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INCREASING THE SUPPLY OF RENEWABLE ENERGY SOURCES IN ISLAND ENERGY SYSTEMS

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The article describes the H_2RES model for optimisation of integration of hydrogen usage with intermittent renewable energy sources (RES) in island energy systems, on Porto Santo, the example of an isolated island in Madeira archipelago. It shows that it is possible to increase the penetration of renewable energy sources by introducing a hydrogen storage component, *albeit* at a relatively high cost. It compares peak shaving case based on storing excess wind with one based on storing excess electricity from a combination of solar PV panels and wind turbines. It shows that significant solar component significantly reduces necessary storage and slightly reduces electrolyser component.

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

INTRODUCTION

With respect to energy production, most islands in the Madeira archipelago depend on importation, mainly of oil and its related products, whereas other islands rely on a weak electricity grid connection to the mainland. In some cases, it is nearly impossible to link the islands to continental European energy networks, making it difficult to implement the solutions to reduce environmental costs, but at the same time increasing the security of supply to the level necessary to maintain the quality of life and competitiveness of island economies. Owing 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 like hydro or geothermal can easily integrate them into the power system, but those with mainly intermittent renewable energy sources (RES) are confronted with the necessity of energy storage. The most promising technologies are thermal storage, where heat is needed, reversible hydro, where geography allows, and hydrogen storage in other cases. In addition, in order to increase the efficiencies of the supply systems of electricity, water and transport fuel, these could be analysed in an integrated approach.

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The need to provide islands with a framework for future development in renewable energies was highlighted in the European Commission's White Paper on renewable energy sources [1], the United Nations Conference on islands and small island states [2] and the first 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 usually one of the most important economic activities in islands. Demand for energy and water 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 are deficient. Tourism is also an activity that produces significant 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 by its intermittent nature, which can only be increased if some kind of energy accumulation is used. A promising accumulation technology, as first suggested for islands in Ref. [5], is based on storing the energy in chemical form – hydrogen – from where it can be retrieved by a fuel cell, or used for other purposes.

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. As 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 the representative year. For energy planning, it is necessary to run a model over the planning horizon, usually 10–30 years.

The conventional planning tools, like Energy and Power Evaluation Program (ENPEP), cannot be used in such situations, and several new energy-planning tools are being developed. EnergyPlan [6, 7], for example, is well adjusted for decentralised power generation, and it also integrates heat demand into the model, enabling the optimisation of combined heat and power generation, which already delivers nearly 50% of power to the Danish system. It also integrates other intermittent resources and optimises different strategies to treat the power excess. On the other hand, it does not treat hydro resource, water demand, hydrogen demand, reversible hydro, hydrogen storage, batteries and other specifics of the isolated power systems. On the other hand, HOMER is designed specifically for small isolated power systems and although it allows for grid connection and has some of the required technologies, it still lacks reversible hydro and water demand treatments, which is the cheapest way to store energy in those islands where potential is there [8]. There are also models that contain more precise physical models of some technologies, like Hydrogems [9], but they also lack hydro resource, reversible hydro storage and water demand, among others, and for the purpose of energy planning it is not necessary to go into conversion detail, besides the necessary level; although when it comes to component dimensioning, it might be beneficial.

H_2RES Model

The H_2RES model [10] is based on an hourly time series analysis of water, electricity and hydrogen demands, wind potential, solar irradiation 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 turbines hub's level, and, for a given choice of wind turbines, converts the velocities to the total potential wind output $E_{W,pot}$ for a given hour. The solar module converts the total radiation on the horizontal surface, obtained typically from the meteorological station, to the inclined surface, and then to electrical potential output $E_{\mathrm{PV,pot}}$. The hydro module takes into account the 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, but is not used in this example, as Porto Santo has no hydro potential. 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 outputs into the system and discards the rest of the renewable output. The excess renewable electricity is then either stored as hydrogen, pumped water or electricity in batteries, or made available for some non-time critical use, or rejected. The energy that is stored can be retrieved later and supplied to the system as electricity. The rest is covered from diesel blocks. The model can also optimise the supply of water and hydrogen demand.

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. This approach, so well suited for conventional energy planning, cannot be used well with intermittent sources when they represent significant part of the system, which is the case of small islands with higher RES penetration. As the renewable sources, combined wind and PV, will give in any hour output, *i.e.* between 0 and maximum installed, which 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 a much shorter timescale, but for dimensioning purposes, hourly periods will represent the real situation reasonably well, because the solar radiation, load and wind usually do not have abrupt changes on the smaller scale. 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. The still unsupplied load will be matched either from storage or from diesel engines. If there were hydro turbines installed, they would be first called upon if there is enough water stored in the upper reservoir. Fuel cells are called upon next, and batteries only if all others fail to cover all the demand. If the rest of the load is under the technical minimum of the smallest diesel block, diesel block will be set on technical minimum, and power coming from other sources will be reduced. The demand is supplied as follows:

$$E_{\mathrm{load}} = E_{\mathrm{I},t} + E_{\mathrm{T}} + E_{\mathrm{FC}} + E_{\mathrm{bat,out}} - E_{\mathrm{P}} - E_{\mathrm{el}} - E_{\mathrm{bat,in}} + E_{\mathrm{D}}, \tag{1}$$

where E_{T}, E_{FC} and $E_{\mathrm{bat,out}}$ are the outputs from the hydro turbines, the fuel cells and the batteries, whereas E_{P}, E_{el}, $E_{\mathrm{bat,in}}$ are the energy consumed by pumping water, electrolysing water and charging batteries, respectively. E_{D} is the output of the diesel blocks in use at that moment.

The intermittent renewable electricity taken by the system, $E_{\mathrm{I},t}$, is defined by the intermittent limit that can be taken by the grid φ_{I}, and the intermittent potential, $E_{\mathrm{I,pot}}$:

$$E_{\mathrm{I},t} = \mathrm{Min}(\varphi_{\mathrm{I}} E_{\mathrm{load}}, E_{\mathrm{I,pot}}), \tag{2}$$

where intermittent potential is a sum of wind and solar PV potentials:

$$E_{\mathrm{I,pot}} = E_{\mathrm{W,pot}} + E_{\mathrm{PV,pot}}. \tag{3}$$

The total intermittent potential will be either taken by the system or used in pumps, by electrolyser or stored in batteries, and the rest will be rejected:

$$E_{\mathrm{I,pot}} = E_{\mathrm{I},t} + E_{\mathrm{P}} + E_{\mathrm{el}} + E_{\mathrm{bat,in}} + E_{\mathrm{r}}. \tag{4}$$

Pumps should only work in their optimal point, whereas the electrolyser should not be turned of and on frequently. The power of each block and switch on time will be a constraint to intermittent energy storage.

The storage module can be based on an electrolysing unit with hydrogen storage unit and a fuel cell, or a hydro pumping storage, or a 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 often also the need for desalination of seawater, which might be a good destination of dumped load, water pumps, or refrigeration units.

The storing facility is working with certain storage efficiency, which is around 50–80% for the electrolyser, μ_{el}, around 70% for pumping and 90% for batteries. The electrolyser is expected to produce hydrogen at a suitable pressure for storage, avoiding the need for compression. The storage vessel and the electrolyser output pressure limit the storage capacity. The upper reservoir volume, and the maximum volume of water available for pumping in the lower reservoir, limit the amount of water that can be pumped, and the capacity of the batteries is given by the producer. The maximum volume of the water available for pumping in the lower reservoir should be set as the total water volume stored in the lower reservoir, which can be infinite if the lower reservoir is the sea, or can be set taking into account the needs of the 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 uses; so, it can possibly serve as a stepping-stone in converting even transport to hydrogen. The fuel cell, with its given efficiency, μ_{FC}, 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 need to have frequency and voltage control. It can only spend 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. The turbine generator will typically have frequency and voltage control, and might often have an 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.

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 should approach the stock at the end of the year.

The energy accumulated in hydrogen storage in hour n is:

$$E_{H_2}^{n} = E_{H_2}^{n-1} - \frac{E_{\mathrm{FC}}}{\mu_{\mathrm{FC}}} - E_{H_2\mathrm{load}} + \mu_{\mathrm{el}} E_{\mathrm{el}}, \tag{5}$$

which satisfies conditions that the hydrogen stored must be in the range between empty and full. In addition, the fuel cell will not be allowed to work in case that hydrogen storage stores less than hydrogen needed to supply hydrogen load for a set number of hours $t_{H_2\mathrm{sec}}$:

$$E_{H_2}^{n-1} < t_{H_2\mathrm{sec}} E_{H_2\mathrm{load}} \Longrightarrow E_{\mathrm{FC}} = 0. \tag{6}$$

This was just a basic description of the H_2RES model, mainly of the modules used in this article.

PORTO SANTO AS A SUSTAINABLE COMMUNITY

Amongst other European islands, Porto Santo, the smaller inhabited island of the Madeira archipelago, Portugal, has decided to become a sustainable community, tapping into renewable energy resources, and trying to achieve the status of a 100% renewable island. It is a challenge owing to its isolation from grid connection and its lack of hydro resources. In its unique position of having only intermittent renewables available and no potential for reversible hydro and grid connection, it has been decided to take the most advanced path of hydrogen storage.

A fluctuating population, due to the primarily tourism-driven economy, varying from 5500 to 13,000 has put enormous strains on the island utilities, especially the water and electricity production that has to be designed for the summer peak needs. The final energy demand per sector is given in Figure 1 for year 2000, showing the great relevance of transport.

The power system consists of a thermal power plant with two diesel-fired 3.5 MW engine blocks and three oil-fired 3.4 MW blocks, and a wind park with two 225 kW Vestas wind turbines and one 660 kW Vestas wind turbine, which was added in December 2000 [11]. Currently, operating 17 MW of thermal power and 1.1 MW of wind power was satisfying a demand of 29.8 GWh which was covered by 27.4 GWh of thermal production and 2.4 GWh of wind production [11] in 2002. The annual peak reached 5.4 MW in year 2000, growing at an annual rate of 20%. The base load, during out of season nights, is around 2 MW [11].

As the base load is only double the wind potential presently installed, in the situation when load is low, 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.

In 2000, Porto Santo road transport consumed 2274 toe of fuel, which corresponds to 75% of the total spent in transport in the island (3028 toe) and almost 40% of all primary energy consumed (5761 toe). The number of vehicles has been growing fast in the last years in the whole archipelago, especially concerning private-owned vehicles, thanks to the increase in wealth of local communities and the great development in road accesses. The total number of vehicles was growing at an annual rate of ~5% during the 1988–1997 period and about 9% during 1998 and 1999 [12]. The land transport sector alone, which globally represents 50%

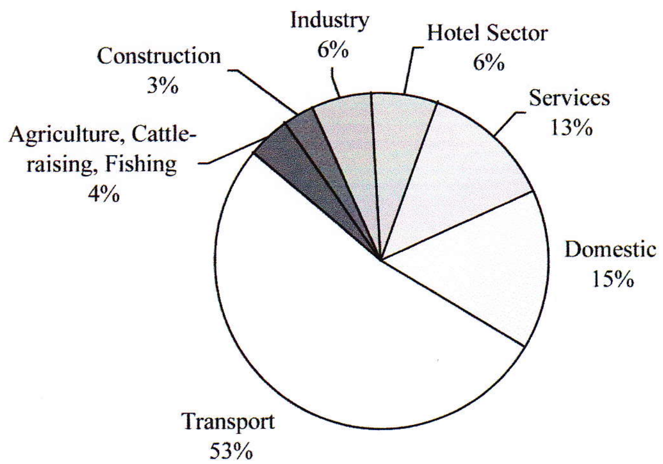

FIGURE 1 Porto Santo final energy distribution in 2000 by sector.

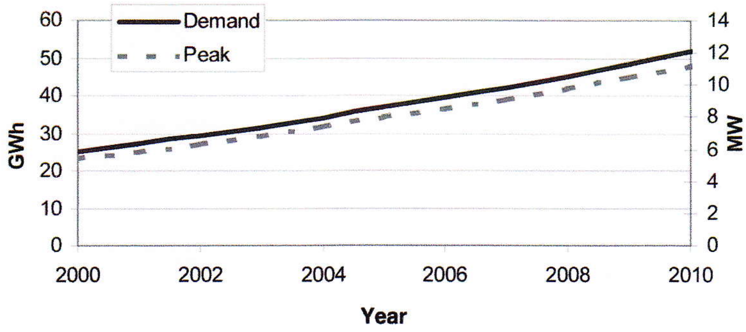

FIGURE 2 Electricity demand and power system peak scenario for 2000–2010.

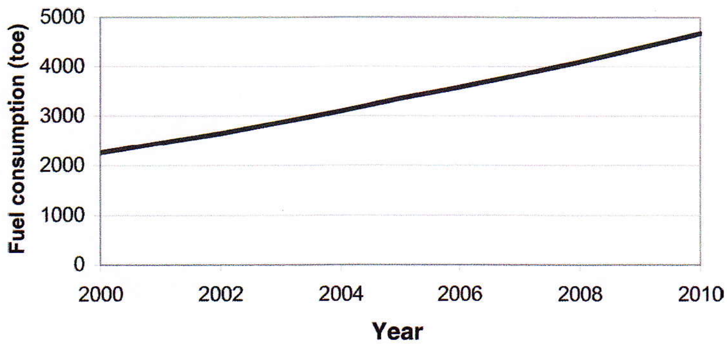

FIGURE 3 Fuel consumption for road transport demand scenario and tons of oil equivalent.

of the demand for final energy (for Porto Santo it corresponds to 53%), doubled consumption between 1991 and 2000.

Based on a hypothesis of regional development, national and European orientations, international markets of energy products, technological progress and environmental aspects, three scenarios (high, low and alternative) were constructed for the energy sector development in the Madeira region, as described in Ref. [12]. The values presented here for the demand are based on the high development scenario forecasts, and it is assumed that Porto Santo will show the same evolution as the Madeira region as a whole. The forecasts can then be used for medium-range planning on the energy sector.

The yearly electricity demand growth rate is expected to be 8% during the 2000–2005 period and 7% during 2006–2010 period. This means that Porto Santo's production will increase from 25.2 GWh in 2000 to 37.0 GWh in 2005 and to 51.9 GWh in 2010 (Fig. 2). If the yearly peak follows the same growth rate, it will increase from 5.4 to 8 MW in 2005 and to 11.1 MW in 2010 (Figure 2).

For the high scenario, the yearly growth rate for fuel demand for road transport is assumed to be 8% during the period 2000–2005 and 7% for the period 2006–2010 (Figure 3).

PEAK SHAVING AS THE FIRST STEP

Electricity generated from intermittent renewable technologies, like wind turbines or solar panels, will not generally follow the pattern of load of the isolated power system. Depending on the quality of the control of such equipment installed, there are limits to its momentaneous penetration. With wind equipment that was usually installed in the islands in 1990s, such momentaneous penetration should generally not cross the 50% limit, allowing for 10–20% yearly penetration rate in case of average to excellent wind. Crossing the 50% limit could shut down the power system, so it is inadmissible. As in the power system, there is a need to balance output and load in every time step and there is no way to treat the excess output. One way is to have extra load, which will be turned on when needed, like pumps, deferrable load, or some kind of storage, and another way is not to produce the power in the first place. Active output control is a normal procedure for generator blocks, which will deliver any output needed between its minimum (30–50%) and maximum outputs. Wind turbines usually do not have active output control following the load, as they were designed to produce tiny outputs compared with continental power system. However, in islands it counts. There is, of course, a blunter tool to manually shut down wind turbines, when necessary.

This article researches the storage path, converting the excess of wind or solar electricity to hydrogen, and using the hydrogen later on for peak shaving, or possibly for transport means. Taking hold of nuances of peak shaving would enable to accelerate the path to significant increase of penetration of the renewable sources in isolated island power systems.

In order to compare peak shaving with hydrogen storage, between wind only (case 3) and wind and solar (case 5) renewable energy sources, the goal set was to have approximately similar ratios of electricity coming from fuel cell, 1% on yearly basis. In both cases, the direct renewable hourly output to grid was limited to 30% of the system load, to be on the safe side of 50% momentaneous intermittent limit.

Those two scenarios were compared with the baseline scenario (case 1), the one that could be considered a best conservative economically viable scenario, whilst maximising the renewable penetration. Wind energy can now be considered economically viable on islands, when not surpassing certain limit of penetration, taken here to be 30% on hourly basis. The wind case will have increased wind turbines capacity, and the wind-solar case will keep wind as in baseline, and the solar PV will be increased as necessary. All the cases will have a limit to

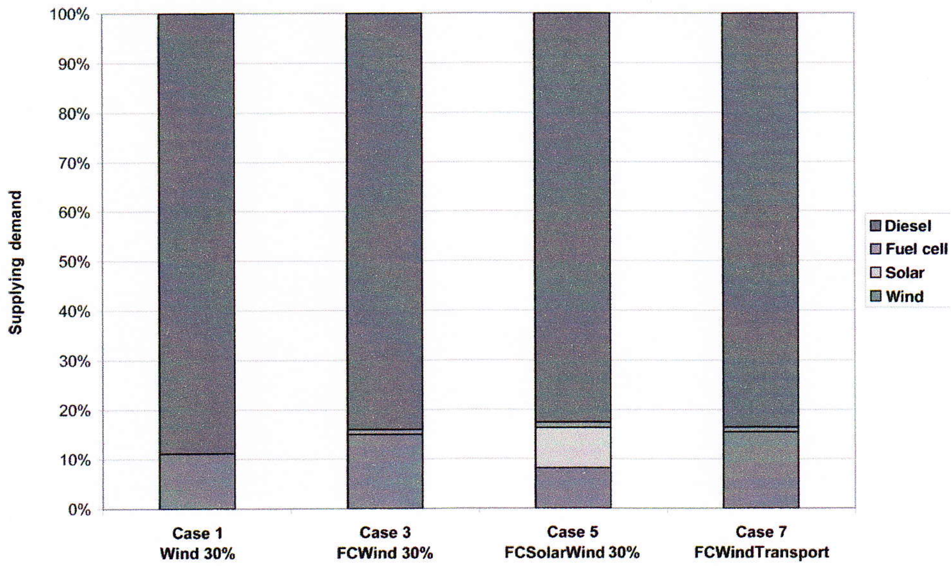

FIGURE 4 Comparison of demand supply per technology in different cases of 30% intermittent limit for the year 2010.

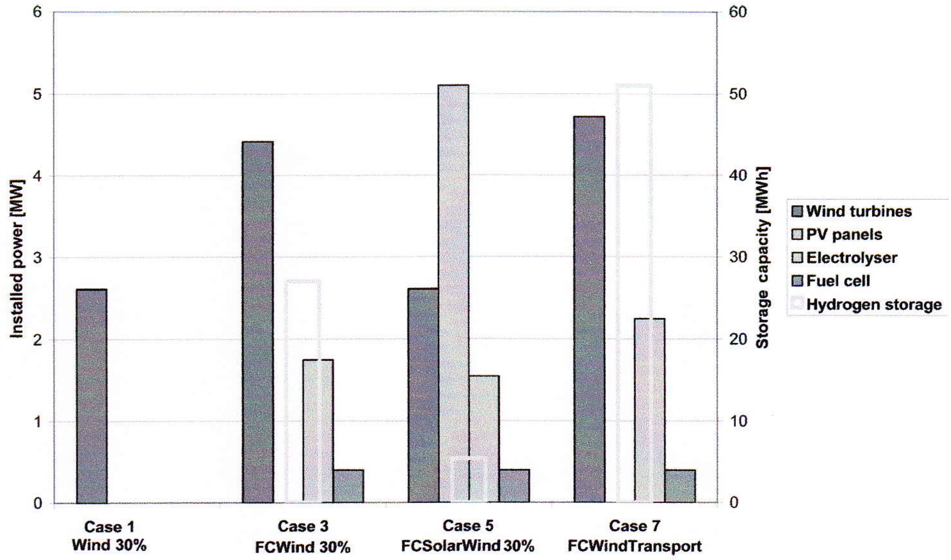

FIGURE 5 Comparison of components installed in different cases of 30% intermittent limit for the year 2010.

rejected intermittent electricity of 10%, which is reasonable on economical grounds, but is not solving technical problems of excess intermittent power.

In addition, a case (case 7) of fuelling three shuttle vans by hydrogen (40,000 km/shuttle/year, 0.05 kgH_2/shuttle/year, 2000 kgH_2/shuttle/year) was tested in conjunction with a wind peak shaving scenario. In order to have reasonable security of supply of hydrogen for shuttle, there has to be one month transport operation reserve (as the stationary use can be

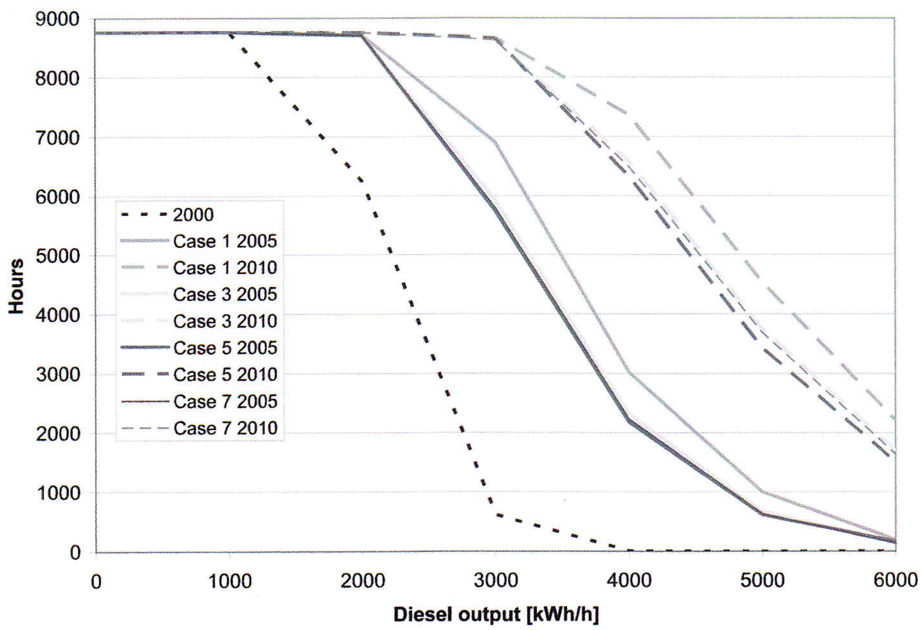

FIGURE 6 Load duration curves for diesel generators.

backed up with a diesel engine). When the hydrogen falls under that level, stationery fuel cell will not be used.

These cases differ in technologies installed, regarding both generation and possibility of storage of surplus energy. Figure 4 shows demand supply per technology, installed power and storage capacity that should be installed for each scenario in the year 2010.

Compared with the baseline, Figure 4, peak shaving scenarios will increase direct renewable penetration from 11% to 17% in case of same yearly excess permitted. This is due to much better handling of intermittent peaks, which can be stored now.

The comparison of peak shaving wind or solar in Figure 5 shows that by installing a convenient power of photovoltaic panels, we can reduce the hydrogen storage to 1/5 (electrolyser power also decreased, although not as significantly), while keeping the fuel cell at the same value, and still increase the overall renewable penetration to a small extent. This is because the intermittence of the solar potential is smaller (daily periodicity) than the intermittence of wind (five-day periodicity in this case), and so the storage is filled up more regularly.

When the three shuttle vans are added, the significant increase in hydrogen storage and electrolyser is apparent due to the increase in security of supply condition for transport, which is more than due to increase of hydrogen load.

The peak shaving will also have consequences to the diesel blocks, as shown in Figure 6, by decreasing the wear of those units.

CONCLUSIONS

Peak shaving by hydrogen storage would reduce the diesel generators wear and increase the renewable penetration significantly. The best combination of wind and solar installed power depends on the relative cost of hydrogen storage and solar PV panels, as utilisation of solar resource for peak shaving reduces hydrogen storage by 80%. The model was developed to simulate demands pertinent to the island system, water, power and hydrogen for transport, using available renewable resources and potential storage technologies, in order to increase the penetration of renewable energy, security of supply and sustainability of development of islands and isolated regions.

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