Dimensioning of Hybrid System with Desalination Units and capability of recovery and utilization of brine for Amorgos Island

Kafasis Konstantinos*, Evangelos Baltas, Maria Margarita Bertsiou

Department of Water Resources and Environmental Engineering, School of Civil Engineering, National Technical University of Athens, 5 Iroon Polytechniou, 157 80 Athens, Greece

*Author to whom correspondence should be addressed

Abstract

Temperatures have been rising constantly and tourism has been growing, making the isolated islands of the Aegean vulnerable to the increasing need for water (PNAI, 2014) and energy (YPEN, 2017). This study focuses on the development of a hybrid system, cooperating with a desalination unit and a pilot brine processing unit, for the arid Aegean Island Amorgos. The hybrid system developed consists of wind turbines and a pump storage unit. The system is set to satisfy the yearly water and energy needs of the island for the next 25 years while reducing the environmental impacts. This will first be achieved by reducing the current usage of conventional fuel through the introduction of RES, and secondly by processing the brine coming from the desalination unit, through the installation of a brine treatment unit. The results were satisfactory, considering that the penetration of the RES units reached over 40% and more than half of the existing conventional units can be removed. The required selling prices of water and energy to make the investment viable, do not exceed the existing ones (Katsoulakos, 2019). With the brine processing unit introduced, the energy demands of the system became exceedingly high, which simultaneously raised the required selling price of water and energy. More specifically, treating more than 20% of the produced brine, the energy needs of the system could not be covered to a satisfactory level. Therefore, this percentage was used to explore this pilot unit's energy needs, the quality of water and brine, and possible economic exploitation of the final product.

Keywords: RES, Desalination, Brine Treatment, Remote Islands

1. Introduction

Amorgos Island, located in the Aegean Sea, is one of the many remote islands in Greece, facing extreme water shortages, especially in the summer due to tourism and heat. The solution provided by the government is transferring water from the mainland by tanker ships, but at a very high cost, reaching almost 10€/m^3 (PNAI, 2014). This approach makes the island's water dependable and increases the overall municipal costs.

In addition, Amorgos depends on autonomous power stations to satisfy its energy needs, which consume conventional fuels, mostly diesel or mazut. The consumption of these conventional fuels, not only from the power stations but from the tankers transferring water, is harmful to the environment, by contributing to the production of ground-level ozone and carbon dioxide.

In particular, on Amorgos, one of the typical arid islands of the Aegean, the lack of water leads to more economic and environmental problems. Water shortages have reduced the primary sector to almost extinction, while the habitats have led to illegal drilling on the island. This leads to the reduction of the level of the underground aquifer, leading to its salinization (YPEN, 2017). Considering the above, it is clear that a new approach is needed to cover the water and energy needs.

The use of Renewable Energy Sources (RES) as part of a hybrid system is very intriguing, as the wind potential of these islands is quite high, and the energy provided by the RES combined with desalination methods is considered to be a more viable and affordable solution (Katsaprakakis, 2015).

The objective of this undergraduate thesis is to develop a model to simulate the operation of such a solution for the island of Amorgos and it will consist of a hybrid system - including wind turbines and a hydropower plant –, and a desalination unit. In a second scenario, a brine processing unit will be added to the model to minimize the environmental impacts, caused by the commonly employed method of discharging the brine back into the sea. The possibility of financial exploitation of the produced brine is also explored.

2. Methods

To resolve the water and energy problem, a system based on renewable energy sources as part of a hybrid system will be combined with a desalination plant, and on a secondary basis, a brine processing unit. The hybrid plant consists of wind turbines, a hydropower plant, and the existing diesel units. The size and number of the wind turbines as well as the size of the

desalination and brine processing unit were decided by the running model, taking into account the energy and water needs of the island. Two tanks of water were required to store the water for the hydropower plant. An additional tank was used to store the water produced for agricultural needs, while the water for urban needs is stored in the existing municipal tanks.

The energy provided by the wind turbines for the energy needs of the island has a penetration coefficient of approximately 30% of the total energy needs. The coefficient exists to protect the system from instability, as in the case of low energy production by the wind turbines, the diesel engines cannot immediately cover the energy needs (Katsaprakakis, 2015). In contrast, the total energy needs of the desalination and brine processing units could be covered by the wind turbines as their operation can be paused for the diesel engines to gradually increase energy production in case of lower energy production by the wind turbines. Therefore, a penetration coefficient, in this case, is not necessary.

The basic concept of the system developed in this study is primarily to produce clean water for urban needs, on a second basis to cover energy needs and on a third basis to produce water for agricultural use. The energy produced by the wind turbines is used to cover the needs of the desalination plant. The remaining energy is then used to cover the urban energy needs with a penetration coefficient of 30% as mentioned above. In the case that there is still an excess of energy, it is used to pump and store water for the use of the hydropower plant. In times of energy deficiency, the hydropower plant release water for the hydro turbine to produce energy that is then used to support the system. If the energy produced by the hydro turbine is not adequate, the desalination and brine processing units will stop their operation for agricultural water needs. The lifetime of the overall system containing the hybrid system and the desalination and brine processing units is considered to be 25 years.

The first stage of the methodology starts with collecting the original data. The original data that must be obtained is:

- Water and energy needs, based on the population for every month of the year.
- Agricultural water needs, which are mostly based on the existing crops and livestock.
- Wind speed series of at least ten years.

- The average monthly temperature and rainfall for the island.

From the above, an estimation of the future water and energy needs for the next 25 years could be done. Moreover, with the obtained historic wind speed series, a synthetic time series of wind speed for the next 25 years could be created (25 series of 1 year each). By using the water and energy needs and the synthetic time series for wind speed, the basic characteristics and sizes of the units were estimated. First of all, as the urban water need is the first needed to be covered, the size of the desalination unit was first calculated. Then, an initial estimation was made for the parameters of the wind turbines and the hydropower plant. The number and size of the units could be changed based on the desirable outcomes.

With the initial unit parameters calculated, the results that were expected are:

- Percentage of urban water reliability.
- Percentage of energy coverage.
- Percentage of agricultural water reliability.
- Percentage of energy penetration for the RES.

Finally, a financial analysis was to determine the viability of the examined scenarios. The analysis consists of 6 indicators:

- N.P.V.-Net Present Value.
- I.R.R.- Internal Rate of Return.
- Payback Period.
- Discounted Payback Period.
- R.O.I.- Return of Investment.
- R.O.E.- Return of Equities.

Depending on the above percentages and the financial viability of each scenario, it was determined if the scenarios are viable and reliable for investment.

A. Estimation of Water and Energy needs.

To estimate the water and energy needs for the following years, the population growth must be determined, as it is the basic factor of the above needs. Considering that the population follows a geometric growth, it was estimated by the equation (Eq.1.):

$$P_i = a \times P_{i-1} \quad (1)$$

Where α=1+γ and $\gamma = \frac{P_i - P_{i-1}}{P_{i-1}}$.

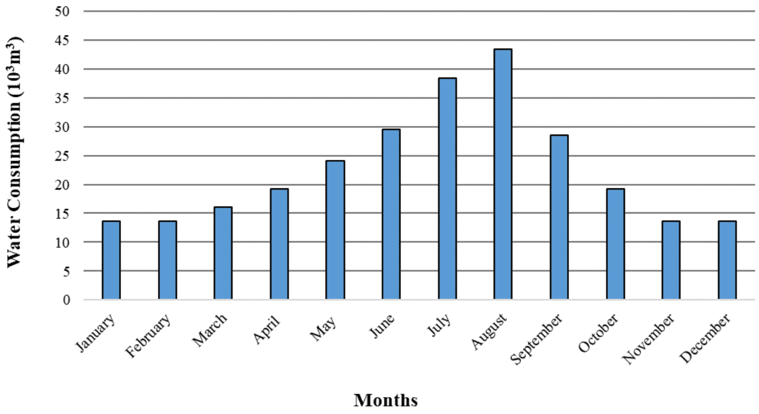
P_i expresses the population during the year i, while γ expresses the variation of the population (Tsakiris, 2008).

Knowing the population for the next 25 years, the water and energy needs were calculated.

The urban water needs were calculated qualitatively as there is no database for monthly consumption on the island. Therefore, the water consumption per monthly period was estimated by gathering data from the transferred water quantities to the island, the quantities from the drillings as well as the water consumption of other Greek Islands (YPEN, 2017).

The numbers are satisfactory so that the average water consumption for each person was estimated at 180 l/day. Therefore, the values for monthly consumption for the maximum water demand, i.e., the last year of the project (25th year), were obtained. The results are presented in Figure 1.

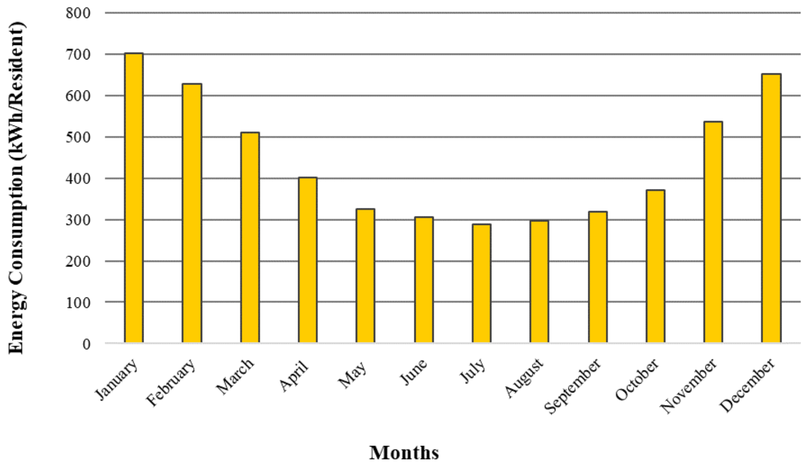
Figure 1: Monthly Water Needs for the 25th year



Source: (Kafasis. K. et al., 2022)

Regarding energy needs, energy consumption for every year has been obtained by the Hellenic Electricity Distribution Network Operator for the years 2012-2019 (HEDNO, 2021). Considering the energy consumption and needs of other Greek islands in the Aegean Sea, an estimation has been made of the daily energy consumption per resident of Amorgos Island for every month. Therefore, by multiplying the estimated energy consumption per resident by the population, the daily energy needs can be obtained. The results are presented in Figure 2.

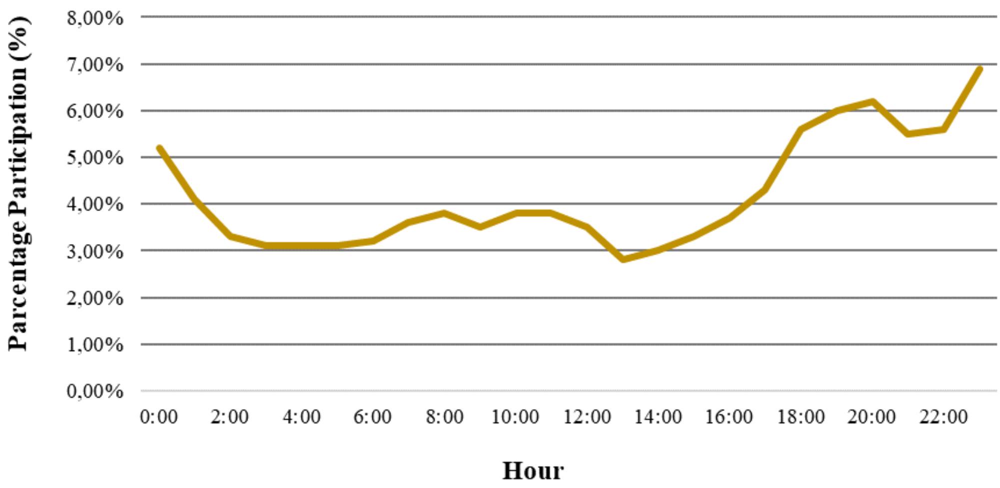
Figure 2: Monthly Energy Needs per Resident



Source: (Kafasis. K. et al., 2022)

To calculate the energy needs on an hourly basis, the variation of energy consumption during the day is needed, as shown in Figure 3 (Mihailov et al., 2018).

Figure 3: Percentage of Energy Consumption during the Day.



Source: (Mihailov et al., 2018)

Regarding agricultural water needs, the existing crops and the number of livestock have been used (PNAI, 2014). For each crop, the total evapotranspiration (ETC) has been calculated by first calculating the evapotranspiration for an average period of one month (ETo) based on the equation (Eq.2) by Blaney-Criddle (FAO, 2021):

$$ETo = p \times (0{,}46 \times Tmean + 8) \quad (2)$$

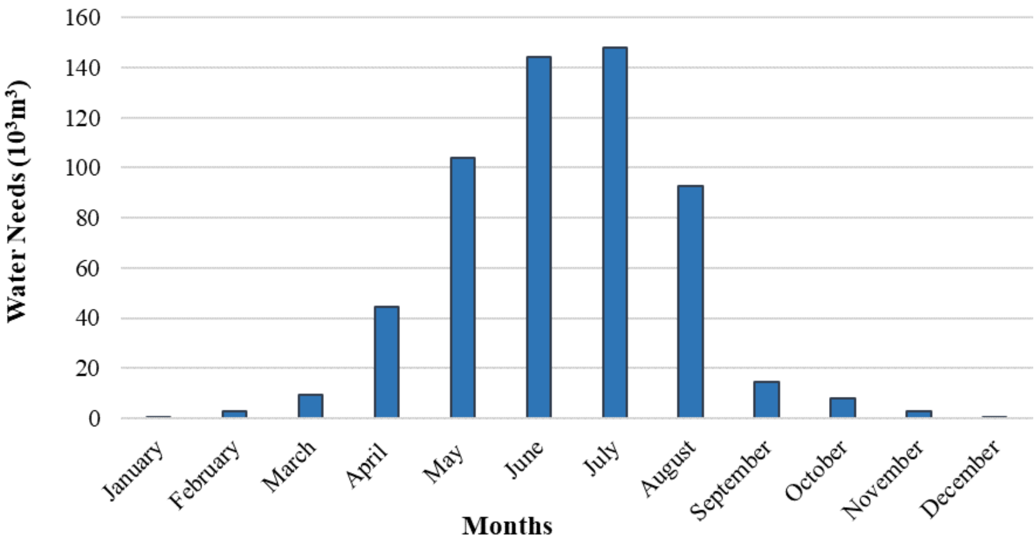
Where:
p: monthly average percentage of sunshine hours
T: average monthly temperature (°C)
ET_o: evapotranspiration over an average period of one month (mm/d)

The total evapotranspiration ET_c was then calculated by the following equation (Eq.3):

$$ETc = ETo \times Kc \quad (3)$$

Kc is the plant factor of each crop and expresses the effects of changes in leaf area, plant height, crop characteristics, growth rates, plant resistance, and soil conditions. The plant factor changes through the growth period of the plant and takes four values in its lifetime (FAO, 2021). Then, the results were multiplied by the crop yield factors. Lastly, by subtracting the average monthly rainfall from ETc, the required water needs for the crops were obtained. The total water needs for agriculture on the island of Amorgos are presented in Figure 4.

Figure 4: Monthly Agricultural Water Needs.



Source: (Kafasis. K. et al., 2022)

B. Production of Synthetic Wind Speed Series

The first step towards the production of the synthetic series was the conversion of the historic wind speed series to the corresponding higher altitude. The original altitude of the data series is 10m, and the location of the wind turbines corresponds to an altitude of 300m. According to the power law (Koutsoyiannis & Xanthopoulos, 1999), the wind speed of 300m was calculated with the bellow equation (Eq.4):

$$\frac{u_2}{u_1} = \frac{\ln\left(\frac{z_2}{z_0}\right)}{\ln\left(\frac{z_1}{z_0}\right)} \quad (4)$$

Where:

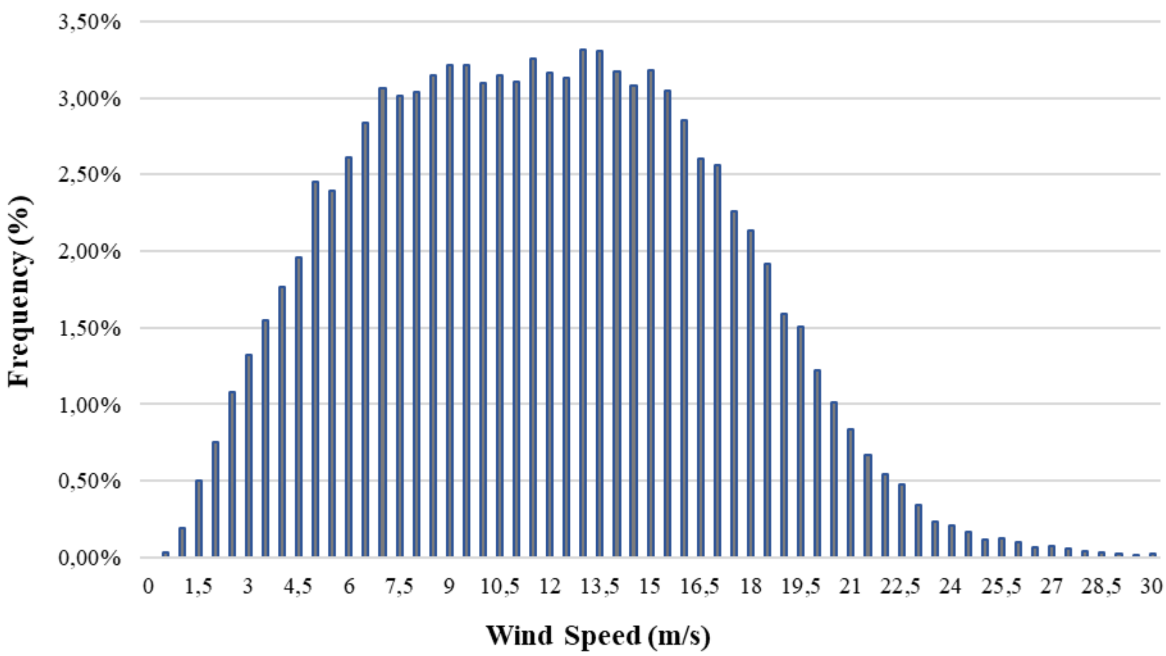
z_1, z_2: the corresponding altitudes, in positions 1 and 2.

u_1, u_2: the corresponding wind speeds in altitudes z_1 and z_2.

z_0: ground roughness parameter

The historic wind speed series for the altitude of 300m was calculated with the above equation, and their frequency of appearance is shown in Fig. 5.

Figure 5: Wind Speed Frequency Distribution at 300m.



Source: (Kafasis. K. et al., 2022)

After the wind speeds have been converted to the desired altitude, the next step was the production of the synthetic wind speed series. According to the estimated lifetime of the project, 25 synthetic times series were generated. The method chosen to generate this data was that of the autoregressive model AR (1). The produced synthetic time series have common characteristics with the historic one. In particular, they express one realization of the particular infinite ones that can occur. Each row consists of 8760 values, which represent the number of hours in one year. The methodology for calculating these according to the AR (1) model is analyzed below:

Methodology for Autoregressive Model AR (1)

1. Calculating Statistical Characteristics and Autocorrelation Coefficient (1st and 2nd order) of the Initial Time Series.
    - Mean, Dispersion, Standard Deviation, Skewness Coefficient, Curvature Coefficient. The autocorrelation coefficient is calculated with the Correl command or using Data Analysis in Excel software.

2. Series Permanence.
    - Calculation of mean, standard deviation and variance for each month.
    - The series permanence is done by subtracting from each value the average and dividing the remainder by the standard deviation of the month to which it belongs.

3. Calculating the Stastical Characteristics and Autocorrelation Coefficient (1st and 2nd order) of the calculated Permanenced Series.
    - Using Correl command or Data Analysis

4. The AR (1) model is used to calculate the autocorrelation coefficient F1 and the Theoretical Deviation Cl.
    - $F(1) = R(1)$ where R(1): Autocorrelation coefficient of In order
    - $C1 = C \times (1 - (F(1)^2)^{0.5}$ where C2 : dispersion of the permanenced series

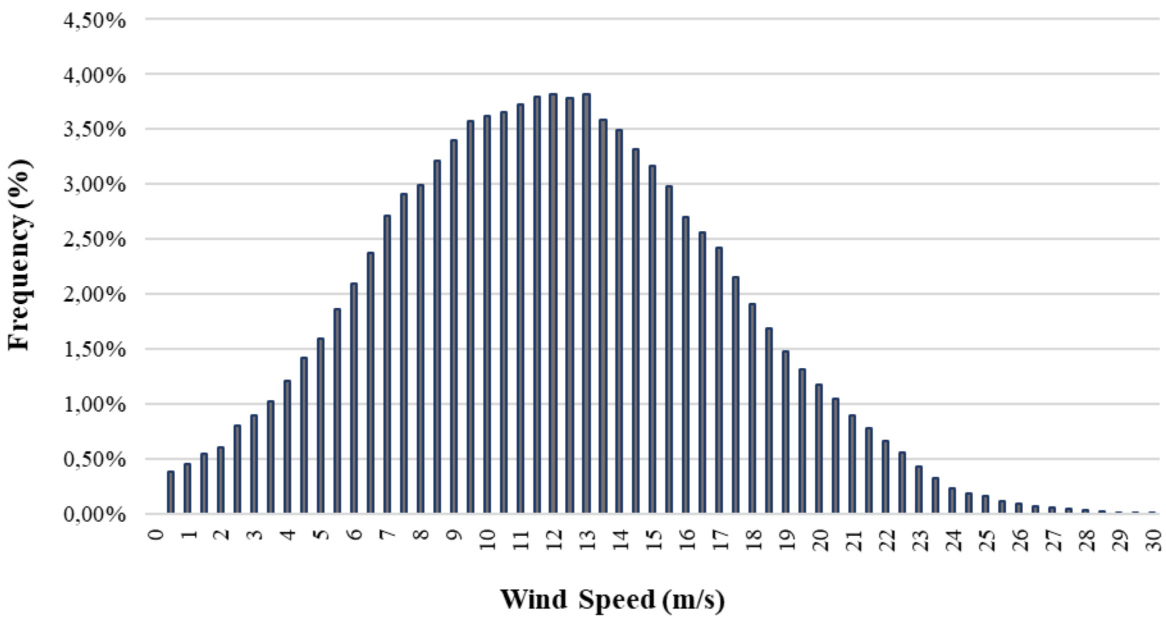
5. Random number generation, with length as the time series, with mean zero and standard deviation 1.
    - The random number generation is done with the command NORM.DIST() and RAND() or with Data Analysis → Random Number Generator

6. Synthetic Permanenced time series values calculation.
    - $\mathrm{X(1) = C1 \times RN(1)}$
    - $\mathrm{X(I) = C1 \times RN(I) + F(1) \times (XI - 1)}$

7. De-permanence of the series.
    - Reversed procedure of permanence method.
    - The statical characteristics and autocorrelation coefficients should agree with those of the real one.

Using the method presented above, the synthetic times series were created and are shown in Figure 6.

Figure 6: Synthetic Wind Speed Frequency Distribution.



Source: (Kafasis. K. et al., 2022)

C. System Units

As mentioned above, the hybrid system consists of the following units:

- An existing power generation unit which consumes diesel fuel.
- Wing Turbines.
- Pump Storage Unit.
- Desalination Unit.
- Brine Processing Unit (2nd scenario).

Diesel Power Generation Unit

The island has 6 diesel units with a total maximum power of 5.28MW and minimum power of 2.99MW, which is approximately 50% of the maximum power (HEDNO, 2021). The minimum power is needed to keep the unit operational, even if the energy needs are less than that. Some of the Diesel units will be excluded, minimizing the use of diesel fuel. The average energy production from 1 litre of diesel fuel is approximately 9.77kWh. This value is vital for the financial analysis of the system, as the primary cost of the unit arises from the consumption of diesel fuel. There is no knowledge about whether any diesel units stop their operation or not for some months of the year.

Wind Turbines

The selection of wind turbines is based on the cost, size, and capacity factor c_f. A comparison of multiple wind turbine models was made through the Bauer & Matysik website (Matysik & Bauer, 2021)for wind turbines rated from 500kW to 2.000kW. The three main ones and their characteristics are shown in Table 1 below.

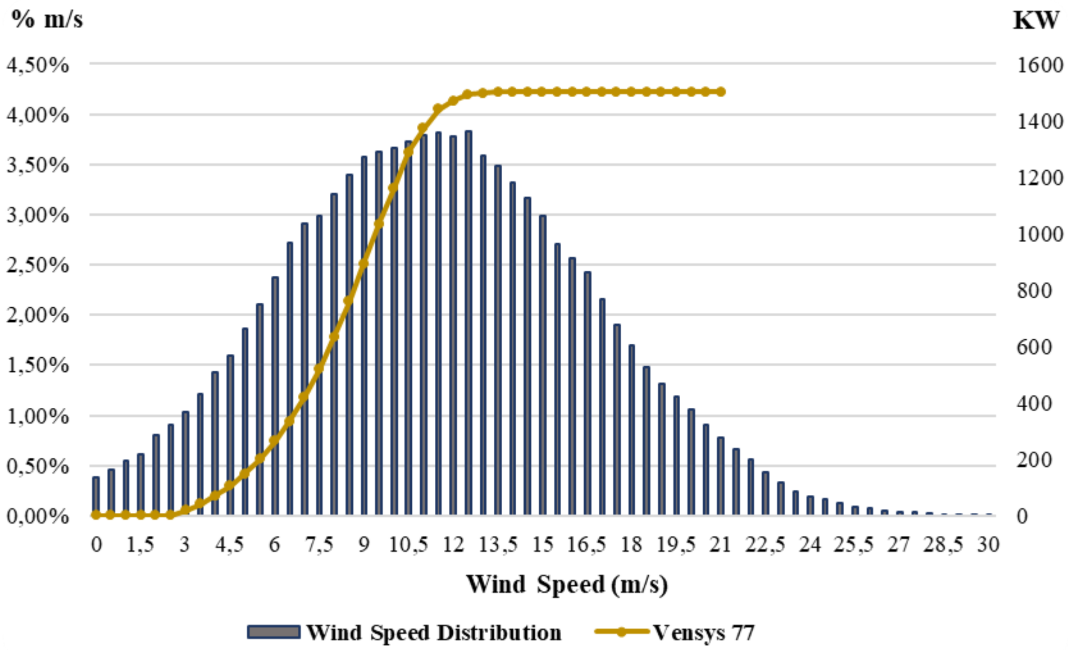
Table 1. Wind Turbines Characteristics.

Wind Turbines Models	Nominated Power (kW)	Capacity Factor cf	Produced Energy (MWh/year)	Rotor Diameter (m)	Total Cost (€)
Enercon-44	910	0,298	2375	44	1.031.205,00 €
Vensys 77	1500	0,35	4599	76,8	1.583.898,00 €
Gamesca G80	2000	0,34	5956	80	2.028.171,00 €

Source: (Matysik & Bauer, 2021)

Based on the above information, the Vensys 77 model was chosen for the developed system, based mainly on its higher capacity factor. According to the produced synthetic wind times series, the power curve of the turbine with the synthetic time series is presented in Figure 7.

Figure 7: Synthetic Time Series – Wind Turbine.



Source: (Kafasis. K. et al., 2022)

<u>Pump Storage Unit</u>

The pump storage unit consists of two tanks, pumps, and a hydro turbine. The first tank was placed at an altitude of 72m and a distance of 650m from the sea, while the second tank was placed at an altitude of 280m and a distance of 580m from the first tank. The volume of tanks was calculated throughout the test of the model. The pumps are used to pump water to the first tank (Tank 1). Tank 1 supplies the desalination unit, and works as a link to pump seawater to the second tank (Tank 2). Both the pipelines that connect the tanks were doubled for bidirectional use. This allowed for the seawater to be returned to the sea through pipes, in the case that Tank 1 was filled from the water of Tank 2 in use of the hydro turbine. Also, it was possible for the brine that comes from the desalination unit to be returned to the sea.

When excess energy was produced, the system provided energy for the pumps to operate, and pumped water from the sea to Tank 1, and subsequently to Tank 2, saving it for storage. In the case of an energy shortage, the water from Tank 2 started to fall into the hydro turbine, generating energy to cover the shortage.

Desalination Unit

The method chosen for desalination is Reverse Osmosis. This method is the most commonly used in Greece and is financially and technically mature to use. Additionally, this method can be supported by the energy produced by wind turbines and hydroelectric project. Typically, a desalination unit by a Greek company (TEMAK, 2022) was chosen for this study. The basic characteristics of the unit are shown in Table 2, while the number of units were determined later.

Table 2. Characteristics of the Desalination unit.

Desalination Unit	
Maximum Water Production (m^3/24h)	1.021
Energy Consumption (kWh/m^3)	2,80
Water Recovery (%)	44%

Source: (TEMAK, 2022)

Brine Processing Unit

The brine processing unit was based on the research of the innovative project “SOL-BRINE” (Kseugenos, 2016). The main characteristics of this brine processing unit are presented in Table 3.

Table 3. Brine Processing Unit Characteristics as developed in the “SOL-BRINE” project.

Brine Processing Unit	
Unit's Lifetime	25 years
Standardized Total Cost	2,7 – 3,7 €/m^3
Water Recovery	73%
Energy Consumption	45 kWh/m^3
Water Quality	50 ppm

Source: (Kseugenos, 2016)

Operating System Procedure

Scenario 1

i. The procedure started with the cover of urban water needs. The pumps pumped water to Tank 1, where the desalination unit takes water from. The desalination unit's capacity was constructed, so it could meet the highest daily water needs in the next 25 years. The wind turbines and diesel units supported the energy needs of the desalination plant.
ii. The remaining energy was then used to cover the energy needs of the island, with the exception that the wind turbines had a direct penetration coefficient of 30% of the total hourly energy needs of the island, and could not provide more than that.

iii. If excess energy was still present after completion of the above, and the capacity of the desalination unit has not reached its maximum, the desalination process for the production of agricultural water started. The agricultural water was then transferred to a reservoir.

iv. Any energy that remained was then used to pump water from the sea to Tank 1 and Tank 2. The tanks had a minimum and maximum capacity which cannot be exceeded.

v. In case of an energy shortage, Tank 2 released water towards the hydro turbine, which then produced energy to cover the energy shortage.

Scenario 2

The operating procedure remained the same, with the only difference being that the brine processing unit was in cooperation with the desalination unit, and consumed more energy. The amount of brine that was processed varied depending on the energy consumption and viability of the system. There were two financial analyses of the 2nd scenario, based on whether the brine produced was being sold or not.

3. Results

Following the calculations and tests performed on the system developed, the following characteristics for the units in each scenario have been calculated and are presented in Table 4. The brine processing unit processed 20% of the produced brine. A rate above that would require more diesel units, and by doing that, the purpose of the unit would come into conflict with the idea of reducing the environmental impacts.

Table 4. Calculated characteristics of the units for each scenario examined.

System Results	Scenario 1	Scenario 2
Maximum Power of Diesel Units (MW)	2,44	2,44
Desalination Unit Capacity (m^3/24h)	5100	5100
Pump 1 Nominated Power (kW)	580	580
Pump 2 Nominated Power (kW)	2175	2175
Number of Wind Turbines (1.500 kW each)	4	5
Hydro turbine Power (MW)	3 X 1,5	3 X 1,5
Agriculture Water Reservoir (m^3)	10.000	10.000
Tank 1 (m^3)	10.000	10.000
Tank 2 (m^3)	100.000	150.000
Brine Processing Unit Capacity (m^3/24h)	-	2.400
Produced Brine that is processed (%)	-	20%

Source: (Kafasis. K. et al., 2022)

The results obtained from the operation of the above units, regarding water and energy efficiency as well as RES Penetration are presented in Table 5 below.

Table 5. System's Operation Results for each scenario.

Scenarios	Water Reliability (%)	Energy Coverage (%)	Irrigation Reliability (%)	RES Penetration (%)
Scenario 1	99,99%	94,15%	46,38%	43,29%
Scenario 2	99,99%	94,23%	46,22%	48,79%

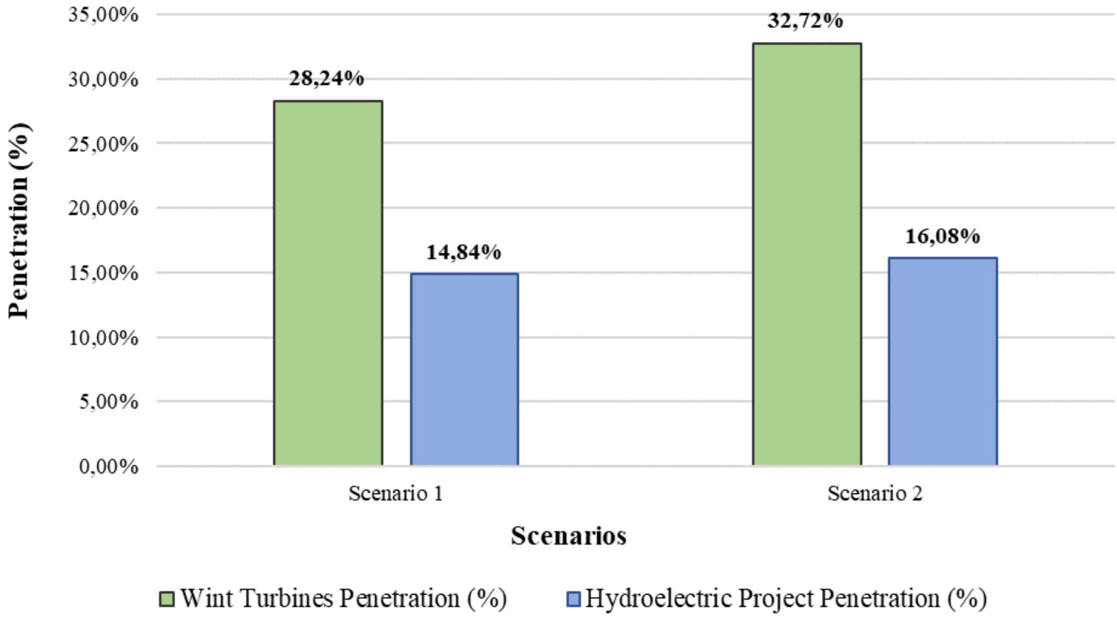
Source: (Kafasis. K. et al., 2022)

As shown above, the RES penetration and the urban water reliability are satisfactory in both scenarios. The first and second scenarios provide positive results for the system operation, in both urban water reliability and energy coverage. The agricultural water reliability, although below 50%, is still considered desirable.

The RES penetration is derived from the wind turbine operation and the hydroelectric project. The specific penetration of each RES unit is shown in Figure 8.

Figure 8: RES Units Penetration for each scenario.

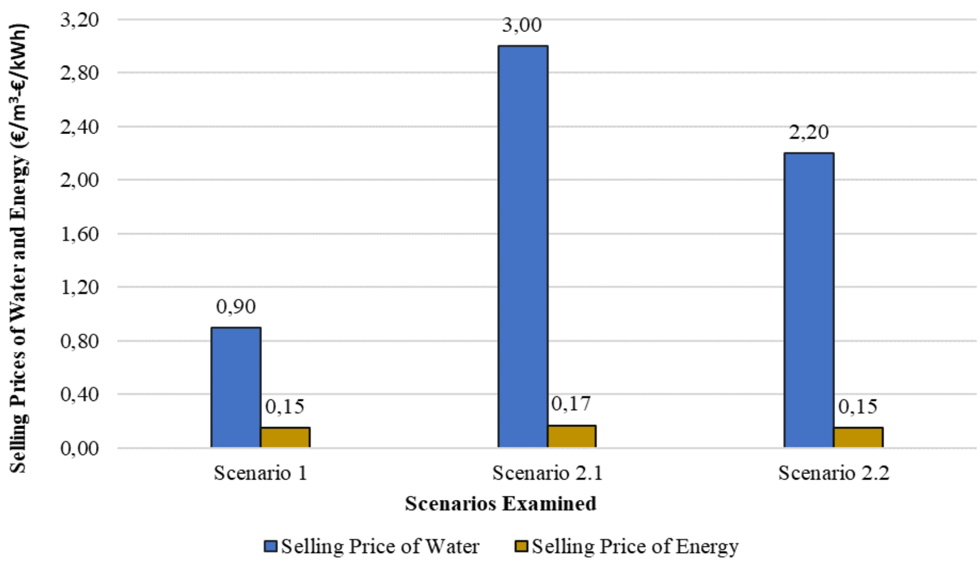
Source: (Kafasis. K. et al., 2022)



Both scenarios are characterized by satisfying RES penetration. The wind turbines have high penetration because they can directly support urban energy needs with a coefficient of 30%, and they can support the energy needs of the desalination and brine processing units. The H/E project cannot easily exceed the above penetration, even if the upper tank was bigger, and the pumps and hydro pumps had more power.

In terms of financial analysis, scenario 1 was tested as known and there were two financial analyses performed on scenario 2. In the first one (Scenario 2.1), the brine produced is not sold and in the other one (Scenario 2.2) it is sold for a price of 5.85€/m^3 (Kseugenos, 2016). The results of these analyses are provided in Figure 9 below.

Figure 9: Required selling Prices of Water and Energy for I.R.R.=3%, for each financial scenario.



Source: (Kafasis. K. et al., 2022)

For the above prices, the N.P.V. is zero. Any increase in these prices increases the N.P.V. value of each scenario, as well as the R.O.E. and R.O.I. values while decreasing the Payback Period and the Discounted Payback Period. The energy produced from the Diesel units has a steady selling price of 0.20€/kWh. As can be seen from the figure above, Scenario 1 is characterized by satisfactory selling prices of energy and water, which makes the investment sustainable. Scenarios 2.1 and 2.2 are characterized as less profitable compared to Scenario 1. A small decrease in the price of water occurs in Scenario 2.2 compared to 2.1 as there is also the sale of the produced brine.

As for the total initial costs and percentage share of owned capital and funding, the results are shown in Table 7 below. The percentage of funding was calculated by the development law (CRES, 2021), the Ministerial Decision 24663/2020 (Gov.Gr, 2020) and the Ministry of Development and Investments (MinDev, 2019).

Table 6: Initial Costs and Percentage Share of Owned Capital and Funding for each scenario.

Scenarios	Scenario 1	Scenario 2
Initial Total Cost (€)	26,525,000 €	30,434,000 €
Percentage share of Units (%)		
PSS (%)	53%	47%
Wind Turbines (%)	24%	26%
Desalination Unit (%)	23%	20%
Brine Processing Unit (%)	-	7%
Percentage Share of Owned Capital and Funding (%)		
Owned Capitals (%)	71%	73%
Funding (%)	29%	27%

Source: (Kafasis. K. et al., 2022)

4. Conclusions

Generally, the results of energy, water and irrigation coverage are satisfactory in all the scenarios examined. Given that Diesel units with a total power of 2.22MW were removed, and the penetration of RES is over 40%, the results are very encouraging.

The first scenario is satisfactory, but as in the other scenarios, the selling price of the energy would be expected to be lower. For a selling price of water above 0.90€/m^3 and energy 0.15€/kWh, the investment is considered sustainable. The selling price of water is very satisfactory, while that of energy, although acceptable, would be expected to be lower, given that today, the selling price of energy from RES is 0.0875€/kWh. At the same time, if it is taken into account that the selling price of electricity from conventional energy production units in the Aegean Islands can exceed 0.40€/kWh in the past years, the investment can be considered to be sustainable. Moreover, funding and grants may exceed estimates, which would make the project even more profitable and sustainable.

The 2nd scenario is characterized by increased energy demand. This has a cost in the economic analysis, as the brine treatment unit requires energy that is often provided by the diesel units. This leads to an increase in fuel costs in the overall system. This can also be seen from the high selling price in economic Scenario 2.1, especially for produced water, which reaches 3.00€/m^3.

Despite the good economic reports that show the reduction of the selling price of water to 2.20€/m^3, in Scenario 2.2 when the brine is processed and economically exploited, this is a pilot project, and there is no guarantee the brine produced will be utilized economically. At the same time, to process the brine at 100%, it was calculated that all diesel units and a total of 9 wind turbines would have to operate, to cover the energy demand. Therefore, it is reasonable to test the treatment of brine in a percentage, so that diesel units are not used. This will enable us to have an initial image of the operation of the system if it is functional, and the possibility of treating the brine since the program is a pilot and has not been tested on a large scale.

Further analysis could be done in different sections of the project. Particularly:

- A complete study of the brine disposal pipeline, calculating both the cost and its improvement to reduce the environmental impact.
- The introduction of further units, to support the present system or improve it, such as storage batteries or solar parks.
- The investigation of the optimal location of the project, based on the current legislative framework.

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