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Increasing renewable energy sources in island energy supply: case study Porto Santo

Neven Duić [a,*], Maria da Graça Carvalho [b]

[a] *Power Engineering Department, Faculty of Mechanical Engineering and Naval Architecture, University of Zagreb, 10000 Zagreb, Croatia*
[b] *Research Group on Energy and Sustainable Development, Department of Mechanical Engineering, Instituto Superior Técnico, Lisbon, Portugal*

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Abstract

While the energy supply of most islands depends mainly on expensive oil derivatives' importation, the others are linked by usually a weak electricity grid connection to the mainland. Due to high energy costs the islands are proving to be excellent test beds for the introduction of new technologies, and some islands are trying to become so-called renewable islands, to satisfy their energy 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 energy sources, such as hydro or geothermal energy, can easily integrate them into the power system, but those with mainly intermittent renewable energy sources are confronted with the necessity of energy storage. The most promising technologies are reversible hydro where geography allows, and storing hydrogen where it does not. The stored hydrogen can later be used for electricity production, and also for transport. This paper describes the H_2RES model for optimisation of integration of hydrogen usage with intermittent renewable energy sources on the example of an isolated island in the Madeira archipelago, Porto Santo. It shows that it is possible to significantly increase the penetration of renewable energy sources, albeit at a relatively high cost, with hydrogen storage technology. The H_2RES model, which includes reversible hydro and batteries as storage technologies, can serve as a valuable tool for island energy planning.

Keywords: Renewable energy; Islands; Energy storage; Hydrogen; Fuel cells; H_2RES model

* Corresponding author. Tel.: +385-1-6168494; fax: +385-1-6156940.
E-mail address: neven.duic@fsb.hr (N. Duić).

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Contents

1. 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 transport costs, 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 dependent 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 it difficult to guarantee the security of supply. The need to provide the islands with a framework for future development in renewable energy has already been 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, while 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 as 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 [5–9]. 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 transport.

Dimensioning the components of such a system, including renewable energy intermittent source, electrolyser, hydrogen storage and a fuel cell, which 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 a statistical approach with load duration and Weibull curves. It is necessary to model the system on an 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.

2. H_2RES model

The H_2RES model is based on hourly time series analysis of electricity demand, wind potential, solar insulation and precipitation. The wind module uses the wind velocity data, typically from the meteorological station, at 10 m height, and adjusts them to the wind turbine 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 typically from the meteorological station, to the inclined surface, and then to output. The hydro module takes into account precipitation data, typically from the nearest meteorological station, and water collection area, and evaporation data, based on the reservoir-free surface, to predict the water net inflow into the reservoir. 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 stored either as hydrogen, pumped water or electricity in batteries, or used some non-time critical use. The energy that is stored can be retrieved later, and supplied to the system as electricity. The rest is covered from diesel blocks.

2.1. Wind module

The wind velocity data are typically obtained from the closest meteorological station, or the data can be constructed by a model. Such data are usually not at the proper location and hub height, so have to be adjusted. In cases such as 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 are equal to the actual one. The wind data adjustment can also be done using the equation:

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

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. The actual hourly average wind velocities at 10 m height for Porto Santo island are shown in Fig. 2.

2.2. 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 a given latitude. Data obtained from meteorological station are usually total radiation on horizontal surface, which are hard to adjust for inclination angle, for the lack of information on diffused and direct solar radiation. RETSCREEN model [10] was used to estimate adjustment factors for a particular geographic position, in order to estimate total solar radiation on the tilted surface (Fig. 3) 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.

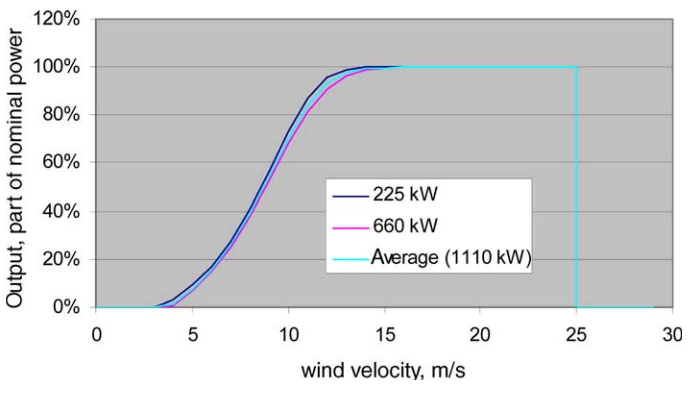

Fig. 1. Porto Santo installed Vestas wind turbine characteristics.

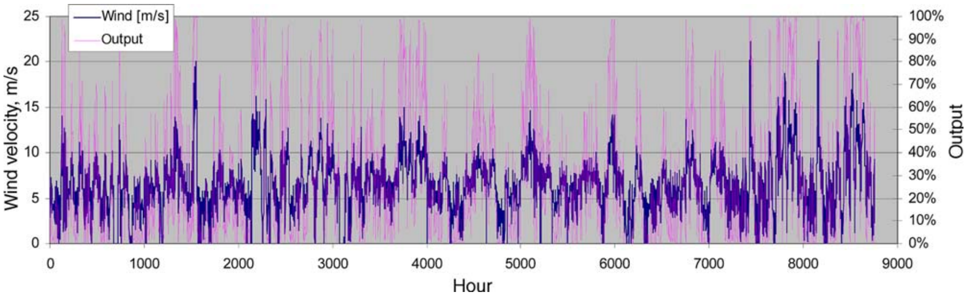

Fig. 2. Hourly average wind velocities and output potential with the installed mix of wind turbines, as of nominal power, Porto Santo, 2000.

2.3. Hydro module

The hourly precipitation data can be either obtained from the nearest meteorological station, or can be estimated using daily, weekly or monthly averages. Generally, the necessary resolution of the precipitation data should be depending on the storage size. Similarly, the evaporation per unit free surface of the reservoir should be estimated. The difference will then produce net water inflow into the storage system.

2.4. Load module

The hourly load of the power system (Fig. 4) has to be obtained from the local utility. This data are 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 a significant part of the system, which is the case of a small island with higher RES penetration. Since the renewable sources, combined wind and PV, will provide output in any hour 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

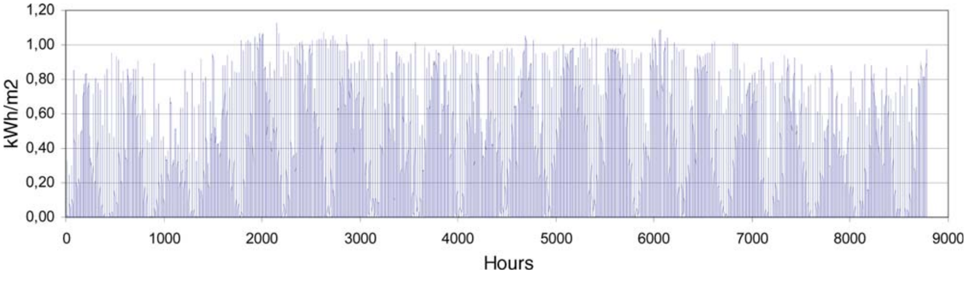

Fig. 3. Hourly average solar radiation intensities on tilted surface, Porto Santo, 2000.

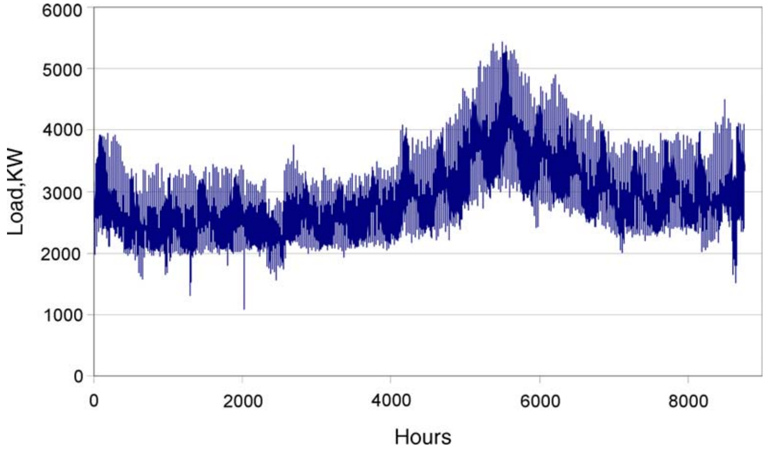

Fig. 4. Hourly average electricity system load, 2000.

actual system if installed will have to make decisions on an even shorter timescale, but for the modelling purposes hourly periods will represent the real situation reasonably well, since the solar radiation, load, and wind usually do not have abrupt changes on the smaller scale. If the wind changes significantly, 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 in any single hour, the maximum power that can come from sources without frequency control is around 30%. That allows for even higher values during shorter 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 Ref. [11] for a 5 MW system, such as Porto Santo, one could possibly expect, at the current level of technology, less than 20% of wind electricity on a yearly basis. That would mean either accepting more than 30% of wind electricity in some periods, with an unacceptably low quality of electricity, or installing variable pitch wind turbines that can easily adjust the output to the load, and/or would condition installation of frequency and voltage control for all wind turbines and other renewable sources, and some kind of energy storage [12–17].

The load module of the 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 1 day in Fig. 5.

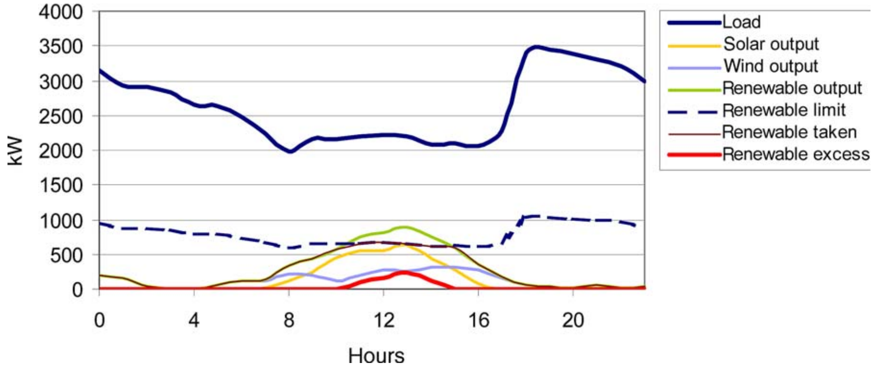

Fig. 5. Porto Santo, January 1, the excess renewable electricity in case of 30% hourly limit to renewable penetration.

2.5. Storage module

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

The storing facility is working with certain storage efficiency, which is around 50–60% for electrolyser, around 70% for pumping and 90% for batteries. The electrolyser is already expected to produce hydrogen on pressure suitable for storage, avoiding the need for compression. The storage vessel and the electrolyser output pressure limit the storage capacity. The upper reservoir volume and maximum volume of the water available for pumping in the lower reservoir limits the amount of water that can be pumped, and the batteries' capacity is given by the producer. The maximum volume of the water available for pumping in the lower reservoir should be set as total water stored in the lower reservoir, that can be infinite if the lower reservoir is the sea, or can be set taking into account the needs of, for example, water supply system, if the water storage is also used for that purpose.

The stored hydrogen can be retrieved at any moment, either for use in stationary fuel cell, or for mobile use, so it can possibly serve as a stepping-stone in converting even transport to hydrogen. The fuel cell, with its given efficiency of 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 have frequency and voltage control. It can only expend as much hydrogen as there is in storage, and its output cannot surpass the load of the power system, at any single moment.

The water stored in the upper reservoir can be retrieved at any moment, either for use in turbines, or water supply. The turbine facility, with its given efficiency of around 70%, can use the water from the upper reservoir, produce electricity that will be supplied to the grid, and fill the lower reservoir. Turbine generator will typically have frequency and voltage control, and might often have output control. It can only use as much water as there is in the upper reservoir, and its output cannot surpass the load of the power system, at any single moment.

Fig. 6 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. At the end of the day, the storage is empty. For this case of peak shaving, the storage is designed for only 6 h of fuel cell operation, which should easily cover peak times, and therefore well distribute the daily fluctuations of intermittent energy sources, but which will not suffice for smoothing over a longer period.

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. 7 shows the sources of electricity taken by the power system, and Fig. 8 shows the hydrogen stock in the storage vessel.

3. Model applied to Porto Santo

3.1. Porto Santo

Situated in the northern hemisphere at latitude of 32° in the Atlantic Ocean, its territory of about 42 km^2 is almost all covered with calcareous matter, especially

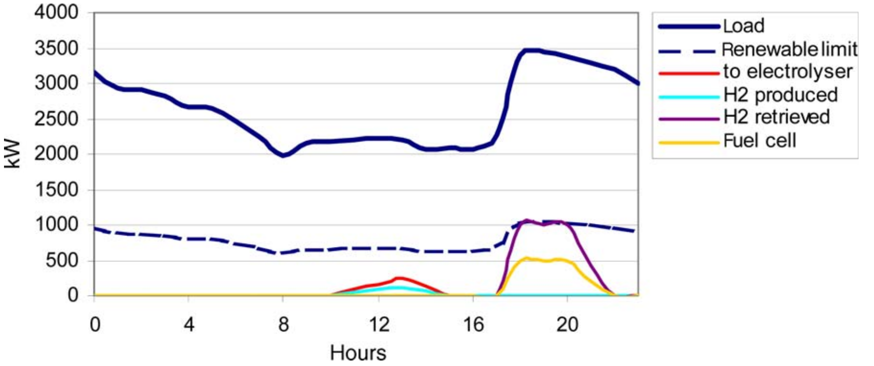

Fig. 6. Porto Santo, January 1, the hydrogen produced from excess renewable electricity and retrieved from storage in peak hours. For this particular day more hydrogen is retrieved than stored.

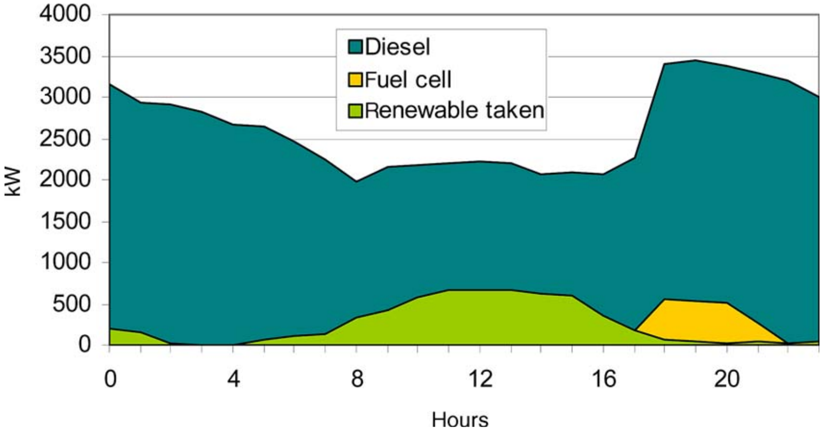

Fig. 7. Porto Santo, January 1, the source of electricity taken by the power system.

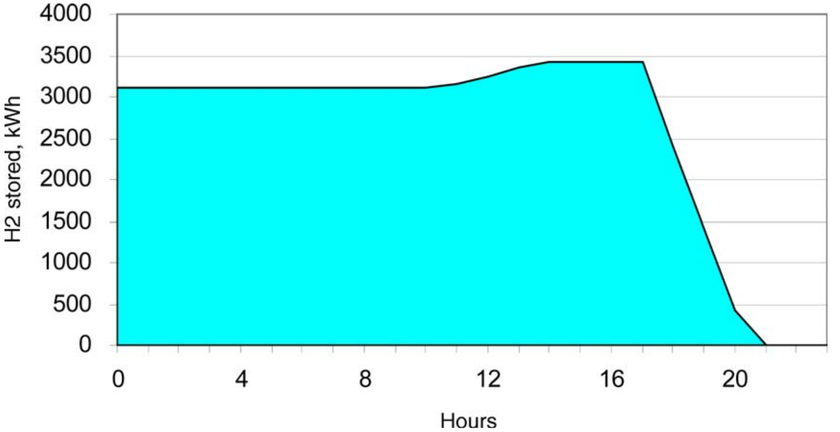

Fig. 8. Port Santo, January 1, the hydrogen stock in the storage vessel.

on the northern side. The island is adorned with peaks, almost all to the north, the highest of which is Pico do Facho at 516 m.

Being one of the islands constituting the archipelago of Madeira, an ultra-peripheral insular region, Porto Santo is 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 a popular resort area (Fig. 9).

Porto Santo is inhabited by 5000 year-long 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

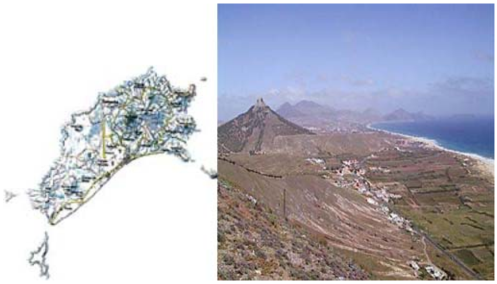

Fig. 9. The island of Porto Santo, Madeiro, Portugal.

500 in the wintertime and reaches up to 15,000 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.

3.2. Porto Santo energy system

A fluctuating population, varying from 5500 to 20,000, 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 forms part, will most probably never be connected to the mainland electricity grid. Therefore, there is a need to develop a local production system. Furthermore, since the local wells cannot satisfy the demand for water, a desalination plant was installed in 1990 (Fig. 10).

Fig. 10. The map of Porto Santo with wind park, thermal power plant and desalination plant, electricity production per source in 2000 [18].

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, which was added in December 2000 [18]. An additional fuel oil-fired 4.1 MW diesel block was added at the end of 2001. Currently operating 17.9 MW of thermal power and 1.1 MW of wind power were satisfying a demand of 28.4 GWh in year 2001, of which 26.1 GWh came from thermal source and 2.3 GWh from wind source [18]. The annual peak reached 5.6 MW in year 2000, growing at an annual rate of 20%. The low load, during out of season nights, is around 2 MW [18] (Fig. 11).

Since this low load is only double than the wind potential installed, in the situation when the wind is good and wind turbines operate at 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.

Table 1 shows electricity generation history from 1991 to 2000, growing on average 9% per year. Fig. 4 shows hourly average electricity load during 2000. The summer peak and yearly variation is clearly obvious.

3.3. Porto Santo renewable island

The plan 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 EU White Paper on Renewable Energies is under way. 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 excess energy in a water reservoir for later hydropower production, as in El Hierro island (Spain), or to store the surplus electricity produced from wind to the mainland grid, as in Samsoe island (Denmark), other ways have to be found [19]. Even with variable pitch wind turbines and better frequency and voltage control equipment, that would enable 100% of wind electricity to be 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 delivered from 6 MW of wind turbines. The rest would still have to come from a thermal power plant powered by fuel oil.

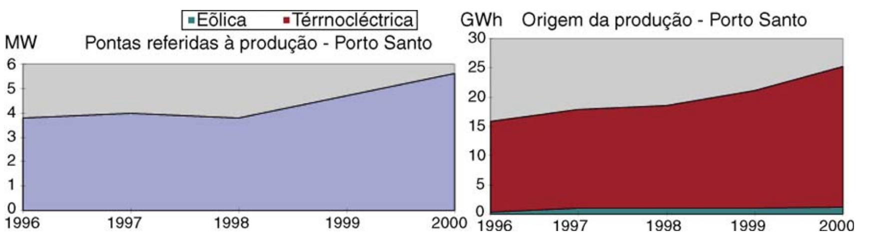

Fig. 11. The peak and electricity production, 1996–2000 [18].

Table 1
Electricity generation history, 1991–2000

Porto Santo [GWh]	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000
Thermal	10.2	12.2	13.0	13.7	14.8	15.5	16.9	17.6	20.1	24.1
Wind	0.3	0.1	–	–	–	0.3	1.0	1.0	1.0	1.1
Total	10.5	12.3	13.0	13.7	14.8	15.8	17.9	18.6	20.1	25.2

The potential solution to the problem is hydrogen storage. The excess wind electricity can be stored in 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 the wind characteristics in Porto Santo, in order to cover 100% of current electricity demand, either directly or through fuel cell, by wind power, a 2-week storage would be necessary, with fuel cell plant sufficiently large to cover the demand when there is no wind, and electrolyser sufficiently large to supply enough hydrogen to the storage facility. The stored hydrogen could also be used for the transport, enabling a switch to a truly 100% renewable island. In the process, there is the possibility to use waste heat, as part of cogeneration fuel cell.

4. 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.

4.1. 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 cells 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 2 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. The wind-only scenario was much more effective from the point of power installed, with 2.5 MW of wind, than the wind–solar scenario with 1.1 MW wind and 2.9 MWp of PV, due to the higher load of wind turbines. Both scenarios produced a similar total amount of renewable electricity, slightly more than 6 GWh, and a similar amount of renewable electricity was taken by the grid, slightly more than 4 GWh. With similar excess electricity, it was necessary to envisage a 50% greater electrolyser unit for the wind-only scenario, because of the stronger intermittency of wind, 1.5 MW against 1 MW, and four times bigger storage unit, 24 MWh against 6 MWh, covering 24 h of fuel cell consumption against 6 h for wind–solar.

Table 2
System parameters comparison for peak shaving hydrogen storage based on excess wind and wind–solar scenario, H_2RES model

	Wind (kW)	Solar (kW)	Renewable (kW)	Electrolyser (kW)	Storage vessel (kWh)	H_2 storage (days)	Fuel cell (kW)
Wind	2500	0	2500	1500	24000	1.00	500
Solar and wind	1100	2860	3960	1000	6000	0.25	500
	Wind output (GWh)	Solar output (GWh)	Ren. output (GWh)	Ren. taken (GWh)	Excess (GWh)	Electrolyser (GWh)	Desal. (GWh)
Wind	6.1	0	6.1	4.1	2.0	1.8	0.2
Solar and wind	2.7	3.6	6.3	4.2	2.1	1.8	0.3
	H_2 stored (GWh)	H_2 retrieved (GWh)	Fuel cell (GWh)	Electrolyser (h)	Fuel cell (h)	Peak serving time (%)	
Wind	0.9	0.9	0.45	1195	906	53%	
Solar and wind	0.9	0.9	0.45	1794	900	62%	

In the wind-only scenario 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 periodic than solar, but more storage will mean less power installed (Fig. 12). This model can help a designer to establish a proper mix, for the particular set of conditions, of different renewable sources coupled with hydrogen storage (Fig. 13).

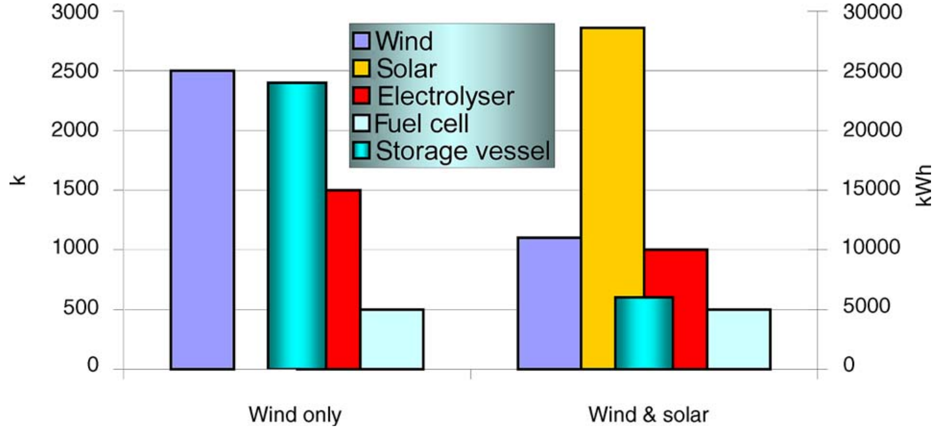

Fig. 12. The peak shaving component optimisation.

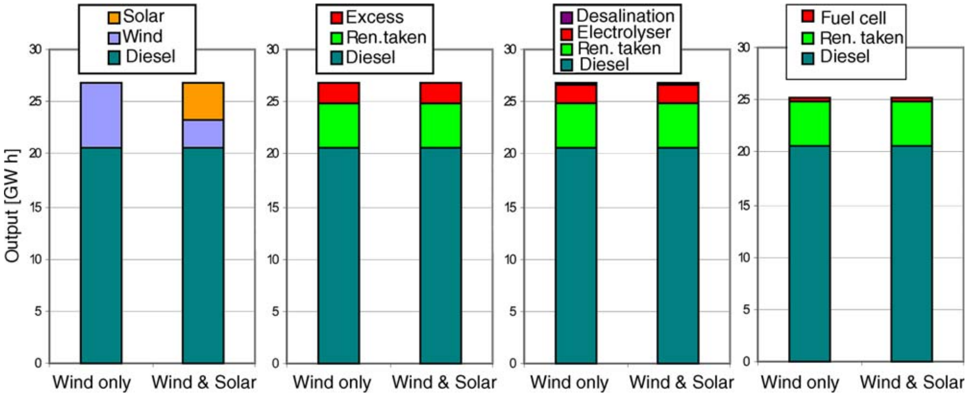

Fig. 13. The peak shaving energy balances, (a) generated, (b) renewable taken and excess, (c) excess electrolysed or dumped to desalination, (d) energy consumed by power system.

4.2. 100% renewable

In order to satisfy all the demand from renewable source, while keeping diesel as reserve, the results were quite different. There is no longer a significant difference between the wind and wind–solar scenarios, since over a 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

Table 3
System parameters comparison for 100% renewable power system with hydrogen storage based on excess wind and wind–solar scenario

	Wind (MW)	Solar (MW)	Renewable (MW)	Electrolyser (MW)	Storage vessel (GWh)	H_2 storage (days)	Fuel cell (MW)
Wind	25	0	25.0	11	2.25	8.5	5.5
Solar and wind	10	19.8	29.8	11	2.25	8.5	5.5
	Wind output (GWh)	Solar output (GWh)	Ren. output (GWh)	Ren. taken (GWh)	Excess (GWh)	Electrolyser (GWh)	Desal. (GWh)
Wind	61.4	0	61.4	18.5	42.9	28.3	14.6
Solar and wind	24.6	25.5	50.1	18.2	31.9	28.0	3.9
	H_2 stored (GWh)	H_2 retrieved (GWh)	Fuel cell (GWh)	Electrolyser (h)	Fuel cell (h)	Fuel cell serving time (%)	
Wind	14.2	13.3	6.6	2576	1206	37%	
Solar and wind	14.0	13.9	7.0	2547	1267	41%	

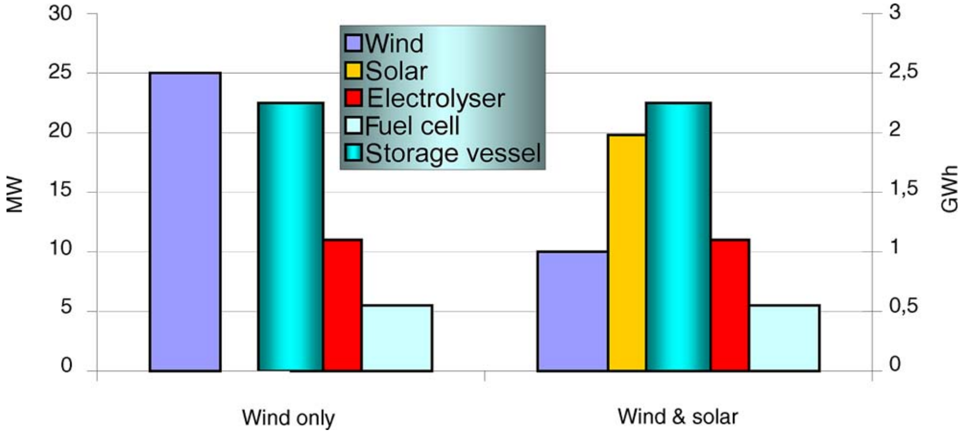

Fig. 14. The 100% renewable case component optimisation.

8.5 days of fuel cell working on full load, 5.5 MW. That will actually mean a capacity of around 2 weeks of full covering of the actual load from a fuel cell. Table 3 shows comparison of these two scenarios.

The wind scenario envisages 25 MW of wind turbines, five times the annual peak, while the wind–solar scenario envisages 11 MW of wind turbines and nearly 20 MWp of solar PV installed. Both scenarios 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 1 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.

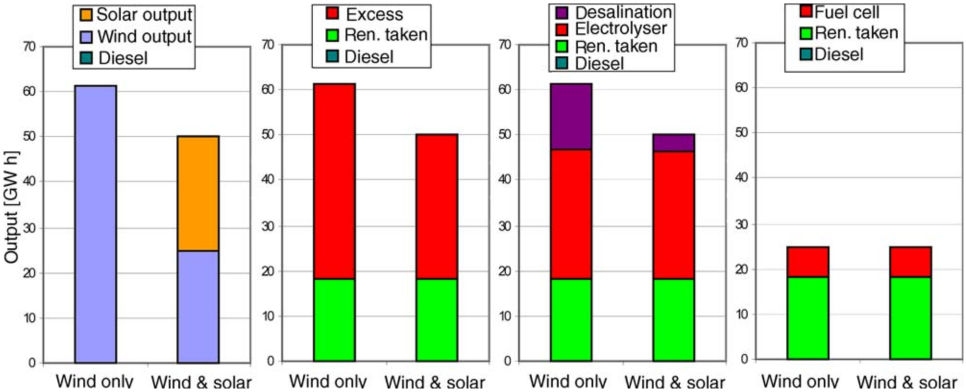

Fig. 15. The 100% renewable energy balances, (a) generated, (b) renewable taken and excess, (c) excess electrolysed or dumped to desalination, (d) energy consumed by power system.

5. 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 wind and solar PV modules, while others can be easily 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 scenarios were optimised, one with only wind as a renewable source, and the other with a wind–solar mix. The results have shown that in the 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 (Figs. 14 and 15).

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