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The Role of Pumped Storage in the Integration of Renewable Energies: Planning the Expansion of Electricity Generation on Santiago Island, Cabo Verde

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Abstract. The growing demand for electricity and the urgent need to mitigate climate change have driven countries towards a decarbonized path, increasing the share of renewable energy sources in the power mix. However, the intermittent nature of wind and solar power poses challenges to grid stability and security of supply, requiring innovative solutions such as energy storage. Hydropower, particularly pumped storage systems, can play an important role by storing renewable electricity excess and stabilizing the grid, thereby supporting higher renewable energy penetration.

The island Santiago, Cabo Verde, is still heavily dependent on fossil fuels, with 87.2% of its electricity coming from thermal sources in 2023. Cabo Verde's 2018–2040 Power Sector Master Plan aims to achieve of more than 50% renewable energy penetration by 2030 and 100% by 2040. Key initiatives include the expansion of wind and solar capacity and the implementation of energy storage solutions. Among these, the 20 MW/160 MWh pumped storage project, and a 9.4 MW/5.5 MWh battery storage system are expected to improve grid stability and reduce dependence on fossil fuels.

This study evaluates the impact of integrating renewable energy and storage solutions into Santiago's power system by modeling different scenarios for 2030 using the Low Emissions Analysis Platform (LEAP) software. Preliminary results suggest that pumped storage can significantly increase the share of renewable energy in the power mix, improve energy supply reliability, reduce carbon emissions, and facilitate the energy transition in Santiago island's power system.

Key words. pumped storage, renewable energy integration, energy planning, simulation, Santiago Island.

1. Introduction

The increasing demand for electricity, coupled with the urgent need to mitigate climate change, has driven many countries to seek sustainable alternatives for power generation. In this context, renewable energy sources have emerged as a viable solution to diversify energy mix, reduce dependence on fossil fuels, and promote sustainable development. These sources also offer opportunities for job creation, technological innovation, and enhanced energy security [1].

However, the increasing adoption of distributed generation (DG) poses significant challenges to power systems worldwide A high share of renewable energy sources (RES), such as wind and solar in a power mix, presents significant challenges due to their intermittent nature, with daily, and seasonal variations, depending on the weather conditions. The aforementioned intermittency impacts grid stability and power quality, leading to voltage instability, frequency fluctuations, and harmonic distortion [2]. Additionally, RES lacks the inherent physical inertia provided by conventional rotating mass generators, which play a crucial role in grid stability [3].
In order to address the abovementioned issues, innovative solutions, such as virtual inertia controllers, have demonstrated their efficacy maintaining grid stability and resilience [4]. Additional measures, including energy storage integration and improved wind turbine control, can further contribute to ensuring a reliable energy supply [5].

Particularly pumped storage systems, have proven their capacity to store energy generated from non-dispatchable sources, such as wind and solar, and convert it into dispatchable energy thereby ensuring the reliability and resilience of power systems. Moreover, they facilitate the large-scale integration of renewable energy into the electricity grid [6].

Located in the Atlantic Ocean, Cabo Verde is an archipelago comprising ten islands, of which nine are inhabited, has an independent electricity system with installed capacity ranging from 1.74 MW to 76.255 MW in size. However, the final price for consumers is set at the national level. Fossil fuels, predominantly fuel oil, are the primary source of energy consumed in the electricity sector. The islands' small market size and dispersed energy systems contribute to the complexity and cost of importing and distributing these fuels leading to high electricity cost, with current costs in 2025 standing at around €0.327 for the domestic low voltage tariff and €0.247 for the medium-voltage tariff [7].

The considerable expense associated with the generation of energy from fossil fuels, when considered in conjunction with the islands' abundant wind and solar energy potential, results in renewable energy sources being highly competitive in Cabo Verde.

Beyond its ancillary function, pump storage has the potential to contribute to the economic efficiency of the system by storing excess renewable energy production during periods of low consumption and providing cost-effective energy during times of high demand, thereby optimizing the economic dispatch of the system.

Santiago, the largest and most populous island in the country, remains heavily reliant on fossil fuels to meet its electricity demand. In 2023, the island's electricity generation reached 263.83 GWh, with 87.2% originating from thermal sources (229.94 GWh), 10.7% from wind (28.19 GWh), and 2.1% from solar (5.70 GWh), marking a 1.4% increase compared to 2022 [8].

Cabo Verde's 2018–2040 Energy Master Plan outlines ambitious targets for the country's energy transition, aiming to surpass 50% renewable energy penetration by 2030.

To facilitate higher renewable energy penetration and ensure supply security, Cabo Verde is planning the development of a 20 MW/160 MWh pumped storage hydropower project on Santiago Island [9], additionally to the deployment of a 6 MW/6 MWh battery energy storage system (BESS).

A. Study Relevance

The transition to a more sustainable and cost-effective energy system on Santiago Island depends on the optimization of the joint behaviour of all systems, including RES and storage, as well as knowledge of the behaviour of energy demand (total and peak) at any given time.

Computational modeling and scenario analysis have been demonstrated to be valuable tools for understanding the of various configurations of the production and storage mix associated with different demand projections. Consequently, these tools can act as a decision support tool to the plan the necessary expansion infrastructure to match supply and demand.

This study focuses on simulating Santiago Island's power system for the year 2030, with a particular emphasis on integrating renewable energy sources couple with storage, particularly pump storage. In light of the ongoing and planned projects, including the expansion of solar, wind, and energy storage capacities, this research aims to provide a comprehensive assessment of the impacts of different production mix configurations on the of share of RES and on the economic efficiency of the power mix, as well as on the ability to match future energy demands.

2. Objectives

A. General Objectives

The aim of this study is to evaluate the impact of integrating renewable energy sources into Santiago Island's power system by modeling future scenarios for 2030, in alignment with the Cabo Verdean government's energy transition goals to maximize the share of renewable energy in electricity supply, reduce dependence on fossil fuels, and enhance the island's energy security and economic efficiency of the power system.

B. Specific Objectives

Power system modeling: Develop a computational model that accurately represents the current electricity system of Santiago Island, including existing thermal, solar, and wind power plants.

Future scenario projection: Simulate the power system's behavior for 2030, considering the expansion of renewable generation (solar and wind) and the implementation of energy storage technologies, such as battery energy storage systems (BESS) and pumped storage hydropower (PSH) to match projected demand scenarios.

Renewable energy penetration analysis: Assess how the pump storage affects the share of renewable sources in the projected scenarios and its effects on the efficiency of the power system.

Economic and environmental benefits assessment: Examine the effects of increased renewable energy integration on the economic efficiency of the system and CO_2 emissions reduction.

3. Methodology

The study's approach is quantitative and computational. It is based on the simulation of Santiago Island's power system for different futures scenario (2023-2030). The base year is set as 2023, which has consolidated data.

A. Simulation Tool

This study uses the LEAP software as the primary tool for simulating the expansion of the electricity system on Santiago Island through 2030. LEAP is a bottom-up, scenario-based energy planning model that enables the analysis of both energy demand and supply evolution across multiple time horizons. Developed by the Stockholm Environment Institute, LEAP is widely recognized for its role in energy policy analysis and climate change mitigation planning. It has been adopted by thousands of institutions in over 190 countries and is increasingly considered the de facto standard for countries undertaking Integrated Resource Planning (IRP), greenhouse gas (GHG) mitigation assessments, and the development of Low Emission Development Strategies (LEDS), particularly in the Global South [10].

B. Literature Review and Preliminary Analysis

A comprehensive review of the existing literature and an analysis of Santiago Island's current energy system were conducted. This included an assessment of the country's energy matrix, government policies, and renewable energy expansion plans. Ongoing projects, such as the development of solar, wind, and energy storage technologies, were also examined.

C. Data Sources and Modelling Base

The energy model is based on data from the following sources:

- Annual report and accounts from ELECTRA SA (2015–2023);
- Annual report and accounts from Cabeólica, the independent wind power producer (2023);
- The 2018–2040 Master Plan for the Electricity Sector;
- National statistical data from INE and regulated fuel prices from ARME;
- Technical and economic parameters from international references (IRENA, IEA, NREL).

D. Model Structure

The energy model was carried out in LEAP using the following components:

- A demand tree only with the total electricity demand for Santiago Island, without disaggregation into subsectors, due to data availability limitations;
- A transformation module (power generation) including thermal processes, renewable sources (solar, wind, pumped hydro), and storage systems (batteries);
- An hourly load curve composed of 8,760 corrected and interpolated values based on real 2023 data.

E. Technical and Economic Parameters

The main technical and economic parameters were defined based on real operational data and reputable international sources [16],[17],[18].

F. Scenarios Building

The following simulation scenarios were developed for Santiago Island:

Business as Usual (BAU): Considers only the installed capacity as of 2023 and an annual demand growth rate of 2.07%, derived from a linear regression based on ELECTRA SA historical data (2015–2023). This scenario also allows an endogenous thermal expansion of up to 11.5 MW, reflecting the potential installation of a new Wartsila thermal unit.

Master Plan (MP): Includes three sub-scenarios with different demand growth rates based on the National Electricity Sector Master Plan: Base: 4.97% per year (337.2 GWh in 2030), Efficiency: 4.00% per year (316 GWh) and High: 6.21% per year (365.94 GWh).

Renewable Energy Scenario for 2030 (RES2030): In this scenario two distinct demand projection were formulated: Moderate: with 3.20% per year, assuming energy efficiency measures and High: 3.80% per year growth, assuming high demand growth.

In the MP and RES2030, it is also assumed that by 2030, all planned renewable energy and storage projects will be fully implemented. These include the expansion of solar and wind generation, as well as the integration of battery energy storage systems (BESS) and pumped storage hydropower (PSH).

4. Case study of Santiago Island in Cape Verde

A. Geographical context

Cape Verde is a small archipelagic country located approximately 500 km off the west coast of Africa. It is composed of 10 volcanic-origin islands in the Atlantic Ocean, with a total surface area of around 4,033 km². The country is situated between latitudes 14º 23’ and 17º 12’ North and longitudes 22º 40’ and 25º 22’ West of Greenwich [11].

The study area is Santiago Island, the largest island in Cape Verde, with an area of approximately 991 km², representing about 24.6% of the archipelago’s total land area. In 2022, the country recorded 506,595 inhabitants, with roughly half of the population residing on Santiago Island, where the nation’s capital, Praia, is located [11].

Figure 1 - Cape Verde archipelago and location of Santiago Island [11].

B. Energy Sector in Cape Verde

The energy sector in Cape Verde falls under the jurisdiction of the Ministry of Industry, Commerce and Energy (MICE) and is overseen by the National Directorate of Industry, Commerce and Energy (DNICE). According to the organizational structure of MICE, DNICE is the public administration body responsible for the design, implementation, and evaluation of energy, industrial, and commercial policies [12].

The Multisectoral Regulatory Agency for the Economy (ARME) is responsible for regulating the electricity and other sectors.

Until 2024, ELECTRA SA was the company responsible for the integrated management of the electricity and water sectors in Cape Verde. Its operations covered the production, transport, distribution and sales of electricity and desalinated water throughout the national territory, with the exception of the island of Boavista, which operated under a sub-concession regime (AEB - Águas e Energia da Boa Vista). As part of the process of restructuring the electricity sector in Cape Verde, three new companies have been created: EPEC (generation), EDEC (distribution), and ONSEC (National Electricity System Operator), which are responsible for the generation, transmission, distribution and sales of the electricity and water on all islands except Boa Vista.

C. Energy Policy in Cape Verde

The Electric Sector Master Plan 2018–2040 is a strategic document that guides the development of the electrical system in Cape Verde. It addresses key areas of sectoral development, including spatial forecasting of electricity consumption, new investments and reinforcements in transmission and distribution infrastructure, the structure of the generation mix (location, size, energy sources, and technologies of power plants), as well as grid management, and the institutional and organizational framework.

D. Goals for Cape Verde's electricity sector

Based on the Electric Sector Master Plan 2018–2040, the following least-cost targets were established for Cape Verde's electricity sector:

i. Achieve 30% of electricity production from renewable energy sources by 2025, in line with the binding commitment made by Cape Verde at the Paris Conference of the Parties (COP21);

ii. Exceed 50% of electricity production from renewable sources by 2030, reaching the level of integration that minimizes electricity production costs;

iii. Continue investing in wind energy while launching an ambitious program for the development of solar energy;

iv. Promote the development of a pure pumped storage power plant on Santiago Island by 2025, and implement battery-based storage solutions on the other islands as cost reductions and technological advancements make them viable;

v. Maintain a strong focus on energy efficiency and loss reduction, as key strategies to lower electricity costs for Cape Verdean citizens and businesses.

E. Energy production plants

Electricity generation in Cape Verde is distributed across three main technologies: thermal, solar, and wind. In 2023, ELECTRA SA operated two thermal power plants on Santiago Island, the main one located in the city of Praia and a smaller facility in the municipality of Santa Catarina, in addition to a solar park. The thermal power plants use fuel oil 380 Sct and diesel for electricity production. The main characteristics of these plants are presented in the following table:

Table I - Distribution of installed and available power among the various production units of ELECTRA SA in 2023 [8].

Thermal Production Unit	Inst. Therm. Cap. [kW]	Inst. Solar Cap. [kW]	Availab. Thermal Cap. [kW]
Palmarejo	72 843	4 280	56 928
Sta. Catarina	3 412		900

F. Independent producers of renewable energy

On Santiago Island, the only independent renewable energy producer is Cabeólica, a company established through a Public-Private Partnership (PPP), whose main objective is to generate electricity for the national grid under the independent power producer regime, using wind energy, a clean, renewable, and naturally abundant resource in the archipelago.

According to Cabeólica's 2023 annual report, there were no changes in the installed capacity of the wind farm on Santiago Island, which remains composed of eleven Vestas V52 wind turbines, each with a rated capacity of 850 kW.

The following table presents the data related to energy production, average annual availability, and average annual penetration rate for the year 2023.

Table II - Data from the independent power producer Cabeólica's wind farm for the year 2023 [13].

Wind Farm	Installed Capacity (MW)	Energy Produced (MWh)	Availability (%)	Wind Penetration (%)
Santiago	9,35	28 086	96,1	11

G. Evolution of energy production

Santiago Island, in Cape Verde, has experienced a significant increase in demand for energy over the years, which has driven a remarkable evolution in electricity production. This growth in consumption has led the island to adapt its infrastructure to meet the growing needs of the population. The following graph illustrates the annual evolution of the energy produced by the various generation units between 2015 and 2023.

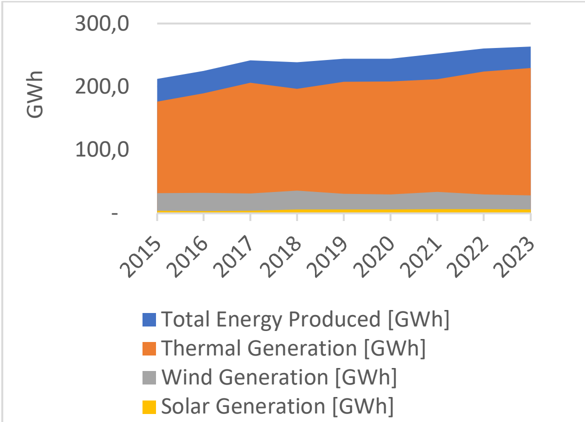

Fig.1. Evolution of energy production on the island of Santiago from 20215 to 2023. Own elaboration based on data from [8].

The graph highlights the strong reliance on thermal generation, which accounts for 87.2% (229.94 GWh) of total electricity production, while wind and solar contribute 10.7% (28.19 GWh) and 2.1% (5.70 GWh), respectively.

H. Energy transportation and distribution

The electricity transmission and distribution system its structured into three voltage levels: High Voltage (60 kV), Medium Voltage (20 kV) and Low Voltage (400/230 V). The network has three main substations operating at 60/20 kV, located in Palmarejo, Achada S. Filipe and Calheta.

I. Challenges and opportunities for the energy matrix

One of the major challenges facing the island is related to electricity losses. The levels of electricity loss are very high, at over 30%, and it should be noted that these are global losses (technical and non-technical). From 2016 to 2023 there was a reduction in losses from 38% to 33.9%, however, the numbers still more than double the average for the other islands, thus requiring a specific and individualized approach. The company ELECTRA SA, now EDEC, has been working to combat losses by implementing the Pilot Project to Combat Losses for the municipality of Praia, based on inspections and validation of consumption billed to customers in that municipality, in order to regularize unbilled consumption, thus reducing the high losses on the island.

Another challenge is related to the high dependence on fossil fuels for electricity generation, with 87.2% of the electricity coming from thermal sources in 2023. The islands' small market size and dispersed energy systems contribute to the complexity and cost of importing and distributing these fuels leading to high electricity cost, with current costs in 2025 standing at around €0.327 for the domestic low voltage tariff and €0.247 for the medium-voltage tariff [7].

The considerable expense associated with the generation of energy from fossil fuels, when considered in conjunction with the islands' abundant wind and solar energy potential, results in renewable energy sources being highly competitive in Cabo Verde [14].

J. Current projects for Santiago Island

In order to achieve the ambitious targets, set out in the Electricity Sector Master Plan 2018-2040, the government of Cape Verde is implementing strategic projects on all the islands, with the aim of surpassing a 50% share of renewable sources in the electricity matrix by 2030.

Santiago Island is the focus of several strategic energy initiatives, among which the following projects stand out:

- Pumped Storage Hydropower Project – 20 MW / 160 MWh;
- Repowering of the Palmarejo Photovoltaic Power Plant – 10 MWp;
- Renewable Energy-Based Storage Service (iSSP) – BESS with 6 MW / 6 MWh;
- Expansion Project of the Independent Power Producer Cabeólica – 13.5 MW (3 turbines of 4.5 MW each).

K. Pumped storage on Santiago Island

The project consists of a 20 MW reversible closed-loop pumped storage power plant, featuring decoupled generation (2 x 10MW) and pumping units (4 x 5MW), a surface penstock, two earth-fill reservoirs (320 000m3), a containerized desalination plant, and an 18 km 60 kV transmission line connected to a substation [9].

From the studies carried out, the locality of Chã de Gonçalves in Ribeira Grande de Santiago was assessed as the best place to implement the project.

5. Analysis of Simulation Results and Recommendations

The results of the LEAP simulation are shown below.

Table III - Energy generation in GWh by source for the different scenarios. Own elaboration based on data from [10].

Power Plant	BAU	MP_ Bas	MP_ EF	MP_ Hi	RES_ Hi	RES_ Mod
Therm Palm.	267,1	191,6	170,4	220,3	197,0	183,3
Therm Sta. Cat.	0,0	0,0	0,0	0,0	0,0	0,0
Wind	29,1	71,2	71,2	71,2	71,2	71,2
Solar	8,3	19,3	19,3	19,3	19,3	19,3
Hydro	-	55,0	55,0	55,0	55,0	55,0
Batteries	-	-	-	-	-	-
Total	304,5	337,2	316,0	365,9	342,5	328,9
% Pen. RES 2030	**12,3**	**43,2**	**46,1**	**39,8**	**42,5**	**44,3**

With regard to electricity generation, as illustrated in Table IV, the BAU (Business as Usual) scenario, where no additional investments in renewable energy are considered, remains heavily reliant on thermal power plants, particularly the Palmarejo facility, to meet the island's electricity demand.

In the Master Plan (MP) scenarios, a greater penetration of renewable energy sources is observed, with wind power playing a leading role, followed by pumped hydro generation and a smaller contribution from solar power. In these scenarios, thermal generation is substantially reduced when compared to the BAU scenario, with the highest thermal share occurring in MP_High, which assumes stronger demand growth.

The RES scenarios exhibit a similar pattern to the MP scenarios, featuring high shares of renewable sources, though associated with more moderate demand growth. Notably, despite maintaining the same generation mix, the MP_Efficiency scenario results in a higher renewable penetration rate. This highlights that combining investments in renewable energy with energy efficiency measures can accelerate the achievement of energy transition targets.

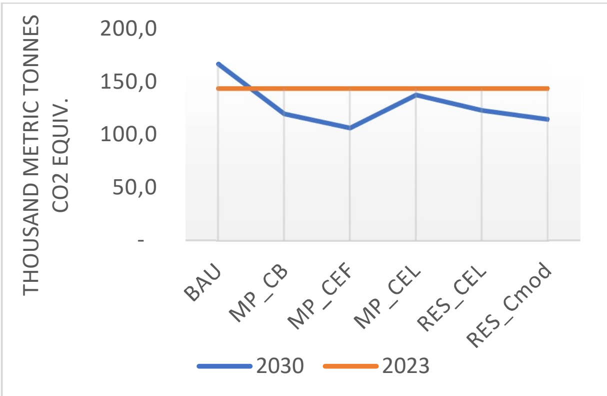

Figure 2 - 100-Year GWP: Direct (At Point of Emissions) [10].

By analyzing the climate impact of greenhouse gas (GHG) emissions based on their 100-year Global Warming Potential (GWP) and considering direct emissions at the point of release, Figure 2 shows that the BAU scenario, where no additional investments in renewables are made results in the highest emissions level by 2030. In contrast, the Master Plan (MP) and RES scenarios demonstrate a significant reduction in emissions, with the MP_Efficiency scenario achieving the lowest levels. The MP_High scenario shows higher emissions compared to MP_Efficiency, due to increased energy demand. Still, both RES_CEL and RES_Cmod remain below BAU levels, highlighting the positive impact of renewable integration even under moderate demand growth conditions.

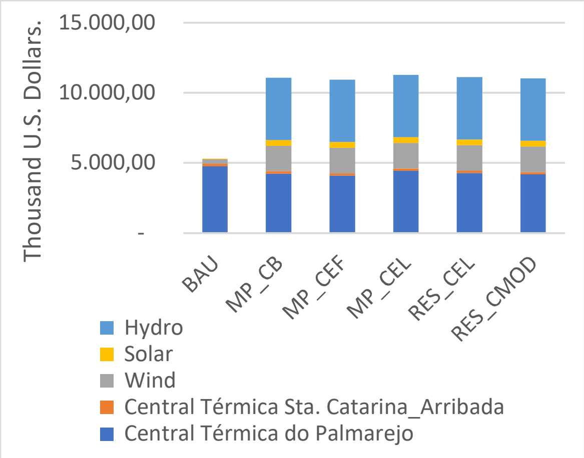

Figure 3 - total energy system costs (Social Costs) [10].

When comparing the total energy system costs (Social Costs) across different planning strategies, an expected increase is observed in scenarios that incorporate investments in renewable energy. This increase is primarily driven by the integration of pumped hydro storage, which accounts for the largest share of additional costs, followed by wind power, with solar energy contributing a relatively smaller portion. At the same time, a progressive reduction in thermal generation costs is evident across the scenarios, reflecting a gradual shift away from fossil fuels. The MP_Efficiency scenario demonstrates the most significant impact, as it combines demand-side improvements with renewable integration. In contrast, the MP_High scenario exhibits a higher total cost than the RES scenarios, mainly due to its assumption of stronger demand growth, despite its high share of renewables.

Conclusions

The proposed pumped storage project for Santiago Island plays a crucial role in enabling higher renewable energy penetration and significantly reducing fossil fuel dependence.
The MP_Efficiency scenario, combining renewable expansion with energy efficiency measures, yields the best overall performance in terms of emissions reduction, lower system costs, and the highest renewable share (46.1%).
Thermal generation remains relevant under high demand growth: Even with renewables and storage, the MP_High scenario shows that higher electricity demand sustains a considerable share of thermal generation.
System costs increase with renewables, but benefits outweigh them: While social costs increase due to investments in Hydro and renewables, the associated environmental, economic, and security-of-supply benefits justify the transition.
LEAP is suitable for energy planning, but has modeling limitations: LEAP's inability to simulate pumped storage in both charge and discharge modes simultaneously, and the constraint that limits battery simulation to optimized scenarios, restricted full cross-scenario comparisons.
Policy goals will guide the choice between MP and RES strategies: Since total system costs are similar across MP and RES scenarios, the final choice will likely depend on national policy priorities and the implementation of efficiency programs.

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