

# INTEGRATION OF RENEWABLE ENERGY SOURCES AND HYDROGEN STORAGE IN THE AZORES ARCHIPELAGO

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**Abstract:** This paper analyses some technological scenarios to increase the penetration of RE sources in Corvo and Graciosa islands. The H2RES model, specially developed for this type of work was used to simulate several scenarios integrating RE sources and hydrogen storage or batteries. Based on existing load and meteorological data, several scenarios are developed and fully modelled for those two islands, in order to increase security of supply and reduce pollution. The scenarios modelled were envisaging the following technologies: wind, solar PV, and batteries and hydrogen storage.

The present study can be the base for a complete approach of a 100% RES island. The Azores archipelago has been very conscious on environmental concerns and the reduction of pollutants and dependence on imported fuels, mainly by the use of renewable energies. For an appropriate integration scheme, strategies should be developed for a regional high-level energy production with RE systems, taking into account local characteristics. They must specifically reflect the needs and behaviour of consumer daily and seasonal patterns, taking into account the economic development and human needs that have an impact on energy consumption. In Corvo island the main drive for RE integration is security of supply and in Graciosa is fuel dependency.

**Keywords:** Energy in Islands, Renewable energy integration, fuel cell, hydrogen.

## 1. Introduction

Energy supply to remote areas face economic and environmental problems due to the high costs of transporting fuel, the emissions caused and the difficulties of interconnection to the main electricity grid. Integrating renewable energy sources in small islands energy systems present several advantages, since their higher technological cost is offset by the high cost of conventional energy sources caused by the small size of the energy systems and expensive security of supply. Integration of renewable energy for power production, along with appropriate policies and regulations on the rational use of energy, is very important for achieving sustainable development. Power generation technologies are seldom adapted to isolated areas conditions and can seriously damage vulnerable ecosystems and natural habitats. It is important that the

energy supply infrastructure be developed to accommodate seasonable variations caused by tourism activity, without destroying the local environment or producing excessive emissions.

Islands produce only a small fraction of global greenhouse gas emissions. However, islands are among the most vulnerable regions of the world to climate change effects such as sea level rise and extreme weather conditions. Most islands are 100% dependent on fossil fuels, yet they are especially suited to utilize combination of efficient renewable energy (RE) integration and energy efficiency technologies.

The Commission's Action: 100 Communities: towards 100% of RES Supply is part of the Campaign for Take-Off and the Community Strategy and Action Plan on Renewable Energy Sources (RES), adopted in 1998 and aimed to double the part of RES in overall gross inland energy consumption from 6% to 12% by 2010.

Islands are the main candidates to become communities with 100% of RES supply by their specific environment, isolated by definition and with an enormous potential of RES while usually energy dependent of imported fossil fuels.

European Union policy and instruments, including legislation and programmes, have been gradually re-oriented and focused in order to address the particular needs of such Communities and to meet objectives agreed at European level concerning climate change and security of supply.

The main message of the Commission's White Paper "An energy policy for the European Union", is that the potential for a technologically based, innovative energy sector contributing to sustainable development is within our reach.

While energy supply conditions are stable and robust at present, there are underlying changes bringing new alignments into the energy equation. Oil is cheaper than previously predicted and the discovery of additional reserves is technically feasible. The growth of nuclear power has lost its momentum in Europe.

Renewable energy technologies (RET) have moved towards mainstream acceptance. However, the growing recognition of the environmental impacts of energy production and use has added a new dimension to energy policy, which has crucial importance in how the energy sector develops in the principle of sustainable development [1].

Intermittent renewable technologies for electricity, such as wind; photovoltaic and solar thermal, can make major contributions in power generation especially for the smaller decentralized end of the electricity market as their production availability is relative low (in the range of 25 to 60 %) when compared to fossil fuels (usually 80 to 90 %). State of the art geothermal technologies and large and small-scale hydro offer the prospect of cheap power generation while advanced biomass

technologies such as gasification and large-scale combustion for power generation can provide modern energy services and help stimulate rural development.

Moreover, it is clear that if the targets of the White Paper on RET are to be achieved, the current policies have to be completely replaced by new ones which would pave the way for RET to compete on equal basis with the other sources of energy and be promoted effectively. The 12 % target of the Green Paper on RET is within reach [2].

This can be shown in Figure 1 that presents the renewable energy penetration by technology for the fifteen EU Member States.

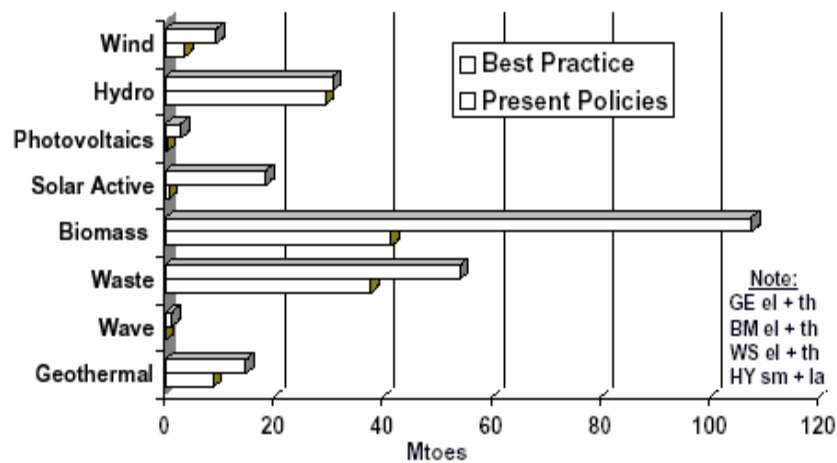


Figure: 1 Renewable energy penetration in 2020 by technology [3]

Figure 1 illustrates that only two of the policy scenarios from the TERES II study have been taken into consideration for reasons of clarity. The data for geothermal, biomass and waste include also the potential for heat production while the data for hydro include small and large applications. These data are impressive since they show that for most of the technologies their penetration will more than double if the best practice policies are adopted.

Establishing a general guideline for the integration of renewable energy sources (RES) in any European island energy system is a complex task. Resources vary in a large amount, as well as needs and island characteristics. Obviously, the approach for powering with RES an island with a population of 500,000 is completely different to supply energy for a much smaller one of 10,000 inhabitants. Therefore, to cover the widest possible range of applications, it was decided to study the

case of two small islands, Corvo and Graciosa in the Azores archipelago.

With respect to energy production and distribution, most of the European islands heavily depend on fuel importation. Some are trying to become renewable islands, satisfying their energy demand entirely from indigenous and renewable sources. Since most available renewable energy sources are intermittent, energy storage or some combination of several sources has to be devised, in order to reduce dependence on fuel delivery.

Islands have been very conscious on environmental concerns and the reduction of GHG and other pollutants emission and the dependence on imported fuels, mainly by the use of renewable energies, such as a photovoltaic, solar thermal power plant, wind farms, small hydro power plant, and geothermal or ocean wave power plants.

In order to meet energy demands, some island governments may have to reduce their investments in infrastructure, industrial, fishery and agricultural development, and allocate more financial resources to their energy sectors [4]. Local and trans-boundary pollutants from energy-related activities degrade environmental quality in many urban and some rural regions.

The supply of electricity to rural and outer islands is very limited. Many people have no access to electricity supply via fossil fuels. People internally migrate from rural areas and outer islands to major urban areas in search of better employment opportunities, education and other social services [5]. This is the case of Corvo Island, where population is decreasing.

Other local environmental issues related to fossil fuel supply are water and land contamination and pollution by oil products and wastes through leakage during shipping handling and storage. There is a great concern in Corvo Island over the incidence of small-scale oil spills during loading, which occur adjacent to storage facilities. Besides, it is frequent to have oil shortages in this island, due to bad weather conditions rendering difficult the oil carrier to reach the loading platform.

The renewable energy sources have advantage on small islands, since their higher cost is offset by the high cost of conventional energy sources, due to small energy systems and expensive security of supply. Renewable sources in the conditions of small isolated energy systems can offer commercially acceptable solutions, especially when combined with conventional fuels.

The large scale installation of renewable energy generation plants, together with the appropriate policies and regulations on energy savings and rational use of energy, is important for sustainable development, as pollutants are not produced like when using conventional fuels.

The trend of the RE market and operators is the increase on the RE installed power. This will enable a more efficient use of areas with the required natural resources.

The most important technical challenge is the assessment on regulation, integration and storage solutions, which are surely bottlenecks for the large-scale implementation of renewables. Several approaches should be considered, including for example the use of fuel cells, hydrogen solutions, batteries, hydro-power storage, thermal storage, among other.

## **2. Islands with high Utilization of Renewable Energy Sources**

Islands have a strong interest in changing energy patterns for instance by demonstrating new sustainable ways of satisfying energy needs [6]. Another reason for the more positive attitude found on islands is the near total absence of fossil fuel resources.

Most islands' main resources are the oceans, the population and geography (tourism). Next to none have fossil fuel resources.

The study from the Forum for Energy and Development (FED) shows that there are islands that use actually modern renewable energy technologies on a large-scale.

The following conclusions can be drawn from the FED's overview:

a) Around the world few islands have already decided to become Renewable Energy Islands (REI) in the short or medium term. A REI is an island 100% supplied with renewable energy sources. Samsøe (Denmark), Pellworm (Germany), Aeroe (Denmark), Gotland (Sweden), El Hierro (Spain), Dominica and St. Lucia have an explicit target of becoming 100% self-sufficient from renewable energy sources.

b) Around the world a few islands have already some of the characteristics of a REI. La Desirade (France), Fiji, Samsøe, Pellworm and Reunion (France) are currently producing more than 50% of their electricity from renewable energy sources. 21% of the islands in the FED's overview that utilize renewables for electricity generation produce between 25-50% of their electricity from renewable energy sources.

Nearly 70% of the islands in the overview that utilize renewables for electricity generation produce between 0.7-25% of their electricity from renewable energy sources. A few islands are using solar water heaters on a very large scale (Barbados and Cyprus).

c) Islands with very big utilization of renewable energy for electricity production are mainly utilizing hydropower.

In the FED's overview more than 50% of the islands with more than 25% of the electricity generated from renewable energy resource use hydropower.

Of the islands producing more than 25% of electricity from wind power all (but one) are connected by sea cable to another electricity grid.

d) Wind power is by far the most used renewable energy resource in electricity production.

Over 50% of the islands in the FED's overview that have utilized renewables for electricity generation have used wind power. More than 25% of the islands in the FED's overview utilizing renewables for electricity generation use hydropower, while about 10% use biomass for the same purpose.

e) Most islands are situated in the North Atlantic Ocean.

Just over 40% of the islands in the FED's overview using renewables are situated in the North Atlantic Ocean. Around 12- 14% of the islands in the FED's overview using renewables are situated in the North Pacific Ocean, South Pacific Ocean and Caribbean Sea respectively.

### **3. Availability of Renewable Energy and Management of Hydrogen Storage**

Renewable energy resources can be separated in two categories in terms of availability: those which are constant and continuous, possessing an intrinsic storage capacity, like bio-fuels, hydro, geothermal and ocean-thermal, and those which are variable and intermittent, lacking any such capacity. This category is subdivided into those resources that vary periodically or cyclically, like solar and tidal, and those that vary rather more randomly, such as wind and wave.

Resources, renewable or not, which have no innate storage mechanism require that energy be otherwise available to "buffer" the variability/intermittence in order that electricity supply can be maintained, i.e. guaranteed at any point in time [7].

In absence of any such buffer, a demand side management technique – which seeks to reschedule demands in order to "level" the load, thereby better matching a constant supply - is not feasible. The emphasis of any management function is thus supply-side management, i.e. the maximization of resource utilization when the availability permits.

The use of energy storage allows electricity generated during periods of high-availability/low-demand to be converted (to a storable energy-form) and stored for subsequent re-supply during periods of low availability/high-demand. This combination of supply-side management

and demand-side management both maximizes utilization of the variable/intermittent resource and minimizes reliance upon “conventional” plant, being in the limit, the 100% renewable scenario.

In the absence of storage, the variable/intermittent resource has to be matched by dedicated conventional capacity in order that supplies can be guaranteed.

Examples of energy storage systems include batteries, pumped storage, flywheels, super conducting-magnets, pressurised-fluid systems and a set of an electrolyser and a fuel cell [8]. Of these, only pumped storage and battery systems are commonly employed, the others are in various stages of research and development. The principal components of an electrolyser-fuel cell system are an electrolyser, a means of gas storage (oxygen and hydrogen) and means of recovering the electrolytic gases to electricity, the fuel cell.

In this paper two solutions for energy storage are presented and analysed, the use of electrolyser and fuel cells for hydrogen and electricity production, respectively, and a set of photovoltaic cells and batteries for electricity production and storage. Both storage systems are not yet commercially available but, at the present pace of research and development, one can predict that the commercial availability will be achieved soon.

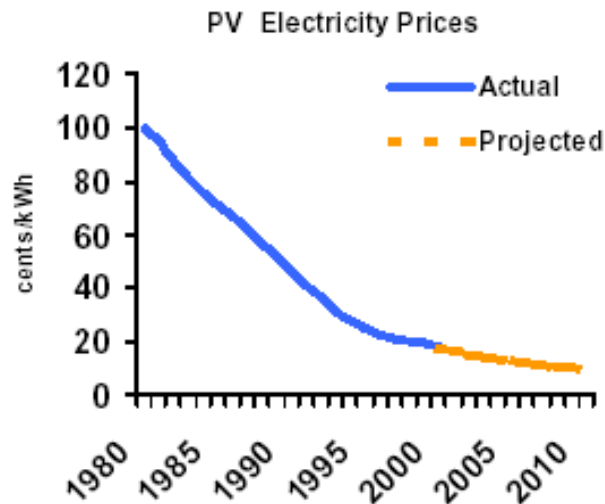


Figure 2: Actual and projected PV electricity prices. [9]

At present, and particularly in small-scale supply systems, most electricity storage systems are battery based, although some small-scale

pumping storage systems exist. The use of batteries reflects the status and availability of the technology.

Batteries, although their short-term efficiencies are comparatively high (~75% inclusive of input/output losses, etc.), are subject to self-discharge, and so their efficiency decreases with increasing storage period [10].

#### 4. Background of the Archipelago



The Azores archipelago is located in the Atlantic Ocean, between the 36 and 43° of latitude North, 25 and 31° longitude West. Distant of about 1,500 km from the Portugal coast and about 4,023 km from the East coast of the United States.

The islands have a land surface of 3,800 km<sup>2</sup>, and its highest point is located in the island of Pico (Peak) — therefore its name — rising to an altitude of 2,351 m, the highest mountain in Portugal. It is not rare for its summit to be covered in snow during the winter months.

The Azores archipelago is composed of nine islands, which are distributed in three groups: the eastern group, consisting on the islands of Sao Miguel and Santa Maria; the Central group formed by the islands of Terceira, Graciosa, São Jorge, Pico and Faial; and the Western group is composed of the islands of Flores and Corvo. Several islets surround certain islands, some of them serving as a refuge to various species of marine birds.

The islands are positioned on a basaltic platform that extends down 1,524 m into the ocean floor. The climate is temperate, registering temperatures of 15 °C in the month of February, increasing progressively to about 23 °C in the month of August.

The ocean Gulf current passes relatively close, and maintains the Atlantic waters at comfortable temperatures, between 17 and 23 °C. The air humidity is about 76%. This conditions of temperature and humidity,



are joined by the microclimates that are produced by the presence of "caldeiras" (small craters of boiling water) and "fumarolas" (steaming earth chimneys) at high temperatures, which originate a luxurious beauty of certain locales, one of the best known is the "Vale das Furnas" (Valley of pits), in the island of São Miguel.

The total electric energy consumption in Azores was 421 GWh in 1999 and 456 GWh in 2000. 20.5% of the energy produced in the archipelago during 1999 was produced with clean energy sources; the rest was generated mainly in fuel oil and gasoil plants.

These figures clarify the pressure that is being made on the environment. Due to the unique pristine environment of the Azores environment, it is essential that a higher effort be made to reduce this impact, increasing the penetration rates of RE technologies. Figure 3 shows the Azores energy production and consumption in 1999.

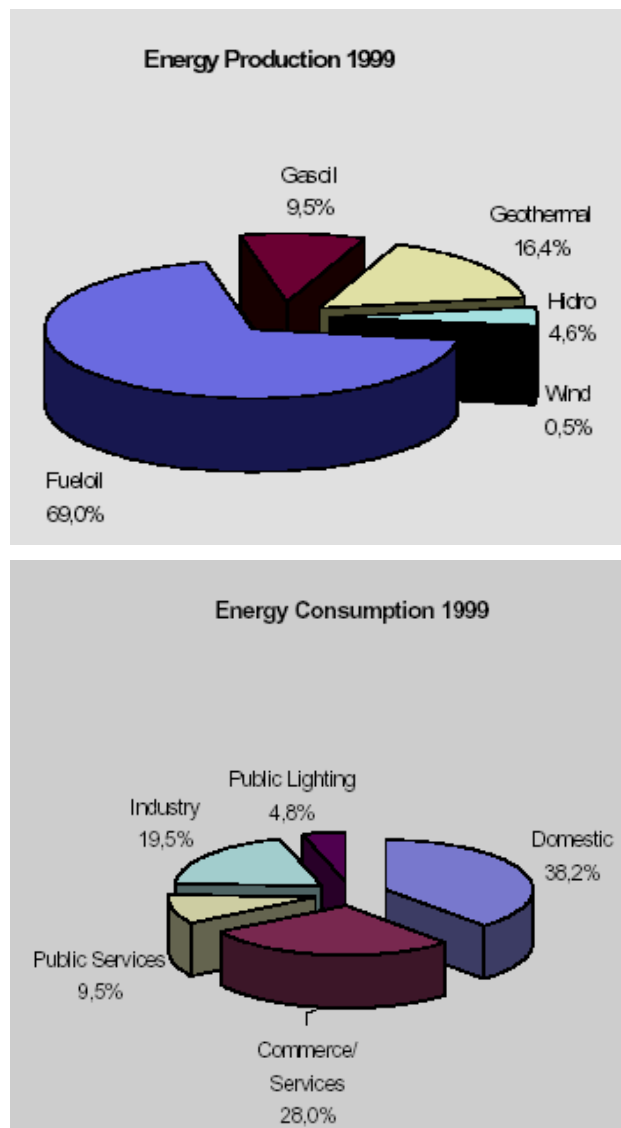


Figure 3: Energy production and consumption in 1999 [11]

## 5. The Islands of Corvo and Graciosa

The island of Corvo has a length of 6.5 km, a width of 3 km and a total area of 17.13 km<sup>2</sup>, this oval-shaped island is the smallest in the archipelago of the Azores. Composed of the outcropping of a volcanic cone, it has a maximum altitude of 718 meters. It is situated at 31° 05' West longitude and 39° 40' North Latitude. The population is around 300 people and all the energy is supplied by diesel engine.



Figure 4: Map of Corvo Island

The energy data for the island of Corvo is shown in Table [12].

Table 1: Energy data for the island of Corvo.

Year	Consumption (GWh)	Production (GWh)
2000	0.678	0.763
2001	0.723	0.809

The island of Graciosa has an area of 61.66 km<sup>2</sup>, with a length of 12.5 km and a maximum width of 8.5 km. Low-lying and flat in the northern and north-eastern areas, it rises gradually until the altitude of 398 meters is reached at Pico Timão, located at the centre.



Figure 5: Map of Graciosa Island.

The island is situated at 28° 05 West longitude and 39° 05 North latitude. The population is around 5000 and diesel and wind generators supply the energy. The energy data for the island of Graciosa is shown in table 2 [12].

Table 2: Energy data for the island of Graciosa

Year	Consumption (GWh)	Production (GWh)
2000	7.188	8.016
2001	7.684	8.573

## 6. RES With Variable Output

The main difference for variable energy output RES integration is that storage is a must, and it should be able to supply peak energy demands for an estimated period when the resource is scarce. Moreover, in a first step, RE production with asynchronous output conditions should not exceed 20 to 30% of system peak demand [13,14,15], as a higher penetration will disrupt the grid power-supply making it unstable. Above these values significant operational changes may be needed to ensure that frequency and voltage tolerances are not exceeded [16] and if the target is a system with 100% renewable energy penetration storage becomes imperative.

The variation of the power output has an impact on both operation of the power system and on the power quality of the system and this impact increases as the level of penetration increases [17].

Table 3 shows the factors influencing absorption of renewables [16].

Table 3. Factors influencing absorption of renewable

Impact	Threshold	Mitigation options
<ul style="list-style-type: none"> <li>- Change in renewable generation output</li> <li>- Unpredictable instantaneous reduction in generation output</li> <li>- Unpredictable short-notice reduction output</li> </ul>	<ul style="list-style-type: none"> <li>- Generation subject to fluctuation &gt;20% of peak demand</li> <li>- Potential instantaneous loss &gt;2% of peak demand</li> <li>- Potential loss &gt;3% of peak demand in an hour</li> </ul>	<ul style="list-style-type: none"> <li>- Purchase additional controllable output</li> <li>- Purchase additional frequency control measures</li> <li>- Purchase additional reserve services</li> </ul>

In medium size isolated systems an increase in the penetration of RE with asynchronous output and improvement in their efficiency and security as a whole can be achieved by the introduction of advanced control systems. These advanced control systems would provide economic operation advice and satisfy security restrictions during operation. An advanced control system should include load/renewable power forecasting, on-line economic dispatch for operational planning and on-line security assessment coupled to a friendly interface.

According to [18], when the target is a system 100% renewable, the implementation of such system should be phased, and the following steps are considered:

1. No regulation: RE power lower than 20 to 30% of power of operating conventional groups
2. With regulation (both RE and conventional) and RE requiring external excitation (wind energy with asynchronous generator): RE power up to twice the power of operating conventional groups
3. With regulation (both RE and conventional) and RE not requiring external excitation (wind energy with synchronous generator): same RE of power operating conventional groups
4. With RE Park disconnection: RE power not limited
5. With conventional plant disconnection and RE not requiring external excitation: RE power up to five times the power of operating conventional groups
6. 100% RES: no conventional plants + synchronous control + storage.

In this paper the increase on penetration of RE sources was tested on Corvo and Graciosa islands power systems and the H2RES model next described was used to simulate several scenarios integrating RE sources and Hydrogen storage or batteries.

## **7. General Description of the H<sub>2</sub>RES Model**

The H<sub>2</sub>RES model used in the two case studies here present was developed in Microsoft Excel sheets and allows the simulation of energy generation for a small energy system (1-100MW) such as an island or an isolated region when introduced the hourly data for electricity consumption, wind velocity and global solar radiation for the considered location together with the characteristics of the technology to be installed. It is prepared to accept energy systems that combine wind power, photovoltaic (PV), diesel and energy storage under the form of

hydrogen or in batteries for future retrieval in the first case with the help of a fuel cell. Although it was not done yet, it is also possible to modify the model to accept water storage and energy retrieval through the installation of a mini-hydric power plant.

Four modules compose the model: wind, solar, load and storage.

The wind module uses the mean hourly velocity available from the nearest meteorological station, usually measured at 10m, it adjusts this values to the hub height of the wind turbines considered and uses its efficiency curve to calculate the output in energy.

The solar module has as input information the hourly global radiation on the horizontal surface; these values are then converted to an optimum tilted surface having in consideration the geographical location of the place considered and finally the output is determined for the particular PV panel choice.

The load module puts a part or all of wind and/or solar output into the system depending on the hourly load and on the percentage of renewable energy with variable output defined as acceptable and if applicable determines the excess renewable electricity, this energy is then either stored or dumped.

As mentioned before, the excess of renewable electricity can be stored as hydrogen or in batteries. The storage module allows the two options and calculates the electricity retrieval to the system whenever a lack of renewable electricity occurs. The rest of the demand is covered from Diesel blocks. A thorough description of the model and each of its modules is presented in [19].

For the two islands studied, the hourly mean wind velocity and global solar radiation was adopted from two other nearby island as the ones here considered do not have meteorological stations. The meteorological data used in Corvo scenaria was from Flores Island and for Graciosa the data adopted belonged to Terceira Island [20].

## **8. Considered Scenaria**

For each of the two islands, several scenaria were considered, some consider low RE penetration with or without storage while others envisage 100% renewables.

### **Graciosa Island**

The simulated scenaria were the following:

**MG.1** - An already planned enlargement by the local utility (EDA) of the wind park up to 530kW with an imposed wind energy limit of 30% of the “instant” load in the system.

**MG.2** - The same conditions as in MG.1 + 2,000 m<sup>2</sup> of installed PV.

**MG.3** - 30% RE contribution: wind power 1,200 kW, no restrains on the percentage of renewable energy with variable output placed into the grid.

**MG.4** – 45% RE contribution to the annual consumption: 1,200 kW of wind power + 20,000 m<sup>2</sup> of PV, in the same conditions as in MG.3

**MG.5** – 100% RE penetration: 9,000 kW of wind power + electrolyser with 8,900 kW power + 74 days hydrogen storage + fuel cell 1,600 kW power, allowing no renewable energy excess in the system.

**MG.6** - 100% RE penetration: 5,000 kW of wind power + 80,000 m<sup>2</sup> of PV + electrolyser with 8,500 kW power + 31 days hydrogen storage + fuel cell 1,750 kW power, allowing no renewable energy excess in the system.

### **Corvo Island**

**MC.1** – 60% RE contribution to the annual consumption: 6,500 m<sup>2</sup> PV + 300 kW battery power, no restrains on the percentage of renewable energy with variable output placed into the grid.

**MC.2** – 80% RE contribution: 10,000 m<sup>2</sup> PV + 400 kW battery power, in the same conditions as MC.1.

**MC.3** - 100% RE penetration: 25,000 m<sup>2</sup> PV + 650 kW battery power

**MC.4** - 50% RE contribution: 200 kW of wind power, no restrains on the percentage of renewable energy with variable output placed into the grid.

**MC.5** - 30% RE contribution: 3,000 m<sup>2</sup> PV, in the same conditions as MC.4.

## **9. Analysis of the Results**

In this section general comments on the considered scenaria will be made and the results obtained for the most interesting cases will be analysed.

## Results for Graciosa Island

In Graciosa case study, the scenaria built allow the comparison between installing wind power only or wind power plus PV panels, for three different situations: RE limited to 30% of the load, relatively high RE penetration and 100% RE penetration.

This comparison is summarised for annual values in tables 4.1, 4.2 and 4.3:

Table 4.1. System parameters comparison for MG.1 and MG.2

	wind	solar	Renewable	electrolyser	storage vessel	H2 storage	fuel cell
	KW	kW	KW	KW	kWh	days	kW
<b>MG.1</b>	530	0	530	-	-	-	-
<b>MG.2</b>	530	170	700	-	-	-	-

	wind output	solar output	ren. Output	ren. Taken	excess	electrolyser	Dump
	GWh	GWh	GWh	GWh	GWh	GWh	GWh
<b>MG.1</b>	1.3	0	1.3	1.1	0.2	-	0.2
<b>MG.2</b>	1.3	0.2	1.5	1.2	0.3	-	0.3

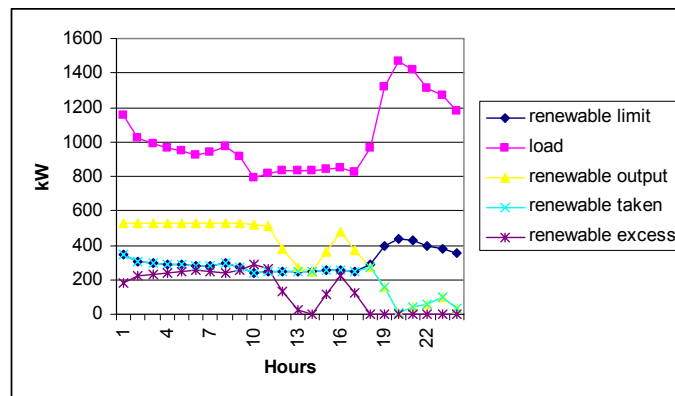


Figure 6. MG.1 simulation, January 1.

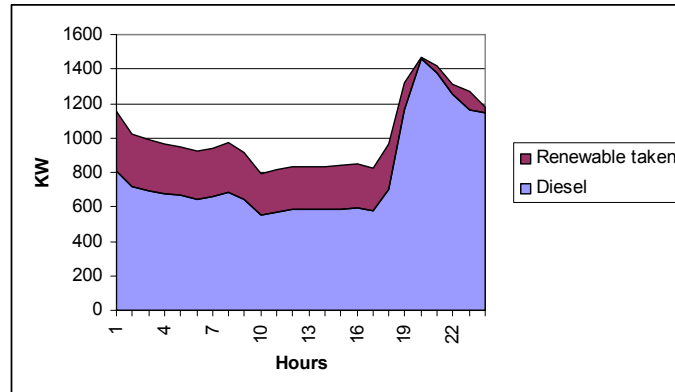


Figure 7. MG.1 simulation, January 1, the source of electricity taken by the power system.

Table 4.2. System parameters comparison for MG.3 and MG.4

	wind	solar	Renewable	Electrolyser	storage vessel	H2 storage	fuel cell
	KW	kW	KW	KW	kWh	Days	kW
MG.3	1200	-	1200	-	-	-	-
MG.4	1200	1700	2900	-	-	-	-
	wind output	solar output	ren. Output	ren. Taken	excess	electrolyser	Dump
	GWh	GWh	GWh	GWh	GWh	GWh	GWh
MG.3	2.8	-	2.8	2.7	0.1	-	0.1
MG.4	2.8	1.7	4.5	4.0	0.5	-	0.5

From the analysis of the two previous tables, it can be concluded that the solar power contribution is only substantial when the PV panels are installed in large scale. When compared to wind, the same PV power installed would generate less than half of the energy obtained through wind.

The annual renewable contributions to the consumption for simulations MG.1 and MG.2 are respectively 12% and 13%. As already mentioned, MG.3 has a contribution of 30% and MG.4 gives 45% RE penetration.

The relatively high values of renewable energy excess present in the first two simulations are a consequence of the imposed 30% RE limit, to avoid the problems that incur from RE sources with variable output. The relative losses (RE excess) obtained in the simulations including solar power are higher than those obtained in the ones that consider only wind.



The fact that PV technology is currently very expensive together with the results obtained in these simulations lead to the conclusion that in these cases the system considering only wind is a better option.

Table 4.3. System parameters comparison for MG.5 and MG.6

	wind	solar	Renewable	electrolyser	storage vessel	H2 storage	fuel cell
	KW	kW	KW	KW	GWh	days	kW
<b>MG.5</b>	9000	-	9000	8900	2.8	74	1600
<b>MG.6</b>	5000	6800	11800	8500	1.3	31	1750
	wind output	solar output	ren. Output	ren. taken	excess	electrolyser	Dump
	GWh	GWh	GWh	GWh	GWh	GWh	GWh
<b>MG.5</b>	22.4	-	22.4	5.8	16.6	16.6	0
<b>MG.6</b>	11.8	6.9	18.7	6.3	12.4	12.4	0
	H2 stored	H2 retrieved	fuel cell	electrolyser	fuel cell	peak serving time	
	GWh	GWh	GWh	h	H	%	
<b>MG.5</b>	8.3	6.5	3.2	1870	2050	45%	
<b>MG.6</b>	6.2	5.5	2.8	1458	1585	40%	

In simulation MG.6 the contributions for annual energy consumption are: solar 32 %, wind 55% and the fuel cell 13%. In MG.5 the contributions are: wind 87% and fuel cell 13%.

When comparing these two simulations the most noticeable differences consist on the fact that in MG.6 the installed power is significantly higher than in MG.5 and storage in MG.5 is more than twice the size of storage in MG.6.

The storage size difference is a consequence of the PV power installed, as the higher solar outputs tend to coincide more frequently with peak demand hours than in wind output case.

The choice between the two scenarios depends mainly on comparing the costs that incur from large scale PV installation with the hydrogen storage prices and the space available to install one or the other. In a very generalist and rough analysis it seems that 80,000 m<sup>2</sup> of PV are unsuitable for the island dimensions and will be very costly, so again the option of using only wind appears to be more suitable.

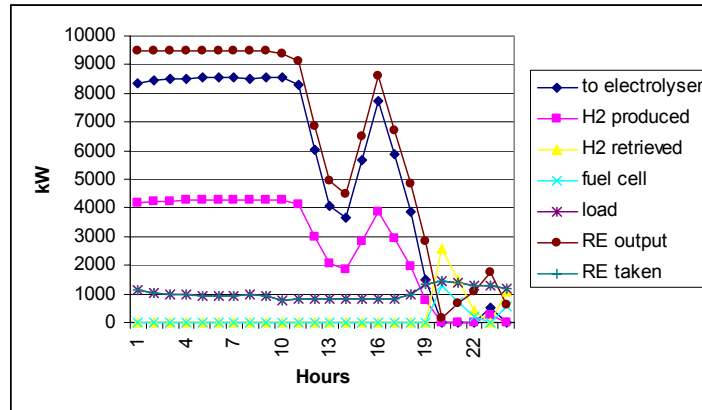


Figure 8. MG.5 simulation, January 1, for this particular day more hydrogen is stored than retrieved.

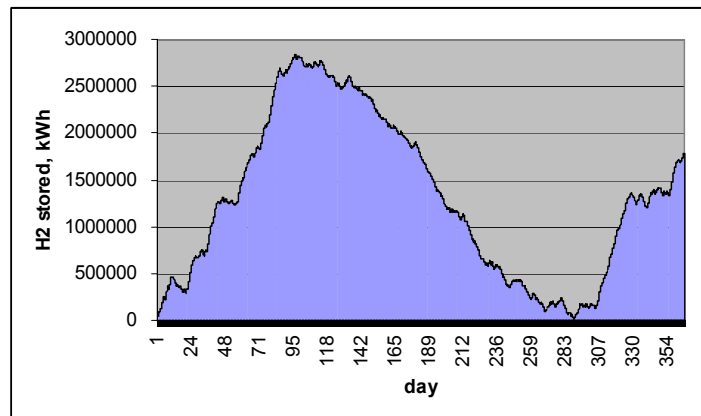


Figure 9. MG.5 simulation, hydrogen stored during the year.

In these two scenarios (MG4 and MG6) the electrolyser power was set to be equal to the maximum annual difference between renewable energy output and load and the fuel cell power corresponds to the absolute value of the minimum obtained for the same difference. The two systems were dimensioned in such way not to have renewable energy excess, so the storage size corresponds to the maximum annual value of the calculated stored hydrogen.

## Results for Corvo Island

The first three scenarios considered for Corvo Island include all PV as RE source and storage in batteries. Excess of energy generated for the

three simulations can be used to pump water or dumped. The other two scenaria foresee only the use of PV or wind with relatively high renewable penetration and do not consider any kind of storage

The comparison will be established between the scenaria that consider storage and the other two.

A synthesis of the results obtain for simulations MC.1, MC.2 and MC.3 is present in table 5.1:

*Table 5.1. System parameters comparison for MC.1, MC.2 and MC.3*

	wind	solar	Renewable	batteries	storage capacity	storage	Battery retrieval
	KW	kW	KW	KW	MWh	Days	kW
MC.1	-	553	553	300	3	0.8	150
MC.2	-	850	850	400	6	1.7	150
MC.3	-	2125	2125	650	27	6.6	170
	wind output	solar output	ren. Output	ren. taken	excess	To storage	Dump
	MWh	MWh	MWh	MWh	MWh	MWh	MWh
MC.1	-	562	562	314	248	245	3
MC.2	-	864	864	350	514	411	103
MC.3	-	2160	2160	403	1758	560	1198
	Total stored	Total retrieved	Electricity produced	storing	Retrieving	peak serving time	
	MWh	MWh	MWh	h	h	%	
MC.1	220	220	198	817	1323		29
MC.2	370	370	333	1027	2219		46
MC.3	504	504	453	861	2667		59

The 100% RE scenarium (MC.3) when compared to scenarium MC.2, that has 80% penetration, presents almost triple value of PV power installed and the energy to be dumped in this scenarium reaches 56% of the renewable output. This two factors lead to the conclusion that for the small system of Corvo Island the studied 100% RE scenarium is unfeasible.

Even though the energy to be dumped in MC.2 is relatively much higher than in MC.1, the difference on the PV and battery power installed is quite low for more than 20% RE penetration.

The next graphs illustrate the results obtained for MC.2:

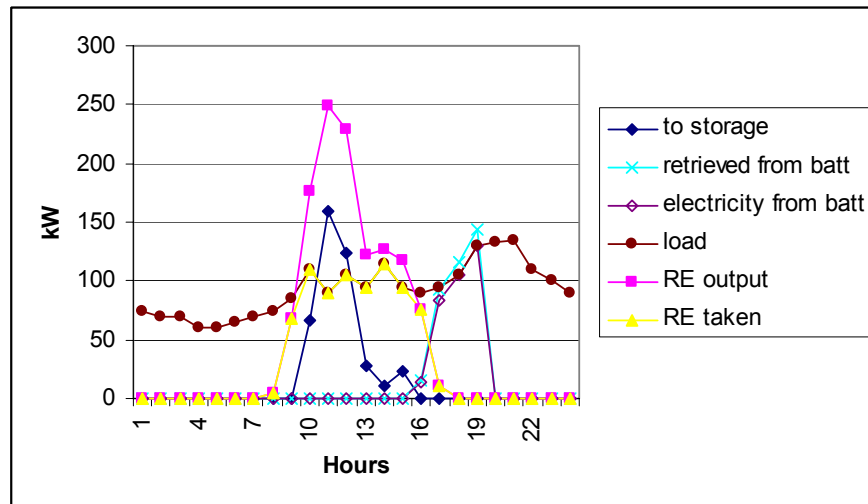


Figure 10. MC.2 simulation, January 1.

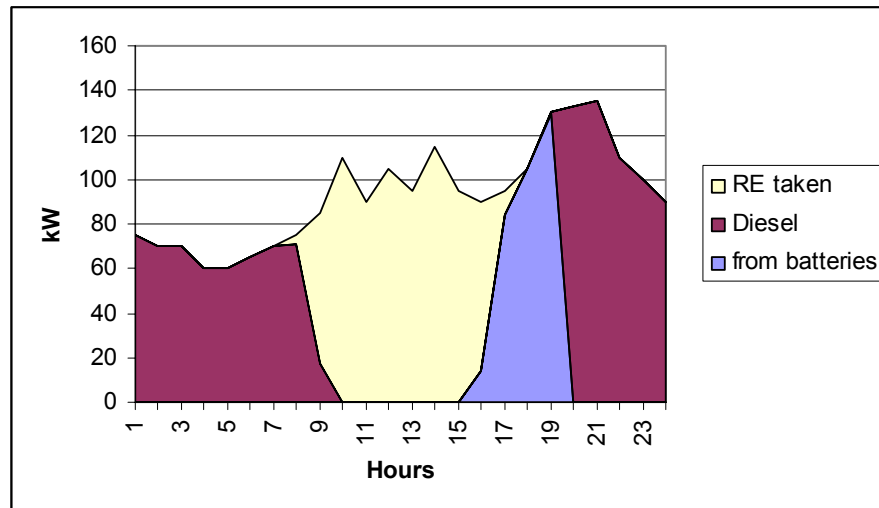


Figure 11. MC.2 simulation, January 1, the source of electricity taken by the power system.

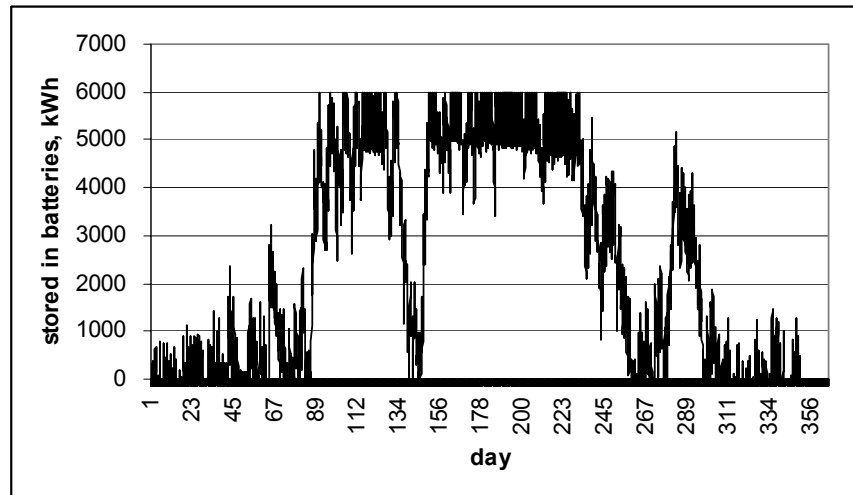


Figure 12. MC.2 simulation, energy stored in batteries during the year.

Table 5.2 shows the results obtained for simulations MC.4 and MC.5:

Table 5.2. System parameters comparison for MC.4 and MC.5

	wind	solar	Renewable	Electrolyser	storage vessel	H2 storage	fuel cell
	KW	kW	KW	KW	kWh	Days	kW
MC.4	200	-	200	-	-	-	-
MC.5	-	255	255	-	-	-	-
-	wind output	solar output	ren. Output	ren. Taken	excess	electrolyser	Dump
	MWh	MWh	MWh	MWh	MWh	MWh	MWh
MC.4	462	-	462	337	125	-	125
MC.5	-	259	259	256	337	-	337

It is again observed that the scenario which considers only PV implies more power installed for less RE penetration than the one with wind alone and is also responsible for more energy excess.

The results obtained for the scenario with wind alone for the 1<sup>st</sup> January are represented in figures 13 and 14:

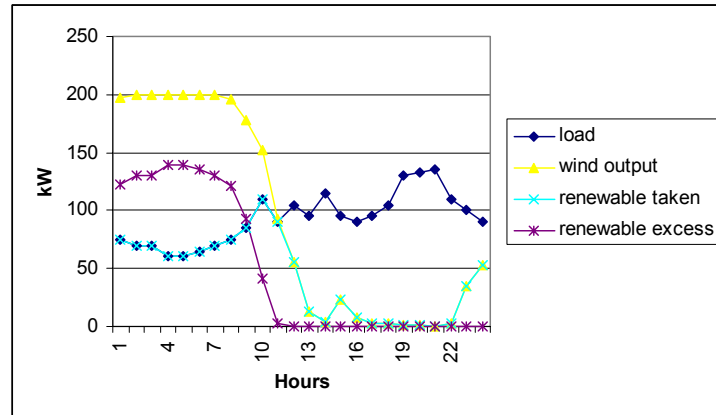


Figure 13. MC.4 simulation, January 1.

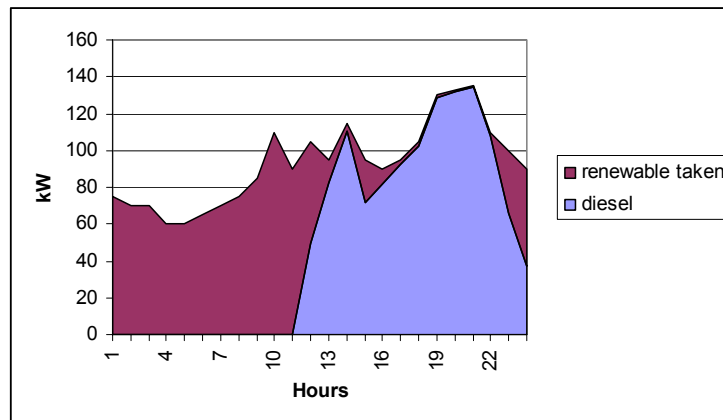


Figure 14. MC.4 simulation, January 1, the source of electricity taken by the power system.

From the studied scenario for Corvo Island it can be concluded that for such a small energy system, 100% RE penetration, achieved with RE sources with variable output, can only be reached through installation of power much beyond the necessary if sources with constant controllable output are used. This fact results in unacceptable values of energy excess. The possibility of using this energy excess to pump water for later energy generation in a mini-hydric power plant may be the best option if the objective is 100% or high RE penetration.

A scenario that considers wind and storage should be studied in the future as the energy to be dumped obtained with PV power appears to be very high in any of the studied scenarios.

## 10. Concluding remarks

The paper analyses the way to increase the penetration of Renewable Energy Sources in two small islands of the Azores archipelago – Corvo and Graciosa. A model was specially developed devote to this kind of work – the H2RES model. Based on existing load data and meteorological data, several scenaria were built and fully modelled. The scenaria considered the following technologies: wind, solar PV, batteries and hydrogen storage.

For the small energy system of the island of Corvo, 100% RE penetration, achieved with RE sources with variable output, can only be reached through installation of power much beyond the necessary. This fact results in an unacceptable values of energy excess. The possibility of using this energy excess to pump water for later energy generation in a mini-hydric power plant may be the best option. A scenarium considering wind and storage should be studied in the future as the energy to be dumped obtained with PV power is very high in any of the scenarium studied.

For the Graciosa Island, the choice among the different scenaria depends mainly on comparing the costs of PV installation and of the hydrogen storage and on the available space. Due to the high cost of PV, the scenaria involving only wind seems to be the preferable solution.

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