OPTIMISING THE INTEGRATION OF HYDROGEN USAGE WITH INTERMITTENT ENERGY SOURCES

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Abstract With respect to energy production, most of the islands in Europe and in the other parts of the World depend on importation, mainly from oil and its related products. Islands are trying to increase the penetration of renewables and some of them have as target to become 100% renewable energy based - island, satisfying their energy demand entirely from indigenous and renewable sources. Since most available renewable energy sources are intermittent, energy storage has to be devised. The most promising technology is storing hydrogen, which can later be used for electricity production, but also for transport. This paper describes one model for optimising the integration of hydrogen usage with intermittent renewable energy sources. The model is applied to the island of Porto Santo, Madeira, Portugal.

Keywords energy in islands, renewable energy integration, fuel cell, hydrogen storage

INTRODUCTION

The European Union includes more than 500 inhabited islands occupying 6% of the Union territory with about 14 million European citizens. Insularity, in general, means isolation and/or dispersion, small local markets, resulting in significantly higher costs of transports, communications and energy, when compared to the closest continental regions. On the other hand, the higher energy costs make renewable energy sources more economically viable in small island energy systems, since their viability is less depending on size and fuel handling infrastructure than fossil fuel technologies.

With respect to energy production, most of the islands depend on importation, mainly from oil and its related products. In some cases, there is no way to link the islands to continental European energy networks, making difficult the implementation of the solutions to reduce environmental costs, such as air pollution and CO_2 emissions. The need to provide the islands with a framework for future development in renewable energies was already highlighted in the European Commission's White Paper on Renewable Energy Sources [1], United Nations Conference on Islands and Small Island

States (Barbados 94, [2]) and the 1st European Conference on Island Sustainable Development. The European Island Agenda [3] highlights "the non-renewable energy sources as provisional solutions, inadequate to solve in the long term the energy problems of the islands.

Tourism is one of the most important economic activities in the Islands. Energy and water demand for tourism is high, mainly during the peak season (summer), when cooling and water needs are very important. Energy production and air conditioning systems present low efficiency, fresh water availability and storage is deficient. Tourism is also an activity that produces important amounts of waste, which is a big problem in a closed ecosystem such an island [4].

The higher penetration of renewable energy sources in islands is limited with its intermittent nature, which can only be increased if some kind of energy accumulation is used. A promising accumulation technology is based on storing the energy in its chemical form, in hydrogen, from where it can be retrieved by a fuel cell, or that can be used for other uses, including the transport.

Dimensioning the components of such a system, including renewable energy intermittent source, electrolyser, hydrogen storage and a fuel cell, that can be successfully integrated in the island power system, and help securing the supply, is not an easy task. Since the intermittence of a renewable source has a different pattern from the intermittence of the load, and when both are of the same order of magnitude, it is very hard to use the statistic approach with load duration and Weibull curves. It is necessary to model the system on hour per hour basis, during a representative year. For energy planning it would be necessary to build a model over the planning horizon, usually 20-30 years.

The H_2RES model was developed to simulate the integration of renewable sources and hydrogen into island energy systems. The use of the model will demonstrate the problems of increasing the penetration of renewable energy source in islands. The H_2RES model was tested on the power system of Porto Santo island, Madeira, Portugal.

H_2RES MODEL

The H_2RES model, developed in Excel, is based on following the hourly values of electricity consumption, of wind velocity and solar radiation. The wind module uses the wind velocity data from the meteorological station in Porto Santo, measured at 10m, and adjust them to the wind turbines hub level, and, for a given choice of wind turbines, converts the velocities to the output. The solar module converts the total radiation on the horizontal surface, obtained from the meteorological station, to the inclined surface, and then to output. 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 excess renewable electricity is then either used by an electrolyser for the production of hydrogen, or for desalination. The hydrogen is stored, and can be retrieved later, and used in a fuel cell. The electricity from a fuel cell is delivered to the system, and the rest is covered from Diesel blocks.

Wind module

The wind velocity data is typically obtained from the closest meteorological station, or the data can be constructed by a model. Such data is usually not at the proper location and hub height, so it has to be adjusted. In cases, like Porto Santo, where wind turbines already exist, and the actual output from wind turbines is known, the velocities can be adjusted by a linear factor, so that the total wind output obtained from the wind velocity data is equal to the actual one. The wind data adjustment can also be done using the equation:

$$v_z = v_{10}\left(\frac{z}{10}\right)^{0.14} \tag{1}$$

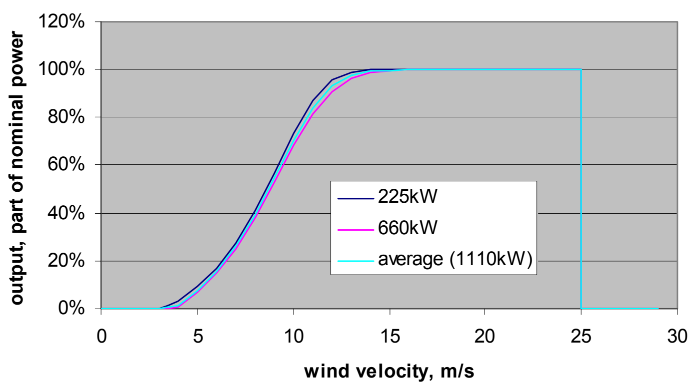

Figure 1. Porto Santo installed Vestas wind turbine characteristics

The conversion from wind velocities to electrical output is done using wind turbine characteristics obtained from the producer, as for example shown in Fig. 1.

Solar module

The hourly solar radiation can be either obtained from the nearest meteorological station, or can be calculated by any of the available models, for given latitude. Data obtained from meteorological station is usually total radiation on horizontal surface, which is hard to adjust for inclination angle, for the lack of information on diffused and direct solar radiation. RETSCREEN model [5] was used to estimate adjustment factors for a particular geographic position, in order to estimate total solar radiation on the tilted surface from the known total radiation on the horizontal surface. With efficiency data obtained from the PV panel producer, it is straightforward to calculate the hourly PV electrical output.

Load module

The hourly load of the power system has to be obtained from the local utility. This data is usually represented as so-called load duration curves (LDC), in which load is sorted by magnitude instead of time. That approach, so well suited for conventional energy planning, cannot be used well with intermittent sources when they represent significant part of the system, what is the case of small island with higher RES penetration. Since the renewable sources, combined wind and PV, will give in any hour output that is between 0 and maximum installed, that can be higher than the total load, the amount of renewable taken by the power system can only be calculated comparing those values on hourly bases. The actual system if installed will have to make decisions on even shorter timescale, but for the modelling purposes hourly periods will represent reasonably well the real situation, since, the solar radiation, load, and wind usually do not have abrupt changes on the smaller scale. If the wind is strongly changing, it might be necessary to adjust the model for 10 min periods. That is straightforward from this model.

Small power systems usually have their power frequency controlled by a single block. Small amount of power coming from other sources will easily adjust to synchronous operation. It is safe to say that at any single hour, the maximum power that can come from sources without frequency control is around 30%. That allows for even higher values during smaller periods of time. Such a limit placed on renewable energy sources, will typically for wind, allow only 10-15% of the total yearly electricity produced. According to [6] for a 5 MW system, as Porto Santo, one could possibly expect, at the current level of technology, less than 20% of wind electricity on yearly basis. That would mean either accepting more than 30% of wind electricity in some intervals, with unacceptably low quality of electricity, or would condition installation of System Control and Data Acquisition (SCADA) for all wind turbines and other renewable sources, and some kind of energy storage [7-12].

The load module of H_2RES model, based on a given hourly wind limit, accounts for the renewable electricity taken by the grid, and the excess is available for storage, desalination or some other kind of dump load. Such a calculation is shown for one day in Fig. 2.

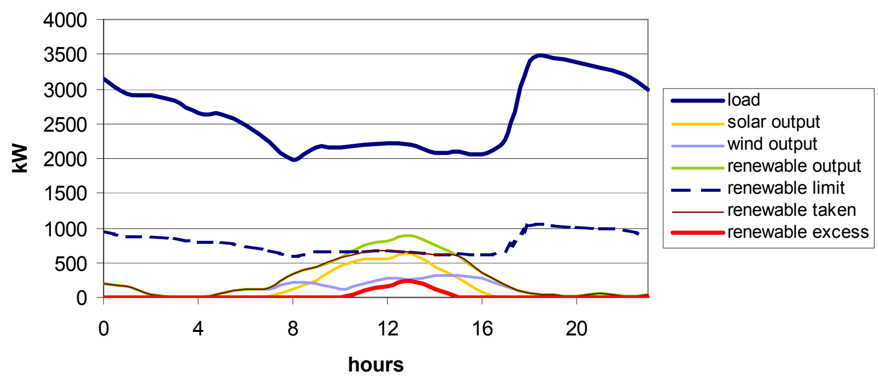

Figure 2. Porto Santo, January 1, the excess renewable electricity in case of 30% hourly limit to renewable penetration

Storage module

The storage module is based on an electrolysing unit, hydrogen storage unit, and a fuel cell, but it can easily be adjusted for hydro pumping storage, reversible fuel cell or batteries. The input into the storage system is limited with the chosen power of electrolyser, so the renewable excess power that is even superfluous to the electrolyser, or cannot be taken to the storage system because storage is full, has to be dumped or rejected. In islands there is often also need for desalination of seawater, which might be a good destination of dumped load.

The electrolyser is working with certain efficiency, which is around 40-50%, and is expected to produce hydrogen already on pressure suitable for storage, avoiding the need for compression, but making the storage vessel bulkier. The storage vessel and the electrolyser output pressure limit the storage capacity.

The stored hydrogen can be retrieved at any moment, either for use in stationary fuel cell, or for mobile uses, so it can possibly serve as a stepping-stone in converting even transport to hydrogen. The fuel cell, with its given efficiency, around 50%, can use the hydrogen from storage, and produce electricity, that will be supplied to the grid. A small fuel cell unit can be controlled by the grid, but a bigger one will have to be controlled by SCADA. It can only spend as much hydrogen there is in storage, and its output cannot surpass the load of the power system, at any single moment.

The model envisages that the fuel cell can be used in the peak time, for peak shaving, or whenever the renewable is not reaching the limit set. In this way it is possible to use more of the renewable electricity.

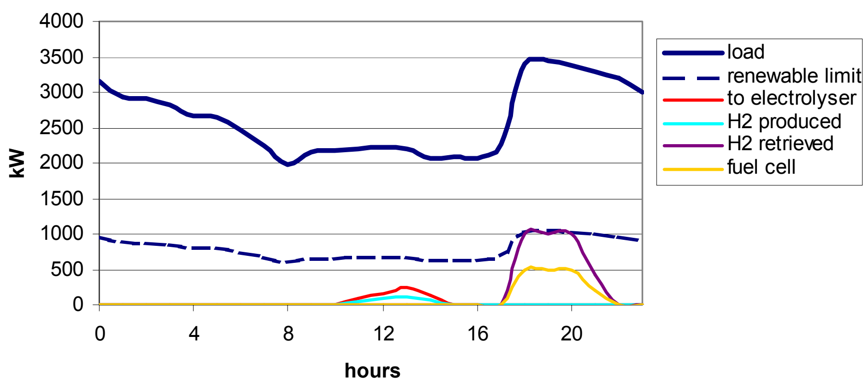

Figure 3. Porto Santo, January 1, the hydrogen produced from excess renewable electricity and retrieved from storage in peak hours. For this particular day more hydrogen is retrieved than stored

The Fig. 3 shows for a particular day how excess renewable electricity is used by electrolyser, stored as hydrogen, and how in the peak hours hydrogen is used by a fuel cell to produce electricity for the grid. For this particular day more hydrogen is retrieved than stored. In the end of the day, the storage is empty. For this case of peak shaving, the storage is designed for only of 6 hours of fuel cell operation, which should well cover peak times, and therefore well distribute the daily fluctuations of intermittent energy sources, but which will not suffice for longer period smoothing.

In order to fairly assess the hydrogen economy, the hydrogen stock difference between the beginning and the end of the yearly period should be negligible. In order to satisfy this condition, the stock at the beginning of the year is set to be equal to the stock at the end of the year.

Fig. 4 shows the sources of electricity taken by the power system, and Fig. 5 shows the hydrogen stock in the storage vessel.

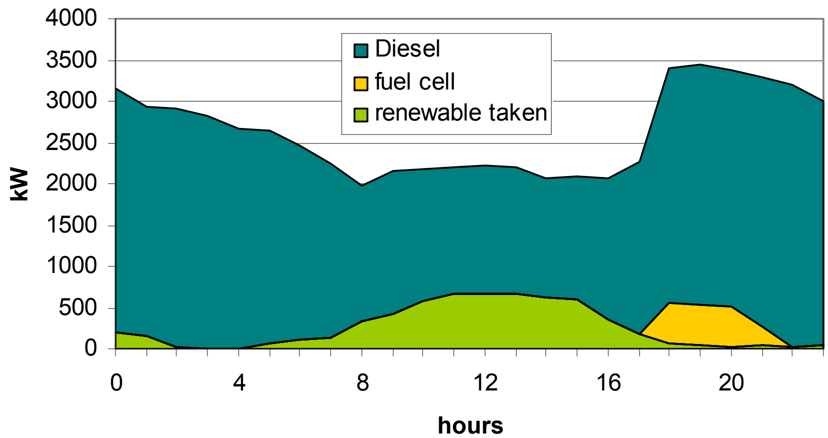

Figure 4. Porto Santo, January 1, the source of electricity taken by the power system

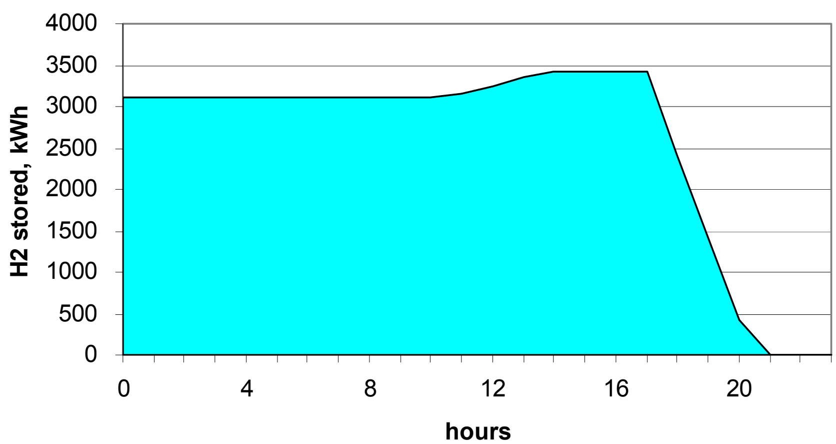

Figure 5. Porto Santo, January 1, the hydrogen stock in the storage vessel

MODEL APPLIED TO PORTO SANTO

Porto Santo

The island of Porto Santo was discovered in 1418 by João Gonçalves Zarco and Tristão Vaz Teixeira, in the reign of King John I of Portugal. Its first governer was Bartolomeu Perestrelo, appointed by Prince Henry the Navigator, who started the first settlement. The culture of cereals, the raising of cattle and the plantation of vines were undertaken successfully, however sugar cane plantation did not find favourable conditions.

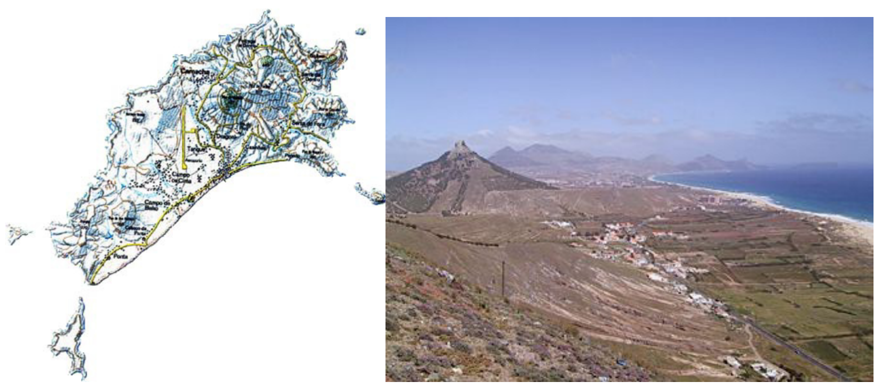

Figure 6 The Island of Porto Santo, Madeira, Portugal

Situated in the northern hemisphere at latitude of 32º, in the Atlantic Ocean, its territory of about 42 km^2 is almost all covered with calcareous matter, especially on the northern side. It is secured on limestone that is visible in several places. The island is adorned with peaks, almost all to the North, the highest of which is Pico do Facho, 516 m.

Being one of the islands constituting the archipelago of Madeira, an ultra-peripheral insular region, Porto Santo is amazingly different from the island of Madeira. While lush green predominates on Madeira, Porto Santo is almost stripped of vegetation and the southern coast is bordered by 9 km long beach of soft sand that makes it an esteemed resort area.

Porto Santo is inhabited by 5000 yearlong residents, most of them living in the capital, Vila Baleira, but the number increases significantly during summer months. The number of tourists and part time second house residents fluctuates between 500 in the wintertime and reaches up to 15000 in the summertime. Nowadays many tourists seek out Porto Santo to enjoy relaxing holidays as the island still maintains an air of tranquillity, and its isolation permits it to keep some of the traditions of the first settlers. The temperate climate, which is felt all year round, is also a major attraction.

Tourism has given Porto Santo an economic dynamism that has been growing year by year. The construction of its airport in 1960, further expanded in 1973, was an important factor that contributed decisively to the island's economic and tourist expansion.

Porto Santo energy system

A fluctuating population, varying from 5500 to 20000, has put enormous strains to the island utilities, especially to the water and electricity production, that had to be designed for the summer peak needs. As an ultra-peripheral insular region, situated in the middle of the Atlantic Ocean, Madeira archipelago, of which Porto Santo makes part, will most probably never be connected to the mainland electricity grid. Therefore, there is need for developing costly local production system. Furthermore, since the local wells cannot satisfy the demand for water, a desalination plant has been installed in 1990.

Figure 7. The map of Porto Santo with wind park, thermal power plant and desalination plant, electricity production per source in 2000 [13]

The power system consists of a thermal power plant with two Diesel fired 3.5 MW Diesel engine blocks and two fuel oil fired 3.4 MW Diesel blocks, and a wind park with two 225 kW Vestas wind turbines and one 660 kW wind turbine, that was added only in December 2000 [13]. It was expected to add one more fuel oil fired 4.1 MW Diesel block by the end of 2001. Currently operating 13.8 MW of thermal power and 1.1 MW of wind power were satisfying a demand of 25.2 GWh in year 2000, of which 24.1 GWh came from thermal source and 1.1 GWh from wind source (basically from two smaller wind turbines) [13]. The annual peak has reached 5.6 MW in year 2000, growing by annual rate of 20%. The low load, during out of season nights, is around 2 MW [13].

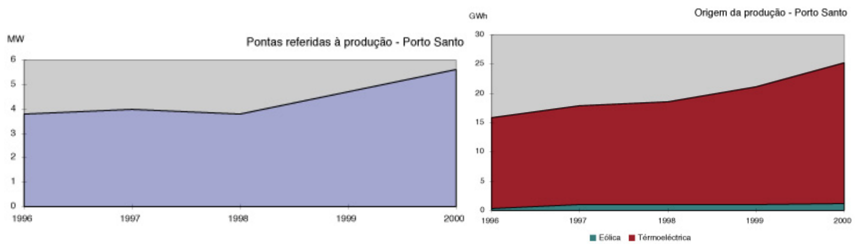

Figure 8. The peak and electricity production, 1996-2000 [13]

Since this low load is only double then the wind potential installed, in the situation when the wind is good, and wind turbines may operate at the full power, there is more wind electricity entering the system (up to 1.1 MW) than the level that is generally considered acceptable, around 30% of the total, the excess wind electricity either cannot be taken up by the system, or can be stored in some way. Currently, it is used by desalination plant, which converts the energy into potable water. The problem for the energy system is that, even though such storage is good form the point of view of sustainability, it does not help the energy system, because, once converted into water, the energy cannot be retrieved any more, though by the avoidance of the future use of energy, in a way this also functions as energy storage.

Porto Santo Renewable Island

The plans to convert Porto Santo into the first Portuguese Renewable Island and to be one of 100 sustainable communities (100% Renewable) in Europe as indicated in the campaign of take-off of the E.U. white paper on Renewable Energies are underway. The island was given such a role in the energy plans. In order to increase the penetration of renewable energies further, the time has come to tackle the problem of energy storage. Since there is no potential for storing potential energy into a water reservoir for later hydropower production, like in El Hierro island (Spain), or to store the surplus electricity produced from wind electricity to the mainland grid, like in Samsoe island (Denmark), other ways have to be found [14]. Currently used system of storing the excess wind energy into potable water, does indeed enable the increase of renewable penetration, by reducing energy demand during peak times, but by no means may enable reaching even 30% of electricity produced. Even with better frequency control equipment, that would enable 100% of wind electricity being delivered to the system, due to the wind quality in Porto Santo, and to its intermittent nature, only up to 45% of electricity demand could be satisfied by 6 MW of wind turbines. The rest would still have to come from thermal power plant firing fuel oil.

The potential solution to the problem is storage of hydrogen. The excess of wind electricity can be stored into hydrogen, by the process of electrolysis. This energy can then be retrieved, when necessary, by supplying the stored hydrogen to a fuel cell. Due to wind characteristics in Porto Santo, in order to cover 100% of current electricity demand, either directly, or through fuel cell, by wind power, a two week storage would be necessary, with fuel cell plant big enough to cover the demand when there is no wind, and electrolyser big enough to supply enough hydrogen to the storage facility. The stored hydrogen could also be used for the transport, enabling a switch to really a 100% renewable island. In the process there is possibility to use waste heat, as part of cogeneration fuel cell.

RESULTS

In order to test the model four hydrogen storage test cases were run for Porto Santo, peak shaving with wind, peak shaving with wind and solar PV, and 100% renewable wind only, and wind and solar.

Peak shaving

In order to compare peak shaving with hydrogen storage, between wind only and wind and solar renewable energy sources, the goal was set to have approximately similar ratios of electricity coming directly from renewables, 16.5%, from fuel cell, 1.8%, and the rest from Diesel. In both cases the renewable hourly output to grid was limited to 30% of the system load.

Table 1 shows comparison between a wind only and a wind-solar mix, as a renewable part of the system. The systems were both optimised to achieve a similar yearly output from a 500 kW fuel cell, satisfying 1.8% of the total electricity demand, or 0.45 GWh. Wind only scenarium was much more effective from the point of power installed, with 2.5 MW of wind, than wind-solar scenarium with 1.1 MW wind and 2.9MWp of PV, due to higher load of wind turbines. Both scenarios produced similar total amount of renewable electricity, slightly more than 6 GWh, and similar amount of renewable electricity was taken by the grid, slightly more than 4 GWh. With similar excess electricity, it was necessary to envisage 50% bigger electrolyser unit for the wind only scenarium, because of the stronger intermittency of wind, 1.5 MW against 1 MW, and 4 times bigger storage unit, 24 MWh against 6 MWh, covering 24 hours of fuel cell consumption against 6 hours.

In the wind only scenarium fuel cell managed only to serve 53% of the peak time, while the wind-solar reached 62%, as defined by a threshold of 80% of moving weekly peak. It is logical that wind needs more storage, since its behaviour is significantly less periodical than solar, but more storage will mean less power installed. This model can help a designer to find out a proper mix, for the particular set of conditions, of different renewable sources coupled with hydrogen storage.

Table 1. System parameters comparison for peak shaving hydrogen storage based on excess wind and wind-solar scenaria, H_2RES model

	wind	solar	renewable	electrolyser	storage vessel	H2 storage	fuel cell
	kW	kW	kW	kW	kWh	days	kW
wind	2500	0	2500	1500	24000	1.00	500
solar & wind	1100	2860	3960	1000	6000	0.25	500
	wind output	solar output	ren. output	ren. taken	excess	electrolyser	desal.
	GWh	GWh	GWh	GWh	GWh	GWh	GWh
wind	6.1	0	6.1	4.1	2.0	1.8	0.2
solar & wind	2.7	3.6	6.3	4.2	2.1	1.8	0.3
	H2 stored	H2 retrieved	fuel cell	electrolyser	fuel cell	peak serving time	
	GWh	GWh	GWh	h	h	%	
wind	0.9	0.9	0.45	1195	906	53%	
solar & wind	0.9	0.9	0.45	1794	900	62%	

100% renewable

In order to satisfy all the demand from renewable source, though keeping Diesel as reserve, the results were quite different. There is no more significant difference between wind and wind-solar scenaria, since over longer period the intermittency of wind is much less influential. The longer period is slightly more than a week, or 8.5 days of storage, meaning that the capacity of storage must provide for 8.5 days of fuel cell working on full load, 5.5 MW. That will actually mean a capacity of around two weeks of full covering of the actual load from a fuel cell. Table 2 shows comparison of those two scenaria. Wind scenarium envisages 25 MW of wind turbines, five times the annual peak, while wind-solar scenarium envisages 11 MW of wind turbines and nearly 20 MWp of solar PV installed. Both scenaria needs an electrolyser unit of 11 MW, double the peak, and a fuel cell that can cover the peak of 5.5 MW. The calculation was made for one year and does not account for the growth of demand that will certainly be significant, due to tourism. Fuel cell will serve the power system 37-41% of time, while the rest of time the full load will come from renewable sources.

Table 2. System parameters comparison for 100% renewable power system with hydrogen storage based on excess wind and wind-solar scenaria

	wind	solar	renewable	electrolyser	storage vessel	H2 storage	fuel cell
	MW	MW	MW	MW	GWh	days	MW
wind	25	0	25.0	11	2.25	8.5	5.5
solar & wind	10	19.8	29.8	11	2.25	8.5	5.5
	wind output	solar output	ren. output	ren. taken	excess	electrolyser	desal.
	GWh	GWh	GWh	GWh	GWh	GWh	GWh
wind	61.4	0	61.4	18.5	42.9	28.3	14.6
solar & wind	24.6	25.5	50.1	18.2	31.9	28.0	3.9
	H2 stored	H2 retrieved	fuel cell	electrolyser	fuel cell	fuel cell serving time	
	GWh	GWh	GWh	h	h	%	
wind	14.2	13.3	6.6	2576	1206	37%	
solar & wind	14.0	13.9	7.0	2547	1267	41%	

CONCLUSIONS

A model for optimisation and energy planning of integration of hydrogen storage and renewable energy sources has been devised for small and medium power systems (1-100 MW). The model includes a wind and solar PV modules, while others can be straightforwardly added.

The model was tested on the data for Porto Santo island, for two different cases, peak shaving and 100% renewable power system. For each of the test cases two scenaria were optimised, one with only wind as a renewable source, and the other with a wind-solar mix. The results have shown that in case of peak shaving wind-solar mix might be more effective, but that for the case of 100% renewable wind system be certainly more cost effective.

ACKNOWLEDGEMENTS

The authors would like to acknowledge the Portuguese Ministério da Ciência e Tecnologia for the financial support for the scholarships of Dr. Neven Duic and Dr. Luís Alves as part of the programme Praxis XXI.

The financial support of DG TREN (Project EURO-ISLAS NNE5/1999/136 -"New and renewable energy sources for islands and remote regions") of the European Commission and the Portuguese Direcção Geral da Energia is also acknowledged. The content of the publication is the sole responsibility of its authors, and in no way represents the views of the European Commission or its services.

The authors would like to thank AREAM and Electricidade da Madeira for the data, information, and fruitful discussions on this work.

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