Integration of renewable energy and demand response technologies in interconnected energy systems

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ABSTRACT

Sustainable island energy systems have been a subject of academic research for some time. Real-life examples of highly renewable and sustainable island energy systems can be found all over the World. Islands on small geographic proximity provide the potential for the development of 100% renewable island energy systems by exploiting their grid interconnections. This paper proposes that interconnections of a group of islands can be used to integrate the production from locally available renewable energy sources. Besides interconnection, electric vehicles were used as a demand response technology to provide storage for electrical energy from variable sources. Electric vehicles were connected to the grid using smart charging systems (vehicle-to-grid). In addition, stationary batteries were explored in sub-scenarios for the year 2035. This enabled to analyse the influence of the battery location through two main different scenarios, i.e. one big central battery and several smaller distributed batteries. Scenarios with different integration dynamic of variable renewable energy sources and electrical vehicles were modelled with EnergyPLAN model, while the interconnection analysis was carried out with the MultiNode tool expansion. The results showed that the interconnections increased the share of energy from renewable energy sources in the final energy consumption and declined the total critical excess electricity production, while vehicle to grid technology enabled exploitation of synergies between sectors.

Keywords: Sustainable island systems, Renewable energy sources, EnergyPLAN, MultiNode, Interconnection

Table of acronyms

CEEP	Critical Excess Electricity Production
DR	Demand-response
DSM	Demand-side management
EV	Electric vehicle
GIS	Geographic information system
PES	Primary energy supply
PP1	Power plant
PV	Photovoltaic
RES	Renewable energy sources
SE	Solar energy

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SEAP	Sustainable energy action plan
TPP	Thermal power plant
V2G	Vehicle to grid
VRES	Variable renewable energy sources

INTRODUCTION

In recent years, increasing penetration of renewable energy sources (RES) through integration of different sectors of energy system, i.e. power system, heating and cooling sector and transport sector is becoming one of the most investigated solutions for achieving more self-sufficient local island communities. Therefore, scientific research in this field has made a lot of effort to develop methods and tools particularly designed for carrying out analysis of energy systems on islands. RenewIslands methodology in Duić, N. et al. [1] provides assessment of technical feasibility of various options for integrated energy and resource planning. The methodology systematically approaches the analysis of needs, available resources, appropriate technologies and creation of scenarios for development of island energy systems in transition to sustainable and independent energy systems powered by locally available renewable energy. It provides the tables with the level and density of particular demands, qualitative potential of particular source and qualitative assessment of technologies which can be used to balance demand for, for example electricity, cooling energy and water with energy supply from locally available sources. Krajačić G. et al. [2] described H2RES software for analysis of islands energy systems as well as micro grid operations. The software is also suitable for modelling 100% renewable energy system. Möller B. et al. in [3] developed a tool for examining islands energy systems as a part of the project "Cradle to Cradle Islands" funded by the EU Interreg IVb North Sea Region Programme. The tool facilitates the identification of islands possibilities for sustainable development. Initially, the tool was developed on a basis of energy system inventories for the case of four islands Samsø (Denmark), Spiekeroog (Germany), Runde (Norway) and Ameland (Netherlands). Inventories were developed and could be used for analysis of the effects on carbon emissions, fuel consumption and investments made for the energy technologies. Moreover, the tool through SWOT analysis contributes to a learning process which can help to develop renewable energy systems on examined islands. Apart from using already developed models, new algorithms have also been examined, for example Gašparović, G. et al. [4] updated the H2RES model by adding the modules for electric vehicle (EV) simulation. Bačelić Medić, Z. et al. [5] highlighted the importance of optimal solar and wind energy integration with storage solution together with energy savings and improvements in energy efficiency in the energy production on the case study of an island Hvar conducted in EnergyPLAN software. Impact that energy production and transport system integration have on the electricity demand curve was investigated in Šare, A. et al. [6], hourly energy demand of the transport system and influence of integration of EV on electricity grid has also been examined in Novosel, T. et al. [7] and, through agent-based modelling of the transport demand, in Novosel, T. et al. [8]. Commercial energy planning software HOMER was used in Sadrul Islam et al. [9] for optimized hybrid RES, storage and diesel generator system for large island communities on an isolated island, while H2RES software was further developed for analyses in already mentioned cases of renewable islands and others, such as cutting the consumption of fossil fuels through hydrogen conversion and storage solutions for energy transition of Malta [10], further investigations of hydrogen as an energy vector in isolated island systems was conducted for the case of Porto Santo [11], and for optimization of annual costs when using hybrid system, which consist of wind power plant, pump hydro storage and water desalinization units on San Vincente and Cape Verde [12]. Moreover, H2RES was used in Segurado, R. et al. [13] to integrate energy and water supply for Cape Verde. For smaller island, and with different approach, penetration of RES into fragile environment was examined in Katsaprakakis, D.A., et al. [14]. Similar research was conducted for wind energy in Europe [15], providing the wind onshore and offshore potential and for Croatia, using geographic information system (GIS), in Međimorec, D., et al. [16], which provided the potential locations for future wind power installations in Croatia, using the GIS.

Modelling of renewable energy systems on islands requires research on technology implementation and research on the impact of renewables on the overall energy system. Balancing of the system is having a crucial role for energy system stability as the energy generation from wind and solar have variable nature. In the Mediterranean region, which is the focus region of this paper, wind and solar are the most promising RES. However, the visual impact and environmental issues caused by wind turbine installation could lead to the limited possibility of their installation close to the coastline. As an example of such restrictions the national legislative framework in Croatia prohibits the wind power installations in the 1000 m from the coastline. Therefore, the focus of this research was placed on the solar energy. Solar energy was elaborated in Haas, R. et al. [17], in relation to power market, as formidable in order to replace fossil fuels on islands with RES installations. Recent research in Lau KY, et al. [18] investigated economic feasibility of photovoltaics (PVs) in island communities in relation to fossil fuel prices and load sizes but did not take into account the integration of systems, for example water supply or transport. Replacement of fossil fuel with solar power, i.e. electricity generation from rooftop photovoltaics for the case of Canary Islands was studied in Schallenberg-Rodriguez, J. [19]. The study focused on development of the method for determining the potential of rooftop PVs showing that electricity can be generated at competitive price and that the potential is sufficient to cover electricity demand of each examined island. Nevertheless, the study did neither take into account ground based PV plants nor synergies with other sectors. Another study [20] emphasized the complexity of PV system installation in urban areas. Detailed geographical and economic analysis was carried out stressing that self-sufficiency can lead to achievement of economic benefits. The implementation of renewable energy technologies can also be fostered through application of incentive measures. This was discussed in K. Reinsberger et al. [21] where the authors analysed the effects of two different bottom-up initiatives for installation of PVs taking into account potential incentives and barriers. It was proved that a quality framework that can contribute to the creation of value added should be promoted for initiation and development of projects such as PVs installation.

Nowadays, balancing of the renewable energy production can be done in several different ways. One of the possibility is integration of sectors and various types of energy. Here, smart energy system is the best way of such integration leading to detection and utilization of synergies between different sectors, as shown in Dominković, DF. et all.[22]. Moreover, this enables to design better technical system which is capable of managing the VRES. In [22] it has also been proven that smart energy systems are cheaper considering the socio-economic costs. Single and multi-action initiatives for transforming island power systems into smart ones were assessed in Sigrista, L. et all. [23]. The research included an assessment of initiatives for implementation of five actions wind, PV, energy storage systems, demand-side management (DSM) and EV. Each initiative consists of a particular combination of different penetration level of mentioned energy technologies. Islands were grouped into clusters in order to identify their similarities for implementation potential of RES. The results of the assessment shows that type of initiative depends on the island size where smaller islands are more suitable for renewable energy source initiative, whereas larger islands for DSM. In Calise, F., et al. [24], the polygeneration system, combining electricity and water supply systems, as well as heating and cooling supply was investigated on the case study of Pantalleria island. The research results show that polygeneration approach can fulfil the water demand of the community and supply significant amounts of electricity, heating and cooling energy with acceptable payback period.

Another solution for balancing of the energy systems with high share of VRES are energy storage technologies, which are crucial for achieving self-sufficiency of islands. Comprehensive study and analysis of leading storage technologies has been reported in Rodrigues E.M.G., et all. [25]. Besides well-known stationary batteries technology, batteries from EVs, i.e. vehicle to grid (V2G) technology can serve as a storage system. Integration of the EVs into a micro-grid was examined in Mortaz, E. et al. [26] where authors proposed an optimisation model for managing the energy in a grid-connected smart grid that includes RES and a parking facility for EVs. The results show that longer parking times and higher price fluctuation ratios produce higher expected savings whilst a high price fluctuation ratio does not necessarily mean high expected savings. A case study for an entire energy system of Croatia was designed including different renewable sources where EVs served as a battery storage in Prebeg, P. et all [27], proving V2G concept for long-term planning on the national level in H2RES software. Various studies investigated the integration of EVs into energy system where the V2G technology was used, also in EnergyPLAN, as shown by Østergaard in [28]. In Colmenar-Santos, A. et all. [29], authors emphasized the importance of EV penetration for the operation of smart grids. The analysis done on the case study for the island of Tenerife show that usage of V2G technology can efficiently support the management of smart grids by significantly reducing the amplitude difference between valleys and peaks of the electric energy demand curve. High penetration level of EVs increases the participation of conventional generation units in the generation mix. In order to provide sustainability of the electric system on island authors advised to examine parallel penetration of RES and EVs in future research. Combination of solar PV, EVs, supercapacitor and diesel generator were used to test the performances of micro grid as an island solution in Yin et all. [30].

Furthermore, interconnections between islands and connection to the mainland grid could serve to balance the variability of renewables. The advantages of the interconnected energy systems were proven on many cases of regionally integrated energy systems. The benefits that regionally integrated electricity supply system has in relation to power generation systems of individual countries was examined in Gnansounou E, et all. [31] for the case study of Western Africa. Integrated system resulted in 38% lower total electricity production. Moreover, the advantages that countries and regions with high penetration of RES have from cross-border electricity transmission were presented in Lynch MÁ, et all. [32]. Benefits of interconnection between energy system of larger scale such as countries and regions can be also used on the case of islands. In Lobato E, et all. [33], the authors dealt with the technical and economic value of island interconnections for the several remote islands of the Spanish Balearic and Canary archipelagos. The results showed that interconnections in the considered case studies enable the flow of cheaper generation power between islands, however economic savings of each interconnection depends on the island characteristics. The RES energy scenarios have been also analysed for a group of interconnected islands in H. C. Gils et al. [34] and M. Child et. al.[35].

In [34], energy system included smart V2G option, however, batteries discharge was not examined in detail. On the other hand, [35] focused on high electrification of transport including both, charging and discharging of EVs. It has been concluded that V2G technology has important role in energy system with high share of VRES. It increases the flexibility because of accepting excess energy from wind and solar PV and providing electricity back to the grid. Nevertheless, the analysed group of the islands in the Baltic Sea which show significant variations in the need for heating and cooling in relation to the Mediterranean islands which is the case of this study. Northern and southern islands require a different combination of technology where northern islands provide significant potential in VRES balancing capabilities due to high heating demand which can serve as a storage system. Direct coupling of solar energy and EVs was investigated in Figueiredo, R. et al. [36], showing the potential to reduce the need for storage with controlled charging, but also demonstrating the compatibility of two technologies. Use of Multinode add-on tool in EnergyPLAN software to model the smaller zone inside a larger one, for example one county inside the national energy system, was employed in Bačeković et- al.[37].

The systematic overview of the most relevant studies presented in the Introduction section is provided in Table 1. The relevance is defined according to the main goal of this research and divided into several characteristic criteria.

Table 1 Systematic overview of the most relevant studies

Author	Software/ Methodology/ Tool	Single island / Group of interconnected islands	100% RES system, sectors included	Closed/ Open system (export to mainland allowed)	Type of transport electrification
Duić, N. et al. [1]	Renewisland methodology	Single island			
Krajačić G. et al. [2]	H_2RES	Single island	Yes, transport and electricity	Open	No
Möller B. et al. in [3]	C2CI insular model	Single island	Model allows 100% RES	Open	Yes, not specified in detail
Bačelić Medić, Z. et al. [5]	EnergyPLAN	Single island	Yes, all sectors	Closed	Yes, not specified in detail
Sadrul Islam et al. [9]	HOMER	Single island	No	Not specified	No
Busuttil, A. et al. [10]	H_2RES	Group of islands	No	Closed	No
Martins, R. et al [11]	H_2RES	Single island	Yes	Closed	
Segurado, R. at al. [12]	H_2RES	Single island	No	Not specified	No
Segurado, R. at al. [13]	H_2RES	Single island			
Katsaprakakis, D.A., et al. [14]	L.C.C. method	Single island	No		No
Calise, F., et al. [24]	Dynamic simulation models, tailor made	Single island	electricity and water supply systems, heating and cooling supply	Closed	No
Yin et all. [30]	Novel method	Single island	No	Closed	No
Lobato E, et all. [33]		Group of islands	No	Not specified	No
H. C. Gils et al.[34]	Mesap-PlaNet, REMix.	Group of islands			
M. Child et. al.[35]	EnergyPLAN	Group of islands	Yes	Open	V2G

I. Bacekovic et. al. [37]	EnergyPLAN	Smaller zone inside the larger zone	No	Open	No
Dorotić et al.[43]	EnergyPLAN	Single island	Yes, all sectors	Open	V2G, partially smart charge

In this paper, a new strategy for the simulation of the energy system was utilized. The novelty of this paper is in utilization of V2G technology as the only balancing demand response (DR) technology in operation without fossil fuel generators and tackling the last part of the supply share with stationary batteries, providing fully electrified systems in the interconnected archipelago. Another novelty is the analysis of interconnected operation of systems without installed fossil fuelled generators combined with discussion of different location possibilities of additional storage technologies.

As shown in the introduction, previous approaches utilized either other technologies or fossil fuel powered generators as a balancing technology. Furthermore, after the exploitation of V2G capacities additional storage technologies were added in order to investigate the influence of their location. The location was examined on the island scale, where one island was considered as one location available for the installation of the large battery banks and small household-size batteries. Here, the specific placement of batteries within the island itself was not taken into account.

METHOD

To simulate the energy system of islands in this research, EnergyPLAN 13.0 model was used. The EnergyPLAN is an input/output model which incorporates heat and electricity supplies as well as the transport, individual and industrial sectors. It has already been used for the scenario analysis of energy systems with a high share of the VRES as well as for the 100% renewable energy systems and various other analyses, which made it an established tool for similar applications [38]. In this version of the EnergyPLAN model, the option of balancing V2G and Hydropower can be used without Power plants (PP) 1 and PP 2 which represent the aggregated groups of power plants, usually supplied by fossil fuels. Moreover, one more balancing option is available in this version of the EnergyPLAN. V2G can be used to balance the need for PP and reduce Critical Excess Electricity Production (CEEP) but also to balance the Import/Export so that import is not needed if V2G batteries can be used, or, otherwise, energy is stored in batteries instead of exporting it from the system. This can be active in the “Simulation” TabSheet. For the purpose of scenario modelling, technical simulation was used. The technical simulation, seeks to find the solution with the minimum fuel consumption.

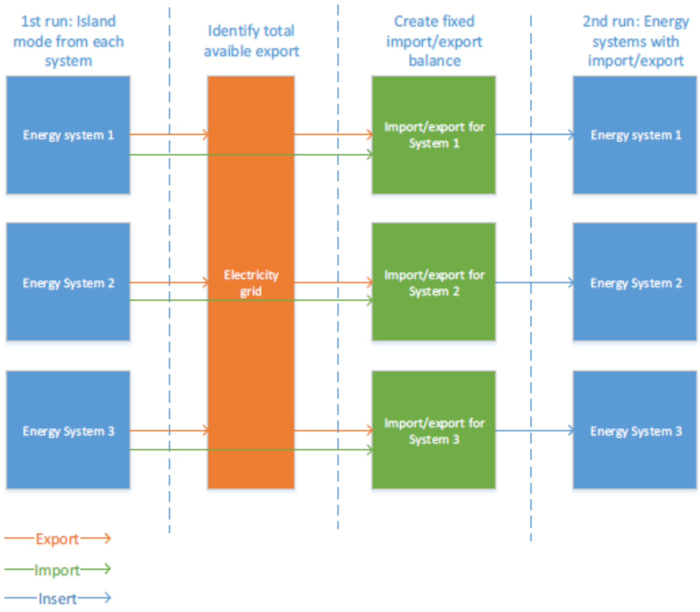

Figure 1 MultiNode tool general scheme [39]

MultiNode is an additional tool in EnergyPLAN, specially designed for analysing integration of local and national systems and plans of their development. The main result from MultiNode analysis is fixed import/export profiles between two or more energy systems. MultiNode seeks hours throughout the year where there is at the same time excess electricity in one system and import demand or condensing thermal power plant (TPP) production in another one.

In such way, the first system can integrate its excess production, which is usually a result of the VRES production, while the second system can meet its import demand or decrease the TPP production, thus increasing the share of RES and decreasing the fuel consumption.

Method for establishing import/export balances in MultiNode operation is described using the equations (1)-(4), which form the mathematical model of this tool [39].

Equation 1 Sum of available exports - identifies the amount of exportable electricity each system delivers and summs them for each hour. Up to 14 systems can be calculated.

$$export_{total} = \sum_{i=1}^{14} export_i \tag{1}$$

Equation 2 Amount of potential imports for each system *i* through summation of the import demand the current operation of the power plants which are installed in the system *i* (PP) in each hour in the year. Import is limited by the capacity of transmission lines between the systems.

$$P_{import\ i} = import_{demand\ i} + PP_{prod\ i} \tag{2}$$

Equation 3 Initial balance for each system, that defines the export as positive and the potential import as negative for each system

$$Balance_{initial\ i} = export_{\ i} + P_{imp\ i} \tag{3}$$

Important condition, which constitutes Equation 4 is, „system can only import if there is available electricity in the grid". This means that the merit order of the systems (in which they will satisfy their import demand from the grid) is determined by their order in the tool (user defined).

$$\boldsymbol{if}(P_{imp\ i} > export\ total)\ \boldsymbol{then}\ Import_i = exportabletotal\ \boldsymbol{else}\ Import_i = P_{imp\ i} \quad (4)$$

Balance is obtained by taking the $Balance_{initial}$ (from (3)) and replacing the export with the sum of imports needed in the other system, while the potential import is replaced with the actual calculated import. The consequence is that now the export is not balanced with the import. The excess accounted electricity is removed by diving the active export in each system (hourly) with the number of systems that exports electricity [39]. Through this procedure, now import/export hourly distributions are being created and this distributions replace the previously user-inputed ones. Those new distributions are used in running systems in a connected mode.

Novel idea in this work is to exploit the new balancing strategies which use the V2G concept to examine how the interconnected system would work if V2G is used as the major DR and storage technology. In this paper, above described tools are used to investigate the impact which grid interconnections between geographically close islands have on their power system, with no fossil fuel powered PP installed. Interconnections accompanied with DR technologies such as V2G concept, and storage technologies such as stationary batteries served to enable higher penetration of RES.

Scenarios for case study areas have been prepared for two categories, which are compared: isolated and interconnected mode. Planning of case study areas was conducted in two different scenarios:

- Scenario 1: business as usual, which follows the local Sustainable energy action plans (SEAP-s) and extrapolates the measures towards year 2035, and
- Scenario 2: RES scenario, which aim for maximal use of RES on the local level, with 5% CEEP being the aim for each system, while achieving as high as possible integration of RES.
    - Sub-scenario 2.1: Main DR technology, V2G, is aided by addition of stationary batteries. All stationary batteries are located in one zone, while the other zones supply the leading zone with the excess energy produced locally.
    - Sub-scenario 2.2: Main DR technology, V2G, is aided by stationary batteries, which are distributed uniformly in all connected zones.

Stationary batteries in EnergyPLAN 13.0 were modelled as pump hydro. This was possible due to the due to the similar behaviour of the energy technology, having the same key parameters, such as total capacity, charging power, discharging power and efficiencies for charging and discharging. Interconnected mode was examined by implementing two approaches: using the MultiNode tool and connecting the islands into a single (common) system. Former approach is new and would have the benefit of giving the exact import/export hourly values between the islands. Latter approach was previously used on regions and countries, but not on islands with the aim of examining VRES and V2G without any fossil fuel powered facility for backup. The approach presented in this paper is most suited for islands which are not far away from the shore and have relatively good connection to the grid or between themselves.

CASE STUDIES

Islands of Vis, Korcula, Lastovo, Mljet have been chosen as case studies. For the islands, RenewIsland methodology has been implemented and results of first two steps are given in tables 1 and 2. The archipelago, including the transmission lines, which are elaborated in Table 4, is presented in Figure 2.

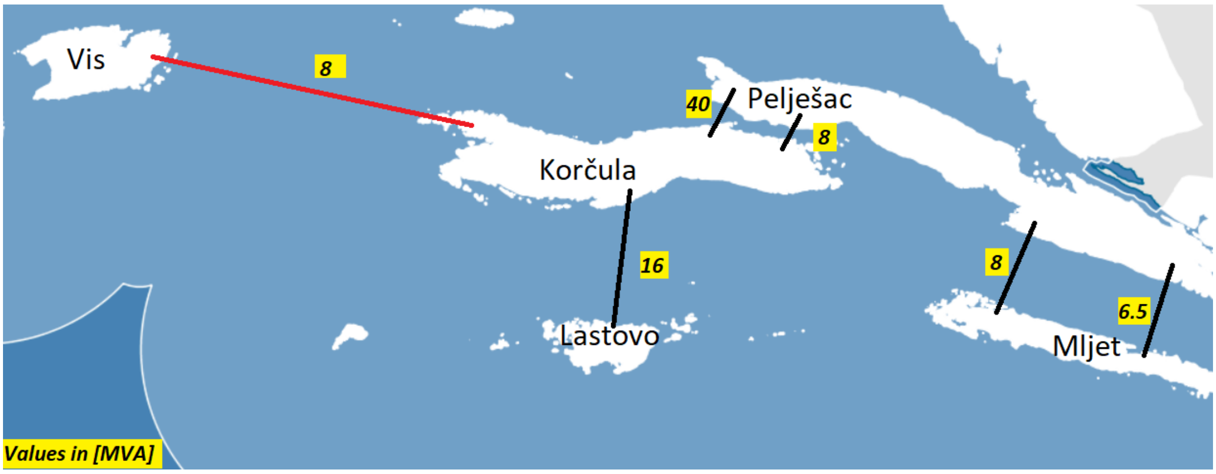

Figure 2 Case study area with transmission lines

A common system was observed, since there are many similarities between the islands, but the difference in size and population provides opportunity for different setting of VRES and DR technologies. Potential was analysed in detail in Pavlinek L. [40], taking into account the input data for all four systems, local VRES potential and consumption. For RES potential, local availability was determined using the data obtained from METEONORM software [41]. The analysis showed that solar PV is the most promising technology for all of the islands in the case study. In the mentioned master thesis [40], scenarios were developed for years 2025, 2030 and 2035. The aim of the work was to cover all the demand with the electricity produced from the locally available VRES, i.e. solar energy (SE). Two scenarios with different penetration level of PVs were developed. In the first scenario, the electricity production from SE was equal to annual electricity demand. In the second scenario, beside the SE technologies integrated V2G as DR technology.

Table 2 RenewIsland methodology - first step, determining the needs

Needs	Level	Geographical Distribution	Code
Electricity	Medium	Concentrated	ElectMC
Heat	Low	dispersed	HeatLD
Cooling energy	Medium	dispersed	ColdLD
Fuel for transportation	Low	Short dist.	TranLS

Water	Medium	dispersed	WaterMD
Processing waste	Low	dispersed	WasteLD
Wastewater treatment	Low	dispersed	WWTLD

The electricity production in the second scenario had a limitation of maximum 5% CEEP. Besides island, this case study area included Peljesac peninsula, with installed wind power plant. In reality, electricity generated from wind is supplied to the mainland grid, whereas in [40] all the generated energy from wind was exploited in the case study area. This allowed to investigate the effect which connections between islands have on the integration of wind power plant in local energy system. The results of this research were presented in Pfeifer, A. et al. [42]. The research was improved by using new version of EnergyPLAN (13.0). New functions enabled to draw the attention from connecting the island's energy systems to deployment of DR technologies. Moreover, this provided the possibility to investigate the influence of different deployment on the transmission capacities between the systems and changes in import/export distributions on an hourly level. For the purpose of this paper, Peljesac peninsula was excluded from the case study area. However, the transmission line between Korcula and Mljet remained in calculations (see footnote 1). In order to simulate the interconnections between island systems in MultiNode tool, connection capacities given in Table 4 were used. Voltage level of connection lines is 35 kV between the islands, while Korcula has supply connection line of 110 kV from the mainland (via Peljesac). Even though In real there is no connection between Vis and Korcula islands, for the purpose of this research the connection capacities which exist on island of Vis were used as if they are interconnected to Korcula, which can be considered as a future investment in the view of opportunities it provides, as shown in analysis below Consumption of energy, installed VRES capacities and number of EVs in all scenarios, in the case of investigating a common connected system, are given in Table 5.

Table 3 RenewIsland methodology – second step for the common system - resources

Resources	Level	Code	Resources	Level	Code	Resources	Level	Code
Local primary energy			Infrastructure for energy imports			Water		
Wind	Medium	WindM	Network connection	Medium	GridS	Rainfall	Low	H2OPL
Solar	High	SolarH	pipeline natural gas	n/a	NGplN	Groundwater	Low	H2OGL
Water potential (altitude drop)	Medium	HydroM	Terminal LNG	n/a	LNGtN	Water supply	Yes	AquaY
Biomass	Medium	BIOMM	Oil terminal / refinery	n/a	OilRN	Seawater	Yes	H2OSY
Geothermal potential	Low (46)	GeothL	Terminal petrol. production	n/a	OildDN			

Table 4 Connection capacities used in calculations

Islands	Connection capacities [kVA]
Korcula-Peljesac	8000
Mljet-Peljesac[1]	8000
Korcula-Lastovo	16000
Vis-Korcula[2]	8000

Table 5 Energy consumption, VRES capacities and number of EVs for all scenarios of the common connected system

	Year	2012	2025 S1	2030 S1	2035 S1	2035 S2
Yearly consumption [MWh]	Electricity	87,000	86,000	94,000	104,000	112,000
	Diesel	40,000	20,000	17,000	13,000	0
	Gasoline	46,000	24,000	20,000	15,000	0
Electric vehicles [no.]		0	1682	2457	3851	7702
PV [MW]		0	5.22	7.225	9.22	61.0

[1] The islands of Korcula and Mljet are connected by the transmission line which is installed accross the Peljesac peninsula

[2] There is no physical link in reality, this link is equivalent of the link that actually supplies the island of Vis with electricity, but via the island of Hvar

Scenario 1 in the year 2012 does not include any variable energy sources in the case study area and all energy demand is supplied by imports from the mainland.

The capacities of stationary batteries in sub-scenarios were designed according to the calculation from Dorotić, H. et al. [43]. This paper introduced V2G technology without PP support in the system. for the island of Korcula.

Table 6 Stationary batteries types and capacities[43]

Smaller battery capacity	Smaller (household) battery charging/discharging power	Bigger (municipality) battery capacity	Bigger battery charging/discharging power
13.5 kWh	5 kW	210 kWh	50 kW

Table 6 represents the installed capacity of different types of stationary batteries in scenarios 2.1 and 2.2. The overall calculated installed capacity was 64.5 MW with the storage capacity of 179 MWh.

The base scenario and dynamics of scenario development through years 2020, 2025 until 2035 have been elaborated in Pfeifer, A. et al. [42] for the case with Peljesac peninsula included in calculations.

The wind power plant from Peljesac peninsula was sufficient to supply all the connected island systems and to deliver 11-30% of energy to the mainland grid, depending on the scenario. This abundant supply of electricity, which is in reality aimed to the mainland grid, makes it difficult to test in more detail the interactions between particular island systems and was therefore removed from calculations in the present paper. Particular peak loads, number of EVs and installed PV capacities on each island are given in Table 7.

Table 7 Peak loads, EV numbers and installed PV capacities for two major scenarios in all island systems in year 2035

	Korcula	Mljet	Lastovo	Vis
Peak load [MW]	16.51	2.79	1.87	5.07
2035 S1				
EV [no.]	3075	182	111	483
PV installed [MW]	5.87	1.04	1.00	1.31
2035 S2				
EV [no.]	6150	364	222	966
PV installed [MW]	40.0	5.0	4.0	12.0

In Table 8, the most relevant inputa data is listed for all island systems in 2035.

Scenarios 2.1 and 2.2 are calculated with the same overall battery power and storage capacity in order to be comparable for discussion.

Table 8 Input data for scenarios in 2035

Year 2035	Korcula	Lastovo	Mljet	Vis
Demand [MWh]	62,200	6,860	7,390	18,860
Installed PV [MW]	40	4	5	12
Installed batteries power [MW] / storage [MWh]				
Scenario 2.1	64.5/179	0	0	0
Scenario 2.2	42.5/118	4.38/12	4.77/13	12.2/34
V2G demand [MWh]	8,500	530	520	1,950

RESULTS AND DISCUSSION

The most relevant results to discuss are those of the scenario 2.1 and scenario 2.2 in the year 2035, when the measures described in [40] have been implemented and further discussion is aimed towards the analysis of interaction between the systems, using the MultiNode tool. In Figure 3, the representative period of operation of Korcula's energy system is illustrated, in this case for scenario 2.1 in the year 2035, showing the synchronisation between production and demand response technologies.

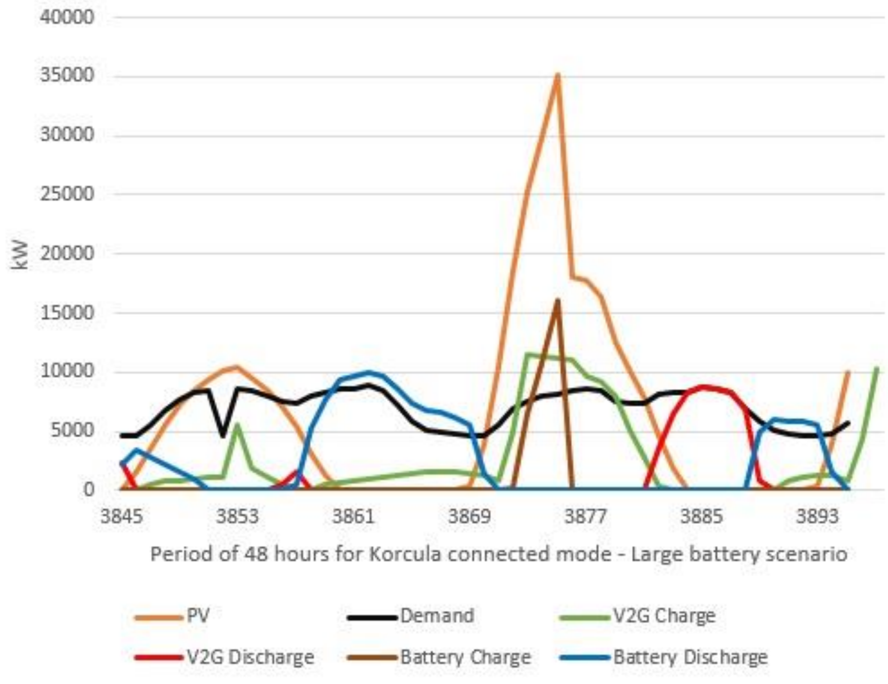

Figure 3 Ilustration of the system operation for an indicative period on the island of Korcula, scenario 2.1 in year 2035

The power generation system was balanced by the stationary batteries for storage and V2G as DR technology. Both V2G and battery banks manage to store energy from the PV plants and use it to satisfy demand during the night. Therefore, MultiNode tool can produce scenarios for connected systems without dispatch able PP, balanced by DR and storage technologies. For scenario 2.1, relevant interactions between the systems are illustrated by Figure 4, which shows the electricity import and export distributions for all island systems. Since the additional storage capacities were placed on Korcula, other islands were supplying Korcula, most of the time, with their excess electricity produced. Overall number of hours in which export/import takes place is 417 hours in the year, with maximum flows between systems reaching 0.957 MW peak hourly export from Vis to Korcula.

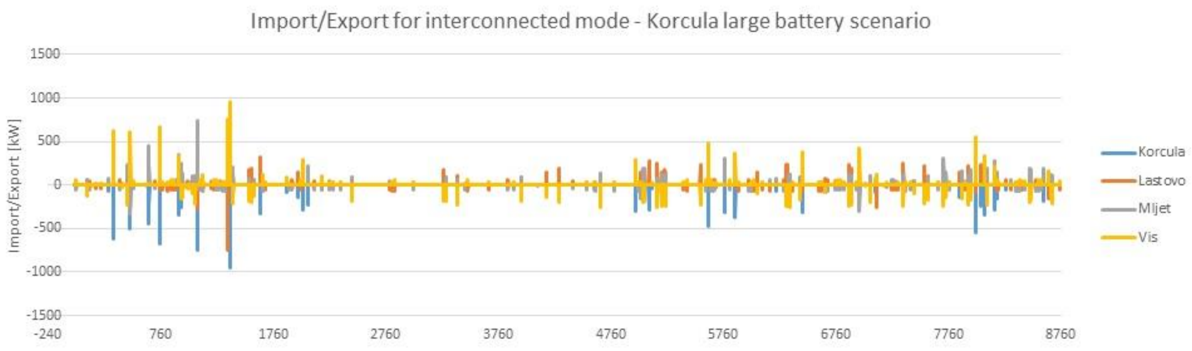

Figure 4 Electricity Import/Export distribution for the interconnected mode of scenario 2.1

In the case of scenario 2.2, the storage capacities were distributed on all islands, so demand and supply were balanced better on local level, which reduced the CEEP in each of the island systems. This resulted in fewer hours in which interconnections were exploited for the purpose of the electricity import/export from a particular island. The total number of hours was 17. In most of the cases, electricity was imported to the island of Korcula as this island has the highest electricity demand. However, in the scenario 2.2 the import/export values were much higher than in the scenario 2.1, reaching 2.539 MW peak hourly export between Korcula and Mljet.

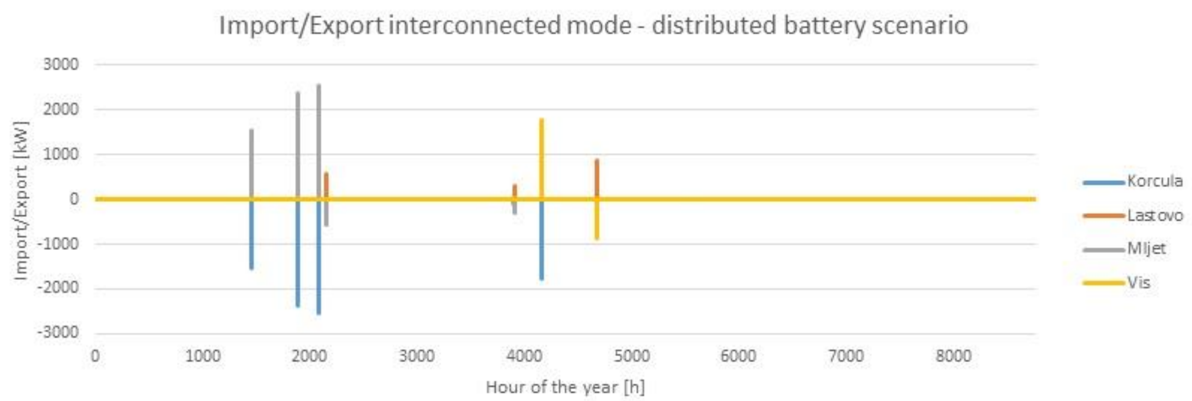

Figure 5 Electricity Import/Export distribution for the interconnected mode of scenario 2.2

At the same time, although comparison of Figure 4 and Figure 5 indicate that the interaction between the systems is lower in scenario 2.2, this is visible in the number of hours in which transmission systems are in operation, but the overall numbers provide different picture regarding the intensity of interaction, as it is demonstrated in Table 9. This is due to 4-5 times higher energy transfers in hours when other systems export energy to the island of Korcula in scenario 2.2.

Table 9 Values of electricity exchange between the systems in 2035, for both scenarios

Import/Export [MWh]	Korcula	Lastovo	Mljet	Vis
Scenario 2.1	-13.05	8.12	8.44	-3.52
Scenario 2.2	-15.55	2.48	12.33	0.75

It can be concluded that Korcula would still need larger capacities of DR technologies or stationary batteries to limit the need for imports, although others systems in scenario 2.2 now have much more independent and balanced operation thanks to their local storage. In Figure 6, the results are given in terms of CEEP for each system.

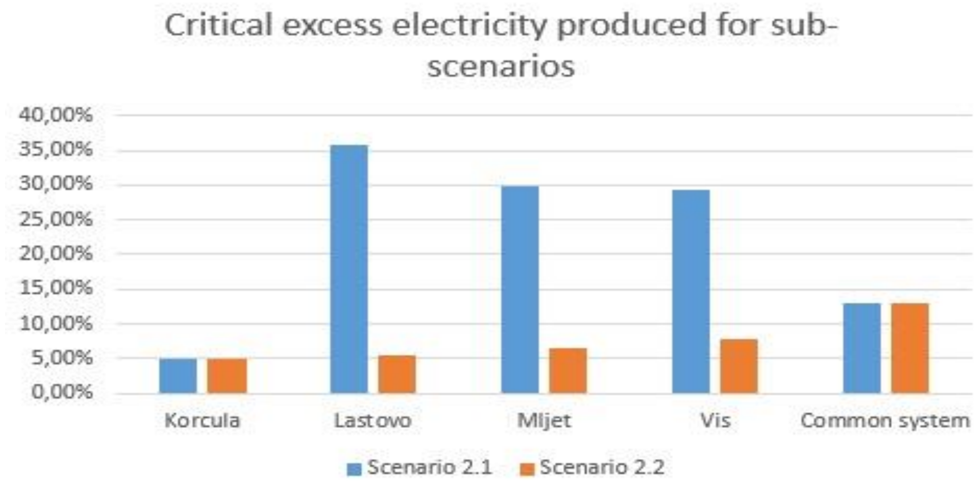

Figure 6 Critical excess electricity production for all systems and a common system in both sub-scenarios

In the case of scenario 2.1, CEEP was limited for the case of Korcula, due to locally available additional storage capacity, while other islands were used as additional suppliers, with lower ability to balance the production and supply locally. In scenario 2.2, the CEEP remains almost the same on Korcula, due to relatively large remaining storage capacities, which are still able to balance and store the energy produced from RES and respond to the needs in almost all hours, except for the cases which are illustrated by Figure 5. Connected system, which does not reflect the interconnections between the islands, has lower overall CEEP then the sum of the systems in scenario 2.1. In general, the transition from the base year, 2012 to 2035 brings the group of islands close to energy independence, which is also demonstrated in Table 10, taking into account the transition from the base year, in which the share of VRES in primary energy supply (PES) was roughly zero.

Table 10 Share of VRES in all systems in 2035

RES share in PES [%]	Korcula	Lastovo	Mljet	Vis
Scenario 2	74.1	85.6	84.3	80.1
Electricity from import	25.9	14.4	15.7	19.9

CONCLUSION

This paper presented the method for planning the energy systems of the grid interconnected islands which are close to the mainland. The analysis of the interconnected island systems was done with EnergyPLAN 13.0 model. The version 13.0 of the model enabled to use the V2G concept without any balancing facilities, such as conventional condensing power plants. This addition made EnergyPLAN a suitable tool for planning the island energy systems and their transition to 100% renewable and sustainable smart island systems.

Further novelty is the use of MultiNode tool, which is able to simulate interconnection between such island systems in EnergyPLAN 13.0. This allowed for the analysis of implications which DR technologies deployment has on the interaction between systems and their ability to integrate more locally available renewable energy.

The results show the increase in the share of energy from RES in total final energy consumption after connecting to a common system, which reaches 85% for systems examined in case study, and decline of total CEEP of all systems from 28-35% individually to 13% after connecting to a common system for the scenario 2.1. Decrease in net import / export can be observed in correlation to the increase in the independence of island energy systems, but the deployment of storage technologies, analysed through interactions between systems, has influence on the intensity of load on the transmission lines, which occurred in 417 hours for scenario 2.1 and only in 17 hours for scenario 2.2. In scenario 2.2, however, the intensity of interaction was 2.5 times higher than in scenario 2.1, with peak export being 2.536 MW compared to peak of 0.957 MW in scenario 2.1. From this data, it can be concluded that distributed storage systems provide more energy security for every single system, compared to the case of storage being concentrated in only one of the connected systems, but it has to be carefully designed to avoid large peaks in some hours.

The combination of VRES and V2G would be the combination of technologies which offers most synergies with least environmental impact in island systems. Proof for this correlation and analysis of combination of VRES which would be able to produce more balanced system is left for future work. Also, in future work, the economic analysis of VRES, V2G and battery storage technologies will be examined, considering solutions such as local energy markets.

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