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RenewIslands methodology for sustainable energy and resource planning for islands

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Abstract

With respect to energy supply, most of the islands depend on importation, mainly from oil and its related products, and others are dependant on weak electricity grid connexions with mainland. Scarce resources are used inefficiently, supplying end-use energy and other life-supporting commodities, like power, heat, cold, transport fuel, water, waste treatment and waste water treatment. It is possible to integrate various flows and decrease the energy intensity, although the task is situation dependant and involves a large number of different systems. RenewIslands methodology for the assessment of alternative scenarios for energy and resource planning is presented here, and applied to several islands. The methodology helps in choosing energy and resource flows integration, based on the island needs, its resources, and the applicable technologies.

Keywords: H_2RES; RenewIslands methodology; Energy storage; Islands; Hydrogen

Contents

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1. Introduction

The islands that are too remote to have interconnections with continental European energy networks, depend on imports of oil and related products for their stationary and transport energy needs, leading to high power costs and environmental emissions associated with oil consumption. The need to provide the islands with a framework for future development in renewable energies was already highlighted in the European Commission's White Paper on Renewable Energy Sources [1], United Nations Conference on Islands and Small Island States (Barbados 94, [2]) and the 1st European Conference on Island Sustainable Development. The European Island Agenda [3] highlights "the non-renewable energy sources as provisional solutions, inadequate to solve in the long term the energy problems of the islands". As an example we can state the Shetland Islands which have some of the best renewable energy resources in Europe while also have among the highest energy costs in the UK and over 50% of the islanders spend more than 20% of their household income on energy [4].

The renewable energy sources, which are usually abundant on islands, are often, like wind and solar energy, intermittent in their nature. The higher penetration of renewable energy sources in islands is thus limited, and a solution to the problem requires energy storage. The storage of electricity is feasible in various forms, like reversible hydro [5,6], hydrogen [4,7–9] or batteries, but those solutions may not be economically viable. On the other hand, by integrating electricity system with other energy systems, like heat, cold, or transport fuel systems, or with other systems, like water supply system, waste treatment system or waste water treatment system, may enable increasing the viability of the entire system, by storing what is most appropriate in a given situation.

The difficulties of integration of various renewable energy technologies into energy systems are discussed in Refs. [9–16]. The energy planning of these systems were done on hourly basis even when calculations had included economic analysis. Results in [9] 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 1/3 of the nominal wind-turbine power and overall efficiencies that may exceed 60%. While papers [9–16] are presenting plans for the development of the island energy systems, Refs. [4,7] present results of existing demonstrational stand alone hydrogen systems which have been installed on two European islands. In Ref. [7], hydrogen is used only for power generation in fuel cell or stationary hydrogen IC engine while in Ref. [4] electricity system is integrated with transport fuel system so hydrogen is additionally used for transport purposes.

The need for different methodologies and models that will be helping tools for decision-making procedures for exploiting local renewable energy sources is recognised in the world and different authors are proposing various solutions. In Ref. [17], authors established a decision support system with the aid of a geographical information system (GIS) to facilitate the evaluation of the economic feasibility of investments for exploiting local renewable energy sources for private investors, policymakers, and lawmakers. An optimal energy model for various end-uses is described in Ref. [18] and it has been tested on European islands [19], another example of algorithm for the selection of the optimum economic renewable system has been given in Ref. [6]. The interesting dynamic bottom-up simulation tool Invert was designed and it is described in Ref. [20]. The Invert tool is used for evaluation of the effects of different promotion schemes on the technology mix and the achievable CO_2 reductions in the building, electricity and transport (bio-fuel) sector till 2020. The tool considers also the effects of learning curves and market barriers, which lead to the concept of dynamic cost–resources curves. Invert tool has been tested on the case study for the island of Crete [21].

RenewIslands methodology [8] was developed in order to enable assessment of technical feasibility of various options for integrated energy and resource planning of island. Finally, the proposed general methodology was applied to several islands, Corvo Island in Azores Archipelago in Portugal, Porto Santo Island in Madeira Archipelago in Portugal and Mljet Island in Croatia.

The methodology also could serve as complement to the energy system sustainability assessment described in Ref. [22] and especially to the calculation of sustainability indicators and strategic design of an energy system which requires holistic planning that meets energy demand and considers all interrelated impacts, e.g. logistic, space planning and resource planning. Regarding the hydrogen energy system, the strategic design may be interpreted as an energy concept with optimisation of local resources, urban and industrial planning with transport optimisation and use of the renewable energy sources [23].

2. RenewIslands methodology

The RenewIslands methodology is based on a four steps analysis approach that has to be applied to an island:

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

The described methodology is actually general and can be applied to systems other than islands. The islands' specificities arise at more detailed level, when characterising the needs and resources and assessing the feasibility of the system, as classifying the different options will be based on islands conditionings (Fig. 1).

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

The resources are locally available ones, like wind, sun, geothermal energy, ocean energy, hydro potential, 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

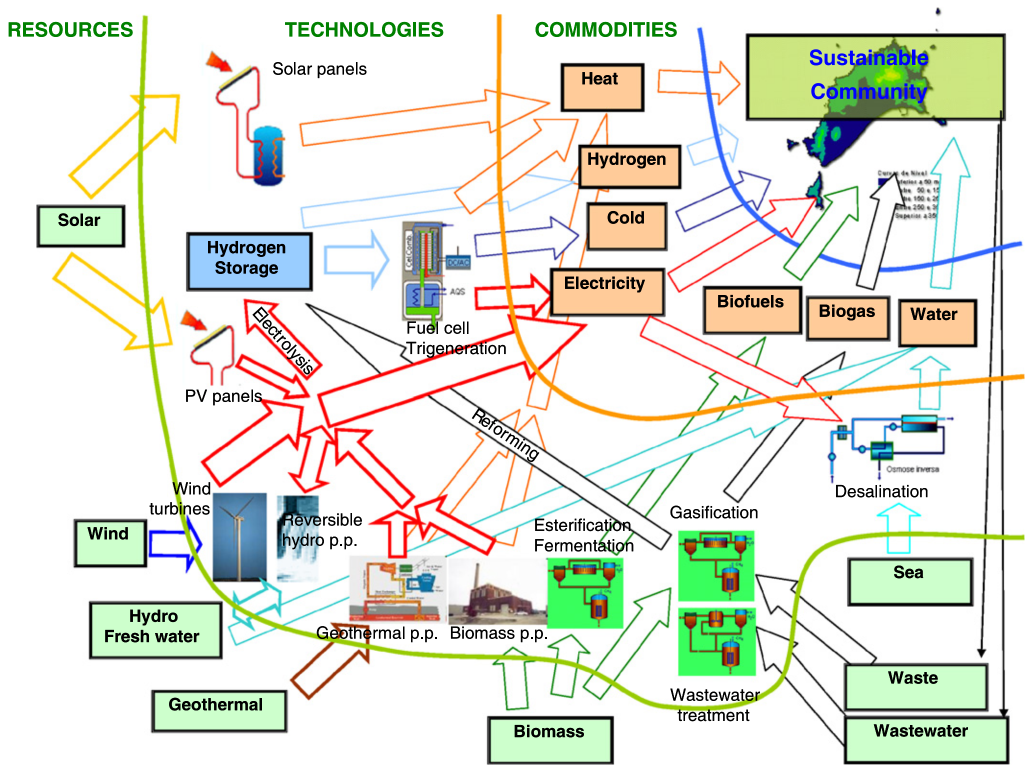

Fig. 1. Sustainable community, its needs and its resources.

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.

2.1. Step 1: mapping the needs

In order to map the needs, a questionnaire should be answered. The level of need for each commodity has to be defined locally, but generally, in order to have sustainable development, water and electricity will always be highly demanded, no matter what is the demand per person, or total actual demand, unless it is a community of only few households, that can then use individual solutions. Heat demand will be deemed high in cold climates, as cold will be deemed high in hot climates. Waste treatment and wastewater treatment will depend on the ability of local environment to absorb the dumped amounts (Table 1).

2.2. Step 2: mapping the resources

Definition of level of the quality of a resource depends on the particular technology, and is not locally dependant. Those values are generally known. On the other hand, as conventional energy costs are higher in islands due to their isolation, endogenous resources that would not be competitive in other regions may became competitive if compared to the difficulties and costs of imported resources in islands. For example, in islands wind energy may become economically competitive for wind regimes characterized by lower wind speeds than in mainland regions (Table 2).

It is possible to envisage potential energy carriers as a result of area needs and its resources. Generally, it will be electricity, one or two transport fuels, and district heating in very cold regions of the world (Table 3).

2.3. Step 3: devising scenarios with technologies that can use available resources to cover needs

Generally, local energy sources will be given priority, due to security of supply reasons. Then, cheaper technologies will be given priority. Technologies will have to be assessed from both a local and global environmental point of view.

Table 1
Mapping the island/remote area community needs

Needs	Level	Geographic distribution	Code	Level	Distribution
Electricity	Low, medium or high	Dispersed, concentrated	Elect	+L/M/H/−	+D/C/−
Heat	Low, medium or high	Dispersed, concentrated	Heat	+L/M/H/−	+D/C/−
Cold	Low, medium or high	Dispersed, concentrated	Cold	+L/M/H/−	+D/C/−
Transport fuel	Low, medium or high	Short, long distance	Tran	+L/M/H/−	+S/L/−
Water	Low, medium or high	Dispersed, concentrated	Water	+L/M/H/−	+D/C/−
Waste treatment	Low, medium or high	Dispersed, concentrated	Waste	+L/M/H/−	+D/C/−
Wastewater treatment	Low, medium or high	Dispersed, concentrated	WWT	+L/M/H/−	+D/C/−

Table 2
Mapping the island/remote area available resources

Resource	Level	Code			
Local primary energy					
Wind	Low, medium or high	Wind	WindL	WindM	WindH
Solar	Low, medium or high	Solar	SolarL	SolarM	SolarH
Hydro (height)	Low, medium or high	Hydro	HydroL	HydroM	HydroH
Biomass	Low, medium or high	Biom	BiomL	BiomM	BiomH
Geothermal	Low, medium or high	Geoth	GeothL	GeothM	GeothH
Energy import infrastructure					
Grid connection	None, weak, strong	Grid	GridN	GridW	GridS
Natural gas pipeline	No, yes	NGpl	NGplN		NGplY
LNG terminal	No, yes	LNGt	LNGtN		LNGtY
Oil terminal/refinery	No, yes	OilR	OilRN		OilRY
Oil derivatives terminal	No, yes	OilD	OilDN		OilDY
Water					
Precipitation	Low, medium or high	H2OP	H2OPL	H2OPM	H2OPH
Ground water	Low, medium or high	H2OG	H2OGL	H2OGM	H2OGH
Water pipeline	No, yes	Aqua	AquaN		AquaY
Sea water	No, yes	H2OS	H2OSN		H2OSY

Table 3
Potential energy carriers

Potential energy carriers	Condition	Code
Electricity	IF ElectC	ECEl
District heating	IF HeatHC	ECDH
District cooling	IF ColdHC	ECDC
Hydrogen	IF (Tran OR ElectC)	ECH2
Natural gas	IF (NGplY OR LNGtY)	ECNG
Biogas	IF (BiomH OR WasteHC OR WWTHC)	ECBG
Petrol/Diesel	IF (OilRY OR OilDY)	ECPD
Bioethanol	IF (BiomH OR WasteHC)	ECEt
LPG	IF (OilRY OR OilDY)	ECLPG
Biodiesel	IF (BiomH OR WasteHC)	ECBD

This step will have four sub steps:

1. Feasibility of technologies (energy conversion, water supply, waste treatment, wastewater technology treatment).
2. Feasibility of technologies for energy, water, waste and wastewater storage.
3. Feasibility of integration of flows (cogeneration, trigeneration, polygeneration, etc.).
4. Devising potential scenarios.

2.3.1. Substep 3.1 feasibility of technologies

The technical feasibility of technologies generally depends on the existence of a particular demand, and availability of particular resource. Its economical viability depends on the status of technology, commercial, emerging, in development, on the quality of resources, but also on the matching of demand and resource. Also, environmental viability as well as social viability of technologies can be pondered. It might be beneficial to apply multicriterial analysis to various competing technologies, in order to choose ones that reach acceptable level of sustainability in given situation. The technologies that have to be taken into account are the ones in energy conversion, water supply, waste treatment and wastewater technology treatment.

Wind energy conversion system (WECS) is for example feasible if there is high or medium need for electricity and if there are medium to high wind resources. Such an analysis should be made for each of the technologies, in order to get a list of relevant ones (Table 4).

2.3.2. Substep 3.2 feasibility of storage

When there is no connexion to the mainland, it is generally necessary to have storage. Water storage will generally be part of water supply system, even in case of water pipeline, in order to use gravity for keeping the pressure constant. Most islands will have oil derivatives storage, which will then be used to cover all other energy needs, like transport fuels, electricity generation, heat and cold supply. Those with hydro potential will sometimes have water reservoirs (Flores). In cold climates, heat can be stored (Ærø). Cold can be stored in ice banks. Waste is usually stored in waste fill where it will continue polluting during long time, while waste water will be stored in wastewater collectors before disposal into sea or some other water. Electricity is difficult to store. The most economically efficient way to store excess of electricity is reversible hydro (as planned for El Hierro), by pumping water to the upper reservoir when there is excess of electricity and turbinating it when there is lack. That can be very efficient strategy for tackling higher penetrations of wind power, in case of hilly islands. There is a need for two reservoirs, which might be costly, a pump and a turbine, or if seawater is pumped, reversible hydro may work with only one, upper reservoir. Meanwhile, in case that there is no altitude difference for reversible hydro, the alternative is hydrogen storage. The excess of wind can be electrolysed into hydrogen and stored, and then the electricity lack can be produced from hydrogen by a fuel cell, internal combustion engine, or hydrogen can be used for powering transport. In case of small power systems, batteries can be used to store electricity (Table 5).

2.3.3. Substep 3.3 integration of flows

In order to increase the efficiency of the system, some resources and commodities flows may be integrated. For example, it is usual to integrate heat and power production, in so-called cogeneration. But it only makes sense if heat and electricity demand are of similar time dependence, or at least made so by heat storage. If there is seasonal need for heat and cold, these two can be integrated with electricity, in technology called trigeneration. A novel idea has been proposed for Corvo Island [5], to integrate water supply system with electricity generation, by using water as a mechanism for ironing demand. The main barrier to wider application of such integration lies in the traditional separateness of water and power utilities. Waste is commonly integrated with heat and/or power generation on the Continent, but rarely on islands, due to relatively small quantities of waste. The integration technologies are waste incineration to produce heat and/or electricity, biomass and/or waste (manure especially) gasification, ethanol production, etc. and using those fuels as energy carriers. Wastewater treatment can also be integrated through gasification,

Table 4
Potential delivering technologies

Technology	Condition	Code
Electricity conversion system		
WECS (wind)	IF (ElectM OR ElectH) AND (WindM OR WindH)	WECS
SECS-PV (solar PV)	IF (ElectL OR ElectM) AND (SolarM OR SolarH)	PV
SECS-Thermal (solar thermal electricity)	IF (Elect) AND (SolarH)	SECS
HECS (hydro)	IF (Elect) AND (HydroM OR HydroH)	HECS
GECS (geothermal)	IF (ElectM OR ElectH) AND (GeothH)	GECS
BECS (biomass)	IF (ElectM OR ElectH) AND (BiomH)	BECS
DEGS (Diesel engine)	IF (Elect) AND (NGplY OR LNGtY OR OilRY OR OilDY)	DEGS
CCGT (combined cycle gas turbine)	IF (ElectH) AND (NGplY OR LNGtY OR OilRY OR OilDY)	CCGT
FC (fuel cell)	IF (Elect) AND (H2Fuel)	FC
Heating system		
Solar collectors	IF (Heat) AND (SolarM OR SolarH)	STCo
Geothermal	IF (HeatH) AND (GeothM OR GeothH)	GeTH
Heat pumps	IF (HeatH AND ECEl)	HPHe
Biomass boilers	IF (HeatH) AND (BiomM OR BiomH)	BMBo
Gas boilers	IF (Heat) AND (NGplY OR LNGtY OR OilRY OR OilDY OR WasteG OR WWG)	GSBo
Cooling		
Solar absorbers	IF (Cold) AND (SolarH)	SAbs
Heat pumps	IF (ColdH AND ECEl)	HPCo
Gas coolers	IF (ColdH) AND (NGplY OR LNGtY OR OilRY OR OilDY OR WasG OR WWtG)	GSCo
Electricity coolers	IF (ColdH AND ECEl)	ELCo
Fuel		
Hydrogen	IF (Tran) AND (ECH2)	H2Fuel
Electricity	IF (Tran) AND (ECEl)	ElFuel
Bioethanol	IF (Tran) AND (ECEt)	EthanolFuel
Biodiesel	IF (Tran) AND (ECBD)	BDFuel
LPG	IF (Tran) AND (ECLPG)	LPGFuel
Natural Gas	IF (Tran) AND (ECNG)	NGFuel
Biogas	IF (Tran) AND (ECBG)	BGFuel
Petrol/Diesel	IF (Tran) AND (ECPD)	PDFuel
Water supply		
Water collection	IF (Water) AND (H2OPM OR H2OPH)	WaterC
Water wells	IF (Water) AND (H2OGM OR H2OGH)	WaterW
Desalination	IF (Water) AND (H2OSY)	WaterD
Waste		
Incineration	IF (WasteHC)	WasteI
Gasification	IF (WasteHC)	WasteG
Wastewater treatment		
Gasification	IF (WWTHC)	WWG

Table 5
Potential storage technologies

Storage technology	Condition	Code
Electricity storage system		
Reversible hydro	IF (WECS AND HECS)	RHECS
Electrolyser + hydrogen	IF (WECS OR SECS OR PV) AND NOT HECS	ELYH2
Reformer + hydrogen	IF (ECNG OR ECBG OR ECPD OR ECEt OR ECLPG OR ECBD) AND NOT HECS	REFH2
Batteries	IF (SECS OR PV) AND NOT HECS AND NOT ECH2	BAT
Heat storage		
Heat storage	IF (HeatH)	HeatS
Cold bank	IF (ColdH)	ColdS
Fuel		
Hydrogen	IF H2Fuel	H2stor
Bioethanol	IF EthanolFuel	Ethanolstor
Biodiesel	IF BDFuel	BDstor
LPG	IF LPGFuel	LPGstor
NG	IF NGFuel	NGstor
BG	IF BGFuel	BGstor
Petrol/Diesel	IF PDFuel	PDstor
Water, waste and wastewater		
Water	IF Water	WaterS
Waste fill	IF Waste	WasteF
Wastewater tanks	IF WWT	WWstor

and usage of gas as energy carrier. Waste and wastewater treatment are here considered supply technologies, since from the point of view of communities they supply clean environment (Table 6).

2.3.4. Substep 3.4 devising the scenarios

The number of potential scenarios is vast, with many branches and loops. It is essential to weed out improbable scenarios, by following previous steps and removing all the combinations depending on low demand of certain commodity, or low resource. When devising scenarios, one should also consider policy issues. Energy policy should give different weighting factors and minimum thresholds to security of energy supply, economic viability, environmental viability, social acceptance. Applying energy policy issues at this stage will weed out some unacceptable scenarios, but others will show to be unacceptable only after detailed modelling.

2.4. Step 4: modelling

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.

Table 6
Integrating the flows

Integration technology	Condition	Code
Combined heat and power	IF (Elect PROPORTIONAL Heat) AND (DEGS OR CCGT OR FC OR BECS OR SECS OR GECS)	CHP
Combined heat and cold	IF (Heat PROPORTIONAL Cold)	CHC
Trigeneration	IF (Elect PROPORTIONAL (Heat + Cold)) AND (DEGS OR CCGT OR FC OR BECS OR SECS OR GECS)	3G-HPC
Combined water and power	IF (HydroM OR HydroH) AND Water	CWP
Combined waste treatment and heat generation	IF (WasteI AND (HeatM OR HeatH))	CWTH
Combined waste treatment and power generation	IF (WasteI AND (ElectM OR ElectH))	CWTP
Combined waste treatment and heat and power generation	IF (WasteI AND (ElectM OR ElectH) AND Elect PROPORTIONAL Heat)	3G-WTHP
Combined waste treatment and heat, power and cold generation	IF (WasteI AND (ElectM OR ElectH) AND Elect PROPORTIONAL (Heat + Cold))	4G-WTHPC
Combined waste treatment and bioethanol production	IF (WasteG AND ECEt)	CWTC2H5OH
Combined waste treatment and gas production	IF (WasteG AND ECBG)	CWTGas
Combined wastewater treatment and gas production	IF (WWG AND ECBG)	CWWTGas
Combined power and hydrogen production	IF (WECS OR PV) AND ECH2	CPH2
Combined heat, power and hydrogen production	IF (SECS OR BECS OR GECS) AND ECH2	3G-HPH2
Combined heat, power, cold and hydrogen production	IF (SECS OR BECS OR GECS) AND ECH2	4G-HPCH2

The conventional planning tools, like energy and power evaluation programme (ENPEP), can not be used in such situations, and several new energy-planning tools are being developed. EnergyPlan [24], for example, is well adjusted for decentralised power generation, and it also integrates heat demand into the model, enabling the optimisation of combined heat and power generation. It also integrates other intermittent resources and optimises different strategies to treat the power excess. The model can be used to calculate other renewable energy sources than wind and PV, such as for example wave power and there are several possibilities to store electricity in the model, by using pumps for hydro storage or batteries as well as converting electricity to fuel by electrolysers [13]. On the other hand, it does not allow treating hydro resource in integration with water demand. HOMER is designed specifically for small isolated power systems and although it allows for grid connexion and has some of the required technologies, it still lacks reversible hydro and water demand treatments, which is the cheapest way to store energy in those islands where there is potential [25]. There are also models that contain more precise physical models of some technologies, like Hydrogems [26], but they also lack hydro resource, reversible hydro storage and water demand, among others, and for the purpose of energy planning it is not necessary to go into conversion detail, besides the necessary level; although when it comes to component dimensioning, it might be beneficial (Fig. 2).

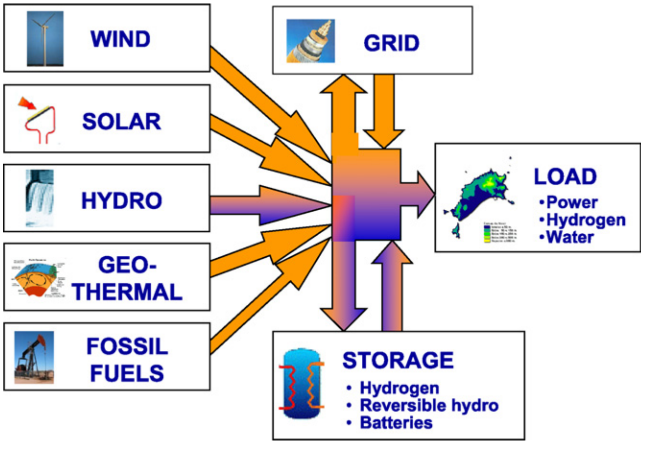

Fig. 2. H_2RES model.

H_2RES is based on hourly time series analysis of water, electricity and hydrogen demand, wind and geothermal potential, solar insulation and precipitation. The wind module uses the wind velocity data, typically from the meteorological station, at 10 m height, and adjusts them to the wind turbines hub level and, for a given choice of wind turbines, converts the velocities to the output. The geothermal module takes into account the needs to service geothermal units. The solar module converts the total radiation on the horizontal surface, obtained typically from the meteorological station, to the inclined surface, and then to output. The hydro module, takes into account precipitation data, typically from the nearest meteorological station, water collection area and evaporation data based on the reservoir free surface, to predict the water net inflow into the reservoir. Load module, based on a given criteria for the maximum acceptable renewable electricity in the power system, puts a part or all of wind and solar output into the system and discards the rest of the renewable output. The excess renewable electricity is then stored either as hydrogen, pumped water or electricity in batteries, or used for some non-time critical use. The energy that is stored can be retrieved later, and supplied to the system as electricity. The rest is covered from conventional thermal blocks, like Diesel or Otto engines, gas turbines, steam turbines, combined cycles or from grid if such link with mainland exists. The model can also optimise the supply of water and hydrogen demand, for example as transport fuel.

3. Corvo case study

The island of Corvo is one of the 9 islands in the Azores archipelago and together with S. Miguel and Flores form the Western Group. It is the smallest island on the archipelago with an area of 17 km^2 and is situated at 31° 5′ West longitude and 39° 40′ North latitude. The island is an inactive volcano named Monte Grosso and its crater, a lake, is the island highest point, circa 720 m. There is only one settlement, Vila Nova do Corvo, where some 400 people reside.

The supply of electricity to an isolated small island such as Corvo is very limited, while there is a great concern with environmental issues related to fossil fuel supply, such as water and land contamination and pollution by oil products and wastes through leakage during shipping handling and storage. The incidence of small-scale oil spills during loading that occurs adjacent to the storage facilities is very common in Corvo. The fuel cost in Corvo is the highest of the entire archipelago, nearly 5 times more than average in Azores. The demand of 884 MWh and peak of 167 kW was covered by 2×200 kW Diesel generator units. Table 7 shows Corvo island energy data.

In Corvo Island, the security of supply is a real and frequent concern, since due to bad weather conditions it is common to have oil shortages in this island. To reduce Corvo's dependency and secure supply, the implementation of an energy system that combines RES and storage is the best solution.

3.1. Corvo as a 'renewable island

Applying RenewIslands methodology to Corvo needs results in Table 8. Electricity is a medium demanded commodity, mainly concentrated in the island only settlement. Heat demand is dispersed over the houses and mainly for hot water, as room heating (or cooling) is generally not necessary due to the climatic conditions. Cold needs are small and distributed in houses. Transport demand is very low, since there is only one village on the island. Water needs are medium and concentrated, mainly for housing. Waste and wastewater treatment are also mainly concentrated (although in isolated units waste and wastewater may be dumped or individual solutions may be present) (Table 9, Fig. 3).

The most important endogenous energy resource at Corvo is wind, although there is also some hydro potential, both being scarce in summer months. Corvo is a typically remote region without any grid connexions to the mainland, or pipelines for fuels or water supply. Imported resources are shipped fossil fuels (petrol, Diesel, and LPG). Fresh water is abundant from precipitation apart from summer months (Table 10).

Table 7
Energy data for the island of Corvo

Year	Consumption (GWh)	Production (GWh)
2000	0.678	0.763
2001	0.723	0.809

Table 8
Mapping the Corvo community needs

Needs	Level	Geographic distribution	
Electricity	Medium	Concentrated	ElectMC
Heat	Low	Dispersed	HeatLD
Cold	Low	Dispersed	ColdLD
Transport fuel	Low	Short	TranLS
Water	Medium	Concentrated	WaterMC
Waste treatment	Low	Concentrated	WasteLC
Wastewater treatment	Low	Concentrated	WWTLC

Table 9
Mapping the island/remote area available resources

Resource	Level	Code
Local primary energy		
Wind	High	WindH
Solar	Medium	SolarM
Hydro (height)	High	HydroH
Biomass	Low	BiomL
Geothermal	Low	GeothL
Energy import infrastructure		
Grid connection	None	GridN
Natural gas pipeline	No	NGplN
LNG terminal	No	LNGtN
Oil terminal/refinery	No	OilRN
Oil derivatives terminal	Yes	OilDY
Water		
Precipitation	High	H2OPH
Ground water	Low	H2OGL
Water pipeline	No	AquaN
Sea water	Yes	H2OSY

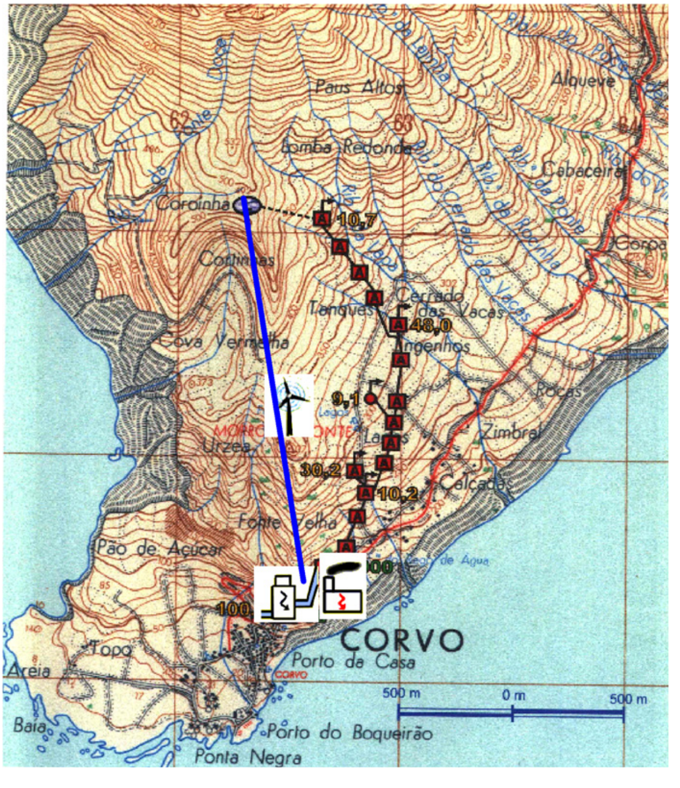

Fig. 3. The hydro-pumping storage system proposed for Corvo Island.

Table 10
Potential energy carriers

Potential energy carriers	Condition	Code
Electricity	IF ElectC	ECEl
Petrol/Diesel	IF (OilRY OR OilDY)	ECPD
LPG	IF (OilRY OR OilDY)	ECLPG

Table 11
Potential delivering technologies

Technology	Condition	Code
Electricity conversion system		
WECS	IF (ElectM OR ElectH) AND (WindM OR WindH)	WECS
HECS	IF (Elect) AND (HydroM OR HydroH)	HECS
DEGS	IF (Elect) AND (NGplY OR LNGtY OR OilRY OR OilDY)	DEGS
Heating system		
Solar collectors	IF (Heat) AND (SolarM OR SolarH)	STCo
Gas boilers	IF (Heat) AND (NGplY OR LNGtY OR OilRY OR OilDY OR WasteG OR WWG)	GSBo
Fuel		
Petrol/Diesel	IF (Tran) AND (ECPD)	PDFuel
Water supply		
Water collection	IF (Water) AND (H2OPM OR H2OPH)	WaterC

The technologies considered are selected in the next tables. We will focus mainly on energy and water supply. Heating and cooling are to be designed at unit level, not island level (Table 11).

Corvo has no connexion to the mainland so it needs storages for energy and other essentials. Storages already exist for supply water (rain collection system) and fossil fuels. The innovative alternative for storing excess electricity is reversible hydro. The excess of wind can be pumped to the upper reservoir, and then the electricity lack can be produced from hydropower (Table 12).

Most of the possible cases of integration of flows are not easy to implement in Corvo. In case of combined generation there are not demands of comparable magnitudes (for instance of heat or cold and electricity). In case of waste or wastewater treatment, the amounts to be treated are not enough to justify the investment that would make possible the energy use of waste. On the other hand, water supply system is well suited for integration with energy storage system as reversible hydro. Same reservoirs could be used for both purposes, which would significantly increase the viability of such a scheme, as well as the penetration of renewables (Table 13).

Due to Corvo's physical and meteorological characteristics there is potential to install water pumped storage for later hydropower production. Water storage is the solution with better prospects for this particular energy system. The water stored in upper reservoir can be retrieved at any moment, either for use in turbines, or water supply.

The turbine facility, with its given efficiency of around 70%, can use the water from upper reservoir, produce electricity that will be supplied to the grid, and fill the lower

Table 12
Potential storage technologies

Storage technology	Condition	Code
Electricity storage system		
Reversible hydro	IF (WECS AND HECS)	RHECS
Fuel		
LPG	IF LPGFuel	LPGstor
Petrol/Diesel	IF PDFuel	PDstor
Water, waste and wastewater		
Water	IF Water	WaterS
Waste fill	IF Waste	WasteF
Wastewater tanks	IF WWT	WWstor

Table 13
Integrating the flows

Integration technology	Condition	Code
Combined water and power	IF (HydroM OR HydroH) AND Water	CWP

reservoir. Turbine generator will typically have frequency and voltage control, and will often have output control. It can only use as much water as there is in upper reservoir, and its output cannot surpass the load of the power system, at any single moment.

In order to show the pathway for Corvo renewable island, 3 scenarios of energy supply where set:

1. *Wind 30%*—baseline scenario, limiting intake of wind electricity to 30% on hourly basis, and thus not overloading wind turbine with supplying ancillary services.
2. *Wind Reversible Hydro*—wind and hydro scenario, with wind turbine being able to supply ancillary services, and thus allowing for 100% momentaneous penetration, storing the excess wind electricity by pumping.
3. *Wind Reversible Max. Hydro*—wind and maximised hydro scenario, similar to previous, but with running strategy-giving advantage to hydro, thus increasing the stability of the grid.

The results were reported in detail in Ref. [8] and Ref. [14]. While in scenario 1 the penetration of renewable energy, wind, reaches 25%, in wind-hydro scenarios it is possible to supply 70% energy from renewable sources, thus significantly increasing the security of supply.

4. Porto Santo case study

Madeira archipelago, with its main islands Madeira and Porto Santo, is situated in the northern hemisphere at latitude of 32°, in the Atlantic Ocean. It is an ultra-peripheral insular region, 800 km off the coast of Africa, 980 km from Lisbon and 850 km away from the Azores.

Porto Santo's territory of about 42 km^2 is almost all covered with calcareous matter, especially on the northern side. The island is adorned with peaks, almost all to the North, the highest of which is Pico do Facho, 516 m. Its landscape is different from the island of Madeira. While lush green predominates on Madeira, Porto Santo is almost stripped of vegetation and the southern coast is bordered by 9 km long beach of soft sand that makes it an esteemed resort area.

Porto Santo is inhabited by 5000 year long residents, most of them living in the capital, Vila Baleira, but the number increases significantly during summer months. The number of tourists and part time second house residents fluctuates between 500 in the wintertime and reaches up to 13,000 in the summertime. Tourism has given Porto Santo an economic dynamism that has been growing year by year. The construction of its airport in 1960, further expanded in 1973, was an important factor that contributed decisively to the island's economic and tourist expansion.

The following chart represents final energy distribution in Porto Santo during year 2000, showing the great relevance of transport (Fig. 4).

The 30 years averaged wind velocity, as measured at the meteorological station on Porto Santo airport, at 10 m height, is only 4.2 m/s, what is not particularly high. The lowest monthly average is 3.4 m/s corresponding to September, while the highest average corresponds to April, 4.5 m/s, which makes it fairly constant throughout the year. The results from exploitation of installed wind turbines are giving 35% higher average wind velocity at 10 m, at the location (Fig. 5).

The total solar radiation on horizontal surface has been measured since 1999 at the meteorological station. For the year 2000, the data are shown in Fig. 6. Unfortunately, the information of total solar radiation on horizontal surface is not directly usable in many studies, since solar panels are mainly placed on tilted surfaces. Since the total radiation is made of direct and diffusive radiation, it is not simple to convert it into total solar radiation on tilted surface.

The precipitation is rather low in Porto Santo and hydro resources are negligible. Since the local wells cannot satisfy the demand for water, a desalination plant has been installed in 1990. The biomass is scarce. The wave conversion technology is not yet feasible. It was not considered technically practical usage of any other renewable resources. Among the fossil fuels, only oil derivatives are imported to Porto Santo: petrol, Diesel, fuel oil and LPG.

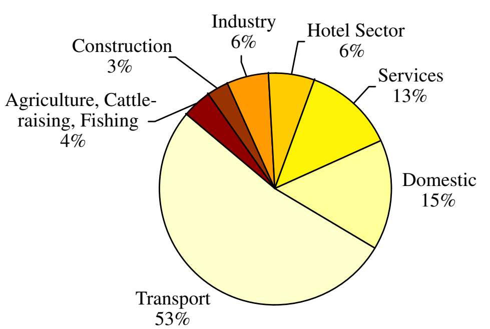

Fig. 4. Porto Santo final energy distribution in 2000, by sector.

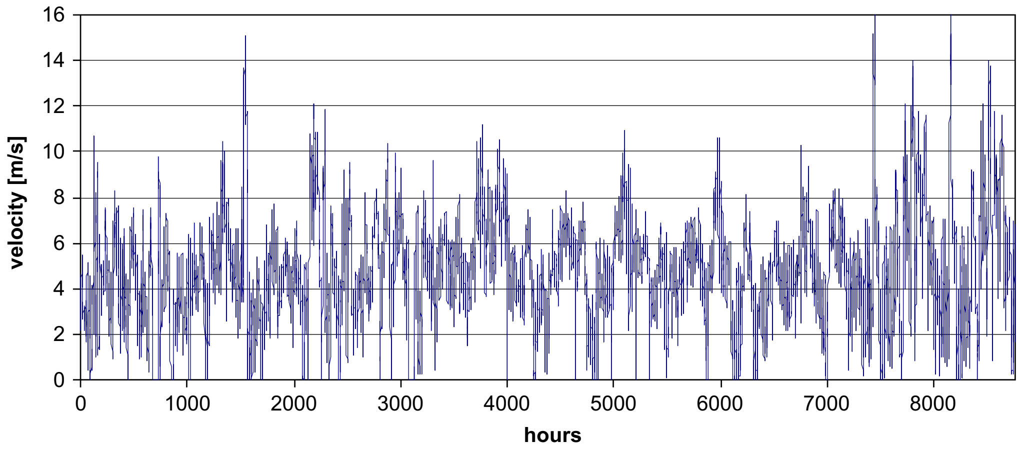

Fig. 5. Hourly average wind velocities at 10 m, meteorological station, Porto Santo, 2000.

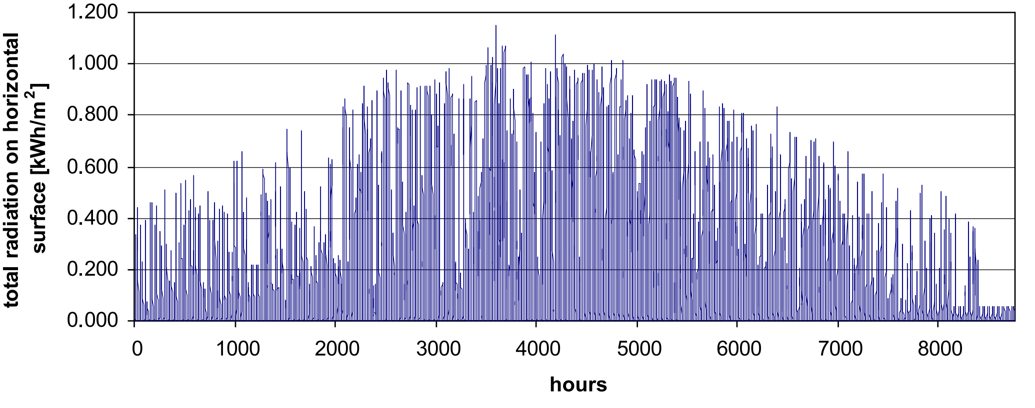

Fig. 6. Hourly average total solar radiation on horizontal surface, meteorological station, Porto Santo, 2000.

There are discussions of the potential for small-scale LNG. The technology of sea transport of liquefied natural gas is well established on large scale. It is expected that with maturing of the technology, smaller-scale applications will become viable, which will show a new way for islands, starting from bigger ones, like Cyprus or Madeira, but if the scaling down does not reach some unsurpassable obstacle, it is probable that it will also be applicable to small-scale islands, like Porto Santo, in the same way LPG distribution is made today.

The current grid capacity is based on thermal units as described in Table 14, and of a wind park with, respectively two 225 kWe and one 660 kWe Vestas wind turbines.

The Diesel-fired groups 1 and 2 are old units, which are only operated for backup power. All together, the thermal units delivered 27.4 GWh to the grid in 2002, with a 2.48 M€ total cost of operation and maintenance, and a 0.128 €/kWh global specific cost of power generation, including investment cost amortisation. The total fuel cost and total maintenance cost have been, respectively 0.060 and 0.031 €/kWh.

Table 14
Characteristics of the existing thermal units connected to the grid

	Group 1	Group 2	Group 3	Group 4	Group 5
Nominal power output (kW)	3500	3500	3410	3410	3410
Type of fuel	Diesel	Diesel	Heavy fuel-oil	Heavy fuel-oil	Heavy fuel-oil
Minimum load ratio (%)	30	30	50	50	50
Beginning of operation			1998	1998	2001

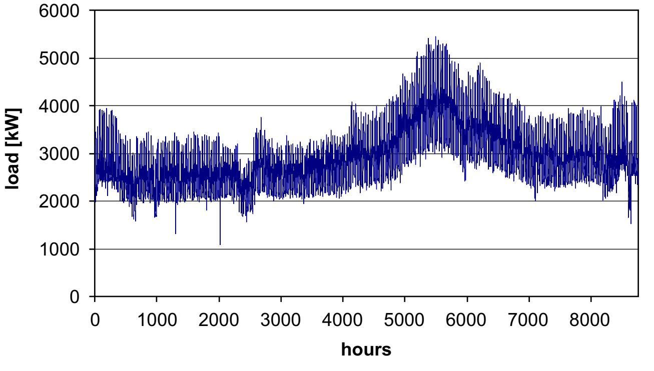

Fig. 7. Hourly average electricity system load, 2000.

Since the low load is only double than the wind potential presently installed, in the situation when load is low, the wind is good and wind turbines may operate at the full power, there is more wind electricity entering the system (up to 1.1 MW) than the level that is generally considered acceptable, around 30% of the total. In such cases, the excess wind electricity either cannot be taken up by the system, or can be stored in some way. Presently, the system does not have any storage component, and so the excess wind energy is simply rejected (Fig. 7).

The number of vehicles has been growing fast in the last years in the whole archipelago, especially concerning private owned vehicles, thanks to the increase in wealth of local communities and the great development in road accesses. The total number of vehicles was growing at an annual rate of approximately 5% during the 1988–1997 period and about 9% during 1998 and 1999 [27]. The land transport sector alone, which globally represents 50% of the demand for final energy (for Porto Santo it corresponds to 53%), doubled consumption between 1991 and 2000.

Porto Santo has 5000 yearlong inhabitants and the penetration rate of private owned vehicles is 522‰, the greatest of all the Municipalities in the archipelago. This represents 3% of the total of Madeira region, or about 2250 vehicles in total. In 2000, Porto Santo road transport consumed 2274 toe of fuel, which corresponds to 75% of the total spent in transport in the island (3028 toe), and almost 40% of all primary energy consumed (5761 toe).

Based on hypothesis of regional development, national and European orientations, international markets of energy products, technological progress and environmental aspects, three scenarios (high, low and alternative) were constructed for the energy sector

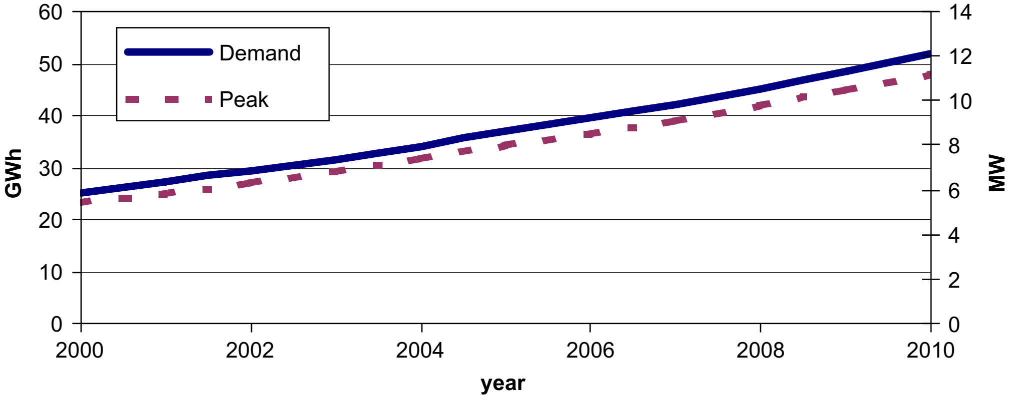

Fig. 8. Electricity demand scenario.

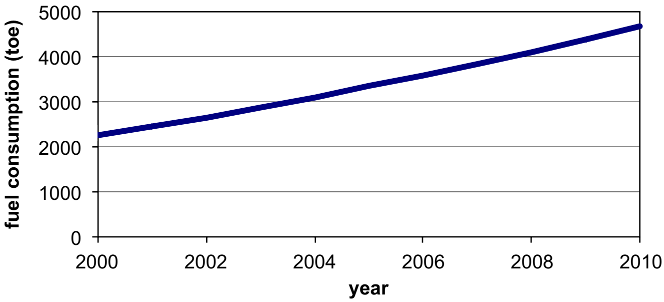

Fig. 9. Fuel consumption for road transport, demand scenario, tons of oil equivalent.

development in the Madeira Region, as described in Ref. [27]. The values for the demand used for this study are based on the high development scenario forecasts, and it is assumed that Porto Santo Island will show the same evolution as Madeira Region as a whole. The forecasts can then be used for medium-range planning of the energy sector.

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

For the high scenario, the yearly growth rate for fuel demand for road transport is assumed to be 8% during the period 2001–2005, and 7% for the period 2006–2010, as shown on Fig. 9.

4.1. Porto Santo as a 'renewable island'

The plans to convert Porto Santo into the first Portuguese renewable island and to be one of 100 sustainable communities (100% renewable) in Europe, as indicated in the campaign of take-off of the EU White Paper on Renewable Energies, are underway. The island was given such a role in the energy plans.

If energy storage is not considered, renewable energy penetration is very limited by its intermittent nature. In what concerns electricity production by wind, even with variable pitch wind turbines controlling output and better frequency and voltage control equipment, which would enable 100% of wind electricity being delivered to the system, due to the wind quality in Porto Santo and to its intermittent nature, only up to 45% of yearly electricity demand could be delivered from 6 MW of wind turbines, even if this 6 MW covers the peak load of 5.4 MW relative to year 2000. The rest would still have to come from thermal power plant firing fuel oil. In order to increase the penetration of renewable energies further, the time has come to tackle the problem of energy storage. Since it is considered that there are no local conditions for storing potential energy into a water reservoir for later hydropower production, like in El Hierro Island (Spain), or to store the surplus electricity produced from wind source to the mainland grid, like in Samsoe Island (Denmark), other ways have to be found [28].

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

Electricity is a highly demanded commodity, mainly concentrated in Vila Baleira, the island capital. Heat demand is dispersed over the houses and mainly for hot water, as room heating (or cooling) is generally not necessary due to the climatic conditions. Cold needs are small and mainly concentrated in hotels. Transport fuel needs are high, mainly for road transport (and also some for air transport) due to the very important motorisation of the island and the tourism activity; however those are short range displacements. Water needs are mainly for housing and service sector (especially tourism related) as industry and agriculture are not significant in the island. Waste and wastewater treatment are also mainly concentrated (although in isolated units waste and wastewater may be dumped or individual solutions may be present) (Table 15).

The most important endogenous energy resources at Porto Santo are wind and solar. Porto Santo is a typically remote region, with established transport infrastructure but no grid connexions to the mainland, or pipelines for fuels or water supply. Imported resources

Table 15
Mapping the Porto Santo community needs

Needs	Level	Geographic distribution	Code
Electricity	Low, medium or high	Dispersed, concentrated	ElectMC
Heat	Low, medium or high	Dispersed, concentrated	HeatLD
Cold	Low, medium or high	Dispersed, concentrated	ColdLC
Transport fuel	Low, medium or high	Short, long distance	TranHS
Water	Low, medium or high	Dispersed, concentrated	WaterMC
Waste treatment	Low, medium or high	Dispersed, concentrated	WasteLC
Wastewater treatment	Low, medium or high	Dispersed, concentrated	WWTLC

are shipped fossil fuel derivatives (petrol, Diesel oil, fuel oil, and LPG). Fresh water is scarce and sea water is a source of drinking water by desalination.

Hydrogen is a strategically sound potential energy carrier. Hydrogen can be used in transport sector as well as storage medium associated to power supply (Tables 16,17).

The technologies considered are selected in the next tables. We will focus mainly on energy and water supply. Heating and cooling are to be designed at unit level, not island level. Heat pumps are interesting for big units/consumers like hotels. Regarding cooling, only electricity coolers may be used in small/private units, the other technologies aim mostly at big units (Table 18).

Porto Santo has no connexion to the mainland so it needs storages for energy and other essentials. Storage already exists for supply water (desalinated), fossil fuels, waste and wastewater.

The innovative alternative for storing excess electricity is hydrogen storage, as reversible hydro is considered not to be feasible for lack of altitude differences. The excess of wind can be electrolysed into hydrogen and stored, and then the electricity lack can be supplied from hydrogen by a fuel cell, internal combustion engine, or hydrogen can be used for

Table 16
Mapping Porto Santo available resources

Resource	Level	Code
Local primary energy		
Wind	Low, medium or high	WindM
Solar	Low, medium or high	SolarH
Hydro (height)	Low, medium or high	HydroL
Biomass	Low, medium or high	BiomL
Geothermal	Low, medium or high	GeothL
Energy import infrastructure		
Grid connection	None, weak, strong	GridN
Natural gas pipeline	No, yes	NGplN
LNG terminal	No, yes	LNGtN
Oil terminal/refinery	No, yes	OilRN
Oil derivatives terminal	No, yes	OilDY
Water		
Precipitation	Low, medium or high	H2OPL
Ground water	Low, medium or high	H2OGL
Water pipeline	No, yes	AquaN
Sea water	No, yes	H2OSY

Table 17
Potential energy carriers in Porto Santo

Potential energy carriers	Condition	Code
Electricity	IF ElectC	ECEl
Hydrogen	IF Tran	ECH2
Petrol/Diesel	IF (OilRY OR OilDY)	ECPD
LPG	IF (OilRY OR OilDY)	ECLPG

Table 18
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
SECS-Thermal	IF (Elect) AND (SolarH)	SECS
DEGS	IF (Elect) AND (NGplY OR LNGtY OR OilRY OR OilDY)	DEGS
CCGT	IF (ElectH) AND (NGplY OR LNGtY OR OilRY OR OilDY)	CCGT
FC	IF (Elect) AND (H2Fuel)	FC
Heating system		
Solar collectors	IF (Heat) AND (SolarM OR SolarH)	STCo
Heat pumps	IF (HeatH AND ECEl)	HPHe
Gas boilers	IF (Heat) AND (NGplY OR LNGtY OR OilRY OR OilDY OR WasteG OR WWG)	GSBo
Cooling		
Solar absorbers	IF (Cold) AND (SolarH)	Sabs
Heat pumps	IF (ColdH AND ECEl)	HPCo
Gas coolers	IF (ColdH) AND (NGplY OR LNGtY OR OilRY OR OilDY OR WasG OR WWtG)	GSCo
Electricity coolers	IF (ColdH AND ECEl)	ELCo
Fuel		
Hydrogen	IF (Tran) AND (ECH2)	H2Fuel
Electricity	IF (Tran) AND (ECEl)	ElFuel
LPG	IF (Tran) AND (ECLPG)	LPGFuel
Petrol/Diesel	IF (Tran) AND (ECPD)	PDFuel
Water supply		
Desalination	IF (Water) AND (H2OSY)	WaterD

powering transport. An alternative way of producing hydrogen is by reforming of available fuels (Table 19).

Most of the possible cases of integration of flows are not easy to implement in Porto Santo. In case of combined generation there are no demands of comparable magnitudes (for instance of heat or cold and electricity). In case of waste or wastewater treatment, the amounts to be treated are not enough to justify the investment that would make possible the energetic use. Integrating power supply and hydrogen production is associated with energy storage and can increase the overall penetration of renewable energy sources (Table 20).

After applying the methodology up to this point, one can start to identify concrete scenarios, using technical characterisation and target results. For Porto Santo and under the approach of RenewIslands, the main demands identified are electricity and transport. The scenarios to be modelled reflect different targets concerning the penetration of RES and also different technologies application. The considered scenarios of energy supply are summarised below:

1. *Wind 30%*—baseline scenario, limiting intake of wind electricity to 30% on hourly basis, and thus not overloading wind turbine with supplying ancillary services.

Table 19
Potential storage technologies

Storage technology	Condition	Code
Electricity storage system		
Electrolyser + hydrogen	IF (WECS OR SECS OR PV) AND NOT HECS	ELYH2
Reformer + hydrogen	IF (ECNG OR ECBG OR ECPD OR ECEt OR ECLPG OR ECBD) AND NOT HECS	REFH2
Fuel		
Hydrogen	IF H2Fuel	H2stor
LPG	IF LPGFuel	LPGstor
Petrol/Diesel	IF PDFuel	Pdstor
Water		
Water	IF Water	WaterS
Waste		
Waste fill	IF Waste	WasteF
Wastewater		
Wastewater tanks	IF WWT	WWstor

Table 20
Integrating the flows

Integration technology	Condition	Code
Combined power and hydrogen production	IF (WECS OR PV) AND ECH2	CPH2

2. *Wind 100%*—maximised wind, wind turbines are able to supply ancillary services and can thus reach 100% momentaneous penetration.
3. *FCWind 30%*—maximised wind and peak shaving fuel cell, limiting intake of wind electricity to 30% on hourly basis, while storing the excess wind into hydrogen using electrolyser, and using fuel cells running on hydrogen for peak shaving.
4. *FCWind 100%*—100% wind, same as above, but allowing for 100% momentaneous penetration of wind.
5. *FCSolarWind 30%*—baseline wind plus maximised solar and peak shaving fuel cell.
6. *FCSolarWind 100%*—100% renewable (wind + solar).
7. *FCWindTransport 30%*—maximised wind plus peak shaving fuel cell and 3 hydrogen shuttle vans.
8. *FCWindLNGTransport 100%*—baseline wind and fuel cell and road transport based on hydrogen reformed from LNG.

The results were in details published in Refs. [8,15]. It has been shown that is technically possible to increase the penetration of renewable energy from 11% in baseline scenario to 16% in wind with peak shaving with fuel cell scenario 3–17% in wind–solar scenario 5 with fuel cell peak shaving, to 50% if wind turbines could supply ancillary services in scenario 2 and to 100% in fully developed wind–hydrogen scenario 4 or wind–solar–hydrogen scenario 6. It was also shown that when hydrogen is used as energy storage media, it is well suited for integrating the electricity and transport systems.

5. Mljet case study

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 3.37 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, 14 small settlements on 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 (Fig. 10) 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 two to three times bigger than in the winter.

According to the RenewIslands methodology and by following its first step the needs of the Island of Mljet were mapped and results are shown in Table 21.

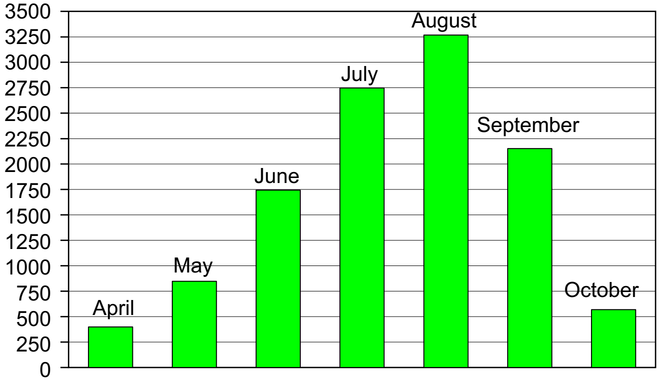

Fig. 10. Tourist arrivals to Mljet in 2003.

Table 21
Mapping the Mljet community needs

Needs	Level	Geographic distribution	
Electricity	Medium	Dispersed	ElectMD
Heat	Low	Dispersed	HeatLD
Cold	Low	Dispersed	ColdLD
Transport fuel	Low	Long	TranLL
Water	Medium	Dispersed	WaterMD
Waste treatment	Low	Dispersed	WasteLD
Wastewater treatment	Low	Dispersed	WWTLD

Electricity is medium demanded commodity which is delivered to the Island of Mljet by two undersea cables which are connected to the mainland grid. Each cable supplies power to one side of the island. In one way electricity consumption on the island is dispersed over the island communities but on the other side all communities are connected to island power grid so power system also can be observed as sufficiently concentrated. Fig. 11 represents hourly average electricity system load which has been calculated for year 2002 from measurements on the one 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).

Heat demand is dispersed over the houses and mainly for hot water, as room heating (or cooling) is generally not necessary due to the climatic conditions. Cold needs are small and distributed in houses. 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 and there is only one fuel station on the island which also supplies fuel for agriculture machinery and boats.

Water needs on the island are dispersed and they are the 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. Waste and wastewater treatment are also mainly dispersed.

The most available renewable resources on the Island of Mljet are solar, wind and biomass. The results of resources mapping are shown in Table 22.

The data for the solar radiation on horizontal surface were obtained from meteorological station in Dubrovnik and they were adapted for tilted surface on Mljet by H_2RES and PV-GIS [29] computer programs.

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 to results of mapping the RES potential (Fig. 12).

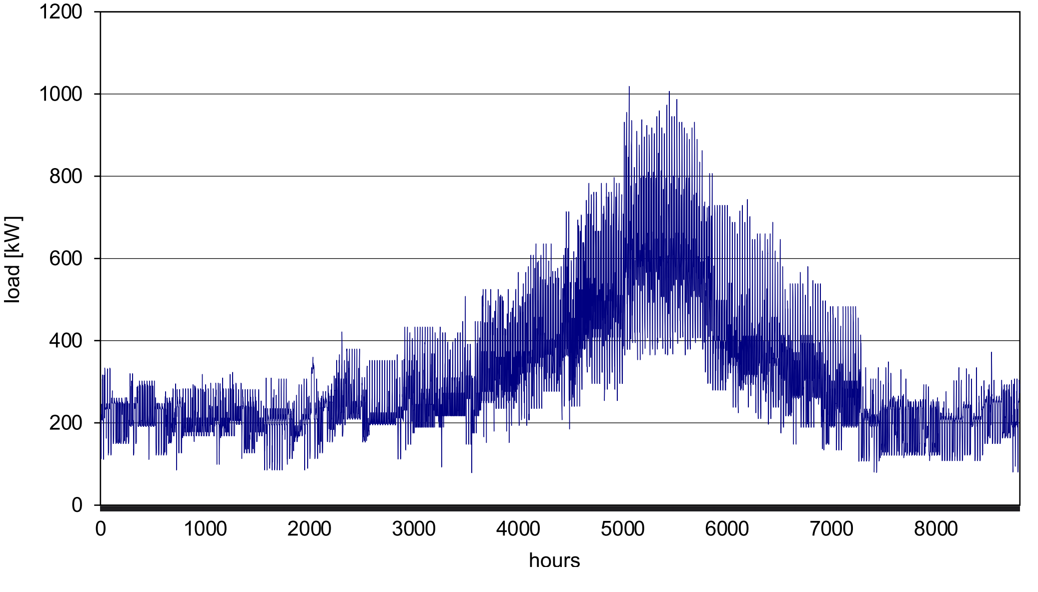

Fig. 11. Hourly average electricity system load, 2002.

Table 22
Mapping Mljet available resources

Resource	Level	Code
Local primary energy		
Wind	Low, medium or high	WindM
Solar	Low, medium or high	SolarM
Hydro (height)	Low, medium or high	HydroM
Biomass	Low, medium or high	BiomH
Geothermal	Low, medium or high	GeothL
Energy import infrastructure		
Grid connection	None, weak, strong	GridS
Natural gas pipeline	No, yes	NGplN
LNG terminal	No, yes	LNGtN
Oil terminal/refinery	No, yes	OilRN
Oil derivatives terminal	No, yes	OilDN
Water		
Precipitation	Low, medium or high	H2OPM
Ground water	Low, medium or high	H2OGL
Water pipeline	No, yes	AquaN
Sea water	No, yes	H2OSY

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 which has been declared National park in 1960 (Table 23).

The technologies considered are selected in the next tables. Focus was mainly on energy supply for power system and transport. Heating and cooling are to be designed at unit level, not island level (Table 24).

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. The similar situation was with water (the construction of water pipelines over the very demanding terrain to dispersed locations for small number of consumers is currently considered too costly and also linked to construction of sewage and wastewater treatment system) (Table 25).

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

5.1. Devised scenarios for the Mljet Island and the results of the modelling

In total, 18 different scenarios for Mljet have been calculated by H_2RES computer model (Fig. 2).

Generally, scenarios are divided into two groups:

1. The group of scenarios in which a limit on hourly penetration of electricity from intermittent sources is set at 30% of hourly system load, meaning that in each hour,

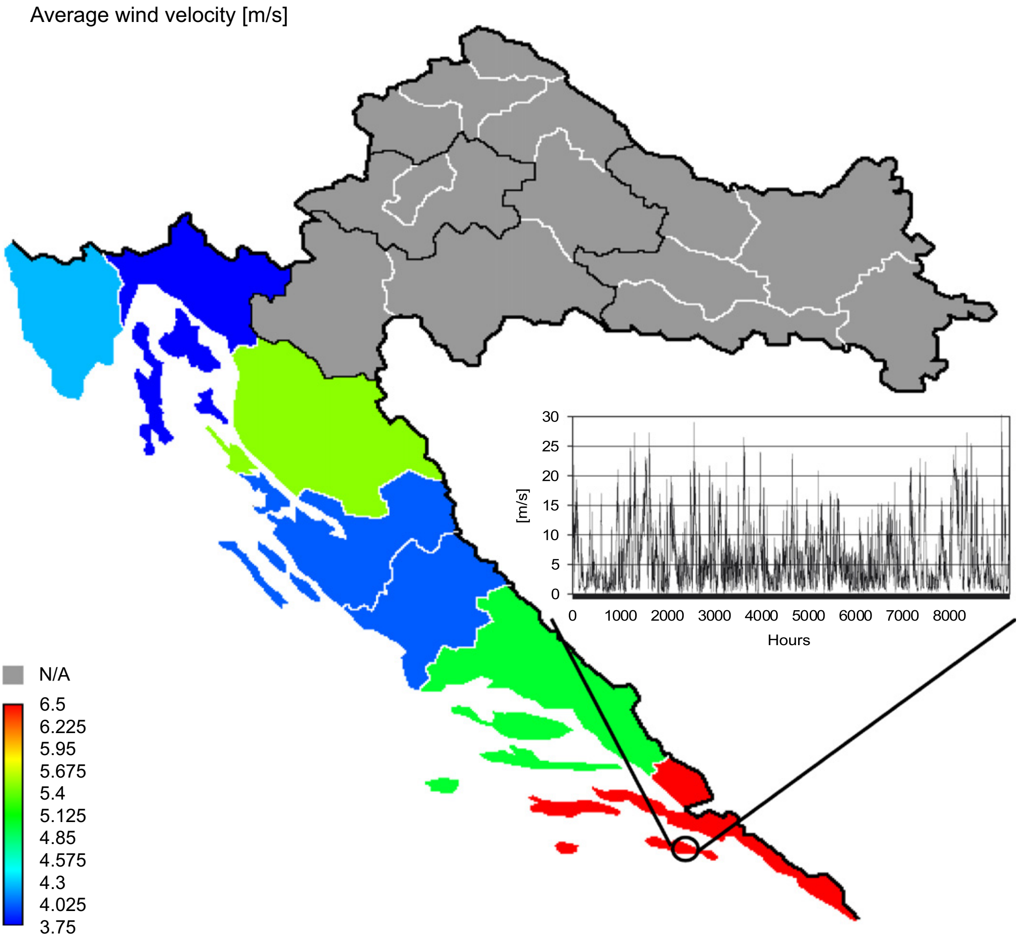

Fig. 12. Mapping the wind potential for DEG [30].

Table 23
Potential energy carriers in Porto Santo

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

power system will accept up to 30% of electricity coming from wind or solar. In these scenarios the undersea connexions 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.

Table 24
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
FC	IF (Elect) AND (H2Fuel)	FC
Heating system		
Solar collectors	IF (Heat) AND (SolarM OR SolarH)	STCo
Fuel		
Hydrogen	IF (Tran) AND (ECH2)	H2Fuel
Electricity	IF (Tran) AND (ECEl)	ElFuel
Water supply		
Desalination	IF (Water) AND (H2OSY)	WaterD
Water collection	IF (Water) AND (H2OPM OR H2OPH)	WaterC

Table 25
Potential storage technologies

Storage technology	Condition	Code
Electricity storage system		
Electrolyser + hydrogen	IF (WECS OR SECS OR PV) AND NOT HECS	ELYH2
Fuel		
Hydrogen	IF H2Fuel	H2stor
Water		
Water	IF Water	WaterS
Waste		
Waste fill	IF Waste	WasteF
Wastewater		
Wastewater tanks	IF WWT	WWstor

2. The second group of scenarios do not have the penetration limit, so if there is enough wind or solar energy, 100% of 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 and wind turbines are able to supply ancillary services.

The scenarios are also different according to the installed technology:

1. The scenarios 1–6 have only installed wind turbines, photovoltaics or their combination.
2. The scenarios 7–12 beside units for RES utilisation have also installed hydrogen loop (fuel cell, electrolyser and hydrogen storage). The fuel cell in the scenarios with 30% penetration limit was used for peak shaving and that means that fuel cell will only operate if load is bigger than 80% of weekly peak. The scenarios with installed hydrogen technology and without penetration limit represents 100% renewable scenarios which means that load is covered from own island resources.

3. In the last 6 scenarios 13–18 the integration of energy flows has been made so besides the power load the scenarios also have a hydrogen load for the transport. The hydrogen load is 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.

Different scenarios also have different modelling and optimisation conditions. The scenarios with 30% penetration limit are optimised in the way that penetration of RES energy is maximised while rejected renewable energy is kept under 10% of total RES production. The scenarios with 100% of momentaneous penetration are also optimised 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.

The detailed description of all results with description of necessary technology for installation has been given in Ref. [31]. The main conclusions that might be drawn from the results are that in the cases with 30% of allowed penetration the amount of RES energy on yearly basis was from 8% to 12%, where higher values were achieved with mixture of technologies, in the case with implemented hydrogen technology, hydrogen for transport and fuel cell for peak shaving the RES penetration was even higher from12% to 17%. In the cases with 100% of allowed penetration and without the hydrogen technology the maximum RES penetration was 50% on the yearly base and by introducing the hydrogen technology and proper size of its components it was concluded the Mljet Island could become 100% renewable island covering all its electricity and transport energy needs from renewable sources and with possibility for the export of RES electricity from the island. A larger investment into utilization of renewable energy sources on Croatian islands could become promising solution for transformation of island energy systems from 100% net importers to energy exporters and to 100% renewable communities which can satisfy all their energy needs from local renewable resources. Furthermore, this will not just have impact on the security of islands energy supply but it will also make great contribution to achievement of Kyoto Protocol target which will be hardly reached if Croatia continues its development according to business as usual scenarios without special investment into renewable technologies [32].

6. Conclusions

The RenewIslands methodology was presented and applied to the islands of Corvo, Porto Santo and Mljet, resulting in different solution for different islands. The application of methodology to those three islands has shown that it might be beneficial to look for possible integration of resource flows, like for example integration water supply system with reversible hydro in Corvo, or electricity and transport systems through hydrogen storage in Porto Santo or Mljet. It was also shown that only by adding storage to energy and resources systems it is possible to significantly increase the penetration of locally available resources, and thus increase the security of supply and import dependence.

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