Evaluation of a Hybrid Renewable Energy System (HRES) in Patmos Island

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Abstract: - The lack of fresh water and energy in remote areas is the starting point for the implementation of Hybrid Renewable Energy Systems (HRESs). HRESs find a wide application, especially in Aegean islands, where there is a rich wind potential. Also, the use of hydroelectric power generate electricity for energy demands of the island and for the desalination of seawater, in order to cover drinking and irrigation demands. In this research work, the proposed HRES in Patmos includes six wind turbines, two desalination plants, a hydroelectric station, a pumping station and a reservoir in high altitude. Two scenarios have been formed for the distribution of energy generated by wind turbines, a percentage of which is integrated directly into the power grid, while the remaining wind energy is used in the pumping and the desalination stations. The simulation model operates with hourly data for the period 2007-2017. Additionally, the optimum distribution of the produced wind energy is investigated. This study presents the results of the HRES simulation about covering water and electricity demands of Patmos island.

Key-Words: HRES, Wind power, Electricity, Water management, Desalination, Patmos, Island

1. Introduction

In most Greek islands, the energy needs of both the residents and tourists are covered mostly by autonomous power stations [1], which produce energy by consuming fossil fuels or the submarine connection to the mainland's national network of Public Power Corporation (PPC). This way, they suffer by the consequences of energy dependency on remoted areas. The reclamation of their rich potential of Renewable Energy Sources (RES) is the key to achieve their energy independency. Due to stochastic nature of wind, the best way to achieve this, is the implementation of energy storage [2].

Hydroelectric energy is produced by the conversion of the potential energy of the water of the lakes and kinetic energy of the water of rivers into electricity. In the case of a reservoir, large amounts of water volume are stored. The potential energy of the water is converted into kinetic and finally into electricity through the impulse turbine.

In this context, HRESs can provide solutions to the supply of remote areas with electricity and fresh water through desalination. The research results of HRES in the Greek islands have shown that these systems have a dominant role in the energy balance of the islands [3,4].

The recent research of the desalination industry has focused on reducing the cost of the produced desalinated water, by combining desalination plants with RES [5]. Reverse osmosis (RO) is the most applicable out of all the desalination processes [6]. The reason for this lies on its low energy consumption, the suitability for connection to solar systems and wind turbines and the production of higher quantities of desalinated water, when compared to other desalination processes. According to studies, energy consumption of RO desalination process ranges from 2,5 kWh/m^3 to 7 kWh/m^3 [7]. In this research work, the proposed HRES in Patmos island includes six wind turbines, two desalination plants, a hydroelectric station, a pumping station and a reservoir in high altitude. The results of the simulation lead to conclusions about the reliability of the system to cover water and electricity demands in Patmos island.

2. Problem Formulation

2.1. General description of the study area

The island of Patmos is an island of the eastern Aegean. It is one of the most northern islands of the Dodecanese complex. It has a population of 3.047 people, number that reaches 13.000 during the summer months and an area of 34,05 km^2. The highest point is Profitis Ilias, 270 m above the sea level. The municipality of Patmos includes the offshore islands of Arkoi, Marathos and several uninhabited islets. Patmos' main communities are Chora, the capital city, and Skala, the only commercial port. Other settlements are Grikou and Kampos. According to the database for the Greek Nature FILOTIS [8] the entire island is included on Landscapes of Outstanding Natural Beauty.

The climate in Patmos island, due to its geographical position and the influence of the sea, is described as Mediterranean of maritime character, with mild winters and long warm and dry summers, low annual rainfall and plenty of sunshine throughout the year. The average annual temperature is 18,3°C. The monthly average minimum is 2,6°C (January), and the mean monthly maximum 38,1°C (July). The prevailing winds are mainly westerly and northerly by tensions over 6 B. Also, wind data are collected from the local weather station [9] and after that this data are analyzed and processed.

2.2. Electricity, water and irrigation needs in Patmos

The island of Patmos is facing a chronic shortage of water resources. Previously, the only source of water was underground aquifers. Since 1996, shipping water has begun to float in an ever-increasing amount of an unsustainable and economically unprofitable solution. Small quantities are covered by the use of rinsing tanks. Irrigation needs are covered mainly by private wells and secondarily by the water supply network. In 2005 Livadi dam was completed with a useful capacity of 443.000 m^3 [10], which was expected to cover a large part of the irrigation needs. However small quantities of water were gathered. At the beginning of June 2017, two desalination units with a capacity of 1.200 m^3/day of drinking water were completed and delivered in operation. Their cost is 900.000 €, while an annual average of 1,2 million € is spent on the transport of water. The monthly variation of water and irrigation needs is shown in Figure 1.

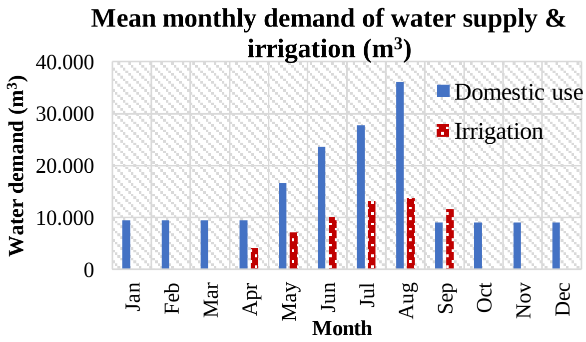


Fig. 1. Mean monthly demand of water supply (m^3)

The island of Patmos has a diesel-powered local power station located in the settlement of Skala. It also has 2 wind turbines of 1.200 kW total, at the northern end of the island at an altitude of 90 m and a 500 kW photovoltaic park. According to PPC data the maximum installed capacity is 4.380 kW [11], the maximum demand reaches 3.580 kW and annual energy demand reaches 11.348 MWh. The monthly fluctuation of electricity needs is shown in Figure 2.

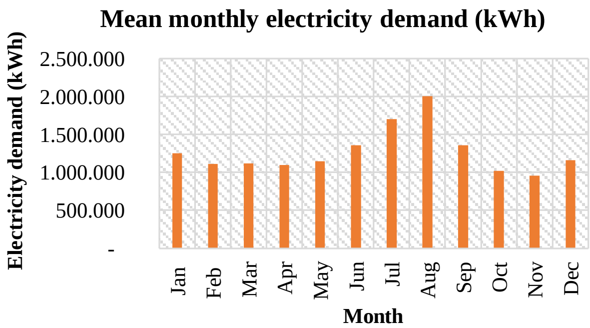


Fig. 2. Mean monthly electricity demand (kWh)

3. Problem Solution

3.1. Methodology

The study of the HRES in the island of Patmos, in order to cover energy and water demands, is particularly important as it can provide solutions to acute problems, like the water scarcity and the instability of local power grids. The system consists of one water reservoir of salt water at an altitude of 90 meters, six wind turbines of 900 kW each, a desalination unit of 1.200 m^3/day, a pumping station of 1.200 kW (800 kW + 400 kW) in order to pump salt water to the upper reservoir. In the case of not satisfied electricity demands, the water of the upper reservoir will supply a hydroelectric station of 1.200 kW, which cover the needs of the local power grid. If the demand for electricity cannot be covered by the produced wind and hydroelectric energy, the deficit is covered by extra energy from the local PPC station.

The concept of this study is to investigate two different connection scenarios between the parts of the hybrid system and the two different desalination plants, in order to control the response of the hybrid system and the reliability of the required demand of electricity, water supply and irrigation. For the simulation of the HRES, hourly data for wind, electricity, water and irrigation demands of the period 2007-2017 are used.

In all scenarios the wind turbines electrify the settlement, providing a percentage of the energy directly to the power grid, while the remaining percentage of the generated wind power (excess energy) is available for desalination and pumping. Additionally, the optimum distribution of the produced wind energy is investigated, which means the percentage of the produced wind energy that is sent directly in the local power network and the percentage that is used for pumping and desalination. Also, the PPC has a steady production of 20% (880 kW) of the maximum installed capacity.

The first scenario is solely tested to meet the demand for electricity needs in the island and all the energy is consumed directly only for the island's energy demands. The second scenario is tested to meet the island's energy and water demands (drinking water and irrigation).

3.2. Scenario 1

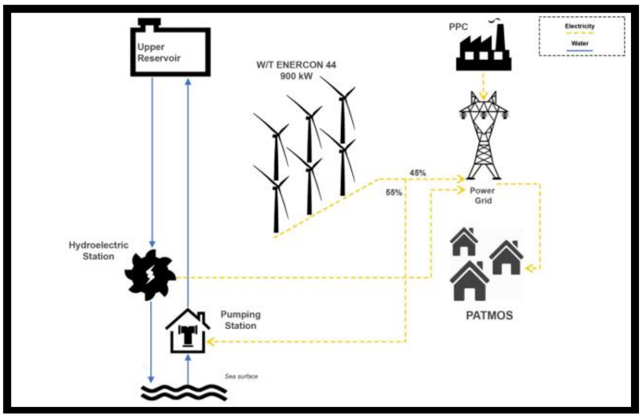


Fig. 3. Schematic representation of the HRES for Scenario 1

The first scenario is considered to cover only energy needs and its schematic representation is shown in Figure 3. There is a contribution of three energy sources – wind turbines, hydropower and energy from the network. The 45% of the produced wind energy is provided directly to the power grid and the remaining 55% supplies the pump station. Figure 4 shows the change of water volume of the upper reservoir for year 2017.

The water volume variation diagram of the upper reservoir shows that in summer months there is water shortage and the reservoir is empty most of the days. Water saving is observed from the end of September to mid-March with the largest volume of 875.000 m^3 recorded in mid-February. Figure 5 shows the participation of each part of the system for 14th and 15th of April, in order to understand the contribution of the HRES to the energy balance of the island of Patmos.

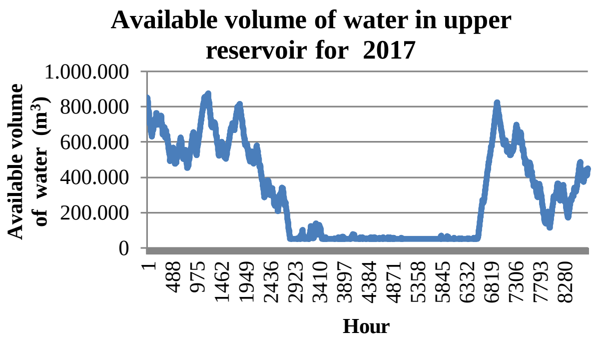


Fig. 4. Available volume of water in upper reservoir for 2017

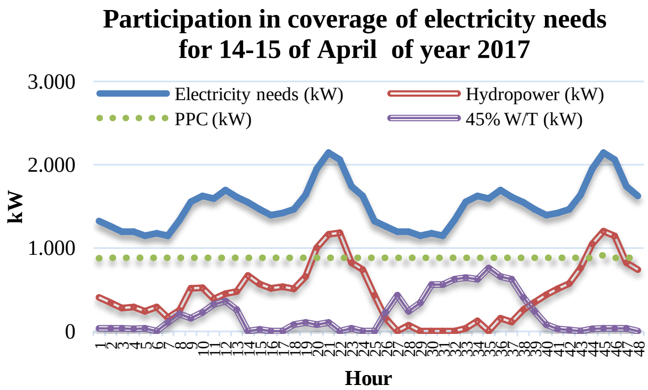
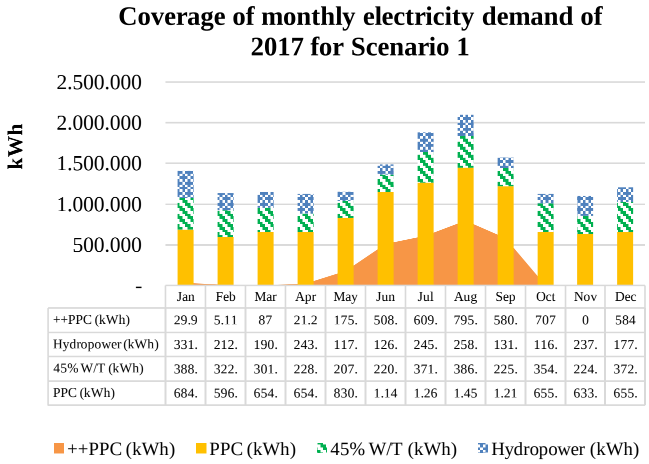


Fig. 5. Participation in coverage of electricity needs for 14-15 of April of year 2017

It is evident from Figure 5, that when the stable production by PPC and the 45% of wind production are not sufficient to cover the electrical needs, then the hydro power is exploited. Also, as shown in Figure 5, the reservoir level is reduced in the spring months, depleting the reservoir's seawater reserve. The monthly cumulative diagram of the participation of each energy system in the coverage of electrical needs is presented in Figure 6. The orange area symbolizes the extra energy from the PPC which is needed in order to cover the needs beyond the preset (880 kW). Significant amount of extra energy from the local station is required to meet the increased needs for the tourist season May-September. The maximum needs are in August, where an additional 795.331 kWh is required, while in November no additional energy is required.



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
++PPC (kWh)	29.9	5.11	87	21.2	175.	508.	609.	795.	580.	707	0	584
Hydropower (kWh)	331.	212.	190.	243.	117.	126.	245.	258.	131.	116.	237.	177.
45% W/T (kWh)	388.	322.	301.	228.	207.	220.	371.	386.	225.	354.	224.	372.
PPC (kWh)	684.	596.	654.	654.	830.	1.14	1.26	1.45	1.21	655.	633.	655.

Fig. 6. Coverage of monthly electricity demand of the year 2017 for Scenario 1

Finally, Figure 7 indicates the annual reliability of the HRES for the period 2007-2017. The reliability of the system is defined as the percentage of the hours of the year in which the electrical needs are covered by the stable production of PPC, the 45% of wind production and the energy of the hydroturbine. The highest reliability is observed for the year 2008 (85,54%), the lowest for the year 2014 (45,68%) while the average is formed at 67,98%.

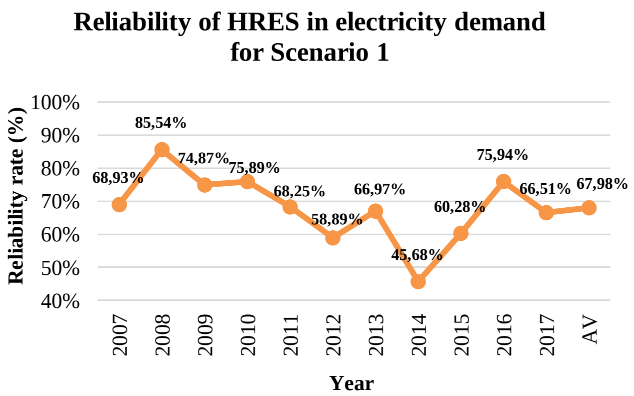


Fig. 7. Reliability of HRES in electricity demand for Scenario 1

3.3. Scenario 2

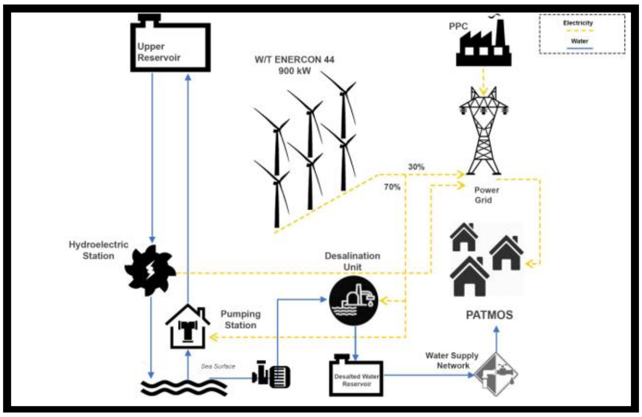


Fig. 8. Schematic representation of the HRES for scenario 2

Scenario 2 is considered to meet the demand for electricity and desalinated water for drinking and irrigation. Figure 8 shows the schematic representation of Scenario 2. The percentage of 30% of wind power is provided to the power grid directly, while the remaining 70% is shared between the desalination unit and the pumping station.

3.3.1. Energy Analysis of Scenario 2

The distribution of produced wind energy among the pumped station and the desalination station is shown in Figures 9 and 10 on monthly and yearly basis respectively.

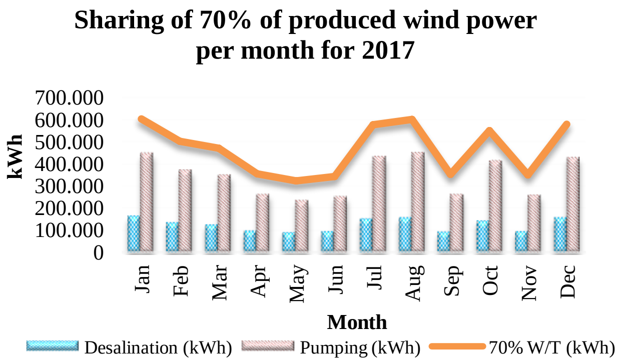


Fig. 9. Sharing of 70% of produced wind power per month for 2017

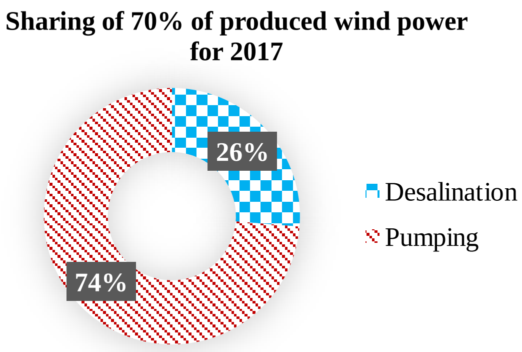


Fig. 10. Sharing of 70% of produced wind power for 2017

In Figure 9 it is evident that the energy for the desalination is proportional to wind production. Also, the months with greater production seem to be January, July and August. Figure 10 shows the percentage distribution of 70% of wind energy that is formed as follows: 26% is absorbed by the desalination station and 74% by the pump station. Figure 11 shows the coverage of electricity needs for 14-15 of April in year 2017 on an hourly basis.

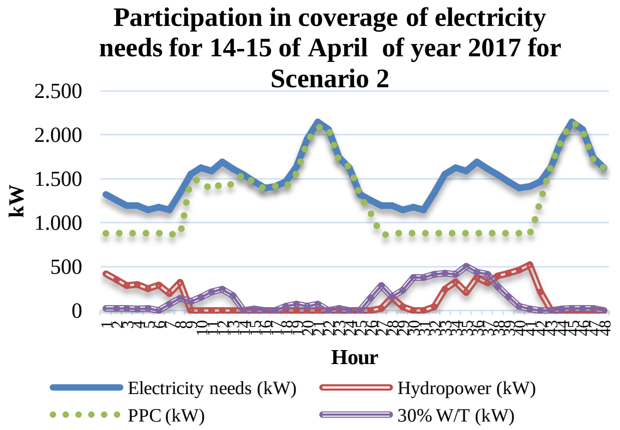
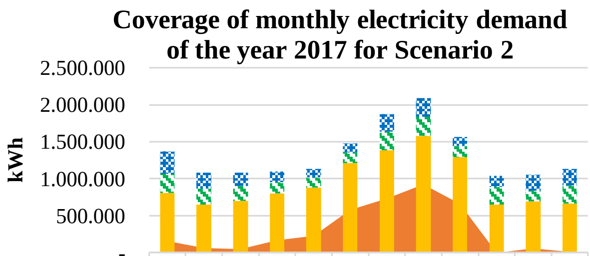


Fig. 11. Participation in coverage of electricity needs for 14-15 of April of year 2017 for Scenario 2

It is evident that the reduced wind power, which is available directly to the network, combined with the depletion of seawater reserves in the upper reservoir and the operation of the desalination plant, increase significantly the additional necessary energy that is required to meet the needs by PPC. This means that the peaks of electric demand are not covered by the turbine energy, as in the case of Scenario 1.

The operation of the desalination plant makes Scenario 2 more intensive than Scenario 1. Figure 12 presents the diagram of monthly needs and shows that the additional energy required to meet the needs is increased compared to Scenario 1, since the maximum value for August is increased to 926.615 kWh and for November to 60.187 kWh.



	Jan	Feb	Mar	Apr	Ma y	Jun	Jul	Aug	Sep	Oct	Nov	Dec
++PPC (kWh)	160.	65.1	51.0	170.	230.	581.	734.	926.	661.	901	60.1	12.8
Hydropower (kWh)	303.	213.	179.	142.	113.	120.	243.	256.	126.	151.	215.	220.
30% W/T (kWh)	258.	214.	201.	152.	138.	146.	247.	257.	150.	236.	149.	248.
PPC (kWh)	814.	656.	705.	803.	885.	1.21	1.38	1.58	1.29	655.	693.	667.

Fig. 12. Coverage of monthly electricity demand of the year 2017 for Scenario 2

In Figure 13 the reliability curve for the coverage of electrical needs has a drop of 10 percentage points and the average is formed to 56,34% versus 67,98% of Scenario 1 for the period 2007-2017.

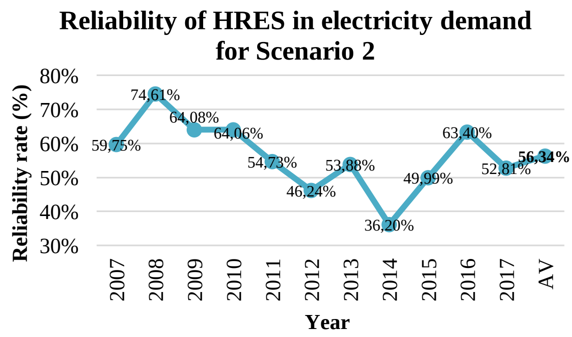


Fig. 13. Reliability of HRES in electricity demand for Scenario 2

3.3.2. Analysis of Scenario 2 about coverage of water supply & irrigation needs

The existing dam with capacity of 443.000 m^3 is used as a reservoir of desalinated water and the variance of the water volume in the reservoir for year 2017 is shown in Figure 14.

The desalination station supplies the reservoir which distribute the desalinated water to the water supply and irrigation network. There is priority in the fulfillment of the water needs against irrigation needs.

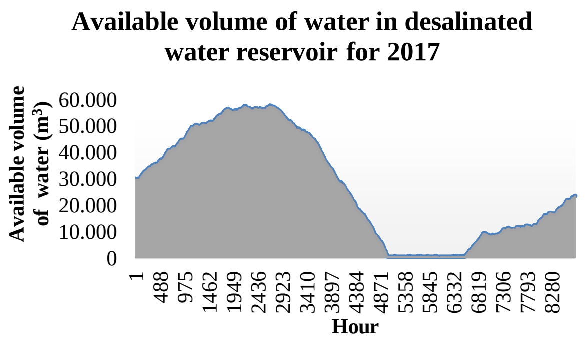


Fig. 14. Available volume of water in desalinated water reservoir for 2017

The periods of water storage and depletion are shown in Figure 14. More specifically, a surplus of desalinated water is observed during the winter and autumn months, while there is a decrease in the level until the reservoir is emptied during the summer months (tourist season).

The operation of the desalination station in Scenario 2 is based on the available energy. In this way the surplus desalinated water is stored during the winter months in the reservoir and is used during the tourist season, when the needs are increased.

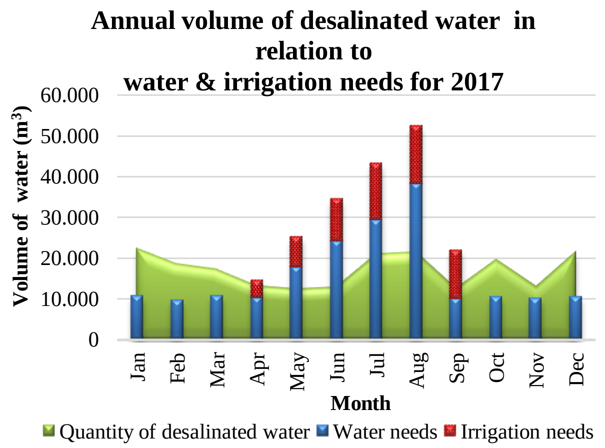


Fig. 15. Annual volume of desalinated water in relation to Water & Irrigation needs for 2017

Figure 15 presents water needs in relation to the volume of desalinated water. It is evident that during the winter months the volume of water goes far beyond the water supply needs, instead of the tourist season from April to September when the needs exceed by far the desalinated volumes of water.

Figure 16 shows the unsatisfied water and irrigation needs per month. As presented in Figure 14 the stocks of desalinated water are depleted during the summer months leaving unmet needs of water and irrigation. For example, in August there are not covered 13.930 m^3 for water supply and 6.751 m^3 for irrigation.

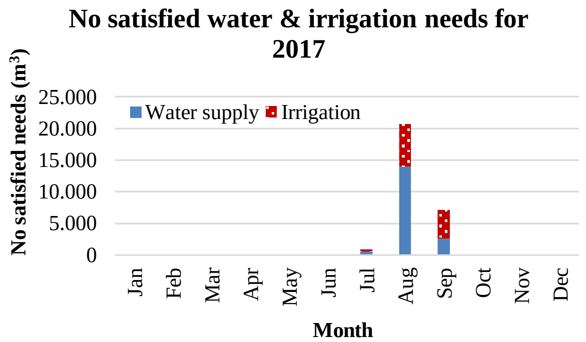


Fig. 16. No satisfied water & irrigation needs for 2017

Finally, Figure 17 shows the reliability in covering the water and irrigation needs for the period 2007-2017. Reliability is defined as the percentage of hourly needs of the year when water and irrigation needs are covered by the reservoir of desalinated water. The average for water supply needs is formed at 92,46% and for irrigation needs at 76,02%.

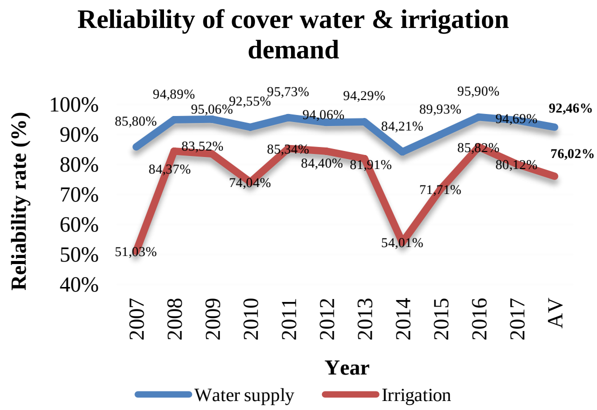


Fig. 17. Reliability of cover water supply & irrigation demand

3.4. Optimum distribution of produced wind energy

At this point there is an analysis of the optimum rate of direct distribution of wind power in the network in relation to electrical reliability. That means the percentage of the produced wind energy that is sent directly in the local power network and the percentage that is used for pumping and desalination, in order to succeed the maximum reliability. Figures 18, 19 show the reliability for the different pairs of percentages for Scenarios 1 and 2. Also, Figure 20 shows the reliability of the water supply needs and irrigation for about pairs for Scenario 2.

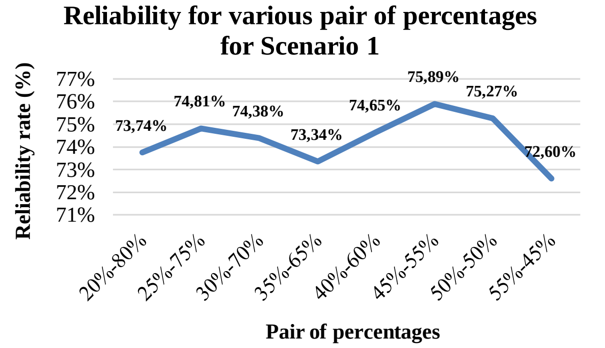


Fig. 18. Reliability for various pair of percentages for Scenario 1

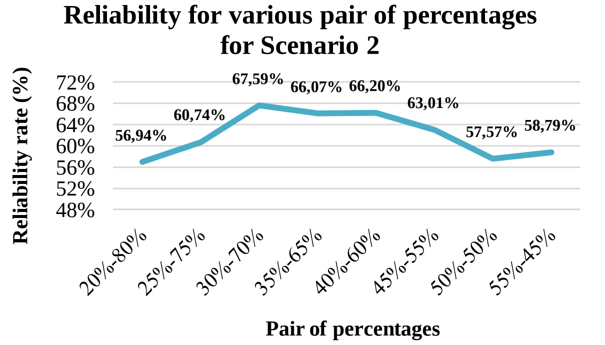


Fig. 19. Reliability for various pair of percentages for Scenario 2

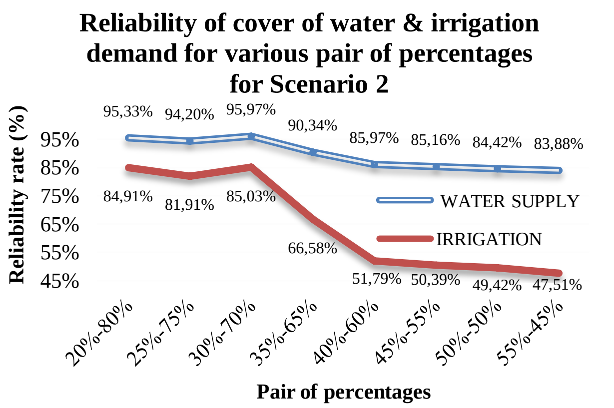


Fig. 20. Reliability of cover of water & irrigation demand for various pair of percentages for Scenario 2

In Scenario 1, the rate 45%-55% of energy distribution results in the maximum reliability in covering the electricity demands. That means that 45% of the produced wind energy that is sent directly in the local power network and 55% is used for pumping and desalination. In Scenario 2 the best results for electricity, water and irrigation demands is given by the rate 30%-70% of energy distribution.

4 Conclusion

In this research work, a proposed HRES in Patmos island is implemented in order to cover electricity, water and irrigation demands. Data on population fluctuation, water supply and electrical needs are collected. In addition, wind data are collected from local weather station NOAN and after that are analyzed and processed. Two different scenarios are formulated for the best investigation and performance of the proposed HRES on the island of Patmos.

Scenario 1 is considered to cover electricity needs of the island by storing a percentage of produced wind energy with the method of pumped storage. Scenario 2 is considered to cover electricity needs and water needs for domestic use and irrigation. The rich wind potential of Patmos gives great energy autonomy during the winter months, but it cannot meet the increased needs of the tourist season.

It is found that Scenario 1 provides larger energy autonomy compared to Scenario 2, as the percentage of 55% of produced wind energy is only used for pumping water for hydro power, while the rest 45% goes directly to network.

The average reliability of coverage of electricity needs for the period 2007-2017 is formed at 67% for Scenario 1 and is significantly reduced by the addition of the desalination plant for Scenario 2. In Scenario 2, HRES covers successfully 92,46% of water supply needs and 76% of irrigation needs for the study period 2007-2017.

The investigation of the optimum distribution of produced wind energy between grid and pumping and desalination results in a rate of 45%-55% for Scenario 1 and 30%-70% for Scenario 2.

Finally, this methodology is suggested to be applied to other islands and remote areas. Also, further research is proposed in the direction of uncertainty analysis of the system's entry data. In addition, a contemplative generation of time series synthetic data would provide a more realistic approach to the coverage of the needs of the island and would increase the reliability of the results.

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