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*Review*

# Challenges, Roadmaps and Smart Energy Transition towards 100% Renewable Energy Markets in American Islands: A Review

**Daniel Icaza [1,2,*], David Vallejo-Ramirez [3], Carlos Guerrero Granda [2] and Edwin Marín [1]**

1 Centro de investigación, Innovación y Transferencia Tecnológica, Laboratorio de Energías Renovables, Universidad Católica de Cuenca, Cuenca 010203, Ecuador; edwin.marin@ucacue.edu.ec
2 Centro de investigación, Innovación y Transferencia Tecnológica, Laboratorio de Simulación en Tiempo Real, Universidad Católica de Cuenca, Cuenca 010203, Ecuador; carlos.guerrero@ucacue.edu.ec
3 Centro de investigación, Innovación y Transferencia Tecnológica, Laboratorio de Luminotecnia, Universidad Católica de Cuenca, Cuenca 010203, Ecuador; david.vallejor@ucacue.edu.ec
* Correspondence: dicazaa@ucacue.edu.ec

**Abstract:** There is no doubt that the transition towards renewable energies is generating many changes on different continents, some with greater impacts than others, but the development that has occurred is recognized and widely accepted. The progress has been significant but it is necessary to analyze the roadmaps that have been proposed so far at the island level so that decision makers have sufficient tools to commit the much-needed economic resources to transform their energy systems into 100% renewable ones. These approaches are not simple and the hard work of the authors who have disseminated their research is recognized. The roadmaps are planned based on the energy potential available in the territories and the future energy demand. Within countries, it is important to increase the economic resources to allocate to investments in environmentally friendly renewable energies. In this review of 100% renewable smart systems on islands, the situation of the American continent, its challenges and its long-term approaches in the different geographical areas facing 2050 are analyzed. This article shows that research into the design of 100% renewable energy systems in scientific articles is fairly new but has gained more and more attention in recent years. In total, 175 articles published since 2002 were identified and analyzed. Many of these articles have a predominant focus on the electricity sector. As a general result, it has been determined that although there has been significant progress towards an orderly energy transition, this has not been consistent with the international agreements signed since the Paris Summit, which is a real challenge in complying with the new commitment of the COP28 of Dubai in tripling the participation of renewables.

**Keywords:** smart energy systems; renewable energy; energy transition; clean energy; energy planning; America

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## 1. Introduction

The Paris Agreement (COP21) of 2015 was the starting point for several countries in the world to be moved and begin to make efforts to limit the anthropogenic climate change that has alarmed the world due to its significant increase [1]. Many researchers have already provided sufficient guidelines for government decision makers to choose to change the energy matrix in their countries [2]. The clear majority of the international community has adopted pro-environmental goals that include short-, medium- and long-term roadmaps to reduce greenhouse gas (GHG) emissions. Since the Paris Summit when the legally binding international treaty on climate change was established, it has been adopted by 196 parties. It was identified that two of the main opportunities to mitigate global climate change are to increase the use of renewable energy sources (RESs) and the radical transformation of current global energy systems [3]. The problem is that despite the important advances made in recent years, they are not enough to achieve the decarbonization of the planet. At COP28, held in Dubai, this aspect was discussed and the importance of tripling renewable energies and doubling energy efficiency to accelerate the energy transition process in the world was highlighted [4]. This implies that the roadmaps proposed in the countries from now on must be much more ambitious. That is why this manuscript evaluates the impact of the policies promoted so far in the American islands and seeks to identify the roadmaps drawn so far with a view towards long-term decarbonization. Likewise, it also seeks to highlight the shortcomings that exist in the rest of the island conglomerates of America for the decision-making by their governments to take concrete actions in favor of the environment and not take long to fulfill the purposes of tripling the production of renewable energy that is still achievable.

Thus, in recent years, many publications have focused on 100% renewable smart energy systems for various countries, regions and cities [5]. Although the energy systems that are proposed in the medium and long term should focus on all types of energy use in different sectors, there is still a greater focus on the electricity sector rather than the entire energy system [6]. Furthermore, to achieve 100% RES penetration, an intelligent combination of technologies is required to ensure the stable operation of the grid with a variable supply of renewable energy [7]. Worldwide, there are more than 85,000 islands registered, of which around 13% are inhabited with a total population of more than 740 million people [8]. In the context of 100% RES regions, islands have been playing an important role during the last three decades, among the main aspects are that they house an incredible number of marine species and are lungs that maintain a large part of the environmental balance [9]. Unfortunately, many islands suffer the effects of climate change, such as in America with the El Niño currents, on the one hand, and the economic and environmental consequences of the supply of energy from fossil fuels [10].

There are countries that are decisively promoting a clear energy transition with protected legislation and established policies towards a sustainable energy system [11]. At the island level, there are also decisions that promote the decarbonization of these sensitive territories, taking advantage of the available renewable energy potentials to convert them into environmentally friendly clean energy [12]. Unfortunately, there are countries that have difficulties in carrying out the energy transition processes. The case of Haiti [13] is an example in which the food subsistence of its inhabitants is in the foreground. In these cases, it is understandable due to the precarious situations and poor economies. Advantageously, there has been, in most people, an environmental awareness that has been achieved in recent times that the countries of the continent and islands long for their energy systems to be sustainable [14]. A significant example is that of the Galapagos Islands, which are considered a Special Regime within the Ecuadorian Legislation, as the decarbonization of the Islands has been proposed and the goal set is 2050 [15]. San Francisco de Quito University, in an event in mid-2023, held a workshop to discuss the roadmap [16] where several studies were evidenced, including that of the Government of Ecuador when ratifying its approach through the Zero Fossil Fuels project in Galapagos [17].

Since 2000, an expanded version of similar island projects was provided that documented the different projects and objectives to facilitate the cooperation and dissemination of these special places [18]. Several studies focused on the topic of renewable energies for islands and some that have even already been implemented [19]. With research in permanent development, investments have been achieved from both the public, private and mixed sectors. The impacts achieved have been notable when observing the higher proportions of variable RESs, which have even focused more thoroughly on guaranteeing service towards demand, addressing new issues related to the technical and economic solutions [20]. It is important to highlight that as studies currently address with more interest the energy structures to be implemented in the medium and long term, there is greater concern about transforming these systems that are still based on fossil fuels into systems that are much more friendly to the environment's atmosphere [21]. The case of Jamaica is striking, as reference [22] examines a path for small islands to replace fossil fuels with renewable sources, such as wind and solar, of up to 100% to economically achieve energy security. The results show that the introduction of intermittent renewable energy in an island network requires an energy backup system. The simulations showed that a battery energy storage system (BESS) using lithium-ion batteries can be employed. The cost of the backup system is worrying since, to achieve a greater capacity against discharge, its use is expected to be economical in about 10 years.

From this perspective, it is expected that islands that maintain systems powered by fossil fuels can begin their renewal processes and avoid much more pronounced social inequalities. Latin America has one of the least-polluting energy matrixes in the world [23]; its efforts involve recognizing that in many cases, despite their weak economies, they are making efforts to preserve life on the planet. On the other hand, oil is depleting its reserves worldwide, it is ceasing to be the element of development for countries, it is no longer as much of an economic strength as it was before, especially for small countries, and in many cases this resource has brought inequalities, social corruption and pollution [24]. In the same localities where oil is extracted, their populations have been excluded from benefiting and in many cases have been displaced from their natural habitat, as in the case of the Amazon in South America [25]. It is important to draw up the roadmaps under much more hopeful schemes for the countries and, where appropriate, for the islands that require much more special action because there are, in some cases, very small populations [26].

According to the United Nations (UN) report [27], the seven main emitters (China, the United States of America, India, the European Union, Indonesia, the Russian Federation and Brazil) have been identified, representing approximately half of the global emissions of greenhouse gases in 2020. Meanwhile, the Group of 20 (Saudi Arabia, Germany, Argentina, Australia, Brazil, China, Canada, France, India, Indonesia, Japan, Italy, the Republic of Korea, Russia, Saudi Arabia, Mexico, the United Kingdom, Turkey and South Africa) is responsible for 75% of global greenhouse gas emissions.

Thanks to this environmental campaign that has been echoed around the world and is supported by the UN, both governments are making macro-energy changes and it is evident that it is having an impact on a medium and small scale at the level of companies, homes and even institutions. Educational institutions have come together to define financial actions that undertake ambitious and immediate measures to reduce emissions by half by 2030. Antonio Guterres, the Secretary General of the United Nations said "We must turn all commitments to net zero emissions into a movement unstoppable world" [28].

The IEA published its official report, *Net Zero by 2050: A Roadmap for the Global Energy Sector* [29]. Since its launch, the energy sector has experienced important changes and renewable energy systems have had greater momentum on all five continents. Reviewing the most recent data on policies, technologies and markets, the IEA presents a reliable and updated version with a view up to 2050. As a path outlined that can be discussed, it is not the only one. A wide range of countries strive to continuously monitor all their national public energy research, development and demonstration (RD&D) activity, and also share the collected data openly to a very good extent. The approaches are specific to each country, the proposals for decarbonization are also presented according to the particular vision, which in various cases has been designed with the support of specialized software Homer Pro Version 3.16.2 and in others according to the perspectives, policies and goals established. The methodologies used and data presentations vary significantly between countries [30].

The roadmaps at the island level are also described, mostly as they are much smaller constituencies, the diversification of their generation sources is limited and to guarantee their continuity in long-term service they require backup systems, typically that are battery-based [31]. There are also a variety of approaches from one island to another; even on the same island, various authors propose roadmaps based on their own methodologies, also identifying the most relevant common aspects [32]. Most researchers carry out an analysis of the current state and its history in its continental territory and islands before proposing medium- and long-term scenarios, including institutional agreements, energy potentials, methods of collection, the classification and validation of data, and existing technology [33]. The objective is not only to define an energy transition guide for islands that are near the beginning of their path towards collecting energy R&D but also for territories with more advanced systems that seek to strengthen specific areas [34].

*1.1. Review Method*

To fulfill the purpose of the present study, we focused on reviewing articles that discuss 100% RESs on islands near the American Continent that were published in peer-reviewed journals. No limitations were considered either in the size of the islands or in the year of publication. We focus on analyzing even the smallest islands with the purpose of identifying whether or not there are previous studies that promote the maintenance of natural island characteristics. On other continents, exhaustive reviews regarding methodologies for identifying transition processes on islands have already been contemplated. Among these reviewed studies: Olav H. Hohmeyer et al. [35] carried out a methodological analysis for a paradigm shift in energy policies and trends towards the supply of 100% renewable electricity in Europe. Similarly, D. Connolly et al. [36] carried out a methodological analysis of the technical and economic impact in the potential scenario of 100% renewable energy for the European Union. Bin Lu et al. [37] conducted a study regarding the low-cost, low-emission 100% renewable electricity system in Southeast Asia supported by pumped hydroelectric storage. Andrew Blakers et al. [38] conducted a study to harness the energy resources available in Australia and achieve 100% renewable energy. Often, the number of inhabitants or area is used to classify an island as large or small. In our methodology, a survey was carried out of the islands that are geographically located within the American Continent, in which the renewable and non-renewable energy component was specified. Subsequently, a search was carried out for the research that has been carried out on these islands that aims to transform their energy system to be 100% renewable. Flavio R. Arroyo M. and Luis J. Miguel [39] presented in their recent research on low-carbon energy governance for Ecuador, scenarios were outlined for accelerating the change of the energy matrix. It is striking that the scenarios that predict greater economic growth and the use of renewable energy are not as closely related as in the past. Ecuador's economic recovery will depend on the promotion of greater investments in technological innovation.

Ozan Erdinc et al. [40] classify the islands according to their annual consumption (GWh). Very small islands are considered (<1 MW and <2 GWh), small islands (1 to 5 MW and 2 to 15 GWh), medium islands (5 to 35 MW and 15 to 100 GWh) and large islands (>35 MW and >100 GWh). For our review, we do not define small islands but we address these criteria and highlight those that have a roadmap or are in a clear transition process towards 100% renewable energy.

Articles included in the review were considered those that resulted after using a keyword search and backward search to identify all relevant journal articles indexed in Scopus. On the other hand, research papers presented in conference papers without a peer review process or reports were not considered in the main analysis.

We analyzed the methodologies of other research focused on designing 100% RES energy markets of continental and insular orders, which evaluate the energy potential using meteorological stations and historical data [41]. Other researchers highlight the usefulness of mapping where the energy potential by the source is identified in detail. Most countries have sufficient and verified cartographies published by official government entities. There is also another type of cartography available and very usefully obtained via satellites. Subsequently, detailed analyzes of the energy resources that can be used by order or legislation can be carried out [42]. Among the very common energy resources within the roadmaps, it is evident that both wind and solar photovoltaics are hopeful technologies for the purposes of energy transition [43]. Among the systematic methodological developments carried out by different authors, it stands out that most of the studies were designed with specialized software such as EnergyPLAN [44], LUT [45], LEAP [46], Message [47], or MATPLAN [48], among others [49].

VOSviewer version 1.6.20 was finally used, as it becomes a tool of great importance to methodologically evaluate the existence of roadmaps in the American islands, thereby making it easier to identify transcendental aspects in detail such as the authors and simulation tools used. What is also interesting is the graphic mode that is presented in the analysis when validating the research and its details.

Several key questions were answered to determine the importance of the energy transition in the islands of the American continent with a view of achieving 100% RE:

- To what extent are wind and solar photovoltaic energy currently being used?
- To what extent do renewable energies contribute to the current energy demand?
- To what extent have the roadmaps for the American islands been designed?
- What other renewable sources are called to integrate the energy mix of the islands?

The review parameters are grouped into:

1. Description of the island located on the American continent, consisting of the name, country, area, population and description of the current energy system.
2. Description of the article including the authors, journal, year and objective of the study.
3. Approach and methods identified: tools and database used, time frame, simulation approach, energy sectors analyzed and technologies considered.
4. Information with sustainability criteria and cost assumptions.

Regarding the objective of each study, various reasons are formulated, with energy transition objectives on islands.

### *1.2. Research Location*

America is located entirely in the Western Hemisphere: it extends between the Atlantic and Pacific Oceans, bathed to the north by the Arctic Ocean and to the south by the Drake Passage, where the Atlantic and Pacific Oceans are found. The northern part leans towards the west and is very close to Asia, since the Bering Strait only measures 66 km; on the other hand, the southern part is more isolated in the middle of the seas and separated from the nearest land masses, Australia and Africa, for thousands of kilometers.

The territory of America covers an area of 42,142,000 km, which represents 29% of the planet's surface land. America is the second largest continent of the world. It is made up of three sections: North America, Central America and South America. Its name comes from Amerigo Vespucci. This explorer, cartographer and navigator introduced the hitherto revolutionary idea that the lands found by Cristobal Colón were part of a continent.

In the territory, there are long mountain ranges like the South American Andes and the Rocky Mountains or Appalachia in North America. The highest peak is the Aconcagua mountain, located in the Andes mountain range in Argentina. It is possible that the youngest mountains in the world are located between the western states of the United States, with an age of 1 million years, approximately.

America is made up of 35 sovereign states and 25 dependent territories of other countries or subject to other countries to some extent. The nation sovereigns are: Argentina, Antigua and Barbuda, Barbados, the Bahamas, Belize, Bolivia, Brazil, Canada, Chile, Colombia, Costa Rica, Cuba, Dominica, the Dominican Republic, Ecuador, the Salvador, Grenada, Guatemala, Guyana, Haiti, Honduras, Jamaica, Mexico, Nicaragua, Panama, Paraguay, Peru, Saint Kitts and Nevis, Santa Lucia, Saint Vincent and the Grenadines, Suriname, Trinidad and Tobago, the United States, Uruguay and Venezuela. Below in Figure 1 the American continent is shown.

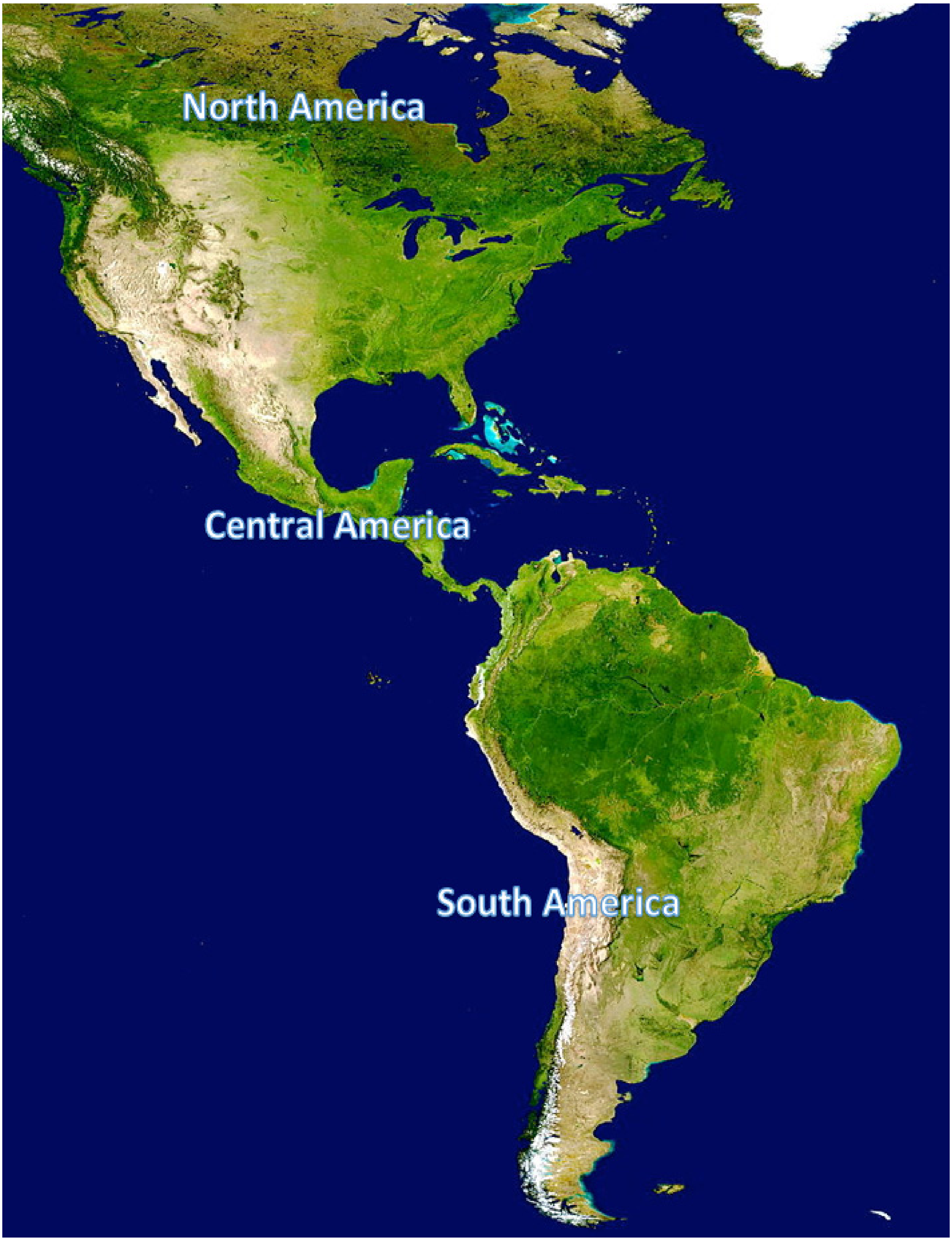



**Figure 1.** America seen from satellite, adapted from [50].

## 2. Analysis of the Renewable Energy Components in the American Islands

Previous global analyses on islands of the American continent highlight those carried out by Ernesto Alberto Alvarez et al. [51], where the expansion of the generation is planned in La Isla de la Juventud in Cuba. Another case study was presented by Javier Mendoza-Vizcaino et al. [52] regarding the application of renewable energy technology on the Island of Cozumel, Mexico. The results of the simulations show that by 2050 a feasible integration of a photovoltaic/wind-based system can be achieved on the island, reducing the price of electricity from 0.37 US$/kW·h to 0.24 US$/kW·h. This review shows that a large part of the islands still do not have at least one roadmap, while on certain islands there is more than one study that proposes a roadmap to achieve a 100% renewable system. This small amount of research on certain islands in evaluating the possibilities of 100% renewable energy reveals the gaps in the research and the need for the scientific community to commit to carrying out research in these sites and navigate together towards a sustainable and equitable future. One of the most relevant examples as an island is that of Costa Rica, which, despite the economic difficulties today, has a system that is practically 100% renewable, including its transportation, as Guido Godínez-Zamora considers in the reference [53].

Most studies analyze the islands individually (85% of the articles reviewed), on a smaller scale they are considered to be archipelagos or future interconnected islands. It is important to take into account the very good experiences that are presented in different parts of the world, such as the one presented by Krajacic et al. [54] and Marczinkowski et al. [55], which compare energy systems and transition pathways for islands belonging to different countries and archipelagos. Few studies focus on groups of islands belonging to the same country or archipelago. For example, analyzing similar islands, Hans Gils and Sonja Simon [56] take the Canary Islands as a case of a carbon-neutral archipelago. The islands are analyzed more than once by different authors, the analysis is much more enriched, which indicates that these islands are kinds of living laboratories for different analyses and research approaches.

Table 1, below, presents the details of the annual energy produced on each island of the American continent and its renewable and non-renewable fraction. Figure 2a shows a general compilation of the islands that are dependent on each country. In Figure 2b, we observe that the United States is the country with the largest renewable component on its islands with 1084 GWh per year, followed by Canada with 280 GWh per year. An important contribution is also made by Mexico and Chile with 63 GWh and 49 GWh, respectively. The other islands of the continent contribute to decarbonizing the planet, but according to their economic possibilities and energy potential. The Caribbean Islands, among all of them, also have a significant contribution of around 22 GWh annually, which is not insignificant. In South America, the deployment that Ecuador, Brazil, Colombia and Peru are beginning to carry out is also important in relation to the attention they provide to their islands with the incorporation of renewable energy sources, especially based on wind and solar photovoltaics.

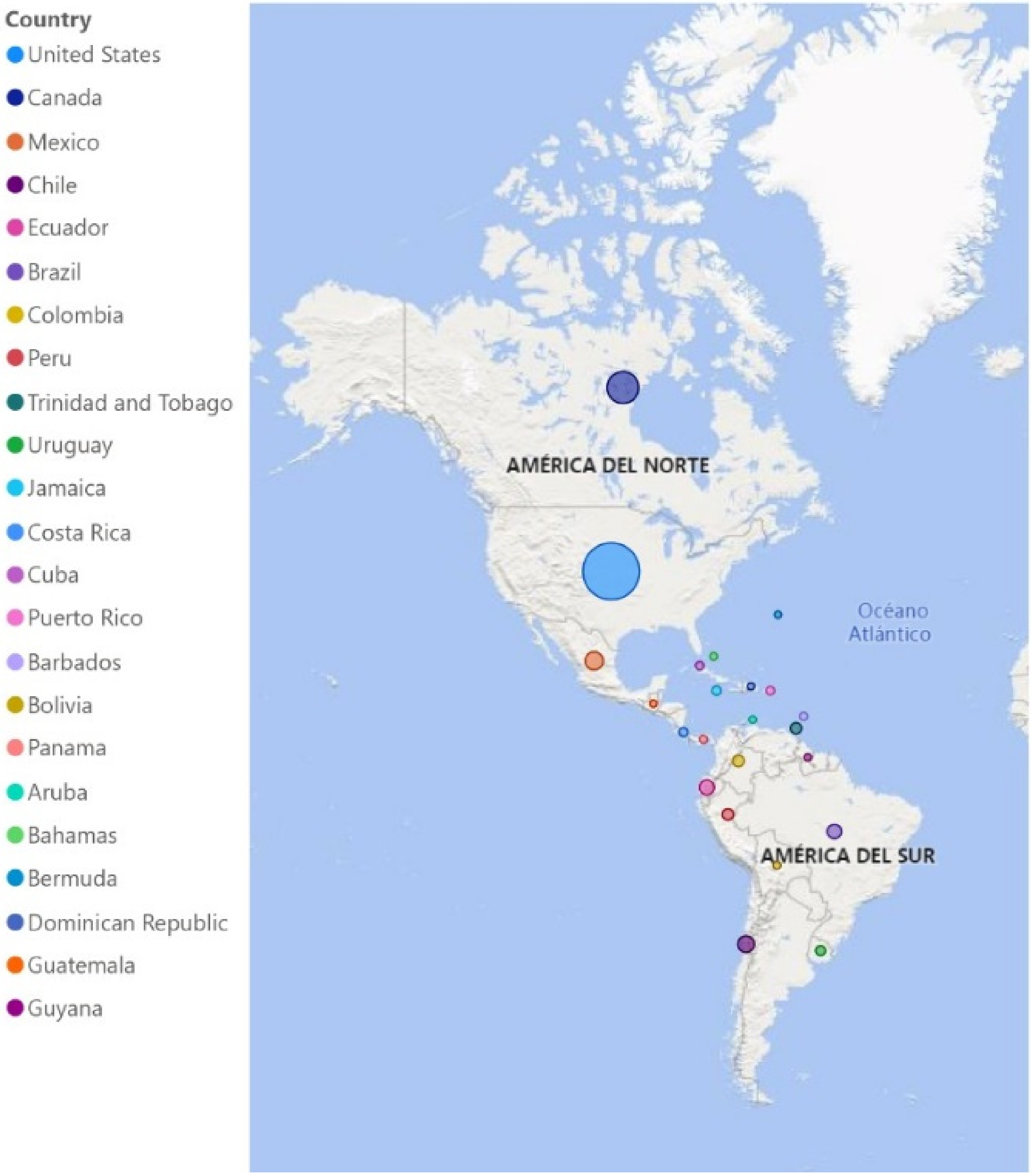
Table 2 shows the generation of renewable energy by the type of technology in detail on each American island.

**Table 1.** Annual energy per island on the American continent and its renewable and non-renewable fraction, adapted from [57–60].

| N° | Island | Country/Region | Latitude | Longitude | Total (GWh) | Non-Renewable (%) | Renewable Energy (%) |
|---|---|---|---|---|---|---|---|
| 1 | Greenland | North America | 71.7069 | −42.6043 | 504.40 | 9% | 91% |
| 2 | Nunavut | North America | 70.2998 | −83.1076 | 294.21 | 99.83% | 0.17% |
| 3 | Newfoundland | North America | 49.2827 | −56.0436 | 44,699.21 | 0.38% | 99.62% |
| 4 | Cuba | Caribbean | 21.5218 | −77.7812 | 15,633.7 | 94.40% | 5.59% |
| 5 | Haiti | Caribbean | 18.9712 | −72.2852 | 1059 | 91.59% | 19.64% |
| 6 | British Columbia | North America | 53.7267 | −127.6476 | 78,904.41 | 1.78% | 98.22% |
| 7 | Jamaica | Caribbean | 18.1096 | −77.2975 | 4346 | 85.27% | 14.73% |
| 8 | Hawaii | United States | 19.8968 | −155.5828 | 10,285 | 62.77% | 31.78% |
| 9 | Nova Scotia | North America | 44.682 | −63.7443 | 8180.02 | 61.05% | 38.95% |
| 10 | Puerto Rico | United States (Unincorporated Territory) | 18.2208 | −66.5901 | 19,430 | 97.62% | 2.54% |
| 11 | East Falkland Island | South America | −51.796 | −59.5236 | 19 | 52.63% | 48.02% |
| 12 | Prince Edward Island | North America | 46.5107 | −63.4168 | 607.97 | 1% | 98.92% |
| 13 | Galapagos Island | South America | −0.8277 | −91.1369 | 55.614 | 84% | 16.02% |
| 14 | American Samoa | United States (Unincorporated Territory) | −14.306 | −170.695 | 0.16941 | 97% | 3.04% |
| 16 | Commonwealth of the Northern Mariana | United States (Unincorporated Territory) | 15.0979 | 145.6739 | 0.10 | 98% | 2.00% |
| 22 | Guam | United States (Unincorporated Territory) | 13.4443 | 144.7937 | 1656 | 94% | 6.00% |
| 34 | Trinidad and Tobago | Caribbean | 10.6918 | −61.2225 | 9262 | 99.94% | 0.06% |
| 35 | Dominican Republic | Caribbean | 18.7357 | −70.1627 | 23,363 | 83.04% | 16.96% |
| 36 | Bahamas | Caribbean | 25.0343 | −77.3963 | 1759 | 99.55% | 0.51% |
| 37 | Bonaire, Sint Eustatius and Saba Island | Caribbean | 12.1784 | −68.2385 | 156 | 76.28% | 24.36% |
| 38 | Cayman Island | Caribbean | 19.3133 | −81.2546 | 733 | 97% | 3.00% |
| 39 | British Virgin Islands | Caribbean | 18.4207 | −64.6399 | 171 | 97.66% | 2.34% |
| 40 | United States Virgin Islands | Caribbean | 18.3358 | −64.8963 | 466.667 | 97.00% | 3.00% |
| 41 | Turks and Caicos Islands | Caribbean | 21.6940 | −71.7979 | 267 | 98.50% | 1.50% |
| 42 | Aruba | Caribbean | 12.5211 | −69.9683 | 1061 | 85.20% | 14.80% |
| 43 | Curacao | Caribbean | 12.1696 | −68.9900 | 794 | 80.48% | 19.52% |
| 44 | Grenada | Caribbean | 12.1165 | −61.6790 | 229.2 | 98.50% | 1.50% |
| 45 | Barbados | Caribbean | 13.1939 | −59.5432 | 1200 | 92.67% | 7.33% |
| 46 | Dominica | Caribbean | 15.4149 | −61.3705 | 102 | 79.41% | 20.59% |
| 47 | Saint Vincent and the Grenadines | Caribbean | 13.2528 | −61.1971 | 144 | 84.72% | 15.28% |
| 48 | Saint Lucia | Caribbean | 13.9094 | −60.9789 | 400 | 97.50% | 2.55% |
| 49 | Martinique | Caribbean | 14.6415 | −61.0242 | 1527 | 76.88% | 23.18% |
| 50 | Guadeloupe | Caribbean | 16.2650 | −61.5506 | 1665 | 66.13% | 33.81% |
| 51 | Saint Kitts and Nevis | Caribbean | 17.3578 | −62.7828 | 228 | 95.18% | 4.82% |
| 52 | Anguilla | Caribbean | 18.2206 | −63.0686 | 108 | 97.22% | 2.78% |

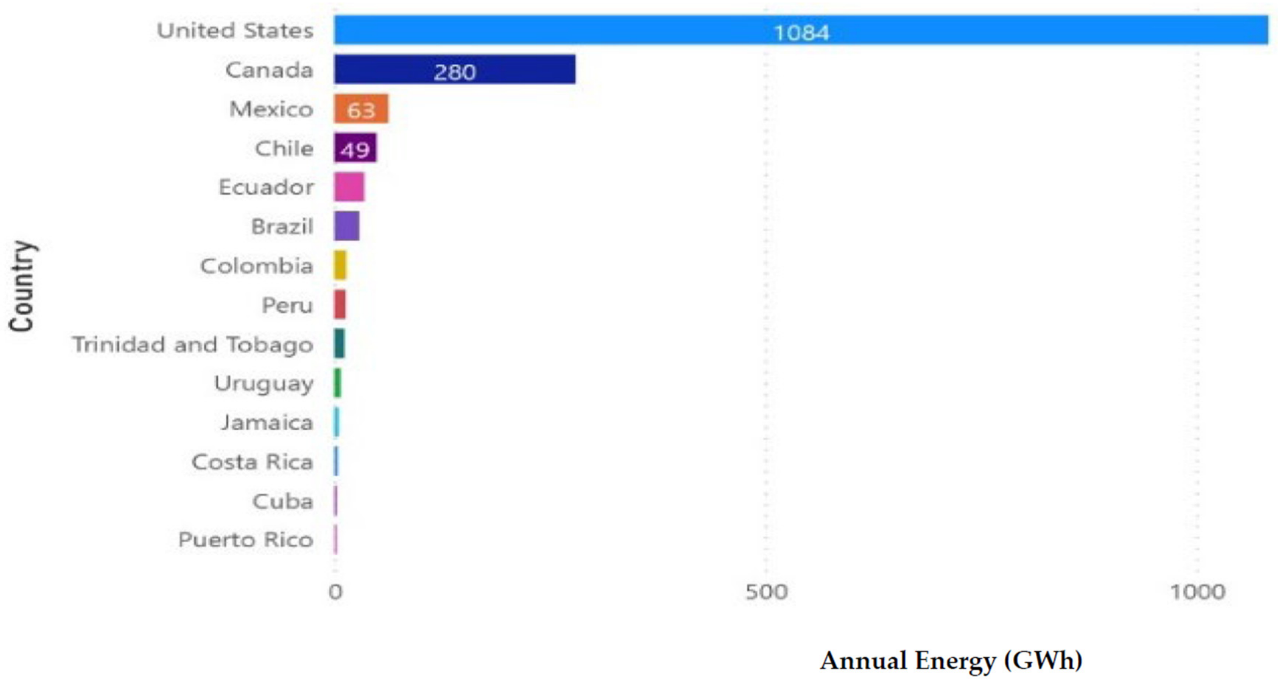
**Table 2.** Renewable energy generation by type of technology.

| N° | Island | Solar (GWh) | Solar % | Hydro and Marine (GWh) | Hydro and Marine % | Wind (GWh) | Wind % | Bioenergy (GWh) | Bioenergy % | Geothermal (GWh) | Geothermal % | Renewable Energy Share of Electricity Capacity (GWh) | Renewable Energy Share of Electricity Capacity (%) | References |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | Greenland | 0 | 0% | 430 | 85.25% | 0 | 0% | 29 | 5.75% | 0 | 0% | 459 | 91% | [57,61] |
| 2 | Nunavut | 0.5 | 0.17% | 0 | 0.00% | 0 | 0.00% | 0 | 0.00% | 0 | 0.00% | 0.5 | 0.17% | [62–64] |
| 3 | Newfoundland | 1.17 | 0.00% | 44,235.28 | 98.96% | 194.5 | 0.44% | 99.73 | 0.22% | 0 | 0.00% | 44,530.68 | 99.62% | [62] |
| 4 | Cuba | 156 | 0.998% | 115 | 0.736% | 40 | 0.26% | 563 | 3.60% | 0 | 0.00% | 862 | 5.59% | [57,65,66] |
| 5 | Haiti | 4 | 0.38% | 200 | 18.89% | 4 | 0.38% | 0 | 0.00% | 0 | 0% | 204 | 19.64% | [57] |
| 6 | British Columbia | 22.15 | 0.03% | 72,486.33 | 91.87% | 1695.92 | 2.15% | 0 | 0.00% | 3292.73 | 4.17% | 77,497.13 | 98.22% | [62,67] |
| 7 | Jamaica | 124 | 2.85% | 136 | 3.13% | 280 | 6.44% | 100 | 2.30% | 0 | 0.00% | 640 | 14.73% | [57] |
| 8 | Hawaii | 1310.74 | 12.74% | 72 | 0.70% | 1052.5 | 10.23% | 294.84 | 2.87% | 538.25 | 5.23% | 3268.33 | 31.78% | [68] |
| 9 | Nova Scotia | 1.87 | 0.02% | 890.45 | 10.89% | 1953.85 | 23.89% | | 0.00% | 340.21 | 4.16% | 3186.38 | 38.95% | [60] |
| 10 | Puerto Rico | 259 | 1.33% | 51 | 0.26% | 143 | 0.74% | 41 | 0.21% | | 0.00% | 462 | 2.54% | [57,58] |
| 11 | East Falkland Island | 0.123 | 0.65% | 0 | 0.00% | 9 | 47.37% | 0 | 0.00% | 0 | 0.00% | 9 | 48.02% | [69,70] |
| 12 | Prince Edward Island | 0.68 | 0.11% | 0 | 0.00% | 598.56 | 98% | 2.19 | 0.36% | 0 | 0% | 601.43 | 98.92% | [62] |
| 13 | Galapagos Island | 2.24 | 4.03% | 0 | 0.00% | 6.67 | 11.99% | 0 | 0.00% | 0 | 0% | 8.91 | 16.02% | [71,72] |
| 14 | American Samoa | 0.00515 | 3% | 0 | 0.00% | 0 | 0% | 0 | 0.00% | 0.0 | 0% | 0.005150064 | 3.04% | [73] |
| 16 | Commonwealth of the Northern Mariana | 0.00209 | 2% | 0 | 0.00% | 0 | 0% | 0 | 0.00% | 0.0 | 0% | 0.00209 | 2.00% | [74] |
| 22 | Guam | 99.36 | 6% | 0 | 0.00% | 0 | 0% | 0 | 0.00% | 0.0 | 0% | 99.36 | 6.00% | [74] |
| 34 | Trinidad and Tobago | 6 | 0.06% | 0 | 0.00% | 0 | 0.00% | 0 | 0.00% | 0 | 0.00% | 6 | 0.06% | [75,76] |
| 35 | Dominican Republic | 878 | 3.76% | 1504 | 6.44% | 1231 | 5.27% | 349 | 1.49% | 0 | 0.00% | 3962.00 | 16.96% | [77] |
| 36 | Bahamas | 8 | 0.45% | 0 | 0.00% | 1 | 0.06% | 0 | 0.00% | 0 | 0.00% | 9.00 | 0.51% | [78] |
| 37 | Bonaire, Sint Eustatius and Saba Island | 9 | 5.77% | 0 | 0.00% | 29 | 19% | 0 | 0.00% | 0 | 0.00% | 42 | 24.36% | [79] |
| 38 | Cayman Island | 22 | 3% | 0 | 0.00% | 0 | 0% | 0 | 0.00% | 0 | 0% | 0 | 3.00% | [57] |
| 39 | British Virgin Islands | 2 | 1.17% | 0 | 0.00% | 2 | 1.17% | 0 | 0.00% | 0 | 0.00% | 4 | 2.34% | [57] |
| 40 | Virgin Islands | 14 | 3.00% | 0 | 0.00% | 0 | 0.00% | 0 | 0.00% | 0 | 0.00% | 14 | 3.00% | [57] |
| 41 | Turks and Caicos Islands | 4 | 1.50% | 0 | 0.00% | 0 | 0.00% | 0 | 0.00% | 0 | 0.00% | 4 | 1.50% | [80] |
| 42 | Aruba | 24 | 2.26% | 0 | 0.00% | 133 | 12.54% | 0 | 0.00% | 0 | 0.00% | 157 | 14.80% | [81] |
| 43 | Curacao | 14 | 1.76% | 0 | 0.00% | 141 | 17.76% | 0 | 0.00% | 0 | 0.00% | 154 | 19.52% | [82] |
| 44 | Grenada | 2.8 | 1.22% | 0 | 0.00% | 0.64 | 0.28% | 0 | 0.00% | 0 | 0.00% | 3.44 | 1.50% | [83] |
| 45 | Barbados | 88.00 | 7.33% | 0 | 0.00% | 0 | 0.00% | 0.00 | 0.00% | 0 | 0.00% | 54.16 | 7.33% | [84] |
| 46 | Dominica | 0 | 0.00% | 20 | 19.61% | 1 | 0.98% | 0 | 0.00% | 0 | 0.00% | 21 | 20.59% | [85] |
| 47 | Saint Vincent and the Grenadines | 3 | 2.08% | 19 | 13.19% | 0 | 0.00% | 0 | 0.00% | 0 | 0.00% | 21 | 15.28% | [86] |
| 48 | Saint Lucia | 7.5 | 1.88% | 0 | 0.00% | 0 | 0% | 2.7 | 0.68% | 0 | 0.00% | 10 | 2.55% | [87] |
| 49 | Martinique | 84 | 5.50% | 0 | 0.00% | 42 | 2.75% | 228 | 14.93% | 0 | 0.00% | 353 | 23.18% | [88] |
| 50 | Guadeloupe | 114 | 6.85% | 11 | 0.66% | 107 | 6.43% | 247 | 14.83% | 84 | 5.05% | 563 | 33.81% | [89] |
| 51 | Saint Kitts and Nevis | 5 | 2.19% | 0 | 0.00% | 6 | 2.63% | 0 | 0.00% | 0 | 0% | 11 | 4.82% | [90] |
| 52 | Anguilla | 3 | 2.78% | 0 | 0.00% | 0 | 0.00% | 0 | 0.00% | 0 | 0.00% | 3 | 2.78% | [91] |




(**a**)

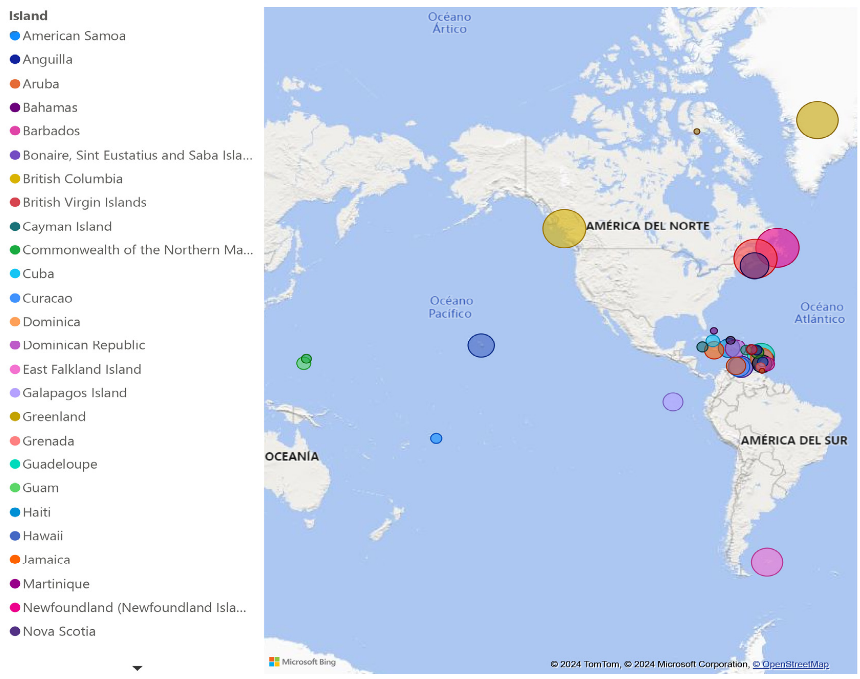
**Figure 2.** *Cont*.




(**b**)

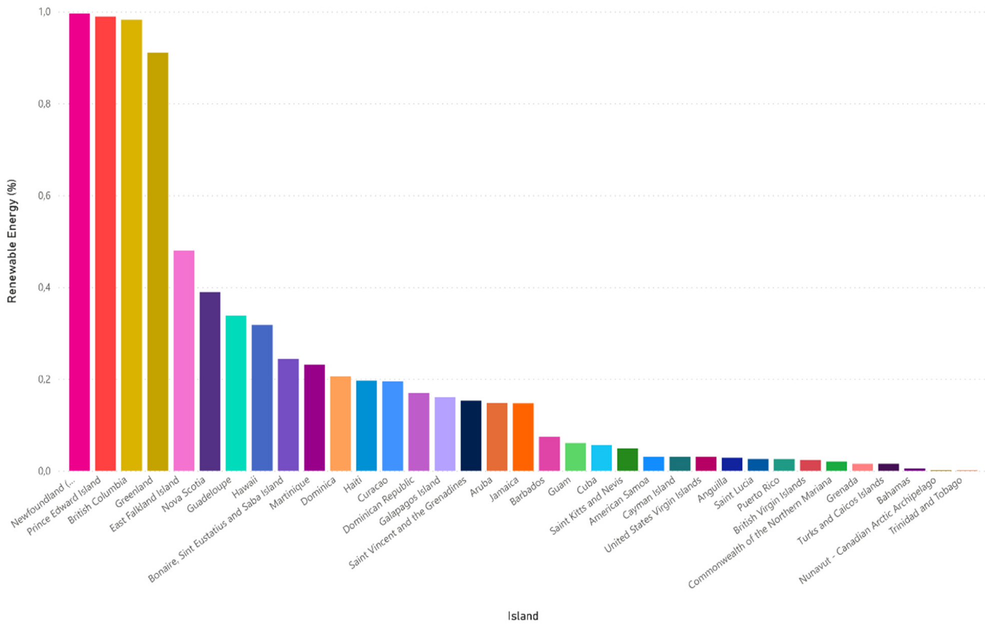
**Figure 2.** (**a**) Map with the islands that are part of the American countries. (**b**) Detail of the level of penetration of renewable energies by country regarding electrified islands.

Below, in Figure 3a, the exact locations of the 52 islands that have a renewable energy component are presented in detail. Meanwhile, in Figure 3b the percentages of renewable energy penetration per island are identified in the bar diagram. Figure 3c shows the circular diagram of the renewable energy components by island (GWh, %).

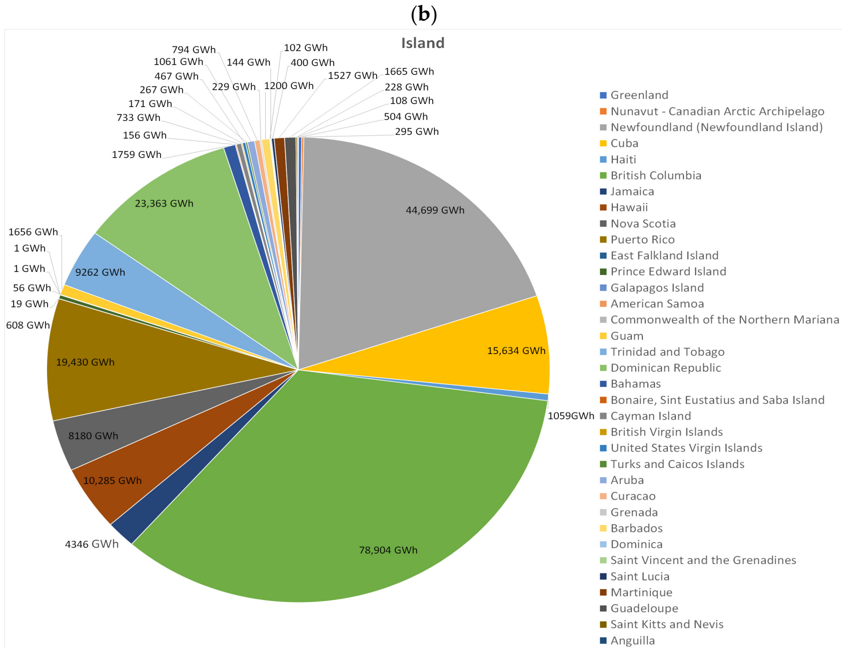



(**a**)

**Figure 3.** *Cont.*




(**b**)




(**c**)

**Figure 3.** (**a**) Map with the location of the islands on the American continent. (**b**) Bar diagram detailing the level of penetration of renewable energies on the islands. (**c**) Pie diagram of renewable energy component by island (GWh, %).

## 3. Renewable Energy Potentials in the American Islands

The date 12 December 2015 is a momentous date in this fight against greenhouse gas (GHG) emissions, the main causes of global warming. The world witnessed the Paris Agreement at the United Nations Conference on Climate Change, the current international protocol to stop the warming process. Its objective is to promote additional efforts to ensure that global warming does not exceed 1.5 degrees Celsius compared to pre-industrial levels. That historic document for renewable energies did not represent an extraordinary discovery since they had been in development for decades. What it did imply was the conception of a solution to limit global warming for two fundamental reasons: RESs come from essentially inexhaustible natural sources, such as the sun, the wind, the force of water or sustainably managed plant material, and by not emitting GHG gases, they are the main bet for the energy transition towards a low-carbon world.

Pacific Small Island Developing States (SIDS) are among the most vulnerable to the impacts of climate change. Furthermore, they are some of the most dependent on petroleum products imported in the world. Taking advantage of the energy potential available on the islands and the appropriate use of renewable energy (RE) can help get rid of the fossil fuel supply companies that seek at all costs to remain in the energy market with legal tricks and that prey on these localities. Advantageously, the region is increasingly adopting renewable energy (RE) objectives and policies, which are gaining ground in the pursuit of environmental preservation and diversifying the economy with increasingly accessible technologies [92]. There are important examples of renewable energy implementation and long-term roadmaps on the continent that can serve as a reference. However, many barriers are present to prevent the use of renewable resources across the continent. Some of the limitations to the deployment of renewable energies on islands have been identified, including:

(i) Missing or unverifiable data;
(ii) The need for regulations;
(iii) Limited financial opportunities;
(iv) The lack of human talent on the islands;
(v) Expensive infrastructure on site;
(vi) Sociocultural impediments.

### *3.1. Referential Cartography to Identify Existing Energy Potentials on the American Continent*

On the American continent, there is considerable potential for renewable energy, as the islands near the coasts and outside their poles also have significant potential in both wind and solar, and, to a lesser extent, biomass. In the case of tidal energy, although it is not yet massively exploited, it can be an interesting option in the future to diversify the energy mix on the different islands; costs can be a barrier to increasing its growth.

#### 3.1.1. Solar Photovoltaic Power

REN21's 2016 Renewable Energy Global Status Report indicates that Latin American and Caribbean countries continue to be world leaders in the deployment of renewable energy [93]. This annual report is the main global reference on the global renewable energy market, industry and policies. The REN21 Secretariat has published it since 2005, relying on a network of 700 actors and groups interested in issues related to renewable energy, energy access and energy efficiency [94]. In this report, which can be downloaded here, experts share their vision and knowledge about the sector. You can find its main conclusions from 2016 in Spanish version here.

Solar energy harnessed from the sun's electromagnetic radiation is presented as an important renewable energy source in both North America and Central and South America, with very interesting development possibilities. The deployment that occurs throughout the continent also ultimately affects the island spaces as a rebound effect since lowering the prices of technologies and their maturation make them more reliable and real on the islands. Public and private decision makers have greater certainty when implementing on the islands near the continent and therefore their inhabitants are the beneficiaries.

In North America, the significant development in solar-based technologies is clear. In 2021, the solar installed capacity in North America reached 104.4 GW, with a decent growth rate compared to previous years. In Latin America and the Caribbean, there are countries that already occupy a notable place in terms of the use of their natural resources. With the implementation of energy reforms, they have led to an exponential development of renewable energies, mainly solar, which tends to be the cheapest, renewable, clean and accessible technologies worldwide. Within Latin American countries, Chile leads this solar revolution. Chile has positioned itself as the first country in Latin America that will provide solar energy 24 h a day. It has been the region that has shown the greatest growth in solar energy. Currently, there are two types of solar energy generation: photovoltaic systems and concentrated solar electricity.

Figure 4 shows the levels of solar radiation throughout the American continent. Interesting radiation levels can also be seen in the islands of North America, the Caribbean Islands and South America, which in all cases are greater than 1400 kWh/kWp.

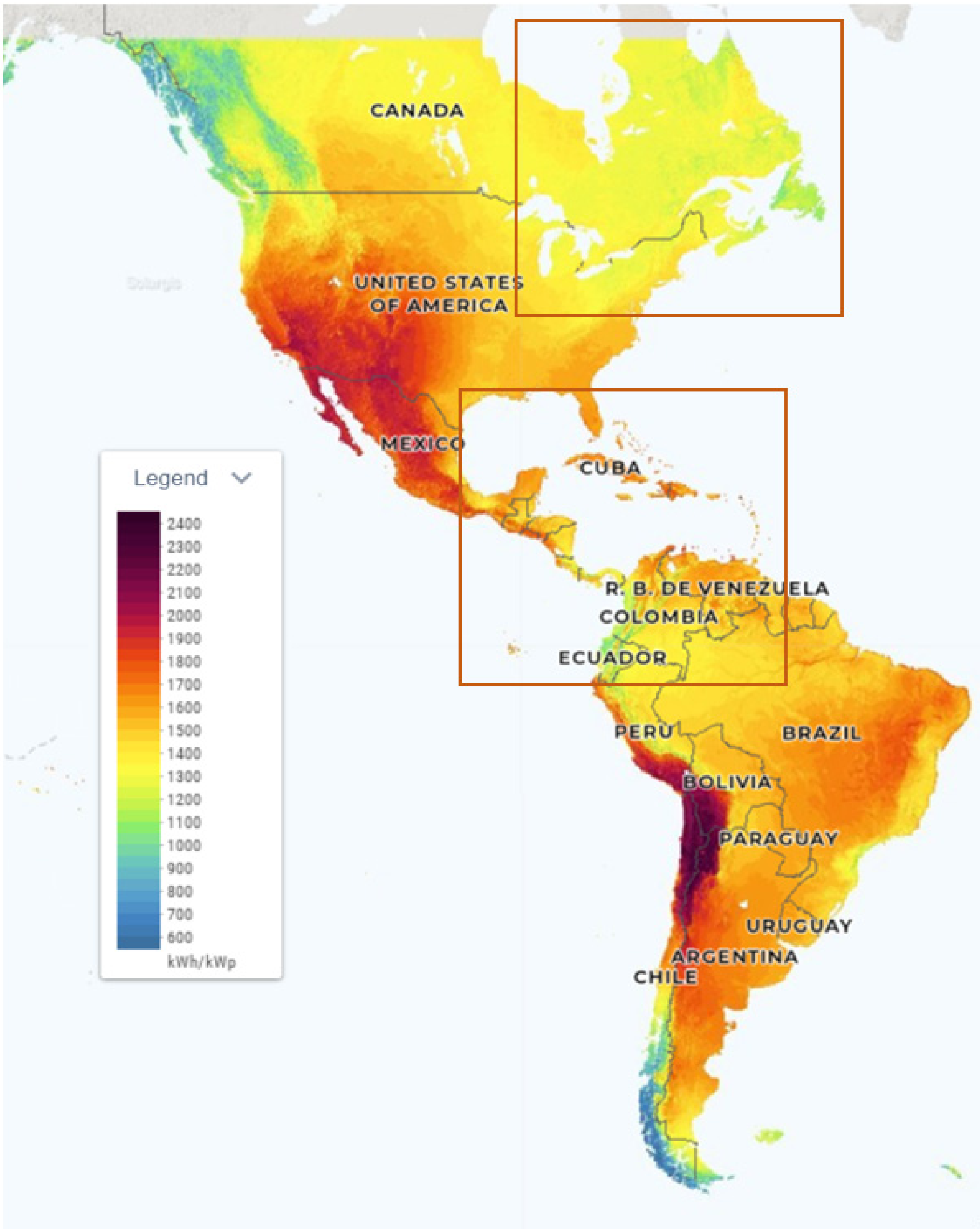



**Figure 4.** Solar photovoltaic power potential in America, analyzed using the free software Global Solar Atlas [95].

3.1.2. Wind Power

The National Renewable Energy Laboratory of the United States, in its recent research, presented that there are up to 1500 gigawatts of technically accessible wind power off the US coast (depths of less than 60 m, wind turbines founded on the seabed) and up to 2800 gigabytes of floating wind power. In its new analysis, NREL takes into account the current state of the art (the technological moment) and, likewise, the economic possibilities, and the results are extraordinary. Simultaneously, the Biden Administration has just launched Floating Offshore Wind Shot, an ambitious plan whose objective is to boost the leadership of the United States in floating wind.

On the other hand, Canada held the Public Policy Forum and has just published a report on the contribution that offshore wind energy could considerably increase to electricity production in Canada, particularly on the Atlantic coast [96]. Ambroise Wattez, director of offshore wind project development at SBM Offshore, a transnational company based in the Netherlands, together with the Irish company DP Energy, presented their intention to install twenty offshore wind turbines off Guysborough, on the east coast of Nova Scotia, before 2030 [97]. This is the first offshore wind project announced in Canada.

Sable Island, located almost 200 km off the coast of Nova Scotia, could become an El Dorado for offshore wind projects due to its extraordinary wind potential [98]. Its geographical location is conducive to a large-scale project, because the waters there are shallow, about 60 m, and ice-free.

Normand Mousseau, professor in the Department of Physics at the University of Montreal and director of the Trottier Institute at the Polytechnic of Montreal [99], recalls that wind remains an intermittent source of energy. However, he recognizes that it is windier on the high seas. Wind turbines will spin more than half the time, while on land they spin a third, he explained [100]. This site could house at least 1000 wind turbines with a capacity of 15 megawatts each, which is equivalent to a production of 70,000 gigawatts per hour, double the energy consumed in the Atlantic provinces [101].

There is enormous untapped resource potential in Latin America and the Caribbean, according to the World Bank [102], which estimated a technical potential close to 8000 GW in the waters of this region and its inhabited islands [103]. Some countries have excellent natural conditions, which means that this energy could be technically and economically viable. Latin America and the Caribbean remain at the forefront in the use of public competitive processes for the development of renewable energy projects, with successful bids and auctions with record participation. Several countries—including Brazil, Chile, Mexico and Peru—carried out major tenders in 2015 and early 2016, resulting in some of the lowest purchase prices in the world [104]. This has been made possible, in part, by the region's enormous renewable energy resources.

Brazil was third in the world in total electricity generation from renewable energy in 2015, after China and the US, while Costa Rica generated 99% of its electricity from renewable sources, and Uruguay generated 92.8%, of which 15.5% was from wind energy [105].

Below, Figure 5 shows the wind potential in North America, the Caribbean and the northern part of South America where there are inhabited islands that can become 100% renewable.

#### 3.1.3. Biomass Power

Biomass is a heterogeneous source of energy since it can appear in various forms: forestry (cleaning of mountains and river basins), agricultural waste (stubble), or agri-food (waste from the livestock industry or industrial oil) [107]. In this sense, America has large green areas thanks to the watersheds that bathe the continent [108]. For its part, at the island level, the conditions surrounded by water preserve the vegetation and can be very useful since much of it must be harvested and properly treated to produce energy. The reference [109] revealed that in South America there is the greatest energy potential derived from biomass, as over 220 million tons (MMt) of bioenergy can be produced. Furthermore, the production of biomass is an alternative that allows us to minimize pollution and the environmental impact produced by synthetic plastics by efficiently and sustainably using the waste generated for agricultural and industrial activities.

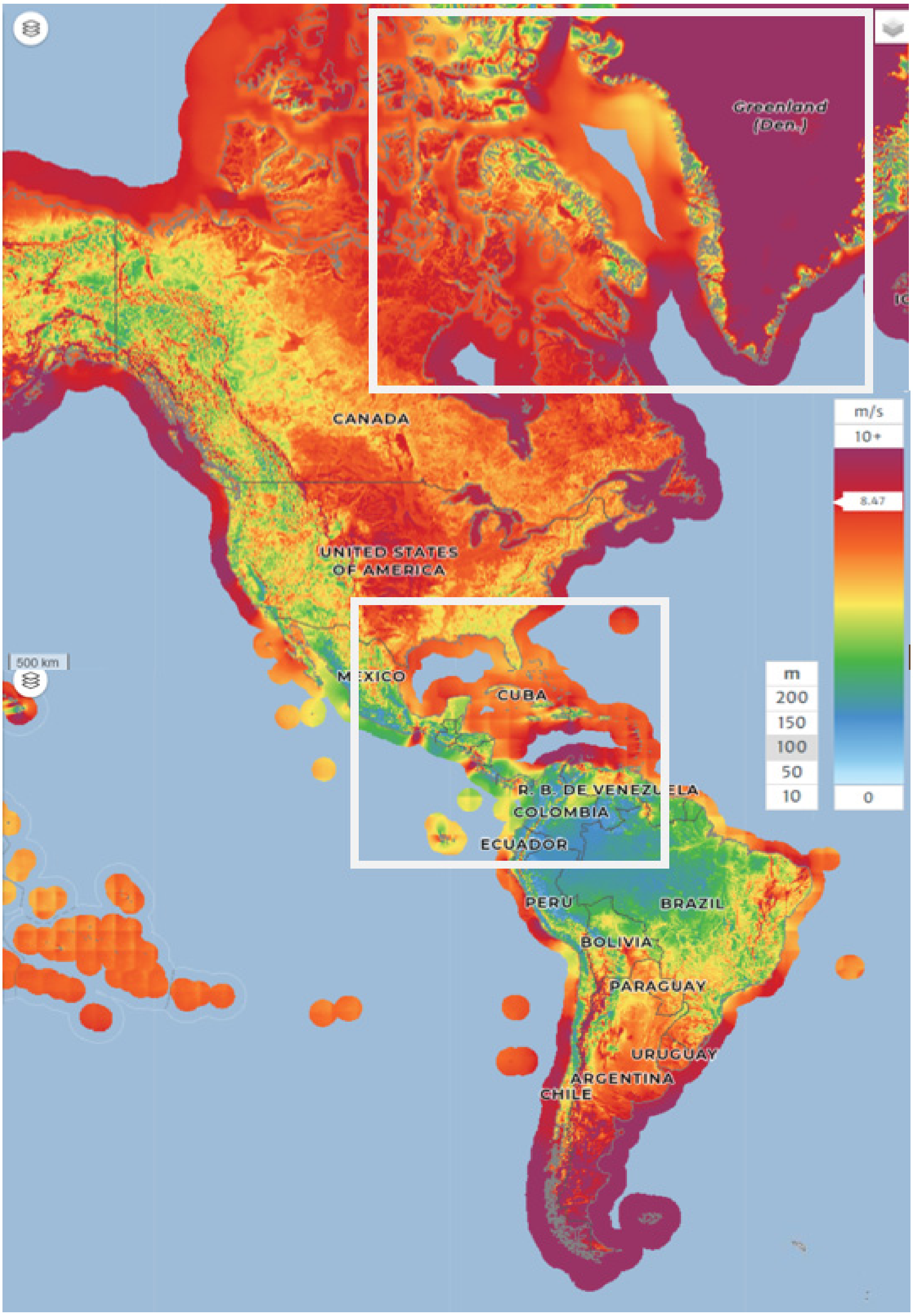



**Figure 5.** Wind energy potential focused on the islands of the American continent, analyzed using the free software Global Wind Atlas [106].

Below, Figure 6 shows the classification of the continental territory. In places where there are islands, most of it is made up of forest, shrubland and herbaceous vegetation very useful for biomass production, bordering 25% of the rest of the territory.

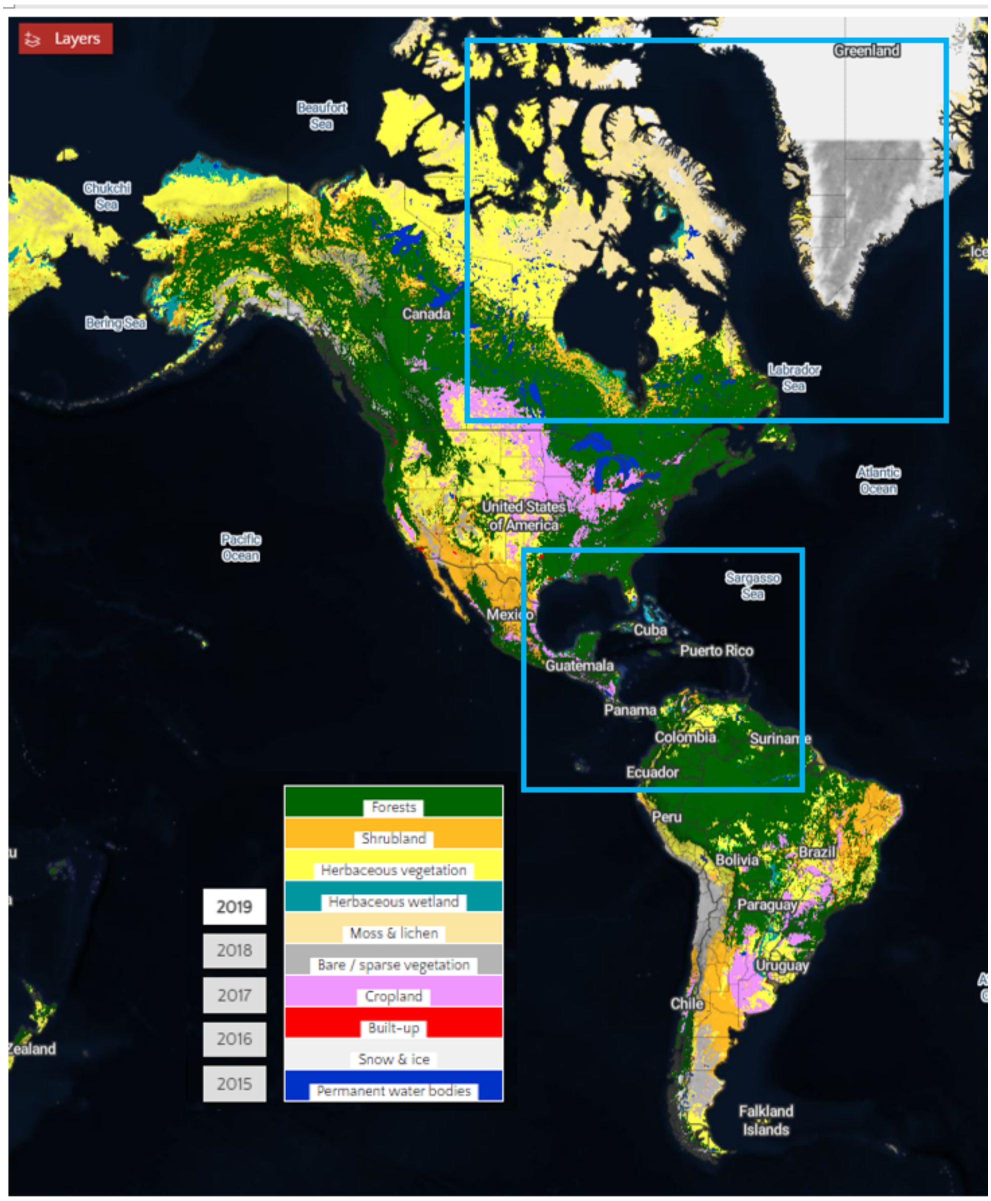



**Figure 6.** Mapping of American land use for biomass exploitation purposes using the Land Cover Viewer tool [110].

## 4. General Results of 100% RES Studies of American Islands

In the review carried out in Scopus, a total of 28 articles were found that analyzed the processes of 100% renewable energies on American islands. The majority of the articles (12) correspond to research carried out in Central America and the Caribbean, in North America 11 articles were found and in South America, 5 articles. In the registry of islands, there are 52 on the American continent but there are only 14 that have energy transition studies with 100% renewable systems. It is striking that their governments, academics or researchers have not yet planned their energy systems and resources will hardly be contemplated economically by not having roadmaps for decision making.

The aspects that this research brings together are focused on analyzing future proposals with 100% renewable energy, with the approaches varying between studies (see Figure 7); however, we highlight the research that has the purpose of decarbonizing the islands, in this case, in the American continent.

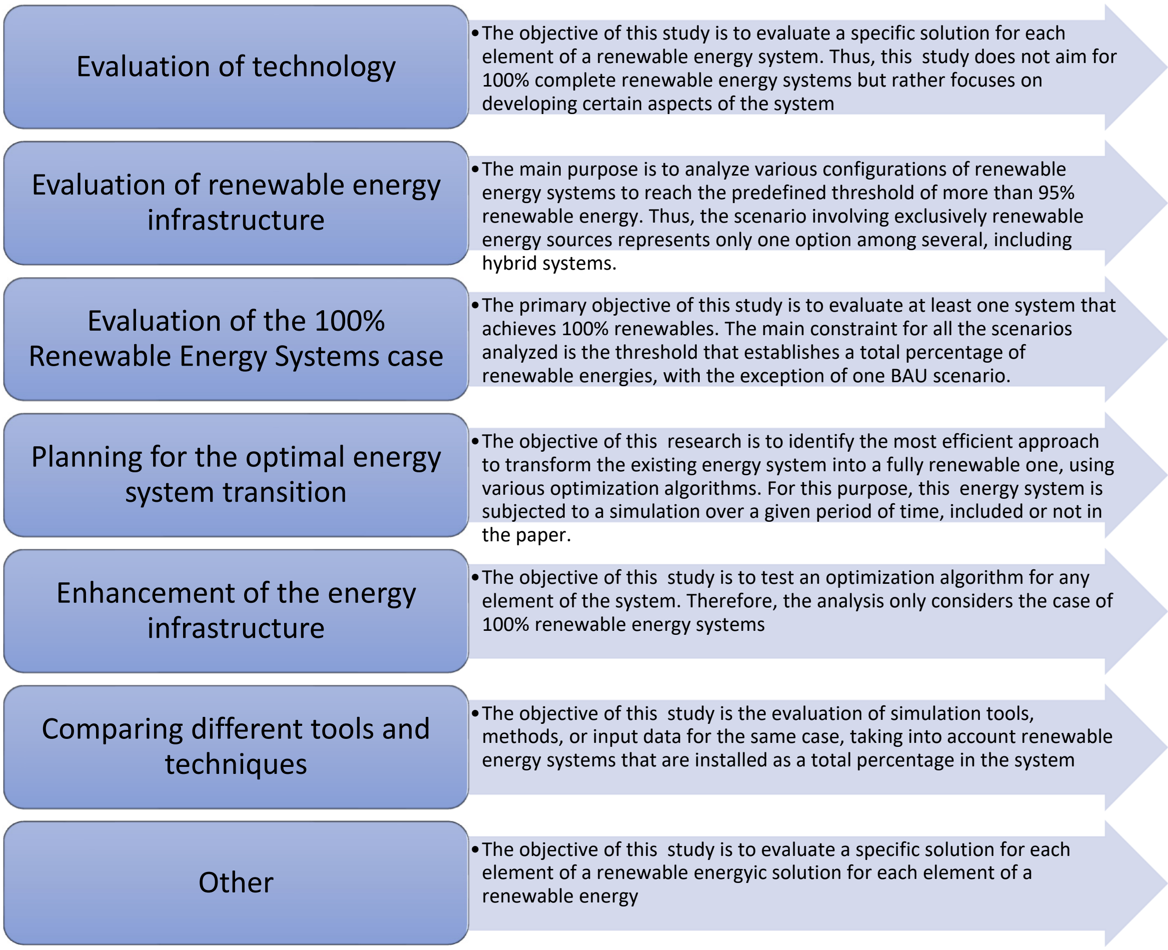



**Figure 7.** Approaches identified in the review that point to a 100% renewable system on American islands.

Research that aims to achieve 100% renewable systems has been detected and we classify it by the amount of research on each island. Table 3 is presented below, where this is detailed.

From this, it follows that of the islands that have the most publications in Scopus, and especially in which roadmaps have already been made for decarbonization processes including 100% renewable energy, two places stand out on the American continent: Cuba, with six investigations, and that of Galapagos, with five. It is also important to highlight the studies carried out in Greenland (three publications), Fiji, Newfoundland and Barbados with two publications on each island, and Jamaica, Hawaii, Samoa, the Cook Islands, Trinidad and Tobago, the Dominican Republic, the Virgin Islands and Dominica with a publication on each island. The above are shown in Figure 8.

According to Figure 8, previously shown, it is identified that on the island of Cuba and the Galapagos Islands, there have been a greater analysis of renewable energy systems, evidenced by them having six and five investigations, respectively, with the search in Scopus for “100% renewable energy Cuba” and “100% renewable energy Galapagos”. The same methodology was used for the rest of the islands, only changing the name of the island. After having identified that these two sites are the most analyzed in different investigations, we download VOSviewer to the computer, which is an application that works under the JAVA programming language, to build and visualize bibliometric networks. Through these networks, we can establish co-relationships of authorship, co-citations, co-relationships and co-ocurrency, respectively, between organizations, researchers, publications and words, inside of a previously established corpus in the area of knowledge of 100% renewable systems that are long-term.

Once the databases were obtained in Scopus, the respective runs were carried out in VOSViewer and the bibliometric links were obtained, as shown in Figure 9. The links were determined according to the keywords for the Galapagos Islands, as shown in Figure 9a. The relationships between authors that promoted these relevant investigations can be also observed in Figure 9b. A similar process was carried out for the island of Cuba; in Figure 9c, the bibliometric links by keywords are identified and in Figure 9d, the collaborative links between authors and co-authors.

Below, in Figure 10, the tools used in the design of energy transition systems in the American islands are presented.

**Table 3.** Classification by island according to manuscripts indexed in Scopus by long-term planning tool.

| N° | Island | Energy PLAN | Homer | Ose MOSYS | LEAP | PLEXOS | Own Program | No Tool | Journal | Congress | Total Research Indexed in Scopus |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | Greenland | [111] | | | | | [112] | [61] | 3 | | 3 |
| 2 | Newfoundland | | [113, 114] | | | | | | 2 | | 2 |
| 3 | Cuba | [115] | | | | | [51,116] | [117–119] | 5 | 1 | 6 |
| 4 | Jamaica | | | | | | [22] | | 1 | | 1 |
| 5 | Hawaii | | | | | | [120] | | 1 | | 1 |
| 6 | Galapagos | [72,121, 122] | [123] | | | | [124] | | 5 | | 5 |
| 7 | Samoa | | | | | | | [125] | 1 | | 1 |
| 8 | Fiji | | | | [126] | | | [127] | 2 | | 2 |
| 9 | Cook Islands | | | | | | | [128] | | 1 | 1 |
| 10 | Trinidad and Tobago | [129] | | | | | | | 1 | | 1 |
| 11 | Dominican Republic | | | [130] | | | | | 1 | | 1 |
| 12 | Virgin Islands | | | | | | | [131] | 1 | | 1 |
| 13 | Barbados | | | | | [132] | [133] | | 2 | | 2 |
| 14 | Dominica | | | | | | | [134] | 1 | | 1 |
| | TOTAL | 6 | 3 | 1 | 1 | 1 | 7 | 9 | 26 | 2 | 28 |

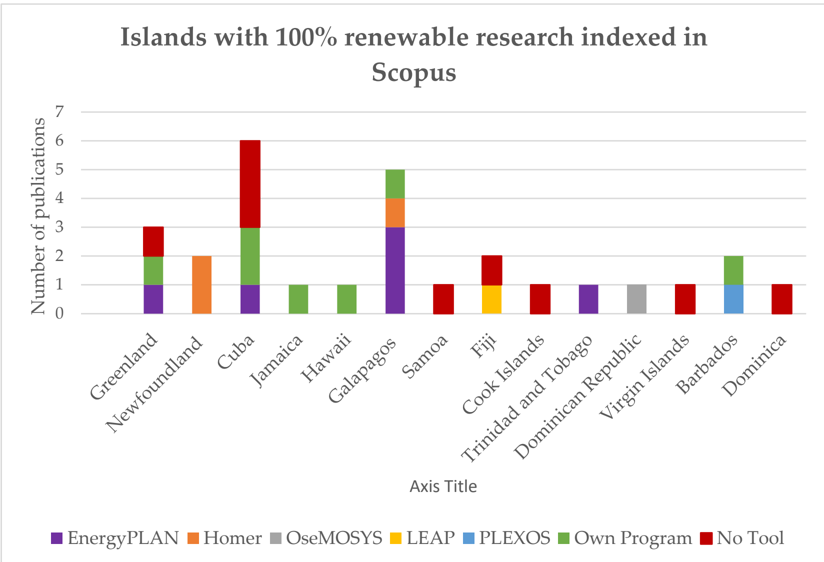



**Figure 8.** Identification of islands that have long-term roadmaps and the number of studies carried out.

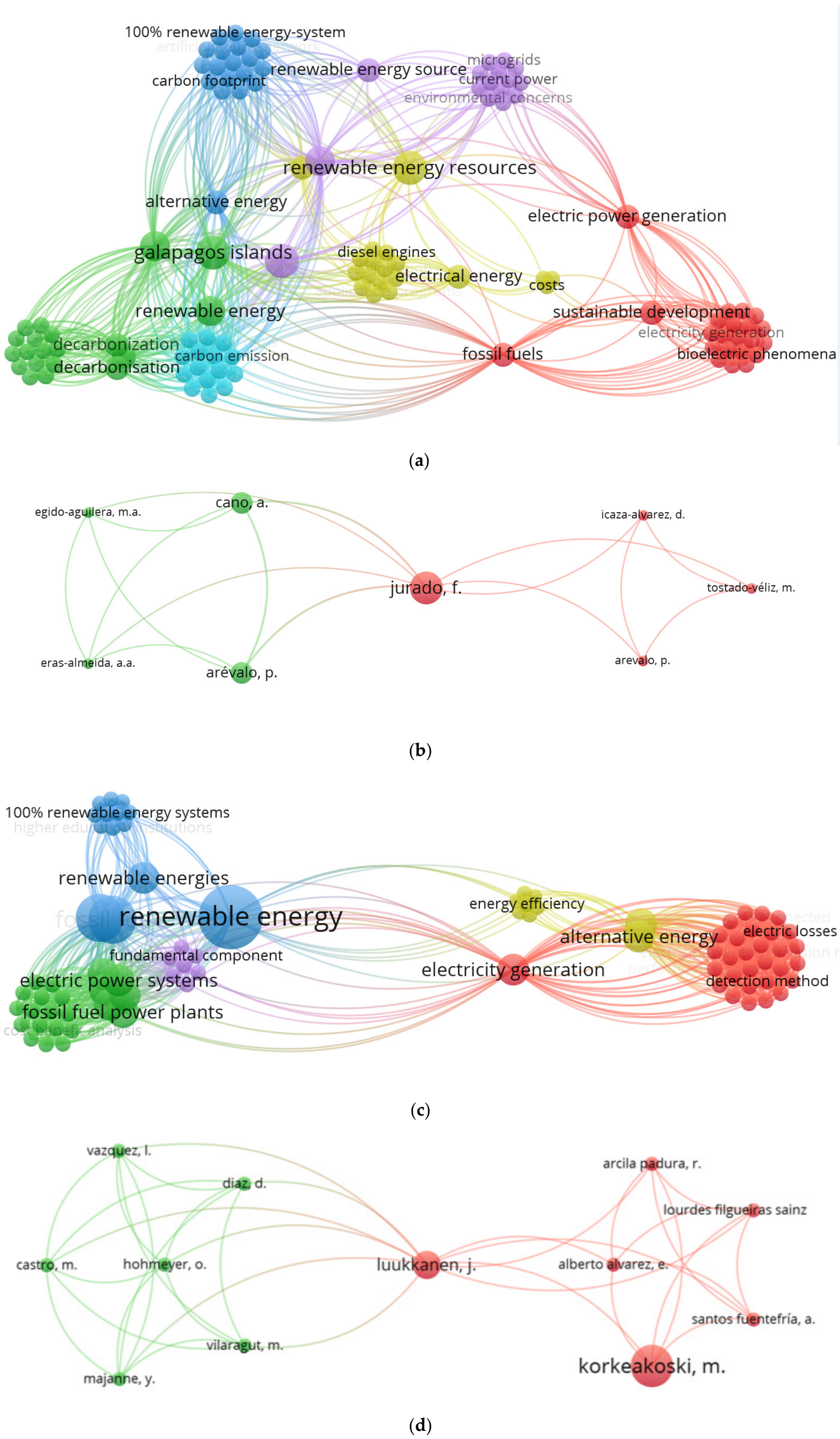



**Figure 9.** Bibliometric analysis with the support of the VOSviewer tool. (**a**) Bibliometric links by keywords for the Galapagos Islands. (**b**) Collaborative links between authors referring to research in Galapagos. (**c**) Bibliometric links by keywords for the island of Cuba. (**d**) Collaborative links between authors referring to research on the island of Cuba.

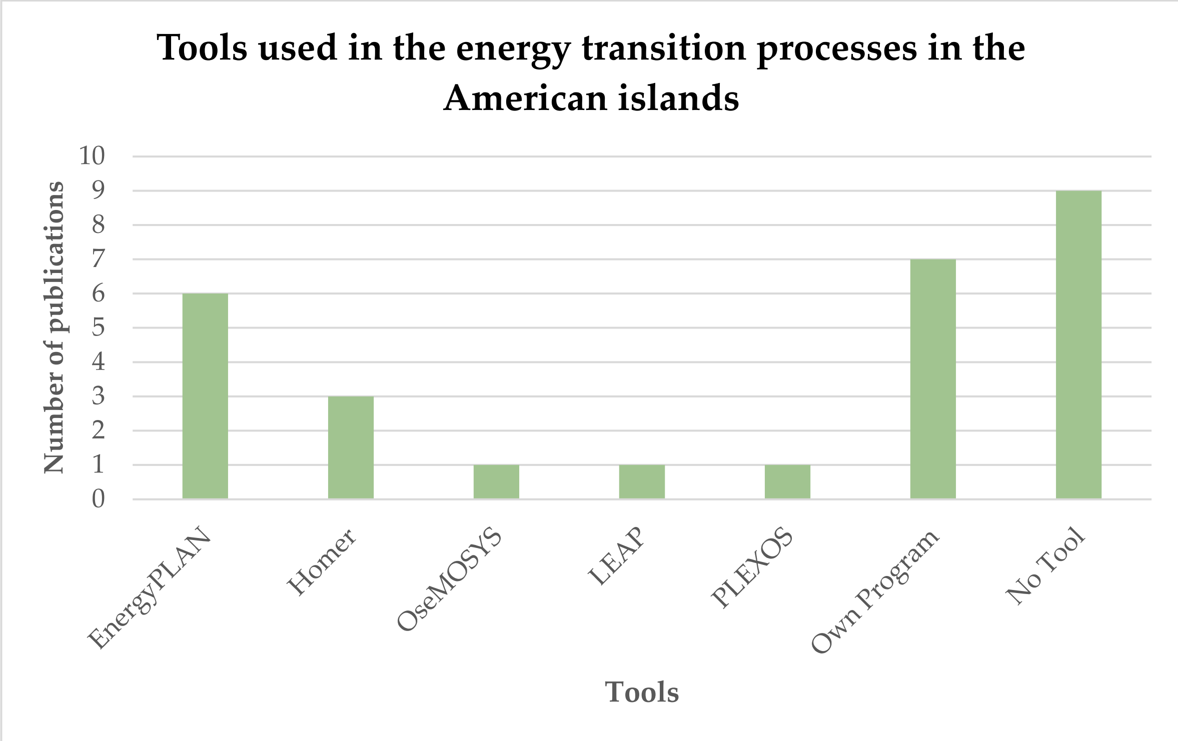



**Figure 10.** Tools used in the designs of energy transition systems in the American islands.

## 5. Conclusions

The present review clearly shows the existence of research that addresses the problem of climate change in the American islands; however, the literature where long-term systems are designed for the decarbonization of the islands with the support of renewable energies is quite limited. The islands thus provide a good representative sample of global efforts towards the complete transformation of the energy system but they still do not have strategic plans to achieve this purpose. In all studies, it was found that 100% RESs are technically applicable and economically viable. The articles that have been identified have reliable and verifiable data, they focus on the evaluation of diversified technologies according to their energy potentials available within the framework of 100% RES scenarios or, in several cases, they have designs and direct the evaluation of 100% RES scenarios for specific regions, which makes them available to governments and private decision makers to create investments in this very promising field. In this context, the isolation of the islands allows good determinations of energy flows and the design of integrated energy systems, as well as the evaluation of energy, economic and environmental impacts. Although it is known that 100% RES islands can be found in different parts of the world, we discovered that several of the studies are very optimistic and idealistic and lack analyses in different conditions. In the Caribbean islands, studies have been found that address hybrid systems in certain sites but do not have comprehensive roadmaps. The studies that provide a much more real panorama and are in different conditions to decarbonize the islands are those presented in Cuba. Analyzed using the VOSviewer tool where the Scopus databases are used, the researcher J. Luukkanen was identified, who was the articulator of research on this island and linked two aspects of knowledge led by M Korkeakoski and O. Hohmeyer. In the same way, rigorous studies have been identified for the Galapagos Islands and the main investigative link was Francisco Jurado, who articulated two networks led by Paúl Arevalo and D. Icaza-Alvarez.

With respect to transition strategies and how to create protections for internal resources, it has been identified that 40% of the publications seek to design long-term ecosystems to maintain themselves over time and preserve native species, 60% aim for systematic development in the long term by protecting their ecosystems, which are less conservative in their ideology and conception of the future. According to these studies, photovoltaic energy and wind turbines are considered key elements for the energy transition; in most of their future designs, at least 70% of participation is identified between these two technologies. To manage the variable nature of these RESs and to maintain their validity, battery-based storage technologies have been designed for the most part. For small and medium-sized islands, they also maintain battery storage technologies as a common solution. In the cases of mountainous islands, hydropower is also pumped, and storage is seen as an alternative. In addition to technologies based on photovoltaic solar energy and wind turbines, biomass is mainly added to its energy mix to achieve 100% self-sufficiency.

In general terms, having evaluated the energy transition systems in the American islands, it can be indicated that a systematic drive is necessary to strongly increase the rates of renewable energy and comply with the Paris Agreement. So far, as could be seen in the review, only 28 studies have been carried out with a view towards long-term decarbonization. This implies that the rest of the conglomerates, since they do not have studies that allow them to have a developmental horizon, are very unlikely to be promoting their renewable energy systems as, in the best of cases, if they are carrying it out, they would be doing so in a disorganized and disjointed way. At COP28, it was projected that countries would triple their contributions of renewable energy; however, in these cases of the American islands, it would become quite difficult to achieve it if severe policies and important budgets in favor of the energy transition are not promoted from now on.

As previously addressed, research is specifically limited to the analysis of the American island systems and only studies in Scopus were considered. For future work, it is considerate to analyze the roadmaps at the continental level of America and subsequently identify the research gap by determining the strengths and weaknesses of each system.

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## Abbreviatures

| | |
|---|---|
| BESS | Battery Energy Storage System |
| $CO_2$ | Carbon dioxide |
| COP 21 | Conference Of Parties 21 |
| COP 28 | Conference Of Parties 28 |
| ESS | Energy storage solution |
| GHG | Greenhouse gas |
| IRENA | International Renewable Energy Agency |
| PV | Photovoltaic |
| RD&D | Research, development and demonstration |
| RE | Renewable energy |
| RES | Renewable energy system |
| SIDS | Small Island Developing States |
| TES | Thermal energy storage |
| UN | United Nations |

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