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Two-level energy planning approach for smart islands energy systems development

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Abstract

Energy planning of islanded systems has always presented a challenge due to their weak connection with the mainland. In order to tackle this issue and make transition of islands energy systems to autonomous, secure and low-carbon systems it is necessary to take into account local needs and resources as well as pay attention to security of electric power system. Two-level energy planning approach presented in this paper provides unambiguous solution to this challenge. Several energy planning scenarios were developed with RenewIslands method and modelled with energy planning software in order to research how integration of transport and energy production facilitate the transition to 100% energy self-sufficient island. Developed scenarios are subjected to load flow analysis that was performed in load flow tool. Research was conducted on island of Vis in Croatia and the results showed that Vis exports 6.8% of its production in HighRES scenario as opposed to LowRES scenario where it is 100% dependent on import. Implementation of parking lot for electric vehicles on island of Vis allowed more control and lowered the voltage values on observed node 45 from 10.3 kV to 10.18 kV for RES scenario.

Keywords: *Energy planning, Smart islands, Load flow, Electric vehicles, Smart Grid.*

1. Introduction

Introducing renewable energy sources (RES) and integrating energy demand of domestic heating, cooling, fuels for transport or larger, commercial demand is becoming one of the most investigated ways of making local island communities more energy self-sufficient. Also, once the larger integration of RES is achieved, it is important to properly understand and quantify the influence of RES and demand response technologies on local electricity distribution network, in order to plan timely upgrades. Unlike conventional approaches that primarily optimize energy balances, this methodology explicitly evaluates the feasibility of integrating high shares of renewables within local grid constraints by considering voltage stability, power flow limitations, network congestion, and dynamic interactions between renewable generation and flexible demand resources. By incorporating load flow analysis, the approach provides insights into potential voltage violations, grid bottlenecks, and power import/export constraints, enabling early-stage identification of technical challenges. Furthermore, the methodology assesses the role of demand-side flexibility measures, including sector coupling and vehicle-to-grid (V2G) interactions, in mitigating these challenges and enhancing grid resilience without extensive infrastructure reinforcements.

In energy planning of small island energy system, integration of other systems, like transport, requires particular care and precision due to lack of resources and space restrictions. The proposed methodology is designed to be adaptable to different island contexts, considering variations in resource availability, grid constraints, and energy demand patterns. By integrating scenario-based energy planning with grid feasibility analysis, this approach can be tailored to islands with diverse renewable energy potentials, different levels of interconnection, and varying degrees of energy autonomy. Regarding comprehensive planning of island energy systems, research was focused on developing methodologies like RenewIslands methodology for resource and technology planning in [2]. In [1] a sophisticated model was developed, linking spatiotemporal capacity planning with power flow analysis, to enable better integration of renewable energy sources into the power systems of island communities. The importance of storage technologies, energy efficiency and energy savings for RES integration was studied with an island of Hvar as a case study, which was conducted in EnergyPLAN software in [4]. Research on the potential for implementing floating solar panels on water reservoirs shows significant promise for additional energy storage and increasing the share of renewable energy [5]. Also, H2RES software was used in [6] on a case study of Cape Verde to integrate energy and water supply. Sector integration impact on the electricity demand curve was studied in [7]. A study on the digitalization and development of smart islands in the Kvarner archipelago demonstrated how digital technologies can enhance energy self-sufficiency through sector integration and improved energy management efficiency[8]. Other software solutions were used in [9] for large island communities. Optimization strategies for integrating renewable energy have advanced significantly with the use of hybrid energy storage solutions, which enhance system reliability and stability [10]. Various combinations of RES and hybrid systems on isolated islands were studied in cases of Porto Santo [11], San Vincente and Cape Verde [12]. The economic implications of hybrid renewable energy systems were analyzed, emphasizing their role in enhancing energy security and promoting sustainable economic growth in small island communities [13]. For smaller island, in the case of environmental restrictions, penetration of RES was studied in [14] In case of integrating wind energy in the electric energy system of Croatia, potential was studied using GIS, in [15]. Regarding the solar energy potential and feasibility, developments and trends, as well as future role of solar PV will play in local and national energy systems was elaborated in [16].

Single and multi-action initiatives, for energy transition of island power systems towards smart islands, were assessed in [17]. Integration of EVs into a microgrid was examined in [18], using an optimization model for managing the energy in a grid-connected smart grid that includes RES and a parking facility for EVs. Another study investigating synergies of EVs and energy production system, where the vehicle to grid (V2G) technology was used is given in [19]. V2G technology was also used in [20] as one of the strategies of demand response and compared to supply side strategies. The authors in [21] modelled EVs as a type of load and compared it to three conventional types of load. A research about integration of transport and energy production sector in the case study area was conducted in [22], discussing also the option for financing the transition. Also, an example of taking the PRISMI approach to the long term planning can be found in [23]. In [24], PLEXOS modelling tool was used to demonstrate that in some cases, for small islands and integrated planning case, smart charging can reach similar effect as V2G. In [25] it was shown, using EnergyPLAN and HOMER tools, that for small islands dump charge and V2G have the opposite effect on electric grid, which is relevant for the present study. In [26], a different approach in choosing the technologies was employed, 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. Replacement of fossil fuel with solar power, i.e. electricity generation from rooftop photovoltaics for the case of Canary Islands was studied in [27]. A study [28] evaluated the long-term energy planning impacts of demand response and reserves on islands, highlighting the importance of these strategies. However, it did not investigate grid conditions under their application, which is a crucial aspect to consider. The aim of research in [29] was to show how it is possible that photovoltaic systems can help with existing power quality problems in network. Even though PV systems are said to be the cause of many disturbances due to their variability, operational results are in contradiction to hypothesis that they can not also offer the improvement of energy quality. Regarding the economic implication of various options, study [30] investigated economic sustainability of hydrogen and battery storage implementation on small islands. In this research, the aim was to use the synergy between power production and transport sectors for storage and balancing.

Taking this line of research a step further, an investigation of connection in the archipelago and influence of demand response technologies on the interaction between the island systems, is conducted in [31]. Once the energy systems are modelled with energy planning tools on hourly level, there is still one step which needs to be taken, namely load flow analysis to investigate the ability of local distribution network to accommodate new installation. In a study [32] planning process which models a power network taking into account detailed information on the power network including the location and capacities of generators, consumers, substations, and power lines was investigated. The load flow (LF) calculation method is perhaps the most widely used method for analysing electric power systems [33]. It appears in several variations and in all of them the objective is invariably the same: to solve the steady-state operation of the grid by calculating the node voltages and currents. Among the various LF solving techniques used in research studies we can distinguish the methods of Gauss-Seidel, Impedance, Piecewise Impedance, Newton-Raphson (NR), PQ-Decoupled method, DC Load-Flow, Optimal Power Flow (OPF), as well as other more sophisticated algorithms that make use of different approaches like. Artificial Intelligence, Genetic Algorithms, Artificial Neural Networks, Fuzzy Logic, Probabilistic Analysis, Mixed Integer-Linear Programming etc. In [34] the authors used Artificial Neural Networks, in [35] the approach was tried with conventional and neural networks. Further on, [36] employed fuzzy logic for load-flow analysis and in [37] probabilistic analysis was used. Finally, in [38], a reconciliation algorithm was used to model optimal power flow with reactive power in real-time for the case of dispatch of wind stations. It is worth noting that most LF-related research studies refer to large-scale electricity grids due to their complexity as opposed to island power systems which are simpler structures and do not require sophisticated analysis methods. As a consequence, there is rather limited literature in terms of using LF tools for the analysis of small power systems. A case in point regarding the use of LF in the analysis of small-scale and island power systems is the reference [39]. Unlike transmission system networks, distribution system networks are characterized with high R/X ratio as well as radial structure. This can cause convergence problems when the load flow calculation is performed with traditional load flow algorithms. To solve this problem and increase the efficiency of solving distribution system load flow, alternative algorithms have been developed. Mekhamer et al. [40]

proposed method which avoids formulation and calculation of Jacobian matrix which reduces the time of calculation and uses less computer memory. In order to shorten the calculation time, a effect of mutual coupling is achieved by using equivalent branch voltage sources or bus current injections in [41]. Another method for solving networks with high R/X ratio is presented in [42], where authors use constant Jacobian matrix with need of only one factorization. A Polar Current Mismatch Version of Newton Raphson which uses polar coordinates for current mismatch functions is presented in [43]. This study uses tool presented in [44] that offers a possibility to calculate electrical grid voltages and load flow as well as visualise electrical grid on geographical island.

The aim of this paper is to demonstrate two-level approach planning of the energy system, in which first step is to model the future outlook of the energy system and then to investigate energy flows in local distribution network, which appear as a consequence of installed technologies. Such approach represents contribution by enabling the possibility to investigate impact of different energy planning scenarios on the electric power grid and which was not possible in several mentioned studies. Possibility of identifying voltage and line capacity violations in electric power grid can lead toward need for either lowering the amount of RES integration, upgrading the electric power grid or using new technology for voltage control. This study investigates the possibilities for improving the voltage conditions in grid by integrating different sectors, namely energy and transport sectors, by implementing EV parking lots with smart charging and discharging.

Batteries of parked EVs can be considered as an aggregated battery with variable capacity, depending on the number of vehicles that are currently on the parking and state of charge (SOC) of the vehicles. V2G provides demand response services, or in other words, EV parking lots can function as a load or generation depending on electricity distribution system requirements.

In chapter 2, methods used in this research are elaborated. Further on, in chapter 3, a case study is described, while in chapter 4 the results of the new approach are elaborated and discussed. Conclusion is given in chapter 5.

2. Methods

During this research, the PRISMI approach, which was developed during the PRISMI Interreg MED project, adding on the RenewIslands methodology (on which it is based) through improved approach, using GIS mapping of resources and load flow analysis, was employed. Steps of the PRISMI approach, employed in this paper, are:

1) Mapping the needs of the island community

2) Mapping the locally available resources

3) Technologies overview for bridging the gap between needs and resources

4) Division of scenarios

Energy system development of any particular island is examined in three main scenarios, of which third one is modular:

LowRES – following the same dynamics of RES use, as already proposed in actual SEAP-s or other available documents

RES – Increase of RES use, with taking into consideration environmental constraints and legislative framework, which is dependent on location of any case study and potential implementation of technologies which offer synergetic effects with other sectors.

HighRES – Modelling for a 100% RES energy system of the island, in this case taking into account possibilities of sub-scenarios of using the wind energy (HighRES wind) and a case without wind turbines (HighRES) and using the synergies with other sectors. This scenario is modular in terms of use of wind energy, but always aims towards 100% RES supplied energy system.

Scenarios are then calculated using EnergyPLAN software, in order to get hourly results of production from all technologies, as well as discharge from storages, in order to balance the system, aiming to achieve a self-sustainable system.

5) Load flow analysis using the tool developed to be user friendly and quickly indicate the issues arising in the grid. The LF tool was developed using purely Matlab® coding and its validation was done by benchmarking it against reference models in Matlab/Simulink. Once the development phase of the tool was finished with the use of Matlab/Compiler a standalone application was generated in order to facilitate the tool usability. Important assumptions are that electric power grid is in steady-state condition, that the operation of the grid is balanced and that the voltages and loads are symmetrical for all three phases of the system. Since LF is the next step of this approach, it can include case analysis in terms of locations of production and consumption facilities proposed by scenarios from the energy system modelling step of the approach. LF tool is used to simulate possible impacts on technical aspects of the grid, primarily voltage and power import/export, by implementing new technology in the distribution grid. Such technology may include different kind of demand response such as desalination plant, EVs, electric boilers or batteries.

In order to use the load flow tool as a final step in modelling of the energy system following data of the electricity distribution system layout and characteristics is needed:

- Buses (nodes)
- Line parameters
- Transformers
- Connectivity of generators and loads to buses
- Active/Reactive power profiles for each bus
- Control method/behaviour:
- Voltage set-points of buses
- Voltage limits of each bus
- Line Capacity limits
- Reactive Power limits for PV generators
- Active Power lower limits of conventional generators

The proposed LF tool is provided in the form of a stand-alone executable application, and uses grid, generation, and consumption data as inputs from previous steps of the PRISMI methodology to calculate the grid voltages and currents. It combines a number of features useful for the proposed method, minimal requirements in terms of input parameters and algorithmic implementation make the tool user-friendly.

This calculation is done by using the NR solving method which is characterized by good convergence on small distribution grids as is case on islands. The goal of NR method in the aspect of power systems is to calculate voltages (Ui) and voltage angles (δi) of every node in electric power grid by solving nonlinear equations into problem of repeatedly solving linear equations while knowing parameters of the grid expressed with admittance matrix (Y). Real power (Pi) and reactive power (Qi) at node i are defined with equations (1) and (2), where n is total number of nodes, g is number of generation nodes, θ_ij is phase angle difference between nodes i and j and Y_ij is element of admittance matrix or admittance between nodes i and j.

$$P_i = U_i \sum_{j=1}^{n} U_j Y_{ij} \cos(\delta_i - \delta_j - \theta_{ij}) \qquad i = 1,2,\dots,n-1 \tag{1}$$

$$Q_i = U_i \sum_{j=1}^{n} U_j Y_{ij} \sin(\delta_i - \delta_j - \theta_{ij}) \qquad i = 1,2,\dots,n-g-1 \tag{2}$$

The tool is equipped with Human Machine Interface (HMI) that allows the user to perform a number of actions such as:

- Select the grid to be analysed. The user can select among a number of pre-set models or to specify their own data.
- Specification of the timeframes to be calculated depending on the available input data.
- Simplified drawing of the selected grid in order to check the correctness of the input data.
- Modification of the operating voltage and capacity limits.

Also, as outputs the tool provides the user with information about the voltage/capacity limits violation as well as a graphical illustration of all the problematic and normal parts of the grid.

Two-level energy planning of islands is presented and tested in this paper.

Hypothesis of this study is that, with presented two-level approach, it is possible to create and validate different energy planning scenarios in steady-state operation of the grid and indicate the appropriate locations for new installations in the grid or possible needed updates of the grid. First level analysis provides framework for energy planning by creating several different scenarios while the second level analysis presents technical feasibility of energy planning scenarios in the context of local electricity distribution system. The modelling of scenarios in second level is done for characteristic periods of the year, where a special emphasis is placed on investigation of power import and voltage profiles.

3. Case study

The island of Vis is a small Croatian island in the Adriatic Sea, with an area of 90.3 square kilometres and it is the farthest inhabited island off the Croatian mainland, with a population of 3,617 in 2011, concentrated in two larger towns, Komiža and Vis, both around 1,500 inhabitants. The highest point of the island is 587 meters above sea level. Once known for its thriving fishing industry in the late 19th and early 20th century, the main present-day industries on the island are agriculture and tourism. Concerning island's electrification, Vis currently depends on a submarine cable with the island of Hvar, which supplied 17 GWh of electricity to the island of Vis in 2016. Vis Island was selected as a case study due to its unique energy characteristics, including its limited interconnection to the mainland grid, high renewable energy potential, and growing need for energy self-sufficiency. These factors make it a representative test case for assessing the feasibility of high-renewable penetration in constrained island energy systems, which often face similar infrastructural and regulatory challenges. Resources charted through the PRISMI method are given in Table 1.

Regarding the possibilities of installation of solar PV on the island of Vis, the surface of all residential area of the city Komiža is estimated to be 108,000 m^2. Solar potential mapped and presented through PRISMI GIS geo-database is illustrated in Fig.1.

Figure 1. GIS map of solar potential on the island of Vis

After taking into account the orientation of rooftops, possible protection of cultural heritage and other restrictions, the possible surfaced is estimated at approximately 32,500 m^2. This surface gives the possible maximum nominal power for installed PVs of 5,000 kW in Komiža and approximately the same for the town of Vis.

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The simulation takes also into account the 2 MW solar power plant that is planned on the island of Vis. Other relevant resource is wind power, but the exploitation is made difficult due to the island being completely covered by the NATURA 2000 network and protected. Table 2. lists all input values for calculation of scenarios for the energy system and transport system on the island of Vis in the year 2030 [45]. As a reference model, energy system of the island of Vis was also modelled in EnergyPLAN for the year 2016, with known electricity load and other data on consumption calculated from documents available online (official documents of local government), as well as from previous research in [22] and [45].

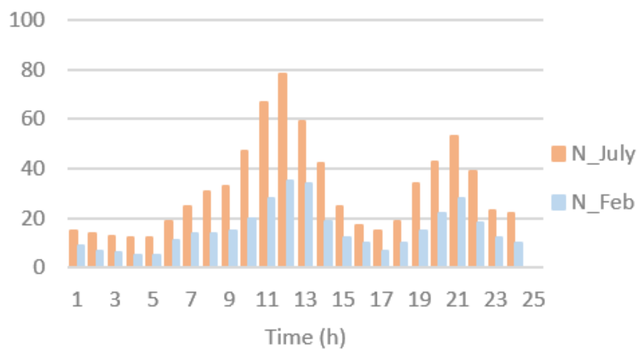

Figure 2. Schedule of number of parked vehicles

Table 1. Resources on Vis

Local primary energy			Energy import infrastructure			Water		
Resources	Level	Code	Resources	Level	Code	Resources	Level	Code
Wind	Medium	WindM	Grid connection	Normal	GridN	Rainfall	Low	H2OPL
Solar	High	SolarH	Natural gas pipeline	None	NGplN	Groundwater	Normal	H2OGN
Hydro	Medium	HydroM	Terminal LNG	None	LNGtN	Water supply	Yes	AquaY
Biomass	Medium	BIOMM	Oil terminal/ refinery	None	OilRN	Seawater	Yes	H2OSY
Geothermal	Low	GeothL	Terminal petrol production	None	OildDN			

Table 2. Input data for calculation in 2030 for all scenarios and sub-scenarios

2030	LowRES	RES	HighRES wind	HighRES
PV [MW]	1	10	12	12
Wind [MW]	0	0	3.5	0
EV [nr. of vehicles]	0	617	1234	1234
EV connection [MW]	0	1.985	9.131	9.131
EV demand [MWh]	0	1778	2767	2767
EV battery [MWh]	0	14.496	48.126	48.126
Electricity demand [MWh]	17690	19290	21180	21180

The number of vehicles vary depending on period of the day as well as the period of the year. Because of many tourists' arrivals in the summer months, the average arrivals to the parking lot are two times higher than in the winter months. Therefore, the EV parking model presented in this paper is considered for two months – July and February. The EV parking lot is placed in node 47 in town Komiža. The day is divided in four periods depending on whether the vehicles are arriving or departing from the parking lot. The arrival periods are from 6am to 12pm and from 18pm to 21pm, while departure periods are from 13pm to 17pm and 22pm to 5am. Detailed schedule of number of parked vehicles is presented on Fig. 2.

The characteristics of EV parking lot are taken from [18] and presented in Table 3, with the exception of setting more strict constraints for minimum SOC.
From the presented data, it is possible to calculate that during one hour an EV can discharge to the grid a maximum of 12 kW and charge from the grid a maximum of 16 kW. Therefore, by multiplying number of parked EVs with maximum charge and discharge power it is possible to present EV parking as a battery with changing capacity according to the Fig. 3., which shows possibilities for charging and discharging during summer and winter months.

Table 3. Parameters of EV parking

Parameter	Value
EV battery capacity	40 kWh
Average SOC of parked EV	50%
Minimum SOC allowed	20%
Maximum SOC allowed	90%
Charger capacity	20 kWh

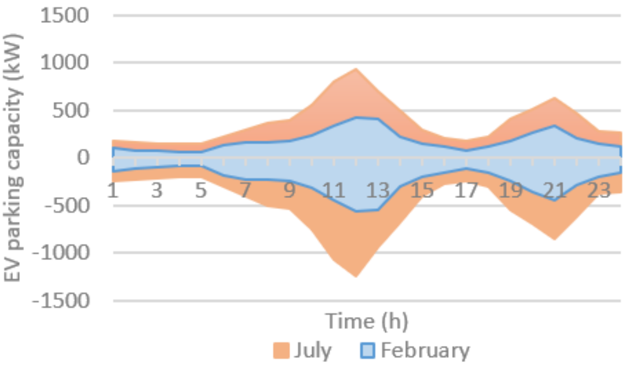

Figure 3. Capacity of EV parking lot

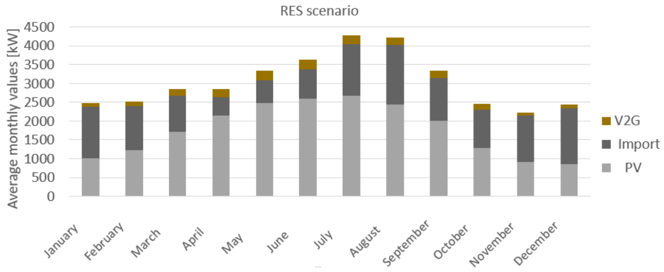

Figure 5. Results of RES scenario as monthly average hourly production of electricity

Table 4. Results of all scenarios

2030	RES share in PES	Import	RES share in Electricity	Import	RES prod. [GWh]
LowRES	33.20%	66.80%	9.10%	90.90%	1.61
RES	74.60%	25.40%	78.80%	21.20%	15.62
HighRES	99.30%	0.70%	106.80%	-6.80%	23.38
HighRES no wind	99.20%	0.80%	85.80%	14.20%	18.74

4. Results

4.1. Results of modelling of the islands' energy system in EnergyPLAN

Results of the calculation in EnergyPLAN demonstrate how increase of RES integration and synergy with electrified transport system gradually take over the supply of electric energy for the island of Vis. For the LowRES scenario, represented by Fig. 4, solar PV covers for only minor amount of energy needs. In case of RES scenario, solar PV covers for the majority of demand, but there is still need for electricity import.
At the same time, there is significant share of energy supply in the form of discharge from the batteries of electric vehicles, represented as "V2G" on the Fig. 5.

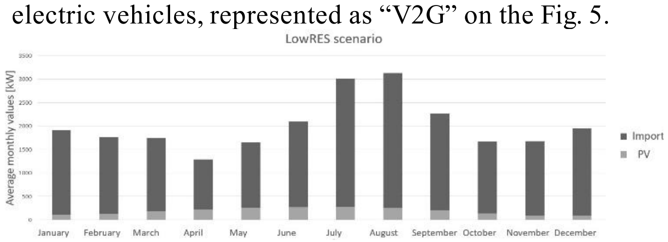

Figure 4. Results of LowRES scenario as monthly average hourly production of electricity

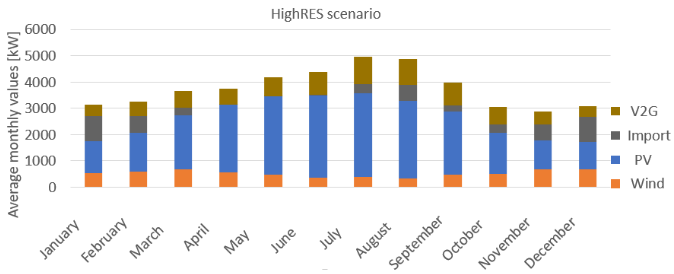

Figure 6. Results of "HighRES wind" scenario as monthly average hourly production of electricity

When two RES technologies are used, as in the case of HighRES scenario with wind power (located in node 41), then almost all of the energy demand is supplied by the local sources and supported with EV batteries for demand response and storage, as demonstrated in Fig.6. Only during winter months and high tourist season there is minor need for import.

In this scenario, synergies between electrified transport and energy production sector is most visible, through many hours of EV batteries discharging energy back to the grid (Fig. 7).

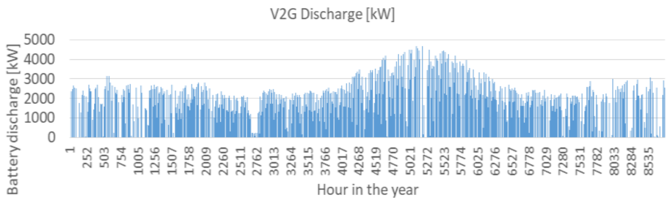

Figure 7. Discharge from electric vehicle batteries

In case only one technology remains the only choice, import will remain significant during the winter and in high tourist season, as it is visible in the Fig. 8, representing HighRES scenario without use of wind power. Results of all scenarios are given in Table 4.

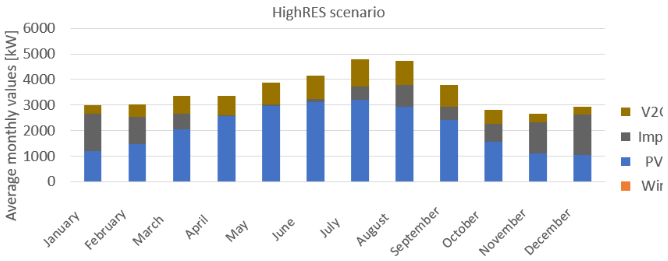

Figure 8. Results of "HighRES" scenario as monthly average hourly production of electricity

4.2. Results of use of load flow tool on the islands' electricity distribution grid

After supplying the tool with data on configuration and data regarding the grid's performance, model of the grid, obtained in such way, was used to test the grid's stability and performance for all the scenarios described above, in characteristic days of the year. The electricity distribution grid of island of Vis is presented on Fig.9. From the LF analysis point of view the following assumptions have been made:

-Part of the line parameters were based on datasheets corresponding to the actual lines, whereas other parameters were based on existing literature models with similar characteristics.

-All distribution (MV/LV) transformers were lumped with the loads at MV level.

-Node no. 38 is assumed as the swing bus of the LF calculation. Apart from keeping the voltage magnitude of it at 1pu (10kV) the specific bus also determines the amount of import/export power as it is the interconnection-to-mainland point of the grid. The assumption of the voltage control of node 38 results in rather limited variations in the voltage profiles in most of the scenarios.

-The loads and EVs are proportionally distributed among the nodes based on the nominal capacity of each distribution transformer.

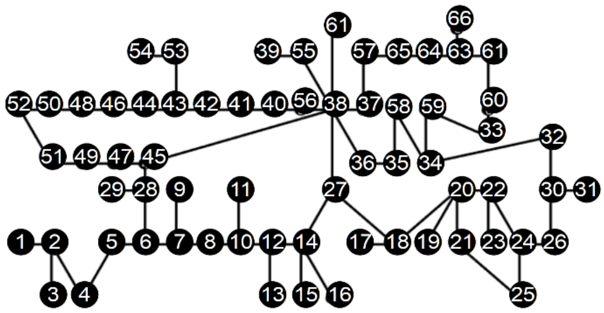

Figure 9. Grid configuration introduced into the LF tool, representing the DG of the island of Vis

As an implementation example, in Fig. 10 and Fig. 11 two days in July, at the peak of the tourist season, when the demand is at the highest level, are presented in terms of voltage level and power import in each hour. The figures present node 45, which is located in the town of Komiža and is the beginning of the line connecting Komiža and the town of Vis. It is visible on the Fig. 11 that the island of Vis is continuously in need of import and on voltage levels below nominal in the base and LowRES scenario, while HighRES scenarios differ in voltage levels and export profiles in the middle of the day. This demonstrates the sensitivity of the tool for the different conditions in the grid, caused by integration of different RES technologies and electric vehicle's batteries. Results of the analysis show that during summer the minimum and maximum voltage and power import amounts are in base and RES scenario. Further penetration of RES in HighRES and HighRESnWG scenarios lowered the maximum values and increased the minimum values of voltage and power import. For example, it is possible to observe that for July the peak voltage value in node 45 has decreased from 10.28 kV in RES scenario to 10.2 kV for HighRESnWG scenario and 10.18 kV for HighRES scenario. This effect is more visible for HighRES scenario with wind which indicates that implementation of different RES technologies such as wind, solar and EVs in this case create better voltage conditions in the grid.

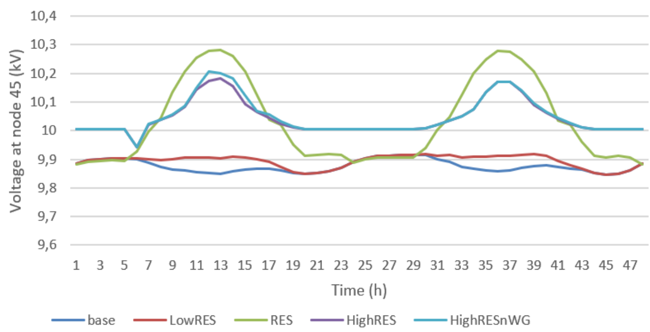

Figure 10. Voltage variation at node 45 during two days in July

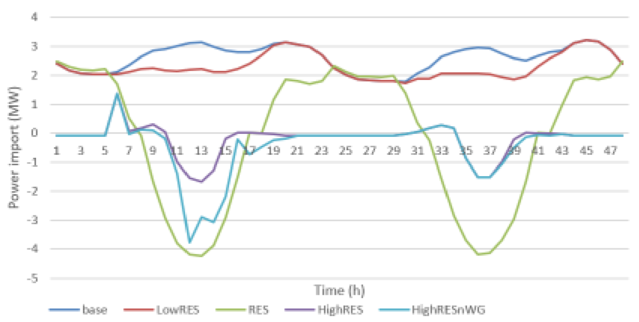

Figure 11. Power import during two days in July

In another time of the year, represented by Fig. 12 and Fig. 13, during the winter, the demand is lower than during summer, which is why the need for import of energy is lower and voltage values higher in the base and LowRES scenario (Fig. 12). Voltage values for all scenarios are in range of 1,5% of nominal voltage which indicates that none of the scenarios is causing any instabilities in steady-state operation of the electric distribution grid (Fig. 13).

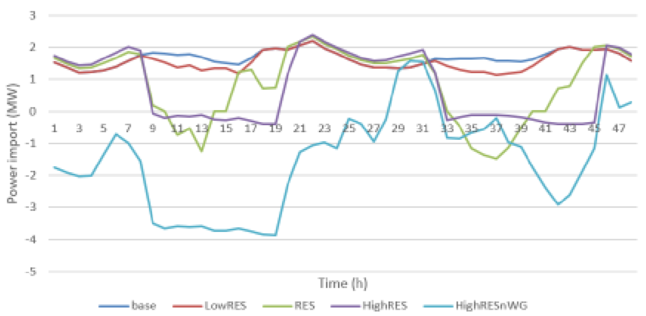

Figure 12. Power import during two days in February

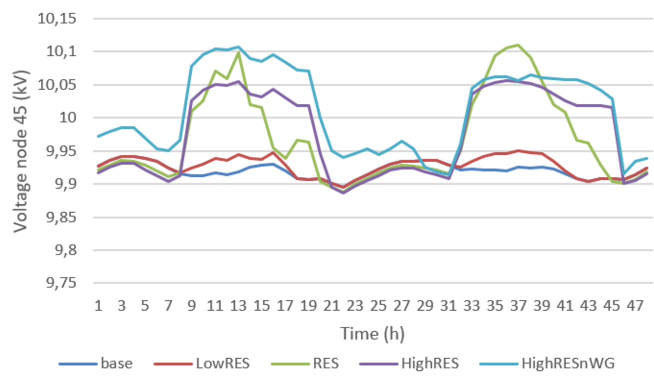

Figure 13. Voltage variation at node 45 during two days in February

In Fig. 14, the final output of the tool is illustrated. The specific output is produced by imposing more rigorous operation limits to the system. In particular, the maximum allowable voltage deviation was set to 1% while the maximum line capacity usage to 50%. In this, way it was possible to show the tools ability to identify potential problems in the grid at midday for the chosen distribution of RES power plants. The result indicates possible problems in the area of the town of Komiža and the location of 2 MW PV power plant in Žena Glava (Node 11), as well as the south part of the island, which consists of a few villages in the south-east part of the grid (all these buses and lines are marked with red in Fig. 14).

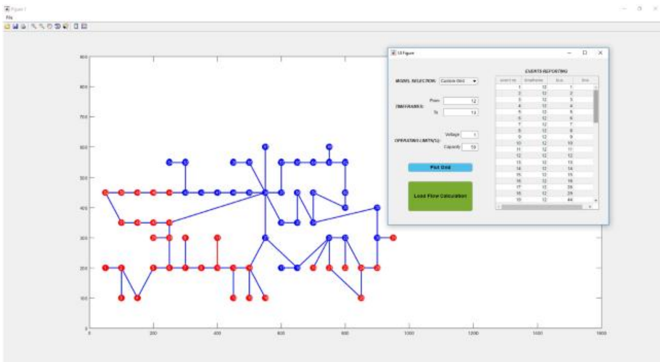

Figure 14. Tool output

This output indicates that the tool provides additional information, which was not realised only through the first level of planning (use of EnergyPLAN tool), namely, that the grid needs to be upgraded in the area of the town of Komiža, if it is to accommodate the installations of 5 MW of solar PV integrated power plants. The possible course of action is to test another distributions of the PV power plants, such as more ground-based plants, reduce the plans of installations to lower capacities or include the upgrading of the distribution grid to the plans. If the lower capacities would be installedfor RES scenario, there would still be problems with the area of the town of Komiža again due to the very strict voltage limit we have chosen. However, in this scenario the line congestion problem between nodes 11 and 10 has disappeared due to the higher allowable capacity of the scenario (85%). The conclusion is that, for the specific operating limits, this part of the grid needs updates in order to accommodate new RES installations on the meaningful scale.

Although voltage and line capacity values on Fig. 14 are very strict, it is clearly shown that with two-level approach it is possible to predict local electricity grid problems depending on maximum allowed values of voltage and line capacity. Once the problems are identified, the adjustments can be made in terms of geographical allocation and sizing of the new installations in order to eliminate the problems.

4.3. Concept of using EV parking lot as battery and its influence on electric distribution grid

This paper presents special form of V2G concept by modelling the parking of EVs. As mentioned before, EV parking lot is considered as a battery that changes capacity over time depending on the number of vehicles that are currently on the parking and SOC of the vehicles.

The impact of EV parking lot on power import and export during two days in July can be observed at Fig. 15 and Fig. 16. It is possible to notice that for HighRES scenario (Fig. 16), the installation of EV parking slightly increases power import, but also decreases the amount of exported power. Implementation of EV parking lot also results with lower amounts of variations of power import and export. In RES case during July (Fig. 15), the EV parking lot slightly decreases the amount of imported power, as well as lowers the amount of exported power. These effects represent synergy between solar power generation and EV parking lot, where EV parking acts as a battery stack, combining all the EV batteries connected together at the given location. This is especially visible in the RES case. During peak solar production, EV parking lot increases total demand because it is in charge mode. This leads to decrease of excess power. In periods when there is no solar generation or when the solar generation is low, the EV parking is in discharge mode and provides additional electric energy needed to satisfy the demand.

Voltage profiles for nodes 45 are provided on the Fig. 17 and Fig. 18 and for node 5 are provided on the Fig. 19 and Fig. 20. Node 45 is located in Komiža and it is right next to node 47 where the EV parking lot is connected. Node 5 will be used for investigating voltage in part of the grid that is distanced, but still impacted by EV parking lot.

For RES scenario, a very positive impact of EV parking lot is visible on Fig. 17 and Fig. 19. The EV parking lot lowers peak values of voltages during high solar production and raises minimum values during low solar production. The highest voltage value for RES scenario in node 45 without EV parking lot is 10.3 kV, while the highest voltage with EV parking lot is 10.18 kV. This effect is more expressed for node 45 than on node 5 due to geographical closeness of node 45 to node 47. For HighRES scenario (Fig. 18 and Fig. 20), the EV parking lot decreases peak voltage values as in RES scenario, but in this scenario this effect is more visible on the distanced node 5.

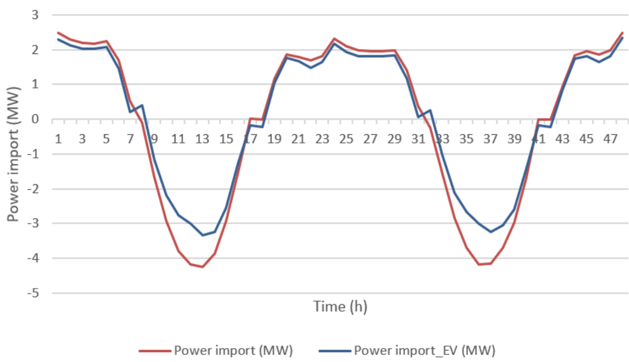

Figure 15. Power import during July for RES scenario

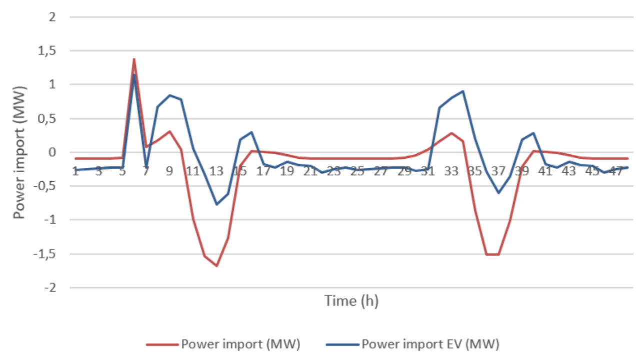

Figure 16. Power import during July for HighRES scenario

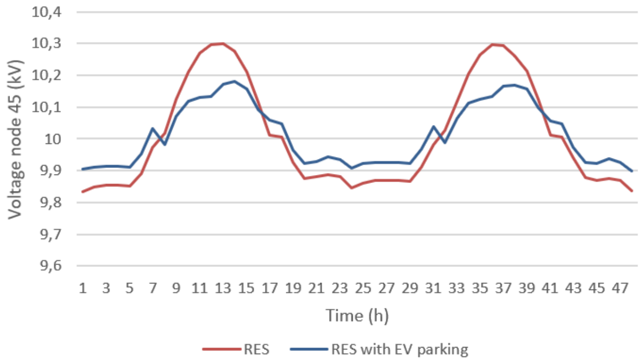

Figure 17. Voltage at node 45 during July for RES scenario

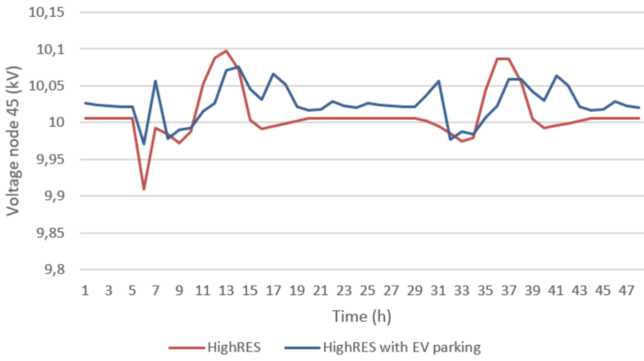

Figure 18. Voltage at node 45 during July for HighRES scenario

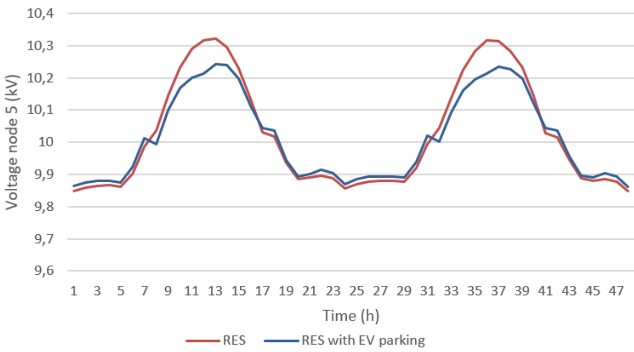

Figure 19. Voltage at node 5 for RES scenario

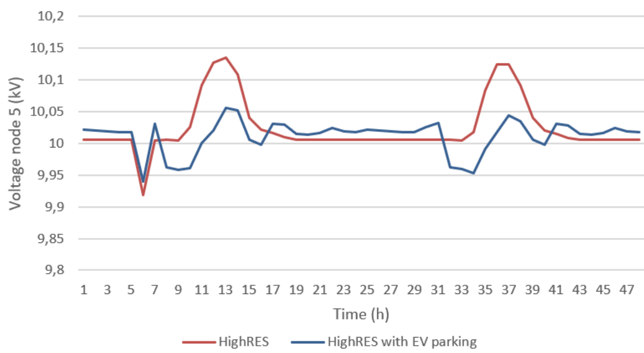

Figure 20. Voltage at node 5 for HighRES scenario

Similar effect is visible during the February on Fig. 21 for RES scenario and Fig. 22 for HighRES scenario. Due to the fact that there is less EVs on the island during winter months than during summer months, the impact of EV parking is lesser in both scenarios. Nevertheless, the impact of EV parking lot is still visible because of the slightly reduced

amounts of power import and power export.
Because of EV parking lot impact, the voltage profile during February is also improving. Fig. 23 and Fig. 24 show voltage profiles of node 45 for RES and HighRES scenarios during two days in February, respectfully. EV parking lot improves voltage on node 45 in RES and HighRES scenario so that voltage deviation isn't greater than 1% of nominal voltage 10 kV. Peak values of voltage at node 5 are also improving, except minor fluctuations of voltage occur during solar production in RES case.

Figure 21. Power import during February for RES scenario

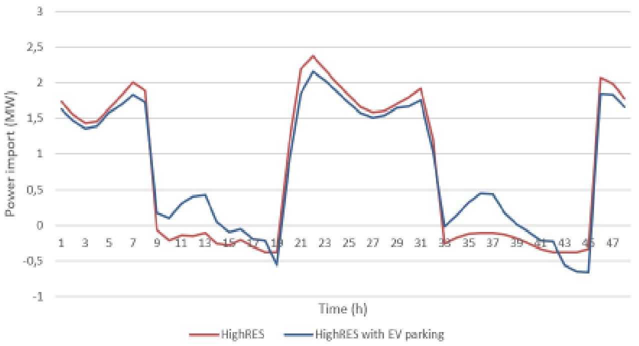

Figure 22. Power import during February for HighRES scenario

Figure 23. Voltage at node 45 during February for RES scenario

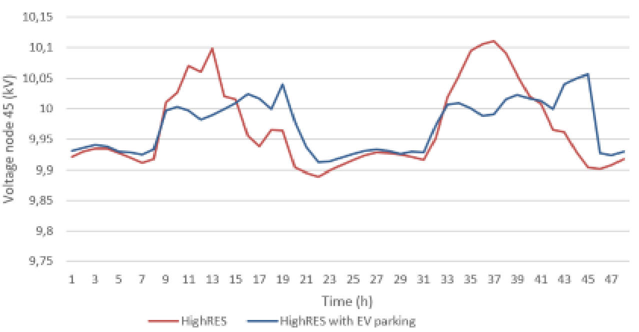

Figure 24. Voltage at node 45 during February for HighRES

Figure 25. Voltage at node 5 during February for RES scenario

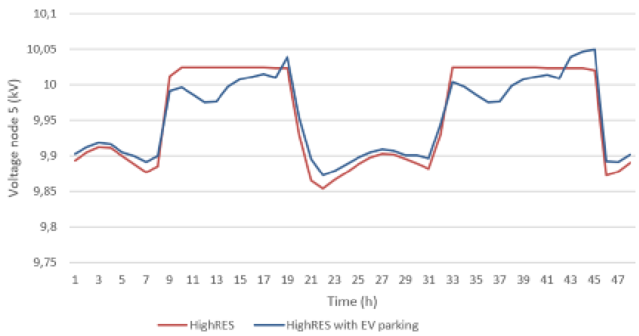

Figure 26. Voltage at node 5 during February for HighRES scenario

The results indicate that implementation of EV parking lot would have positive impact on grid performance. The impact is more visible during summer months due to higher capacity of EV parking lot. The amount of exported and imported power decreases and the peak values of voltages are closer to the nominal value of 10 kV. The impact of EV parking lot is more visible for RES scenario than for HighRES scenario which shows the synergy between EV parking lot and solar generation. This is because the most of the EVs is parked during the highest solar generation which results in synchronisation between these two technologies.

5. Conclusion

A two-level approach to energy planning of the island's energy systems is presented in this paper. First level provides hourly calculations and solutions regarding the integration of RES technologies and other sectors, such as heat, water and transport sector. In this paper, particular attention in the scenario approach was given to the synergy of RES exploitation and electrified transport as a demand response technology. Results of this step indicate the possibility for the island's energy system to become almost self-sufficient regarding the energy supply in terms of need for electricity and transport needs. This is in particular shown in the HighRES scenarios, which offer continuous local supply of energy from solar and wind power, combined with electric vehicles. It is concluded that with implementation of new technologies and RES it is possible to significantly reduce the islands dependence on power import. The second level of planning involves investigation of the conditions in the electricity distribution grid for all the scenarios examined in the first level. This level offers insight in terms of ability of the present grid to accommodate large installations of RES. On the case study of the island of Vis, for which a model of distribution grid was created in the LF tool, the sensitivity and ability of tool to provide outputs which are helpful in answering the question of distribution of installations within the grid are demonstrated. The results show that in case of the HighRES scenario and with chosen voltage limits, planned installations cannot be placed exclusively in the towns of Komiža and Vis, because it would cause problems in the local grid. There are several possible solutions for resolving this problem. Two possibilities are to upgrade the local grid or to change the layout of the installations across the island and the third possibility is to integrate new technology that will allow voltage control. Thus, in order to tackle the issue, the paper presents model of EV parking lot for island of Vis, located in town Komiža and connected in V2G mode, that is considered as a battery with fluctuating capacity, acting as a typical example of synergy between energy production and storage system and transport system in transition of island's energy system towards self-sufficiency. While this study focuses on Vis Island, the proposed methodology is designed to be applicable to other remote and islanded energy systems worldwide. The insights gained from integrating scenario-based energy planning with grid feasibility analysis can support broader energy transition efforts, particularly in isolated systems with high renewable energy potential and grid constraints.

This kind of approach brings many benefits to the distribution system such as improvement of voltage profile, better frequency control and better electric power quality. Moreover, V2G concept represents clean and sustainable technology that will significantly contribute to power grid transition to low carbon smart grid. The calculation shows that LF tool allows execution of wide variety of scenarios and analysis of impact of these scenarios on different electricity distribution characteristics such as voltage and power import. EV parking can provide demand response to the electric distribution grid in higher or lower amount depending on period of the day and year. The impact of EV parking lot is simulated for RES and HighRES scenarios and the results indicate that EV parking lot has positive impact on conditions in the grid. The imported and exported power is reduced for all scenarios and the voltage levels are closer to the nominal voltage. This is especially visible for RES scenario where the voltage on node 45, located in Komiža, during July is reduced from maximum value of 10.3 kV to 10.18 kV and minimum value increased from 9.83 kV to 9.9 kV. This analysis shows that, with LF tool, it is possible to simulate wide range of scenarios and models to investigate electric distribution system. The proposed two-level energy planning approach provides valuable insights into the integration of renewable energy and grid feasibility on islands. While this study focuses on Vis Island, the methodology is designed to be adaptable to various island systems with different grid structures, renewable energy potentials, and population densities. Future work should focus on testing this approach on islands with varying levels of interconnection, sectoral integrations, and network constraints to further validate its robustness and generalizability. Additionally, applying this method to more densely populated islands or those with higher energy demand could provide additional insights into how demographic and economic factors influence the feasibility of high-renewable penetration. While this study primarily examines the technical feasibility of high-renewable energy integration, a techno-economic analysis was not included in its scope. Future research should incorporate an economic assessment to evaluate the financial feasibility, investment requirements, and potential policy incentives necessary for the practical implementation of the proposed transition pathways.

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7. References

[1] M. Mimica, D. F. Dominković, V. Kirinčić, and G. Krajačić, "Soft-linking of improved spatiotemporal capacity expansion model with a power flow analysis for increased integration of renewable energy sources into interconnected archipelago," *Appl Energy*, vol. 305, p. 117855, Jan. 2022, doi: 10.1016/j.apenergy.2021.117855.

[2] N. Duić, G. Krajačić, and M. G. Carvalho, "RenewIslands methodology for sustainable energy and resource planning for islands," *Renewable and Sustainable Energy Reviews*, vol. 12, no. 4, pp. 1032–1062, May 2008, doi: 10.1016/j.rser.2006.10.015.

[3] Z. Bačelić Medić, B. Ćosić, and N. Duić, "Sustainability of remote communities: 100% renewable island of Hvar," *Journal of Renewable and Sustainable Energy*, vol. 5, no. 4, Jul. 2013, doi: 10.1063/1.4813000.

[4] V. Vidović, G. Krajačić, N. Matak, G. Stunjek, and M. Mimica, "Review of the potentials for implementation of floating solar panels on lakes and water reservoirs," *Renewable and Sustainable Energy Reviews*, vol. 178, p. 113237, May 2023, doi: 10.1016/j.rser.2023.113237.

[5] R. Segurado, G. Krajačić, N. Duić, and L. Alves, "Increasing the penetration of renewable energy resources in S. Vicente, Cape Verde," *Appl Energy*, vol. 88, no. 2, pp. 466–472, Feb. 2011, doi: 10.1016/j.apenergy.2010.07.005.

[6] A. Šare, G. Krajačić, T. Pukšec, and N. Duić, "The integration of renewable energy sources and electric vehicles into the power system of the Dubrovnik region," *Energy Sustain Soc*, vol. 5, no. 1, p. 27, Dec. 2015, doi: 10.1186/s13705-015-0055-7.

[7] M. Mimica, G. Krajacic, D. Medved, and D. Jardas, "Digitalization and Smart islands in the Kvarner archipelago," in *2020 43rd International Convention on Information, Communication and Electronic Technology (MIPRO)*, IEEE, Sep. 2020, pp. 1837–1842. doi: 10.23919/MIPRO48935.2020.9245328.

[8] A. K. M. S. Islam, Md. M. Rahman, Md. A. H. Mondal, and F. Alam, "Hybrid energy system for St. Martin Island, Bangladesh: An optimized model," *Procedia Eng*, vol. 49, pp. 179–188, 2012, doi:

10.1016/j.proeng.2012.10.126.
[9] M. Thirunavukkarasu, Y. Sawle, and H. Lala, "A comprehensive review on optimization of hybrid renewable energy systems using various optimization techniques," *Renewable and Sustainable Energy Reviews*, vol. 176, p. 113192, Apr. 2023, doi: 10.1016/j.rser.2023.113192.
[10] R. Martins, G. Krajačić, L. M. Alves, N. Duić, T. Azevedo, and M. G. Carvalho, "Energy Storage in Islands - Modelling Porto Santo' s Hydrogen System," *Chem Eng Trans*, vol. 18, pp. 367–372, 2009.
[11] R. Segurado, M. Costa, N. Duić, and M. G. Carvalho, "Integrated analysis of energy and water supply in islands. Case study of S. Vicente, Cape Verde," *Energy*, vol. 92, pp. 639–648, Dec. 2015, doi: 10.1016/j.energy.2015.02.013.
[12] M. A. Bhuiyan, Q. Zhang, V. Khare, A. Mikhaylov, G. Pinter, and X. Huang, "Renewable Energy Consumption and Economic Growth Nexus—A Systematic Literature Review," *Front Environ Sci*, vol. 10, Apr. 2022, doi: 10.3389/fenvs.2022.878394.
[13] D. Al. Katsaprakakis, N. Papadakis, G. Kozirakis, Y. Minadakis, D. Christakis, and K. Kondaxakis, "Electricity supply on the island of Dia based on renewable energy sources (R.E.S.)," *Appl Energy*, vol. 86, no. 4, pp. 516–527, Apr. 2009, doi: 10.1016/j.apenergy.2008.07.013.
[14] D. Medimorec, S. Knezevic, V. Vorkapic, and D. Skrlec, "Wind energy and environmental protection: Using GIS to evaluate the compatibility of Croatian strategies," in *2011 8th International Conference on the European Energy Market (EEM)*, IEEE, May 2011, pp. 764–772. doi: 10.1109/EEM.2011.5953113.
[15] S. Bera, D. Sengupta, S. Roy, and K. Mukherjee, "Research into dye-sensitized solar cells: a review highlighting progress in India," *Journal of Physics: Energy*, vol. 3, no. 3, p. 032013, Jul. 2021, doi: 10.1088/2515-7655/abff6c.
[16] L. Sigrist, E. Lobato, L. Rouco, M. Gazzino, and M. Cantu, "Economic assessment of smart grid initiatives for island power systems," *Appl Energy*, vol. 189, pp. 403–415, Mar. 2017, doi: 10.1016/j.apenergy.2016.12.076.
[17] E. Mortaz and J. Valenzuela, "Microgrid energy scheduling using storage from electric vehicles," *Electric Power Systems Research*, vol. 143, pp. 554–562, Feb. 2017, doi: 10.1016/j.epsr.2016.10.062.
[18] P. Prebeg, G. Gasparovic, G. Krajacic, and N. Duic, "Long-term energy planning of Croatian power system using multi-objective optimization with focus on renewable energy and integration of electric vehicles," *Appl Energy*, vol. 184, pp. 1493–1507, Dec. 2016, doi: 10.1016/j.apenergy.2016.03.086.
[19] A. Aoun, H. Ibrahim, M. Ghandour, and A. Ilinca, "Supply Side Management vs. Demand Side Management of a Residential Microgrid Equipped with an Electric Vehicle in a Dual Tariff Scheme," *Energies (Basel)*, vol. 12, no. 22, p. 4351, Nov. 2019, doi: 10.3390/en12224351.
[20] Y. Kongjeen and K. Bhumkittipich, "Impact of Plug-in Electric Vehicles Integrated into Power Distribution System Based on Voltage-Dependent Power Flow Analysis," *Energies (Basel)*, vol. 11, no. 6, p. 1571, Jun. 2018, doi: 10.3390/en11061571.
[21] A. Pfeifer *et al.*, "Building smart energy systems on Croatian islands by increasing integration of renewable energy sources and electric vehicles," in *2017 IEEE International Conference on Environment and Electrical Engineering and 2017 IEEE Industrial and Commercial Power Systems Europe (EEEIC / I&CPS Europe)*, IEEE, Jun. 2017, pp. 1–6. doi: 10.1109/EEEIC.2017.7977401.
[22] H. Dorotić, B. Doračić, V. Dobravec, T. Pukšec, G. Krajačić, and N. Duić, "Integration of transport and energy sectors in island communities with 100% intermittent renewable energy sources," *Renewable and Sustainable Energy Reviews*, vol. 99, pp. 109–124, Jan. 2019, doi: 10.1016/j.rser.2018.09.033.
[23] D. F. Dominković, G. Stark, B.-M. Hodge, and A. S. Pedersen, "Integrated Energy Planning with a High Share of Variable Renewable Energy Sources for a Caribbean Island," *Energies (Basel)*, vol. 11, no. 9, p. 2193, Aug. 2018, doi: 10.3390/en11092193.
[24] D. Groppi, D. Astiaso Garcia, G. Lo Basso, and L. De Santoli, "Synergy between smart energy systems simulation tools for greening small Mediterranean islands," *Renew Energy*, vol. 135, pp. 515–524, May 2019, doi: 10.1016/j.renene.2018.12.043.
[25] F. Calise, A. Macaluso, A. Piacentino, and L. Vanoli, "A novel hybrid polygeneration system supplying energy and desalinated water by renewable sources in Pantelleria Island," *Energy*, vol. 137, pp. 1086–1106, Oct. 2017, doi: 10.1016/j.energy.2017.03.165.
[26] J. Schallenberg-Rodríguez, "Photovoltaic techno-economical potential on roofs in regions and islands: The case of the Canary Islands. Methodological review and methodology proposal," *Renewable and Sustainable Energy Reviews*, vol. 20, pp. 219–239, Apr. 2013, doi: 10.1016/j.rser.2012.11.078.
[27] D. Groppi, F. Feijoo, A. Pfeifer, D. A. Garcia, and N. Duic, "Analyzing the impact of demand response and reserves in islands energy planning," *Energy*, vol. 278, p. 127716, Sep. 2023, doi: 10.1016/j.energy.2023.127716.
[28] D. Galzina, "Voltage Quality Improvement Using Solar Photovoltaic System," *Journal of Sustainable Development of Energy, Water and Environment Systems*, vol. 3, no. 2, pp. 140–150, Jun. 2015, doi: 10.13044/j.sdewes.2015.03.0011.
[29] D. Groppi, D. Astiaso Garcia, G. Lo Basso, F. Cumo, and L. De Santoli, "Analysing economic and environmental sustainability related to the use of battery and hydrogen energy storages for increasing the energy independence of small islands," *Energy Convers Manag*, vol. 177, pp. 64–76, Dec. 2018, doi: 10.1016/j.enconman.2018.09.063.
[30] A. Pfeifer, V. Dobravec, L. Pavlinek, G. Krajačić, and N. Duić, "Integration of renewable energy and demand response technologies in interconnected energy systems," *Energy*, vol. 161, pp. 447–455, Oct. 2018, doi: 10.1016/j.energy.2018.07.134.
[31] D. Ciechanowicz, D. Pelzer, B. Bartenschlager, and A. Knoll, "A Modular Power System Planning and Power Flow Simulation Framework for Generating and Evaluating Power Network Models," *IEEE Transactions on Power Systems*, vol. 32, no. 3, pp. 2214–2224, May 2017, doi:

10.1109/TPWRS.2016.2602479.

[32] F. Milano, *Power System Modelling and Scripting*. Springer, 2010.

[33] H. H. Muller, M. J. Rider, C. A. Castro, and V. Leonardo Paucar, “Power flow model based on artificial neural networks,” in *2005 IEEE Russia Power Tech*, IEEE, Jun. 2005, pp. 1–6. doi: 10.1109/PTC.2005.4524546.

[34] L. Imen, L. Djamel, S. Hassiba, D. Abdellah, and F. Selwa, “Optimal power flow study using conventional and neural networks methods,” in *2015 International Conference on Renewable Energy Research and Applications (ICRERA)*, IEEE, Nov. 2015, pp. 1422–1427. doi: 10.1109/ICRERA.2015.7418642.

[35] J. G. Vlachogiannis, “Fuzzy logic application in load flow studies,” *IEE Proceedings - Generation, Transmission and Distribution*, vol. 148, no. 1, p. 34, 2001, doi: 10.1049/ip-gtd:20010032.

[36] M. A. Abdullah, A. P. Agalgaonkar, and K. M. Muttaqi, “Probabilistic load flow incorporating correlation between time-varying electricity demand and renewable power generation,” *Renew Energy*, vol. 55, pp. 532–543, Jul. 2013, doi: 10.1016/j.renene.2013.01.010.

[37] E. Mohagheghi, A. Gabash, M. Alramlawi, and P. Li, “Real-time optimal power flow with reactive power dispatch of wind stations using a reconciliation algorithm,” *Renew Energy*, vol. 126, pp. 509–523, Oct. 2018, doi: 10.1016/j.renene.2018.03.072.

[38] A. Esmaeli, M. Abedini, and M. H. Moradi, “A novel power flow analysis in an islanded renewable microgrid,” *Renew Energy*, vol. 96, pp. 914–927, Oct. 2016, doi: 10.1016/j.renene.2016.04.077.

[39] S. F. Mekhamer, S. A. Soliman, M. A. Moustafa, and M. E. El-Hawary, “Load flow solution of radial distribution feeders: a new contribution,” *International Journal of Electrical Power & Energy Systems*, vol. 24, no. 9, pp. 701–707, Nov. 2002, doi: 10.1016/S0142-0615(02)00005-4.

[40] E. R. Ramos, A. G. Exposito, and G. A. Cordero, “Quasi-Coupled Three-Phase Radial Load Flow,” *IEEE Transactions on Power Systems*, vol. 19, no. 2, pp. 776–781, May 2004, doi: 10.1109/TPWRS.2003.821624.

[41] W.-M. Lin and J.-H. Teng, “Three-phase distribution network fast-decoupled power flow solutions,” *International Journal of Electrical Power & Energy Systems*, vol. 22, no. 5, pp. 375–380, Jun. 2000, doi: 10.1016/S0142-0615(00)00002-8.

[42] B. Sereeter, K. Vuik, and C. Witteveen, “Newton Power Flow Methods for Unbalanced Three-Phase Distribution Networks,” *Energies (Basel)*, vol. 10, no. 10, p. 1658, Oct. 2017, doi: 10.3390/en10101658.

[43] E. Rikos and C. Perakis, “The PRISMI proposal for a user-friendly load-flow tool for analysis of island grids,” *Renew Energy*, vol. 145, pp. 2621–2628, Jan. 2020, doi: 10.1016/j.renene.2019.08.017.

[44] “Interreg MED PRISMI project, D.3.4.2 RES Feasibility study and comparative analysis,” Feb. 2018.