the Cooperative Patent Classification (CPC) created code Y02, which groups climate change mitigation or adaptation technologies or applications. Through a broad classification scheme, it indexes patents that seek to control, reduce, or avoid greenhouse gas (GHG) emissions [14, 57]. In this regard, the following indicator is proposed to evaluate sustainable co-occurrence. This ratio establishes the percentage of patents that have been published in each country that can be considered sustainable, by presenting co-indexation with code Y02:

$$\text{PFST}_{jk} = \frac{\text{PPC}(Y02)_{jk}}{\text{NTP}_{jk}} * 100 \quad (2)$$

PFST_{jk}: Patents friendly to sustainable technologies of country j for patent type k . PPC(Y02)_{jk}: Number of patents published in country j belonging to IPC k that are co-indexed with the CPC Y02 classification. NTP_{jk}: Total number of patents published in country j belonging to IPC k . J Corresponds to the analyzed country, e.g., Brazil, Mexico, etc. K : Corresponds to the analyzed IPC, in this case "H01M."

The indicator can take values between 0 and 100%, reaching the maximum value when all its patents present attributes that respond to mitigation and/or adaptation to climate change.

Based on the analysis of sustainability technologies, the most relevant assignees in terms of the acquisition of sustainable technologies were identified. Within this analysis, the role of universities was also identified. These analyses were performed using a co-occurrence map of the Y02 vs Assignee family of codes (see Fig. 9).

2.5 Technological evolution and forecast

One of the most widely used tools for analyzing the speed of adoption, maturity, prognosis, and technological evolution, in general, is the s-curve. This graphical method allows a technology to be assessed based on the number of scientific publications and/or patent publications [58]. The evolution of the publication record over time makes it possible to place the assessed technology in one of the four stages: emergence, growth, maturity, and saturation. At the same time, it makes it possible to forecast when the next stage will be reached when the saturation stage has not yet been reached. Detailed descriptions of the s-curve method can be found in Baumann et al. [42], Chanchetti et al. [59].

In this research, the s-curve method was performed by employing patent data, specifically for LIB and fuel cell technologies, accumulating patent publication records over time during the period 1973–2020 for codes H01M10/052 and H01M8. The year 2021 was not used because it was not complete at the time of data download.

The s-curve model was built using the Loglet Lab 4 software that allows specialized analysis in this method [60]. It presents a simple and informative user interface that through four simple steps produces the set of graphs for analyzing the model. Additionally, Loglet Lab 4 presents an advanced fitting engine for analyzing complex data [61].

Before using the software, the type of curve to be used has to be defined, evaluating between Gompertz and logistic curves. In our case, following the methodology proposed by Franses [62], it was determined that logistic curves are the most appropriate.

2.6 Tool for strategic analysis of technology adoption

In this study, we also analyze technological adoption of ECB by considering two dimensions. On the one hand, the capacity to generate technologies, reflected in the number of patents. On the other hand, the capacity to identify and assimilate technologies, reflected in the number of patents extended from other countries. Correspondingly, a matrix was proposed to evaluate the degree of technological

adoption of LATAM countries in a specific sector (conversion of chemical products into electrical energy) (Fig. 3).

Other studies have used similar matrix models, for example, to evaluate patent portfolios in companies, using as variables (axes) the relative growth rate of patents and relative participation of technology, in order to facilitate decision making in terms of R&D spending by organizations [63]. A recent study focused on analyzing trends in the patenting of three energy technologies with a focus on Germany and the leading countries in the field. In their case, the variables on the x axis were the patenting activity in a given technological field per GDP and on the y axis the growth rate of patents in recent years [42]. The present study proposes using a TAM for LATAM countries, which is similar to the one proposed by the authors cited above. In this case, the four quadrants are formed from the combination of the country's patent production divided by its number of inhabitants, represented on the x axis, and the patents that are transferred to the country (extension from other countries) on the y axis. A bubble representing the total value of patents registered in that field by each country is also included. On the x axis, the division by the number of inhabitants was applied to reduce the distortion inherent to the size of the countries.

The proposed matrix provides information on the state of adoption of these technologies, given that the country may have the capacity to generate patents and/or extension from other countries. The four possible scenarios are described below:

ATE: The country produces and adopts patents from other countries, in practice it means that the nation

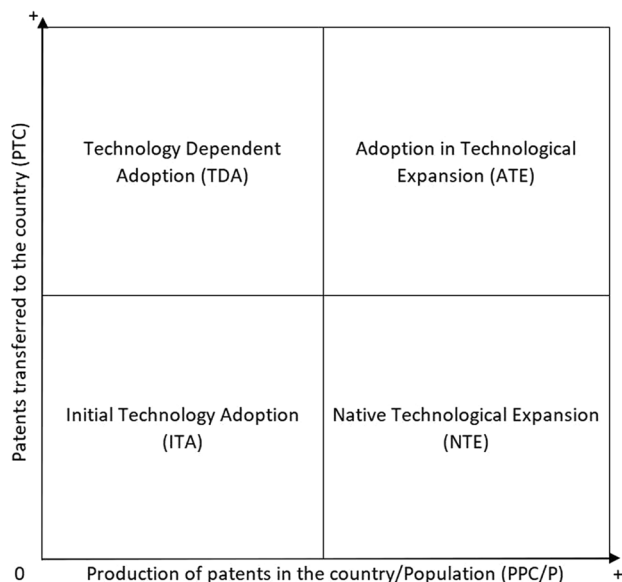


Fig. 3 Technology adoption matrix (TAM) for countries. Source adapted from [42, 63]

is combining the two strategies to adopt technologies, therefore, it is in technological expansion for that sector.

- TDA:** The country adopts patents from other countries, in practice it means that there is a technological adoption with high dependence on other countries. In other words, the national innovation ecosystem is underdeveloped.
- NTE:** The country produces and does not adopt patents from other countries, in practice it means that there is an autochthonous technological adoption, which produces a slow growth of the sector in the case of a LATAM country.
- ITA:** The country produces and/or adopts patents from other countries in small quantities, in practice it means that there is no technological development for this sector, or that it is at an initial stage that has not yet taken off.

For a country to be placed in the upper quadrants, its value for the evaluated variable has to be higher than the average of the set analyzed.

3 Results and discussion

3.1 Quantitative description

3.1.1 Priority countries from which patents are transferred to LATAM

The priority countries that have transferred the largest number of ECB patents to LATAM countries are led by the USA with 2975 patents, Japan with 736 patents and Germany with 606 patents. Together they have transferred 64.6% of the total number of patents (Fig. 4). The study by Baumann et al. [42] shows that Germany presents a lower patenting activity worldwide in relation to other countries such as Japan, China, or the USA in the case of LIB. On the other hand, for all ECBs transferred to LATAM, Germany ousts China (Fig. 5) [42]. The latter has only transferred 89 patents to the region. On the other hand, it is important to highlight Brazil with 564 in its role as the country of first registration.

3.1.2 Latin American countries of publication

Figure 5 shows the evolution of the number of patents registered in the countries of publication in LATAM. Brazil has concentrated the largest number of publications with

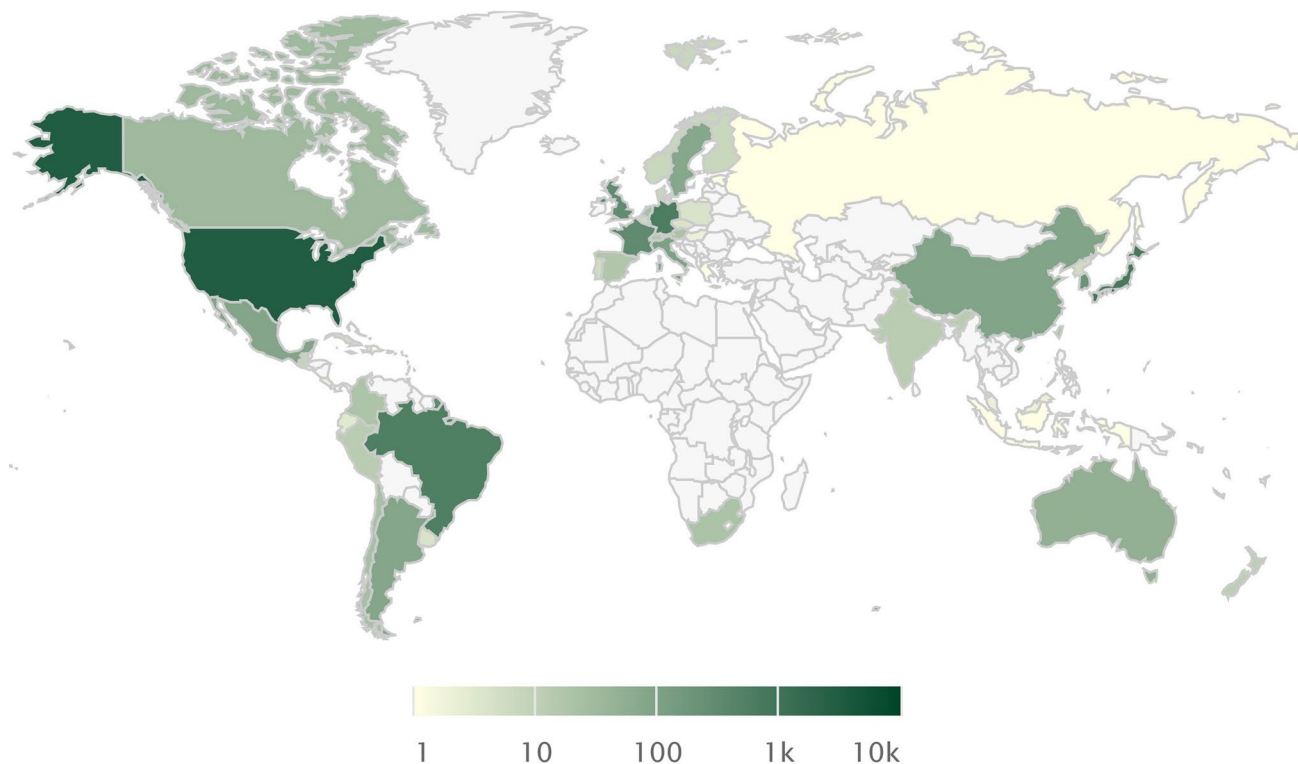


Fig. 4 Priority countries from which patents registered under the H01M code have been transferred to LATAM. *Source* Own authors using Pat-Seer

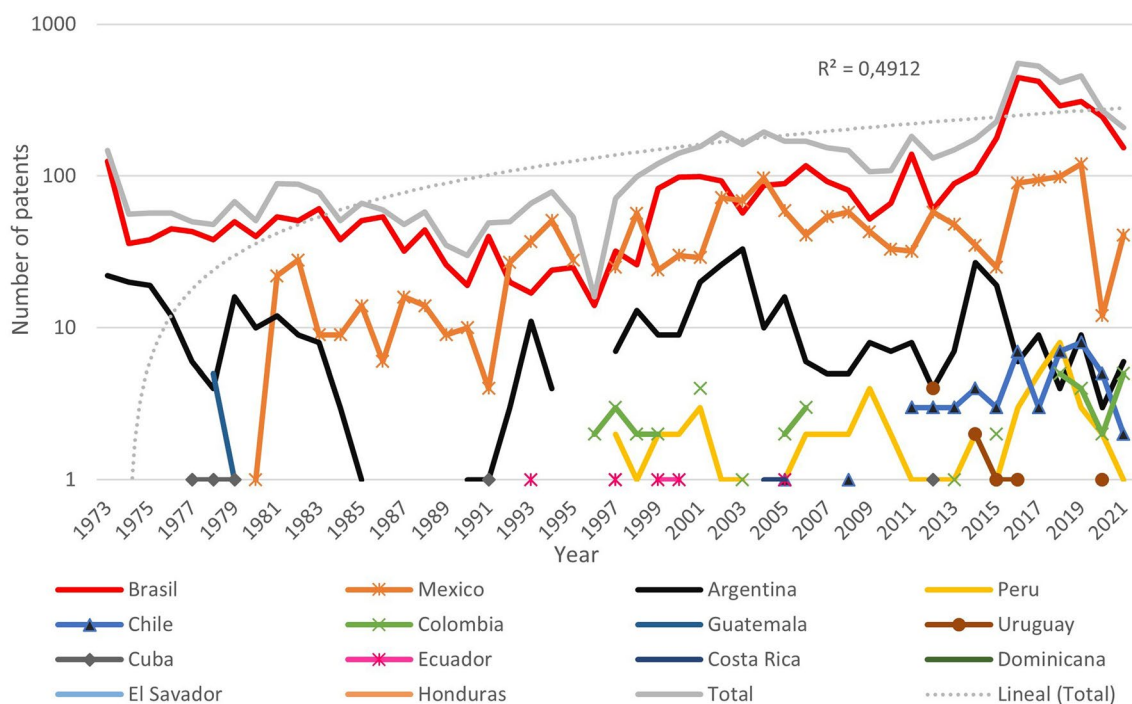


Fig. 5 LATAM countries in which patents registered with the H01M code have been published in the period 1973–2021. *Source* Own authors

58.7%, followed by Mexico (29.1%) and Argentina (7.5%). The other ten LATAM countries that complete this list represent only 4.7%. In terms of evolution over time, there is no statistically significant growth trend; however, the number of patents published in Brazil has increased significantly over the last 10 years. Brazil is the only country that presents results for all the years of the series. In the case of Mexico, it presents results since 1980, with the exception of 1996. Argentina presents a continuous series since 1979, with results that had not been systematized. As shown, generally the results before 2011 are discrete, this seems to be typical behavior worldwide as demonstrated by the study of [37], which only collected 2269 patents for the case of fuel cells for the period 1976 and 2011, using the US Patent and Trademark Office. This shows that these patents were underdeveloped until that period. On the other hand, the study developed by Díaz et al. [64] on patent analysis in general for the LATAM region determined that 21 countries in the period 1996–2007 presented patent registrations. Although the registrations were generally discrete, the same leadership structure shown in our study was observed (Brazil, Mexico, and Argentina). In the world more than 65,000 patents on electricity storage were filed [2] only within the period 2000 and 2018. Considering the existing methodological differences with respect to the information cited from this study, we can have an approximation of LATAM's weak performance in this field.

3.2 Transfer flows to and between Latin America (code H01M)

The main patent transfer flows to and between LATAM countries are shown in Fig. 6. Brazil is at the epicenter of the adoption of these technologies in the region, with a wide network of 47 countries (including incoming and outgoing), making it possible to compute a WDC of 5758 patent publications (including those registered by the country itself). In second place is Mexico, which has the same DC (47), however, its WDC is much lower with 2660. In both countries, the main flows come from the United States, Japan, and Germany. In the case of Argentina, it has a DC of 30 with 757 WDC patents, although the registrations are also led by the USA, in this case followed by the UK and Germany. Following in the ranking (DC-WDC) are Chile (23–173), Colombia (16–124), and Peru (15–86). It is noteworthy that in all LATAM countries, the USA leads in the registration of these patents, except in Cuba, which is the only country in the region that does not register any patents from this destination. This is a clear example of how political differences can affect technology transfer relations. An important aspect that we can observe is that there is little transfer between LATAM countries, only tenuous links are shown from Argentina and Chile to Brazil, from Argentina to Brazil and Mexico, and from Brazil to Argentina, all within a range of between 3 and 5 patents transferred.

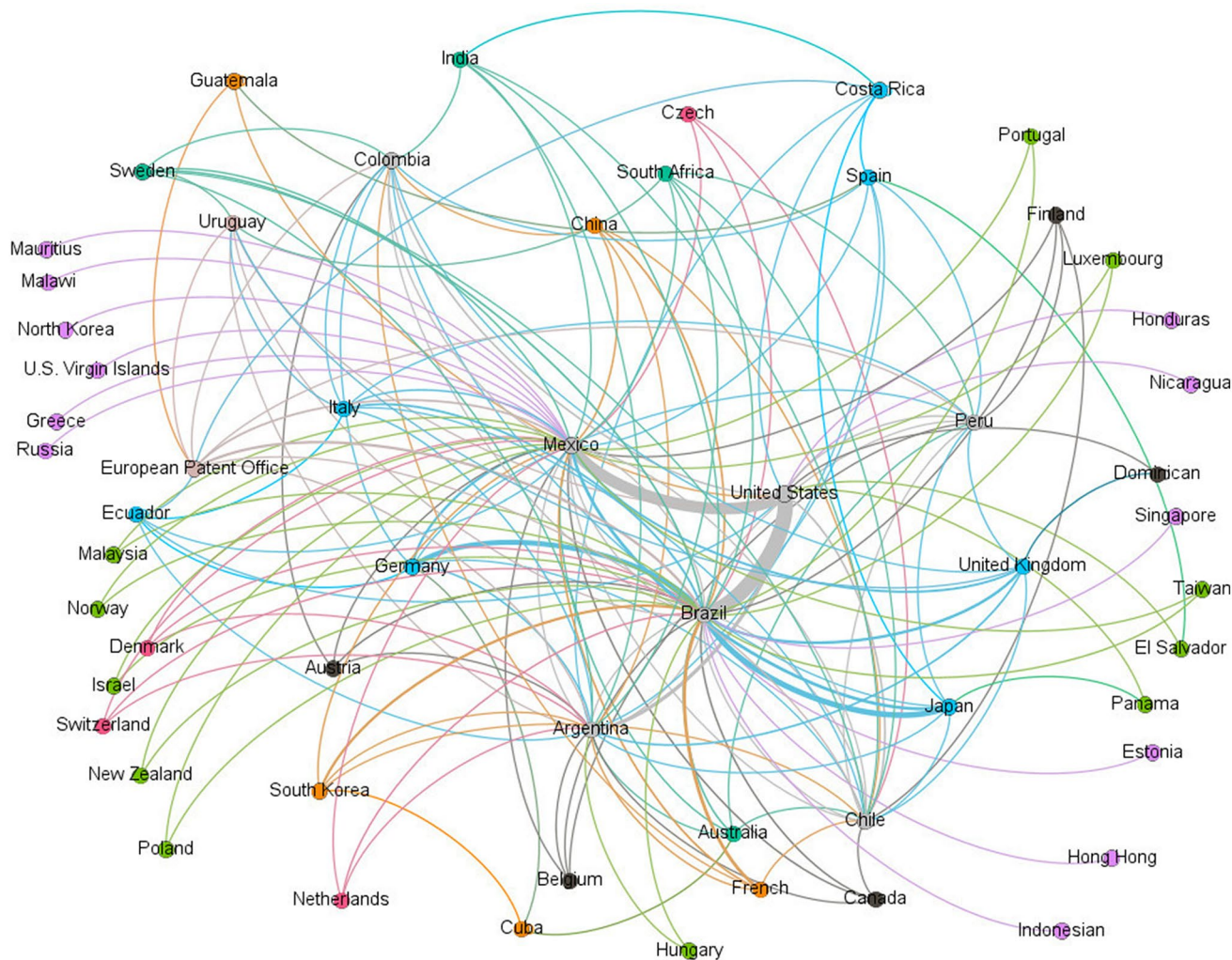


Fig. 6 Patent transfer map to LATAM (Code H01M). *Source* Own authors using Gephi

3.3 Analysis of patents published in LATAM

3.3.1 Analysis of technology share indicators

As stated by Baumann et al. [42], IPC searches may contain a large number of subcategories [42]. The analysis of these codes allowed us to understand which are the most relevant topics for the region in terms of ECBs. Accordingly, Fig. 7 shows the main 20 published technology subgroups in a structured way, the most relevant being H01M8/04: “auxiliary arrangements, e.g., for pressure control or for fluid circulation.” These elements are used to control heat exchange fluids and are associated with fuel cells. Other codes of the fuel cell family are also displayed among the most published. On the other hand, the specific indexing for LIB (H01M 10/052) presents a

discrete record. This result differs from other research that has concluded that LIBs widely lead the world in patent applications compared to other ECB patents [36, 38, 44].

The calculation of the RTS for the groups that form subclass BCE shows the following: group H01M4: “Electrodes” is the most relevant in terms of participation, followed by H01M2, which, as explained above, is equivalent to H01M50: “Details of construction or manufacturing processes of inactive parts of electrochemical cells other than fuel cells.” Then code H01M10: “Secondary cells.” Fourth, the code pertaining to “fuel cell” (H01M8) (Table 3). Although some fuel cell system subgroups lead the patent registrations of subclass H01M, at the group level, the H01M8 group is relegated to fourth position.

Most notably among the main industries where these patents have been transferred are the “battery and

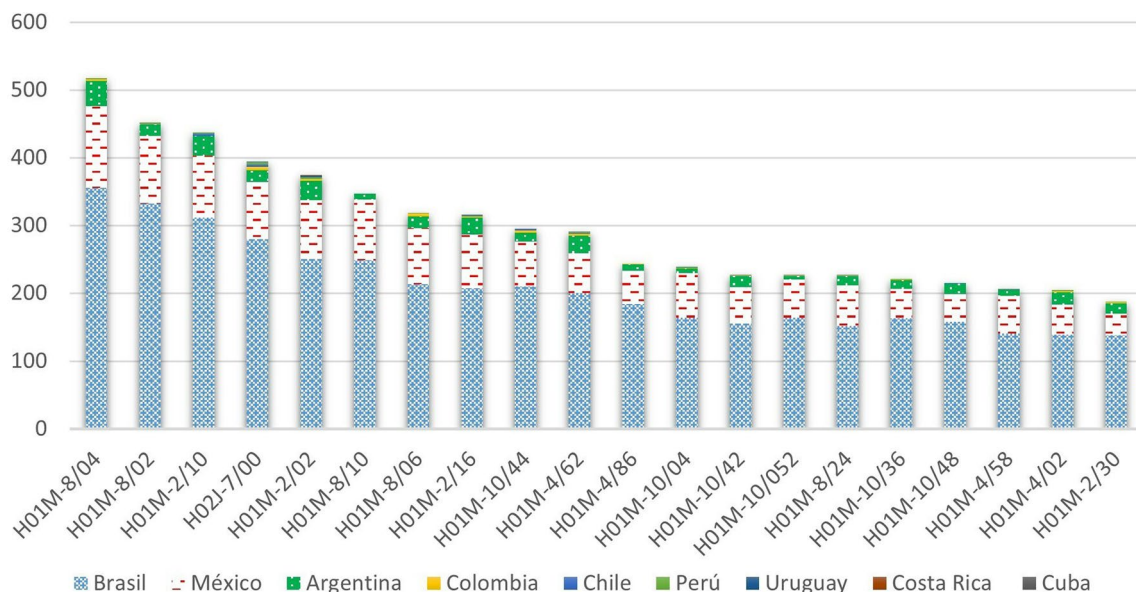


Fig. 7 Share by country in each of the top 20 technology subgroups. Source Own authors

accumulator” and “motor vehicle” industries, accounting for more than 76.4% (Fig. 8). The former can be considered a supplier to the automotive industry, although not exclusively, but it does show the general relevance of the automotive sector for the development of this field. According to some authors, in the case of this industry, the regulatory context has encouraged the innovative activities of automakers and their suppliers [16]. Correspondingly, it can be established that the LATAM countries that lead the adoption of patents on the subject are those where foreign automakers have established factories, as is the case of Brazil [65], Mexico [66], and Argentina [67]. This means that the adoption of patents on specific topics is related to the industrial development of the sector, thus reaffirming that patents can be a useful metric to evaluate the sectoral performance of industries.

Table 3 RTS indicator results in LATAM

Group	RTS (%)
H01M2	21.96
H01M4	27.41
H01M6	6.19
H01M8	20.01
H01M10	21.78
H01M12	1.65
H01M14	0.62
H01M16	0.40

Source Own authors

3.3.2 Analysis of Patents friendly to sustainable technologies

Table 4 illustrates the results obtained for the PFST indicator (see Eq. 2). In general, the results show a high co-indexation of ECB technologies with code Y02. This can be interpreted as 79.3% of the ECB patents published in Latin America countries present attributes that respond to climate change mitigation or adaptation. It should be stated that in the case of Dominican Republic, Honduras, and Ecuador, which present values of 100% for the co-occurrence indicator, this is due to few records of publications. In turn, there are other countries, such as Peru and Uruguay, where the technologies published have little to do with sustainability approaches. Brazil undoubtedly stands out, as it is the leader in the number of patent publications, with greater than (or >) 80% of them having sustainable attributes.

The co-occurrence map of the Y02 vs assignee code family shows the most prominent assignee companies in the acquisition of these ECB patents with sustainable attributes (Fig. 9). Most noticeable among them are foreign companies, led by GENERAL ELECTRIC CO (US), TOYOTA MOTOR CO LTD (JP) and NISSAN MOTOR CO LTD (JP). The role of certain national and international universities can also be seen, led by Brazil, where 99 universities are the assignees of 166 patents; Mexico, 36 universities with 62 patents; Argentina and Chile, 7 universities with 8 patents. Universities in the other countries have little or no participation. In general, Y02E 60/10 (energy storage using batteries) and Y02E 60/50 (fuel cells) are the highest grade.

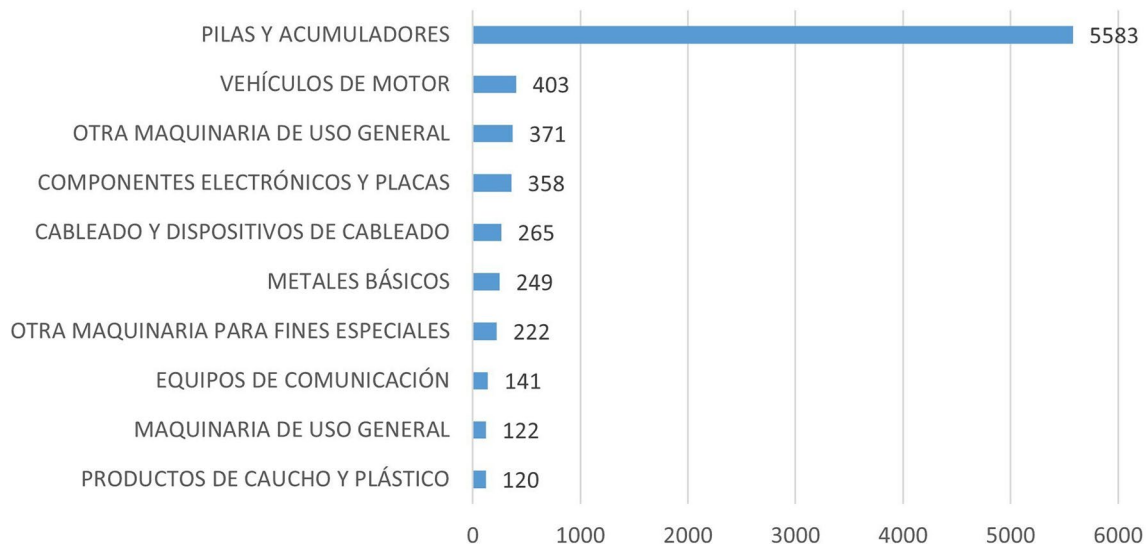


Fig. 8 Main industrial sectors related to patent publications on ECB in LATAM. *Source* Own authors

3.4 Analysis of technological evolution and forecast

Patenting in the field of LIBs in LATAM has been in a growth-consolidation phase (II) since 1998 (Fig. 10). This differs from the results of Baumann et al. [42], which found that in the case of the countries leading in LIB patenting, they are in a phase of strong maturity [market penetration (III)], even estimating that they may be entering a saturation phase (IV). The difference between the two studies can be largely explained by the fact that only a small part of LIB patents are transferred to LATAM, and that there is a significant lag between the publication date in the priority country

and the publication date in Latin American countries. On average, this lag is 5.1 years with a standard deviation of 3.2 years.

On the other hand, fuel cell technology is in a maturity phase and could enter its saturation phase within the current decade in LATAM. Mock and Schmid [68], using information on world fuel cell patents up to 2003, estimated that fuel cells should reach their saturation phase by approximately 2015. Subsequently, Haslam et al. [69], using patent information up to 2011 from China, Japan, and South Korea, noted that since 2009 there has been a drop in the number of publications. However, the authors consider various causes such as delays in updating the database, the financial crisis of 2008, or simply arrival at the saturation stage. In general, the results shown in the s-curve for fuel cells in LATAM (Fig. 10) reinforce the idea that they are very close to the saturation stage. Considering that in the case of these patents there has been a greater number of transfers to LATAM, with a lower lag of 4.3 years and a standard deviation of 2.8 years.

Table 4 PFST indicator results in LATAM countries

Publication Country ($N=6742$)	PFST (Y02; H01M) (%)
Brazil	83.9
Mexico	68.9
Argentina	77.8
Peru	33.9
Chile	64.0
Colombia	68.4
Guatemala	88.9
Uruguay	44.4
Cuba	60.0
Ecuador	100.0
Costa Rica	75.0
Dominican Republic	100.0
Honduras	100.0
Total	79.3

Source own authors

3.5 Strategic analysis of technology adoption: the Technology adoption matrix (TAM)

Figure 11 shows the strategic analysis of the technological performance of each country in the LATAM context where, in addition to the position in the quadrants, the total number of patents adopted is also represented by the diameter of the bubble. This reaffirms the technological development achieved by Brazil, which is in the Expansion quadrant. In second position is Mexico, but in the Adoption quadrant, which means that its performance has depended on transfer from other countries. Argentina

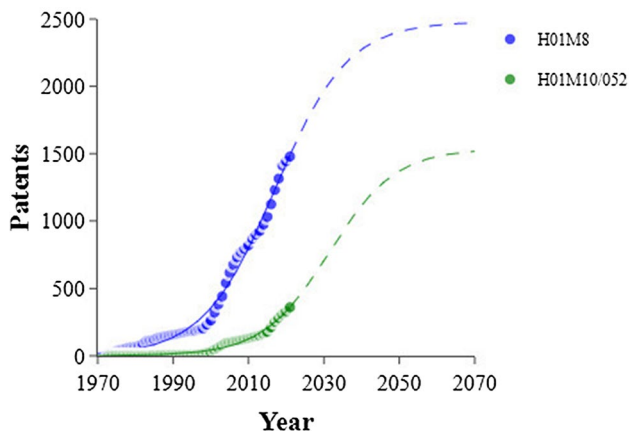
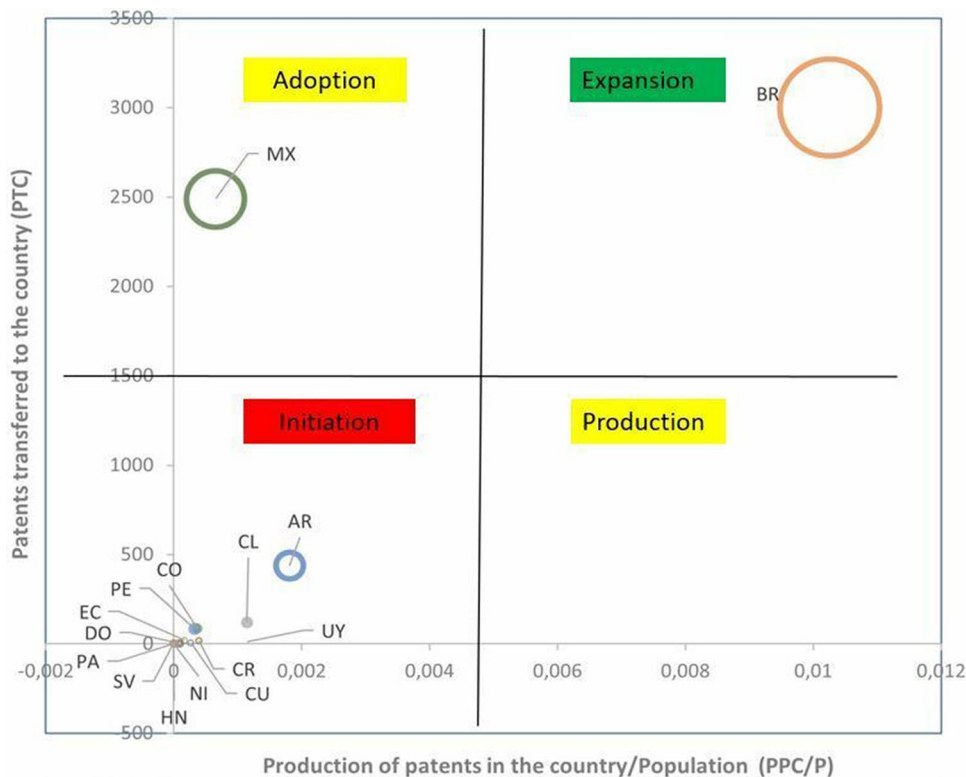


Fig. 10 LIB and Fuel cells s-curves in LATAM. *Source* Own authors using Loglet Lab

other governments such as Bolivia, Costa Rica, El Salvador, Panama, Paraguay, Trinidad and Tobago, and Uruguay are working on their own strategies [71]. Furthermore, South America has the world’s largest lithium reserves, located specifically in Chile, Argentina, and Bolivia, in an area known as the lithium triangle [72].

Despite the Region’s enormous potential in these areas, the findings of this study regarding the low rate of adoption of patents on ECBs in LATAM countries and the technological lag in the evolution of key technologies, ring alarm bells regarding these countries’ real possibilities of developing a full strategy to exploit hydrogen through the use of fuel cells or to make maximum use of lithium reserves by manufacturing components for LIB systems in the Region. The present low or null patenting rate indicates the fledgling state of these industrial sectors in the Region. This leads us to believe that, if the current levels of patenting in these

Fig. 11 Technology adoption matrix for LATAM countries. *Source* Own authors



4 Discussion

Currently, some LATAM countries are clearly focused on developing hydrogen as the energy carrier of the future. As is the case with Chile, which outlined a strategy that seeks to take its production worldwide [70], being supported by other countries such as Colombia, which also published a roadmap, and Brazil, which presented the basis for consolidating the Brazilian hydrogen strategy. At the same time,

areas are maintained, LATAM will maintain its current role as an exporter of commodities or low value-added goods [73]. In general, countries develop R&D policies according to their technological leadership position and the complexity of technologies [74]. For this reason, it is unlikely that LATAM countries will achieve leadership in the production of highly complex technology such as ECB systems. Instead, the development of a policy focused on the adoption of new inventions would allow them to play a more active role in

the supply chain within the framework of the expansion of green technologies.

In this regard, the key is to strengthen open innovation ecosystems, allowing them to adopt major inventions in order to reach their maximum potential in terms of exploiting these resources with a sustainable approach [75]. For this purpose, it is essential to continue strengthening alliances with countries such as the USA, Japan, China, and Germany, which have high productivity in patent registration on the subject [42]. In this case, South Korea should also be considered, despite not currently being among the countries leading the transfer of patents to the region, however, its national hydrogen strategy includes plans to position itself as a leader in the production of technologies related to the hydrogen chain [76].

On the other hand, the low patenting rate in some countries may be related to what was raised in a recent Chilean based study that identified a very fragmented inventor system, consequently the authors emphasize the need for strong government intervention to direct research funding and greater collaboration among inventors, especially local ones [77]. Additionally, we consider that funding should be conditioned to projects containing clear goals in terms of patent registration since, as Popp [17] posits, innovation responds quickly to incentives. Another cause may be associated with the low presence of the automotive industry in the Region, given that these countries have traditionally been exporters of commodities and importers of technologies [78].

Given the strong sustainable focus of patents on ECBs, these technologies are expected to be strongly supported by governments in the pursuit of achieving environmental goals and achieving greater national competitiveness of their companies [74]. There is evidence that innovation incentive policies can have a positive effect on technological development and consequently a higher production of inventions [17]. In addition, national environmental regulations could force the sector's clusters to develop mechanisms to provide the innovation ecosystem with the means to achieve concrete goals in terms of solutions that allow the massive incorporation of new inventions that respond to local problems. As shown in Fig. 8, the automotive industry and its suppliers play a leading role in adopting these patents, according to Borgstedt et al. [79], therefore, regulations could have greater effects if applied within these sectors. In this sense, it is important to indicate that the automotive industry has not established itself in many countries of the Region, consequently regulations or actions should focus on those companies that exploit natural resources (copper, lithium, nickel) and those companies that will be in charge of the future development of hydrogen, i.e., formal requirements should be established to develop innovation ecosystems and therefore develop a value chain around primary resource. As evidenced in the study by Yeh et al. [80], who used patent data to demonstrate that

in the cases of Japan, Germany, and the USA, control technologies for innovations in nitrogen oxides (NO_x) were not implemented until strict government regulations were established, and that this forced innovation [80]. This is also the case for the Zero Emission Vehicle Mandate, introduced by the California Air Resources Board in 1990, where automakers focused on developing more efficient engine technologies [16]. In turn this innovative pressure is transmitted from automakers to their suppliers [79].

Some regulatory instruments have in fact been formulated among the countries analyzed, such as the energy efficiency label in Chile, the energy efficiency and CO₂ emissions standard in Mexico, and the Inovar-Auto program in Brazil [65, 81, 82]. In this regard, we consider that LATAM countries currently require more demanding standards to enable progress with the commitments assumed in the main international agreements for climate change mitigation [18, 83].

5 Conclusions and future research directions

Using IPC data and taking the registration of patents associated with ECBs as a reference, it can be concluded that in the LATAM region, Brazil and Mexico are clearly leading in the inventor and publication country categories. Argentina, on the other hand, shows some progress in adopting these technologies, being mostly dependent on the extension from other countries. Therefore, in their case, it is necessary to promote innovation challenges to stimulate the production of local solutions that respond to the problems of this industrial sector and balancing dependence on foreign inventions. In any case, the relevant LATAM policies should promote a balance between national and international patents. However, when initially developing the sector, greater dependence on international inventions would be acceptable to accelerate and create new capacities both in production and in the innovation ecosystem.

In terms of transfer flows, it can be concluded that there is a high dependence on patents from the USA, Japan, and Germany. Therefore, there is an opportunity to increase the number of patents transferred by diversifying the transfer of knowledge from those countries that command worldwide leadership in the registration of patents, such as China, South Korea, and other European bloc countries. To achieve this, LATAM governments and companies should consider the high dependence of these countries (China and South Korea) on the region's raw materials, which are essential components for the manufacture of ECBs. Therefore, if they succeed in negotiating changes in value chain structures by implementing greater integration with LATAM countries, this could have positive medium-term effects for developing

new patents registered in their national offices and the development of the industrial sector.

Patent publications classified under the specific codes for fuel cell (H01M 8/00) have performed better than those indexed for LIB (H01M 10/052), however, in both cases they are mainly concentrated in three countries: Brazil, Mexico, and Argentina. Therefore, it can be concluded that considerable asymmetry exists within the region in terms of adopting these technologies. In general, patent publications have depended mainly on foreign countries.

Technological evolution in LATAM for LIBs has been affected by the low production and transfer of patents, as well as the existing lag in the transfer from priority countries to LATAM countries. On the other hand, in the case of fuel cells, there is greater synchronization with respect to the evolution shown by other studies, which can be explained by the fact that there has been a greater number of transfers to LATAM with a smaller lag.

The analysis of the IPCs carried out is a first step towards future studies on these topics, since it provides a general overview of the codes that have been most widely adopted in LATAM. The most important industrial sectors have also been defined, making it possible to establish that the major technological adoptions are related to the automotive industry and battery suppliers.

Given that most LATAM countries are at an early stage of technological adoption, it is necessary to formulate strategies in three directions: the first, the development of applied research with challenges related to these technologies; the second, the subsidized adoption of technologies in this sector [84, 85] in order to advance the promotion of the best inventions and consequently the development of these industrial activities; and the third, to design and implement restrictive or incentive legislations focused on the automotive industry and its battery suppliers, also considering mining companies and future H₂ suppliers, due to their importance in the automotive manufacturing value chain, as well as their great financial capacity.

In parallel and in correspondence with the first strategy mentioned above, it would be beneficial to bring universities closer to the productive sector. In practice, many LATAM countries have clear policies regarding the promotion of research, and these policies are part of the requirements for university accreditation, which is reflected in the number of scientific papers published, however, no specific goals focused on the generation of patents are set. Therefore, we believe that promoting regulations in both the productive sector and universities may foster an important symbiosis in generating patents that respond to environmental problems and the development of this industrial sector in the national spheres. In this sense, it is essential to strengthen the legal aspects of university technology transfer, such as the obligation in some cases of academics to cede their inventions to the university

for which they work, the ownership of the patent when an academic works in collaboration with an external company on a university project, and the use of patents for educational purposes, among others [86].

By means of the sustainable concurrence indicator or Patents friendly to sustainable technologies, it was determined that 79.3% of the patents on BCE published in LATAM have attributes that contribute to mitigating or adapting to climate change. Therefore, the efforts and actions carried out in this field would contribute to strengthening the commitments assumed by the countries of the region within the framework of the Paris Agreement and the SDGs [18, 19]

The proposed Technology adoption matrix makes it possible to establish comparisons and evaluate the degree of technological incorporation for a set of countries. Although it does not seem useful when comparing countries with high asymmetry in terms of their level of development, it is a useful tool for evaluating developing countries. This is because the high values of patent registration presented by countries such as the USA, Japan, China, among others, would always place LATAM countries in a relatively lower position.

The present study has focused exclusively on patent publications associated with ECB, including fuel cells that would lead to large-scale use of H₂. However, given that the H₂ production chain involves a wide spectrum of technologies, future lines of research include studies analyzing the state of adoption of patents for other phases, such as energy production, electrolytic separation of H₂ (production), storage and distribution, and even other forms of H₂ use. It would also be interesting to address other phases related to EVs, such as charging systems.

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Data availability The datasets used and/or analyzed during the current study are available from the corresponding author.

Declarations

Competing interests The authors confirm that there are no conflicts of interest with this publication.

Ethics approval and consent to participate Not applicable.

Consent for publication Not applicable.

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