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Integrated Energy and Water Planning on an Arid Island, Case of S. Vicente, Cape Verde

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Abstract

In general, most islands depend for energy supply mainly on the imports of fossil fuels. Arid islands also depend on water desalination, again often depending on fossil fuel imports. On the other hand, most of the islands present a considerable potential in renewable energies. Several initiatives have been carried out in some islands, mostly in Europe, for the use of this potential in the production of electricity and fresh water. Due to high energy costs, the islands present an excellent experimentation platform for the introduction of new energy technologies. Some islands are trying to become renewable islands, to satisfy their energy and water demand mainly or entirely from indigenous and renewable sources, thus increasing the security of supply and employment opportunities, without necessarily increasing the costs. Islands that have renewable energy sources, such as hydro or geothermal energy, can easily integrate them into the power system, but those with mainly intermittent renewable energy sources (wind, solar) have to tackle the need of energy storage. Here, advanced energy planning must be used to combine different intermittent and regular sources in order to match electricity demand and assure security of supply. The main objective of this paper is to analyse different scenarios for increasing the penetration of renewable energies in the energy system of S. Vicente Island in Cape Verde, using the H2RES model, a tool designed to simulate the integration of renewable sources in the energy systems of island or other isolated locations. This island is extremely dry, and fresh water is provided to the population by sea water desalination, a very high energy intensive process. The electricity supply system is based on diesel and wind (still low penetration). S. Vicente has significant wind resources that are not fully used because of its intermittent nature. In this paper, an integrated approach is used to analyse the electricity and water supply systems in order to increase their efficiency. In the centre of the island there is a 774 meters high mountain. The present study incorporates the possibility of using reversible hydro as a storage technique to increase the penetration of renewable energy sources, using desalinated sea water.

Keywords: Renewable Energy, Islands, H2RES Model, Reversible Hydro, Desalination..

1. Energy Planning in Islands

With respect to energy production, most islands depend mainly on the importation of fossil fuels, with all the economical problems that causes mainly due to the high costs of transporting the fuels. In most cases there is no way to connect the islands to the energy production network, making it difficult to implement solutions that reduce the environmental costs, such as atmospheric pollution and greenhouse gas emissions.

Generally, tourism is one of the most important economic activities in islands, being the energy and water consumption in this sector very high, mainly in high seasons, when the cooling and water needs are very high. Usually in these locations, the energy production systems and the air conditioned systems present a very low efficiency, while the availability and storage of fresh water is deficient. Tourism is equally an activity that produces a great amount of waste, which is a big problem for a closed ecosystem that is an island. [1]

Integrate renewable energy sources in energy systems of small islands presents several advantages, because their high technological cost is compensated by the high cost of the conventional sources of energy due to the small dimension of the energy systems and because of a very expensive security of supply. In order to achieve sustainable development it is very important the integration of renewable energy sources for the production of electricity, together with suitable policies and regulations regarding rational use of energy. The electricity production technologies are rarely adapted to

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the conditions of isolated areas and can seriously damage the vulnerable ecosystems and natural habitats. It is important to develop energy supply infrastructure taking into consideration the seasonal variations caused by the tourist activity, without destroying the local environmental or produce too many emissions.

Other environmental local problems related with fossil fuels are the pollution and contamination of the water and the land by the oil products and residues due to their leak during transport, handling and storage.

Many of these islands present numerous sources of renewable energy that could represent a large fraction of the total energy distribution. However, the intermittent nature of most of these sources (wind and solar) as well as the small energy systems of islands introduce barriers to their penetration, like the struggle to match the demand with the supply and the problems related with the integration in the network.

Renewable energy resources can be separated into two categories in terms of availability: the ones that are constant and continuous, that have an intrinsic storage capacity, such as biofuels, hydro, geothermal; and the ones that are variable and intermittent, that do not own this capacity. This category is subdivided in resources that vary periodically and cyclically, such as solar and tidal energy, and resources that vary randomly, such as wind and wave energy.

The integration of intermittent renewable energy sources in energy systems requires the development of energy storage technologies, energy management technologies and a bigger sophistication of these systems.

2. H2RES Model

The H2RES model (Figure 1) simulates the integration of renewable sources and hydrogen in the energy systems of islands or other isolated locations. It is based on hourly time series analysis of demand (water, electricity, hydrogen, heat), storage (reversible hydro, batteries, hydrogen, heat) and resources (wind speed, solar radiation, precipitation). The main purpose of this model is energy planning of islands and isolated regions which operate as stand-alone systems, but it can also serve as a planning tool for single wind, hydro or solar power producer connected to a central power system. Throughout time, the model is evolving and several new modules have been developed such as wave, biomass, solar heat and desalination.

Several papers describe H_2RES model with details of its operation [1], [2], [3], [4]. The version that has been used for calculating Portugal case study has been updated with a wave module.

The main characteristic of H_2RES model is that it uses technical data of equipment, hourly meteorological data for intermittent sources and according to description in [3] energy balancing is regulated by equations.

Wind velocity, solar radiation and precipitation data obtained from the nearest meteorological station are used in the H_2RES model. The wind module uses the wind velocity data at 10 metres height, adjusts them to the wind turbines hub level and, for a given choice of wind turbines, converts the velocities into the output.

The load module, based on a given criteria for the maximum acceptable renewable electricity in the power system, puts a part or all of wind and solar output into the system and discards the rest of the renewable output. The hourly load of the power system is obtained from the local utility.

The excess renewable electricity is then stored either as hydrogen, pumped water or electricity in batteries. The energy that is stored can be retrieved later, and supplied to the system as electricity. The rest is covered from diesel blocks.

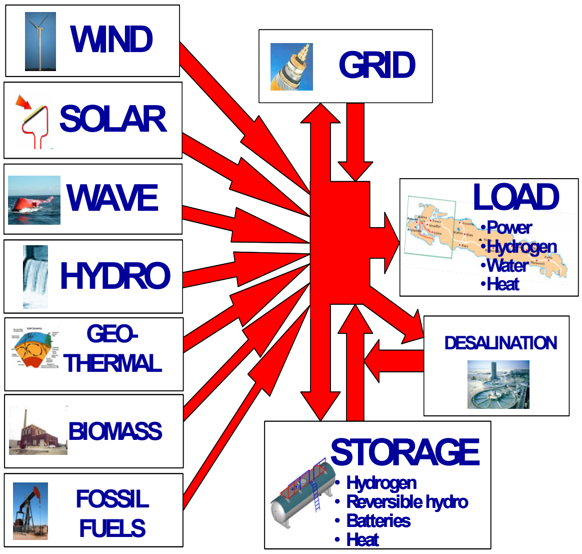

Figure 1. H_2RES computer model v2.8.

The desalination module uses the electricity produced from excess wind to supply the desalination units, that produce drinkable water and put it on the lower reservoir, this reservoir is then used to supply the population. This module takes into account the total capacity of these units (m^3 of water produced per hour) and their electricity consumption per unit of water produced. At each hour, the desalination module verifies if the lower reservoir has at least one day of water demand, if it does not, and if the user allows this option, the desalination units are supplied with electricity from the fossil fuel blocks.

Figure 2. S. Vicente Island [16]

3. The Island of S. Vicente

S. Vicente is the second most crowed island, with about 74,031 inhabitants in 2005 [15], in the Archipelago of Cape Verde, which is composed of ten islands and is situated at about 450 kilometres of the West African coast, in the Atlantic Ocean.

This island has about 228 square kilometres of area and is semi-plane, having just one high point – Mont Verde – located at 774 meters of altitude.

The island is extremely dry, the fresh water is provided to the population by sea water desalination. There are five desalination units in the island, three use reverse osmosis, each one with a capacity of 1,000 m^3 per day, one uses mechanical vapour compression, with a capacity of 1,200 m^3 per day, and the other uses multiple effect distillation, with a 2,400 m^3 per day capacity. A sixth unit was installed in 2007, with a capacity of 1,200 m^3 per day, this unit also uses reverse osmosis.

Regarding electricity production, there are three types of technologies installed in the island: diesel production, wind production and thermal (cogeneration) production. However, this last one is in a deactivation process.

In the following table the electrical power installed in São Vicente by the end of 2005, is stated.

Table 1. Installed capacity in São Vicente by the end of 2005 [17]

Plant	Thermal plant powered by fossil fuel (kW)	Wind (kW)	Cogeneration (kW)
Matiota	11,680	-	780
Lazareto	7,440	-	-
Selada Flamengo	-	1,050	-
Total	19,120	1,050	780

The hourly electricity load of the island in 2005 is depicted in the graphic of the next figure.

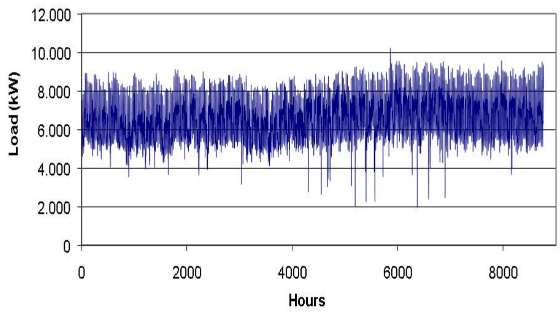

Figure 3. Hourly electricity load of São Vicente in 2005.

In 2005, the electricity production in São Vicente was about 57.173.807 kWh, and the peak power was 10.200 kW.

The electricity demand is relatively stable throughout the year, as there are not large climate variations.

The island has important wind resources. The hourly wind speed of 2005 was collected from the local meteorological station. In this year, the average wind speed was about 7.9 meters per second.

4. Scenarios

In order to apply the H_2RES model to the Island of São Vicente, five scenarios were elaborated, having all as base the year of 2005.

The first scenario is the Business As Usual (BAU), as it only considers the projects that are already foreseen for the island. Regarding the evolution of the demand, a study made by the Research Group on Energy and Sustainable Development was considered. This study, elaborated in the scope of the National Energy Plan for Cape Verde [18], considered the forecast of the evolution of the Gross Domestic Product and of the resident population in order to forecast the growth in the consumption of electricity in the different islands of Cape Verde (Table 2).

Table 2. Forecast of the annual demand growth of electricity in the island of S. Vicente [18]

Period	Annual growth
2006 – 2009	7.92%
2010 – 2014	6.40%
2015 – 2019	4.20%
2020 – 2024	3.36%
2025 – 2030	3.08%

Nowadays, wind energy can be considered economic viable in islands, as long as it does not surpasses a certain limit of penetration. The base scenario is then defined delimiting 30% of the hourly renewable energy penetration, which means that only 30% of the load of one hour can be covered by electricity generated from wind.

According to ELECTRA, the local utility, it is foreseen the installation of more 6,800 kW of wind turbines in the island, and most probably they will be eight turbines of 850 kW each.

The second scenario considers the supply of electricity produced from wind to the desalination plants already installed on the island. This scenario considers the construction of a 30,000 m^3 reservoir, at low altitude, where the water that comes out of the desalination plant will be stored before being supplied to the population. It is believed that S. Vicente has several reservoirs of smaller dimension spread through the island. When the excess electricity from wind is not enough to desalinate all the water needed, the diesel blocks are used to supply the remaining required electricity.

The succeeding scenario maximizes the desalination from wind electricity. Scenario four considers the storage of the excess wind production through pumping of the desalinated water. This scenario contemplates the construction of a dam or water reservoir with about 50,000 m^3 at 500 meters of altitude. Thus, the wind park would supply electricity to a desalination plant and to a pumping station that puts desalinated water in the upper reservoir. When it is necessary to supply water and electricity to the population, the water is turbinated from the upper to the lower reservoir (Figure 4).

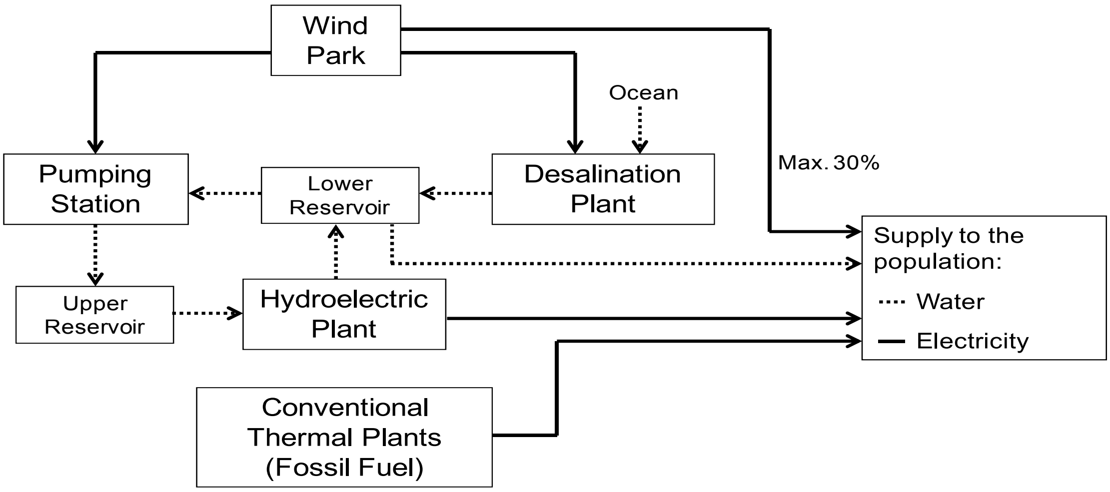

Figure 4. Scheme of scenario 4.

5. Results

Scenario 1 – BAU

Regarding the first scenario, the electricity production in São Vicente from 2005 to 2030 is stated in the following figure. It was considered the above mentioned installation of 6,800 kW of wind energy by 2010 and the addition of diesel blocks to satisfy the growth of the demand.

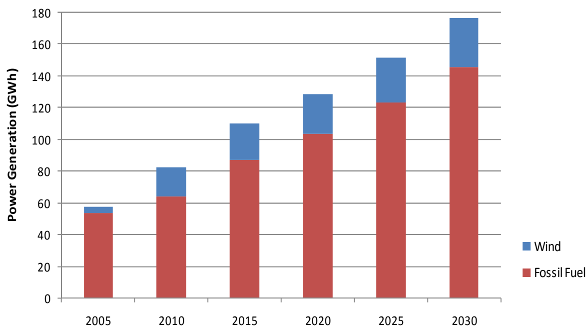

Figure 5. Power production in S. Vicente from 2005 to 2030, for the BAU scenario

It is clear that the penetration of the wind electricity production increases from 2005 to 2010, due to the installation of the new wind turbines, it increases from 6 to 22%. However, from then on, it decreases, as no more wind turbines are added to satisfy the demand growth, only diesel blocks.

In this scenario, the electricity produced from wind has a large amount that is rejected, especially in 2010, with 45% of wind electricity rejected. As the years go by, this rejection decreases due to the growth of demand and the non installation of more wind turbines, in 2030 it reaches about 9%.

Scenario 2 – Desalination from wind

An excellent way to decrease the wind electricity rejected is to supply the desalination plant with this excess electricity. However, when modelling this scenario, the first conclusion reached was that the wind produced was not enough to desalinate all the water needed. Hence, it was considered the supply of electricity from the diesel blocks, when the electricity from wind was not enough.

The evolution of the water demand was considered to be the same as the electricity demand. These calculations considered desalination units already installed in the island, and the addition of desalination units to satisfy the growth of the demand over the years.

The load considered in the first scenario included the electricity needed to desalinate water and to supply the population, thus, in this scenario, there was the need to subtract the electricity used for desalination. According to [17], 14% of the electricity produced in S. Vicente in 2005 was to supply the desalination units. Hence, and because hourly consumption of water does not vary very much, as there are not large water storages, this percentage was deducted from the hourly load.

Regarding the supply of electricity from wind, although there is a 30% limit for the supply of the population, there is no limit for the supply to the desalination units. A reservoir of 30,000 m^3 was considered, in order to have water storage with a capacity of about five days of the demand of 2010.

In this scenario, the penetration of wind electricity reaches higher levels than in the previous one. The proportion of wind electricity rejected in this scenario is much lower, reaching its higher value, about 23%, in 2010.

Scenario 3 – Maximize the desalination from wind

In order to maximize the desalination from wind, the influence of the wind turbines installed, of the capacity of the desalination units and of the capacity of the lower reservoir was studied. Although the most important factor was the power of the wind turbines installed, the increase of this value leads to an increase of the wind electricity rejected. To avoid this, the capacity of the desalination units needs also to increase. Hence, the number of wind

turbines and desalination units was optimised so that yearly wind desalination was maximised while keeping the rejected wind electricity close to 10% [5].
With the installation of wind turbines throughout the year, it is possible to increase the penetration of wind electricity and keep it more or less constant along the years. The production of desalinated water, by electricity from wind and from the fossil fuel blocks is stated in the next figure.

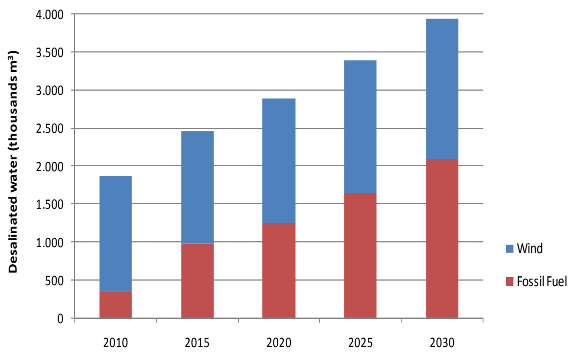

Figure 6. Production of desalinated water in S. Vicente from 2005 to 2030, for scenario 3.

The fraction of desalinated water produced from wind reaches 82% in 2010, and although it decreases slightly in the following years, it never goes below 47%.

Scenario 4 – Reversible hydro and desalination

This scenario considers the pumping of desalinated water to the upper reservoir, and its later supply to the population producing also electricity from de hydroelectric plant. It was considered that the hydroelectric plant is used for peak shaving, about 80% of the weekly peak. The capacity load factor of the hydro turbines was kept above 20%.

Scenario 5 – Maximize RES penetration

In order to maximize the RES penetration in the energy supply system of the island of S. Vicente, the installation of more wind turbines is crucial. However, when modelling this scenario, there was the need to, when testing all the possibilities; verify if none of the reservoirs overflowed. This is a very important issue, especially in an island as dry as S. Vicente. Thus, the two restrictive factors in maximizing RES penetration were the prevention of overflow of the reservoirs and the control of the intermittent rejected. The electricity production along the years for this scenario is indicated in figure 7.
In 2010, the hydroelectric plant produces about 3% of the total electricity produced in the island, 35% is produced from wind, totalizing 38% of RES electricity.
100% hourly intermittent energy penetration scenarios
These scenarios allow the hourly intermittent energy penetration rate to reach 100%. The number of wind turbines was optimised so that yearly wind penetration was maximised while keeping the rejected wind electricity close to 30%. [5]

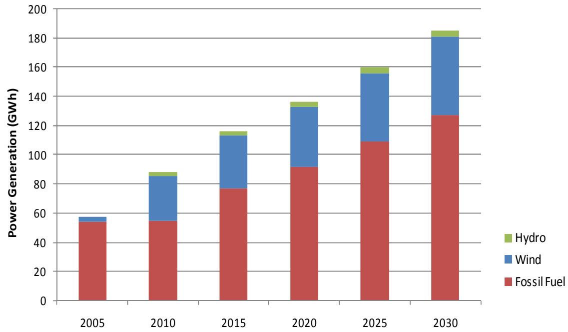

Figure 7. Power production in S. Vicente from 2005 to 2030, for scenario 5.

Unsurprisingly, in these scenarios the penetration of wind electricity is much higher. In scenario 7, where the desalination from wind is maximized, this value reaches 88% in 2010 and around 70% in the following years. The electricity produced from wind is about 70%.
In scenario 9, where the RES penetration is maximized, the hydroelectric plant produces about 7% of the total electricity produced in the island in 2010, 69% is produced from wind, totalizing 76% of RES electricity.
Comparison between scenarios
In the following figure the power generated to supply the island of S. Vicente in the year 2020 in stated for four different scenarios.
It is clear that in scenario 9 the renewable energy sources have a higher fraction. In this scenario, the avoided electricity production from fossil fuel reaches 62.2 GWh. Using an overall electricity emission factor of diesel generators of 0.75 kgCO_2 per converted kWh [10], the avoided greenhouse gas emissions are 46,671 tonCO_2.
Considering the 30% of hourly penetration limit (scenario 5), the avoided electricity production from fossil fuel reaches 11.8 GWh which corresponds to 8,860 tonCO_2 of avoided greenhouse gas emissions.
The next figure illustrates the amount of desalinated water produced from wind and from fossil fuel in the different scenarios
In scenarios 3 and 4, the desalination from wind is always balanced with the desalination from fossil fuel. In 2020, these scenarios present a fraction of desalinated water produced from wind of 53% and 56% respectively. Scenarios 7 and 9 have a higher fraction of desalinated water produced from wind, 75% and 59% respectively.

6. Conclusions and Future Developments

This paper analyses the way to increase the penetration of renewable energy sources in the island of S. Vicente, in Cape Verde. Based on existing load data and meteorological data, several scenarios were built and modelled using the H_2RES model. The scenarios considered wind, reversible hydro and desalination technologies.
The maximization of desalination from wind resulted in fractions of desalinated water produced from wind of about 80% in 2010 for most of the scenarios, but from the following years, this value decreased to around 50%.

The maximization of renewable energy sources in this supply system resulted in a penetration of about 38% of these technologies, with a major fraction from wind and a much lower contribution from hydroelectricity.

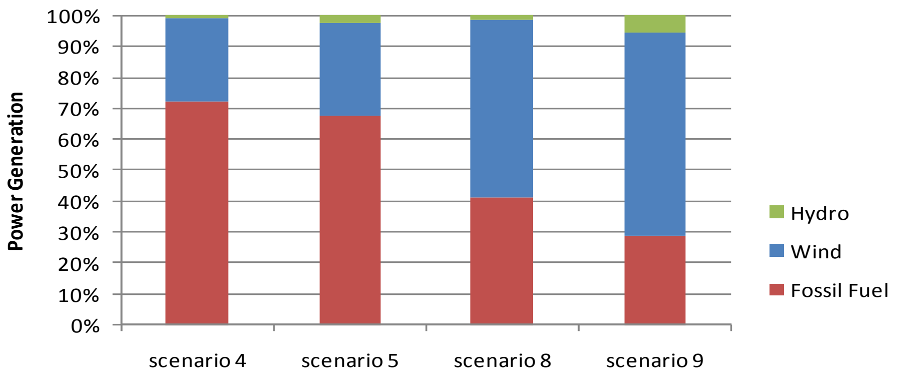

Figure 8. Power production in S. Vicente in 2020, for four scenarios

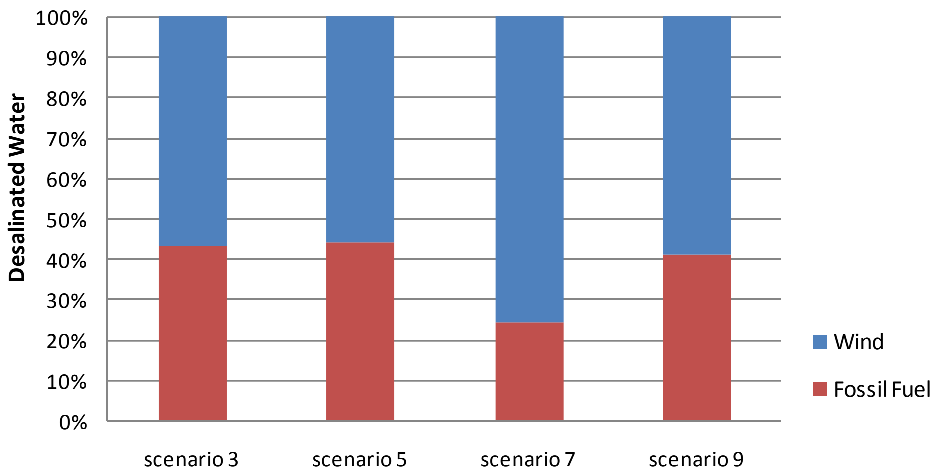

Figure 9. Desalinated water produced in S. Vicente in 2020, for four different scenarios

If an hourly intermittent energy penetration rate of 100% is allowed, the percentage of desalinated water produced from wind can reach 81-88% in 2010 for the scenarios 9 and 6, but for the following years, this value reduced to 60-68%. Regarding the maximization of renewable energy sources, the penetration of these technologies in this supply system reached 76%, with 69% of wind and 7% of hydroelectricity.

These scenarios need to be analysed in environmental and financial terms. There is also the need to examine the sites were the reservoirs can be built and the wind turbines installed, for instance to determine if it is possible to install reservoirs with this dimension, and what is the effect of the local environment.

In order to improve the input data of the first scenario and the baseline year, an update of the forecast of the demand growth will be carried out, together with an assessment of the demand in water and energy of the tourist projects foreseen for the island.

Later work will be done on modelling the fog occurrence in Mont Verde, and consider its collection to the upper reservoir.

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