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HYBRID POWER PLANT WITH STORAGE ON A NON-INTERCONNECTED GREEK ISLAND

HIBRIDNA ELEKTRANA SA SKLADIŠTENJEM ELEKTIČNE ENERGIJE U OTOČNOM REŽIMU RADA NA GRČKOM OSTRVU

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Abstract: In this work we present the design of a PV plant comprising storage for the transition of the fossil fuelled power plant of a non-interconnected Greek Island to a hybrid one with high RES penetration. Simulations are performed using the OpenDSS software. The proposed design offers 58.1% reduction in both fuel consumption and CO_2 emissions for the first year of operation, which reduces to 44.2% and 42.2% after 20 years.

Keywords: Non-interconnected Islands, PV Systems, Storage Systems, CO_2 emissions, OpenDSS

Sažetak: U radu je predstavljena fotonaponska elektrana sa ugrađenim sistemom za skladištenje električne energije koja bi trebala da zamijeni postojeću elektranu na fosilni pogon. Analiza je urađena na realnom elektroenergetskom sistemu sa velikim udjelom obnovljivih izvora energije koji nije povezan na krutu mrežu, a nalazi se na Grčkom ostrvu. Simulacije su izvršene u softveru OpenDSS. Dobiveni rezultati pokazuju da se sa predloženim hibridnim sistemom, mogu ostvariti smanjenja u iznosu od 58,1 % za upotrebu fosilnih goriva i emisiju CO_2 u prvoj godini realizacije, dok se nakon 20 godina očekuje smanjenje od 44,2% za fosilna goriva i 42,2% za emsiju CO_2.

Ključne riječi: ostrva nepovezana na krutu mrežu, fotonaponski sistemi, sistemi za skladištenje, emisije CO_2, OpenDSS

INTRODUCTION

The Greek Power System includes 32 Non-Interconnected Grids supplying 60 islands in the Aegean Sea [1], [2]. These grids are fed by conventional power supply stations using oil as a fuel, causing the average electricity production cost to increase by 2.5 times with respect to the interconnected electricity grid of Greece [2]. High CO_2 emissions, as well as high consumption and maintenance costs make them unprofitable. On the other hand, the wind potential in the Aegean Sea region is one of the largest in the EU. More specifically, the average wind velocity reaches 10-11m/s [3], almost 80% of the rated output speed of atypical wind turbine [4]. In addition to that, solar irradiation of Greece typically exceeds 1000 W/m^2 [5].

Hybrid power systems (systems with a conventional power source, one or more renewable energy sources and storage) and microgrids offer a sustainable solution for electricity supply to remote areas and non-interconnected islands [6]-[10].

This study concerns a non-interconnected Greek island located in the south east Aegean and focuses on the energy transition of its power supply system towards a hybrid one where part of the island's demand will be met by a PV plant with storage.

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The paper is organized as follows: in the first section the existing power system is described, sections 2 and 3 present the wind and solar potential of the island. Section 4 presents the demand profile of the island and in section 5 the proposed power grid is presented. Finally, sections 6 and 7 present simulation results and the source mixture used to cover the load of the island on an hourly basis during a representative day of each season of the year.

1. EXISTING POWER SUPPLY SYSTEM

The power supply system of the island consists of 6 Diesel generators of total power 1.45 MW. The total power consumption, for 2018, reached 3796 MWh.The yearly peak in power demand was recorded in August and reached 970 kW. The power demand for a typical winter day ranges between 300 kW and 490 kW. The projected growth of the total power consumption of the island and the peak power demand until 2024, based on available grid data, are listed in Table I.

Table I: Estimation of the annual power consumption and peak power demand till the year of 2024

Year	Annual power consumption (MWh)	Peak power demand (MWh)
2020	3833.4	1.56
2021	3833.3	1.57
2022	3941.5	1.58
2023	3988.8	1.59
2024	4044.6	1.61

2. WIND ENERGY POTENTIAL OF THE ISLAND

Primary meteorological data for the wind potential of the island concerning 2014, 2015, 2016, 2017 and 2018 [3], [5] show that the average wind velocity does not exceed the 5.5 m/s. Considering that the cut in speed of a common wind turbine is set at 4.5 m/s, it is obvious, that the specific wind potential of the island is very low. Table II shows the average wind speed and the probability that this value is exceeded by the instantaneous wind speed.

Table II: Average wind speed

Year	Average Wind speed (m/s)	Probability of exceeding average wind speed
2014	5.18	41.27%
2015	5.72	39.10%
2016	5.23	35.88%
2017	4.85	38.12%
2018	3.34	37.90%

Figure 1 presents the yearly profile of the average wind speed in the island, based on data collected over the decade 2007-2016 [5].

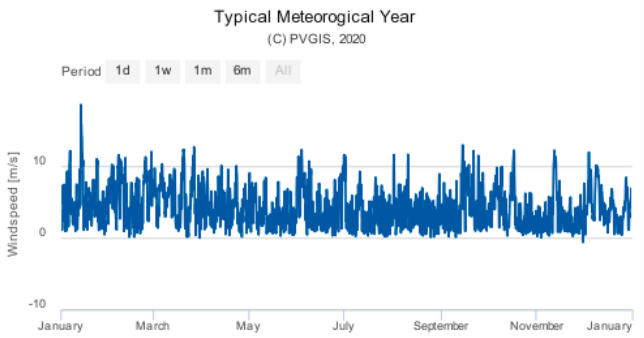


Figure 1: Yearly profile of the average wind speed 2007-2016.

3. SOLAR ENERGY POTENTIAL OF THE ISLAND

While the wind potential of the island is not exploitable, the solar irradiation of the island is quite high. Concerning the years 2014, 2015 and 2016, Tables III, IV and V, show the average values of the solar irradiation of the specific area in W/m^2.

Table III: Average solar irradiation for 2014 (W/m^2)

Winter / Summer	6:00 / 7:00	7:00 / 8:00	8:00 / 9:00	9:00 / 10:00	10:00 / 11:00	11:00 / 12:00	12:00 / 13:00	13:00 / 14:00	14:00 / 15:00	15:00 / 16:00	16:00 / 17:00	17:00 / 18:00
Jan	0	54	160	250	353	429	445	396	265	142	7	0
Feb	2	119	274	406	521	591	595	470	378	239	85	0
Mar	53	177	333	510	598	679	625	555	434	299	128	3
Apr	78	261	455	597	722	731	705	643	547	339	156	19
May	95	268	416	542	653	678	660	629	475	326	147	21
Jun	128	314	506	662	739	775	768	710	535	365	183	39
Jul	124	317	512	679	795	849	836	755	615	434	234	54
Aug	116	315	518	690	811	865	832	759	612	421	213	36
Sep	100	297	507	679	792	859	814	699	546	343	137	4
Oct	72	221	408	556	658	690	677	537	403	228	50	0
Nov	17	145	285	461	549	586	530	429	295	127	0	0
Dec	0	100	218	343	417	504	433	332	211	86	0	0

Table IV: Average solar irradiation for 2015 (W/m^2)

Winter / Summer	6:00 / 7:00	7:00 / 8:00	8:00 / 9:00	9:00 / 10:00	10:00 / 11:00	11:00 / 12:00	12:00 / 13:00	13:00 / 14:00	14:00 / 15:00	15:00 / 16:00	16:00 / 17:00	17:00 / 18:00
Jan	0	73	174	325	442	403	386	336	199	117	0	0
Feb	4	119	219	332	412	497	464	378	254	113	33	0
Mar	48	192	370	499	611	630	562	552	403	284	112	0
Apr	112	286	469	631	750	809	742	625	478	315	140	3
May	151	334	507	636	700	730	698	618	502	313	142	8
Jun	156	340	518	680	775	800	742	681	551	372	166	21
Jul	146	331	515	677	767	828	825	725	578	392	201	33
Aug	135	339	540	701	818	859	837	717	587	394	184	19
Sep	120	310	488	669	768	778	764	672	516	303	124	0
Oct	87	251	412	536	658	676	615	472	326	175	14	0
Nov	26	226	390	528	636	665	582	476	337	162	0	0
Dec	0	129	272	412	462	531	494	404	277	125	0	0

Table V: Average solar irradiation for 2016 (W/m^2)

Winter / Summer	6:00 / 7:00	7:00 / 8:00	8:00 / 9:00	9:00 / 10:00	10:00 / 11:00	11:00 / 12:00	12:00 / 13:00	13:00 / 14:00	14:00 / 15:00	15:00 / 16:00	16:00 / 17:00	17:00 / 18:00
Jan	0	0	101	251	351	447	456	433	399	253	0	0
Feb	0	7	169	295	440	566	625	647	548	375	181	0
Mar	0	80	232	425	582	776	684	658	563	444	272	12
Apr	15	144	316	523	716	796	841	783	677	508	286	93
May	37	162	325	446	604	684	684	637	514	423	240	93
Jun	43	205	393	576	688	758	767	730	600	479	299	124
Jul	32	178	367	565	717	802	835	804	698	540	341	145
Aug	20	185	377	571	734	827	853	792	677	501	325	134
Sep	3	175	381	569	734	812	830	788	638	460	270	24
Oct	0	133	342	545	708	784	740	714	566	390	101	0
Nov	0	24	205	355	465	619	630	564	428	272	0	0
Dec	0	0	117	245	387	421	420	390	288	215	0	0

The stability of the irradiation values, especially during the spring and summer months, for three continuous years, according to the above tables, leads to the conclusion that the installation of PV panels as a renewable source on the island is the appropriate solution.

4. THE DEMAND PROFILE OF THE ISLAND

Most of the Greek islands, due to the high influx of tourists during the summer months, are faced with a significant difference in power demand between winter and summer. This results in the need for increased reserved capacity, for a short period of high-power demand. Figures 2, 3 and 4, illustrate the monthly average values of power demand for 2018.

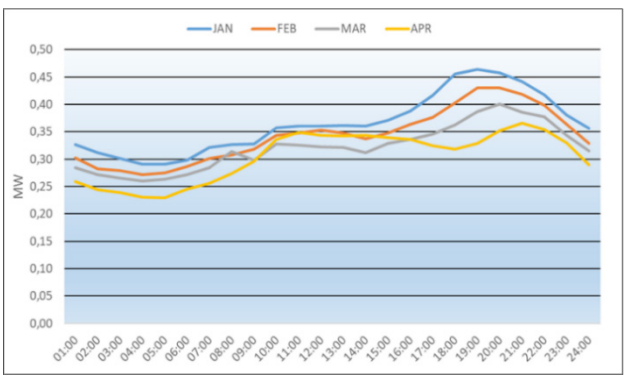


Figure 2: Average power demand for the months of January through April

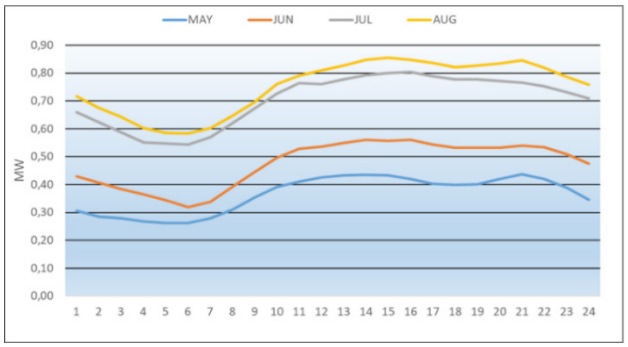


Figure 3: Average power demand for the months of May through August

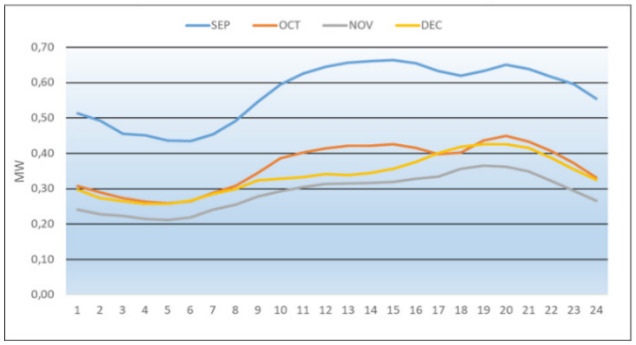


Figure 4: Average power demand for the months of September through December

These figures indicate that power demand during the summer is twice the power demand during the winter. In the winter months, the peak demand shifts towards the early evening hours while in the hot summer months, the demand reaches a plateau in the early afternoon hours which is maintained until the evening.

Figure 5 shows the solar irradiation for the month of August [5]. The power demand, as shown in Figures 2-4, is not synchronized with the power production of PV panels, therefore the use of an energy storage system is essential in order to store energy during the day and supply energy to cover the peak in the evening hours.

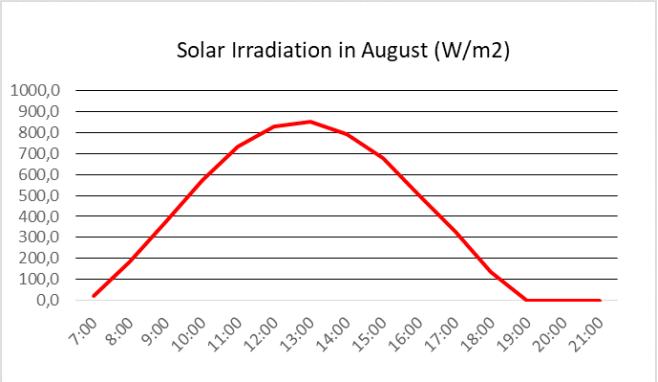


Figure 5: Solar irradiation in August

5. THE POWER GRID OF THE ISLAND

The goal of this work is to design a PV plant with storage that will complement the existing thermoelectric plant in such a way as to decrease the usage of its generators and therefore reduce oil consumption and CO_2 emissions.

To this end, we used the OpenDSS software [11] to simulate the Island's grid and perform the required load-flow analyses, Matlab to drive the OpenDSS and Matlab and Excel for the post processing of the results obtained by OpenDSS.

Figure 6 depicts the proposed electrical grid design of the island. The PV plant is presumably installed in an available area close to the existing thermoelectric station. Two 4.16/20 kV 2.5 MVA step up transformers drive the main distribution feeder. Three 20/0.4 kV 650 kVA step down transformers located along this feeder are used to drive low voltage lines serving residential loads, while a dedicated 20 kV line is used to supply the loads of the island's airport.

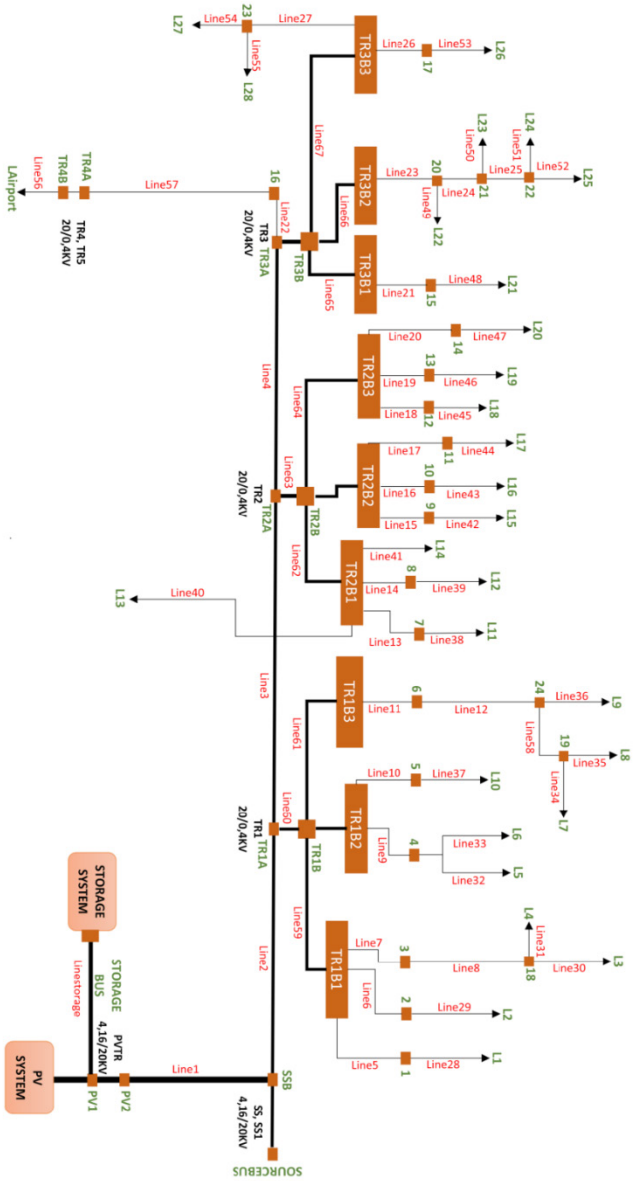


Figure 6: The power grid of the island used in the simulation

6. SIMULATION RESULTS

Several simulations were performed to determine the optimum combination of power of the PV system and storage capacity needed to minimize the rejected power during the spring and fall periods.

Finally, the total nominal power of the PV panels was set at 2400 kWp, whereas the total nominal capacity of the storage system was set to 5500 kWh. The PV plant is assumed to also supply reactive power to the grid, using the respective functionality of the OpenDSS.

Figure 7 depicts the hourly active (blue curve) and reactive power (red curve) consumption of the system on an annual basis.

The storage system can discharge up to 30% of its nominal capacity, i.e. the minimum state of charge (SOC) of the batteries is 30%.

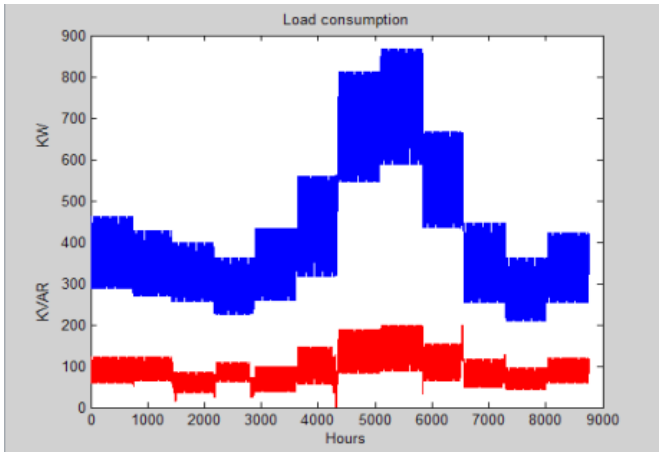


Figure 7: Active and reactive load consumption from January to December 2018 (Active Power – blue curve, Reactive Power – red curve)

Figure 8 illustrates the generated active (blue curve) and reactive (red curve) power by the 2400 kWp PV plant on an annual basis.

As can be observed, the installed PV generating capacity is such that the peak PV generated power surpasses the load demand, regardless of the season of the year. This way, the excess amount of power is used to charge the batteries of the storage system daily. The charging level reached each day depends on the SOC before charging begins, the amount of the available power and the corresponding charging time interval. As shown in Figure 9, which illustrates the resulting state of charge of the storage system for one year, during high loading periods (summer), SOC does not surpass 40%, while during low loading periods SOC values exceed 50% and approach 100% for increased irradiation and relatively low demand periods, as in the months of spring and fall.

After introducing RES into the system and according to the simulation's results, the number of required diesel generators was reduced from six to four, with nominal power 1.05 MW, instead of 1.45 MW.

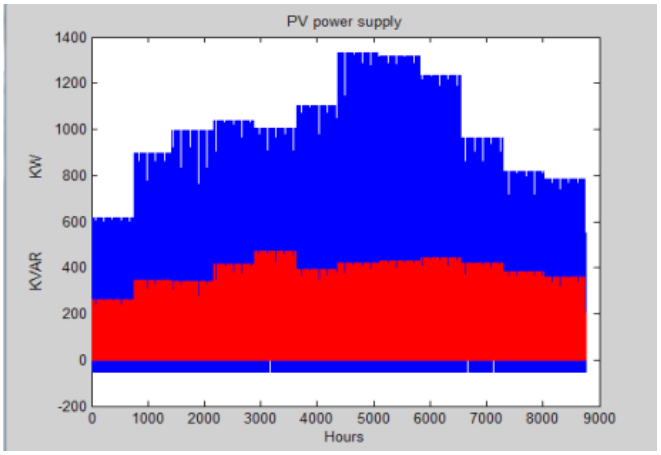


Figure 8: Power generation of the 2400 kWp PV plant from January to December 2018 (Active Power – blue curve, Reactive Power – red curve)

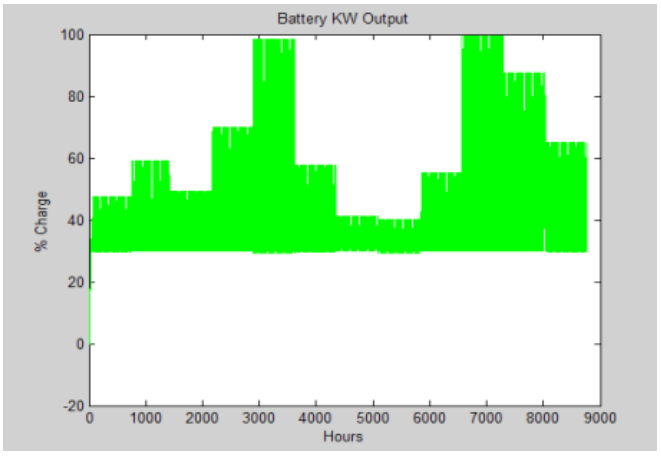


Figure 9: State of charge of batteries from January to December 2018

7. THE LOAD – SUPPLY PROFILE

Figures 10, 11, 12 and 13 illustrate the average hourly load demand for a 24-hour interval of a typical month of each season of the year, namely one day in January, one in April, one in August and one in October, against the mixture of the different power supply sources.

In these figures, the green line corresponds to the average daily load curve of the given month and the colour bars represent the contribution of the various supply sources used to cover the instantaneous power demand.

During daylight, and for the time period corresponding to high irradiation values, the load is served exclusively by the PV plant. In all cases, the peak PV power exceeds the load demand. This excess power is charging the batteries of the storage system, which is fed into the system during low irradiation periods of the day. The rest of low irradiation periods, as well as nighttime load, are served by the

diesel generators of the existing power station, according to their technical limits and a predefined commitment priority, shown in Table VI.

Spring and fall days are characterized by relatively low loadings in combination with extended irradiation time intervals. This results in increased amounts of energy stored in the storage system, and as a result reduced need for support by the diesel generators.

Figure 12, compared to Figures 10, 11 and 13, shows the significant load variation during the high tourist season, as well as, the use of almost all of the available generating capacity, especially during the night. Introducing more PV panels in order to decrease the rate of the generators' operation would result in large amount of excess generated power by the PV panels, especially in the spring period.

Table VI: Diesel Generators data and commitment priority

Unit	P_{max} (MW)	P_{min} (MW)	Unit Commitment Priority
gen 1	0.4	0.225	1
gen 2	0.18	0.11	2
gen 3	0.18	0.11	3
gen 4	0.25	0.1	4

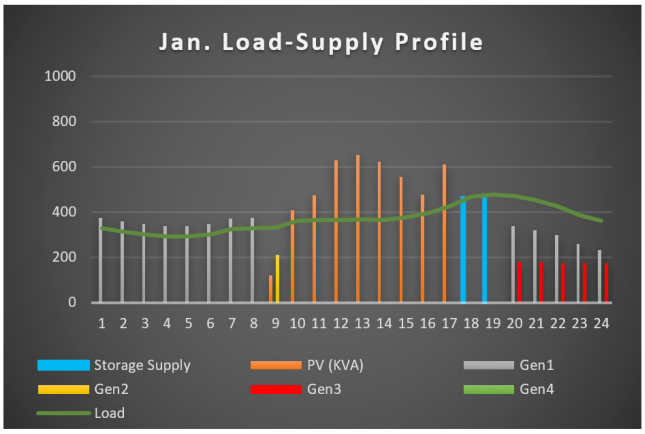


Figure 10: Load-supply profile of January

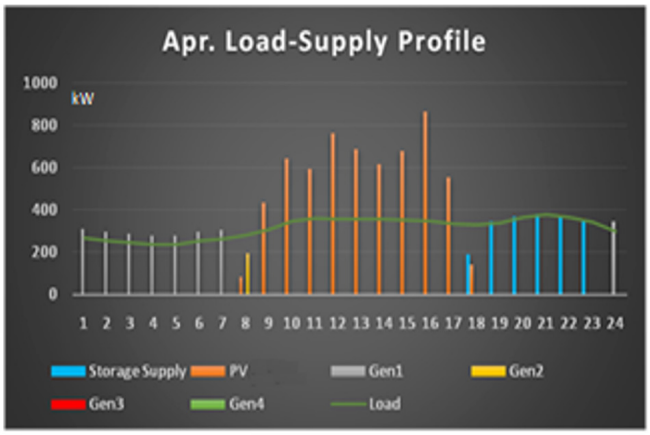


Figure 11: Load-supply profile of April

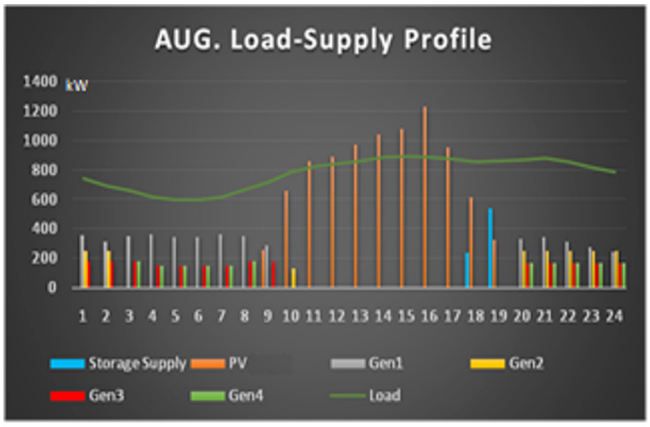


Figure 12: Load-supply profile of August

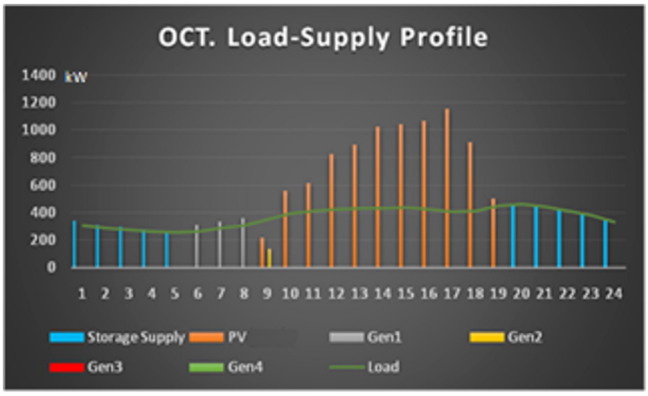


Figure 13: Load-supply profile of October

In case the installed PV panels were sized in order to cover the yearly load, the nominal capacity of the storage system, in order to store the excess amount of energy, should be some hundreds of MWh. In that case, the investment would not be beneficial because of the huge cost of the storage system. Such high capacity storage systems are mostly used to contribute to the balance of main grids. Another way to allow for PV panels capable to cover the load would be the introduction of a properly sized controllable load (for example a desalination park) which would absorb the excess power produced during low demand periods and go offline during high demand periods.

The installed capacity of the PV panels used in this simulation, contributes to a reduction of the use of the conventional power sources by more than 50%. This results in respective decreases in diesel fuel and, consequently, CO_2 emissions. Table VII summarizes the most important results of this study for 2018 data. In the proposed configuration of 1.05 MW diesel generators, 2.4 MWp PV generators and 5.5 MWh storage capacity, approximately 45% of the 3787 MWh yearly demand is served by the diesel generators, 18% is served by the storage, and the rest by the PV plant. The stored energy not assigned approaches 22%.

In the last part of the study, the simulations were repeated taking into consideration the annual growth of energy demand in the island for the next 4 years (Table I) and the decrease in the PV panels efficiency by about 0.7% to 1.5% per year [12], [13].

Table VII: Summary of results for the year 2018

Summary results for the year 2018	
Installed PV power	2400 KWp
Efficiency of PV panels	97%
Capacity of storage system	5500 KWh
Yearly energy demand	3787 MWh
Produced energy of PV panels	2552 MWh
Yearly stored energy	862 MWh
Assigned energy from the store sytem	673 MWh
Storage losses	21.94%
Net produced energy from RES	2363 MWh
Generators' total produced energy	1693 MWh
Gen. 1 produced energy	1158 MWh
Gen. 2 produced energy	122 MWh
Gen. 3 produced energy	294 MWh
Gen. 4 produced energy	111 MWh
Diesel consumption (opt-in of RES)	468.2 Kltrs
Diesel consumption (opt-out of RES)	1117 Kltrs
Rate of the produced energy by RES	58.3%
Primate assigned energy of Diesel fuel	11322 MWh
Tns of CO_2 emissions (opt-out of RES)	3017
Tns of CO_2 emissions (opt-in of RES)	1264
Percentage of CO_2 emission reduction	58.1%
Percentage of Diesel fuels' savings	58.1%

Next, the simulations were performed for 2024 and 2038 with the PV system efficiency reducing by 1.1% per year as depicted in Figure 14 [14]. According to the results for 2024, the projected rate of the produced energy by the RES will cover 52.4% of the annual energy demand thus reducing CO_2 emissions by 51.5%. For 2038, the corresponding figures are 44.2% and 42.2% respectively.

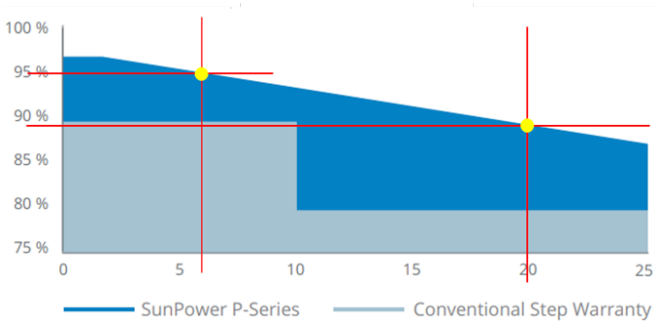


Figure 14: Efficiency of PV panels over time [14]

CONCLUSION

The transformation of the island's power plant to a hybrid one by introducing a PV system with storage reduces the use of diesel generators by more than 50%, thus resulting in a corresponding decrease of fuel consumption and CO_2 emissions by more than 50%. These figures remain practically unaltered for a time period of 20 years, a result that is encouraging for the implementation of the project. OpenDSS is an open software which interfaces with other programs used for calculations and may be used in feasibility studies of similar investments. The problem of converting the island's power system into an autonomous RES power system with storage through the expansion of the PV plant, the addition of controllable loads and the adoption of storage means other than batteries will be studied next. Future work will also focus on interfacing the OpenDSS with advanced optimization routines in order to develop decision support tools.

REFERENCES

[1] http://www.rae.gr/site/categories_new/electricity/market/mdn.csp
[2] N. M. Katsoulakos: An Overview of the Greek Islands' Autonomous Electrical Systems: Proposals for a Sustainable Energy Future. Smart Grid and Renewable Energy, 10, pp. 55-82, 2019, doi: 10.4236/sgre.2019.104005
[3] http://www.hnms.gr/emy/en/climatology/climatology_month
[4] A. Kalmikov: Chapter 2 - Wind Power Fundamentals, Editor(s): Trevor M. Letcher, Wind Energy Engineering, Academic Press, 2017, pp. 17-24, ISBN 9780128094518
[5] https://ec.europa.eu/jrc/en/pvgis
[6] A. Gupta, R. P. Saini, M. P. Sharma: Hybrid Energy System for Remote Area – An Action Plan for Cost Effective Power Generation, 2008 IEEE Region 10 Colloquium and the Third ICIIS, Kharagpur, INDIA December 8-10, 2008
[7] A. Razmjoo, R. Shirmohammadi, A. Davarpanah et al.: Stand-alone hybrid energy systems for remote area power generation, Energy Reports, Vol. 5, pp. 231-241, November 2019
[8] B. Tudu, K. K. Mandal, N. Chakraborty, I. Mukheree: Stand-alone Hybrid Renewable Energy System-An Alternative to Increased Energy Demand, 2014 International Conference on Control, Instrumentation, Energy & Communication, 31 Jan.-2 Feb. 2014
[9] Z. Ma et al.: Solutions for Remote Island Microgrids: Discussion and analysis of Indonesia's remote island energy system, 2018 IEEE Innovative Smart Grid Technologies - Asia (ISGT Asia), Singapore, 2018, pp. 493-498, doi:10.1109/ISGT-Asia.2018.8467954.
[10] K. B. Jones, M. James, R-A. Mastor: Securing our energy future: three international perspectives on microgrids and distributed renewables as a path toward resilient communities, Environmental Hazards, Vol. 16, 2017
[11] https://smartgrid.epri.com/SimulationTool.aspx
[12] Photovoltaic Degradation Rates -- An Analytical Review: Preprint, https://www.nrel.gov/docs/fy12osti/51664.pdf
[13] https://energyhub.org/wp-content/uploads/2018/05/SunPower-Module-Degredation-PDF.pdf
[14] https://us.sunpower.com/sites/default/files/media-library/data-sheets/ds-sunpower-p17-355-commercial-solar-panels.pdf

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