Hydropower plants in arid regions
A dream come true in Cape Verde

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Abstract

Cape Verde islands are famous for many things, from volcanoes and white-sand beaches to the warmth and hospitality of their inhabitants, but definitely not for their (virtually inexistent) rivers. Long drought periods and torrential but scattered rainy events hardly generate more than a couple of days of superficial runoff after the storm. Only three of the populated islands escape the desert area categorization having an average annual rainfall higher than 250 mm, but still fall on the semi-arid range with an average annual rainfall lower than 500 mm.
That's not a friendly setting for a hydro power plant. At least not a conventional one.
GESTO ENERGY developed a Renewable Energy Master Plan for the Cape Verde Government, where many renewable energy sources were studied and, against some odds, hydro wasn't forgotten. As for the development of the abundant, widespread, solar and wind resource in the archipelago, and to allow a deeper penetration of renewable energy, energy storage was required. Hence the idea to develop preliminary design and feasibility studies of pumped storage plants (PSP) on the main power consumption islands.
The dimension of the plants, however, proved to be the next barrier to overcome (after the dryness of the territory), since the peak demand forecast was much lower than the average PSP projects, especially given the scale economies these schemes are associated with. In fact, the two biggest populated islands, Santiago and São Vicente, have less than 300,000 and 100,000 inhabitants, respectively, and, for instance, Santiago actually has an installed capacity of about 30 MW on-peak with an yearly demand of 160 GWh, while the forecast for 2020 estimated the need for 60 MW of on-peak installed capacity and 310 GWh of consumption. Still, PSP were considered as better alternatives for energy storage than other storage technologies currently available.
Aiming to find adequate solutions for the PSP placements, a Geographical Information System based survey model (including technical, hydrological and economical preliminary analysis) was developed and as a result the pumped storage potential was mapped. In this way, the regions that had highest potential were identified and projects were pinpointed. This model, built exclusively by a multidisciplinary team using state-of-the-art software, had already been used on different (continental) geographies with very successful outcome, and was upgraded to the project specificities (islands with steep terrain, narrow volcanic valleys, small river basins) also with extremely good results.
After the preliminary site selection, hydrological studies were carried out in order to access the monthly and yearly runoff. The obtained data was used to determine if the initial filling (and yearly replenishment) on an average rain year was possible. As a consequence of the low required installed powers for the plants (ranging from only 10 to 50 MW) and the high heads available on some parts of the territory, the volume needed for the reservoirs was both compatible with the yearly estimated runoff and steep terrain. However in São Vicente Island (with global mean annual rainfall of around 120 mm) a natural filling reservoir was not reasonable. It was then considered to use raw seawater (or instead desalinated seawater) as "fuel" to pumped storage plants. Preliminary feasibility studies, including site assessment, were thus developed for the selected projects.
All in all, the development of the projects consisted on a big number of technical difficulties which yielded on a blend of innovative and conventional solutions. This article aim is to describe this process, not only from the engineering point of view but also from the economical (and sociological) aspect and impact of the proposed schemes, which revealed itself as fundamental. In fact, the levelized cost of energy (LCOE) calculated and the actual islands system's showed that pumped storage allowed not only a higher weight of RES on the system and also a lower LCOE. As a conclusion, hydropower plants in arid regions can be a valid tool with economical viability.

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1 Synopsis

Cape Verde islands are famous for many things, from volcanoes and white-sand beaches to the warmth and hospitality of their inhabitants, but definitely not for their (virtually inexistent) rivers. Long drought periods and torrential but scattered rainy events hardly generate more than a couple of days of superficial runoff after the storm. Only three of the populated islands escape the desert area categorization having an average annual rainfall higher than 250 mm, but still fall on the semi-arid range with an average annual rainfall lower than 500 mm.
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2 Introduction

GESTO ENERGY developed a Renewable Energy Master Plan for the Cape Verde Government [1], where many renewable energy sources (RES) were studied and, against some odds, hydro wasn't forgotten. As for the development of the abundant, widespread, solar and wind resource in the archipelago, and to allow a deeper penetration of renewable energy, energy storage was required. Hence the idea to develop preliminary design and feasibility studies of pumped storage plants (PSP) on the main power consumption islands.
The dimension of the plants, however, proved to be the next barrier to overcome (after the dryness of the territory), since the peak demand forecast was much lower than the average PSP projects, especially given the scale economies these schemes are associated with. In fact, the two biggest populated islands, Santiago and São Vicente, have less than 300,000 and 100,000 inhabitants, respectively, and, for instance, Santiago actually has an installed capacity of about 30 MW on-peak with an yearly demand of 160 GWh, while the forecast for 2020 estimated the need for 60 MW of on-peak installed capacity and 310 GWh of consumption. Still, PSP were considered as better alternatives for energy storage than other storage technologies currently available.
Aiming to find adequate solutions for the PSP placements, a Geographical Information System based survey model (including technical, hydrological and economical preliminary analysis) was developed and as a result the pumped storage potential was mapped. In this way, the regions that had highest potential were identified and projects were pinpointed. This model, built exclusively by a multidisciplinary team using state-of-the-art software, had already been used on different (continental) geographies with very successful outcome, and was upgraded to the project specificities (islands with steep terrain, narrow volcanic valleys, small river basins) also with extremely good results.
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All in all, the development of the projects consisted on a big number of technical difficulties which yielded on a blend of innovative and conventional solutions. This article aim is to describe this process, not only from the engineering point of view but also from the economical (and sociological) aspect and impact of the proposed schemes, which revealed itself as fundamental. In fact, the levelized cost of energy (LCOE) calculated and the actual islands system's showed that pumped storage allowed not only a higher weight of RES on the system and also a lower LCOE. As a conclusion, hydropower plants in arid regions can be a valid tool with economical viability.

3 Pumped storage potential analysis

Rainfall in Cape Verde is characterized as being heavily seasonal, concentrated in just three months of the year, and registering very low average levels, traducing itself in a low ability to generate enough runoff conditions for operating a conventional hydroelectric power plant.

Still, studies developed during the Cape Verdean Renewable Energy Master Plan have identified several feasible locations for non-conventional hydroelectric plants such as pumped-storage projects. In these schemes, water circulates between two reservoirs (inland based) or between an upper reservoir and the sea (seawater pumped storage), thus allowing water to be pumped from the lower reservoir to the upper reservoir at times of low electricity consumption and high wind production, and then reverse the process at times of peak consumption using the stored water on the upper reservoir to generate electricity. The fact that this works in closed circuit on inland based schemes is even more appropriate given the scarcity of the hydro resource in some situations like the current one.

In addition, the relationship between pumped-storage plants with wind farms allows for the maximum penetration of Renewable Energies in electric systems, given that wind energy generated during hours of low consumption may be stored and consumed at periods of peak demand.

The current pumped storage potential analysis is part of a broader study named "Cape Verde 50% Renewable" [2]. It was the aim of this project to achieve that renewable target through the identification and feasibility analysis of renewable projects in the islands, after their resource mapping, as well as their integration on the grid, respecting technical issues and parameters for system safety. As a strong potential of solar and wind power is available throughout the territory, systems to overcome grid technical restrictions (i.e. storage) need to be available for a greater renewables integration, whether it might be flywheels, batteries, network improvement or pumped storage plants, specially on higher consumption islands such as Santiago and São Vicente, where we focus on this paper.

This analysis in Cape Verde was strongly dependent on the water resources available for the initial filling of one of the reservoirs. Knowing the adverse hydrology of the islands and the upfront computational efforts, the first step was to translate the water resources availability constraint in some simple conditions for geographical analysis.

Besides the well known water scarcity, the first barrier in this study was the inexistence of hydrometric registries. Only a few meteorological stations with rainfall registries were available (although with several missing values) and even lesser stations with climate normals [3]. Turc and water balance method were applied in order to obtain a mean annual runoff approach. These two methods were then compared with a rainfall-runoff transformation expression available from a previous found study [4] of one of the islands of the archipelago (although its scope was different and it was not possible to validate its conclusions).

After mapping the mean annual runoff on each island (Figure 1), all streamlines with drainage basins over 20 km^2 area were identified.

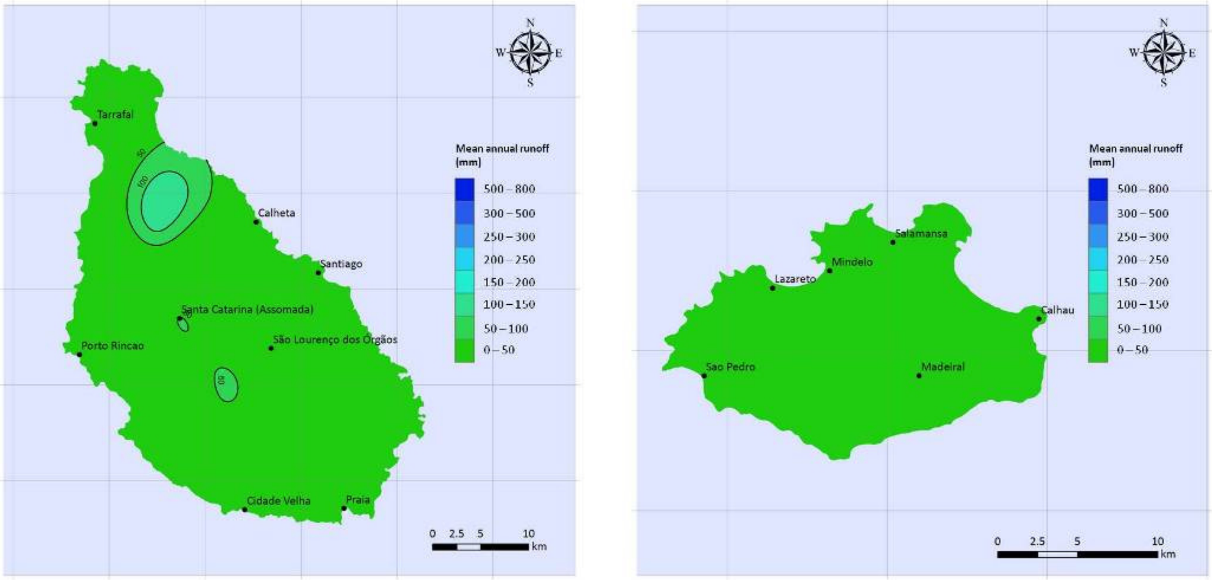
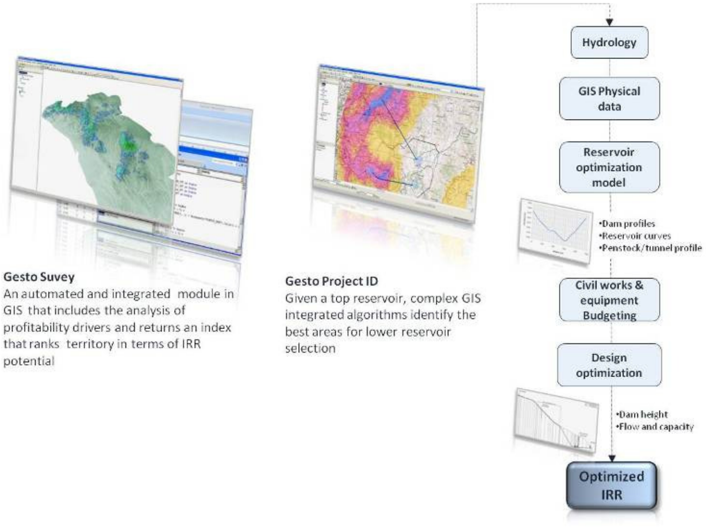


Figure 1 – Mean annual runnof maps using Turc method for Santiago (left) and São Vicente (right) Islands.

A custom built GIS model was applied to these locations to identify the pumped storage potential based on technical, hydrological and economical criteria. This methodology is conceptually described in Figure 2 and the results are presented in Figure 3.



Gesto Suvey
An automated and integrated module in GIS that includes the analysis of profitability drivers and returns an index that ranks territory in terms of IRR potential

Gesto Project ID
Given a top reservoir, complex GIS integrated algorithms identify the best areas for lower reservoir selection

Figure 2 – Gesto Survey Concept

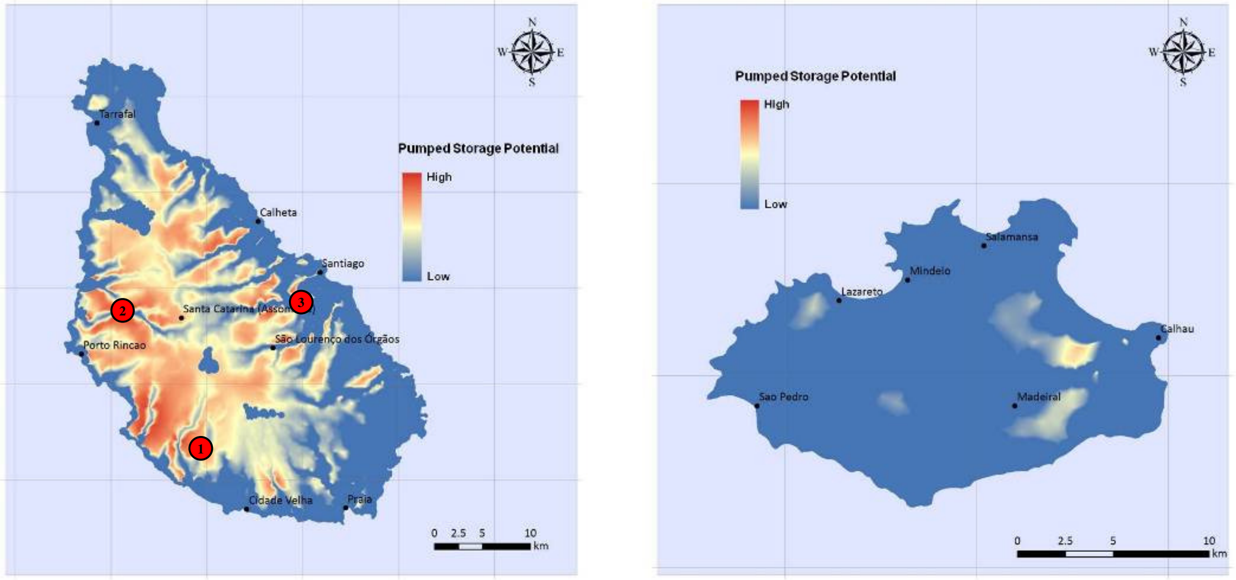


Figure 3 – Pumped storage potential for Santiago (left) and São Vicente (right) Islands.
Identified projects: 1 – Chã Gonçalves, 2 – Mato Sancho, 3 – Ribeira dos Picos

From Figure 3, Santiago island shows higher and most widespread pumped storage potential compared with São Vicente, mainly due to less favourable topographic and hydrological settings. In fact, even a close up to areas with higher potential in São Vicente shows no suitable conditions for the placement of a natural filling lower reservoir and most of the hills are too steep for an upper one.

Therefore, another type of scheme was considered for São Vicente island: seawater pumped storage (SWPS). It consists at the same concept as usual PSP though seawater is used and the lower reservoir is the sea and it has already been used in Okinawa island, Japan, in the Yanbaru SWPS plant [5].

Seawater pumped storage potential for both islands can be observed in Figure 4 (for the sake of comparison, Santiago island was also analysed).

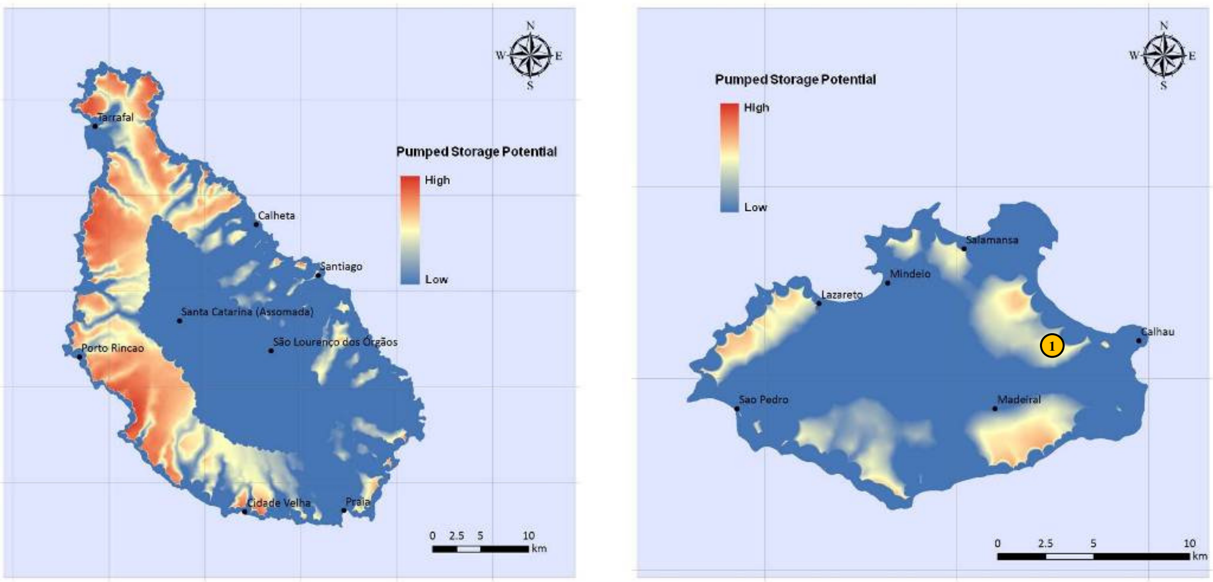


Figure 4 – Seawater pumped storage potential for Santiago (left) and São Vicente (right) islands.
Identified projects: 1 – Monte de Goa (A and B).

4 Project identification and site assessment

4.1 Criteria

After obtaining the pumped storage potential maps, a thorough analysis of the territory was made for project identification, using 1:10 000 scale cartography maps. The aim was to find adequate engineering conditions on higher potential areas for the implementation of the main infrastructures such as reservoirs, dams, penstocks or power stations. Hydrological restraints were also considered, and the following criteria were used:

a) Less than 2% of time over the simulation period with lack of water for the minimum operation volume (8 hours of operation per day);

b) The global mean annual flow on a drainage basin should allow for the initial filling in less than 1 year.

After the identification of possible projects, a pre-design was made followed by a site assessment activity.

4.2 Santiago Island

Several places were found on Santiago island, the majority of which in the Southwest part where one can find torrential type streams in valleys with almost vertical walls. Geotechnical questions arose in some of these places and where therefore integrated on the analysis.

Among the identified and visited sites, the following were considered to gather the best technical features for a pumped storage project: Chã Gonçalves, Mato Sancho and Ribeira dos Picos (Figure 3).

4.3 São Vicente island

Concerning São Vicente, the territory screening for SWPS led to three different locations, two of them with off stream reservoirs. After performing the site assessment with a team of experts the conclusion was that only one of the off stream reservoirs appeared to have technical feasibility: Monte de Goa (Figure 4).

Two seawater pumped storage alternatives where then studied for this location, one using raw sea water (Monte de Goa-A), and the other desalinated sea water instead (Monte de Goa-B).

5 Project development

After the site assessment, the final schemes for development were selected and studied in order to prepare a public tender. The main features of the projects are shown in the following tables, as well as a budgetary estimate. Operation costs were also estimated, and though there are no hydropower facilities currently in Cape Verde, an annual value of around €350 000 per project was considered.

Table 1 – Main features of PSP in Santiago Island.

FEATURES		CHÃ GONÇALVES	MATO SANCHO	RIB DOS PICOS
HIDROLOGY AND ENERGY	Drainage basin (downstream)	24,5 km^2	33,1 km^2	28,3 km^2
	Mean annual runoff	75 mm	53 mm	72 mm
	Max. generation flow	12,2 m^3/s	9,6 m^3/s	11,3 m^3/s
	Gross head	197,4 m	251,2 m	211,1 m
	Net head	191 m	243,5 m	205,7 m
	Installed power	20 000 kW	20 000 kW	20 000 kW
	Mean annual production	43,8 GWh	43,8 GWh	43,8 GWh
UPSTREAM RESERVOIR	Normal water level	316,5	400,0	241,7
	Minimum operation level	305,0	388,0	225,0
	Max. reservoir height	38 m	28 m	30 m
	Spillway design flood (T=500 years)	61,5 m^3/s	23,6 m^3/s	9,8 m^3/s
	Net reservoir volume	0,7 hm^3	0,5 hm^3	0,7 hm^3
DOWNSTREAM RESERVOIR	Normal water level	129,1 m	161,2 m	38,4 m
	Minimum operation level	118,6 m	148,8 m	30,6 m
	Max. reservoir height	32 m	33,7 m	18,3 m
	Spillway design flood (T=500 years)	464 m^3/s	642 m^3/s	540 m^3/s
	Net reservoir volume	1,0 hm^3	1,4 hm^3	1,7 hm^3
	Max. pumping flow	8,8 m^3/s	7 m^3/s	11,3 m^3/s
HYDRAULIC CIRCUIT	Cross section	ϕ 2000	ϕ1800	ϕ 2000
	Length	1105 m	1 290 m	1190 m
POWER HOUSE	Type	underground	underground	underground
	Pump Turbines	2 x Francis reversible vertical axis	2 x Francis reversible vertical axis	2 x Francis reversible vertical axis
	Axis elevation	88,6 m	118,8 m	-3,0 m
TRANSMISSION LINE	Voltage	60 kV	60 kV	60 kV
	Length	15 km	8 km	3 km
TOTAL COST ESTIMATE		39,5 M€	41 M€	39 M€

Table 2 – Main features of SWPS in São Vicente Island.

FEATURES		MONTE GOA - A	MONTE GOA - B
HIDROLOGY AND ENERGY	Drainage basin (downstream)	-	-
	Mean annual runoff	-	-
	Gross head	444 m	409,3 m
	Net head	427,3 m	401 m
	Installed power	15 000 kW	15 000 kW
	Mean annual production	32,9 GWh	32,9 GWh
UPSTREAM RESERVOIR	Normal water level	444 m	444,5 m
	Minimum operation level	432,5 m	432,5 m
	Max. reservoir height	11,5 m	12 m
	Net reservoir volume	183 800 m^3	194 700 m^3
DOWNSTREAM RESERVOIR / INTAKE	Type	onshore water intake	reservoir
	Normal water level	0	35
	Minimum operation level	-10	24
	Max. reservoir height	-	11
	Net reservoir volume	-	221 000 m^3

FEATURES		MONTE GOA - A	MONTE GOA - B
HYDRAULIC CIRCUIT	Cross section	ϕ 1200	ϕ1400
	Length	1900 m	1 870 m
POWER HOUSE	Type	underground	underground
	Turbines	2 x Francis reversible vertical axis	2 x Francis reversible vertical axis
	Axis elevation	-40,0 m	-16 m
	Max. generation flow	4,2 m^3/s	4,4 m^3/s
	Max. pumping flow	3,0 m^3/s	3,2 m^3/s
	Net head	427,3 m	401 m
TRANSMISSION LINE	Voltage	60 kV	60 kV
	Length	15 km	10,58 km
TOTAL COST ESTIMATE		32 M€	37,4 M€

6 Grid integration and system cost analysis

Pumped storage should not be seen as an energy resource, but a time shifting platform for the exceeding energy from periods were it was meant to be wasted to others where it can be properly used. Thereafter, in an island system, pumped storage should not be seen as an additional energy source, but as an ancillary service for the grid, representing an investment to benefit the use and grid connection of RES. The integration analysis and economic feasibility then depends on the set goals. In this paper we propose the analysis of two scenarios to find the role of pumped storage in Cape Verde Renewable Action Plan:

- The economical scenario
- The 50% RES scenario

The achieved renewable energy shares are presented in Figure 5.

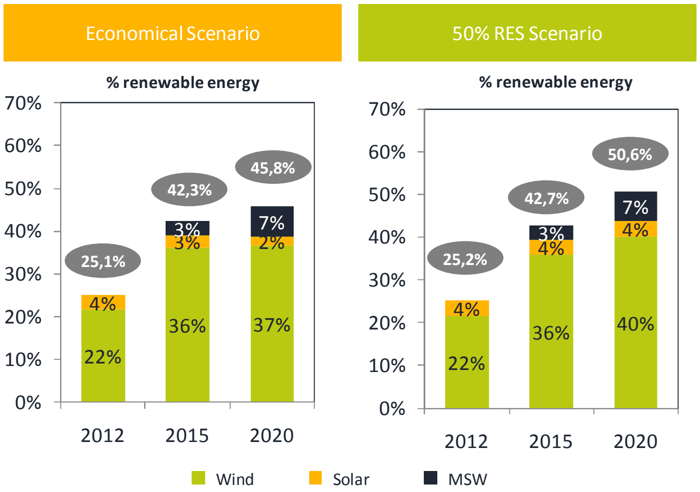


Figure 5 – Renewable energy scenarios in Cape Verde: years 2012, 2015 and 2020.

The economical scenario was drawn to achieve the LCOE on the energy mix. The 50% RES is the most effective scenario in the set of islands that conducted to 50% of renewable and diversified energy sources in the grid.

To achieve 50% of RES, the most effective set of projects require the generation of more than 55% of RES in Santiago Island and 57% of RES in São Vicente Island, the two main islands in the archipelago.

Several prospective LCOE portfolios were simulated. On Figure 6 we present the increase of RES on the system and the decrease in the generation cost of electricity for Santiago Island, identifying the rate of RES that obliges to overcome technical restrictions on the grid and the related cost per each consumed MWh.

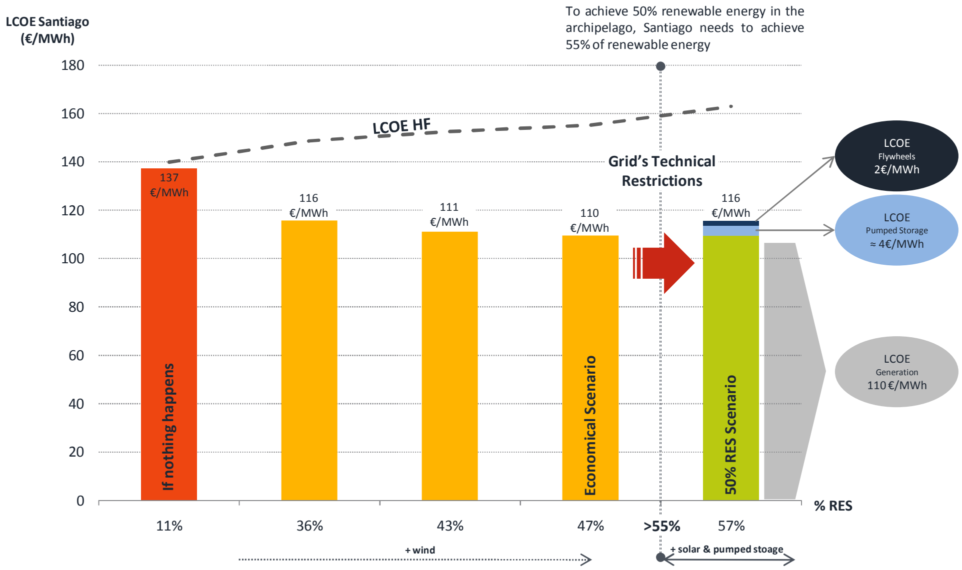


Figure 6 – Santiago's Island LCOE for increasing renewable energy sources on the grid.

It can also been noted that the Heavy Fuel LCOE increases with RES, which is easily understood as the thermal units remain in back up consumption (i.e. with less production hours and lower efficiencies).

When it comes to São Vicente Island, the capital and operational expenditures of the pumped storage solution were higher but the wind resource was stronger, thus leading to a cheaper wasted renewable energy. To achieve the 50% RES scenario, only the grid integration of flywheels is needed for system safety. Nevertheless, it should be stated that compared to the *status quo*, where heavy fuel generation prevails, pumped storage stills is a fairly competitive option.

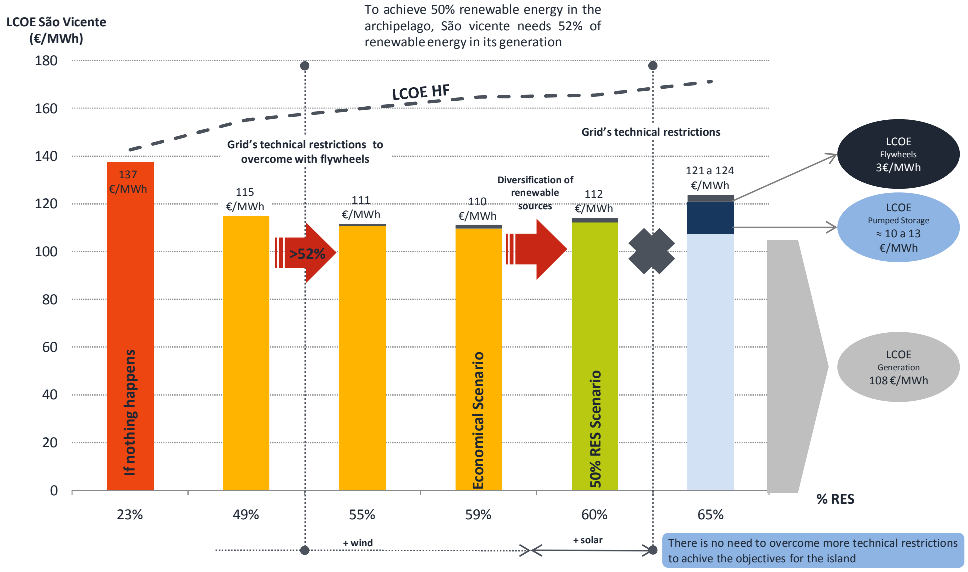
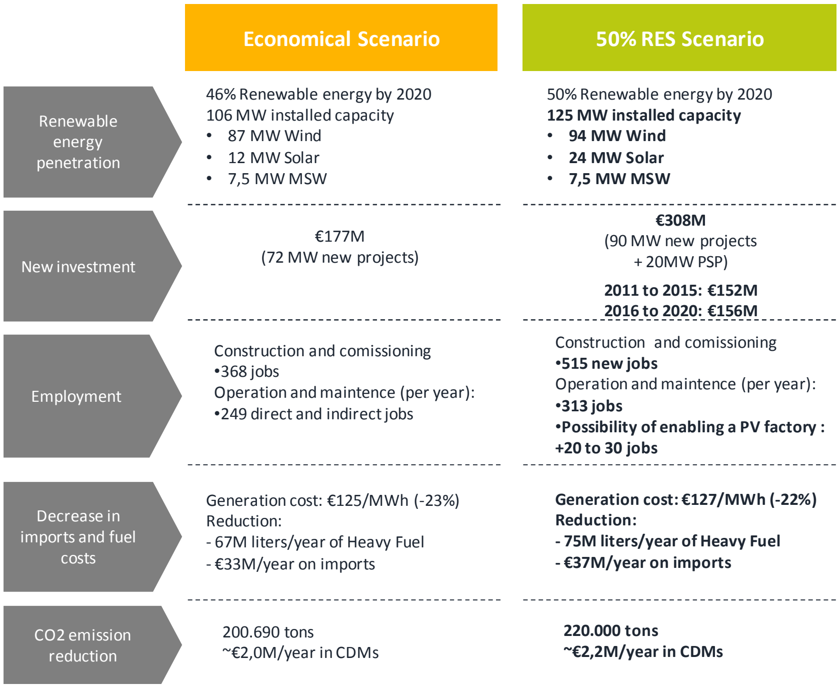


Figure 7 – São Vicente's Island LCOE for increasing renewable energy sources on the grid.

As a final remark, in Figure 8 is presented the socio-economical impacts of both scenarios. It can be noted that the difference when considering pumped storage and correspondent additional renewable energy generation costs from the Economical Scenario (125€/MWh) to the 50% Renewables Scenario (127€/MWh) is only 1,5%.

It is our conclusion, then, that hydropower plants in arid regions can be a valid tool with economical viability and should therefore be considered on Energy Planning.



	Economical Scenario	50% RES Scenario
Renewable energy penetration	46% Renewable energy by 2020 106 MW installed capacity • 87 MW Wind • 12 MW Solar • 7,5 MW MSW	50% Renewable energy by 2020 **125 MW installed capacity** • **94 MW Wind** • **24 MW Solar** • **7,5 MW MSW**
New investment	€177M (72 MW new projects)	**€308M** (90 MW new projects + 20MW PSP) **2011 to 2015: €152M** **2016 to 2020: €156M**
Employment	Construction and comissioning •368 jobs Operation and maintence (per year): •249 direct and indirect jobs	Construction and comissioning **•515 new jobs** Operation and maintence (per year): **•313 jobs** **•Possibility of enabling a PV factory :** **+20 to 30 jobs**
Decrease in imports and fuel costs	Generation cost: €125/MWh (-23%) Reduction: - 67M liters/year of Heavy Fuel - €33M/year on imports	**Generation cost: €127/MWh (-22%)** **Reduction:** **- 75M liters/year of Heavy Fuel** **- €37M/year on imports**
CO2 emission reduction	200.690 tons ~€2,0M/year in CDMs	**220.000 tons** **~€2,2M/year in CDMs**

CDM - Clean Development Mechanism

Figure 8 – Economical scenario and 50% RES scenario results comparison.

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