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Research paper

Smart energy planning for the decarbonization of Latin America and the Caribbean in 2050

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ABSTRACT

Latin America and the Caribbean is a region that has grown enormously in public policies and especially in the implementation of renewable energy generation plants, which is why it deserves to study its growth to provide long-term deep decarbonization routes. It has approximately 634 million inhabitants, and it is expected that by 2050 it will reach 784 million inhabitants, which worries researchers to establish a new model of energy supply in accordance with future demand. The concern does not end here, the new energy supply must be friendly to the environment and renewable energies are the appropriate option to avoid the increase in global temperature. The challenge of this research is to provide an adequate option for the decarbonization of Latin America and the Caribbean to achieve 100 % renewable energy by 2050. For this purpose, the energyPLAN tool is used, a flexible tool, very useful to transform large energy systems based on fossil fuels and achieve comprehensive 100 % renewable markets. Power systems are considered a challenging task and are widely studied around the world to avoid the great negative effects of altering the climate. Modeling the zero carbon energy system was implemented using the concept of smart energy. The combination shows that it is necessary to use a wide variety of energy sources and that no energy source more than 35 % stake, to increase energy security. The historic hydroelectric technology will continue to be an essential part of the Latin American energy mix. However, in 2050, the technologies that are destined to have the greatest participation will be wind turbines and solar photovoltaic with 32.7 % and 31 % respectively. Technologies with less participation such as renewable thermal and geothermal are also identified. Achieving a 100 % renewable energy mix by 2050 will prove to be economically beneficial. Based on the results obtained, it will be effective to achieve a 100 % renewable scenario when Latin America and the Caribbean form a solid regional alliance exclusive to fight for the environment and legislate favorably so that its member countries contemplate important budgets in a conscious, responsible and supportive way.

1. Introduction

1.1. Background

The integration processes in Latin America and the Caribbean (LAC) are undergoing renewed political momentum with advances on different fronts and at different speeds, including environmental protection and energy development. There are currently various regional or subregional integration organizations (Para and y el Caribe, 2011). The latest current of integration is the Pacific Alliance. The established organizations are: Unión de Naciones Suramericanas (UNASUR), Comunidad Andina (CAN), Mercado Común del Sur (MERCOSUR), Comunidad del Caribe (CARICOM), Alianza Bolivariana para los Pueblos de Nuestra América (ALBA), Sistema de la Integración Centroamericana (SICA), Comunidad de Estados Latinoamericanos y Caribeños (CELAC) and the Pacific Alliance.

Deep decarbonization to achieve zero net CO_2 emissions in LAC is technically feasible and could bring enormous social and economic benefits, improving air quality and biodiversity. However, to overcome the great existing challenges it is necessary to plan (ILPES, 2019). The latest COP26 climate summit held in Glasgow keeps the fight against global warming alive (admin, 2021). Long-Term Strategies (LTS) enshrined in the Paris Agreement on Climate Change remain in force, they can help in structuring the policy packages necessary to achieve climate objectives and development priorities simultaneously (Bataille

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Nomenclature

ACM	Absorption cooling machine
ADFD	*Abu Dhabi Fund for Development*
ALBA	Alianza Bolivariana para los Pueblos de Nuestra América
CAPEX	Capital Expenses
ECLAC	Economic Commission for Latin America and the Caribbean
CAN	Comunidad Andina
CARICOM	Comunidad del Caribe
CELAC	Community of Latin American and the Caribbean
COE	Cost Of Energy
COP	Coefficient of performance
CLACS	*Community of Latin American and Caribbean States*
CRF	*Capital Recovery Factor*
DDPLAG	*Deep Decarbonization Routes of Latin America and the Caribbean*
EEC	*European Economic Community*
EU	European Union
ESI	*Energy Savings Insurance*
ESR	*Energy Supply Ratio*
ESRL	Electricity Sector Regime Law
FDA	*French Development Agency*
FPC	Flat plate collectors
GEP	Generation Expansion Plan
GDP	*Gross Domestic Product*
HDI	*Human Development Index*
HL	Heating load
IDB	Inter-American Development Bank
IEA	International Energy Agency
IRENA	*International Renewable Energy Agency*
IRES	Integrated Renewable Energy System
LAC	*Latin America and the Caribbean*
LAFTA	Latin American Free Trade Association
LPG	*Liquefied Petroleum Gas*
LTS	*Long-Term Strategies*
MERCOSUR	Mercado Común del Sur
N	*Number of years*
NCEC	*National Center for Energy Control*
NCRE	Non-Conventional Renewable Energy
NDC	*Nationally Determined Contributions*
OPEX	Operating Expenses
PV	Photovoltaic
PE	Primary energy
RE	Renewable Energy
RF	Renewable Factor
SICA	Sistema de la Integración Centroamericana
TAPE	*Total Additional Projected Energy*
UNASUR	Unión de Naciones Suramericanas
V2G	*Vehicle to Grid*

Formulae

$f_{maxp_{load}}$	Incremental annual AC charge element that allows maximum use of excess power.
P_{LY}/C	Energy yearly electricity consumption per capita in kWh/y/person.
$f_{max_{SE}}$	Element of maximum consumption of surplus electrical power.
P_{SE}	Annual energy surplus in kWh/y.
n_{HUMAN}	Number of people with access to renewable power generated.

et al., 2018). The Deep Decarbonization Routes of Latin America and the Caribbean (DDPLAC) project, supported by the French Development Agency (FDA), the Inter-American Development Bank (IDB) and the Pathways 2050 Platform, managed by IDDRI, has been designed to help build local research capacity in LTS design based on sound scientific evidence and to input data into national and international policy dialogues (Bersalli et al., 2020). It has brought together teams from Colombia, Argentina, Costa Rica, Ecuador, Peru and Mexico with the aim of developing capacity to generate models of energy development and land use, create a modeling community, shape existing scenarios of Nationally Determined Contributions (NDC) and develop deep decarbonization routes (La descarbonización profunda en América Latina y el Caribe,n.d). These developments were based on sound scientific data, driven by countries and consistent with the Paris Agreement, the latest developments at COP26, and local socio-economic priorities (Kuzemko et al., 2020). The integration of LAC has allowed it to play an important role in the processes of participation of decision makers and other types of actions, in the preparation of LTS, as well as coherent complementary policies until reaching concrete implementation actions of new plants of renewable energy.

The population of LAC will increase from 634 million current inhabitants to 784 million in 2050, which represents an increase of 26.3 percent, which in turn represents 9 percent of the total world population (Press, 2015). LAC has had a sustained socioeconomic development during the last 15 years. The growth rate of the Gross Domestic Product (GDP) is around 3 % in the region (Hanif, 2017) meanwhile, the demand for electrical energy during the coming decades has maintained a significant growth especially in the South American countries. It is important to increase investments in the electricity sector to achieve greater efficiency and energy security (Mahlknecht et al., 2020).

Compared to other regions such as Asia, Europe and North America itself, the combination of electrical energy from South America and Central America is the least carbon intensive in the world due to the higher proportion of renewable energy (Zhang et al., 2018). The main factor is due to the fact that South America has large flows in its rivers, which historically has given rise to take advantage of the hydroelectric capacity (Hernández-Padilla et al., 2017; Moran et al., 2018). However, it does not imply avoiding efforts, on the contrary, all efforts are required to restrict the increase in global temperature of the planet and do not exceed 1.5 degrees Celsius (Zhao et al., 2021). All regions are part of the same planet and renewable energy systems must be properly planned. In the region, lethal actions such as river overflows, landslides, land subsidence in the face of a changing hydrological regime, which makes the electrical system more vulnerable, have already occurred repeatedly. Extreme weather events have been changing the water cycle and the water regime at the drainage base, thereby threatening the availability and reliability of hydroelectric sources (Posso Rivera et al., 2022; Nadaleti et al., 2022; Lazaro et al., 2022). Prolonged droughts and intense rains have originated in the region, among them the larger Brazil and its consequent 45 % reduction in the water levels in the reservoirs of hydroelectric dams in the last five years (Ruffato-Ferreira et al., 2017), and due to that 71 % of the electricity supply in the country depends on hydroelectric energy (Grottera et al., 2022), leading to the revision of the electrical system in one that is more diversified and among them, it is committed to wind and solar photovoltaic (Miravet-Sánchez et al., 2022). In this way, the consequences of climate change will be prevented from altering the lives of the population and putting the security and electricity supply in imminent danger. During the last years, hydroelectric power generation rates have been decreasing in Latin America and this downward trend will continue (de Moura et al., 2018). Advantageously in relation to the potential of non-hydroelectric renewable energy (RE), it is available in LAC due to the vast potential of wind and solar energy and biomass, which will allow it to maintain its high contribution from renewable energy (Viviescas et al., 2019).

Most of the region's territory is influenced by the Solar Belt with the highest solar radiation, among them Argentina, Chile and Bolivia are among the ten countries in the world with the highest possible irradiation through photovoltaic systems (Global Solar Atlas,n.d). The Atacama desert, the driest non-polar place on Earth, has the best maximum global solar irradiation of 2770 kWh/(m^2.y), available for the use of energy through fixed photovoltaic systems with optimal inclination (Martínez-Martínez et al., 2022; Schmid and Breyer, 2010). Regarding the potential for wind power generation, Paraguay (north region), Bolivia (southeast region), Brazil (northeast region), Chile (northwest region) and Argentina (east and south region) have high potentials for energy generation through wind energy sources (Global Wind Atlas, n.d). The area that stands out for its characteristics is Patagonia, Argentina, one of the best wind sites in the world (Lässig et al., 1999; Lu et al., 2009). However, it cannot be underestimated that the rest of the region also has very good characteristics for the use of solar and wind energy. From this it is consolidated that LAC is a natural paradise not only for its flora and fauna, but also for its clean energy potential (Icaza et al., 2022a; Perevochtchikova et al., 2019).

In relation to the fuel that has been widely used by LAC in various applications and at the time they were very useful. However its uses currently bring growing social and environmental problems (Zachl et al., 2022). In the first decades of the 21st century, the processes of massively exploitation of fossil fuels accelerated in the so-called era of industrialization (Oskouei et al., 2021). However, these levels of extraction alarmed the international community since its effects triggered a growing global warming (Zhao et al., 2021) and its effects are felt to this day. Global climate change, in addition to causing effects on living beings, includes problems of the scarcity of fossil fuels and a widening of the gap between rich and poor (Mutezo and Mulopo, 2021).

The energy requirement is for all human beings, however not all countries enjoy the service in its proper and timely manner. Several countries to date make very high investments in fuels to generate energy at prices that are inaccessible to the poorest sectors (Hanif, 2017). In this century, the levels of industrialization increased remarkably in relation to the previous century. Several areas developed quickly and unexpectedly, such as telecommunications, robotics, at extraordinary levels, however, global pollution levels came to affect the climate and species like never before (Christidis et al., 2021).

Climate variation around the world has added to the problem of fossil fuel depletion. Given this situation, it is reasonable to strengthen the structure of the electricity market or start looking at other energy production systems that are friendly to the environment, which in this case, renewable energies are the best option. Despite these adverse conditions, in some countries it is still difficult to overcome the traditional model based on energy consumption from oil exploitation. Precisely because of the lack of roadmaps and more adequate planning based on renewable energies such as the one presented in this research and discussed for effective decision-making (Bersalli et al., 2020). Undoubtedly, above all, oil has been of great use to several countries, but the environmental damage it has caused has also been questionable (Viviescas et al., 2019). In this sense, Ecuador is one of the countries that is the victim of contamination in the Amazon, the uncontacted peoples had to migrate to other areas to survive in the face of the inclement logging of their protective forests after drilling oil wells and the most denigrating that several species were affected for oil spills (Buccina et al., 2013). The global energy matrix is changing advantageously, perhaps not at a rate that would be desired. There are positive factors that suggest that renewable energies will have a greater impact in the coming years thanks to the results and excellent experiences that are being noticed in practically all regions of the world (Oskouei et al., 2021). Although investors in fossil fuels are given multiple ways to stay in the market protected in legal aspects, or entrenched in geographically poor sectors or islands, this wave of changes will undoubtedly have an effect in the medium and long term (Cano et al., 2021). Governments now have greater clarity about the environmental, economic and social implications behind polluting energies and, above all, citizens are increasingly critical thanks to the fact that the sources of information and knowledge have crossed all barriers (Mirakyan and De Guio, 2013). 2015 was one of the years that generated the greatest initiatives from the countries themselves in relation to measures to protect and adapt to climate change, the year in which the COP21 was held in Paris (Pires, 2017). International conglomerates pledged to promote joint actions to limit global warming below 2°C (Rogelj et al., 2016). Four years later, a new summit was planned, the COP25 in Madrid, which unfortunately had to put up with certain countries that opposed the initiatives outlined (admin, 2019). At COP26 held in Glasgow, despite the questioning and criticism from certain sectors, the encouragement was still held for countries to make more ambitious efforts (Smith et al., 2021). They must include investments in their planning with a view to reducing their emissions and increasing technologies related to renewable energies as a true option to decarbonize the planet in compliance with the Paris Agreement (Kamalinia et al., 2014).

In LAC there is still no reference study in the scientific literature in which the roadmap for the region is presented, there are reports from Agencies and non-governmental entities that have biased interests, legitimate of course, but it is necessary to impartially investigate where LAC must be addressed in energy matters. Based on this reality, this research aims to structure the energy system for LAC and provide the roadmap so that decision makers can restructure their energy systems. It can be done from the countries, establishing alliances between them and lateral contributions to commit their necessary investments in this fight for climate change that affects the region and the entire world.

1.2. Previous work

Several studies have shown that renewable energies are effective solutions for the supply of electricity in rural areas and for cities in constant growth.

The alternative that best fits is to take advantage of the renewable energy potential of the same localities to provide sufficient electrical power to the demand. Depending on each area, the technologies will be coupled very well in isolation or forming hybrid systems according to proper planning (Lee et al., 2009).

Several researchers insist on adequate planning to carry out the energy transition processes. For this, a lot of emphasis has been placed on drawing the roadmaps of the decarbonization processes, the use of specialized software is an appropriate option to draw the development scenarios before committing financial resources. The most current technologies are solar photovoltaic, wind, biomass, hydraulic and they are viable. It has been widely demonstrated that they integrate well forming hybrid systems with connection to the public or isolated network. D Connolly et al (Connolly et al., 2010). made an exhaustive review of the computer tools that allow analyzing the integration of renewable energies in various electrical systems.

Dominkovic et al. (2021) presents a base scenario with a mixture of renewable and polluting energies and through the energyPLAN tool developed by the University of Aalborg (Dominković et al., 2016) he traced the energy scenario for 2050 and compensates it with renewable energies in southeastern Europe.

There are also relevant tools to analyze long-term energy systems, several of which are detailed below: Pypsa Python for Power Systems Analysis (Brown et al., 2018), is a free software toolbox for simulating and optimizing modern electric power systems over multiple periods. It is designed to be easily extensible and scale well with large networks and long time series. PyPSA includes models for conventional generators with unitary commitment, variable renewable generation, coupling to other energy sectors, storage units and mixed alternating and direct current networks. There is also the open source EMPIRE Model based on multi-horizon programming for energy transition analysis (Backe et al., 2022), which combines short-term operations with the representation of long-term planning decisions, including infrastructure expansion. The EMPIRE model has a unique mathematical modeling structure based on multi-horizon stochastic programming, meaning that investment decisions are subject to short-term uncertainty represented by different realizations of operating scenarios. The model is open source and ready to be used to analyze energy transition scenarios towards 2050 and beyond. Another of the tools currently developed is HighRES: The high spatial and temporal solving electrical system model (Price and Zeyringer, 2022). The model is specifically designed to analyze the effects of a high proportion of variable renewables and explore integration/-flexibility options. highRES is a high-resolution power system model that simultaneously considers infrastructure planning (investment) and operational (dispatch) decisions to identify the most cost-effective strategies to address the growing share of intermittent renewables.

There are currently challenges of reliability-oriented grid restructuring and reconfiguration that arise in the long term when considering future trends in demand growth as well as power line degradation. From this point of view, a relevant work is the one proposed in (Braga and Saraiva, 2005). This research considers three criteria: investment costs, operation costs and expected energy not supplied. The solution algorithm adopts an interactive decision-making approach that begins with a non-dominated solution to the problem. After obtaining this first solution, the decision maker can alter the aspiration levels and run the application again to obtain a new solution. Once an expansion plan is accepted, the algorithm calculates long-run marginal costs, these costs are more stable than short-run costs and inherently address the revenue reconciliation problem well known in short-run approaches.

Esteban et al. (2018) presents a 100 % renewable energy mix for Japan. Along the same lines of long-term market planning with 100 % renewable electricity systems, V Krakowski et al. (2016) designs a prospective electric system supported by clean energy for France transferring from 40 % to 100 % renewable energy by 2050. Bogdanov et al. (2021) presented an investigation for the energy sector to achieve a 100 % renewable energy supply by integrating the energy, transport, industry sectors and heat. According to data presented by Energy Monitor (Portal Energético para América Latina and Global Energy Monitor,n.d), the requirement for renewable electrical power in Latin America is around 212 GW with reference to 2015.

Various investigations show that it is possible to get markets with high inputs of renewable energy to achieve zero carbon in the long term (Lohrmann et al., 2021; Román-Collado et al., 2021; Cantarero, 2019). The variety of technologies that use renewable energies are achieving enormous developments both in territorially large and small countries around the world. The different strategies and policies that are drawn within the countries allow restructuring the electrical system with contributions of varied renewable energy (Barbero et al., 2020; Zaborowska et al., 2021). There are countries, including regions, that have taken the lead in restructuring their energy systems with a view to complete long-term decarbonization, while other countries are considerably behind schedule which was also a matter of concern at COP26 held in Glasgow. In order to reduce this gap between countries that promote public policies in favor of the use of renewable energy technologies, reference (Elie et al., 2021) presents financing options through highly developed countries, international agencies or through green bond swaps. The Macedonian case presented by Ćosić et al. (2012) is an interesting example of analysis by posing completely pollution-free, highly flexible and economically viable scenarios. M Doepfert and R Castro (Doepfert and Castro, 2021) presented the case study of Portugal in which it maintains high proportions of hydraulic energy to transform the system into 100 % renewable by 2050. Meanwhile, Child et al. (2019) state that it is advisable to have systems of energy storage within renewable production systems to maintain the continuity of electricity service in hours of low production from renewable sources and the case of European stands out.

F Polzin et al., through (Polzin et al., 2019), makes a strong criticism of decision makers and states that various policies should articulate processes and should not remain in good intentions. Along the same lines, Blazquez et al. (2018) state that it is important to specify a coherent, fast and efficient development. Renewable energies are the most certain and fully identified way to fight global warming, it is not possible to wait for another alternative that is not visualized (Hansen et al., 2019). UB Akuru et al (Akuru et al., 2017). present the case of Nigeria, while Tin et al. (2010) emphasizes that energy efficiency actions should be considered in order to optimize energy. Ahmadi et al. (2020) suggests carrying out synergies between countries, especially to make effective and comprehensive investments for the implementation of renewable energy generation plants.

Wu et al. (2012) highlighted that the costs of clean generation technologies tend to decline each time, allowing more and more localities to be supplied, allowing a greater contribution of renewable energies in the different countries. As these technologies give citizens confidence, costs will continue to trend downward and the long-awaited energy transition will take place. Morales et al. (2017) proposes to provide consistent responses to energy demands taking advantage of the sustainable energy potential of the Galapagos Archipelago. Meanwhile, Yin and Lu (2022) specify that it is important to take advantage of communication systems to equip these energy systems in smart grids. Several researchers consider the need to have an Integrated Renewable Energy System (IRES) in different parts of the world (Swain and Shyamaprasad, 2022; Abdin et al., 2022; Mao et al., 2022), especially in places with low population density and especially far from conventional distribution networks (Stefenon et al., 2022; Zeng et al., 2022). Neupane et al. (2022) shows that it is advisable to form hybrid generation systems while having diverse energy resources. It is about not depending on a single generation system and guaranteeing the supply of energy on demand. The diversity of renewable sources minimizes energy storage requirements either through batteries or green hydrogen as is already available in most countries (Legrand et al., 2022). At the same time, the need for storage units is less, and the reliability of the integral electrical system is noticeably increased.

In some countries, the legislation is designed to encourage the consumer to include photovoltaic solar panels in their own installations, bidirectional meters are included (Tostado-Véliz et al., 2021), these clients are rewarded who also become generators with lower payroll and even if there is a final value in favor of the client this is pending for the next month (Yang et al., 2018). The reality, the basis of these actions between the client and the company is to install bidirectional meters by the local company (MansourLakouraj et al., 2022). The control system allows to maintain the production levels or fluctuation in a certain range without affecting the load, it also controls the energy production by renewable energy sources. Modern controllers equipped with power electronics and internal communication systems allow the storage subsystems to be programmed within the required or preset voltage and current limits (Chauhan et al., 2015). In the state of having excess power available, it is directed to the storage system, typically configured with battery banks (Gonzalez-Longatt et al., 2018). These surpluses are used in the different activities of the residential sector, such is the case of water heating, food cooking, heating and cooling, etc (Zhang et al., 2022). If there are exceptional conditions in which electricity generation widely exceeds consumption in the home, the use of these surpluses can also be extended for loads related to ornamental lighting and electrical outlets for additional applications (Alvarez et al., 2009).

In the context of LAC, there are few relevant articles for specific countries or cities, this describes that this region lacks a higher level of research related to energy transition processes. The references that provide the greatest contribution are those presented by are Barbosa et al. (2017) and Icaza et al. (2022a). The approach presented here is a novel approach to progressively transform power generation systems sustained on fossil fuels into a 100 % renewable one according to the economic reality of the region, which advantageously from the point of view of the renewable resource is a unmatched advantage. Several studies that are presented and transform regional markets put special interest in achieving the energy transition (Ahmadi et al., 2020; Lund, 2005; Bogdanov and Breyer, 2016), while in LAC it must be considered from a technical point of view that this transition is feasible but also that the resources that are scarce are invested at costs that do not compromise the need for food for example in the region (Araujo, 2010). This reality in the countries of great economic progress may be important but not as important as in LAC (Nonhebel, 2005). It is fully agreed with all regions of the world that it is unavoidable for all states to move towards an environmentally friendly energy matrix, emphasizing that diversified renewable energies are essential for this purpose (Sueyoshi et al., 2022).

1.3. Novelty and key contribution

Latin America and the Caribbean is a region that is trying to make efforts to transform its energy systems into ones that are more environmentally friendly. However, the efforts so far are isolated and through this study the general lines are provided so that the countries in a single block address the problem of transition with very precise methods and their efforts have a reference from the integration point of view as a region. The European Union has already proposed a regional development approach after the situation presented by the Russia and Ukraine conflict. Although they are different realities, there is the organizational power that allows us to advance strongly as a region, something that Latin America and the Caribbean lacks and that is proposed in this study, recognizing above all the high energy potential available in the region but also its economic limitations. A novel techno-economic structure is proposed, especially in progressively limiting the use of fossil fuels in the region and on the other hand increasing the contributions of renewables, mainly wind and solar, which are available energy resources and are called to be an effective solution to long term that would significantly change the current energy matrix. A viable-recommended development panorama is provided considering the diversity of the countries, but most of them have common characteristics and with regional political will they can make important efforts. Decision makers can adopt this study as a reference input and consider in their budgets the resources that contribute to the decarbonization of the region and comply with the commitments acquired and declared at COP 21 held in Paris and ratified until the COP 28 in Expo City, Dubai. The roadmap developed in this study has been made possible with the support of the selected design tool EnergyPLAN. Therefore, a certain degree of simplification is necessary to achieve a good relationship between the level of detail and the computational requirements. In terms of optimization constraints, the approach is to establish default values, renewable energy quotas and time steps, from a current scenario to a potential 100 % renewable system based on the energy potentials defined in the base scenario. This innovative approach follows the real decarbonization objectives of the region and will be useful for government institutions to allow themselves to increase investments as much as possible in installed capacity, honoring their agreements and achieving 100 % renewable electricity production until 2050.

The scientific methodology is organized as specified: In this first section a review of the state of the art is carried out. Section 2 the methodology is presented. Section 3 the current context of LAC is analyzed, and with the support of the EnergyPLAN tool, the energy scenario for 2050 is presented, transformed and diversified to 100 % extractable renewable energies. Results and analysis are presented in Section 4. In Section 5 the results are discussed and analyzed. Limitations of the work and future research directions are presented in Section 6. At the end, Section 7 presents the conclusions.

2. Methodology

The methodology used in this research consists of four parts. The first part reviews the literature on the history, current situation and aspects related to the development of the future energy market in LAC is carried out. Most of the countries come from being eminently oil-producing and this dependence is deeply rooted in the economic aspect of the region, however practically all the countries already include new technologies of a renewable type in addition to the historical hydraulic ones. This aspect becomes key as the countries are beginning to trust in clean technologies, but it is important to provide development avenues to increase the transforming pace of the electricity market to a 100 % renewable one for the entire LAC region. It is here where this novel research plays a transcendental role to present in a flexible and achievable way the scenario that satisfies the future energy demand of the region accompanied by a pattern of progressive substitution of renewable energies in exchange for fossil fuels. The second part presents statistical data on installed capacity and energy production detailed by source for LAC countries and defines the base year (2020) with the criteria of projecting the system in the long term with 100 % renewables. Third part, the comprehensive results are presented in a feasible scenario recommended for LAC in which a diversified system with 100 % renewable energy is available, taking advantage of the potential of the region and achieving a zero carbon energy system in 2050. It is an investigation It will provide a different perspective so that both government leaders, investors and decision makers in the field of electricity have a clearer vision of the development opportunities for the region and, above all, protect ecosystems and the health of the population. LAC is a region of great natural wealth but one that has been working due to short-term political and association situations. Although there have been important achievements, there is no articulated planning as a region to draw the roadmap for the regional energy transformation with goals for 2050 according to the signed Paris agreement.

Finally, the fourth part shows the results of this research in a zero carbon energy scenario for LAC is designed and in tune with the global changes that are being managed in favor of the planet. The complete elimination of energy production with fossil fuels is considered until 2050. It implies a process of systematic reduction over time with social responsibility and that allows proportionally transferring jobs from the side of polluting energy producers to side of renewable energies, even involving training which also requires allocating time and a fraction of resources. To establish the scenario with reference to 2050, it is supported by the EnergyPLAN model available on its official site (EnergyPLAN,n.d), which presents a flexible methodology for modeling medium and large energy systems from the perspective of intelligent energy. The tool allows long-term projections to be made mainly considering the data established in the base year, which involves increasing the incidence of long-term renewable energy generation systems.

In the overall outline of this article, the current energy development instruments for LAC are presented, an integral analysis of the countries that comprise it is carried out, extracting general quantitative data that show their energy development pathways, which are useful at the time of proposing the general base year for the region, something that none of the authors synthesizes. Indeed, it is possible to make an exhaustive review of the literature but with relevant and contrasted sources that are as up-to-date as possible. Subsequently, it is grounded in the general energy system of LAC to transfer these analyzes to a prospective and viable-recommendable one. With this organized, systematic and critical structure, the scenario is designed for 2050, radicalizing the energy matrix scheme to a 100 % renewable one in LAC. The approach developed here exemplifies a very outstanding and transformative aspect of the reasonable change processes of the regional electricity system for future demands.

2.1. EnergyPLAN model

Currently, various models allow long-term energy planning. In this work the concept of smart energy systems is assumed. The smart energy system detects and uses synergies between different sectors of the electrical system, that is, heating sector, power system, cooling and gas network. A model, specially developed for intelligent energy modeling is EnergyPLAN, mentalized and developed at the University of Aalborg in Denmark (EnergyPLAN,n.d).

Today, there are many models with different benefits for energy planning in cities, countries or regions. There are two references that make a complete review of energy planning tools. Sinha and Chandel (2014) reviews 19 energy planning tools, while Connolly et al. (2010) reviews 37 with details of their benefits and limitations. Both reviews provide a very clear overview of the tools and their methodologies for long-term modeling and simulation. However, of all of them, only seven incorporate electricity, heat and transport sectors, while only four of them have already simulated a 100 % renewable energy system, with case studies, these are: EnergyPLAN, INFORSE, MesapPlaNet and LEAP.

In the present research, EnergyPLAN is preferred because it is a much more flexible tool to achieve the goal of achieving 100 % renewable energy by 2050, its analyzes allow it to be carried out by the hour and requires a base year and in its results it offers different design alternatives of the joint energy system according to the reality of each country or region. Additionally, it presents a greater world scientific production, which each one of them presents important recommendations, among them detecting instabilities in the electrical network, management of the critical excess in the production of electricity, its frequency magnitude.

Among the investigations carried out in different parts of the world that use EnergyPLAN are 3 regional ones that analyze energy markets that contain fossil fuels to transform them into 100 % renewable in 2050, Child et al. (2019) present the European case, Bogdanov and Breyer (2016) with the Asian case, D Icaza et al (Icaza et al., 2022b). that of South America. In the case of analysis by country, a variety of studies are found, among the most prominent are: Jordan (Kiwan and Al-Gharibeh, 2020), France (Krakowski et al., 2016), Hungary (Sáfián, 2014), Italy (De Luca et al., 2018), Denmark (Lund and Mathiesen, 2009), Portugal (Doepfert and Castro, 2021), Spain (Chang,n.d), United States (County Energy Systems for Humboldt, 2007), Mexico (Oropeza-Perez, 2014), Nicaragua (Cantarero, 2019), among others. There is no doubt that it is a well structured, reliable, flexible tool for modeling 100 % renewable systems and that permanently continues to be sophisticated according to contractual requirements. The first version was V 6.0, from January 2004, 14 update versions have passed, the current version is V16.0 from June 2021 downloadable with 6874 kB (Documentation, 2013), the same one that is used in this research and is shown in Fig. 1.

The methodological analysis is summarized in three phases: The first phase is the entry of data on the renewable energy resources available at the site and also the data on the fossil fuels used in the base year. The second phase is the adjustment with the support of the EnergyPLAN tool. Evaluations are included on aspects that may influence the energy transition process, such as: Technical, economic, environmental, political and social, as presented in Fig. 1a. In the third phase the results are presented. Fig. 1b details the relationship that exists between the renewable energy resources evaluated and the presentation of results. Thanks to EnergyPLAN it is possible to achieve the greatest adjustment of resources to supply the demand that will increase in the long term. The generation and consumption relationship are fundamentally linked, of course knowing that there are losses between blocks. The input data to form the base year is typically obtained from reliable sources, similar to how information is treated in other energy planning software tools.

3. Case study: zero carbon LAC for 2050

3.1. Situation in Latin America and Caribbean

The countries and territories (islands) that make up LAC are 42 and are located in the American continent from Mexico to Argentina, among which are: 13 South American countries, 7 Central American, 21 Caribbean between countries and islands and one North American country. It is a middle-income region, most mainland and island countries fall into that category. There is economic diversity in the countries that make up LAC, including the only low-income country, Haiti. There are also some of the world's emerging powers that are part of the developed countries. They are members of the OECD, Mexico and Chile, which together with Brazil and Argentina is a member of the G20, and in turn, Brazil is the largest country in South America and with the seventh largest economy worldwide. Below is Table 1 with the member countries of LAC.

According to data from the IDB (Cinco cosas que debes saber sobre el sector energía en América Latina y el Caribe, Energía para el Futuro, 2021), 18 million people do not have access to electricity in LAC. Regional goals state that there should be only one citizen without electricity by 2030. This figure is equivalent to the unified population of Nicaragua, Costa Rica and Honduras, or comparatively it is a figure close to the total population of Ecuador. The reference (Acceso al servicio de electricidad,n.d) provided in its official report that the region has made significant progress in energy matters. Its coverage went from 52 % in 1970 to 97.2 % in 2019. This growth has transformed the lives of the region's inhabitants. With these results, LAC has become one of the regions with the highest electricity coverage worldwide.

In the last 20 years, subregions such as Central America have increased the coverage rate from 70 % to 92 %, while at the same time they have increased the installed capacity of hydroelectric and photovoltaic solar energy. The reason for the existence of the gap in access to electricity in the region is mainly linked to the geographical dispersion of homes, being one of the challenges faced in providing service to those who currently do not have electricity. Both the IDB (Cinco cosas que debes saber sobre el sector energía en América Latina y el Caribe, Energía para el Futuro, 2021) and the Energy Hub (Acceso al servicio de electricidad,n.d) agreed in their latest reports that around 4.5 million homes do not have electricity, and of these, two thirds are located in rural areas.

In Latin America they make up 12 countries and Brazil is always considered a benchmark for development in addition to being the largest in extension with 8516 million km^2 (Filho et al., 2021). The countries on the continent have always sought to integrate and complement each other, from Latin American Free Trade Association (LAFTA), created in 1962) (L.E.M. R et al., 2012) to the current CLACS (Community of Latin American and Caribbean States, created in 2011) (CELAC and CELAC INTERNATIONAL, 2018). The integration initiatives that are being taken in the region seek to boost the economy of the countries and grow together in various transversal aspects such as the fight for the environment, technological and energy development, zero hunger, etc. These efforts were made thanks to the excellent results that the European Economic Community (EEC) was achieving in the early 1960s, since then it has continued to develop into the present European Union (EU) (History of the EU,n.d). Consequently, in Latin America, similar initiatives are also having a regional effect both in the andean zone and in the southern cone (Gonzalez-Perez et al., 2021; Goldfajn et al., 2021). However, they are far from providing comprehensive solutions to basic service problems, including electricity service. Lately, the COVID-19 pandemic hit certain strata of the Latin American population much harder (del Guayo Castiella and Marmolejo Cervantes, 2021).

Latin America has an extraordinary wealth, a high value in its marine and wild reserves in addition to its freshwater slopes, its wildlife and marine fauna are unique in the world, it has large forested areas that are the lungs of the world. Most of the vegetation is concentrated along the length and breadth of the Amazon River in humid areas in southern Chile (Vauchel et al., 2017; Fletcher and Moreno, 2012). The greatest energy production comes from the hydroelectric power plants of reservoirs thanks to their mighty rivers (de Jong et al., 2021). Latin America has also based its wealth thanks to high oil production, which has allowed at least the last six decades to satisfy the internal needs of services to a good part of the population (Goldemberg et al., 2014). However, this resource is being depleted in recent years, more than its derivatives cause a negative ecological impact for the conservation of

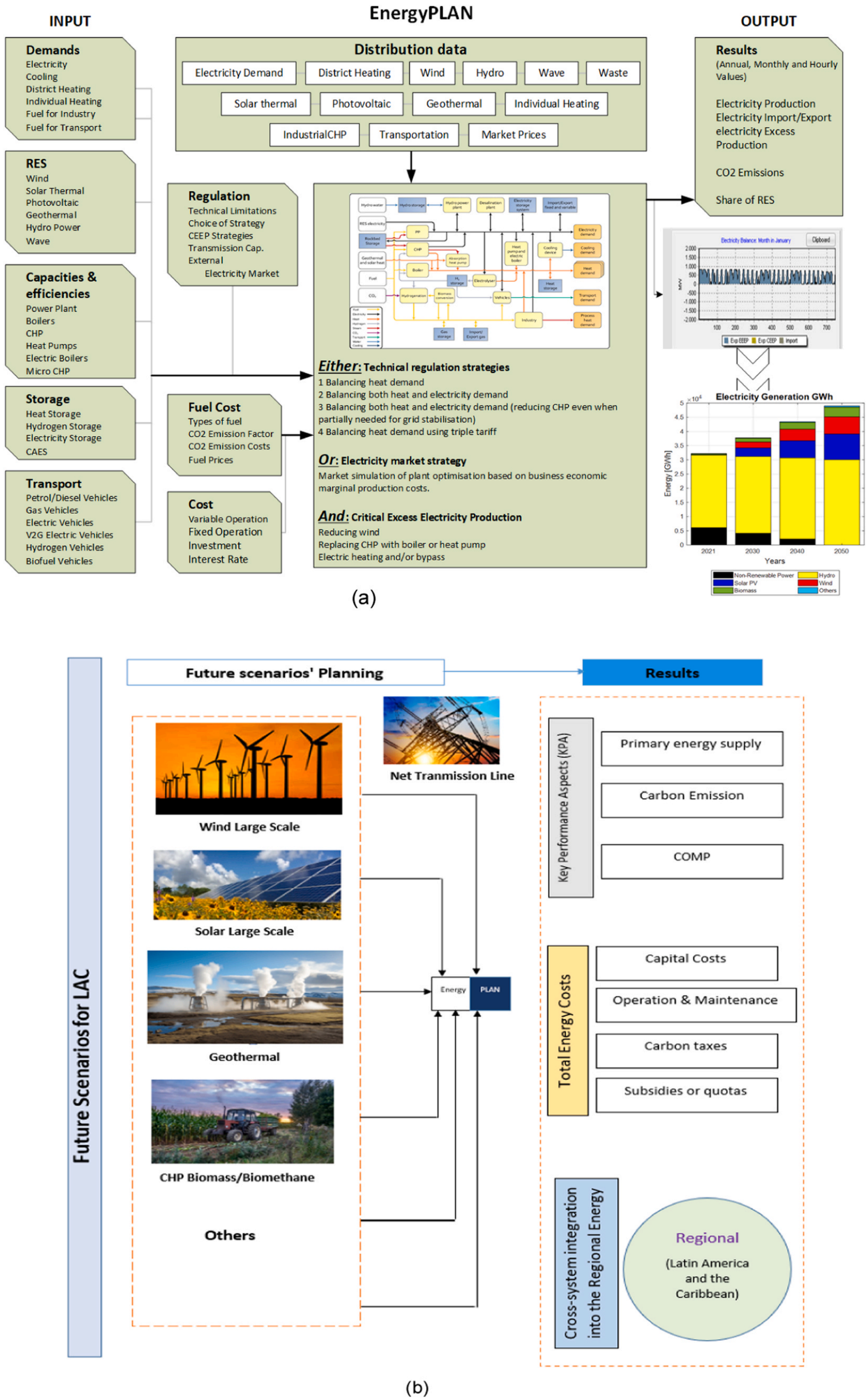

Fig. 1. The energyPLAN model in version V16.0 (EnergyPLAN,n.d). (a) Demonstrative graph of the three phases of methodological analysis. (b) Adjustment phase using the EnergyPLAN tool.

Table 1
Countries and Territories that make up LAC (Countries in Latin America & the Caribbean,n.d).

Caribbean	South America	Central America	North America
Bahamas	Brazil	El Salvador	Mexico
Antigua & Barbuda	Argentina	Guatemala	
Cayman Islands	Chile	Belize	
Aruba	Bolivia	Honduras	
Barbados	Colombia	Nicaragua	
Dominica	Ecuador	Costa rica	
Cuba	Guyana	Panama	
Grenada	French Guiana		
Guadeloupe	Peru		
Dominican Republic	Paraguay		
Haiti	Suriname		
Jamaica	Uruguay		
Puerto Rico	Venezuela		
Martinique			
Saint Barthélemy			
Turks & Caicos Islands			
St. Vincent and the Grenadines			
St. Kitts & Nevis			
St. Lucia			
Trinidad & Tobago			
Virgin Islands			

life on the planet. Several countries are reorganizing themselves, they began to change their laws with a view to transforming their energy structure based on renewable energies. Hydroelectric power accounts for about 80 % of renewable energy in the world energy mix, and covers 50 % of the total electricity needs of Latin America (Balza et al., 2020). The levelized cost of generating electricity through hydroelectric power has been reduced from $65/MWh in 2010 to $50/MWh in 2016 due to strong investments and technological advances (Bolinger et al., 2015). This means that it continues to compete with the cost of fossil fuels (which ranges from $40/MWh to $150/MWh), but with little room for further cost reductions due to its level of maturity (McElroy et al., 2018). In addition, the most profitable locations have been exploited and the environmental and social struggles are becoming more intense and if there is an increase in their costs, there is no doubt that there will be a massive rejection. South America is constantly interested in initiatives in favor of environmental conservation as it has ecosystems that are very sensitive to human action (Martínez-Martínez et al., 2022). Unfortunately, in several countries, freshwater slopes are at risk because several companies are intervening in large areas with extractivist interests.

Various investigations show the existence of higher rates of water contamination, especially with lead, where various aquatic species live (Jones et al., 2021), at least 22 % of fish worldwide and approximately 72 % of the mussel species in the world have been affected. North America according to reports from the World Conservation Union (Leprieur et al., 2008). These levels of destruction have had a strong impact on South America, also generating problems on the coasts of the continent and islands such as the Galapagos, which are receiving tons of plastic (Jones et al., 2021).

In relation to the Caribbean countries, energy security is a top priority for the Caribbean authorities and has been for a long time (Energy Resource Guide - Renewable Energy - Costa Rica, n.d). The average cost of electricity is very expensive in the Caribbean, basically due to the need to transport fuel to the islands, with an average of US$0.34 per kWh and as high as US$0.50 per kWh, being four times higher than in rich countries like the United States (The Global Transition to Renewable Energy, 2017). The high costs of energy in the Caribbean countries not only constitute a daily difficulty for the inhabitants, it is also one of the main problems for economic growth, added to the effects on the environment due to fuel spills and a high risk of health conditions. of the settlers.

In recent years, the fall in oil prices has partially meant economic relief, the problem continues and it is necessary to radically change the energy policy in the region and generate forceful strategies for the decarbonization of the islands, including a large amount of renewable energy. In this sense, Costa Rica is an example to follow, this country reached 99.98 % in clean energy production during 2021 (Lous,; Costa Rica's electric grid powered by 98% renewable energy for 7th straight year, 2021). According to the National Center for Energy Control (NCEC), this is the seventh consecutive year in which the country has achieved renewable electricity generation above 98 % with clean resources such as water, sun, wind, biomass and geothermal energy (Costa Rica's electric grid powered by 98% renewable energy for 7th straight year, 2021). The situation also represents an opportunity to consider strategies to increase energy security in the region. This is one of the positive experiences that will allow more trust in renewable resources in the Caribbean and indeed in all of LAC.

In order to contribute to this transformation, the leaders of the Caribbean countries and prominent allies in the electricity sector agreed to develop a joint regional framework for energy development. Unfortunately, most of the small Caribbean countries, especially those in the Eastern Caribbean, still depend almost entirely on oil to cover their electrical energy needs (Want to Learn More About Energy in the Eastern Caribbean?, Energía Para El Futuro, 2016). For them spending on oil and gas constitutes between 7 and 20 percent of gross domestic product.

The region has reached an almost universal level of electrification, and virtually all homes are connected to the public electricity grid, except in Haiti. After the earthquake that devastated the capital Port-au-Prince on January 12, 2010 (Haiti earthquake: Devastation and more than 2,000 dead, BBC News, 2021), the availability and reliability of modern energy services remain crucial to the country's recovery and sustainable development. Only 28 % of the population has regular electricity supply (Perry, 2020). To start this recovery, we are already starting to rely on renewable energies. Now on the streets of Port-au-Prince, Saint Kitts and Nevis, much of the street lighting is powered by solar energy. Advantageously, the Caribbean region has great potential to develop various renewable energies, including not only solar, but also wind, biomass, geothermal and marine (IDB and CDB fund Sustainable Energy Facility for Eastern Caribbean, CARICOM, 2015). Although wind and solar energy are intermittent, they can be used in combination with renewable geothermal or clean energy from natural gas.

3.2. Current scenario in LAC and its expectation of zero carbon by 2050

The expectation caused by the regional integration of LAC is framed in achieving mutual benefits between the countries that integrate it based on individual potentialities. The benefits include: Being able to avoid or postpone investments in generation due to reserve margin. Achieve greater efficiency in the use of generation and transmission infrastructure. Achieve greater use of economies of scale and the diversity of sources and patterns of supply and demand (Bahmani et al., 2020). Establish more competitive markets and less possibility for companies to exercise market power (CELAC and CELAC INTERNATIONAL, 2018). Reduce commercial risks and greater rationality of regulations by requiring to be homologated or adapted to international energy exchanges (Integración eléctrica regional: Oportunidades y retos que enfrentan los países de América Latina y el Caribe and Publications, n.d).

On the other hand, there are risks in market integration such as dependence on another country for the supply of a critical input for the economy. There is also the transfer of foreign currency from the importing country to the exporter that could have important macroeconomic impacts (Kurdve and Bellgran, 2021). Technically unlikely but necessary to consider are cascading effects that could lead to regional blackouts. In any case, in the vast majority of bilateral interconnections between countries and also at the regional level, multiple studies conclude that the potential benefits are much higher than the costs, and that the investments are highly profitable. Energy integration can become a dynamic element in the economy when energy exchanges respond to economic rationality (CEPAL, 1986). The electrical integration of neighboring countries or a group of countries arises as a possibility when their transmission systems get closer to the border in such a way that their interconnection would allow, in principle, to consume energy in a country when it was generated at a lower cost in another country or due to lack of generation capacity in one and surplus in the other (Zahed et al., 2020). However, for such exchange to be truly feasible, there are a number of conditions that must be met for the flows to occur (Barbosa et al., 2017). First, there are the technical aspects. It is absolutely necessary that the national transmission network, in addition to the interconnection, be prepared to support these new flows of power exchange without affecting the normal operation of the national energy supply, even in cases of contingency (failure in any of its sections) (Integración eléctrica regional: Oportunidades y retos que enfrentan los países de América Latina y el Caribe and Publications,n.d).

This approach to integration between countries would be a notable advance, however this should not imply that this is the only path to integration (Alvarado et al., 2019). The fact of having legal frameworks that promote the use of clean energy, commitments and investment agreements in infrastructure in favor of environmental protection are routes that also lead to regional integration and joint development (Integración eléctrica regional: Oportunidades y retos que enfrentan los países de América Latina y el Caribe and Publications, n.d). It is already evident that taking advantage of renewable energies and progressively substituting instead of fossil fuels are determined actions that are already beginning to be noticed throughout LAC (Barbosa et al., 2017).

The COP26 held in Glasgow keeps hope alive for a better future for the planet (Dwivedi et al., 2022), in this sense, the energy sector of LAC is already in constant growth and development, placing its trust in renewable energy systems (Olade,n.d). It has not been easy for the region to start its path towards this energy transition, requiring modification of the legal framework in the countries (The Global Transition to Renewable Energy, 2017). The challenge is to give concrete answers to the agreements celebrated at the international level and not to compromise the life and health of future generations, for this reason an orderly energy transition is necessary to build from today (Bogdanov et al., 2021). Energy security will also be achieved when energy systems have a greater diversity of sources of electricity generation, as most countries worldwide are developing (Cabeza et al., 2021). The countries of Europe are an example to follow in taking advantage of their diverse energy potential available in the territory (Barbero et al., 2020). LAC hopes to be in tune with these currents of development that are framed in protecting life on the planet (Aide and Grau, 2004). Table 2 and Fig. 2 show the levels of energy diversification by source.

Table 2 shows that there are 457,031 MW of installed capacity in the region for the production of electricity according to reference (Olade,n.d). It stands out that most of the electricity production corresponds to reservoir hydroelectric plants (43.11 %) followed by non-renewable thermal plants (38.89 %). Non-Conventional Renewable Energy (NCRE) sources such as solar, wind, biomass (renewable thermal) and geothermal contribute 16.83 % of the installed capacity of the region in

Table 2
Installed generation capacity in LAC.

Source	(MW)
Non-Renewable Thermal	177,718
Hydro	197,020
Nuclear	5353
Wind	32,552
Geothermal	1704
Solar	20,007
Others	385
Renewable Thermal	22,292
Total	457,031

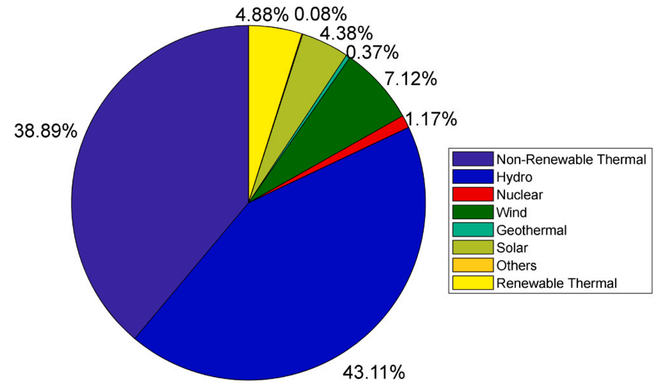

Fig. 2. Percentages of energy contribution by source in LAC (Barbosa et al#, 2017).

2020. In fact, Latin America has the highest rate of hydroelectric production relative to the world generation. However, there is a downward trend in this record from the last decade. Due to this circumstance and other parallel effects on the environment, it is related to a greater citizen sensitivity towards the economic and social environmental impacts related to this technology (Zhou et al., 2021). The so-called energy transition or also called in some countries as ecological transition, implies a more diversified and resilient generation to the impact of drought episodes on the hydrology of the region. These effects are associated with phenomena typical of climate change, as well as cushioning the economic impacts caused by the volatility of the price of polluting energies.This transition is being leveraged on non-conventional renewable energies. With regard to the latter, the evolution that is being registered in the region by solar and wind technologies, whose insertion in the regional energy matrix is fundamentally located in the present decade. As an example, about 25 % of the total electricity recently incorporated in the region comes from wind, which in 2010 was derisory and today already represents 6 % of the total installed electricity (CELAC and CELAC INTERNATIONAL, 2018). The wind source constitutes around 80 % of the installed capacity of the NCRE in the period 2021 in the region. Although solar is in a recent implementation stage, there is a portfolio of important projects and after a few years its deployment may go hand in hand with wind power.

Regarding production levels in LAC, there is a sustained growth of around 12 % due to the fact that new generation plants have entered the different countries. Production by 2020 is 1543.25 TWh according to the reference (Olade,n.d). The energy sources that have provided the greatest contribution are hydraulic with 43.11 % and thermal with 39.89 %. However, despite the fact that renewables, excluding hydraulics, still do not have a greater incidence (Barbosa et al., 2017), it must be taken into account that both wind and solar will come with great force in the future. It is worth referring to the recent study by International Renewable Energy Agency (IRENA) (del Guayo Castiella and Marmolejo Cervantes, 2021), which points out that the achievement of the Paris climate goals will require a significant acceleration of investments across a range of sectors and technologies (Miravet-Sánchez et al., 2022). In accordance with the data available in LAC, among all the low-carbon technology options, wind energy, together with solar energy, are already paving the way for the transformation of the electricity sector. Table 3 and Fig. 3 of detailed production by source in LAC are presented below.

Using the e¡Sankey diagram presented in Fig. 4, it is possible to observe the energy balance summarized in percentages of contribution from the generation sources to the demands in LAC with a cut-off date of 2020 (2021 Latin American and the Caribbean Energy Outlook, OLADE, 2021). On the left side are the generation sources, while on the right the demands classified in the region. In this diagram, the following considerations were taken into account:

Table 3
Energy production by renewable source in LAC.

Source	(GWh)
Non-Renewable Thermal	562,807
Hydro	717,082
Nuclear	35,579
Wind	104,266
Geothermal	9309
Solar	30,056
Others	626
Renewable Thermal	83,529
Total	1543,254

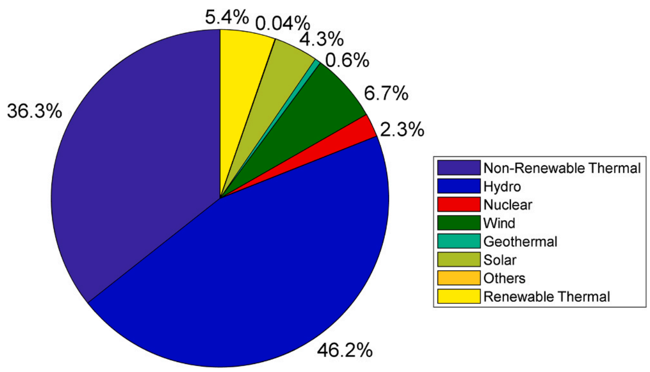

Fig. 3. Percentages of energy production by source in LAC.

- Total Supply = Production + Import - Export +/- Inventory Variation - Not Used.
- Other primaries include: Biogas, vegetable residues, cane products, firewood, solar and wind (This applies to each country depending on the availability of energy sources that each one has).
- Inputs from Other Primary to Refineries, refers to the transformation centers, distilleries or other centers (biodiesel plants), being the ethanol or biodiesel outlets.

The IDB in its reference (¡A todas luces!: La electricidad en América Latina y el Caribe, 2040 and Publications, n.d) already launches its first expectations about the impact that the electricity market may have in the LAC region. According to estimates, in terms of unplanned new capacity (that is, investment that exceeds expansion plans), the countries of the region should add between 135 and 272 GW of new generation in the next two decades. Depending on the scenario proposed, the region must invest between US$195 billion (in a historical trend demand scenario) and some US$412 billion (in a GDP-weighted demand scenario). In the next few years, 163 MW of installed capacity will reach their useful life in the region. Among all the technologies, the highest percentages today come from hydroelectric plants and natural gas-based plants. This is an expected result, due to LAC's dependence on these technologies. Fig. 5 shows the installed capacity that must be replaced by year and type of technology starting from 2016 to 2040. From this it follows that the technologies that will dominate the energy mix in 2040 will be the old hydroelectric and the new solar and wind that are starting to disdain from now on. It can also be identified that both oil and coal are going to be significantly reduced, however by 2040 a percentage of the market will still remain below 2.8 GW.

3.3. *Wind and solar energy as a fundamental basis for the energy transition in LAC*

After having analyzed the current LAC scenario, it is not new that the hydroelectric source plays an important role in the energy mix and that it will surely be present in the long term (Washburn and Pablo-Romero, 2019). It draws attention to two sources in particular that are beginning to affect LAC, such as wind and solar (Alvarado et al., 2019). Comparatively, an effect similar to the one Europe began to experience a few years ago is taking place, in which wind and solar power did not have much participation but currently their growth rate is above 8 % annual average (Costoya et al., 2022; Golombek et al., 2022; Statistical Profiles, n.d).

In this sense, it is necessary to analyze the potential of these two energy sources. Regarding the wind potential, it can be identified in Fig. 6 provided by (BNamericas - Proyectos eólicos a tener en cuenta en Latin…, BNamericas.com, n.d) that the average speeds are very good even in some excellent countries. It is very striking that in the Caribbean, which is made up of islands and currently depends mostly on fossil fuels, wind speeds are excellent, very conducive to taking advantage of its high potential of between 6.50 and 9.25 m/s. average, presenting a serious option to reach zero carbon by 2050.

In relation to the rest of the region, both Central and South America, it was expected that its takeoff would be based on the use of wind energy due to its high potential. Among the various projects, several in the region can be mentioned: With an investment of US$850 million, Chile will have the largest wind project in Latin America (Definiciones sobre las subastas de energías renovables y su relación con los contratos bilaterales en Latinoamérica - Energía Estratégica, 2020). The Horizonte Wind Farm will have an investment of US$850 million and a capacity of 778 megawatts (MW). The works began in December 2021 and it is

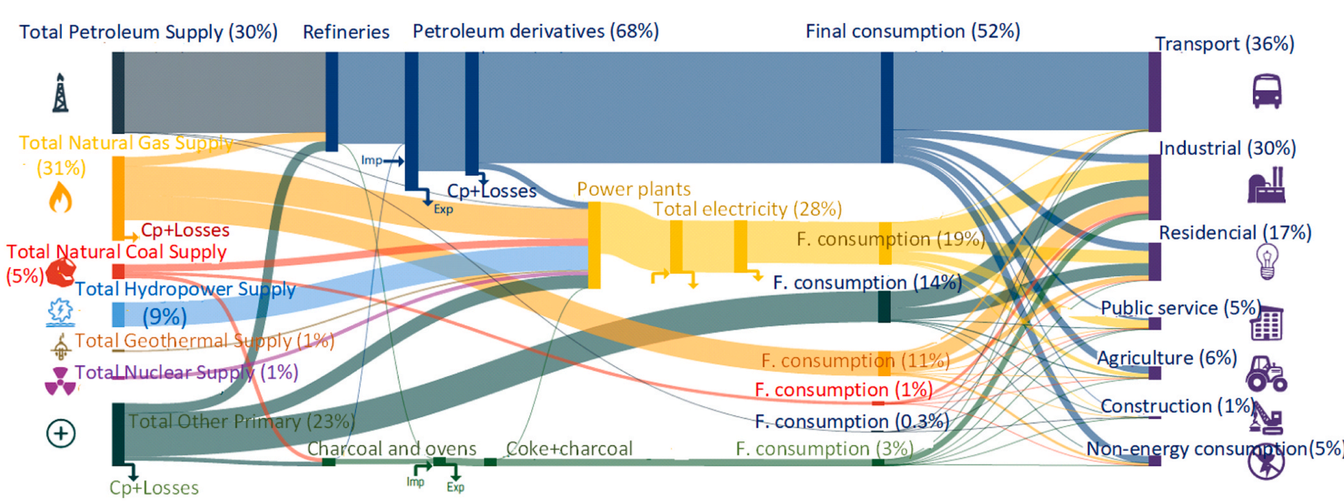

Fig. 4. Summarized diagram in the e¡Sankey tool for LAC, reference year 2020.

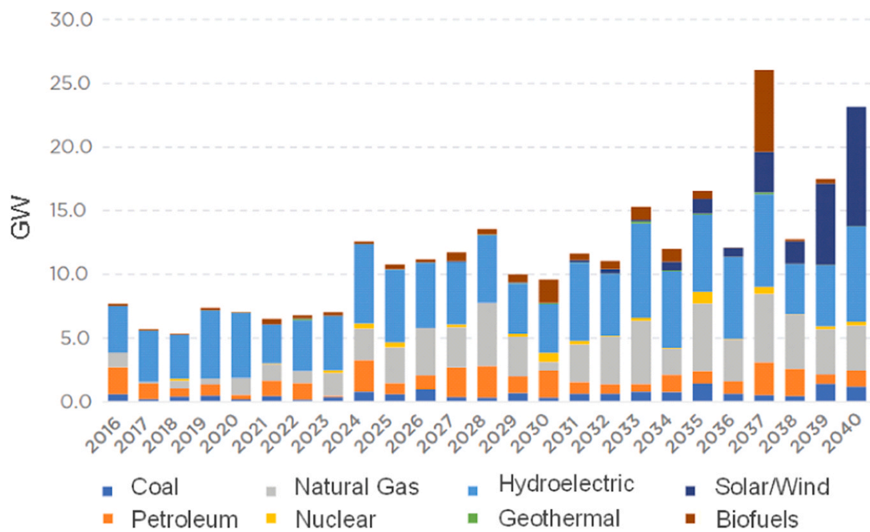

Fig. 5. Installed capacity projected by IDB (¡A todas luces!: La electricidad en América Latina y el Caribe, 2040 and Publications,n.d) until 2040 for LAC.

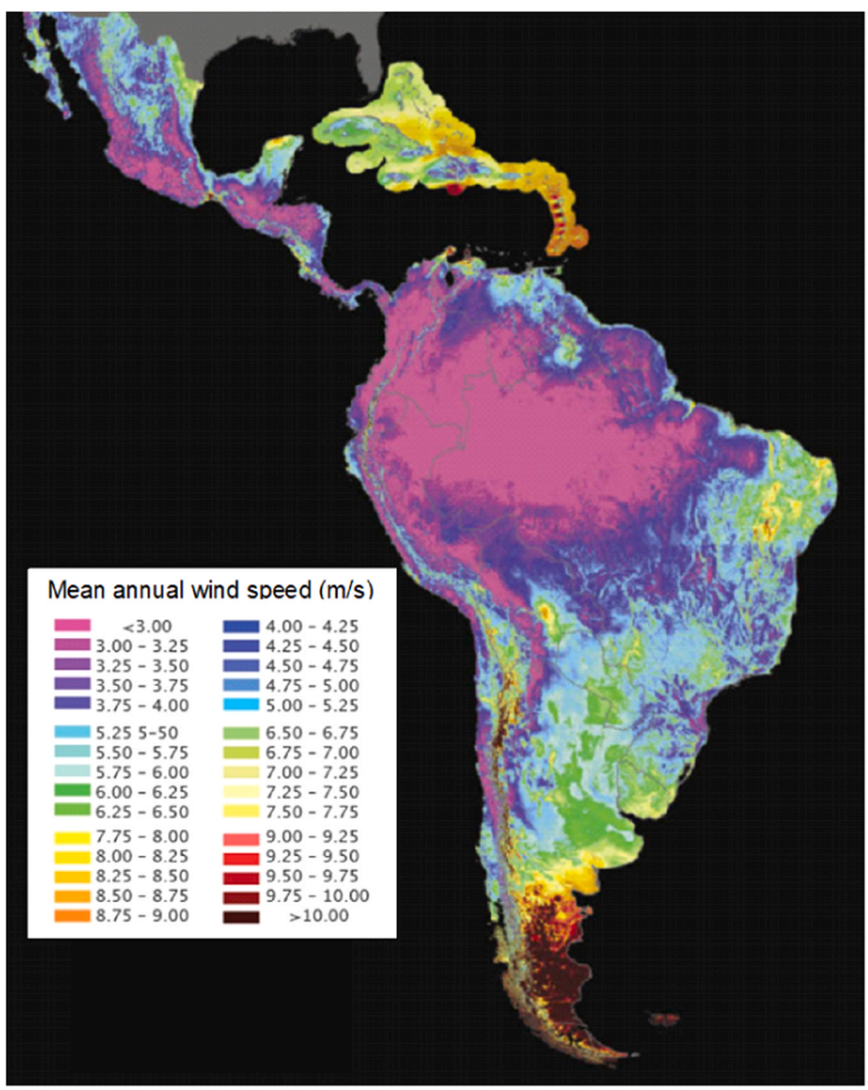

Fig. 6. Wind resources in LAC, adapted from (Viaintermedia.com, Eólica,n.d).

planned that it will come into operation in 2024. Under this perspective, Brazil goes further, an extremely large increase in wind energy is projected (in the non-intervention scenario) 21 % by 2050, and 42 %, in 2100 (Desplazamiento de vientos al Sur beneficiará energía eólica, América Latina y El Caribe,n.d.). Small countries like Ecuador are also seeking to take advantage of the available wind potential, progress is being made in the construction of the 50 MW Minas de Huascachaca Wind Project (Icaza et al., 2020). The work is 80 % complete according to the comprehensive planning of the project. It is executed with an investment of USD 90,000,000, financed by the Banco del Estado de Ecuador and own funds of the Elecaustro Generator. In Guatemala, the most recent plant is Las Cumbres, which has a capacity of 31.5 MW, and is located in the municipality of Agua Blanca. The total installed power capacity as a whole is 106.5 MW, with an energy generation in 2019 of 330 GWh, representing 2.48 % of the total generation in that year (Energía eólica en Guatemala,n.d).

Although for now the wind has taken the lead within renewable energies on the rise, there are clear indications that photovoltaics will also play an important role in the region in the future (Jacobs et al., 2013). In Fig. 7 the solar irradiation in the region is shown.

Until now, solar energy production has been profitable globally with only state subsidies. However, in recent years the prices of solar modules have fallen drastically and it is believed that they will continue to decline to the point that they will become extremely affordable and the projects will be very profitable. Huge solar panel factories are being built especially in China. From 2006 to today, the price of solar installations has been reduced by 60 %. One of the consequences of this is that last year the solar power installed worldwide increased by 40 % (Welle, n.d). Good conditions for the development of photovoltaic energy in LAC is also due to the fact that it has a region with great solar radiation.

The countries with the highest annual average solar radiation are Mexico, Brazil, Chile and Peru (Prăvălie et al., 2019). However, also in the rest of the region, except for the southernmost areas, the sun's energy can be used without any complications. They are used in the form of roof modules as well as large solar plants.

Examples of the implementation of this technology include: In Peru, the development of a 20 MW photovoltaic park has begun in Alto de la Alianza, Tacna region, which will be the first in the country with delivery to the grid. It is planned to produce 45 GW per year, thanks to its excellent location (Espinoza et al., 2019). Its 80,000 photovoltaic solar panels will generate a power of 22 MWp. The constructed area of the project will exceed 60,000 square meters.

In Chile, large-scale electricity production has been opened in recent years, thanks to the new conditions of the legal and economic framework for its development. Northern Chile is the region with the highest solar radiation in the world. The most interesting current project is Calama Solar 3, a cooperation between the Solarpack company and state-owned cobra producer Codelco. Due to the high solar radiation, the

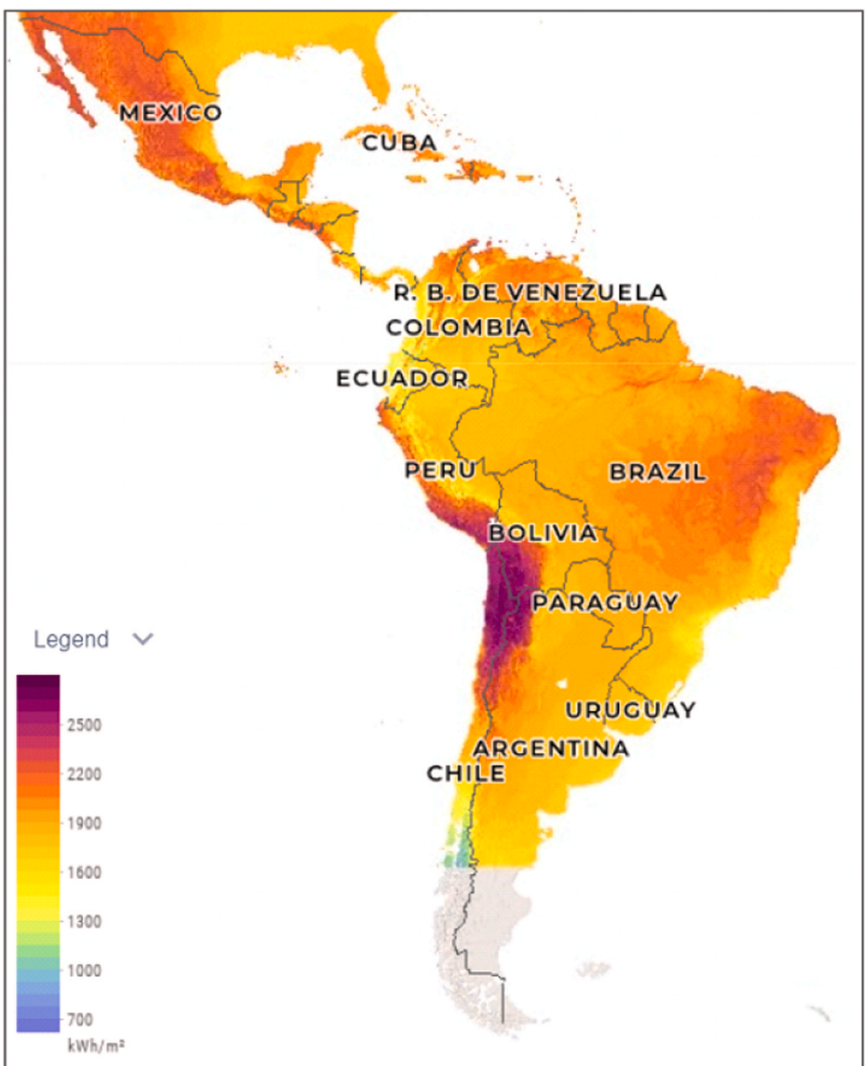

Fig. 7. Global horizontal irradiation in LAC (IRENA entrega un proyecto de energía solar fotovoltaica de 10 MW en Cuba, World Energy Trade,n.d).

installation is expected to produce a total of 2.69 GW per year (Bustos et al., 2016).

The Cuban Ministry of Energy and Mines, in a tripartite effort with the Abu Dhabi Fund for Development (ADFD) and IRENA, inaugurated a 10 MW photovoltaic solar energy project (IRENA entrega un proyecto de energía solar fotovoltaica de 10 MW en Cuba, World Energy Trade, n.d). The project is integrated into the network contributing electricity to almost 7000 homes in Cuba. These actions are aligned with the revolutionary goals of the Cuban government to reduce the use of fossil fuels for electricity production and increase the proportion of renewable energy. The project will mitigate around 12,700 tons of CO_2 per year.

3.4. Zero carbon energy system by 2050

The Zero Carbon LAC 2019 report presented by the UN (U.N. Environment, 2020) emphasizes as an opportunity for the development of peoples, the cost and benefits of decarbonization would repay with a higher quality of life for the population. The UN also called on the region to focus all its efforts on the complete decarbonization of four areas responsible for 90 % of greenhouse gas emissions: power generation, industry, transportation and land use.

The World Bank (La energía que necesita la América Latina del futuro, World Bank, n.d) stated that between 2011 and 2030 electricity consumption in Latin America and the Caribbean will grow by 80 %, and that in Central America alone the growth will be more than 120 %. The demographic increase in the region will lead to an increase in the use of household and electrical appliances, which, added to greater industrial activity, will trigger the demand for energy.

According to IRENA (Renewable Energy Market Analysis: Latin America, /Publications/2016/Nov/Renewable-Energy-Market-Analysis-Latin-America, n.d), between 2010 and 2015 in Latin America more than 80,000 million dollars were invested in non-conventional renewable energy, excluding large hydroelectric plants. And in the region, a quarter of the total primary energy comes from renewable sources, which makes Latin America one of the most dynamic markets in this sector.

Certainly, to reach zero carbon energy, a higher rate of participation of renewable energies is required in order to meet the demand energy future, eliminate the current gap being filled by natural gas, and displace future use of fossil fuels. Fortunately, there is a huge endowment of renewable energy resources in LAC (U.N. Environment, 2020). However, except for hydroelectric power, most of these resources have not yet been used consistently with their competitiveness at higher levels. The case of wind and solar energy, which has a high potential for use in the region, in addition to other contributions on a smaller scale, has already been analyzed in this same article. It is estimated that the regional supply of renewable energies is around 93 PWh annually (U.N. E. Programme, 2016), with a nominal maximum capacity corresponding 39 TW. For reference, global energy demand stood at 23 PWh in 2019 (World Energy Outlook, 2019 – Analysis, IEA,n.d). Literally, the endowment in the region of Latin America and the Caribbean could meet the demand world several times. It is clear that it will never reach full utilization of this potential, but in any case the theoretical maximum capacity illustrates the considerable untapped potential of resources renewables in LAC.

Although the existence of renewable energy resources is significant throughout the region, also has of global resource intensity hotspots. Such is the case, the Atacama desert in the northern part of Chile and the southern zone of Peru has an irradiance of about 275 W/m^2, which is the highest in the world, knowing that the world average of irradiation is 198 W/m^2 (Nielsen, 2005). With an area of around 14 million hectares, the Atacama region is a solar resource of global relevance.

However, recent trends show a growing financial advantage for renewable energy in the region (Washburn and Pablo-Romero, 2019). For example, tenders recent for the energy supply in the market Brazilian have overwhelmingly favored energy wind (Juárez et al., 2014). It is observed that the conditions of market in Uruguay, Mexico, Brazil and Nicaragua, among others favor wind power over gas (Vargas Gil et al., 2020). This indicates that wind and solar energy can compete and surpass gas under conditions of equality, that is, in situations in which renewable energies are not penalized and/or fossil fuels are not subsidized (Arango and Larsen, 2010).

Variations in the world market and in LAC make it possible to consider a scenario in which considerations related to economic development, security energy and climate change can be met by deploying renewable energy sources at scale. The bases of this alternative energy future are already being developed in LAC and reaching a zero carbon system in 2050 is possible. It is noted that the market is challenging the trend decarbonization thesis since its growth rate increased incredibly, some aspects are identified: a) recent and significant changes in the market share of renewable energies; b) the evolution of policy frameworks in the countries that make up LAC; c) the establishment of goals and political guidelines for renewable energy; d) the perspective of integration of the regional transmission network, with the advantages that would contribute to the large-scale deployment of energy renewable; and, e) the evolution in technologies, with the consequent improvement in economic competitiveness.

Globally, investments in energy resources renewables in the last decade have been substantial. From 2010–2020, investment in renewable energies annual global growth grew by 500 %, from 45 billion to 270 billion dollars (Latin America and the Caribbean, UNEP - UN Environment Programme, n.d). In Latin America, although it still represents a small fraction of the total, the capacity of sources of renewable energy, other than hydroelectricity and biomass (the traditional renewable sources) also has shown accelerated growth in 2021. Markets for wind energy and photovoltaic solar energy are already established in the region, and we can give as an example several tenders that have been carried out by countries such as Colombia (Colombia renewables tender in, 2021 to contract 5 GW, Renewablesnow.Com, n.d), Peru (Latest Global Tenders and Bids, Global Tenders,n.d), Ecuador (Ecuador Launches 500 MW Renewable Energy Tender-nuukopower.com,n.d), Argentina (BNamericas - Argentina power watch: Renewables tender, ne…, BNamericas.Com, n.d), Brazil (Brazil publishes guidelines for May 27 energy tender, Renewablesnow.Com, n.d), among others.

Building a 100 % renewable energy system in a sustainable way consists of several steps. The first step to consider is that the energy and district heating sectors should be integrated to allow more than 25 % of intermittent electricity generation, it is the case of wind and solar. The integration of these two contributions must achieved by heat pumps and advanced CHP and together with thermal systems energy storage. This will increase the efficiency of the system and reduce fuel consumption. Second, electrification must take into account that the majority of light vehicles should enter the LAC market and progressively leave the internal combustion vehicle. Vehicle to Grid (V2G) is necessary to implement, this technology helps balance the electrical grid when there is a significant level of growth. Further, it is necessary to install pumped-storage hydroelectric plants, will further improve the integration of intermittent energy sources.

The next step is to ensure that the penetration levels of large-scale wind and photovoltaic energy are further reduced in cost and the path to zero carbon will be greatly facilitated.

In addition, it is important to consider that other low-input renewable energy sources are also recognized as useful to form part of the system and obtain greater diversification, such as in the case of incineration plants for the collection of urban solid waste, small hydroelectric plants of open channel. It is also required to introduce solar energy with thermal storage. In the heating sector, it is particularly important to introduce geothermal energy on medium and large scale. In the individual heating sector, parts of houses and buildings that cannot be connected to the district heating network must be heated by heat pumps or solar thermal energy. In relation to transportation, it is necessary that medium and heavy vehicles that cannot be electrified by battery-based technology need be fueled by biofuels. Most of the transportation the medium is assumed to be powered by biofuels or synthetic fuels produced from biomass.

3.5. Energy model with a prospective to 2050

3.5.1. Technical effects

The ultimate climate goal on a global scale would be to reach zero emissions. This perspective is also considered in LAC that is looking for ways to progressively reduce CO2 emissions until achieving net zero emissions by 2050, as proposed at COP21 and emphasized at COP26. Electrification including wind and solar power in significant proportions is a suitable path. In addition, hydrogen, synthetic fuels, advanced biofuels and carbon management will be critical, along with innovative business models, structural changes and behavioral adaptation.

The diversity of renewable energy sources is recommended in a region and to take advantage of the different potentialities of the countries that comprise it. 2050 is a year of global projections, several investigations propose it this way and it was detailed in the literature of this manuscript, being possible and recommendable to achieve a 100 % renewable system. At this level, it is important to evaluate the level of incidence that can be achieved with a considerable use of renewable energies, evaluating the Renewable Factor (RF) through Eqs. (1) and (2):

$$RF = \left(1 - \frac{\sum P_{non-renewable}}{\sum P_{renewable}}\right) x100 \quad (1)$$

$$RF = \left(1 - \frac{\sum P_{diesel} + \sum P_{gasoline} + \sum P_{coal} + \ldots\ldots \sum P_{others\ non-renewables}}{\sum P_{PV} + \sum P_{wind} + \sum P_{hydro} + \ldots\ldots \sum P_{other\ renewables}}\right) x100 \quad (2)$$

Renewable energy sources are considered those that are integrated into the energy mix such as hydraulic, solar, wind, among others that are of renewable origin $\sum P_{hydro} + \sum P_{PV} + \sum P_{wind} + \sum P_{biomass} + \ldots\ldots \sum P_{other\ renewables}$. Regarding non-renewable energies are mainly those from oil and coal derivatives expressed with $\sum P_{diesel} + \sum P_{gasoline} + \sum P_{coal} + \ldots\ldots \sum P_{others\ non-renewables}$. Other sources of a pollutant type can also be evaluated depending on the reality of each region. By 2050, achieving zero carbon energy in the region will mean that the RF factor is mathematically equal to 1.

Evaluating the base year as a reference, the 2050 horizon is designed, the mathematical expression is as follows (3):

$$TAPE = \sum P_{rene-2050} - \left(\sum P_{rene\ base\ year} - \sum P_{non-rene}\right) \quad (3)$$

$P_{rene-2050}$ is the total supplied power evaluated in 2050, $P_{rene\ base\ year}$ is the supplied power evaluated in the base year, TAPE is the Total Additional Projected Energy, $P_{non-rene}$is the produced power non-renewable, from polluting sources to be replaced by reference or nascent renewable energy sources in the base year.

The parameter that relates the renewable energy sources with the total satisfied demand is the Energy Supply Ratio (ESR) for a time range from 0 to T, as shown mathematically in (4).

$$ESR = \sum_{0}^{T} \frac{P_{rene-2050} - P_{DEMAND\_2050}}{P_{rene-2050}} \quad (4)$$

Where $P_{rene-2050}$ is the total RE supplied in 2050, P_{DEMAND_2050} is the demand by 2050.

If $P_{rene-2050} > P_{DEMAND\_2050}$ a surplus of electrical power is produced in 2050.

If $P_{rene-2050} < P_{DEMAND\_2050}$ a shortage of electrical power in the year 2050 (Not desirable).

When $P_{rene-2050} = P_{DEMAND\_2050}$ balance point between the generation and consumption of electrical power in 2050.

Strategically including energy storage systems is technically convenient to guarantee the availability of electricity service in the region.

3.5.2. Cost of energy (COE)

Within the system design 100 % RE, the COE is considered as a determining factor to obtain an optimal and profitable system. The COE is evaluated by (5):

$$COE = \frac{TNPC}{\sum_{H=1}^{H=8760} PL} \ x \ C_{RF} \quad (5)$$

Where, C_{RF} is the capital recovery rate, PL is the kilowatt hour energy consumption, TNPC is a current total net cost in US dollars. The C_{RF} is a ratio used to calculate the current estimate of benefits, that is, a progression of equivalent annual monetary flows. It is evaluated by the following equation:

$$C_{RF} = \frac{i(1+i)^N}{(1+i)^N - 1} \quad (6)$$

i is the real interest rate, N is the number of years.

3.5.3. Human Development Index (HDI)

The HDI is used as a parameter that evaluates the general achievements of a region around its financial and social measures. It is a composite indicator, defined by the UNDP (United Nations Development Program), which represents a measure of the progress made by a region in three basic dimensions of human development:

(i) access to education, (ii) decent standard of living and (iii) long and healthy life, and is calculated as a geometric mean.

Sawle et al. (2018) evaluates the HDI by adding the elements y and the control focus z based on expression (7) below:

$$\begin{aligned} HDI &= 0.091\ln[P_{LY}/C] + 0.07214 HDI_{y,z} \\ &= 0.0978\left[\left(P_{LOAD} + \min\left(f_{\max_{SE}}.P_{SE}.f_{maxp_{load}}.P_{LOAD}\right)\right)\Big/ n_{HUMAN}\right] \\ &\quad - 0.319 f_{\max_{SE}} \end{aligned} \quad (7)$$

Where;

P_{LY}/C: Annual energy consumption per capita in kWh/y/person.

$f_{\max_{SE}}$: Parameter of maximum consumption of excess electrical energy that can be used for additional AC load.

$f_{maxp_{load}}$: Parameter that allows increasing the annual AC load and to make the most of the surplus energy.

P_{SE}: Annual surplus energy of the system in kWh/y.

n_{HUMAN}:Number of people who consume the energy generated by the hybrid system.

4. Results and analysis

To issue the results for 2050, the global socioeconomic viability of the electricity system and the marginal viability of renewable energy sources in the region were considered. With regard to hydroelectric production, a growth of only 5 % is considered due to the fact that there are projects underway and that will come into operation in the following years in several countries (Solarin and Ozturk, 2015; Almeida et al., 2021; Llamosas and Sovacool, 2021). The starting scenario was analyzed in detail in Section 3, its installed capacity is 457,031 MW between renewable energies and those from fossil fuels. By 2050, 750,175 MW of power will be obtained in LAC.

It is important to indicate that the scenario drawn up to 2050 with 100 % renewable energy is presented as recommended realistic. That is to say that the levels of contribution by sources are feasible for use in the region and would meet the demands of the population that would rise in LAC to 784 million inhabitants in 2050 as estimated by reference (Press, 2015).

Geothermal energy does not figure significantly in the future energy mix in the region. However, within the pre-feasibility studies there is a high potential that can be exploited in several countries in the region (Energía geotérmica: una opción costosa, pero atractiva para América Latina, World Bank, n.d). The current limitations of geothermal energy are the high costs involved in drilling, but in the future it is considered that their costs may drop significantly, as indicated by Yue Yao et al. in the reference (Yao et al., 2021). However, in the scenario developed for LAC in this specific case, it is considered that this technology does not exceed 12 %. In the same way, the same wind and solar energies can be exploited massively, but the use ranges will be maintained at balanced levels in order not to fall into a scenario similar to the current one where hydroelectricity has extreme levels of over 43 %. The scenario for 2050 is presented below in Fig. 8 and Table 4.

As shown in Fig. 9 and Table 5, the sources that are called to strongly substitute fossil fuels and be the support according to the growth in demand are wind and solar. Hydroelectric contributions to the energy mix do not vary radically from the base year with reference to 2050 by more than 7 % in what corresponds to generation. The hydraulic proportion is maintained until 2050 as shown in Table 4. As presented, a diversified matrix will be available by 2050, the region will be consolidated and basically sustained by the three generation sources: Hydraulic (782,940 GWh), wind (795,800 GWh) and solar (788,750GWh). Other small contributions of renewable energy such as geothermal and biomass, which will be a complementary part in the region, are not neglected.

Fig. 10 shows the 100 % renewable energy installed power capacity by 2050.

The proportions of energy that are specified are feasible and advisable according to the future energy demand by 2050. It would go from a high dependence on electricity generation from fossil fuels to a complete energy transformation in the region based on renewable energies. It is the main challenge for a healthier and pollution-free future, each member state is a fundamental part of achieving this purpose. In LAC, efforts are being made in each country, but there is still a need to build a sustained joint agenda to carry out actions in a single direction and in an articulated manner. Long-term policies have the advantage that in their planning they do not require immediate financial resources and in high proportions, and the most important thing is that they are developed progressively with a view to meeting large objectives and avoiding being reactive with ineffective solutions. Advantageously, there is a reduction in the costs of these new technologies, especially in wind and photovoltaic, others are also being developed such as geothermal, biomass and will allow maintaining the current infrastructure based on hydroelectric energy. Renewable energies in LAC are beginning to be incorporated and promise to play a transcendental role in the production and consumption of energy in the coming years. An orderly energy transition with a growing economy is important in the fight for the climate in LAC and the world. The effects of extreme weather events that are already being felt in the region due to pollution levels outside normal ranges will be avoided. The actions aligned to carbon emissions are generating the rejection of the entire world because they bring with them alterations in human health and the economy of the countries. The reason for still maintaining these polluting systems is because the large companies in the world avoid at all costs that their investments go down and take refuge in legal aspects and agreements that have been carried out in previous years with governments. In addition to this, it is due to the need to balance current power systems that the option is to progressively replace current energy based on high concentrations of carbon with renewables.

Employing higher rates of low-cost renewable energy in LAC would likely discourage the extractivist industry. This research identifies a long-term positive balance relationship, including legal agreements between governments and multinational companies (Por segunda vez, 2022; para and el Caribe, 1998) will mostly expire in the next 15 years, which makes the switch to renewable energy attractive. This study

Table 4
Current and projected installed capacity by 2050 in MW.

Source	2020	2050
Non-Renewable Thermal	177,718	0
Hydro	197,020	206,875
Nuclear	5353	5700
Wind	32,552	245,500
Geothermal	1704	9700
Solar	20,007	235,200
Others	385	6500
Renewable Thermal	22,292	40,700
Total	457,031	750,175

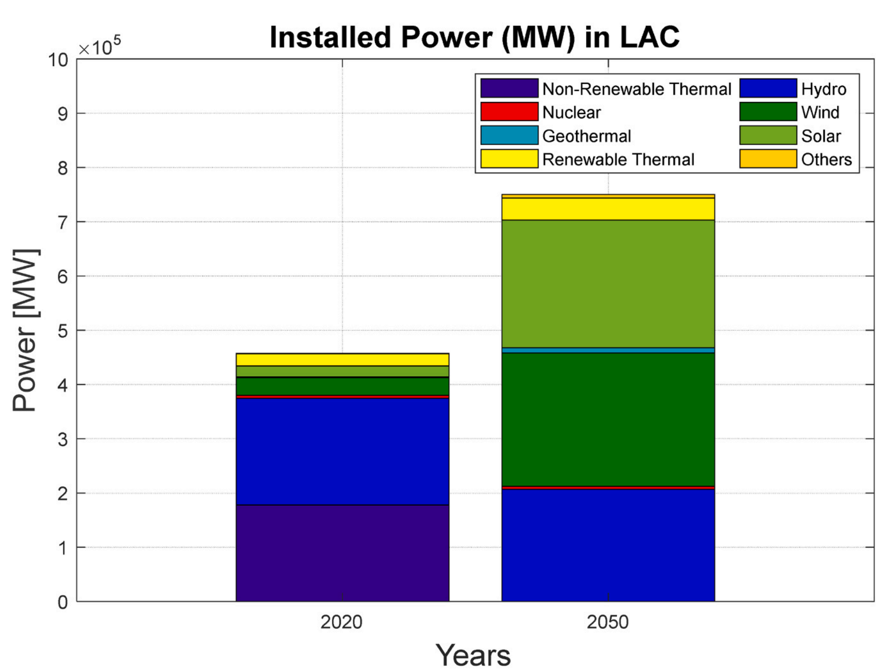

Fig. 8. Installed capacity in the scenario 2020 and 2050 for LAC.

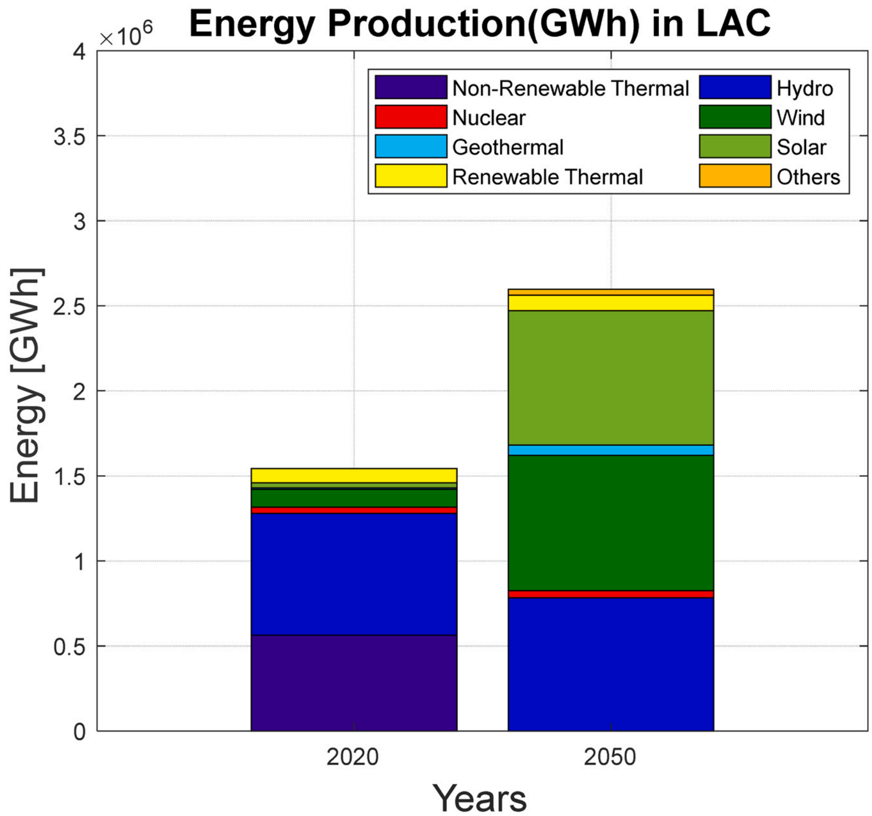

Fig. 9. Energy supply in 2020 and 2050 in LAC.

Table 5
Energy produced (GWh) in 2020 and in the 100 % renewable scenario in 2050 for LAC.

Source	2020	2050
Non-Renewable Thermal	562,807	0
Hydro	717,082	782,940
Nuclear	35,579	42,500
Wind	104,266	795,800
Geothermal	9309	60,670
Solar	30,056	788,750
Others	626	91,440
Renewable Thermal	83,529	34,800
Total	1543,254	2596,900

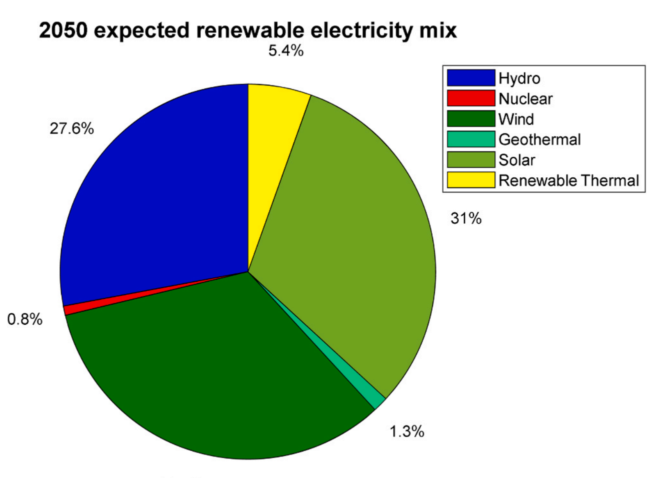

Fig. 10. Mix of renewable energy installed power capacity in the year 2050.

already shows that the electricity market in LAC will grow around 1.6 times in 2050, from 1543,254 GWh to 2596,900 GWh. This reality forces us to take immediate action in the region and maintain that same line of action in future governments regardless of whether they are politically from the right or left, here the need to transform the electrical system together for the good of the population must prevail. There are other benefits that the promotion of renewable energies will bring, which is to invigorate and stimulate both macro and micro economic growth in the region, especially with new jobs.

The important thing is to recognize the work that has been carried out in the LAC countries, whether alone or jointly, the efforts are noted when their master plans and their legal sections are pointing out that renewable energies are the hope to achieve coal. neutral as a mandatory objective if we want to maintain temperature levels below 1.5 °C. It has been widely highlighted in the literature reviewed in this article and it is addressed that renewable energies are the future of the region. Table 6 summarizes the processes carried out by the countries that make up LAC and it is recognized that all have adapted their legal aspect and their future energy transformation plans based on renewable energies.

4.1. Financial mechanisms to increase renewable energy

Financing instruments are essential to break down barriers and promote public and private investment that contributes to restructuring the productive matrix of the region in a progressive way to replace fossil fuels to achieve zero carbon in the region (Zero Carbon LAC-UNEP-REGATTA, n.d). Among the financing entities is the most renowned IDB, which has structured innovative instruments such as green bonds, loans, energy saving insurance (Mecanismos Financieros para Energías Sostenibles and Green Finance Lac, 2021), donations, advice on process and technology innovation, among others. The actions have focused on the institutional strengthening of the states of the region, promoting investment and legal advice on the fronts of renewable energy, energy efficiency, sustainable transport and energy storage

Table 6
Policies, Plans or Goals whose purpose is to increase renewables in the different countries that make up LAC.

Country	Polices, Plans or Goals for Renewables	Ref.
Brazil	The Brazilian energy authorities published the national energy plan for the nation towards 2050. Brazil will introduce 45 % renewables to its energy matrix by 2030.	(Brasil introducirá 45% de renovables a su matriz energética para, 2030, Energía Hoy, 2020)
Venezuela	Homeland Plan 2019–2025 of Venezuela. Section 5.1.5. It promotes the production of clean energy, increasing its participation in the national energy matrix.	(Plan de la Patria, 2019-2025 de Venezuela and Observatorio Regional de Planificación para el Desarrollo,n.d)
Colombia	Inclusion of renewable energies in 15 % in the energy matrix by 2029. Law 1715 created in 2014.	(Amaya Pineda, 2016)
Chile	The goal is to increase electricity capacity by 20 % by 2025. About 60 % of electricity generation is planned to be renewable.	(Climatescope, 2021)
Argentina	A goal of 10000 MW of RE is set by the year 2025. Law 27191 on Renewable Energies.	(Vizzuality,n.d)
Paraguay	Paraguay 2040 Energy Policy approved in 2016, establishes a new challenge that is implementation.	(Laino, 2015)
Bolivia	Plan to increase the participation of RE in 79 % to 2030. Bolivia aims to reach 183 MW of RE production by 2025.	(Benkraiem et al., 2019)
Peru	In 2008, Law for the Promotion of Investment in Electricity Generation with the use of Renewable Energies. Legislative Decree 1002,	(Decreto Legislativo No, 1002,n.d)
Uruguay	Interparty agreement that took shape in the Uruguay Energy Policy 2015–2030, which it gives solidity and continuity.	(Estrategia Nacional de Desarrollo Uruguay, 2050 and Observatorio Regional de Planificación para el Desarrollo,n.d)
Ecuador	National Energy Plan of Ecuador to 2050 – PEN 2050. Development of wind, hydro and solar infrastructure that can supply 80 % of all energy by 2030 and 100 % of all energy in 2050.	(MINISTERIO DE ENERGÍA INICIÓ LA ELABORACIÓN DEL PLAN ENERGÉTICO NACIONAL DEL ECUADOR PROYECTADO AL, 2050 – Ministerio de Energía y Recursos Naturales no Renovables,; Press, 2019)
Guyana	Officially declared to double its energy efficiency by 2030 and approach 100 % RE generation by 2040	(Guyana -Renewable Energy, International Trade Administration – Trade. Gov,n.d)
Suriname	Suriname aims to keep its amount of electricity from renewable sources above 35 % by 2030	(Suriname's climate promise, for a sustainable future, UN News, 2020)
Mexico	Sener predicted that by 2030, renewable energies would add 24 thousand 296.5 MW to the total capacity and together they will have little more than 32 % of the total electric power generation.	(¿Cuál es el potencial de México en energía renovable?, Greenpeace México,n.d)
Costa Rica	National Energy Plan 2015–2030. Carbon Neutral Country Program. Developed country and is currently over 98 % renewable energy. 100 % electricity generation with renewable sources 2030	(231, Energy Resource Guide - Renewable Energy - Costa Rica,; Costa Rica's electric grid powered by 98% renewable energy for 7th straight year, 2021)
Cuba	Installation of 2144–2382 MW of renewable energy.	(Semana del Clima de Am£©rica Latina y el Caribe Montevideo … Pre industrial se refiere a temperaturas - PDF Document, fdocuments.ec,n.d)
El Salvador	Increase in renewable energy by 2025 at least 12 %, reach 58 % of renewables.	(El Salvador prevé que en, 2025 el 58% de la energía sea renovable,n.d)
Panama	Panama has will install 1.7 GW of distributed solar photovoltaic by 2030.	(Panama could install 1.7 GW of distributed-gen PV by, 2030, Pv Magazine International,n.d)
Belize	Its plan is that 85 % of renewable energy by 2030 is through the implementation of hydroelectric, solar, wind and biomass energy, and reduction of transmission and distribution losses.	(Vizzuality, Energy - Climate Targets - Belize - Climate Change Laws of the World,n.d.)
Guatemala	In 2015, the National Interconnected System (SNI) had 58 % renewable electricity generation and it is expected that by 2030, the electricity generation is 80 % from renewable sources.	(Messina, 2020)
Nicaragua	Electricity Generation Expansion Plan (2013–2027)	(Policy database – Data & Statistics, IEA,n.d)
Honduras	In 2007, the National Congress approved the Law on Incentives for Electricity Generation with Renewable Energy (Decree 70–2007). In 2013, through Decree 138–2013 that reformed Decree 70–2007, an important boost was given to solar energy photovoltaic.	(Para and el Caribe, 2018)
Grenada	Grenada proposes a 30 % reduction in emissions by 2025 with 10 % renewables	(Messina, 2020)
Barbados	Renewable generation has progressively broken into solar energy, which is advancing at an annual average GWh growth rate of 37 % from 2015 to 2018. They bet to generate 65 % of electricity based on renewable energies in 2030.	(Messina, 2020)
Guadaloupe	Renewable energy penetration rate: 59 % in 2023; 71 % in 2028. 100 % energy independence in 2030.	(Hatching an Energy Plan: From PRERURE to PPE - Regional Strategy, Guadeloupe Energie,n.d.)
French Guiana	Through a new plan, the government hopes to reach a cumulative PV capacity of 80 MW by 2023. By 2030, installed solar power is expected to reach 105 MW. The plan completely excludes the construction of new fossil fuel power plants.	(France releases renewable energy plan for French Guiana, solar FITs to be increased by 35%, Pv Magazine International,n.d)
Bahamas	Wärtsilä will support the Bahamian government's plans to increase its share of renewable sources, especially solar, by 30 percent by 2030.	(BNamericas,n.d)
Antigua y Barbuda	The Department of the Environment, trade unions and NGOs, such as the Environment Awareness Group and the like, continue to sensitize stakeholders and end users about alternatives to save energy first, and others to cover electricity demand with wind or solar energy.	(Islas del Caribe abren juego a inversiones en energía eólica y solar - Energía Estratégica, 2021)
Aruba	The Aruban government is promoting the use of renewable energy, most notably solar and wind power. With more than 5000 and 2500 wind hours and solar hours, respectively, Aruba has enormous potential for sustainable power generation.	(Sostenibilidad,n.d.)

(continued on next page)

Table 6 (*continued*)

Country	Polices, Plans or Goals for Renewables	Ref.
Cayman Islands	The Cayman Islands in its approach considers obtaining 70 percent of the electricity supply from renewable sources in 2037. Renewable energies include wind, solar, biomass and geothermal energy sources.	(BMR Energy adquiere una planta solar de 5 megavatios en las Islas Caimán, 2019)
Dominica	Dominica Island and the Renewable Energy Fund of the United Arab Emirates and the Caribbean will sign a contract for a clean energy plant of 50 million dollars.	(Press, 2021)
Dominican Republic	Law Number 57–07 on the incentive to develop sources renewable energy and its special regimes aims to promote the Dominican Republic towards a more sustainable energy matrix.	(Decreto No 202/08 - Reglamento de la Ley No 57, Ley de Incentivo a las Energías Renovables y Regimenes Especiales,n.d.)
Haiti	The IDB will grant funds to the Haitian government to develop a new energy infrastructure that takes advantage of the country's wind, solar and hydroelectric potential. Such an initiative could cost some $1 billion, but it will help the poorest nation in the Americas.	(Haití recibirá ayuda para impulsar energías renovables, América Latina y El Caribe,n.d.)
Jamaica	Until 2025, the goal is 320 MW solar or wind and 74 MW of hydroelectric, waste-to-energy or biomass conversion	(BNamericas - Jamaica lanzará convocatoria por suministro …, BNamericas.com,n.d.)
Puerto Rico	Puerto Rico authorities require that renewable energies represent 40 % of electricity generation by 2025, 60 % by 2040 and 100 % by 2050.	(Carbó, 2020)
Martinique	Martinique is moving towards energy self-supply with the 14 MW Grand-Rivière wind farm. It seeks to rely solely on RE by 2030.	(Martinique makes strides towards energy self-sufficiency, New Energy Events, 2019)
Saint Barthélemy	France is the state that is concerned with providing energy logistics to the small and beautiful island of Saint Barthélemy. 100 % renewable energy is available, basically with two furnaces for converting waste into energy, solar panels and wind turbines.	(llegada a San Bartolome,n.d)
Saint Lucia	Saint Lucia is estimated to be able to produce 15 MW of geothermal electricity between 2020 and 2022, with a further 15 MW during 2025–2027.	(Santa Lucía: del uso de combustibles fósiles al despliegue de fuentes locales de energía renovable, ECPAmericas,n.d.)
Saint Kitts and Nevis	The government of Saint Kitts and Nevis, the state-owned electric power company St. Kitts Electric Company and Leclanché SA, have announced the largest solar generation and storage project built to date in the Caribbean.	(Leclanché y la isla "Saint Kitts" acuerdan construir el mayor proyecto de generación y almacenamiento de energía solar en el Caribe - Energía Estratégica, 2019)
Saint Vincent and the Grena dines	Within its goals is 60 % renewable energy by 2024	(Securing Energy in Saint Vincent and the Grenadines, Caribbean Development Trends, 2016)
Turks and Caicos Islands	In 2021, the country invested $1.6 billion in renewable energy projects and its goal is to achieve 100 % renewable energy in less than 2030.	(Islas del Caribe apuestas por las energías renovables: eólica y energía solar fotovoltaica,n.d.)
Trinidad and Tobago	The Government of Trinidad and Tobago has a target for 30 % of electricity generation to be from renewable energy by 2030	(Latin America and the Caribbean Announce Ambitious New Renewables Target,n.d.)
Virgin Islands	It is close to covering 75 % of its energy demand with solar, wind and smart technology applied to energy storage. It is expected to reach 100 % in 2030.	(Viaintermedia.com, Panorama - Una isla de ricos y famosos renovable,n.d.)

(Almeida et al., 2021).

The Energy Savings Insurance Program is aimed at eliminating the barriers related to investments in renewable energy by applying four risk reduction instruments in projects that provide confidence to investors: standard contract, energy savings insurance, savings validation and financing (Mecanismos Financieros para Energías Sostenibles and Green Finance Lac, 2021). The contract guarantees the execution of the project and is backed by an insurance policy that is activated in the event of non-compliance with the promises made in the contract. The execution will be in charge of an independent but binding institution for the parties (La energía que necesita la América Latina del futuro, World Bank, n.d). Typically, the requesting country asks the bank for a loan to finance its project, while the supplier is responsible for managing and acquiring the insurance policy in favor of the requesting country.

The model is available for LAC countries applicable to both energy efficiency projects and distributed generation projects, mostly solar photovoltaic and wind power given the high energy potential in the region as analyzed in Section 3 of this manuscript, which makes it more attractive as an investment. Energy savings or energy generated must be guaranteed for a period of time sufficient to recover the investment, additionally considering the risk represented by electronic money, as recommended by references (Rinaldi et al., 2021; Arauz et al., 2021).

Around the world, the private sector and governments are determined that countries achieve significant development (Doepfert and Castro, 2021; Alvarado et al., 2021). The growing concerns related to environmental degradation in the world are actively contributing to reorganize its energy production processes. A question that has received increasing research interest in the field of economics and energy is how countries can improve their production and use of clean energy (Zabaloy and Viego, 2022). Europe is a great reference (Dominković et al., 2016), as is China (Luo et al., 2021), in the production of clean and safe energy, some of its good experiences can be assumed to avoid making investments that are detrimental to the countries that make up LAC, especially the poorest. Undoubtedly, the existing primary energy resource in the region is important and not to say excellent, however, from the point of view of implementing plant implementations, resources are required, this is where decision-making must be fundamental and It has been mentioned that the contribution of governments and private entities must play a transcendental role. When delving into the case of LAC, according to reference (Zero Carbon LAC-UNEP-REGATTA, n.d.), electricity consumption in the region has increased considerably in the last three decades and has almost tripled since 1970.

The Brady Plan is an example of macroeconomic adjustment that has been in force in the region for the liberalization and opening of the market [227 and, finally, to boost the economy in the region (Murshed, 2020). Despite the rapid growth of renewable energies in LAC (Almeida et al., 2021), a large part of the states continue to depend on fossil fuels, either as consumers or as producers (Lous, n.d.).

Historically, several countries have used the subsidy-based policy mechanism. For many analysts it is not an appropriate option, for others it is an interesting option to try to make the projects more viable, especially so that the poorest social class has access to these services. The options that the region or even each country takes is a decision that as long as the horizon that is to transform the energy systems and have carbon zero in the region is not lost, they are always welcome. In this way, it is possible to have greater availability of energy services without fossil fuels. Electric systems can achieve long-term values equal to or less than $0.14 per kWh.

Several energy agencies have proposed different energy transition and investment recovery plans that provide a roadmap for governments around the world. With regard to LAC, in order to reactivate the economy while reducing global emissions, it is working hard on financing projects. In this sense, the International Energy Agency proposes a Sustainable Recovery Plan to boost the economy, improve the resilience and sustainability of energy, and create jobs (IEA offers world governments a Sustainable Recovery Plan to boost economic growth, create millions of jobs and put emissions into structural decline - News, IEA, n. d.). To meet these wishes, investments are planned in the electricity sector, along with civil works, transportation, industry, and in innovation and development of new technologies. There is the potential to generate 3.5 % growth in global GDP by spending $1 trillion annually through 2023, creating more than 9 million jobs, and reducing about 3.5 gigatons of CO_2. The International Renewable Energy Agency has made a proposal that includes short-term measures to promote recovery and energy transition, and a plan, with a time horizon of 10 years, based on the Sustainable Development Goals (SDG) by 2030 and in the Paris Agreement. These stimulus measures are expected to generate investments, in renewables and other types of technologies related to the energy transition, worth 2 trillion dollars in the 2021–2023 period, and to achieve an annual investment of 4.5 trillion dollars. until 2030, and that they create 25 and 10 jobs in renewables and in efficiency for every million dollars invested. These plans are discussed in LAC, they have a favorable context to implement a long-term sustainable recovery plan and benefit from the potential for reactivation and job creation. It is considered from this perspective that a recommended realistic scenario will require around 100 trillion until 2050. For this analysis, the respective scenarios that provide long-term investment alternatives are drawn, see Table 7.

In relation to the financial aspect, three scenarios are presented as shown in Table 7, these are: conservative (S_1), expected (S_2) and optimistic (S_3). The value that most influences the proposed scenarios is the total cost of the technology, which is the fundamental basis for these transition processes and is between 80 and 120 trillion dollars. Items that are quite strong but that without a doubt in a regional structure and in an incremental way can be invested, add to this the financing possibilities of international agencies and banks and the own resources of each country can be balanced. This study presents a roadmap with investment options that will surely influence government and private sector decision, additionally it will be a fundamental basis for new research proposals and approaches in search of better channeling the transition processes that the region needs to experience.

Next, Fig. 11 presents the scenarios developed in terms of forecasting the cost of energy production based on a regional policy that is exempt from subsidies. Of course, different countries in the region are motivated to partially subsidize their basic services, including electricity. However, it is important to indicate that when subsidies are decreed by the central government, in most cases it is difficult to withdraw the population and chaos and demonstrations ensue. In Fig. 11 three different values of production costs are presented in three scenarios, but when reaching 2035 it is possible to level the energy production at 14 cents of a dollar per kWh, in which the technologies are much more mature. in the region and a much clearer economic horizon.

S_1 is the highest, causing a high rate until 2035 that is based on the investment made, which will end up falling on the electricity rate. Within the analysis of the curves of the three scenarios S_1, S_2, S_3 becomes interesting around 2050 and costs in all three tend to remain constant at 14 cents USD/MWh. It implies that a real rate, free of subsidies and above all requires a change of 100 % renewable technology and will remain operational around 50 years after the transition processes have been completed.

Although there are financing mechanisms as indicated in this section, some countries in the region have an inclination towards subsidies and it is a reality that cannot be ignored. In this sense, below in Fig. 12 a structure is presented considering subsidies of around 24 %, this implies that the outlined scenarios will be subsidized until 2035. These resources will come from the same fiscal funds of the different governments in power, the criterion is that these subsidies be applied for a certain time, that is, until 2035. It implies a maturity in the application of subsidies and extending beyond this year can lead to countries having imbalances and leading to patchwork solutions. In the same way that in the scenario without subsidies, it is possible to have a cost of 14 US cents per kWh from 2035, which would be possible while the transition processes continue until 2050.

It is important to indicate that whether in a structure based on subsidies or not, great progress will be made in the region, such as a better quality of life for the population, job creation, a cleaner industry, conserving unique species on the planet, among other important reasons.

5. Analysis and discussion

After interpreting the results obtained in scenarios S_1, S_2, S_3 corresponding to the financial part, it should be specified that it will allow a clearer vision of reality for government decision-making and invite investors from the same region or from other parts of the world. world so that they can participate in the renewable energy auctions in the different LAC countries. On these scenarios it is possible to decide within their countries the policies that are adopted with the purpose of achieving zero carbon emissions in the long term. There is a series of studies worldwide that have enriched the literature on transition processes, each one has its particularities and has been a fundamental basis for outlining investment scenarios for LAC. This study will be essential, on this basis new research will provide alternatives for the transformation of the electricity market in the region. It is clear that our analysis is based on a high production of wind and photovoltaic energy and form the cornerstones of the future market based on renewable energies with the accompaniment of the old hydraulics. It has been shown that the region has taken a radical turn in the legal aspect towards renewable energy, it has cost a lot to break those old schemes that consisted of oil exploitation and fuel import. The region strongly believes that the new energy model will be led by renewable energies and it has cost a lot to gain confidence in decision makers. It is possible that this transition will ensure the incorporation of higher rates of renewables in the different LAC countries. Not acting in a timely manner can lead to paying a high price, typically late reactions will only achieve patchwork solutions.

The oil reserve/production ratio exceeds 35 years and that of natural gas exceeds 40 in the region. In turn, the hydroelectric potential is the most exploited compared to other renewable energy sources with 43 %.

Table 7
Construction of scenarios to calculate the average cost of production.

Item	Scenarios		
	S_1	S_2	S_3
Costs up to 2050 (trillions of dollars)	80	100	120
Estimated time to achieve full transition (years)	30	30	30
Useful life time after complying with the transition process (years)	50	50	50
Growth of electricity service until 2050 compared to the base year(%)	50	75	100
Technical and non-technical losses (transmission and distribution) until 2050 (13.22 % in 2020) (%)	12	10	8
EV sales growth to 2050 (%)	75	100	100
Repowering of electrical grids (%)	40	50	60
LPG substitution rates for electricity consumption to heat water (%)	12	20	40
Level of use of electric stoves	15	20	25
Government subsidy for electricity (YES/NO)	No	No	No

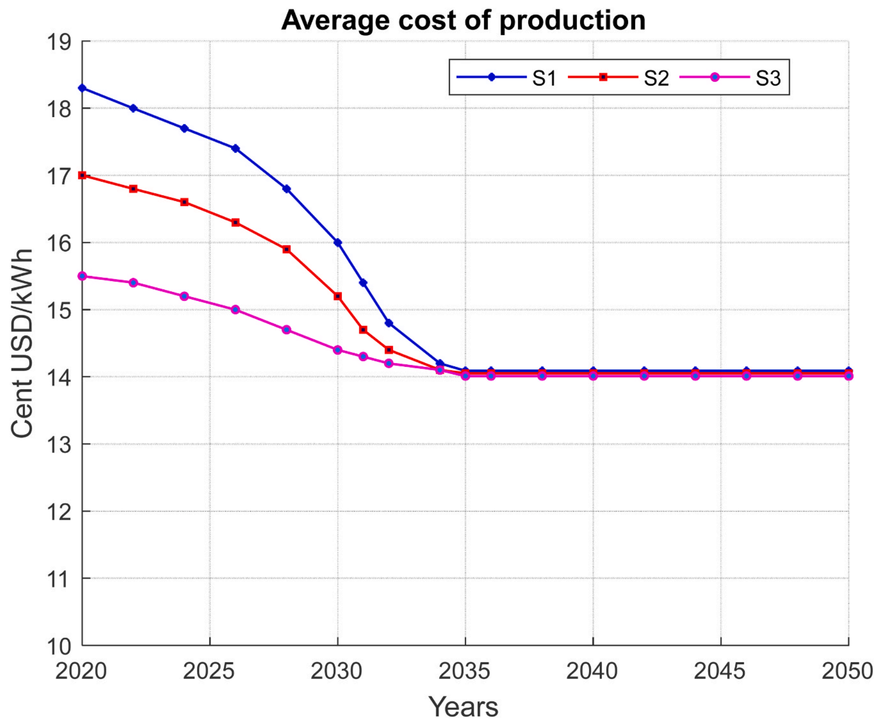

Fig. 11. Average cost of production in a regime without subsidies.

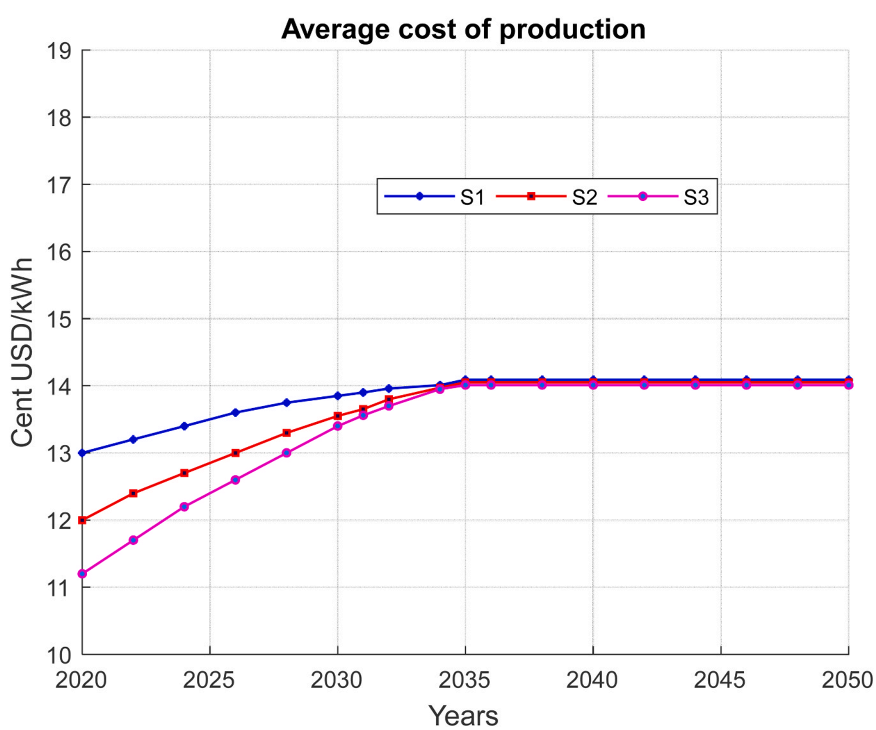

Fig. 12. Average cost of production in a regime with subsidies.

Despite the available resources, an adequate development of geothermal energy is not observed, which other researchers can consider as a line of research for future work. On the other hand, as observed according to the available potential and the use of wind and solar sources are little exploited, it seems that there are still barriers that are probably because the current policies have not been able to give the adequate effect. However, according to the country-by-country analysis, the great confidence that the member states have in wind and solar power is impressive, the legal framework allows these two sources to be better used and will surely be successful in later years given that there are projects who are on that line. The year 2050 is the reference to jointly achieve zero carbon for LAC. The actions of the region are consistent with the immense potential of wind and solar, however it is also observed that other renewable sources will be incorporated in the future to a lesser extent, as is the case of geothermal and biofuels, among others. The balanced integration of the dimensions of sustainable development constitutes the frame of reference on which LAC must continue to discuss and act at the same time. Therefore, this study will manage to cover the economic, social, energy and environmental fields from an integrating perspective by 2050.

6. Limitations of the work and future research directions

The attention of this research is focused on the future energy system and how it will work, rather than on the current energy system, which is why if we see as a limitation, simulations of the reference system or base year are not provided. Therefore, EnergyPLAN includes relatively detailed modeling of future technologies including wind, solar, biomass, and hydraulics, but relatively aggregated modeling of current technologies.

The future is never certain, especially when considering a term such as the year 2050. Consequently, there is always significant limitations and uncertainties associated with any study when modeling the future energy system. Therefore, the internal power system bottlenecks of the LAC countries are not considered, which probably lead to an underestimation of electricity grid costs

fictional. Additionally, the electricity network costs assumed here may be overestimated because equipment costs are trending downward and in the future they may be much more accessible.

In general terms, the model used in this study is a deterministic input/output model. The main objective of the model is the design of regional energy planning strategies based on technical and economic analyzes of the consequences of the implementation of different renewable energy systems and investments. The structure of the energy system encompasses the entire regional energy system. The products are the energy balances and the resulting annual productions.

In relation to future work, the purpose is to carry out an advanced analysis that reflects various risks such as financing, policy change, risk preference in LAC subregions, determination and uncertainty in energy prices for each subregion and electricity rates in the formulation can be determined. This study is considered to be transcendental for carrying out new research, uncovering new opportunities for exploration and analysis in the energy system of Latin America and the Caribbean. Investment opportunities are also seen in the region since, as has been determined, the policies and legislation of the LAC countries themselves point to a change in their energy matrices.

7. Conclusions

This research analyzed in great detail how the region is and renewable energy systems are having a positive impact and are achieving great acceptance. At the same time, the transition processes that LAC countries are developing to move from an electricity production system sustained by fossil fuels to a 100 % renewable system that achieves zero carbon in the region are highlighted. This model was emphasized in the review of the literature and the strategies that will have a direct impact on the LAC countries are provided here. Unfortunately, this energy model is adopted after the bad experiences of contamination due to oil spills and, above all, due to the reduction in production. After having analyzed this series of aspects, this study presents the roadmap for the renovation of the electrical system based on renewable energies in an adaptable and flexible way by 2050. Progressive but visionary clean energy inclusion rates are used with economic conscience. The EnergyPLAN tool is very useful for this type of long-term planning, particularly in this study it allowed the prospective transformation of the electricity system for LAC into a completely renewable one.

A fairly complete analysis made it possible to design the new energy model that LAC must assume, depending on the pace of economic growth in the region as a whole. After an analysis of the goals and objectives of each country in relation to their energy policies, it can be concluded that the regulatory framework of LAC offers very good possibilities to increase the pace of energy transition, highlighting the fact that they are already being implemented. various projects in the region. In the scenario proposed for 2050, it is possible to derail fossil fuels with joint efforts in the region. It is introduced towards a 100 % renewable and feasible energy model, it will provide flexibility when it comes to increasing production levels without involving substantive changes in the current network, but it will require calibrations. Purely partisan political trends or aspects are not included in this study, so it is assumed that the provisions of the laws and action plans in each country and in the region as a whole will be fulfilled over time without political interference in the countries. members. From the methodology used, it is concluded that structuring consistent and diversified markets in full presence of renewable systems is a fairly complex process and should not ignore collateral aspects such as the priorities of each country, their available extractable resources and their levels of maturity to take advantage of their own energy resources in addition to the socioeconomic sphere. On the one hand, there is the need to transform the world seeking to protect the environment and in fact it can be achieved with various strategies, however on the other hand, each measure that is taken must be mindful of not inadvertently affecting the lifestyle of the citizenship.

CRediT authorship contribution statement

Daniel Icaza Alvarez: Writing – original draft, Software, Methodology, Data curation, Conceptualization. **Francisco Jurado:** Writing – original draft, Conceptualization. **Marcos Tostado:** Writing – original draft, Conceptualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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