INTERNATIONAL JOURNAL OF HYDROGEN ENERGY 33 (2008) 1091–1103

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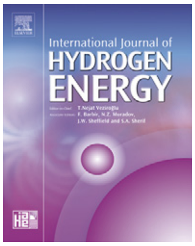
journal homepage: www.elsevier.com/locate/ijhydene



Hydrogen as an energy vector in the islands' energy supply

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ARTICLE INFO

Article history:
Received 2 March 2007
Received in revised form
4 December 2007
Accepted 4 December 2007
Available online 8 February 2008

Keywords:
RenewIslands methodology
H_2RES
Islands
Hydrogen
Renewable energy
Energy vector

ABSTRACT

Hydrogen as an energy vector can increase penetration of renewable and intermittent sources in the energy supply of the islands and it can serve as an energy vector that may allow reaching 100% renewable energy supply of island communities. This article presents summary of the results of several case studies: Island of Mljet—Croatia, Porto Santo—Madeira, Terceira—Azores, and Malta. The islands were analysed by RenewIslands methodology and it was decided to apply hydrogen as an energy vector. Different scenarios for each island were modelled by H_2RES software and required installed powers of necessary technological options are described for chosen scenarios.

Basically, there were two types of scenarios. Scenarios with 30% hourly penetration limit for electricity generated by intermittent sources, as a proxy to the current conversion technology being installed in island, and scenarios without this limit, as a proxy of available conversion technology that can also provide output control and ancillary services. When hydrogen as an energy vector was introduced in the scenarios with penetration limit, it was possible to increase penetration by 4–6% of total yearly electricity demand and it was possible to satisfy 100% of transport load by hydrogen from renewable energy sources. In scenarios without penetration limit it was possible to satisfy all electricity demand and hydrogen demand for transport from renewable sources.

1. Introduction

During the history the islands were places that provided shanty (shelters) for castaways; also they were places where people constructed lighthouses in order to show ships the safe way through dangerous waters. Today, islands may play another noble rule in global development by becoming perfect places for demonstration of new clean technologies and new pathways for sustainable development.

In Ref. [1] is stated "a tool that allows the transportation and/or storage of energy is called energy vector". The following is proposed as definition for an energy vector: "An energy vector allows to transfer, in space and time, a quantity of energy". So energy vectors allow to make energy available for use at a distance of time and space from the source, intended as the point of availability of the primary resource in nature [1].

Possibility for using hydrogen as an energy vector in the islands' energy supply is not a novel idea. In 1990s, the authors in [2,3] calculated the size of necessary hydrogen equipment for the energy supply of the Island of Lastovo in the Adriatic Sea; the authors also made the optimization of hydrogen storage. Ten years later the authors in [4,5]

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doi:10.1016/j.ijhydene.2007.12.025

presented similar solutions and proposed hydrogen produced by electrolyses as a tool for increasing penetration of intermittent sources. The authors also tackled the problem of energy storage, which is necessary to use in combination with intermittent renewable sources to make their better integration in energy systems and achieve security of supply. The integration of intermittent sources might be a complex problem but with a proper planning of energy systems it could be solved or minimized. No matter of size of power system the problem exists. The authors in [6,7] tackle the problem of surplus electricity and intermittence on the country/region level while articles [4–10] give solutions for islands. The conclusion of all these articles is that in order to solve intermittence problem, there is need for energy storage.

Depending on strategies and goals of system optimization, there have been different solutions which include hydrogen. Additional proposed solutions for achieving higher penetration of intermittent sources are integration of energy flows, combining power production and transport sector and investment in flexible energy supply and demand systems [6,7], or integration with sea transport [9]. In [4] authors find out that peak shaving by hydrogen storage would reduce the diesel generators' wear and increase the renewable penetration significantly. Combination of hydrogen technologies and operating strategies can increase penetration [11]. In the same article, the authors proposed strategy to increase wind energy penetration in an autonomous network. Their recommendation is to initially install *interrupted operation* systems in which the power produced every instant by the fuel cell is the average excess energy fed by the wind turbine through the electrolyser to the storage tanks during the immediately previous time step. The time step is chosen to be 24 h, since production planning is usually done on a daily basis. These systems can effectively increase annual penetration even up to the point when the direct wind-turbine power in the grid approaches the power quality limit of 30–40%. After that point, it might make sense to make transition to fuel cell-first systems, which may extend penetration factor up to 100%—total coverage of the island's energy needs from wind power [11]. Results in [8] show that it is possible to replace conventional power stations on islands with a hybrid system, delivering energy under constant power with fuel cell sizes that reach almost up to $\frac{1}{3}$ of the nominal wind-turbine power and overall efficiencies that may exceed 60%.

While all mentioned articles are presenting plans for the development of energy systems on the islands, [12,13] present results of existing demonstrational stand-alone hydrogen systems, which have been installed on two European islands. In [13] hydrogen is used only for power generation in fuel cell or stationary hydrogen IC engine, while in [12] electricity system is integrated with transport fuel system so that hydrogen is additionally used for transport purposes. Another example of using renewable hydrogen is the Yakushima Island which is abundant with rainfall and it has huge hydropotential. A hydrogen fuelling station was constructed on the island with on-site production of hydrogen by water electrolysis; produced hydrogen is then stored as a compressed gas and supplied to the fuel cell vehicles for their testing [14]. Researchers also proposed the Yakushima Island as one of the most suitable areas in Japan for a hydrogen economy system to be realized in the future [15]. More demonstrational plants for hydrogen generation from renewable sources are given in the report in [16].

These installations are valuable for development of hydrogen as an energy vector as much as it is valuable decision of Iceland to transfer into to a hydrogen-energy economy [17]. Iceland captured world attention in February 1999 when it declared a national goal to convert its economy to hydrogen energy by 2030. With only 294,000 inhabitants and no fossil fuel resources, Iceland has tapped its ample hydroelectric and geothermal energy resources to supply over half of its energy requirements and almost 100% of its electricity needs [17]. The oil-import dependence of Iceland's significant automobile and fishing boat fleets is high, however, which are the primary targets for the planned conversion to hydrogen. With inexpensive electricity at 2 cents/kW h, Iceland already makes 2000 ton of electrolytic hydrogen a year and thus hopes to provide sufficient renewable hydrogen for its entire transport sector [18].

The most island energy systems are highly dependent on import of fossil fuels, and in the time when crude oil price is hovering under 100$ per barrel (2007), sustainability of life and economy on islands is becoming increasingly strained. The cost of clean energy from renewable sources (wind, tidal, gravitational, geothermal, and solar) should not increase in constant dollars because these sources are not affected by the exhaustion of oil [19], which makes another argument to use hydrogen produced by renewable as an energy vector in islands.

The wider idea that certainly supports use of hydrogen as an energy vector is hydrogen economy [20] and it becomes more and more attractive as problems related to use of fossil fuels become significant: their price, security of supply and greenhouse gas emissions. The attractiveness of idea is shown in the article in which authors propose use of hydrogen produced by renewable energy in the rural areas of Venezuela, country among top 10 world producers of oil and with significant proven oil reserves [21].

The primary goal for using hydrogen as an energy vector on islands was to increase the penetration of renewable energy and to ensure security of energy supply or to satisfy the demand with local resources. But hydrogen also gives other benefits like reduction of CO_2 emissions and integration of flows (it allows to integrate production of electricity and fuel for transport).

The second section of the article gives short description with basic facts about RenewIslands methodology and H_2RES model, which has been updated for calculations. This section is followed by results summary of four islands' case studies and conclusion.

2. Methodology

2.1. *RenewIslands methodology*

RenewIslands methodology [22] was developed in order to enable assessment of technical feasibility of various options for integrated energy and resource planning of island:

1. mapping the needs,
2. mapping the resources,

3. devising scenarios with technologies that can use available resources to cover needs,
4. modelling the scenarios.

The needs are commodities that the local community demands, not only energy (electricity, heat, cold, fuel for transport, etc.), but also all other types of commodities (or utilities in the old command jargon), like water, waste treatment, wastewater treatment, etc., that are dependent on energy supply.

The resources are not only locally available ones, like wind, sun, geothermal energy, ocean energy, hydropotential, water resources, but also imported ones like grid electricity, piped or shipped natural gas, oil derivatives or oil, water shipped, the potential to dump waste and wastewater, etc.

The technologies can be commercial energy conversion technologies, like thermal, hydro- and wind electricity generation or solar thermal water heating, commercial water, waste and wastewater treatment technologies including desalination, or emerging technologies, like geothermal energy usage, solar electricity conversion systems, or technologies in development, like fuel cells, wave energy, etc.

The scenarios should try to satisfy one or several needs, by using available resources, and satisfying preset criteria. Due to global warming and falling reserves, and sometimes security of supply problems, fossil fuels should generally be used as the option of last resort in setting scenarios, even though they will often provide the most economically viable solution with the current price levels, and advantage should be given to locally available renewable resources.

The methodology was applied to four islands and the conclusions differed more in first two steps, depending more on local conditions, while the third and fourth steps resulted in more similarities, predicting that electricity and hydrogen were good solutions for energy carriers or energy vectors, in case of given constraints.

2.2. H_2RES computer model

The H_2RES model is designed as a tool for balancing hourly time series of water, electricity, heat and hydrogen demand, appropriate storages (hydrogen, reversible hydro, batteries) and supply (wind, solar, hydro, geothermal, biomass, fossil fuels or mainland grid). The model has been designed as support for simulation of different scenarios devised by RenewIslands methodology [22] with specific purpose to increase integration of renewable sources and hydrogen into island energy systems. The main purpose of the model is energy planning of islands and isolated regions that operate as stand-alone systems, but it can also serve as a planning tool for single wind, hydro- or solar power producers connected to bigger power systems.

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

The solar module converts the total radiation on the horizontal surface into the inclined surface, and then into the output.

The hydromodule 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.

The biomass module takes into account the feedstock information, the desired mix of feedstocks, conversion processes (combustion, gasification and digestion) and desired output production (power, heat or combined heat and power). Biomass module is set to follow the heat load and it generates electricity as by-product. This module has the ability to calculate the minimum and maximum potential energy output in order to make optimization of production to avoid unwanted shutdowns. The minimum energy output (power or heat) of single block is a factor between the installed capacity and the minimum load factor. This assures that the unit never goes below minimum design value. If the available energy is below this, it shuts off. The maximum also depends on the available energy and, if it is necessary, maximum is reduced to value given by optimization, which is based on the guarantied production days. Basically the system tries to plan continuous production during guarantied period according to available energy in biomass storage and it does not take into account possible further deliveries of biomass, considering only what is in storage at a certain hour. This is a major factor when dealing with isolated systems that cannot afford to run out fuel constantly and hence why it is highlighted here.

The geothermal module functions as base load, where the installed power generates electricity for the system continuously, except when it is in maintenance. The system primarily uses the electricity produced from geothermal source in detriment of the other power sources, because this is a constant, not intermittent, source. The H_2RES allows managing the amount of electricity produced from geothermal that enters in the grid and satisfies the electricity demand and the one that goes for storage; this becomes very useful when intending to use the geothermal potential for hydrogen production for transports.

The load module, based on a given criteria for the maximum acceptable renewable electricity in the power system, integrates a part or all of the available renewables output into the system and either stores or discards the rest of the renewable output. The excess of renewable electricity can be stored either as hydrogen, pumped water or electricity in batteries, or for some non-time critical loads. The energy that is stored can be retrieved later and supplied to the system as electricity or hydrogen for transport purpose. If there is still unsatisfied electricity load, it is covered by fossil fuel blocks or by the mainland grid where such connection exists. The model can also optimize the supply of water and hydrogen demand.

The sequence of sources in supplying of demand could be easily set up according to the criteria. In the most cases, first the system will take geothermal energy, then biomass and then the rest of renewables. Current model does not support the automatic choice of sources according to minimal cost of electricity or according to minimal environmental pollution.

The wind module of the H_2RES system is designed for accepting up to four types of wind turbines, which may be located in two different wind parks. The conversion from wind velocities to electrical output is done using wind-turbine characteristics obtained from the producer. The solar module can use either data for solar radiation on a horizontal surface, which then has to be adjusted for the inclination of PV array, or it can use direct radiation on a tilted surface. The adjustment of solar radiation to the inclination angle is done by monthly conversion factors, which are calculated by the RETScreen [23] or the PV-GIS programme [24]. Efficiency data for PV modules and other components (inverter, line losses, etc.) can be obtained from the producer and they serve for calculation of the hourly PV output. The hourly precipitation data of the hydromodule can either be obtained from the nearest meteorological station, or can be estimated by using daily, weekly or monthly averages. Generally, the necessary resolution of the precipitation data should be dependent 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. The load module of the H_2RES model, based on a given hourly renewable and intermittent 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 excess electricity can be exported if the island has a connection with the mainland grid. The storage module can either be based on an electrolysing unit, a hydrogen storage unit and a fuel cell or a hydropumping storage, a reversible fuel cell or batteries. The input into the storage system is limited by the chosen power of the electrolyser, the pumps or the charging capacity of the batteries, so the renewable excess power which is superfluous to the storing facility or cannot be taken to the storage system because the storage is full has to be dumped or rejected. On islands, there is often also a need for the desalination of seawater, which might be a good destination of dumped load, water pumps or refrigeration units.

For the purpose of calculation of case studies described in this article, the basic version of H_2RES 2.0 has been upgraded by grid module (version 2.1), which in the case of the Island of Mljet enabled import and export of electricity, fossil fuel module (version 2.2), which allowed use of six different types of fossil fuel blocks in the case of Malta, and geothermal module (version 2.3), which has been used for the Terceira Island case study.

As it was mentioned earlier, detailed description of the model with equations has been given in [4]. The main equation for a energy demand for a certain hour that has been changed is

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

where E_{geo} represents the geothermal energy, E_{T}, E_{FC} and $E_{\mathrm{bat,out}}$ the hydroenergy, the fuel cell and the battery energy, E_{P}, E_{el} and $E_{\mathrm{bat,in}}$ the energy used for pumping of water into higher reservoirs, water electrolysis and battery charging, E_{G} the energy from the grid (mainland), E_{ff} the energy from the fossil fuel blocks and $E_{\mathrm{I,t}}$ the intermittent renewable electricity taken by the system.

The total intermittent, $E_{\mathrm{I,pot}}$, potential will be either taken by the system or used in pumps, by electrolyser or stored in batteries, sent to the grid if there is possibility for export $E_{\mathrm{G,s}}$ and the rest will be rejected E_{r}:

$$E_{\mathrm{I,pot}} = E_{\mathrm{I,t}} + E_{\mathrm{P}} + E_{\mathrm{el}} + E_{\mathrm{bat,in}} + E_{\mathrm{G,s}} + E_{\mathrm{r}}. \tag{2}$$

The current version of the program H_2RES 2.8 has also integrated biomass module, heat module including heat storage, wave module and desalination module.

3. Results

As each island in Table 1 has its own specific condition (weather, resources, size, population, economy, etc.), the case studies of the islands should not be compared with each other, only the scenarios of each island case should be compared. The price of electricity in the scenarios on different islands certainly could be a good parameter for overall comparison, but economy of the scenarios is not discussed in this article.

For each island hourly load data and hourly meteorological data have been collected and used in H_2RES model.

3.1. *The results of the Island of Mljet case study*

The Island of Mljet is situated in the southern Dalmatian archipelago, Croatia, 30 km west from Dubrovnik and south of the Peljesac Peninsula, separated from it by the Mljet channel. While tourism is the most valuable economy sector on the island, it also strains the resources (water, environment, electricity), especially during the summer months when population on the island is two to three times bigger than in the winter. The power system of the Island of Mljet is connected to mainland grid with two undersea cables.

Table 1 – Island characteristics

Island	Surface (km^2)	Population	Predicted electricity demand in 2010 (kW h)	Electricity per capita (kW h/cap)	Installed units for RES utilization in 2005
Mljet	100.4	1111	4,632,832	4170	No
Porto Santo	49	5000	51,826,341	10,365	Yes
Terceira	396.75	55,000	231,003,977	4200	Yes
Malta	320	400,000	2,985,976,563	7465	No

Forecasted peak load for 2010 is 1750 kW and it will be reached during the summer months when tourist season is the most intensive.

According to the RenewIslands methodology, the needs and resources of the Island of Mljet were mapped and different scenarios were devised and finally modelled by H_2RES program [22,25,26]. In total 18 different scenarios were calculated and here the most interesting results are presented. The scenarios are different according to installed technology, penetration conditions and optimization constraints.

Generally, all scenarios were divided into two groups. The first group of scenarios has a limit on hourly penetration of electricity from intermittent sources. The limit is set at 30% of hourly system load meaning that in each hour, power system will accept up to 30% of electricity coming from wind or solar. In these scenarios the undersea connections with mainland grid are considered only as energy sources, without possibility to evacuate the excess of electricity produced on the island. This is set to ensure the grid stability and to be sure that electricity will have proper voltage. The H_2RES does not have capability to calculate grid dynamics and momentaneous penetration, so limit is introduced according to calculations [5]. Supplementary analysis of the local influences of the renewable energy sources on the grid behaviour and possible grid penetration with current state of the Island of Mljet was calculated afterwards by another dynamic simulation tool "POwer System SIMulations" (POSIM) and it has been presented in article [27].

The second group of scenarios calculated by H_2RES does not have the penetration limit, so if there is enough wind or solar energy, whole power system load will be covered by the renewable sources. In these scenarios it is possible to export the excess of electricity to the mainland grid.

The scenarios with hydrogen used in transport had hydrogen load represented by three shuttle vans doing 56,800 km yearly with the fuel consumption 0.05 kg H_2 per km and by scooters with fuel consumption 0.33 kg H_2 per day.

As it was mentioned earlier, different scenarios also have different modelling and optimization conditions. The scenarios with 30% penetration limit are optimized in the way such that penetration of RES energy is maximized while rejected intermittent energy is kept under 10% of the total intermittent potential. The scenarios with 100% of momentaneous penetration are also optimized for maximal penetration of RES while keeping the exported electricity at 30% of yearly intermittent potential. In the 100% renewable scenarios, the size of installed components is kept as small as it is possible. All scenarios are calculated for 2005 as a base year and targeted years 2010 and 2015. The 7% yearly growth of energy consumption is used for the power system and for the transport purpose.

3.1.1. *Scenarios with 30% limit*

The total installed power or capacity of components in chosen scenarios with 30% limit on hourly penetration of intermittent sources for year 2010 is given in [28]. Installed components in selected scenarios are presented in (Fig. 1). The grid connection with mainland is the same in all scenarios and two cables can together accept maximal power of 7676 kW. Scenario 5 represents hybrid solution that includes installations of wind turbines and PV panels. The maximized penetration of energy from intermittent sources in Scenario 5 in 2010 was achieved with installation of 255 kW of PV or 3000 m^2 covered by PV panels and three FL30 (3 × 33 kW) wind turbines. In all scenarios efficiency of PV modules was set to 8.5% and total efficiency of PV installation was 5.8%. Four types of wind turbines were selected and they been considered in calculations. The smallest Fuhrländer FL30 has power of 33 kW, Vestas V27 225 kW, ENERCON type E-30 300.5 kW and the biggest Vestas V-47 660 kW. The smaller size of wind turbines was chosen because of the low load of the power system during wintertimes and easier integration of smaller wind turbines into the environment.

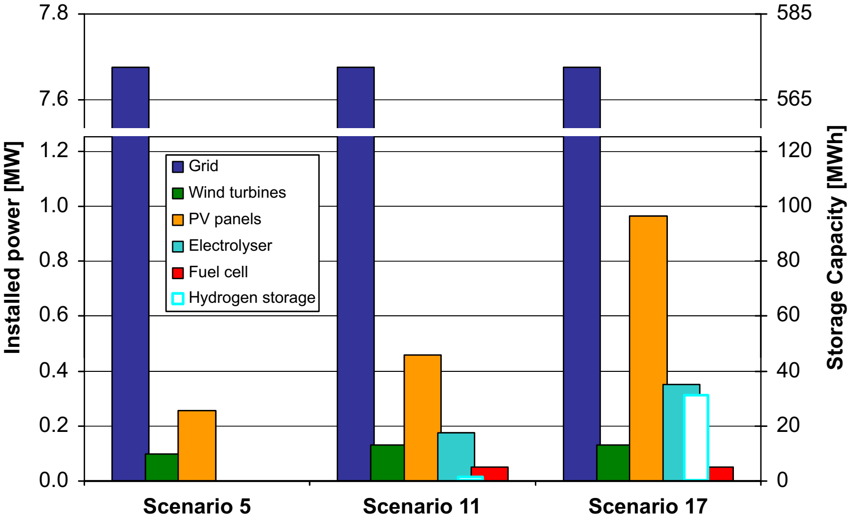

Fig. 1 – Installed components in scenarios with 30% penetration limit in 2010.

Scenario 11 is similar to Scenario 5 but it has an additionally installed fuel cell, electrolyser, and hydrogen storage. The fuel cell was used for peak shaving and it means that fuel cell will operate only when power load is bigger than 80% of weekly peak. Hydrogen was produced when there was excess of wind or solar energy. The optimization constraints in Scenario 11 were satisfied with installed 132 kW or four FL30 wind turbines and with 459 kW of PV or 5900 m^2 covered by PV panels, 175 kW electrolyser, 50 kW fuel cell and hydrogen storage with capacity of 1.2 MW h or 400 N m^3. In all scenarios the efficiency of fuel cell was set to 50% and efficiency of electrolyser including the compressor was 60%.

The last three scenarios in this group differ from Scenario 11 only by the additional hydrogen load for transport. The main reason for increasing the storage capacity in these scenarios was security of supply of transport fuel which was set to 720 h; this limit ensures that there will always be enough hydrogen for transport purposes and that fuel cell will not operate when hydrogen level is below the quantity determined by that limit.

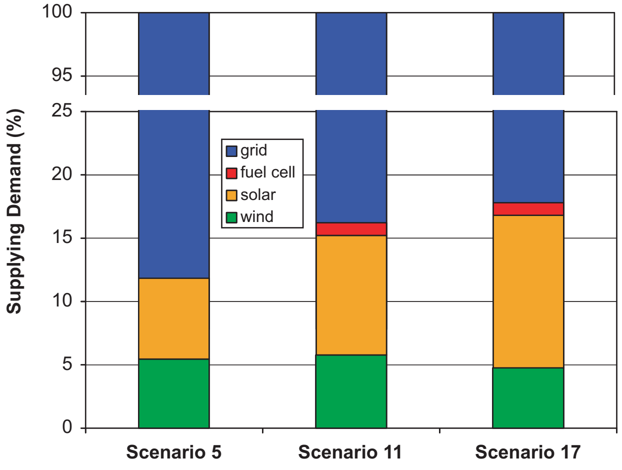

Fig. 2 – Supplying demand in scenarios with 30% penetration limit in 2010.

Achieved penetration is shown in Fig. 2 and for Scenario 5 it was 12%. When hydrogen was introduced as in energy vector, it was possible to increase penetration by 4% to total 16% of electricity demand. Scenarios with hydrogen load represent 100% renewable scenarios concerning the hydrogen transport and maximal penetration of 18% was achieved in Scenario 17. This scenario demonstrates a combination of sources and integration of flows (production of electricity and hydrogen).

3.1.2. *Hundred percent renewable island*

The second group of scenarios did not have penetration limit, so it means that if there is enough wind or solar energy all load will be satisfied from this intermittent renewable sources with possibility to export excess to the mainland grid. In Scenario 6 only wind turbines and PV panels were considered while all other scenarios also considered installing fuel cell big enough to satisfy peak load (Fig. 3). With this size of fuel cell and with calculated minimal size of other components, it was tried to achieve 100% renewable scenarios while in the same time exporting 30% of yearly intermittent potential.

Supplying demand in 2015 is shown in Fig. 4. It can be noticed that with only installed wind and PV it is maximally possible to supply 50% of demand while the rest of electricity must be supplied from mainland grid. In the scenarios with installed fuel cell there was no electricity coming from the mainland grid, so Scenarios 12, 14, 16 and 18 were 100% renewable. Scenario 12 was 100% renewable only concerning electricity demand, while other scenarios were 100% renewable concerning both electricity and hydrogen demand for simulated transport.

More detailed description of the use of intermittent potential is shown in Fig. 5. Categories wind and solar taken represent energy that was used for direct supply of the load, while wind and solar stored represent excess that was stored in the form of hydrogen and later used on fuel cell or for transport purposes. The intermittent taken into grid

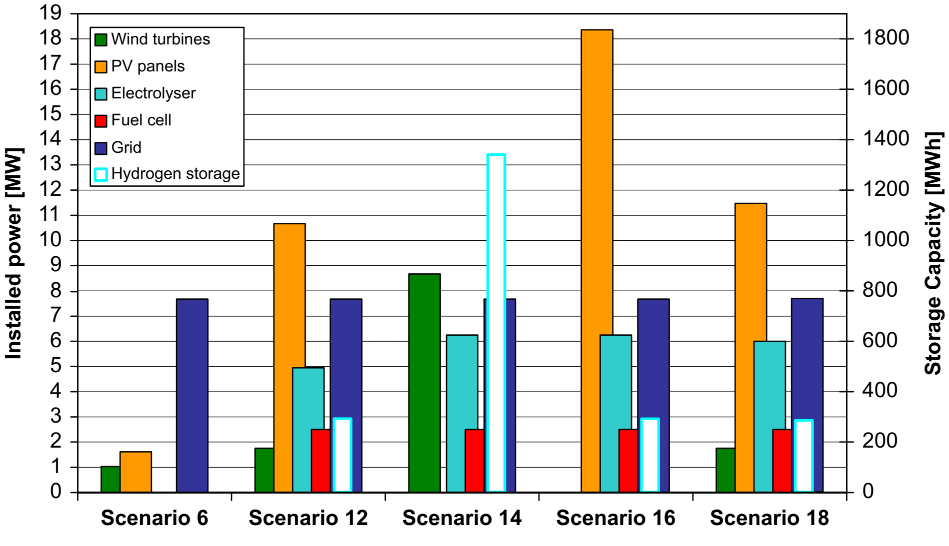

Fig. 3 – Installed components in 2015 in scenarios without penetration limit.

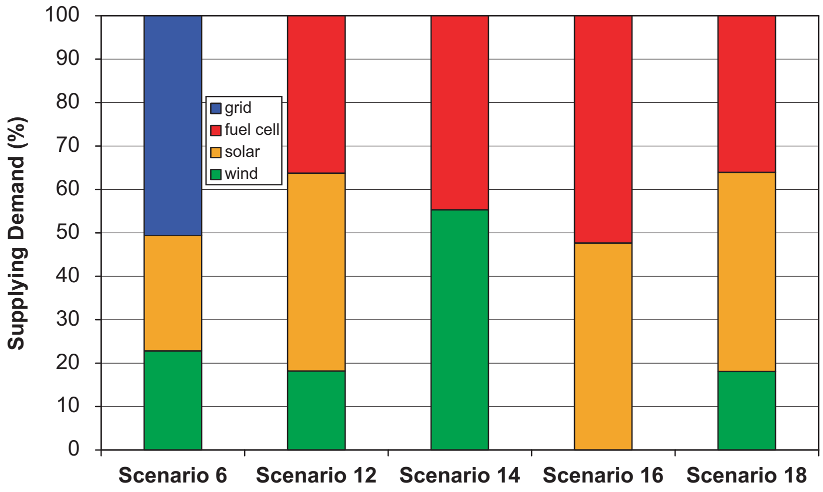

Fig. 4 – Supplying demand in 2015 in scenarios without penetration limit.

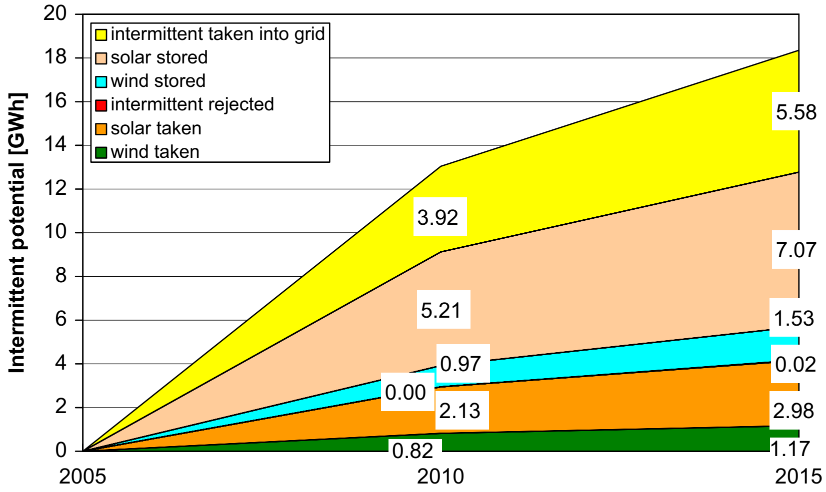

Fig. 5 – Intermittent potential in Scenario 18.

represents all excess that could not be stored, so it was exported to the mainland grid. The intermittent rejected represents the rest of potential excess that could not be stored or exported to the mainland grid. This was in the case when potential was bigger than electrolyser and undersea cable capacity.

Use of hydrogen as an energy vector allowed harvesting of all intermittent potential and covering of all electricity demand of the island and demand of simulated transport.

The primary generation for Scenario 18 on the Island of Mljet in 2015 is shown in Fig. 6. The same figure shows the amount of electricity directly taken into the grid, stored or exported and also shows which part of hydrogen is used for electricity production and which goes for the transport purposes.

The growth of hydrogen storage capacity in Scenario 18 is shown in Fig. 7. Comparing Scenario 18 that has hydrogen load for the transport and Scenario 12 without hydrogen load, it can be concluded that the size of hydrogen storage is almost the same while the need was covered by bigger generation capacities and electrolyser. This was not a case in scenarios with penetration limit as fuel cell was used only for the peak shaving, so there was a need to introduce bigger storage in case of hydrogen load. In Scenarios 12 and 18, fuel cell is used when there is no wind or sun, so storage was big enough to use a part of hydrogen also for transport purposes. The bigger solar installations allow more regular daily filling of the storage.

3.2. *The results of case study of the Island of Porto Santo*

More detailed description of the island and its energy system is given in articles [5,24].

Porto Santo is inhabited by 5000 yearlong residents, most of them living in the capital, Vila Baleira; their main occupation is tourism and activities that depend on it. The number of tourists and part time second house residents fluctuates

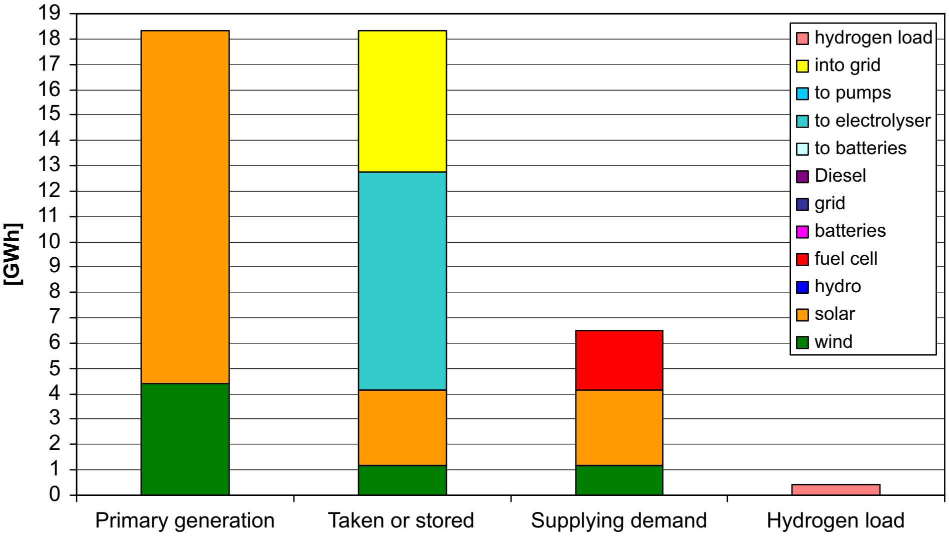

Fig. 6 – Primary generation in 2015, Scenario 18.

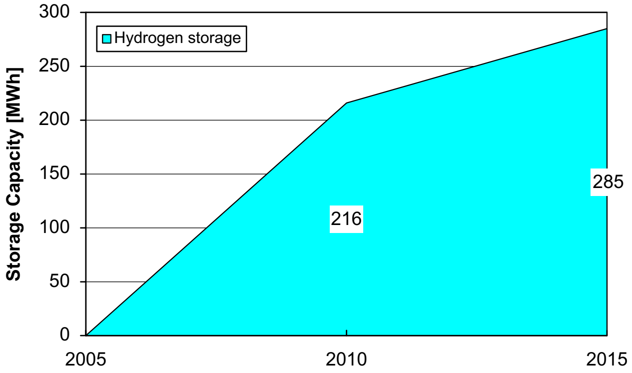

Fig. 7 – The growth of hydrogen storage capacity in Scenario 18.

between 500 in the wintertime and reaches up to 10,000 in the summertime. Tourism has given Porto Santo an economic dynamism that has been growing year by year.

The results of case study of the Island of Porto Santo are in detail described in [4,5]. Only new results for 100% renewable island will be presented here.

Scenarios 2, 4, 6, 8 and 9 differ in technologies installed, regarding both generation and possibility of storage of surplus energy, but they all allow for 100% penetration of intermittent renewable sources. Also, Scenarios 4, 6, 8 and 9 represent 100% renewable scenarios for electricity generation. Scenarios 8 and 9 besides basic load have a hydrogen load represented by three shuttle vans operating on fuel cell, and doing 40,000 km per year per shuttle. With an average car economy of 0.05 kg H_2/km, that makes 2000 kg H_2 per shuttle per year. For simplicity reasons the hourly load of hydrogen for the shuttles will be considered as constant throughout the year, which does not cause much error as the load is quite small. Fig. 8 shows the equipment power and storage capacity that should be installed for each scenario in 2010.

Efficiencies, type of equipment and optimization constraints were the same as in the case of the Island of Mljet. It is clear that, for 100% renewable scenarios, the storage size reduction thanks to PV introduction is not very important. This happens because, as the hydrogen cycle must cover all unsupplied demand, the storage is not allowed to be empty at any time and the relevance of the smaller intermittence of solar resources is not as important as in the peak shaving cases.

To achieve 100% renewable island in the year 2010 with 11.1 MW yearly peak and electricity demand of 51,826,341 kW h, there has to be installed more than 50 MW of power, Scenarios 4 and 6. In scenarios that included transport, the values of installed power rise up to 73.2 MW in Scenario 8 and 93.4 MW in Scenario 9. For both scenarios 27,250,711 kW h of additional hydrogen demand for transport has been supplied.

As seen in Fig. 9, in Scenario 2, when 100% intermittent limit is allowed but no storage is used, the electricity supplied by wind is about 50% on yearly basis. With storage based on hydrogen cycle (Scenarios 4 and 6), one manages to increase the renewable penetration to 100%, and virtually eliminate the use of diesel blocks, which are kept as backup.

3.3. *The results of case study of the Terceira Island*

The Terceira Island is an island in the Azores, in the middle of the North Atlantic Ocean, with an area of 396.75 km^2. Terceira is the third largest island after São Miguel and Pico. The island's length is 29 km and the width is 18 km; the perimeter is 90 km. Population is 54,996, down from a peak of 59,000. Population density is 140.73 km^2. The western part of Terceira is covered with vegetation. The northern part of the island is made up of a volcano. The highest point in the island is the peak of the Santa Bárbara mountain at 1022 m.

The Island of Terceira has good wind and geothermal potential and it is decided to increase the use of this renewable sources. In presented scenario the goal was to produce hydrogen for transport starting in 2010 and increasing

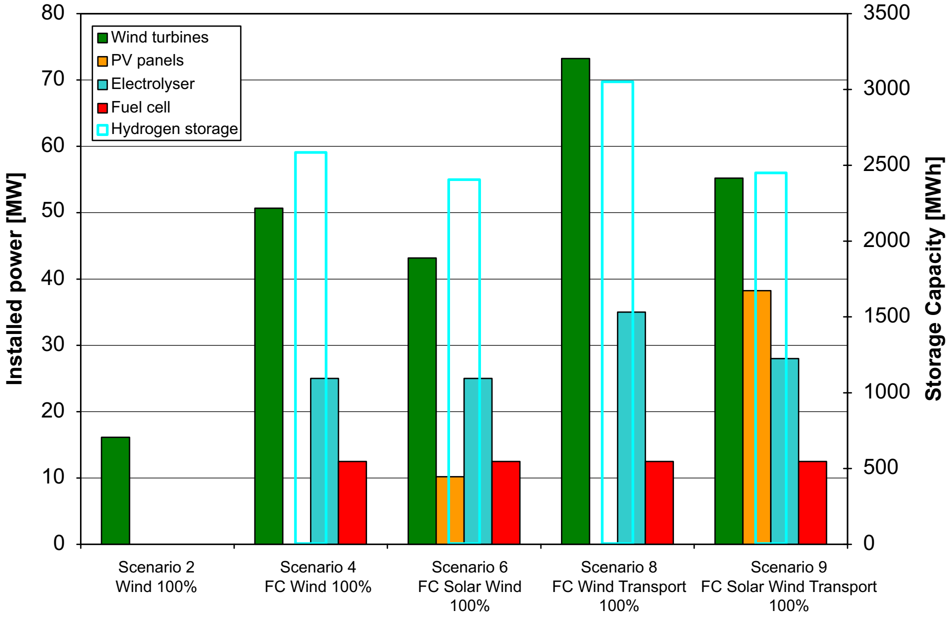

Fig. 8 – The comparison of components needed to be installed in different scenarios with allowed 100% intermittent penetration, Porto Santo year 2010.

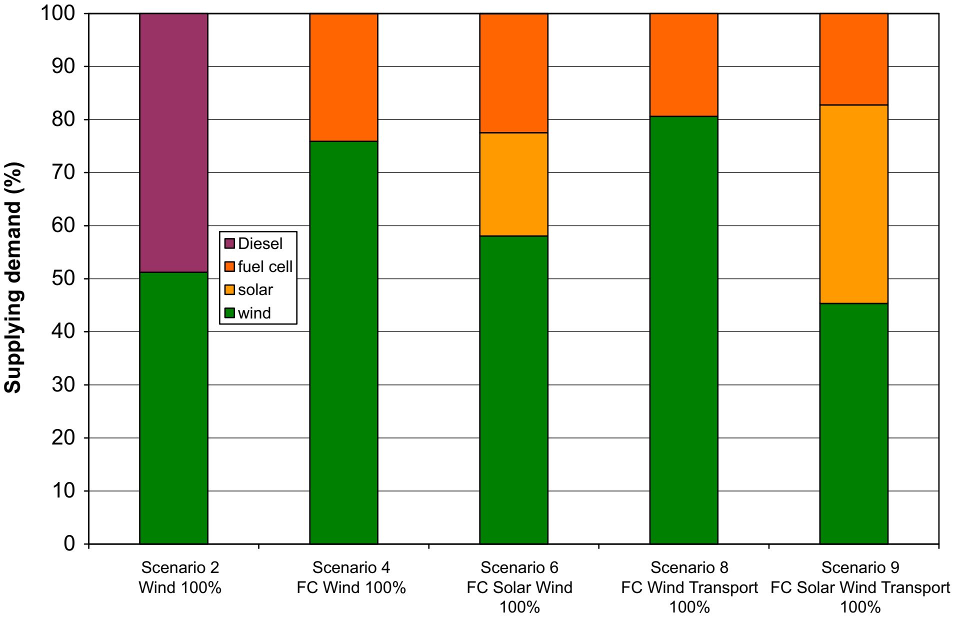

Fig. 9 – The demand supply per technology, in different scenarios with allowed 100% intermittent penetration, Porto Santo year 2010.

until 2025, so that in the end 100% of the transports in the island are propelled by renewable hydrogen. In this scenario it was necessary to install a very large geothermal power plant (250 MW in 2025) and electrolyser (234 MW in 2025) to satisfy the transport demand, also the fuel cells were installed either to increase the penetration of the intermittent sources or just for peak shaving. This is not the scenario with maximum reduction of greenhouse gases from the thermoelectric power plants, but in island terms this is the cleanest scenario because all the transports would stop emitting this kind of gases.

Fig. 10 presents the size of installed equipment until year 2025 when all transport loads on the island would be switched to hydrogen. It also can be noticed that size of fossil fuel power plants will be unchanged while installed power of other technologies increases significantly. The large amount of hydrogen used for transport (Fig. 11) not only requires big power of electrolysers but also the sources of electricity production, in case of this scenario geothermal energy.

Geothermal energy is a reliable energy source with good characteristics for power production so that in calculations different blocks of geothermal power plants have been used and described only by installed power, minimal load for operation scheduled maintenance period and efficiency that is connected to own consumption of the power plant. The supplying of electricity demand presented in Fig. 12 shows that electricity from geothermal sources decreases after 2015, which is the outcome of increased production of hydrogen for transport purposes by geothermal plants. If Fig. 12 is compared to Fig. 13, it can be seen that in 2015 around one-fifth of geothermal potential is used to satisfy electricity production while the rest goes to production of hydrogen; in 2025 this ratio drops to $\frac{1}{20}$ of used geothermal potential. On the Terceira Island a project for installing 12 MW of geothermal power is ongoing and will be finished in 2009. This installation will certainly give contribution to development of geothermal energy on Terceira Island, which lies in the Middle Atlantic Ridge with huge geothermal potential, but to commercially exploit 250 MW of geothermal power in 2025 the further estimations of available potential would be required. Another solution is to use novel technologies for production of hydrogen from geothermal sources explained in [29,30], which may contribute to better efficiency of hydrogen production and decrease necessary installed power.

3.4. *The results of case study of Malta*

The Maltese archipelago is centrally located in the Mediterranean Sea and comprises six small islands. The main islands are Malta, Gozo and Comino all of which are inhabited, while the islets of Filfa, Cominotto and St. Paul's Islands are uninhabited. The Maltese Islands cover a total area of 320 km^2 with a total coastline perimeter of approximately 140 km. With a current population of almost 400,000, Malta has one of the highest national population densities in the world, 1272 inhabitants per square kilometre. The present population growth rate is in the region of 0.75% according to UNFCCC report [31]. This small annual increase in the net population is primarily sustained by high life expectancy and a low emigration rate. Furthermore, population density is accentuated by the annual inflow of tourists, which is equivalent to about 30,000 additional residents mainly during the summer months.

3.4.1. *Malta hydrogen scenario: fossil fuel, renewable energy and hydrogen storage scenario for the transport sector*

The necessary blocks in order to obtain 5% of transport energy from renewable energy in 2015 are presented in Fig. 14. Type of selected wind turbine for calculation was Vestas V90 1.8 MW, and total efficiency of PV panels was set to 14.45%. Fuel cell efficiency is set to 60%, while electrolyser efficiency including compression was set to 80%. Supplying of electricity demand in devised scenario for calculated years is showed on Fig. 15 while distribution of intermittent potential in same scenario is presented on Fig. 16. In determining the hydrogen amounts necessary to fulfil the 5% target, a growth rate was worked out using figures extracted from the 10 year period 1990–2000 [32]. This growth rate (3.4%) was then applied to the 2003 values, 90 × 10^6 l of petrol and 90.40 × 10^6 l of diesel [33].

In order to keep the rejected energy within a 10% bracket, fuel cell blocks had to be integrated in the system, which

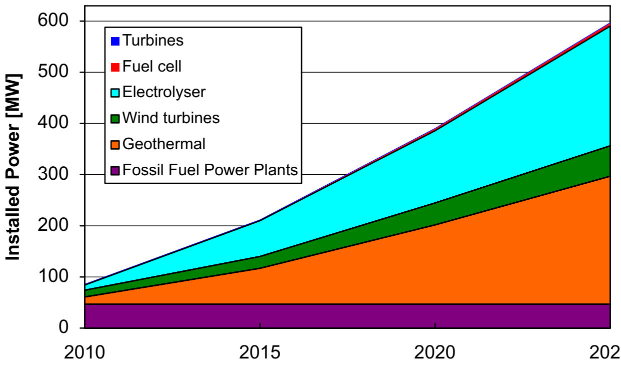

Fig. 10 – Installed power, Terceira.

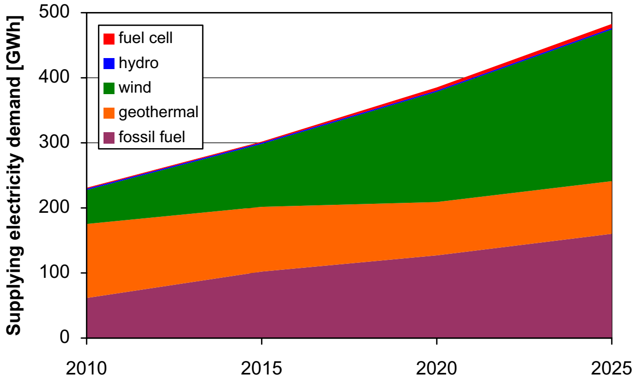

Fig. 12 – Supplying electricity demand, Terceira.

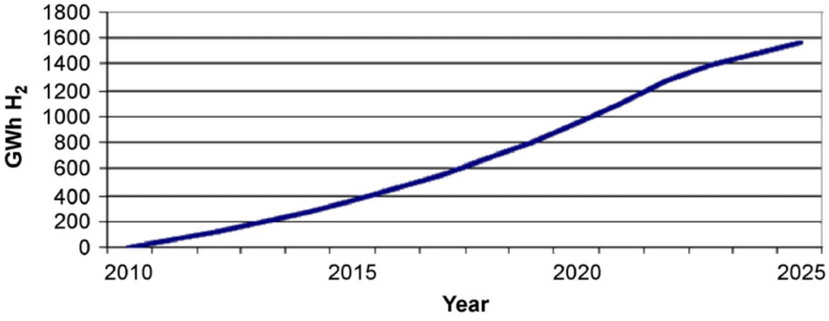

Fig. 11 – Hydrogen consumption in the transport, Terceira.

would operate when excess hydrogen is produced, provided a security of supply of 240 h is stored. The 10 day security of supply was chosen so as to balance the need for security and the size of the storage. The net effect of the energy supplied to the grid by the fuel cells is negligible; however, this was done to minimize the rejected energy. A rejected energy of less than 10% was imperative in the results. Utilizing all of this energy is quite impractical when opting for a high level of renewable energy. The blocks of fuel cells were chosen such that a minimum operation of 1500 operating hours was achieved. This ensures correct figures in wattage and numbers. Similarly, in choosing the size of blocks it was ensured that adequate period of operation was reached.

4. Conclusion

The results of case studies show that hydrogen as an energy vector is a technically feasible solution beyond fossil fuels and that hydrogen can ensure security of energy supply and increased utilization of local renewable sources. It is also proven that hydrogen as an energy vector could be applied to smaller islands as well as to bigger ones. In the case of smaller islands, hydrogen technology will allow them to become 100% renewable islands concerning electricity supply and transport, while in the case of bigger islands, as Malta, hydrogen could give a very valuable contribution in reduction of use of fossil fuels, especially if it is used as fuel in transport.

With allowed maximal penetration of intermittent sources and without hydrogen as an energy vector for given constraints, it was possible to satisfy 50% of island power demand in the cases of the islands Mljet and Porto Santo and for achieving higher penetration it was necessary to introduce energy storage. The size of energy storage depends on installed components for utilization of renewable and intermittent sources and on the optimization conditions. The best combination of wind and solar installed power depends on the relative cost of hydrogen storage and solar PV panels, as utilization of solar resource for peak shaving reduces hydrogen storage by 80% [4].

The results of four case studies could also become input for bottom up development of hydrogen economy stated in [34] where hydrogen is described as a swing producer for intermittent power generation units especially in connection with wind power parks and solar systems. This concept is well suited for island societies. It is recommended to start with two islands of about 10,000 inhabitants. This is an arbitrary size chosen in order to have a reasonable size and a most likely infrastructure to build on [34].

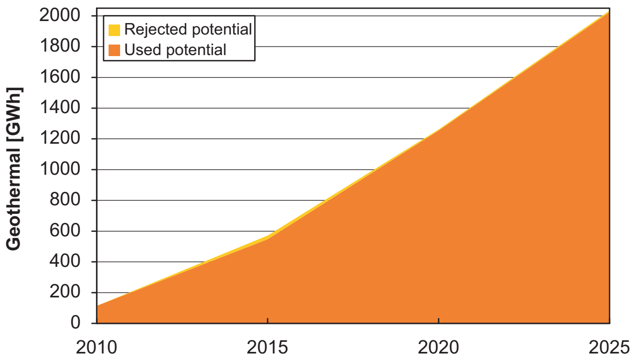

Fig. 13 – Using of geothermal potential, Terceira.

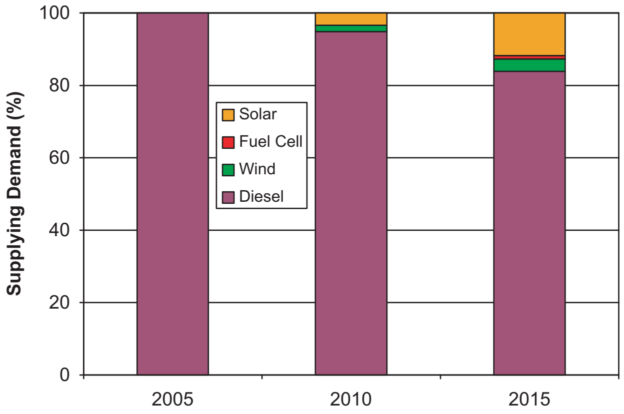

Fig. 15 – Supplying demand in devised scenario for Malta.

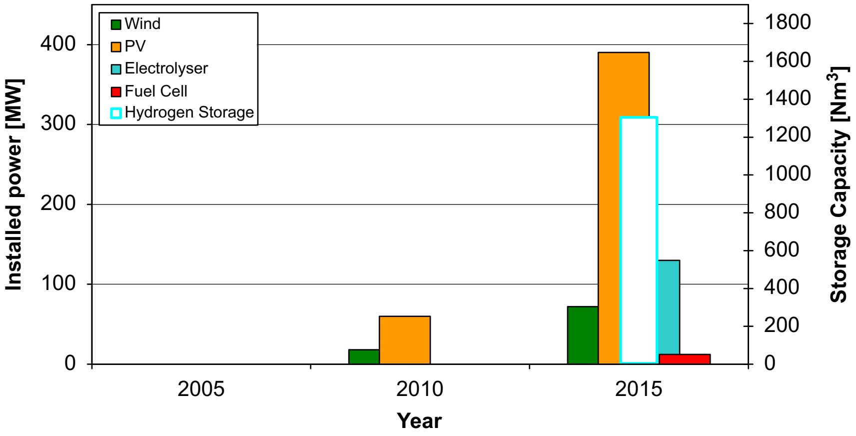

Fig. 14 – Installed components for renewable energy utilization and hydrogen production, Malta.

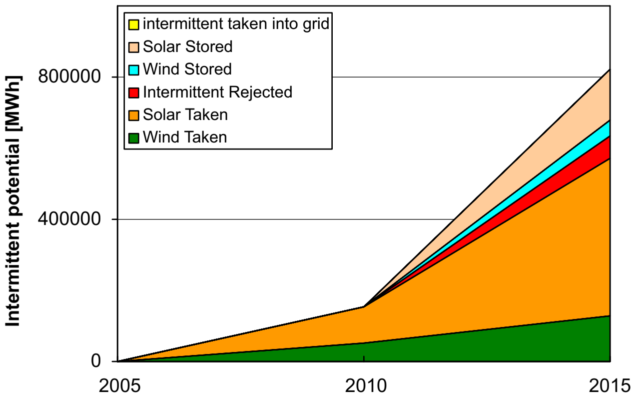

Fig. 16 – Intermittent potential, Malta hydrogen scenario.

Stepping stone for introduction of hydrogen in the energy system of the described Island of Porto Santo is ongoing installation of demonstration plant conducted within EDEN project [35]. The installation will consist of 10 kW fuel cell, 15 kW electrolysers and 60 N m^3 hydrogen storage, which are in purchase phase. The authors in [35] conclude that increased level of investment into research, development and deployment of hydrogen and fuel cells is needed with particular focus on the island applications.

The H$_2$RES 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 [4]. Currently, H$_2$RES program does not support economic and environmental evaluation of calculated scenarios and even if it is simple to calculate price of electricity or reduction of emissions from H$_2$RES results, it will be very valuable to expand the model with economy and environment modules in order to have other parameters for the optimization.

Acknowledgements

The authors would like to thank the European Commission and its DG RTD for supporting the projects RenewIslands, Renewable Energy solution for Islands, and ADEG, Advanced Decentralized Energy Generation Systems in Western Balkans, Ministry of Science, Education and Sport of Republic of Croatia, which is supporting the project Smart Energy Storage for Sustainable Development of Energy Systems, and Portuguese Ministry of Economy and Innovation for financing PRIME Programme, which is supporting the project EDEN, Endogenous New Energies, that resulted in this work.

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