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H_2RES, Energy planning tool for island energy systems – The case of the Island of Mljet☆

Goran Krajačić[a,*], *Neven Duić*[a,b], *Maria da Graça Carvalho*[b,1]

[a]*Department of Energy, Power Engineering and Environment, University of Zagreb, Faculty of Mechanical Engineering and Naval Architecture, Ivana Lučića 5, 10002 Zagreb, Croatia*

[b]*Department of Mechanical Engineering, Instituto Superior Técnico, Lisbon, Portugal*

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ABSTRACT

When it comes to the energy planning, computer programs like H_2RES are becoming valuable tools. H_2RES has been designed as support for simulation of different scenarios devised by RenewIsland methodology with specific purpose to increase integration of renewable sources and hydrogen into island energy systems. The model can use wind, solar, hydro, biomass, geothermal as renewable energy sources and fossil fuel blocks and grid connection with mainland as back up. The load in the model can be represented by hourly and deferrable electricity loads of the power system, by hourly heat load, by hydrogen load for transport and by water load depending on water consumption. The H_2RES model also has ability to integrate different storages into island energy system in order to increase the penetration of intermittent renewable energy sources or to achieve a 100% renewable island. Energy storages could vary from hydrogen loop (fuel cell, electrolyser and hydrogen storage) to reversible hydro or batteries for smaller energy systems. The H_2RES model was tested on the power system of the Island of Porto Santo – Madeira, the islands of Corvo, Graciosa, and Terrciera – Azores, Sal Island – Cape Verde, Portugal, the Island of Mljet, Croatia and on the energy system of the Malta. Beside energy planning of the islands, H_2RES model could be successfully applied for simulation of other energy systems like villages in mountain regions or for simulation of different individual energy producers or consumers.

1. Introduction

Decentralized energy generation (DEG) is becoming a promising solution for supplying the increasing energy demand, especially on islands and remote regions. There are several advantages of DEG: it allows use of diverse renewable energy sources (RESs), it allows the heat energy normally wasted in fossil fuel-based electricity production to be captured and used [1]; it is also very suitable for trigeneration and polygeneration with integration of different energy flows (heating, cooling, electricity, transport fuel, etc.) and installation of various energy storages. These advantages, together with possibility of installation of DEG near the place of energy consumption, represent a platform for achieving the efficient energy use and thus contributing to the sustainable energy development.

☆ The views expressed in this paper are the author's own and do not necessarily reflect those of the European Commission.

* *Corresponding author*. Tel.: +385 1 616 8433; fax: +385 1 615 6940.
E-mail address: goran.krajacic@fsb.hr (G. Krajačić).
[1] Present address: BEPA, Bureau of European Policy Advisers, European Commission.

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Although DEG was present from the beginning of modern energy utilization, cheaper energy generation in centralized units and cheap fossil fuels held back the advanced research in technologies suitable for DEG. The islands and isolated regions were only places where installation of DEG was unavoidable and that is the reason why research in the integration of DEG technologies in island energy systems went the furthest. A sufficient growth of energy supplies to meet human needs [2] is essential for achieving the sustainable energy development. In the isolated regions which do not possess own fossil fuel resources, as it is on most of the islands, the only way to achieve sustainability goals is to generate energy by a growing range of clean and renewable sources; wind power, solar energy (PV and solar thermal collectors), biomass and ocean energy. The main problem of these sources, except biomass, is their intermittent nature, so in order to use them effectively and to ensure security of supply, it is essential to integrate energy storage in the energy system. Such an energy system has to be planned by time series modelling approach, on the hourly basis [3–7].

Because of the several available RES, increasing number of technologies for RES utilization and different options for energy storage, the planning and modelling of energy systems are complex and demanding. Specialised models were developed to help in solving that problem [7,8]. In order to tackle the wider problem of DEG and RES integration in the lights of sustainable development, besides the energy planning model, a special RenewIslands methodology for sustainable development of islands was devised [9].

Authors in article [11] present nuclear energy as major source for clean production of large amounts of hydrogen which will be essential for solving the problem of fast growing energy demand in all sectors in the world, including the transportation. In the same article authors conclude that limited contribution of the renewables to total energy supply is due to their characteristics of being low-density and intermittent sources [11]. May be intermittent sources with current utilization technologies could not compete with large scale hydrogen production from nuclear sources, but still there are places like islands and remote regions which are abundant with renewable intermittent sources. In these small markets production of hydrogen from nuclear could be very limited while hydrogen production from local intermittent sources could ensure security of supply and increase penetration level. Similar conclusion of the ability to store excess energy so as to match supply with demand can greatly increase the usefulness of local renewable energy, especially in the case of hydro, solar and wind is given in [12]. In the same paper authors shown that in very remote and inaccessible locations where grid extension is very costly (perhaps impossible) renewable energy systems with hydrogen storage may provide a relatively high level of service to users at a cost less than or similar to grid extension [12]. One of the conclusion stated in [13] points out combination of hydrogen energy technologies combined with renewables as key components of sustainability of future energy systems due to the fact that they favour system decentralization and local solutions that are somewhat independent of the national network, thus enhancing the flexibility of the system and providing economic benefits to small isolated populations. Also, the small scale of the equipment often reduces the time required from initial design to operation, providing greater adaptability in responding to unpredictable growth and/or changes in energy demand [13].

This article presents case study of the Island of Mljet and results of H_2RES computer program modelling of new energy system which includes renewable energy sources, energy storage and fuel cells. The article also contains a short description of ADEG methodology which evolved from RenewIslands methodology for optimizing RES/FC/H_2 systems devised in scope of the RenewIslands – renewable energy solution for Islands project [9,14].

Eighteen different scenarios of energy system development of the Island of Mljet have been modelled and the results are optimized for maximal penetration of renewable energy. Some of the presented results have been partially used by authors in their previous publications for different purposes. The comparison of H_2RES computer model with other similar energy planning models has been given in the paper [8] and comparison was build on the case of the Island of Mljet. The same case has been used for presentation of RenewIslands methodology in [9] and promotion of hydrogen as an energy vector in the islands' energy supply [10]. This paper brings complete overview of results of modelling of the Island of Mljet with basic description of used equipment, installed power, economic and environmental analyses which are drawn up from ADEG methodology.

2. H_2RES computer model and ADEG/RenewIslands methodology

The H_2RES model [6,15] is designed as support for ADEG/RenewIslands methodology and it is primarily used for balancing between hourly time series of water, electricity, heat and hydrogen demand, appropriate storages and supply. The main purpose of the model is energy planning of islands and isolated regions which operate as stand-alone systems, but it can also serve as a planning tool for power producers from renewable energy sources connected to bigger power systems. During the time the model has evolved and several new modules have been developed like wave, biomass, solar heat and desalination.

Several papers are describing H_2RES model with details of its operation [4,5,8,9]. The version that has been used for calculating Mljet case study has been updated by grid model so it was possible to achieve export and import of electricity from mainland grid. The main characteristic of H_2RES model is that it uses basic technical data of equipment, hourly meteorological data for intermittent sources and according to description in [5] energy balancing is regulated by equations. The main 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.

A very detailed description of RenewIslands methodology has been given in [9,14]. In this article only the most interesting results and parts important for understanding of methodology and its change to ADEG methodology will be stated.

The RenewIslands and ADEG (Fig. 1) methodologies are based on a four steps approach that has to be applied to an island.

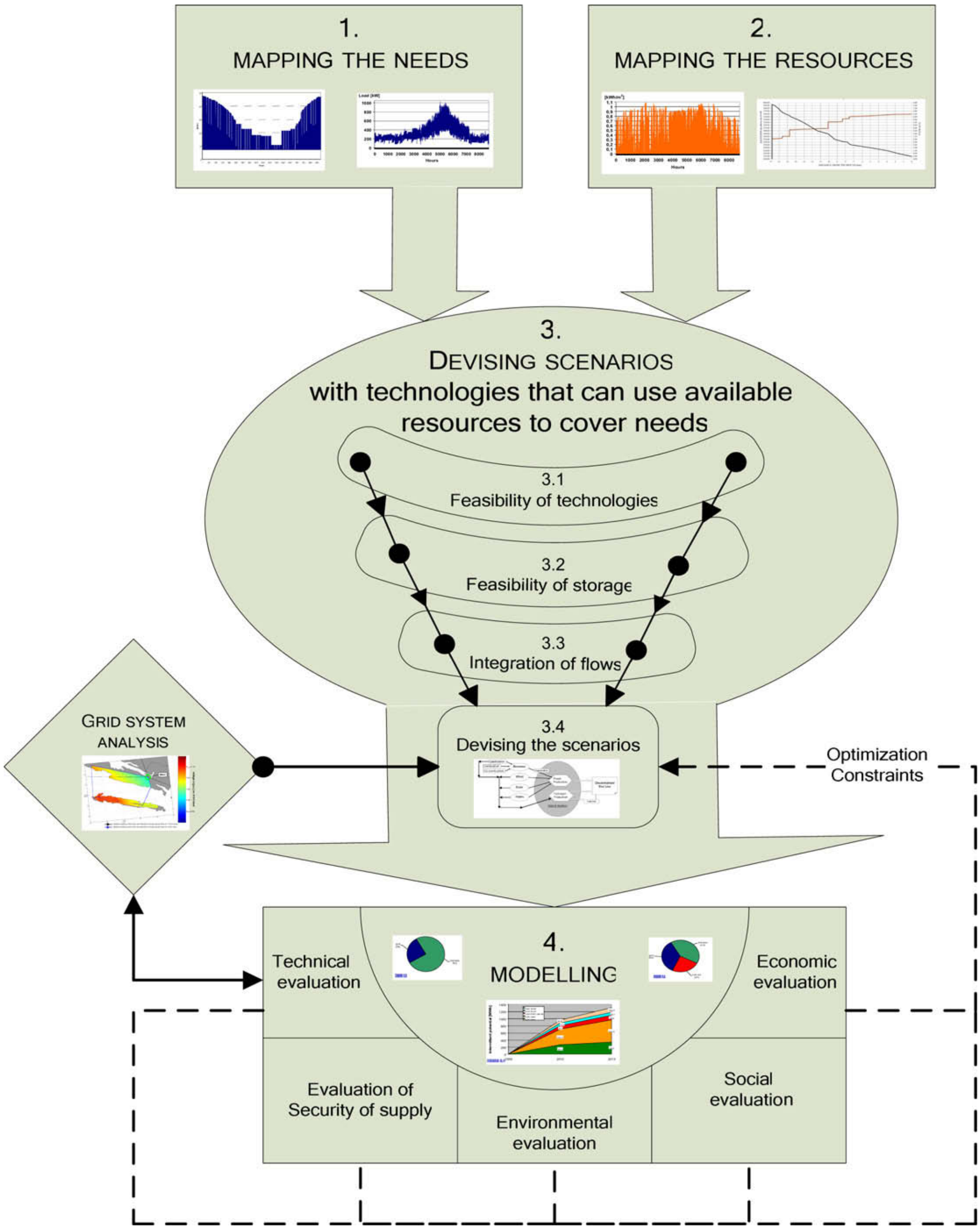

Fig. 1 – ADEG methodology scheme.

1. Mapping the needs.
2. Mapping the resources.
3. Devising scenarios with technologies that can use available resources to cover needs.
4. Modelling and evaluation.

Difference between two methodologies could be found in third step where different optimization constraints have been added and in fourth step which have been expanded by different evaluation of scenarios.

Since complicated strongly coupled flows depend on timing of resources, demands, etc, the only practical way to check the viability of the scenarios is to model them in detail. After the technical viability of scenarios is thus checked, and many of the potential ones are dropped due to not being acceptable or viable, the economic viability should be checked, even when it is clearly demonstration activity. The scenarios have to be evaluated after the modelling but to get some specific results which depends on local particularities and to save modelling time some technical, economic, security of supply, social and environmental parameters could also be included in the process of development of scenarios so this parameters could be made as optimization constraints which will be used in modelling. If no changes in power system are

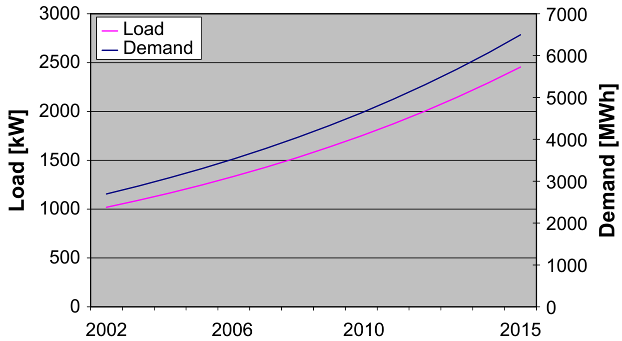

Fig. 2 – Increase of electricity demand and peak load until 2015.

predicted according the results of grid analysis as constraints could directly lead to exclusion of some scenarios or DEG configuration which are not technically feasible.

The economic evaluation will show which scenarios are the most attractive and which one are not economically feasible, the environmental study can show environmental benefits.

3. Application of methodologies to the Island of Mljet

The Island of Mljet is situated in southern Dalmatian archipelago, 30 km west from Dubrovnik and south of the Peljesac Peninsula, separated from it by the Mljet channel. Mljet is an elongated island, with an average width of 3 km, 37 km long, total area of island is 100.4 km^2 and the highest peak is Veli Grad (514 m). The climate is Mediterranean; an average air temperature in January is 8.7 °C and in July 24 °C. In the year 2001 the Island of Mljet had population of 1111 people. Economy is based on farming, viticulture, production of wine, olive growing, cultivation of medicinal herbs, fishing and tourism. The regional road (52 km) runs throughout the island. Mljet has ferry lines with Peljesac and Dubrovnik. Tourism is the most valuable economy branch on the island but it also makes big stress on the resources (water, environment, electricity) especially during the summer months when population on the island is 2–3 times bigger than in the winter.

3.1. *Results of RenewIslands methodology*

Results of application of RenewIslands methodology and its steps to the Island of Mljet are described in detail in [9].

Electricity is delivered to the island by two undersea cables. Each cable supplies power to one side of the island. It has been mapped as medium demanded commodity and increase of peak power load and power demand through years has been set to 7% (Fig. 2). Data used in H_2RES calculations were average electricity system load which has been calculated for year 2002 from measurements in transformer station on the line that includes undersea cable on the east side of the island and from the consumption of the Hotel Odisej the biggest electricity consumer (on the west side of the island). Data have been transferred to base year 2005 according to assumption of 7% yearly increase in consumption.

After electricity water demand is only medium demanded commodity and it has been dispersed over the island. Water needs are most stressed during summer months when there are lot of tourists on the island and when there is no precipitation. The potable water is produced by three desalination plants or during the peak consumption it is shipped to the island. Heat demand, cooling, waste and wastewater treatment are dispersed over the island and they are low demanded commodities. The only concentration of bigger amount of heat (hot water) and cold (room cooling) needs is in the Hotel Odisej which has 312 beds. Transport fuel demand is low, per capita fuel consumption is just one-third of the mainland consumption and there is only one fuel station on the island.

In the second step the most available resources has been mapped and the most promising renewable sources on the Island of Mljet are solar, wind and biomass. The data for the hourly solar radiation on horizontal surface were obtained

Table 1 – Potential energy carriers.

Potential energy carriers	Condition	Code
Electricity	IF ElectC	ECEl
Hydrogen	IF Tran	ECH2

Table 2 – Potential delivering technologies.

Technology	Condition	Code
Electricity conversion system		
WECS	IF (ElectM OR ElectH) AND (WindM OR WindH)	WECS
SECS-PV	IF (ElectL OR ElectM) AND (SolarM OR SolarH)	PV
BECS	IF (ElectM OR ElectH) AND (BiomH)	BECS
FC	IF (Elect) AND (H_2Fuel)	FC
Heating system		
Solar collectors	IF (Heat) AND (SolarM OR SolarH)	STCo
Fuel		
Hydrogen	IF (Tran) AND (ECH2)	H_2Fuel
Water supply		
Water collection	IF (Water) AND (H_2OPM OR H_2OPH)	WaterC
Desalination	IF (Water) AND (H_2OSY)	WaterD

Table 3 – Integrating the flows.

Integration technology	Condition	Code
Combined power and hydrogen production	IF (WECS OR PV) AND ECH2	CPH2
Combined heat, power, cold and hydrogen production	IF (SECS OR BECS OR GECS) AND ECH2	4G-HPCH2

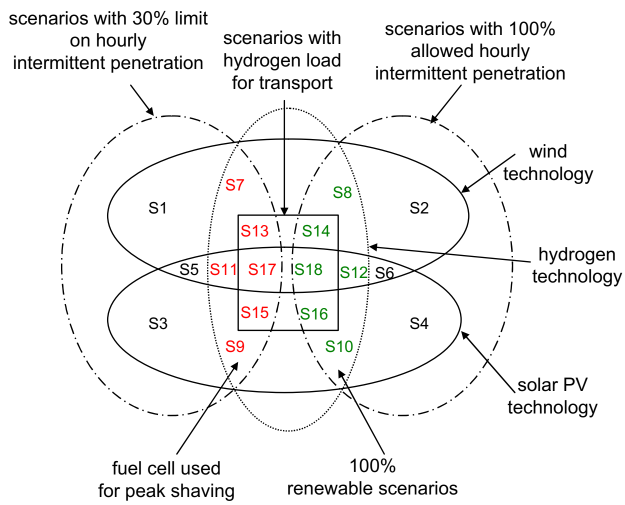

Fig. 3 – Classification and basic description of calculated scenarios.

from meteorological station in Dubrovnik and they were adapted for tilted surface on Mljet by H_2RES and PV GIS [17] computer programs.

Hourly wind data for the Island of Mljet are calculated from the wind measurements which were conducted on meteorological stations in Dubrovnik and Mljet and they were adapted to the Island of Mljet according [19].

The most of the biomass on the island is in the form of thick green forest of Aleppo pine which covers its larger part (72%), especially around the two salty lakes in the north-western part of island that has been declared National park in 1960. The use of biomass was not considered in further solutions because of the specific terrain which is not suitable for biomass collection and because of protected area which occupies the large part of island.

According to a result of mapping of area needs and its resources possible potential energy carriers have been selected Table 1.

The technologies considered are selected and presented in Table 2. Focus was mainly on energy supply for power system and transport. Heating and cooling are to be designed at unit level, not island level. Beside fuel cell hydrogen can also be used in internal combustion engines with heat recovery as stationary source for power or (co-generation–trigeneration). Electrolyser + hydrogen has been selected as possible storage for electricity and appropriate hydrogen storage for storing hydrogen for transport purposes.

Because of dispread system there were not lot of possibilities for integration of flows (Table 3). The most significant was integration of power and hydrogen production. The other possibility is integration of electricity and water production by desalination. The possibility for integration of flows exists in smaller hybrid units which may be installed at the location of consumption (hotels, remote villages, etc).

4. Scenarios and modelling

In total 18 different scenarios have been calculated by H_2RES computer model and additional two calculations for scenarios S6 and S12 for year 2015 are calculated.

In the case of modelling of the Island of Mljet and applying ADEG/RenewIslands methodology in certain scenarios security of supply, social and some environmental issues were included as constraints (100% renewable scenarios, giving advantage to PV systems instead of wind turbines, excluding biomass from modelling because difficult terrain for its collection and because there are no available workers on the island, etc.). In the same case the technical evaluation of grid stability has been done after modelling so grid system analysis has shown that some scenarios are feasible with current state of the grid and connections to mainland while in others the power system control should be introduced to make them feasible which have repercussion financial side of scenario. The grid system analysis could be done independently [20] and it can show how much DEG power we can accept in the current system without any changes.

Fig. 3 shows classification and basic description of calculated scenarios. Generally, scenarios are divided into two main groups. The first group of scenarios has a limit on hourly penetration of electricity from intermittent sources. The limit

Table 4 – Main characteristics of the wind turbines used in calculations.

Provider	Type	Yaw control	Speed control	Nominal capacity [kWe]	Hub height [m]	Diameter [m]/area swept [m^2]
Enercon	E-30	Active via adjustment gears	Yes	300.5	42	30/707
Vestas	V27	Variable pitch	Fixed speed	225	31.5	27/572
Vestas	V47	Variable pitch	Limited ±10% variable speed (Optislip): fed asynchronous generator, variable rotor resistance of the squirrel cage generator	660	40	47/1735
Fuhrlander	FL30	Active, geared yaw motor	Fixed pitch, stall regulated	33	27	13/133

Table 5 – PV efficiencies.

Scenario	3,4,5,6,9,10,11,12,15,16,17,18	6B, 12B
Module efficiency $\mu_{PV,mod}$	0.085	0.15
Inverter efficiency $\mu_{PV,inv}$	0.8	0.97
Losses coefficient $\mu_{PV,los}$	0.85	0.9
Total efficiency μ_{PV}	0.0578	0.13095

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 island. This is set to ensure the grid stability and to be sure that electricity will have proper voltage. This constraint is included in the model and can be easily set to desirable value. The intermittent renewable electricity taken by the system, $E_{I,t}$, is defined by the intermittent limit, φ_I, and the intermittent potential, $E_{I,pot}$:

$$E_{I,t} = MIN(\varphi_I E_{load}, E_{I,pot}) \quad (1)$$

where E_{load} is system energy demand and intermittent potential $E_{I,pot}$ is a sum of wind and solar PV potentials:

$$E_{I,pot} = E_{W,pot} + E_{PV,pot} \quad (2)$$

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:

$$E_{I,pot} = E_{I,t} + E_P + E_{el} + E_{bat,in} + E_r \quad (3)$$

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

The scenarios are also different according to the installed technology. There are scenarios with only wind turbine installations, solar PV installation and their combination. Further scenarios beside installations for utilization of renewable sources have installation of hydrogen technologies that include installation of electrolyser, hydrogen storage and fuel cell. All scenarios include power load while the last six scenarios (scenarios in square, S13–S18) have additional hydrogen load for the transport in years 2010 and 2015. The hydrogen load is represented by three shuttle vans doing 56,800 km yearly with the fuel consumption 0.05 kgH_2 per km and by scooters with fuel consumption 0.33 kg H_2 per day. The increase of hydrogen load in period 2010–2015 is predicted to 7% per year.

As it has been previously mentioned each group of scenarios is optimised with different modelling constraints and optimization conditions. The scenarios with 30% penetration limit are optimised in the way that penetration of energy coming from RES is maximized while rejected renewable energy is kept close to, or under 10% of total RES potential. The scenarios with 100% of allowed 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.

The scenarios with hydrogen technology and 30% limit on hourly penetration are using fuel cell only for peak shaving which means that fuel cell is operating only when load is bigger than weakly peak that has been determined in each week. Additional constraint is that fuel cell should supply around 1% of yearly consumption.

Table 6 – Data for calculation of conversion factor χ_m.

Month m	$E_{PV,hor}$-solar radiation on horizontal surface [kWh/m^2/day] PV-GIS	$E_{PV,hor}$-solar radiation on titled surface 36° [kWh/m^2/day] PV-GIS	$\chi_m = \frac{E_{PV,tilt}}{E_{PV,hor}}$
1	1.737	3.038	1.749
2	2.527	3.799	1.503
3	3.874	4.944	1.276
4	5.218	5.724	1.097
5	6.389	6.269	0.981
6	6.946	6.459	0.930
7	7.38	7.053	0.956
8	6.424	6.794	1.058
9	4.969	6.168	1.241
10	3.324	4.872	1.466
11	2.029	3.44	1.695
12	1.517	2.762	1.821

Table 7 – Installed components in scenarios with 30% limit on hourly penetration.

	Wind [kW]	PV [kW]	Electrolyser [kW]	Fuel cell [kW]	H_2 storag [kWh]	Grid [kW]
S1						
2010	132	0	0	0	0	7676
2015	198	0	0	0	0	7676
S3						
2010	0	323	0	0	0	7676
2015	0	452.62	0	0	0	7676
S5						
2010	99	255	0	0	0	7676
2015	132	369.75	0	0	0	7676
S7						
2010	264	0	200	45	4500	7676
2015	357	0	225	65	10500	7676
S9						
2010	0	587	175	50	1200	7676
2015	0	822	250	65	3900	7676
S11						
2010	132	459	175	50	1200	7676
2015	165	670.65	200	60	3900	7676
S13						
2010	526	0	350	40	87000	7676
2015	751	0	500	55	111000	7676
S15						
2010	0	1105	375	50	33000	7676
2015	0	1564	550	75	44400	7676
S17						
2010	132	963.05	350	50	31050	7676
2015	366.5	1071	450	75	44400	7676

Table 8 – Installed components in scenarios with 100% of allowed penetration.

	Wind [kW]	PV [kW]	Electrolyser [kW]	Fuel cell [kW]	H_2 storag [kWh]	Grid [kW]
S2						
2010	826	0	0	0	0	7676
2015	1126.5	0	0	0	0	7676
S4						
2010	0	1891.2	0	0	0	7676
2015	0	2635	0	0	0	7676
S6						
2010	733	1198.5	0	0	0	7676
2015	1033.5	1615	0	0	0	7676
S6B						
2015	1033.5	1254	0	0	0	7676
S8						
2010	5698	0	4450	1800	873000	7676
2015	8372	0	6850	2500	1155000	7676
S10						
2010	0	12070	4350	1800	873000	7676
2015	0	17340	5300	2500	321300	7676
S12						
2010	1159.5	7820	4000	1800	187500	7676
2015	1760.5	10667	4950	2500	291600	7676
S12B						
2015	1760.5	8400	4950	2500	288000	7676
S14						
2010	5968	0	3350	1800	1185000	7676
2015	8672	0	6250	2500	1339500	7676
S16						
2010	0	12623	4025	1800	240000	7676
2015	0	18360	6250	2500	291000	7676
S18						
2010	1159.5	8330	4000	1800	216000	7676
2015	1760.5	11475	6000	2500	285000	7676

The scenarios with hydrogen technology and without penetration limit represent 100% renewable scenarios which means that all load has been supplied from renewable sources or fuel cell which size then needs to be big enough to cover the yearly peak load.

In all scenarios with hydrogen load it has been supplied by renewable hydrogen so these scenarios represent 100% renewable scenarios concerning the transport load. All

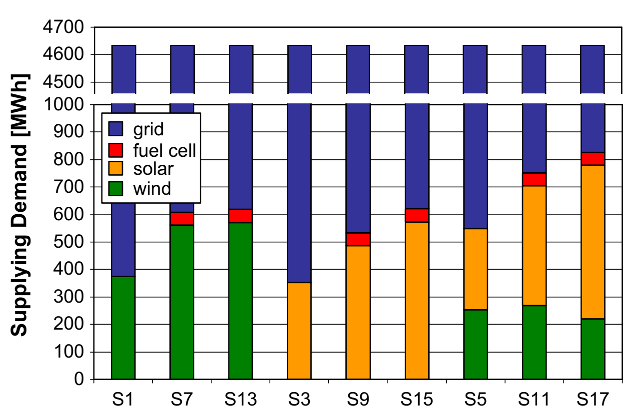

Fig. 4 – Supplying demand in scenarios with 30% limit on hourly penetration.

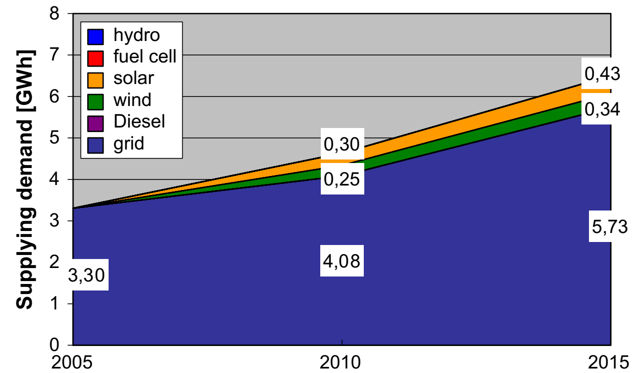

Fig. 5 – Supplying demand in scenario 5.

scenarios are calculated for 2005 as a base year and targeted years 2010 and 2015.

As previously mentioned H_2RES model is using technical data of equipment which usually could be obtained from equipment provider. Tables 4 and 5 show main characteristics of wind turbines and solar PV technology. Beside these data original wind power curves were used in calculations.

Solar thermal electricity technology is cheaper than solar PV [18] but its best performance is limited to a lower range of 2000 kWh/m^2 of solar global radiation, the Island of Mljet with its yearly radiation of 1527 kWh/m^2 is below this limit so only PV technology are investigated for electricity production.

The scenarios with lower efficiency values (Table 5) represent worst typical cases of installed technology while the higher values represent best cases calculated for year 2015.

Adoption of data for global solar radiation on horizontal surface to radiation on titled surface has been done according to PV-GIS [17] data showed in Table 6 and in formulas presented in next paragraphs.

Potential for electricity generation of PV panel in n hour:

$$E^n_{PV,pot} = \chi_m \mu_{PV} E^n_{PV,m} \tag{4}$$

where $E^n_{PV,m}$ is measured total global solar radiation on horizontal surface, μ_{PV} total efficiency of PV system, χ_m is representing conversion factor from total global solar radiation on horizontal surface to total solar radiation on titled surface. Each month m has its own conversion factor.

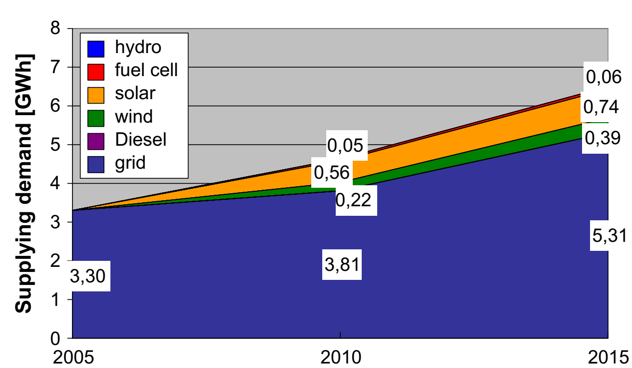

Fig. 6 – Supplying demand in scenario 17.

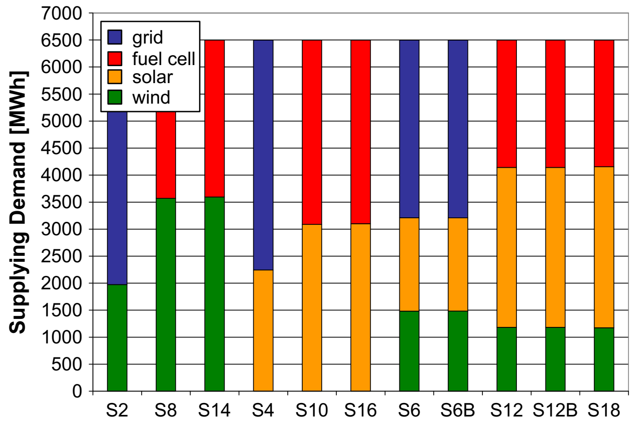

Fig. 7 – Supplying demand in 2015.

Total efficiency of PV system:

$$\mu_{PV} = \mu_{PV,mod}\mu_{PV,con}\mu_{PV,los} \tag{5}$$

where $\mu_{PV,mod}$ efficiency of PV module, $\mu_{PV,con}$ efficiency of DC/AC inverter and losses coefficient $\mu_{PV,los}$.

Electrolyser's efficiency (including compressor) was set to 60% in all cases and minimum switch on time was set to 0.5 h.

Fuel cell efficiency was set to 50% with minimum switch on time of 0.25 h.

5. Results

Installed power in all scenarios has been presented in Tables 7 and 8. In year 2005 there was no power generation on the island so all demand was covered from the mainland grid.

Supplying of electricity demand in scenarios with 30% limit on hourly penetration in year 2010 is presented in Fig. 4.

The supplying of demand in the most feasible scenario which includes in 2010 only combination of three FL 30 wind turbines and 255 kW of solar PV and has 30% limit on hourly penetration is shown in Fig. 5. The combination of intermittent sources has positive effect and it helps to increase yearly penetration of intermittent RES from 8% in scenarios (S1, S3) which have only wind or PV installations to 12% in S5.

The additional increase of yearly RES penetration could be achieved by adding fuel cell, electrolyser and hydrogen storage into energy system. It will allow to store energy in time of surplus and to use it when it is needed. Fig. 6 shows supplying of demand in scenario 17 which has installed fuel cell for peak shaving and hydrogen load for transport. The yearly penetration of RES is 18%. The calculated load factor of fuel cell used for peak shaving was around 11% achieved by 1000 h in operation during which it cover up to 42% of weekly peak load. In scenarios without penetration limit fuel cells were operating from 5100 h in scenario S10 in year 2010, to 3800 h in scenario S12, load factors were accordingly around 15% and 11%. The low load factors and high operation time indicate that fuel cell was not operating at maximum power which has been result of constraint on security of supply which required covering the peak demand where there was no available wind or solar energy. It is shown that combination of solar PV technologies and wind could save time of fuel cells operation, which is important if there will be no significant progress in prolongation of fuel cell operational lifetime. Electrolysers had bigger load factors than fuel cells 21% in scenario S10 and 16% in scenario S12 for year 2010.

Load factors of small wind turbines were in the range from 29% to 32% while bigger turbines had from 28% to 30%. The difference was due to different shape of wind turbines' power curves. PV load factor was at 14% or 18% in scenarios with more efficient photovoltaic modules.

In the scenarios without hourly penetration limit it was feasible to achieve bigger penetration of intermittent sources on yearly base (Fig. 7) Around 30% of yearly electricity demand was covered in scenarios with only wind or PV DEG while additional 30% of intermittent potential was exported to the

Fig. 8 – Surface of the island necessary to cover by PV modules in scenario 12.

Table 9 – Exported electricity in the scenarios with 100% allowed penetration [MWh].

Scenario/year	2010	2015
S2	648	851
S4	694	958
S6	1019	1383
S8	4413	6139
S10	4342	6382
S12	3727	5172
S14	4342	6382
S16	4550	6733
S18	3917	5578

mainland grid. Due to combination of RES and lower intermittence 50% of demand is covered by DEG in scenario 6.

The scenario S12 has integrated hydrogen loop and it represents 100% renewable scenario for electricity demand. Surface of the island necessary to cover by PV modules in scenario S12 is presented in Fig. 8. Red and yellow colours show only surface of PV modules in year 2015 for, scenarios S12 and S12B while red square shows the size of whole PV power plant, yellow hatch in red square represents surface of PV power plant in S12B. It is obvious that more efficient PV modules will need fewer surfaces. Coloured circles represent surfaces necessary for installation of wind turbines.

Scenario S18 is 100% renewable scenario for both transport and electricity. All scenarios with 100% penetration have allowed export of electricity to the mainland grid Table 9.

5.1. *Results of simple economic and environmental analyses*

A simplified economic analysis of most scenarios for installation in 2010 was conducted (the analysis did not include taxes). In all scenarios discount rate was set to 10% while lifetime of equipment is set to 20 years. The investment cost for wind technology varied according to installed types of wind turbines (Table 10). Cost of Solar PV also includes inverter and installation cost. The O&M cost was considered as percentage of total investment cost that should be paid each year during the lifetime.

$$PMT = PV \times \frac{i \times (1+i)^n}{(1+i)^n - 1} [€] \tag{6}$$

Table 10 – Costs of installed equipment and lifetime.

Technology	Investment Cost [€/kW]	O&M cost [%]	Lifetime [years]
Wind	1500–3500	2	20
PV solar	5500	2	20
Fuel cell	3000	2.5	20
Electrolyser	2700	2	20
Hydrogen storage	38 €/Nm^3	0.5	20

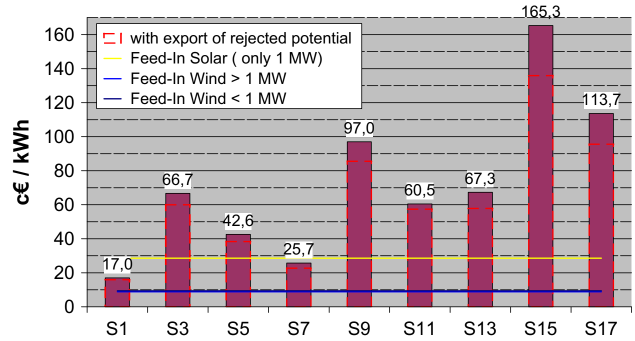

Fig. 9 – Cost of electricity in scenarios with 30% penetration limit.

$$PV_{OM} = Y_{OM} \times \frac{(1+i)^n - 1}{i \times (1+i)^n} [€] \tag{7}$$

$$PV = PV_{INV} + PV_{OM} [€] \tag{8}$$

$$Y_{OM} = \varphi_{OM} \times PV_{INV} [€] \tag{9}$$

where PMT is payment made each year during the lifetime of equipment, PV is present value of investment cost, PV_{INV} together with $PV_{O\&M}$ which is discounted value of yearly operation and maintains cost (O&M), $Y_{O\&M}$, i is discount rate and n number of years.

Cost of produced electricity per kWh was calculated dividing the PMT with total amount of yearly produced electricity by wind, solar and fuel cells.

The Fig. 9 shows comparison of electricity cost in scenarios with 30% of hourly penetration limit. The high price of electricity in these scenarios is result of expensive technology and optimization constraint which did not allow electricity export. With allowed export the cost of electricity production could be lower (dashed line).

In all scenarios the price of electricity is higher than feed in tariffs proposed by Croatian government.

Better financial situation is reached in scenarios without penetration limit where mainland grid was able to accept excess of generated electricity (Fig. 10).

The scenario S2, which includes only installation of wind turbines, is also economically acceptable for proposed feed in

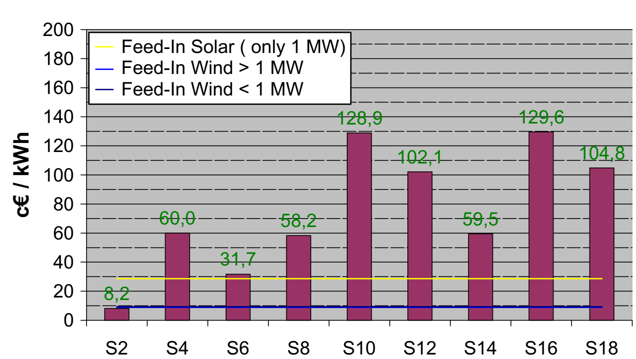

Fig. 10 – Cost of electricity in scenarios with 100% allowed penetration.

Table 11 – Reduction in emissions in scenarios with 30% limit.

	Reduction in emissions (tons/year)		
	CO_2	SO_2	NO_x
S1	119.84	0.43	0.26
S3	113.05	0.40	0.24
S5	175.57	0.62	0.37
S7	194.78	0.69	0.41
S9	170.87	0.61	0.36
S11	240.66	0.85	0.51
S13	198.15	0.70	0.42
S15	198.89	0.71	0.42
S17	264.19	0.94	0.56

tariffs. The cost of electricity in other scenarios is still too high and in scenarios that allow the realization of ''100% renewable island'' the cost of electricity is 10–15 times higher than current price of power generation. In scenario S18, beside the environmental benefits and 100% of renewable generated electricity, the extra 95,356 Nm^3 of hydrogen for transport purposes in 2010 and 133,756 Nm^3 in 2015 could be generated.

By current technology fuel cells could hardly achieve lifetime of 20 years so changing of fuel cell after 10 years will increase total cost of electricity in 100% renewable scenarios from 2 to 3 c€/kWh and around 1 c€/kWh in scenarios with 30% penetration limit. In both cases increase in total cost of electricity due to replacement of fuel cell is below 5%.

By utilization of local renewable energy sources for generation of electricity certain amounts of green house gases and other pollution emissions could be reduced. Tables 11 and 12 present environmental benefits of RES and hybrid decentralized systems in case of Island of Mljet. If certain amount of electricity from grid is substituted by clean renewable sources than the reduction is calculated according to the average emissions of generated kWh in Croatian power system (thermal power plants). In scenarios S13–S18 additional reduction of 60 tons of CO_2 could be achieved by use of hydrogen in transport. Surfaces presented on Fig. 8 also form part of environmental analysis and it shows that installations for 100% renewable island will not occupy more than one hill on the island. Surface necessary for hydrogen storages, electrolyser and fuel cell is not drawn as it needs smaller size of layout than layout required by wind turbines and solar PV. Detailed environmental analysis should include visibility impact of power plants, sound impact and shadowing of wind turbines and its influence to birds and bats as there are some endemic spices on the Island of Mljet.

Table 12 – Reduction in emissions in scenarios with 100% allowed penetration.

	Reduction in emissions (tons/year)		
	CO_2	SO_2	NO_x
S2	666.04	2.36	1.42
S4	735.97	2.61	1.57
S6	1070.65	3.8	2.28
S8	2897.21	10.28	6.17
S10	2874.49	10.2	6.12
S12	2677.57	9.5	5.7
S14	2928.35	10.39	6.23
S16	2941.31	10.44	6.26
S18	2738.33	9.72	5.83

6. Conclusion

There are several reasons for large number of calculated scenarios. The scenarios with wind technology are considered as the most economical but Croatian government has forbidden installation of wind turbines on islands so additional scenarios only with solar energy are calculated. Finally, the scenarios with combination of wind and solar are calculated because of the best technical characteristics (the highest penetration of RES).

The results of this paper just have proven thesis that decentralized energy generation could offer good solution for harvesting of renewable energy sources on Croatian Islands. It also should be mentioned that all scenarios are optimized for the highest RES penetration and not according to financial parameters.

By installation of four small wind turbines, 33 kW each, we could satisfy the 8% of the Island of Mljet electricity needs in 2010, this percentage could be bigger up to 4% with installation of three 33 kW wind turbines and if we add 7 m^2 of PV panels on each house on island. If we allow 100% of RES penetration and install two bigger 300 kW and four small wind turbines and have 14,200 m^2 of PV panels (approximately to cover southern roofs of all ~442 households on island) we could produce 3.34 GWh of electricity which is equal to 72% of the Island of Mljet electricity needs in 2010. With new installation of additional three wind turbines and 120,000 m^2 of PV panels up to 2015, together with installation of ''hydrogen loop'' the Island of Mljet could become 100% renewable island concerning electricity and simulated transport needs and also could export additional 5.57 GWh to Croatian power system.

Proposed ADEG methodology which includes use of H_2RES program and Grid system analysis described in [20] forms the standard procedure for applications of decentralized energy generation in Western Balkans. By following the steps of procedure it is easy to find solution for different decentralized energy installations and to address the most important issues as: intermittent and seasonal nature of renewable energy sources, storage capacity, security of supply, necessity for low cost technologies, system control, operational safety and power quality management and integration of decentralized energy generation into grid according to characteristics of the transmission and distribution system.

As H_2RES program supports only hourly energy balancing, to check grid stability and voltage quality supplementary analysis of the local influences of the renewable energy sources on the grid behaviour and possible grid penetration needs to be calculated by another dynamic simulation tool ''POSIM'' (POwer System SIMulations) [20]. In the same paper authors conclude that 1 MW of active power export can be considered as a limit for power feed-ins on the Island of Mljet for the current outline of the distribution system. Since then there was some progress in construction of new transformer station on the peninsula Peljesac and it is now expected that it will be possible to achieve higher power export from the island. Nevertheless, results from [20] indicate that all scenarios with 30% penetration limit are technically feasible from the grid stability point of view while scenarios with 100% allowed penetration and with installed of more than 2 MW of power should be reconsidered.

The further scientific work will consist of development of complex optimization system and its integration in H_2RES model or application of multicriterial evaluation tool described in [21,22] in model. If renewable energy sources and hydrogen need to be evaluated and compared to other sources of energy it will desirable to include other economic valuation techniques since some benefits and costs do not have monetary values. In this way new technologies may become competitive with traditional energy sources. Performing a cost–benefit analysis for a renewable energy project requires taking into account every possible economically relevant attribute of a project [23].

There is certain lack of financial and cost data that could be easily accessed for fuel cells and electrolyser and it drives to similar conclusion given by authors in [12] that economic feasibility of the proposed systems has necessarily been incomplete due to the lack of detailed cost and benefit data [12]. Today in the era of internet and globalization the producers of fuel cells, electrolysers and hydrogen technologies should not hide the price of its products even if it is too high compared to other technologies. By listing the price and availability of their products they could help other experts to make proper planning and thus increase visibility of their products.

If hydrogen will start to play important role in the world energy system merely after 2050 as it is concluded in [24] and if nuclear energy will be major source for clean production of large amounts of hydrogen [11] current focus of researchers and producers that seek promising solutions for coupling renewables and hydrogen production should be put on the solving of problems for decentralized energy supply on the islands and remote regions where they can take advantage of small markets and small applications. In the same time actual implementation of hydrogen-based systems, especially in remote sites, should be approached with caution [12] and to avoid unnecessary negative perception of new technology, demonstrational systems are the most welcome installations.

Scenarios for 100% renewable island in 2010 does not seem realistic as there should be a lot of installations in short period of time and this solution seems more reasonable for year 2015.

For the first step in process that will achieve the most positive effect of decentralized energy generation together with maximal penetration of renewable energy, the authors of this paper strongly recommend implementation of energy efficiency measures on islands, which were not discussed in this paper. The special attention should be given to use of solar thermal collectors for hot water production. It should be followed by installation of decentralized units for RES utilization and demonstrational site or small installation of hydrogen technologies in the place where integration of flows could be achieved. The hotels and restaurants which have needs for electricity and heat could be good candidates while extra produced hydrogen could be supplied to vehicles or boats in the national park.

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