PV-based Integrated Energy and Water Demand Fulfillment Solution for Very Small Islands

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Summary

The current study investigates the prospects of integrated PV-based configurations, devoted to the coverage of both electricity and water needs, with the support also of dedicated water desalination plants. The proposed solution is evaluated in an area of great interest, i.e. the Aegean Archipelagos, focusing on the very small scale islands facing electricity supply and water shortage problems. Emphasis to that end is given on the analysis of both the energy and economic performance of such configurations, as compared to the current status of oil-based power generation and water transfers, challenged also by the scale of application itself. Results obtained to that end derive from the application of the solution to representative, very small scale islands of the Aegean Sea, covering a wide spectrum of island features, which is eventually found to further strengthen the argument on the general applicability and cost-efficient performance of the proposed solution.

Keywords: Non-Interconnected Islands, Water Shortage, Solar Energy, Energy Storage, Desalination

1. Introduction – Position of the Problem

Small island communities all over the world face serious water and energy infrastructure problems that deteriorate the quality of life of the local permanent population. In Greece, there are more than 6,000 islands and islets, 227 of which are inhabited, while approximately 50 of them are very small, having less than 200 inhabitants. The majority of these tiny islands are located in the Aegean Sea. For all these islands the electricity production is almost exclusively based on autonomous power stations (APSs) which consume imported diesel oil and present extremely high electricity generation cost [1]. Another crucial problem of remote islands is the coverage of clean water, which up to now is mainly supported by water tanks delivered to the islands through shipping [2]. The pronounced seasonality of electricity and potable water demand due to tourism is usually handled with difficulty by the local authorities and involved actors [1]. For example, the Greek Public Power Corporation (PPC) transfers portable power generator units between islands in order to cover the corresponding load demand. Moreover, the load demand cannot be always satisfied and insufficient generation problems arise, causing several black-outs, especially during the summer period. On the other hand, the significant water shortage problems are covered mainly with water transfers [2,3] from either bigger, nearby islands, or the mainland at a very high cost, while in some islands, reverse osmosis desalination units have been installed, adding to the local electricity consumption needs [4].

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2. Proposed Solution-Simulation Results

In order to ameliorate the current situation and to achieve energy autonomy (independence from oil products) in these tiny non-interconnected islands [5], a PV-based system is proposed (Fig.1) in collaboration with energy and water storage infrastructure, able to cover the electricity and fresh water needs of the inhabitants at a rational installation cost [6,7].

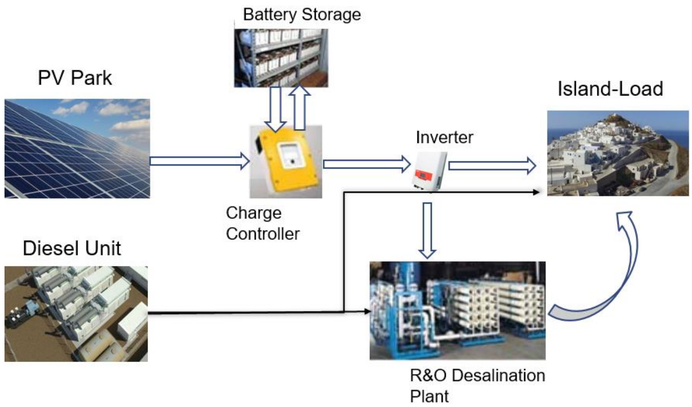
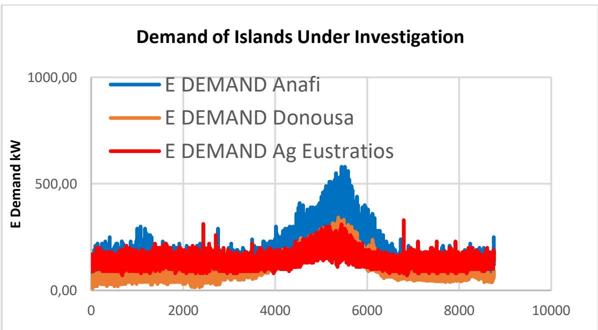


Figure 1: Proposed Energy-Water Solution for Very Small Islands

Accordingly, several representative PV-based configurations have been investigated for selected tiny islands taking also into consideration different water management strategies. According to the results obtained it is obvious that the proposed solution is able to achieve more than 95% energy autonomy for the selected islands, including the water desalination energy requirements, while the corresponding investment pay-back period is less than five years.

The cases examined for each of the configurations are:

- **Case 1:** The island's water load will be treated immediately as electricity load to the R&O plant with a coefficient of 7 kWh/m^3 and will be added to the total electricity load of the island. (steady water profile)
- **Case 2:** The island's water load will be treated separately from electricity. The system will convert the rejected electricity from the PV park that is not able to be stored in the ESS and fill a water tank. In situations that the water tank is unable to meet the demand, excess water will be bought (steady Water profile).
- **Case 1b:** The operational characteristics are the same as in Case 1, but the water profile is different (in accordance to the typical daily water demand profile of a remote island Figure 2) opposite to a constant consumption throughout the day.
- **Case 2b:** Same principles as in case 2 but with the difference in the water profile.



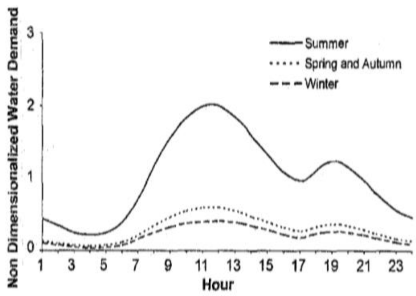


Figure 2: Electricity demand profile and typical daily water demand of the investigated islands

Apart from the 4 cases that refer to the configuration of the demand profiles, there are also 4 cases of economic interest about every island which are:

Case 1 and 1b: A PV unit that will operate as in the previous cases 1 and 1b which means that the water demand will be immediately covered and counted as electricity load.
Case 2 and 2b: A PV unit which operates like in the previous cases 2 and 2b. The water and electricity demand will be treated separately. The electricity load will be covered from the direct production of the PV park and energy stored in the battery system. The water demand will be covered via an installed water tank that will be fed from the desalination plant when the PV park produces excess energy and any deficit will be covered via water transports.

Case 3: A diesel only based unit that will feed the electric network of the island and water needs will be covered via water transports exclusively.
Case 4: A diesel only based unit combined with a desalination unit which will use diesel-produced electricity for the production of fresh water.

To that end, a representative, very small-scale Aegean island, i.e. the island of Anafi, has been selected as the main test-bed for the application of the different cases presented earlier.

Main characteristics of Anafi are given in the following bullets, while for comparison purposes, application results are next obtained for the islands of Agios Eustratios and Donousa as well.

- The population of Anafi according to the 2011 census is 273 people.
- High touristic activity during the summer period.
- The current solution of electricity production is diesel-based with a capacity of 1.15 MW.
- The total demand of Anafi is approximately 1500 MWh_e/year.

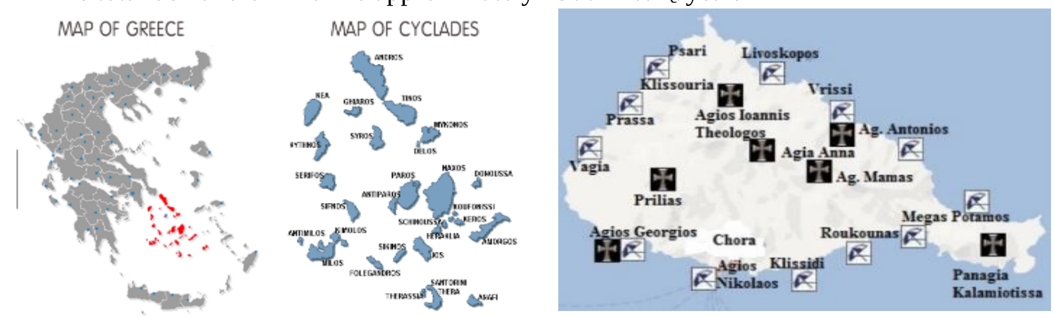


Figure 3: Map of Anafi Island

  - For the island of Anafi the selected solution is a PV Park since the island has very low energy needs during the winter and the "heavy" loads are noted in the summer period.
  - For this specific installation, a BIOSOL monocrystalline PV module of 265W panel has been selected.
  - For the first approximation of the nominal power of the PV park the following equation is being used:

$$Po = \frac{E}{CF * \Delta t * ESS_{efficiency}}$$

Where CF is assumed to be 20% for the first approach and $ESS_{efficiency}$ = 65% which suggests a rather low value

In any case, the percentages of CF and ESS efficiency are estimations chosen in order to have a first sizing of the park.

To that end, energy balance (storage) analysis results together with the resulting diesel fuel consumption are given in Figure 4, for cases 1 and 2 respectively:

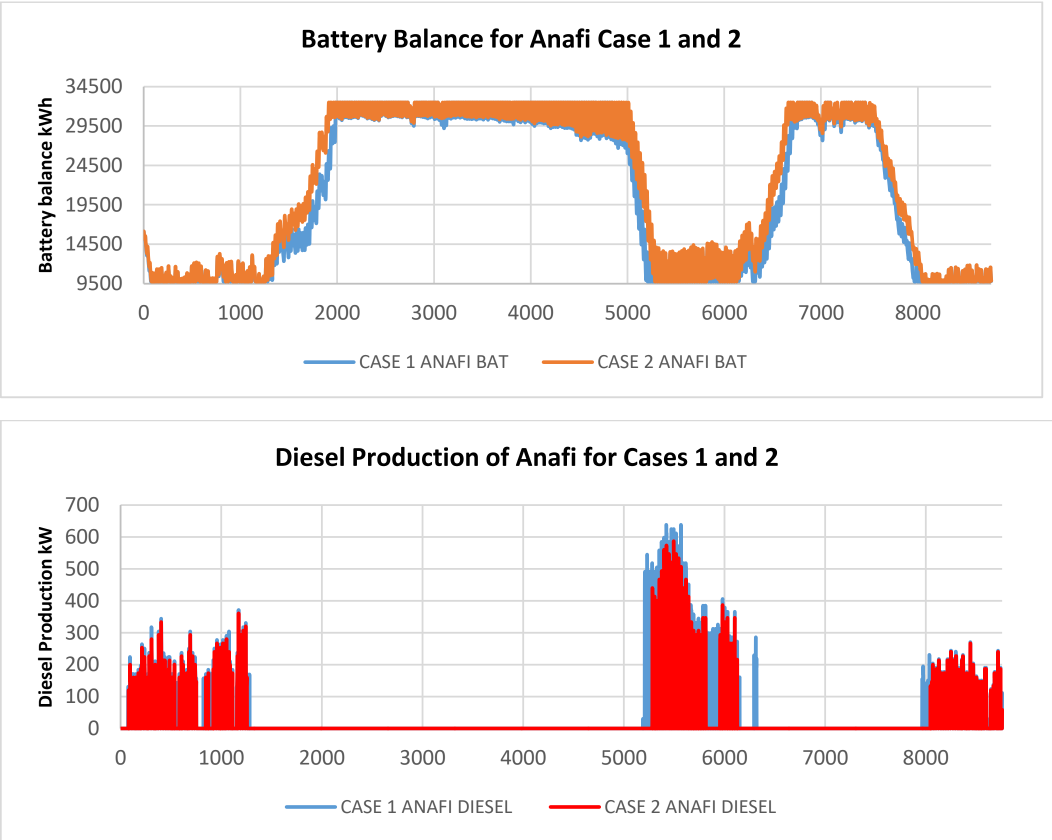


Figure 4: Storage balance and diesel usage for Anafi island, Cases 1 and 2

The batteries that will be used to cover the park will be 6V / 415Ah with DOD at 70% and will be connected in series in order to create each park's corresponding voltage.

For Anafi Island the battery capacity is Q(bat) = 656.25kAh

Cases 1 and 2 for Anafi present 85% and 87% of RES autonomy respectively, while in case 2, the water bought in order to cover the island's water needs is 6500m^3. Some points worth mentioning are the following:

- During the winter period the storage balance remains relatively low since the solar radiation is also low so most of the production of the PV park feeds the demand directly and only a small portion of that can be stored (Figure 4).
- In contrast, for the spring period, because the radiation is much higher than that of the winter season and the demand remains the same, the energy storage system increases its state of charge close to the maximum for the biggest part of the period.
- Lastly, during the summer months the PV park "struggles" to keep up with the demand because it is the touristic period and the demand is much higher than the rest of the year.

For cases 1b and 2b, the results are also being demonstrated below:

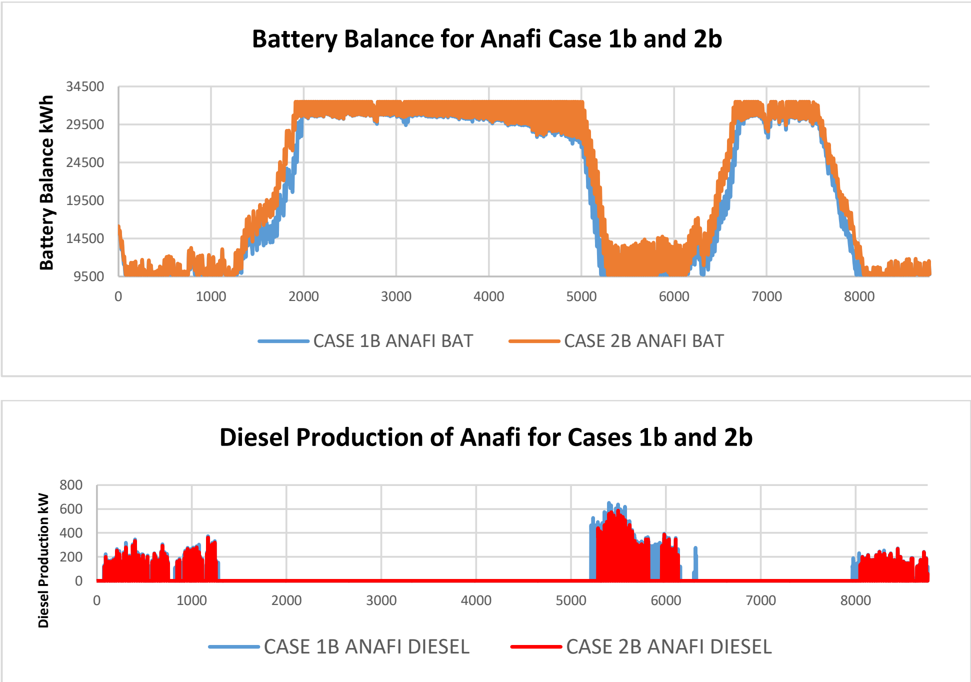


Figure 5: Storage balance and diesel usage for Anafi Island, Cases 1b and 2b

In cases 1b and 2b presented in Figure 5, the profiles are similar to the ones demonstrated in case 1 and 2. The RES autonomy of these cases is 85.2% for case 1b and 87.1% for case 2b.

Considering the water tank balance of cases 2 and 2b there is a graph below that depicts the results on an hourly basis throughout the year.

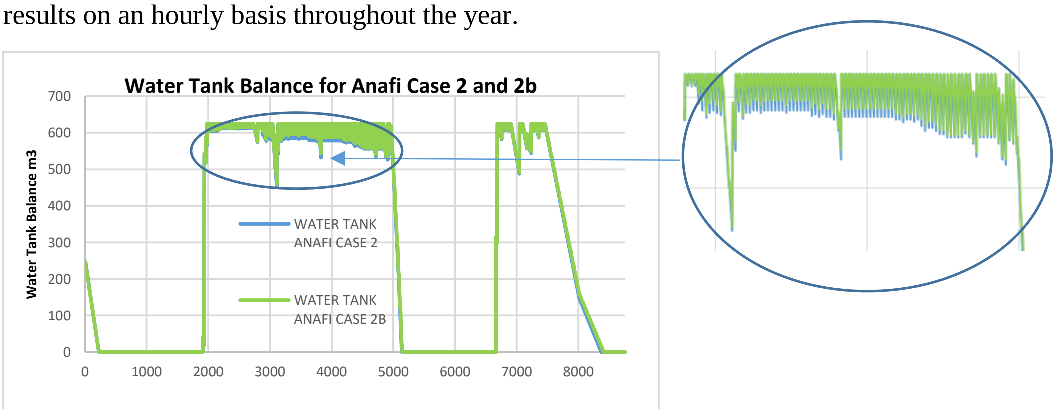


Figure 6: Water tank balance Cases 2 and 2b

The water tank of Figure 6 follows a similar variation profile as the battery storage system. This means that the water tank cannot cover the summer load because the energy demand is so high that there is almost zero excess energy to feed the desalination unit. The total water bought in this case is 6314.4m^3/year.

Economic Scenarios

Cases	PV (MW_p)	DIESEL (MW_p)	ICo M€	Oil Usage (m^3)	Total Cost no Tax M€
1	1.4	1,15	1309840	1544.94	3.24
2	1.4	1,15	1353590	1159.08	3.39
3	0	1,15	100000	1031.,68	8.61
4	0	1,15	0	9610.09	8.64
1b	1.4	1.15	1309840	1501.66	3.20
2b	1.4	1.15	1353590	1159.08	3.38

Table 1: Economic evaluation of Anafi cases

The economic results presented in Table 1 have taken into consideration the following parameters:

a) Each year the energy demand increases by 2% since the trend of increasing energy demand is a common phenomenon in modern societies.
b) The costs of buying water are 2 € / m^3 in the cases 2-2b and 3 which is a low special price and has been selected in order to examine if the lower water costs result in less expenses than case 1
c) The diesel engines are being replaced after 20.000 hours of usage. The capacity factor equation is being used in order to calculate the hours of diesel operation for each year.

$$E = Po * CF * \Delta t => CF = \frac{E}{Po * \Delta t}$$

For example in the 1st year of operation for Anafi, the island's diesel installed power Po is 1.15MW_p, and the energy produced is E=185.5 MWh_e so the CF is 1.84% and the diesel operation hours are 0.018 x 8760=161h.

From the above tables someone can identify that the lowest cost solution is Case 1b. The main reason is that the system is directly treating water demand as an electric load (the desalination plant) which leads to lower energy losses from the storage system. In addition, fluctuating water has better behavior than constant water demand since at nighttime the demand in the fluctuating case is much lower than the one of the constant value. This means that the water demand needed to be covered in the constant demand scenario does not add to the electricity load during the hours that the PV park production is zero.

Taking into consideration the different cases and making economic evaluations about each one of them the conclusion is that case 1b presents the best results, next followed by case 2b. The sensitivity analysis is based on the economic results of case 1b for different values of PV park capacity.

The following figure takes into consideration the cost parameters of each of the cases mentioned above, and a sensitivity analysis of cost vs RES autonomy of the islands in order to conclude on the most beneficial solution regarding the nominal capacity of the PV park.

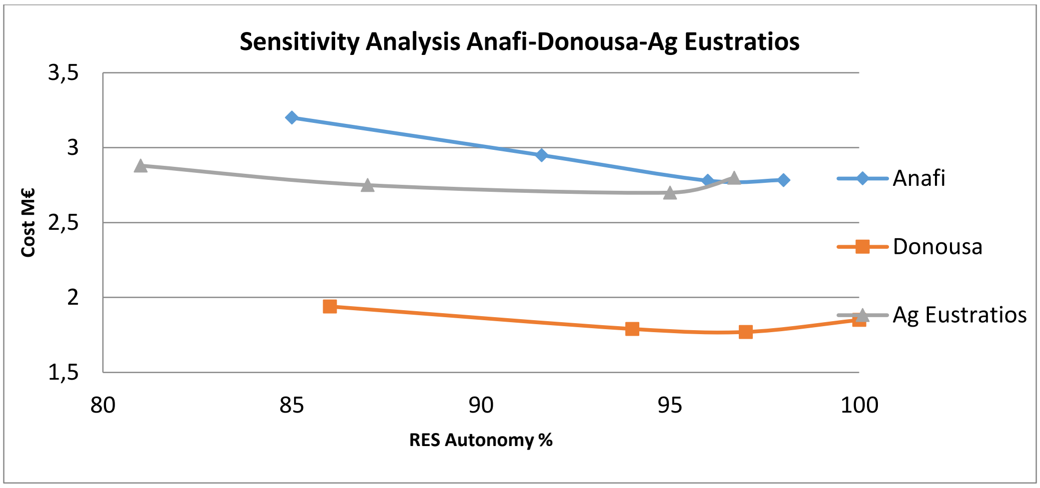
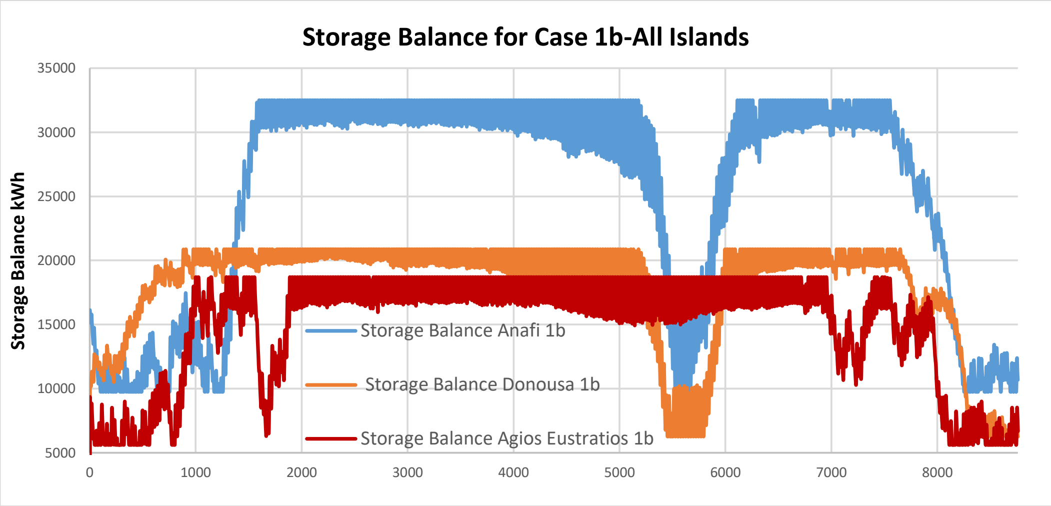


Figure 7: Cost vs RES Autonomy of Anafi, Donousa and Agios Eustratios

- Similar to Anafi island, Donousa and Agios Eustratios present an improvement in the RES autonomy on Figure 7 with the increase of the nominal power of the PV park without any economic "burdens".
- More specifically, for Anafi the optimum economic point appears for 96% autonomy with a cost of 2.78 M€ which results to 1.8MW$_p$ of PV park power, offering 96% autonomy for the island.
- For Agios Eustratios island, the optimum point is at 95% RES autonomy with a cost of 2.7M€ and a 1.8MW$_p$ of PV park power, with an expected autonomy of 95%.
- For Donousa island, the trend of cost reduction stops after 1.2MW$_p$ which yields 97% RES autonomy, while for 100% energy autonomy the cost is increased compared with the 1.2MW$_p$ solution.
- The gradual increase in the PV parks peak power in all islands examined seems to lead to a positive outcome since the cost is reduced and the RES-based energy autonomy of the local remote communities is increased.
- However, the optimum point of each proposed configuration is based on the price comparison between the oil-based and the PV-based solutions.
- The diesel expenses for electricity production are more than the initial and maintenance cost of a larger PV park before the optimum point. After that point the costs of diesel produced electricity has less expenses than adding more PV units to cover the demand.

The following diagrams (Figure 8) represent the results of the proposed solutions that have been analyzed during the sensitivity analysis for each island. These concern cases 1b and 2b with the corresponding battery balance and diesel usage throughout the year. For cases 2b there is also a presentation of the water tank and the water needed for annual operation.



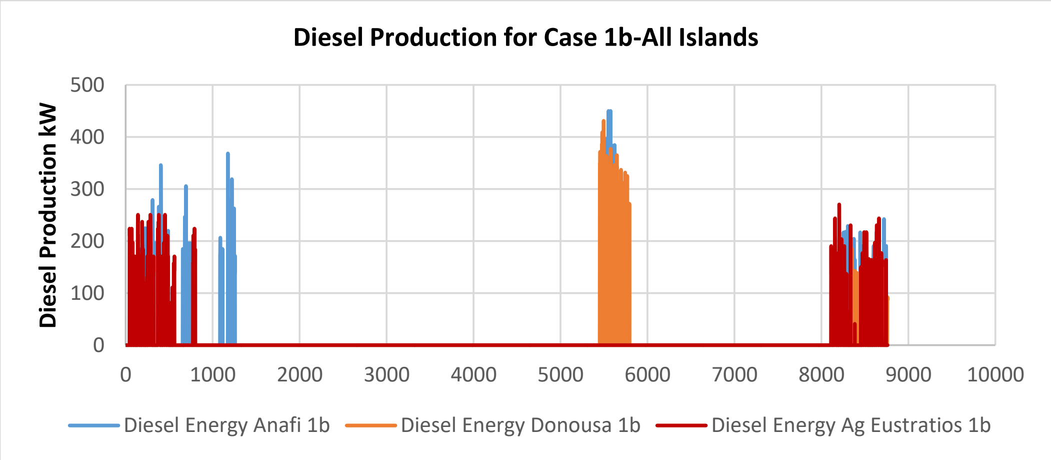


Figure 8: Storage balance and diesel usage for all islands – Analysis of case 1b

After the completion of the sensitivity analysis, the proposed configurations are described in the following bullets:

Anafi Island:

- A PV Park with nominal power of 1.8MW$_p$ is proposed that will cooperate with the current diesel system of the island in order to cover the total water and energy demands.
- This solution leads to 96% of energy autonomy and a reduced cost (2.78M€) compared with the first approach which costs 3.2M€ for a 85% RES autonomy.
- An energy storage system consisting of lead acid batteries and a total capacity of 650 kAh that will be able to cover two (2) consecutive typical summer days is required also.
- Land usage of 18000m^2.
- Oil usage of 19.7tn/year or almost 400tn for the entire 20 years of operation.
- Desalination Unit of 125m /day or 5.2m^3/h

Donousa Island:

- A PV Park with nominal power of $1.2MW_p$ is proposed that will also be supported by the diesel unit of the island since the autonomy obtained is slightly less than 100% as well as for energy security reasons.
- This solution estimates an expected energy autonomy of 97% and will cost 1.77M€ for a life time of 20 years.
- An energy storage system of lead-acid batteries with a capacity of 435kAh able also to cover the island's needs for two consecutive days during the summer period is also necessary.
- Land usage of $12000m^2$
- Oil usage of 8.5tn/year or 170tn for the entire 20 years of operation.
- Desalination unit of $65m^3$/day or $2.7m^3$/h.

Agios Eustratios Island:

- A PV Park with peak power of $1.8MW_p$ is proposed, taking into consideration the necessity of support by the existing diesel generator along with an appropriate energy storage system.
- This solution will provide 95% RES autonomy at the cost of 2.7M€ for 20 years of operation and the diesel usage is expected to be 20.5tn/year or almost 410tn for the entire 20 years of operation.
- An energy storage system (lead-acid batteries) with 390kAh capacity designed to cover the island's needs for two (2) consecutive typical summer days of demand.
- Land usage of 17400 m^2
- Desalination Unit of $125m^3$/day or $5.2m^3$/h

The battery balance and the diesel usage of the proposed solution mentioned earlier are being demonstrated in Figure 9 for both cases 1b and 2b.The graphs for cases 1b of Anafi and Donousa islands are presenting a similar fluctuation which is justified by the presence of heavy loads during the summer and winter period. In these situations the battery balance reaches its minimum capacity (DOD_{max}) and the diesel unit is taking over the electricity production loads in order to cover the island needs.

In the spring and fall periods of the year, the behavior of the battery balance is the same like with the $1.4MW_p$ park that was examined for Anafi and the $900kW_p$ park for Donousa. The increase in the nominal power of the PV configuration has a better behavior in the load coverage during the summer period.

On the other hand, for Agios Eustratios case 1b, the summer load was not a real problem because the island does not experience high touristic activity like Anafi and Donousa due to its remote location. For this island, the increase of the PV configuration nominal power results in the better handling of the winter loads, while for the rest of seasons the load demand is almost completely covered by the PV park.

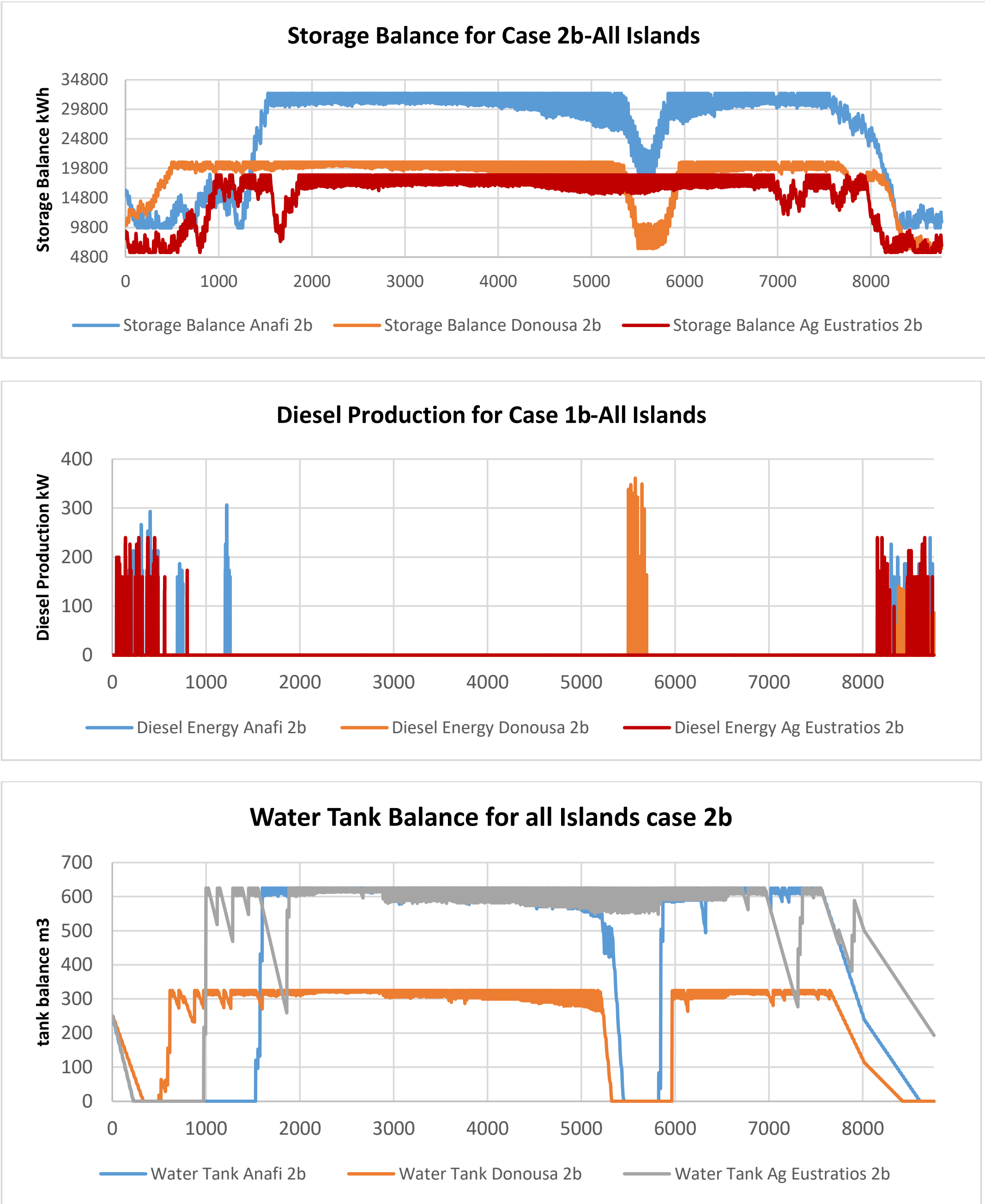


Figure 9: Results for case 2b for all islands

Advantages:

The most critical advantage of the renewable energy solution (on top of the optimum environmental improvement) for the islands examined is the financial performance. For a better understanding there will be a comparison of the costs between the current situation and the renewable based one for each island.

For Anafi, the current diesel costs for producing energy and buying drinkable water are estimated to be 8.64M€ for a 20-year period, while the proposed PV-based one costs only 2.78M€ for the same time period. Donousa's operation provides a total cost for a 20-year lifetime on the basis of the diesel unit equal to 5.37M€ whereas the RES-based proposal cost is expected to be only 1.77M€ for the entire lifetime of the system. Finally, Agios Eustratios's energy production cost for the 20-year period analyzed is 7.2M€ while the corresponding 1.8MW_p PV-park based one will cost only 2.7M€. Summarizing, the total cost of the PV-based solutions for all very small islands examined is almost one third of the expected cost of the current situation for a twenty years operation period and if assuming constant the oil prices in the future.

Apart from the economic factor, which is a very important aspect, there are also advantages concerning the environmental aspect for each island. A renewable proposal will dramatically reduce the diesel oil consumption of the electricity generators because its usage will be minimized. More specifically Anafi's 20 year oil consumption is expected to be 7700 tn while with the proposed solution it will be reduced to only 880 tn for 20 years. For Donousa and Agios Eustratios the current solution will use 4700 tn and 6270 tn for a 20 years operation respectively. The proposed renewable-based solutions will reduce it at 170tn for Donousa and 410 tn for Agios Eustratios, which is a remarkable difference with economic benefits as well. In the environmental spectrum, it is also worth mentioning that since Donousa has protected Natura areas, the addition of renewable energy sources on the island will also benefit this aspect of wildlife.

Finally, another important advantage is the installation of desalination plants for the islands. These units will provide water security for the islands because the current state of buying water that is transported in water tanks with shipment is not very safe. To that end, water deficit can easily occur during adverse weather conditions, when shipments are forbidden.

Disadvantages:

The disadvantages of this proposal are mainly based on the fact that it is a new investment that requires a certain initial capital that may be unattractive for an investor. However, if subsidized by the state or organizations that provide capital support for this type of projects, it can be a very attractive investment on a life cycle analysis.

Another factor to be faced is the land usage. As mentioned above, the PV park for each island requires a certain amount of land usage which may be a problem and create negative feedback from the local community.

3. Conclusions

An integrated energy and water demand coverage solution for very small scale islands has been developed in order to cover the corresponding needs on the basis of RES, and more specifically through the exploitation of the excellent solar potential met across the Aegean Archipelagos. According to the results obtained for selected representative remote islands of very small scale, the proposed solution presents minimum environmental impacts, almost zero diesel oil contribution and rational first investment cost. Actually, and on a life cycle basis, the proposed PV-based configuration proves to be much more cost-efficient than using diesel oil and importing clean water. Finally, it is important to mention that the developed solution may equally well be applied in several other small islands, all around the Mediterranean Sea.

4. References

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