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SWOT Analysis of the Benefits of Hydropower Energy in Four Archipelagos

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Abstract

Increasing energy production through renewable sources is a challenge for islands. This paper investigates the potential of hydropower as a renewable energy source for islands in the Macaronesia region, which includes the Azores, Madeira, Canary Islands, and Cape Verde. Ecological transition towards renewable energy sources is crucial for these islands due to their current dependence on imported fossil fuels and their remoteness. The methodology used in this paper combines a SWOT analysis with a review of relevant literature. The SWOT analysis evaluates the Strengths, Weaknesses, Opportunities, and Threats associated with hydropower development on each island. The results show that each island has unique characteristics that influence its hydropower potential. The Azores has existing mini-hydropower plants and opportunities for pumped storage systems due to its rainfall and volcanic features. Madeira also utilizes hydropower, including the world's first underground pumped storage plant (UPHS) in Socorridos. However, limitations exist due to the mountainous terrain and competition for water resources. The Canary Islands showcase the success story of El Hierro Island, which significantly increased renewable energy penetration through a wind farm and pumped storage hydropower system. The topography and lack of rainfall on Cape Verde make the development of hydropower a significant challenge and, as a result, the focus has shifted to wind power. The study concludes that hydropower can play a significant role in the ecological transition of these islands. However, careful planning and consideration of environmental factors are necessary to maximize the benefits and minimize the potential drawbacks. The paper emphasizes the importance of island-specific assessments and exploring opportunities for pumped storage systems.

Keywords: Azores; Canary Islands; Madeira; Cape Verde; Electricity Alternative; Decarbonization Strategies.

1. Introduction

Island territories face unique challenges in transitioning to ecological sustainability. Their dependence on imported fossil fuels and remoteness necessitate innovative solutions [1]. Dependence on the outside world and the remoteness

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of the outermost regions further complicate the energy scenario [2]. The European Union, in one of its resolutions, states, *"whereas European islands can contribute to strengthening sustainable development in the Union, given their high potential for producing energy from renewable sources due to specific exposure to wind streams, ocean swell and sunlight"* [3]. There is awareness of the specificity of the territory and, in turn, the possibilities for a small territory to implement measures that can be exported to larger areas.

Ecological transition in island territories presents unique challenges and opportunities. Islands, isolated and characterized by favorable wind and solar conditions, hold immense potential for renewable energy resources (RES) [4]. Despite being large energy consumers, many small islands lack fossil fuel resources, relying heavily on costly imports for power generation, which poses challenges for meeting ambitious decarbonization objectives [5, 6]. Reducing greenhouse gas emissions on the islands, in relation to their energy production, is imperative. A study by Ioannidis et al. [7] found that between 2000 and 2015, island energy intensity rose by an average of 23.4%, with a corresponding increase of 12.4% in emissions intensity. This highlights the urgent need for a shift towards cleaner energy sources. In addition, this translates into a reduction of their energy dependence on the outside [8]. The islands are territories vulnerable to any crisis, and gaining independence increases their resilience.

Recognizing this, the European Union acknowledges the potential of islands to strengthen sustainable development and funds energy-related programs, with European islands as pilot hosts. While small islands may contribute only modestly to global greenhouse gas reductions [9], they play a crucial role in demonstrating the technical, economic, and political viability of adopting high proportions of renewable energy systems, which can influence high-polluting countries [10]. Access to renewable energy is not only an improvement in the energy transition of these islands but also in greater energy autonomy and the creation of specialized jobs linked to this sector [11]. Therefore, there is growing interest in projects that facilitate decarbonization of the islands [5]. Little by little, there are renowned achievements, such as the case of Gorona del Viento on the island of El Hierro (Canary Islands), where a wind-hydro power plant covers most of the island's energy demand [12].

The energy transition concept involves shifting from conventional fossil fuels to generating electricity, heat, and mechanical energy through renewable energy sources (RES) [13]. This transition aims to achieve ecological goals such as carbon neutrality in the energy sector by 2060 and limiting global temperature increase to 1.75°C by 2100, as per the Paris Agreement [14]. It serves as a crucial strategy to mitigate global warming, a prominent consequence of climate change (CC), and addresses concerns related to natural resources [15].

The trend towards implementing solar and wind power as alternatives to fossil fuels on islands is encouraging. A study by Blechinger et al. [10] demonstrated the significant potential of renewables. Their research suggests that islands could economically install and operate nearly 7.5 GW of solar photovoltaic power and 14 GW of wind power. This shift could achieve a remarkable reduction in greenhouse gas emissions and fuel consumption, reaching approximately 50%. Nevertheless, one of the main challenges faced in implementing renewable energy is that, in some cases, pilot projects have been proposed that have not gained sufficient momentum and have not been replicated. This is due to a lack of knowledge among stakeholders and the infrastructure of countries, among other aspects [16]. This has made it difficult for islands to commit to renewable energy, as they have indeed been considered residual energy sources, and the lack of space also hinders the progress of renewables [17].

In this regard, hydropower is also one option for decarbonizing European archipelagos [18]. In global terms, this type of energy accounts for 16.6% of the world's total energy production, and, in 2015, it accounted for 70% of all renewable energy [19]. Countries generating over 90% of their electricity, including Albania and Paraguay, rely on hydropower as the primary energy source [20]. Pumped hydro storage (PHS) systems represent 3% of the world's total installed electricity generation capacity and 99% of electricity storage capacity in recent years, making them the most widely used mechanical storage systems [14].

Essentially, a PHS system is an extensive, reversible technology for storing and releasing electricity, harnessing the potential energy of water. As the most prevalent energy storage system, PHS plays a crucial role in energy management by enabling the storage of substantial energy quantities for prolonged periods [21]. PHS systems usually store energy during periods with low demand and price, and release it during periods with high demand and price, effectively substituting higher-cost energy generation. The capacity for utility-scale energy storage ranges from a few hours to several days or even weeks, and exhibits flexibility in start/stop operations and rapid response times. Additionally, PHS systems contribute to frequency regulation and voltage control services, seamlessly integrating renewable energy sources into the power system [22].

Hydroelectric energy has been explored on the islands of Macaronesia for many years; among other factors, the orography allows for the generation of relevant waterheads that help produce energy in a simple manner on these islands [23, 24]. An exceptional case of this type of infrastructure, an underground pumped hydroelectric scheme, is located on the island of Madeira (Portugal). In this type of reversible hydroelectric power plant, the lower reservoir is located underground, where abandoned facilities such as mines can be used [25]. On the islands of the Azores archipelago, hydroelectric plants, along with wind energy, contribute to fulfilling a portion of the energy demand on these Portuguese islands. In the case of Cape Verde, which is part of Macaronesia but remains an independent country outside the European Union, the nation features thermal, wind, and solar power plants. However, the Cape Verdean government aims to have 50% of its electricity supply from renewable sources by 2020; they plan to install an off-stream pumped storage hydropower plant on the island of Santiago [26], which is the largest island in the archipelago.

The application of hydroelectric power schemes has underscored their importance in island electric energy supply systems. It is imperative to analyze the hydroelectric capacity of selected islands within the Macaronesia region through a SWOT analysis, in order to assess the current state of this type of energy on the islands and how it can be developed to play a crucial role in the ecological transition of these islands.

This article investigates and evaluates the hydroelectric potential of these islands through a comprehensive study. First, the designated research area is introduced, providing a clear overview of the islands under consideration. Subsequently, this study examines four archipelagos with similar geographical characteristics, three of which are considered outermost regions of Europe. In light of the pressing European challenge of promoting ecological transition on islands, this study proposes to evaluate the current state of hydropower in each of these archipelagos. The aim is to draw sound conclusions and improve current knowledge about the status of hydropower in these four island regions.

2. Research Methodology

To comprehensively analyze the hydropower potential in Macaronesia islands, a two-pronged methodological approach was employed, combining a Strengths, Weaknesses, Opportunities, and Threats (SWOT) analysis with an in-depth literature review: i) SWOT Analysis: This phase focused on dissecting the internal characteristics (strengths and weaknesses) of each island relevant to hydropower development. These internal factors encompass aspects like topography, water resources, existing infrastructure, and technical expertise. Additionally, the analysis explored external factors (opportunities and threats) that could influence hydropower feasibility. These external factors include aspects like government policies, environmental regulations, technological advancements, and regional energy markets. By systematically evaluating these internal and external factors, the SWOT analysis provided a holistic understanding of the opportunities and challenges associated with hydropower in each island; ii) Literature Review: In parallel, an extensive review of relevant academic literature was conducted. This review aimed to establish a strong theoretical foundation for the study by delving into existing research on hydropower development in island contexts. The review encompassed themes such as the specific challenges and considerations for island hydropower projects, global best practices in mitigating environmental impacts, and recent advancements in pumped storage technologies. By integrating this knowledge base into the analysis, the study ensured a well-rounded understanding of the topic and provided a robust framework for interpreting the results of the SWOT analysis.

This combined approach, leveraging both structured SWOT analysis and a comprehensive literature review, strengthens the study's credibility and validity. It allows for a nuanced examination of the hydropower potential in each island, considering both internal island-specific factors and the broader external influences.

2.1. Study Area

Macaronesia refers to a geographical region in the northeastern Atlantic Ocean that comprises a group of volcanic archipelagos. It includes the islands of Azores, Madeira, the Canary Islands, and Cape Verde (see Figure 1).

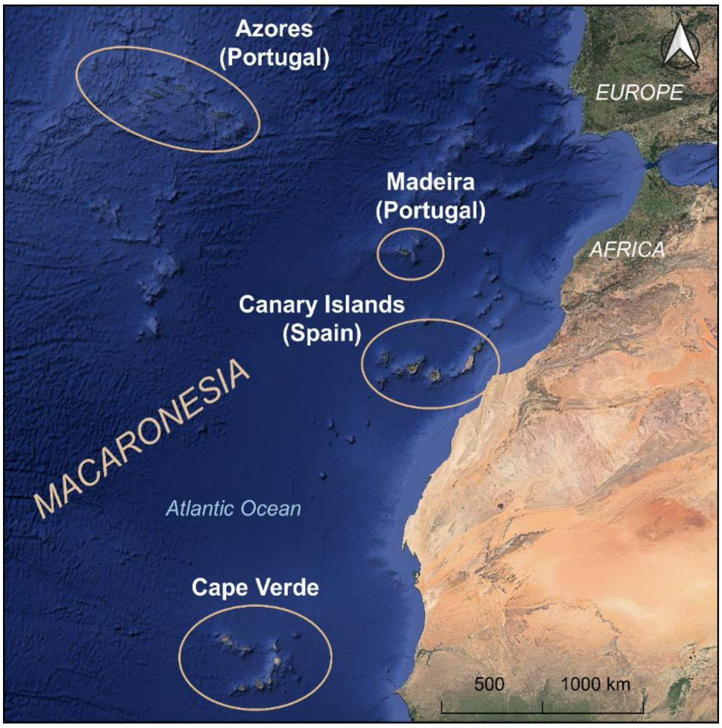

Figure 1. Macaronesia area, which includes Cape Verde, Canary Islands (Spain), Madeira (Portugal) and Azores (Portugal)

The Autonomous Region of the Azores (RAA) is a territory within Portugal, situated in the Northeast Atlantic and consisting of nine volcanic islands. The climate is predominantly influenced by the North Atlantic Subtropical Anticyclone (Azores Anticyclone), the proximity of the Gulf Stream, and sea water temperature [27]. Classified as predominantly humid temperate, according to the Köppen–Geiger climate classification, the region experiences consistent precipitation throughout the year, lacking a distinct dry season, and with a temperate summer climate [28].

The nine islands have nine isolated, independent power generation systems, comprising nine thermal power plants, ten wind farms, twelve hydroelectric power plants, three geothermal power plants, one photovoltaic power plant, one waste recovery plant, and one biogas power plant. There is no connection to either the mainland or neighboring islands, indicating a significant reliance on fossil fuels for energy provision [29]. In 2019, approximately 61.7% of the electrical energy produced was of thermal origin, and 38.3% was of renewable origin [30]. The 12 hydroelectric power plants in the Azores have a total installed power of 10,301 kVA, all designated as mini-hydro plants (<10 MW)—a limit generally used internationally to separate small and large hydroelectric plants [31].

The Madeira Archipelago is composed of the islands of Madeira, Porto Santo, and Desertas. The islands are situated in the North Atlantic Ocean, above the Canary Islands, and they constitute an autonomous region of Portugal. Madeira is the largest and highest island, with a volcanic origin, while Porto Santo has a different origin and is mostly flat [32].

The climate on Madeira Island is primarily temperate with dry, warm summers. In the coastal areas, summers are hot and dry, while in higher altitudes, summers are cool and dry [33]. Notable differences in elevation create a high number of different microclimates. The average rainfall increases with elevation; it is higher on the northern slope, ranging from 600.1 to 2663.6 mm per year. The period with the most precipitation is from November to January [34]. The average temperature is 25 ºC in the summer and 17 ºC in the winter, with temperatures decreasing with altitude.

In 2000, Madeira obtained 16% of its electricity from renewable energy sources [11]. Twenty years later, this percentage climbed to 33% and is projected to reach 50% in the next couple of years. Despite recent efforts to include more RES in electricity production, the Madeira Archipelago still secures most of its electricity from diesel fuel [35].

The Canary Archipelago, which is part of Spain, consists of seven islands: Lanzarote, Fuerteventura, Gran Canaria, Tenerife, La Palma, La Gomera, and El Hierro. Situated adjacent to Western Sahara, the archipelago is approximately 1,400 kilometers away from the Iberian Peninsula. Characterized by a subtropical climate with minimal seasonal temperature variations, the Canary Islands' weather is influenced by the trade wind belt and the Azores high [36]. The presence of a high vertical range results in a multitude of micro-climates, except for Fuerteventura and Lanzarote, which are flat islands and are predominantly arid. Precipitation across all the Canary Islands notably decreased in the latter half of the 20th century [37].

Similar to many oceanic islands, the Canary Archipelago heavily relies on the importation of large quantities of fossil fuels for electricity production, as it is not connected to the mainland grid [38]. Oil is transported to the islands via large ships and, in 2012, 98% of energy was derived from this source. In 2019, the share of renewable energy reached 15.9%, but data for 2020 is not representative due to the pandemic [39]. In 2022, the Canary Archipelago set a new record, with RES penetration at 20.1%, marking a 6.3% increase from 2021; however, this achievement still falls short of the EU target of 32% by 2030 [40].

Cape Verde is a small archipelagic nation situated approximately 500 km off the coast of Senegal in West Africa. It comprises ten islands, nine of which are inhabited, along with several islets. Estimated population in 2019 was 550,000 and is primarily concentrated on Santiago, the largest island, which also hosts the capital city, Praia. Consequently, Santiago accounts for the highest energy consumption, representing 55% of the country's generation and consumption in 2018 [41].

The Cape Verde archipelago is an integral part of the Sahel, characterized by a tropical and arid climate with two distinct seasons, marked by erratic rainfall, prolonged drought periods, and an average temperature of 24ºC [42]. Due to the absence of rivers amidst its renowned landscapes, warmth, and facing water scarcity, the archipelago relies on desalination for human consumption. The arid climate has historically posed challenges to water sustainability on the islands [43]. Additionally, the country relies heavily on fuel imports, with 80% of electricity generated from fossil fuel thermal power plants contributing to high electricity tariffs.

3. Results and Discussion

3.1. Azores

In the context of a SWOT analysis, various aspects of the Azores can be considered strengths. The volcanic nature of the islands, featuring widespread steep elevations, inherently meets the geomorphological requirements for potential energy projects, exemplified by the renovated Salto do Cabrito hydroelectric plant built in 2006 [44]. The climate further adds to the advantages of the study area, characterized by steady rainfall throughout the year and sufficient surface and groundwater. Existing hydropower potential is recognized as a significant strength, represented by 12 hydroelectric power plants, combined with accumulated knowledge. The installed hydropower capacity for the Azores hydrographic basin in 2023 was 8MW, according to the national data. From 2008 to 2019, electricity production from renewable sources increased by 39.6%, with an additional 3.3% increase in the last three years [30]. In the first half of 2023, the Autonomous Region of the Azores generated 403 GWh of electricity, with 40.7% from renewable sources, including 4.3% from hydropower [45]. These notable rates are the result of systematic studies and strategic action plans at both the national and local levels, exemplified by initiatives like the Regional Program for Climate Change in the Azores (PRAC) and – the Azorean Energy Strategy 2030 (EAE) [46].

Nevertheless, despite investments in alternative renewable sources for electricity production in the Azores, the region still relies heavily on thermal generation [47]. The feasibility of hydropower is contingent on site-specific conditions, requiring a river and the possibility of constructing a dam. Also, as mentioned earlier, the islands' electrical systems operate in isolation, without interconnections, a critical issue for ensuring acceptable supply quality and promoting the deployment of renewable energy sources [48].

Given that the study area currently houses operational mini hydro plants (see Table 1), the primary opportunities lie in the implementation of pumped hydro storage systems [29]. Introducing such a storage system would offer various advantages. First, it enables increased utilization of renewable energy, thus supporting and integrating fluctuating renewables in weak, isolated island power systems [49]. Additionally, storing energy during low-demand periods for later use, particularly with the islands' large geothermal and wind potential, can reduce fuel imports and enhance the reliability of intermittent energy sources [50].

Table 1. Hydroelectric production plants in the Azores, by island and by installed capacity (Source: Relatório do Estado do Ambiente dos Açores)

Name	Construction	Island	Gross head (m)	Nº and type of turbines	Installed Power [MW]	Production in 2022 [GWh]
Além Fazenda	1966	Flores	104	3 Francis	1.6	5.1
Canário	1990	Sao Miguel	23	1 Francis	0.4	2.4
Cidade	1954	Terceira	72	1 Pelton	0.3	0.3
Fábrica Nova	1927	Sao Miguel	275	1 Pelton	0.6	0.3
Foz da Ribeira	1990	Sao Miguel	40	1 Francis	0.8	5.5
Nasce Água	1954	Terceira	182	1 Pelton	0.7	0.9
Ribeira da Praia	1991	Sao Miguel	166	1 Pelton	0.8	4.1
S. João de Deus	1954	Terceira	120	1 Pelton	0.5	0.5
Salto do Cabrito	2006	Sao Miguel	137	1 Pelton	0.7	4.9
Tambores	1909	Sao Miguel	10	1 Francis	0.1	0.4
Túneis	2000	Sao Miguel	81	1 Francis	1.6	10.0
Varadouro	1961	Faial	574	1 Pelton	0.3	0.20

The rehabilitation and enhancement of existing hydropower infrastructure provide an opportunity to modernize the operational framework through digitization. This not only extends equipment lifespan and mitigates cybersecurity risks but also contributes to increased energy output and compliance with changing contextual conditions [51]. Interconnecting islands or linking with the mainland can enhance overall cost efficiency, especially in addressing challenges like high capacity-to-peak load ratios and extensive reliance on diesel generation, leading to greater grid stability and improved exploitation of existing renewables [28].

As main threats, the construction of dams results in substantial changes to land use, leading to habitat loss, fragmentation, and degradation, which negatively affect local ecosystems and biodiversity [52]. Concurrently, the natural flow patterns of water are disrupted, impacting both aquatic and terrestrial habitats, and exacerbating ecological consequences [53]. Furthermore, even though there are either no rivers or short rivers in the Macaronesia islands, the location of dams and the habitat of the fish inhabiting those rivers should be considered, in order to disturb their way of life and reproduction as little as possible [54].

The Azores archipelago faces a significant flood threat, primarily stemming from flash floods triggered by intense, sporadic rainfall, which is particularly perilous when impacting urban areas situated in flood-prone zones [55]. Notably, five islands (Santa Maria, São Miguel, Terceira, São Jorge, and Flores) host hydrographic basins with elevated flood risks, totaling 43 basins covering 344 sq km or approximately 15% of the regional area [56].

In 2022, the Azores recorded a total of 1.8 million air passenger disembarkations, representing growth of 67% compared to 2015. The destination recorded 3.2 million overnight stays and 1.0 million guests, indicating growth of 107% and 102%, respectively, compared to 2015 and an increase of 6% and 5%, respectively, compared to 2019 [57]. These trends underscore the imperative for promptly incorporating renewable energy systems to mitigate the risk of overreliance on thermal sources.

3.2. Madeira

The mountainous topography of Madeira makes installing large reservoirs difficult, but, out of the ten hydropower plants operating in Madeira, nine are built on rivers. These are crucial during heavy rain, as the need for thermal electricity is lowered, reducing CO_2 emissions [58]. The locations with the most precipitation are on the northern side of Madeira Island, at higher altitudes [25]. In addition to rainfall, hidden precipitation is essential; the trade winds bring humidity that is captured by forests [59]. This phenomenon is called horizontal or fog rainfall, and it can have condensation rates above 900 mm [60].

Additionally, there is a reversible hydropower plant in Madeira called Socorridos. Both reservoirs are located underground, making it the world's first underground pumped hydroelectric scheme (UPHS). The principle is the same as for classic pumped hydro storage. However, due to the underground location, environmental impacts are lower than they would be on the surface, and the use of geospace offers various advantages. For example, it is less sensitive to earthquakes, noise, or other hazards present on the surface [61]. Both reservoirs are tunnels; the upper one is called the Covão tunnel, and the lower one is the Socorridos underground reservoir. Not only does it provide electric energy during rush hours, but it is also used as an irrigation system and ensures public water supply. Additionally, it was constructed to integrate levadas, a network of aqueducts and channels from the 15th century, into the scheme [25].

In addition to Socorridos, several run-of-river hydropower plants operate in the Madeira Archipelago, including Serra de Água (SDA), Calheta 1, 2, and 3, Stream de Janela (RDJ), and Fajã da Nogueira (FDN) [62]. Together, they produce approximately 60 megavolt-amperes, while operational mini hydropower plants contribute 0.9 megawatts [63]. Despite Socorridos being a valuable contributor to RES penetration, the utilization of natural resources for new hydropower plants is approaching its limits, exemplified by constraints on the stream of São Vicente due to its use by the Socorridos power plant. Insufficient hydrological data further complicates planning [62].

For its part, Porto Santo Island lacks potential for hydropower pumped storage due to its limited surface altitude difference, with the highest peak at only 402 m [62].

In the work of Marczinkowski and Barros [64], the crucial role of institutions in the development of renewable energies is emphasized, highlighting the need for them to move away from the fossil fuel model and embrace leadership in ecological transition and the alternative of green energy sources. The Portuguese government on Madeira island has sought to make energy consumption more flexible by making night-time electricity tariffs attractive to consumers. However, these tariffs do not consider the electricity mix or how that energy is produced [64].

Finally, one of the fundamental aspects that can be categorized as a threat is the proliferation of small hydroelectric plants throughout the territory, as these small plants may neglect large-scale ecological and evolutionary processes [65]. Additionally, they can hinder the dispersion and migration of organisms, increasing the risk of local extinction [66].

3.3. Canary Islands

The Canary Islands boast notable strengths in their hydropower potential, primarily exemplified by the El Gorona del Viento power plant on El Hierro [12]. This facility, operational since 2015, integrates a wind farm and a pumped storage hydropower system, significantly increasing RES penetration on the island (see Table 2). In 2016, RES penetration rose by 21.3%, reaching an impressive 79.4% by July 2017 [67]. In 2018, renewable energy sources accounted for 55% of the electricity generated in El Hierro [68].

Table 2. Energy demand covered by different energy sources per island for the year 2021 (Gobierno de Canarias [69])

Demand Coverage (MWh)/Island	Gran Canaria	Tenerife	Lanzarote	Fuerteventura	La Palma	La Gomera	El Hierro	Canary Islands
Conventional fossil fuels	2,661,453	2,678,027	645,327	508,727	239,089	71,022	26,133	6,829,778
Wind	632,818	524,474	65,696	97,696	22,075	114.69	0	1,342,875
Photovoltaic	55,823	175,052	9,753	15,685	5,393	6.34	47.41	261,760
Mini-hydraulics	0	3,048	0	0	0	0	0	3,048
Wind Hydro	0	0	0	0	0	0	33,343	33,343
Biogas (landfill)	0	8,000	475	0	0	0	0	8,475
Total Demand Coverage (MWh)	3,350,094	3,388,601	721,251	622,108	266,557	71,143	59,523	8,479,279
% RES 2021	20.6%	21,.0%	10.5%	18.2%	10.3%	0.2%	56.1%	19.5%

Although the El Electron hydroelectric plant in La Palma, the oldest in the archipelago, is no longer operational, it symbolizes the historical importance of hydropower in the region. Recognizing the commitment of La Palma's residents, the local government initiated the La Palma renewable project, aiming for a transition to 100% clean energy [70].

Traditionally, smaller islands have been the testing ground for hydroelectric power systems, such as those mentioned on the islands of La Palma and El Hierro. This is why the Chira Soria project on the island of Gran Canaria (one of the Canary Islands, along with Tenerife) is now gaining great importance [71].

With growing electricity demand, the implementation of new RES projects is essential. The proposed Chira-Soria project in Gran Canaria (Figure 2), a reversible pumped storage hydroelectric power plant, faces delays in construction initiation and potential inadequacy in meeting the rising energy demand [71]. The power plant will have a capacity of 200 MW and will supply energy for a maximum of 18 hours, which equates to a storage capacity of 3.6 GWh, ensuring 36% of the electrical demand during peak hours.

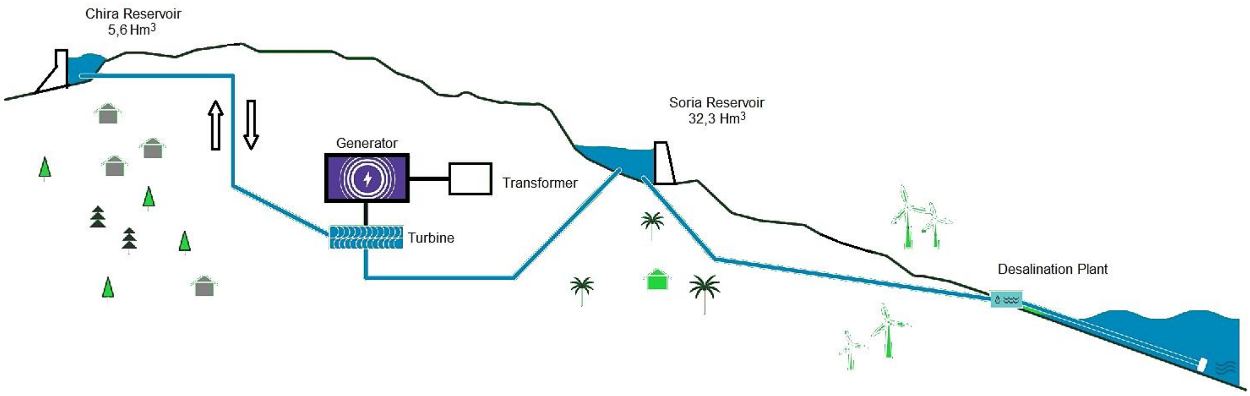

Figure 2. Hydropumping project of 200 MW with desalinated water (Salto de Chira, Gran Canaria)

Identifying topographically suitable sites with sufficient water capacity for hydro storage remains a challenge. High capital costs, despite low operating costs, pose an obstacle to renewable energy projects [72]. Therefore, optimization of existing hydro storage facilities and the potential construction of new ones, such as the Chira-Soria project, offer opportunities for job creation, increased RES production, and reduced CO_2 emissions [73]. Additionally, the exploration of abandoned hydroelectric power plants like Salto del Mulato on La Palma or the integration of mini hydropower plants in urban sewer systems holds promise for further energy production. Nevertheless, environmental concerns, such as dams located within protected areas on Gran Canaria, further complicate the sustainable development of hydropower [74].

A positive aspect of the Canary Islands is that there is no risk of disrupting river ecosystems, as there are no rivers considered to exist in the Canary Islands. However, it is true that the infrastructure required for the development of hydroelectric power can generate critical situations for animals and plants, such as the loss of shelter and food, and the alteration of variables such as humidity and temperature [75]. This is something that was also mentioned when discussing Madeira and the local extinctions that occurred there.

3.4. Cape Verde

As one of the 15 Small Island Developing States (SIDS) with a 100% renewable energy target, Cape Verde's 2008 National Energy Policy initially aimed to secure half its electricity from renewable sources by 2020 [76]. The nation has since elevated this goal to achieving 100% renewable electricity by 2025, emphasizing the use of domestically available, renewable, and low-carbon energy sources.

Cape Verde strategically utilizes its abundant renewable resources to establish local power sources. Between 2012 and 2017, wind energy accounted for approximately 22% of the country's total electricity consumption, significantly reducing fuel usage [77]. The nation's commitment to sustainability is evident in the total penetration of renewable energy sources, reaching 20.8% in 2018, marking a 2.3% increase from 2017 [77].

A PSH project for Santiago Island in Cape Verde, scheduled for 2020, was in the planning stages [20]. This off-stream PSH plant is distinctive, featuring independent reservoirs not reliant on natural stream flow, emphasizing stored potential energy derived from previously pumped water. Segurado et al. [58] proposed a solution to address the island's freshwater scarcity by incorporating desalinated water into the pumping and hydro station, subsequently distributing it to the population. Utilizing excess wind power in desalination units serves as a demand-side management strategy, considering the impracticality of converting water back into electricity. The study suggests achieving over 30% of yearly power production from renewable energy sources, with 33% from wind power and 3% from pumped storage hydro. Approximately 50% of the water supplied to the population can be sourced from wind power.

Cape Verde encounters formidable challenges in harnessing hydropower due to insufficient availability of surface water resources [78]. While three populated islands manage to avoid desert classification, with an annual rainfall exceeding 250 mm, they still fall within the semi-arid range, averaging less than 500 mm annually. This natural condition significantly impedes the feasibility of both hydroelectric electricity generation and hydro storage.

From a security of supply perspective, especially for a country like Cape Verde, which lacks fossil resources or known reserves, the role of renewable sources is crucial and stresses the importance of establishing significant storage capacity, whether through pumped hydro, batteries, or other technologies to ensure grid reliability and successfully meet its environmental targets. It is essential to recognize Cape Verde's heavy reliance on water desalination plants, a process that demands a substantial electricity supply. In 2018, over 8% of the electricity generated was allocated to water desalination, as 99.5% of the water supplied to the population came from desalination plants [79].

It is important to note that, of the four archipelagos studied, only Cape Verde is not a European outermost region. In other words, it is not a European territory, and therefore the guidelines that Europe sets for its overseas territories through its Smart Specialization Strategies do not apply to Cape Verde. However, due to its proximity to the continent and its historical ties, this country has become a beneficiary of international cooperation in renewable energy, which provides an opportunity for growth and investment in clean energy [80].

3.5. SWOT

Despite the promising outlook for integrating renewable energy sources into the grid, several barriers hinder their effective implementation in electricity generation processes across African countries, including Cape Verde [81] (Figure 3). High renewable potential often encounters limitations due to cost barriers, financing challenges, existing policy and regulatory frameworks, technical issues related to the grid structure, and the unpredictable nature of certain renewable resources [82]. These challenges pose significant obstacles to the integration of renewables into the energy landscape for Cape Verde and many SIDS with similarly ambitious renewable energy goals, risking the possibility of falling into an eco-island trap [83].

S	**W**
• Geomorphological requirements • Water availability • PRAC - Regional Program for Climate Change in the Azores • Citizen awareness • Gorona del Viento • Run-of-the-river power plants • Fog rainfall	• Dependency on fuel • Lack of surface water reservoirs • Isolated, unstable grids • Demographic fragmentation • Storage capacity • Production efficiency • No possibility of tidal hydropower • Electricity demand
O	**T**
• Building of new pumped hydro storage systems • Connection of island grids to those on the mainland • Establishment of substantial storage capacity • Optimization of existing structures • Mini hydropower plants • Private investment in RES	• Environmental impact • Floods • Climate change • Unpredictability of RES • Volcanism • Challenges in administration • High initial cost of hydro power plants

Figure 3. SWOT Analysis of the strengths, opportunities, threats, and weaknesses of the Macaronesian Islands for the implementation of renewable energies

After conducting this analysis, similar challenges were observed in the four archipelagos studied, which can be summarized as follows: i) the decentralized electrical system, comprised of grids corresponding to each inhabited island, poses a barrier to achieving economies of scale [8, 84]; ii) the distribution of fuel storage capacity and logistical resources among the islands is generally inadequate [85]; iii) the demand for electricity continues to rise, driven by factors such as population growth and the thriving tourism industry on the islands, including nautical tourism [34]; iv) the significant dependence on fossil fuel-based power plants, coupled with expensive fuel imports, highlights the importance of reducing reliance on imported fuels through increased penetration of renewable energies for the economic well-being of the State [86]; and v) a fully decarbonized electrical system would also be the most job-generating option among other alternatives [87].

Seawater-pumped hydro storage (S-PHS) emerges as a geographically relevant solution for islands and semi-arid regions, offering an alternative or supplement to traditional PHS plants. The technology operates based on hydraulic potential energy storage, utilizing the elevated position of seawater relative to sea level for electrical energy storage. During periods of low demand, water is pumped to a high reservoir, typically an inland bay, and is released to the sea—acting as the natural lower reservoir—during peak hours [88]. S-PHS projects distinguish themselves from conventional pumped storage power projects in various ways. Notably, construction costs are reduced, as the sea functions as the lower reservoir, eliminating the need for a dam and lower reservoir land [89]. Additionally, the minimal variation in head, as the water surface level of the sea only fluctuates between high and low tides, is advantageous for pump-turbine design [90]. However, despite these advantages, the use of seawater in energy storage presents challenges. Corrosion poses a significant issue for metal components, necessitating the development of corrosion-resistant materials [50].

Global demand for energy is rapidly escalating, with a significant portion still met by fossil fuels, contributing to CO_2 emissions and climate change [91]. To address this issue, an effective strategy involves increasing the utilization of renewable energy sources, particularly hydropower, which holds the highest share of RES worldwide and plays a pivotal role in combating climate change.

Isolated islands, such as those in Macaronesia, face more substantial challenges in energy and electricity compared to mainland areas. While distant archipelagos predominantly rely on fossil fuels, their impact on environmental pollution is less pronounced than that of mainland regions. However, the ecosystems of these islands are exceptionally vulnerable to greenhouse emissions [92]. The remoteness of these areas prevents them from connecting to mainland grids, and utilizing RES is challenging due to the instability of insular grids. Additionally, islands must diversify their energy sources since weather-sensitive renewables like wind and solar power require alternative options. Fortunately, many islands possess multiple RES, and hydropower, especially in the form of pumped hydro storage, serves as a reliable complement, generating electricity independent of weather conditions. Some islands, such as Trinidad and Tobago and Bahrain, rely on oil and gas resources, posing challenges for a transition to more environmentally friendly alternatives [93]. Conversely, Iceland stands as an exemplary case, achieving an RES penetration of 99.8% in 2015 through geothermal and hydroelectric energy [94].

Remote islands globally are increasingly striving to integrate renewable energy sources into their electricity production. Successful sustainable energy solutions have been implemented in various island locations, including Samsø (Denmark), the Galápagos Islands (Ecuador), the Caribbean, Tokelau (New Zealand), and the study area islands – the Azores and the Canary Islands. Hybrid RES systems, as mentioned earlier, are widely adopted in these cases [92].

Hawaii, another volcanic archipelago aiming for higher RES penetration, encounters challenges akin to those faced by Macaronesian archipelagos. Shifting water consumption from agriculture to tourism has strained water resources, prompting debates about sustainable practices. Proposals for a pumped hydro storage system, while aiming to address water diversion concerns, have encountered opposition, prolonging deliberations over a decade [95]. The suitability of pumped hydro storage in certain areas, as seen in Croatia, is contingent on topography and geological factors. For instance, flat and arid Croatian islands connected to the mainland grid present less favorable conditions for pumped hydro storage [96].

In short, the path to energy independence for the studied archipelagos lies in a strong commitment to renewable energy, grid modernization, and improved storage. It is crucial that the islands take ownership and make their ecological transition as soon as possible, as they are highly vulnerable to climate change. In addition, due to the potential environmental risks, this transition requires a thorough study of the pros and cons of each project, in order to choose the best option and the most suitable energy alternative in each case.

4. Conclusions

In this study, a comprehensive SWOT analysis was conducted to assess the feasibility of and challenges associated with hydroelectric energy in the islands of Macaronesia. Through the evaluation of strengths, weaknesses, opportunities, and threats, we have gained a comprehensive understanding of the current and future outlook of this form of energy generation in a specific island environment.

The Macaronesian islands must systematically address the technological, environmental, and socioeconomic obstacles related to the use of hydropower, in order to proceed. The archipelagos could move toward a more sustainable energy future by utilizing their natural resources and taking inspiration from successful international models. This will lessen their reliance on fossil fuels and help the world community fight climate change.

In terms of strengths, the availability of water resources in the islands stands out, providing a sustainable source of renewable energy. Water storage capacity also offers flexibility in energy generation, allowing for adaptation to demand variations. The reduction of greenhouse gas emissions and energy independence are key benefits associated with hydroelectric power. Administrative challenges, lengthy approval processes for new power stations, and bureaucratic hurdles contribute to threats facing hydropower projects.

In summary, the exploration of hydropower potential in Macaronesia unveils both opportunities and challenges. Escalating energy demand, coupled with the environmental impacts of climate change, necessitates swift action. Broadly speaking, the studied archipelagos share common energy-related issues, including the inability to connect to mainland grids, resulting in a reliance on fossil fuels. Additional challenges encompass an unstable grid, high initial costs, and demographic dispersity. The Canary Islands, Azores, and Madeira Archipelago, characterized by mountainous topography, present an opportunity for the installation of pumped hydro storage. However, despite the Azores and Madeira Archipelago having notably higher precipitation rates, their hydropower penetration remains relatively modest. The current penetration rates of RES in these three archipelagos underscore the potential for improvement, with a particular emphasis on enhancing hydropower. In contrast, Cape Verde, grappling with similar challenges, stands out as the most arid and flat among the Macaronesian archipelagos, imposing constraints on hydropower potential. Despite these hurdles, there is a discernible commitment among the islands to adopt sustainable energy solutions, as evidenced by the increasing penetration of renewable sources.

5. Declarations

5.1. Author Contributions

Conceptualization, J.C.S. and N.C.P.; methodology, V.L.P.K. and A.J.; software, J.S.R.A.; validation, J.C.F.; formal analysis, A.G.G.; investigation, J.R.M.; writing—original draft preparation, J.C.S., N.C.P., V.L.P.K., A.J., J.S.R.A., J.C.F., A.G.G. and J.R.M.; writing—review and editing, J.C.S., N.C.P., V.L.P.K., A.J., J.S.R.A., J.C.F., A.G.G., and J.R.M. All authors have read and agreed to the published version of the manuscript.

5.2. Data Availability Statement

Data sharing is not applicable to this article.

5.3. Funding

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5.4. Conflicts of Interest

The authors declare no conflict of interest.

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