DEVELOPMENT OF A METHODOLOGY OF HYBRID SYSTEMS FOR COVERING WATER DEMAND ON DRY ISLANDS

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Abstract - Remote areas, such as small islands, suffer from water scarcity. Wind-powered desalination system combined with a pumped hydro energystorage system is implemented to provide drinking and irrigation water to a small Mediterranean island in Greece.Thepumped hydro energystorage systemcanoperate in pump and turbine mode and utilize sea water to produce energy, while the desalination plant utilizeshydro energy and energy from the wind turbines to desalinate seawater for both domestic and agricultural purposes.

Keywords - Water-energy nexus, Remote areas, Desalination, Irrigation

I. INTRODUCTION

Water scarcity is a major problem for both the quality of life of the inhabitants and the environment [1]. The lack of drinking water in many islands of Greece results in the use of aquifers for its transportation. This process increases dramatically the cost of the water.At the same time, the use of private wells for irrigation needs, leads to the lowering of the aquifer and the depletion of groundwater. Also, fresh water availability is expected to decrease because of climate change [2]. The solution for these islands lies in the abundant seawater and in the integration of desalination plants [3]. However, one crucial obstacle is the high energy consumption of the desalination plants.Conventional forms of energy are used in large desalination systems with high operational cost.For this reason, it is necessary to combine the use of renewable energy sources (RES). RES plants reduce the cost of desalinated water [4], help the avoidance of conventional fuels and thus contribute to the protection of the environment [5].There are many desalination methods and are categorized to thermal and membrane, depending on the method that the desalination is taken place.The selection of the appropriate combination of RES and desalination method depends on many factors. However, reverse osmosis (RO), a membrane-based method, possesses today the largest installed capacity [6] and is suitable to combine with RES because of its high efficiency [7].

Also, the increasing penetration of RES in the global energy balance has been a priority for the European Union (EU) in recent years. According to 2009/28/EC, the key objectives of the Europe 2020 strategy are to reduce greenhouse gas emissions by 20% compared to 1990 levels, increase RES by 20% and improve energy by 20% efficiency. In Greece, according to the current legal framework (Law 3851/2010), the corresponding targets for 2020 are to increase the share of RES by 20% in final energy consumption and by 40% in electricity consumption. Also, in the new thresholds set by the EuropeanParliament as part of the Clean Energy for all Europeans Package and following the Paris climate agreement, the share of RES in 2030 is expected toincrease to 32%.

Greece is a country with rich wind potential that should be exploited to solve problems related to water autonomy [8]. On the other hand, wind energy, like other renewables, is distinguished for its stochastic nature. The production of energy from wind turbines (W/T) depends on the instantaneous wind potential and does not conform to the actual needs of electricity [9].Also, RES energy connected to standalone systems, such as local power plants of non-interconnected with the mainland islands, is subjected to output power constraints [10].These are imposed by the technical constraints of conventional generators, such as diesel power plants, and by restrictions in dynamic response, due to the stochastic nature of the energy from RES. As a result, a large proportion of this energy is rejected if it cannot be used as soon as it is produced. For this reason, the introduction of storage plants into the research project increases the reliability of the final system and the coverage of the electrical needs by storing the surplus or wasted energy and by using it to cover peak-hour demand [11]. Pumped-Storage Hydroelectricity method (PSH) is a completely environmentally friendly method, able to be installed in areas where topographical features and water availability allow it. Also, is perfectly combined with wind applications and contributes to maximizing their energy balance penetration [12, 13].

Under this framework, the international scientific community is focusing in the field of hybrid RES systems (HRES), which combine at least one form of RES with a method of storing the produced energy. The advantages are summarized in tackling water scarcity, the ability to penetrate more RES, the controlled distribution of energy produced, the reduction of carbon dioxide and all the above in regard of environmental protection. The research is carried out in the context of the construction and analysis [14],

but also of the optimization of the proposed systems [15,16]. The possibility of increasing the productivity and sustainability of agriculture through renewable energy is also being considered [17]. Finally, techno-economic studies [18, 19] on proposed systems are carried out in order to investigate the most appropriate combination of generated power and consumed energy, through optimal design of projects, in order to reduce construction and maintenance costs. In this research work an evaluation of a wind-powered desalination system combined with a PHS is implemented to provide drinking and irrigation water. A methodological framework is developed for dry islands, which utilizesproduced energy from wind turbines and hydroelectric energy to cover electricity needs for the desalination of the demanded drinking and irrigation water through adesalination plant operation. Results are concentrated on the percentage of the covered water demands and on the energy distribution of the proposed system.

II. MATERIALS AND PROCEDURES

A. Study Area

Fournoi is the capital of a cluster of islands in the Aegean Sea, named FournoiKorseon (Fig. 1).The population of Fournoi is 1400 inhabitants. Its Mediterranean climate involves mild winters and dry summers. According to Hellenic National Meteorological Service HNMS, the average annual temperature is about 18^{o}C, with its minimum in February (10^{o}C) and maximum on July (28^{o}C). The island has a rich wind potential Fig. 2 shows the frequency of wind speeds at the weather station of Ikaria in 2015. Over the 50% of wind speeds range between 6 and 10 m/sec.

According to data provided by the technical service of the island, households meet their domestic water needs through rainwater harvesting, bottled water or by refilling bottles in a public tap. For agricultural purposes they use water through private wells.Monthly needs in drinking water range between 5400 m^3, from October to April,to 15600 m^{3}in August. The monthly population of the island is shown in Fig. 3. The island is a major attraction for many tourists, especially during the summer months. The peak is on August where population is 2.5% over the permanent number.This means increased drinking water needs, in the summer, to the already increased irrigation water needs of the island.



Figure 1 Study area

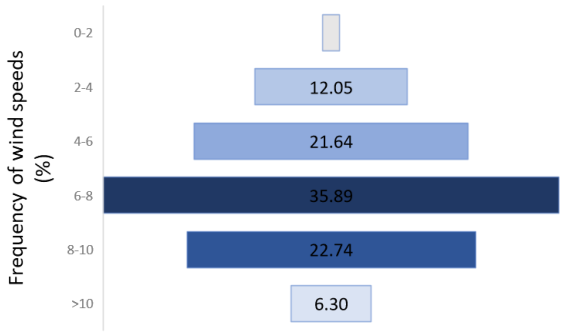


Figure 2Frequency of wind speeds at the weather station

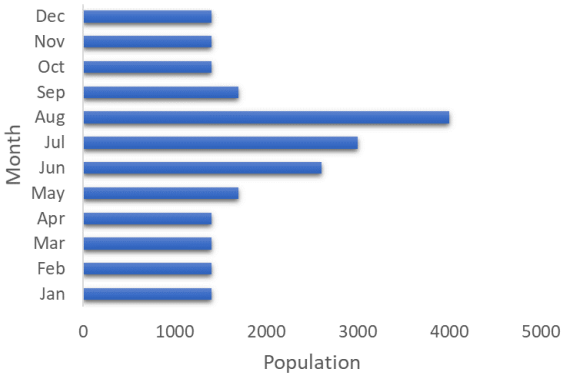


Figure 3 Monthly population

B. Methodology

The proposed HRES consists of a wind-powered desalination system, combined with a PHS plant, with two water reservoirs. The first is at a high altitude and the second one is near the desalination plant for storing the desalinated water for use. Wind turbines generate energy to meet the desalination's electrical needs, and excess energy is used by the pumping station to raise seawater to the higher reservoir to generate hydro energy through the turbine. When the desalination needs are not satisfied only by the wind turbines, the hydroelectric energy produced by the turbine is used. Produced hydroelectric energy is predominantly less than the energy required for pumping. However, HRES enables to meet demand at peak hours, when there is no alternative for desalinating water.

Monthly needs in drinking water provided by the technical service of the island, while irrigation water has been calculated using Blaney-Criddle method andis given by (1).

$$ET = k(1.8T + 32)p/3.94 \quad (1)$$

where k is the seasonal vegetation coefficient, T is the temperature and pis the percentage of daylight hours per month. According to Hellenic Statistical Authority, the agricultural production of the island includes grain, vegetables, citrus fruit and fruit bearing. Using daily temperature data and seasonal vegetation coefficient k values for the various crops, as determined by Blaney and Criddle, the seasonal water requirements reported in each vegetative period of each crop are calculated. Monthly needs in irrigation water range between 6400 m^3 in April to

19800 m^3 in August. Fig. 4 shows monthly drinking and irrigation water needs.Irrigation period is set from April to September and therefore irrigation water is not required during the remaining months.

Two wind turbines (W/T) 900kW are used, model E-44 from Enercon. The power curve of the W/T is shown in Fig. 5 and is provided by the company. It helps the calculation of the wind power output, according to the estimated wind speed at the hub height.According to Fig. 5, for wind speeds at the hub height lower than 2 m/sec the W/T does not produce any power output. For values between 2 m/sec and 17 m/sec the power is given by the power curve and the maximum power output of 900 kW is succeeded for wind speeds over 17 m/sec.

Data of the wind speeds and temperatures in the weather station Ikaria from HNMS, in 2015, are used in thisstudy with a 24-h time step.The wind turbine efficiency coefficient is 30%.

The wind speed (v_2) at the hub height is calculated by (2).

$$v_2/v_1 = \ln(z_2/z_0)/\ln(z_1/z_0) \quad (2)$$

where, v_1 is the wind speed at the weather station (m), z_1 is the weather station height(m), z_2 is the hub height (m) and $z_0$is the roughness length (m), with values depending on the natural surface of theinstallation. Results are shown in Fig. 6

The pumping station is 300kW with 69% efficiency coefficientand the flow of the hydroelectric station is 5m^3/s.The RO desalination system's capacity is 500 m^3/day with 90% efficiency coefficientand energy consumption of the process is taken equal to 7 kWh/m^3.

The hydraulic power P (in kW) available for conversion is calculated according to (3).

$$P = n \cdot \rho \cdot g \cdot Q \cdot H \quad (3)$$

where n is the overall plant efficiency, ρ is the water density and equals to 1000 kg/m^3, g is gravity density equals to 9.81 m^2/sec, Q is the flow through the turbine (m^3/sec) and H is the net head across the turbine (m).

It is evident from (3) that the amount of P is proportional to the altitude of the second reservoir H and the flow Q. In this research H is equal to 192 m. Every time step the water in the upper reservoir is added to the remaining water from the previous time step. This amount is stored in order to be used when the demand in energy for desalination is higher than the produced energy from the W/T.

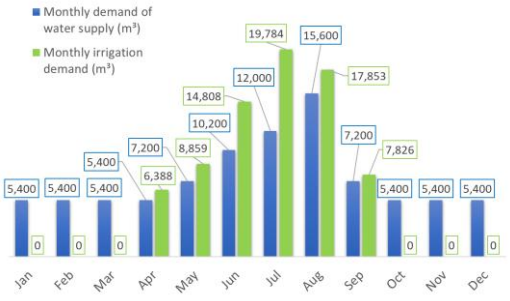


Figure 4 Monthly drinking and irrigation water needs

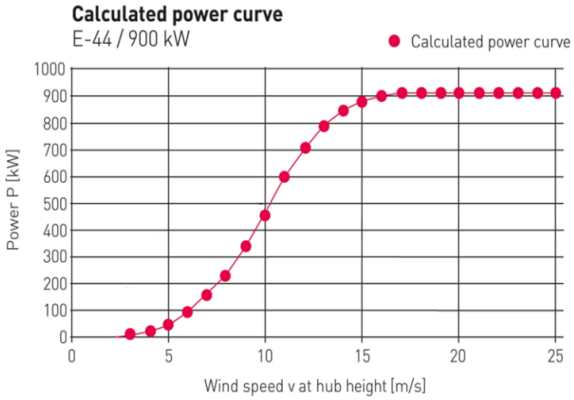


Figure 5 Power curve diagram for W/T Enercon 44/900 kW

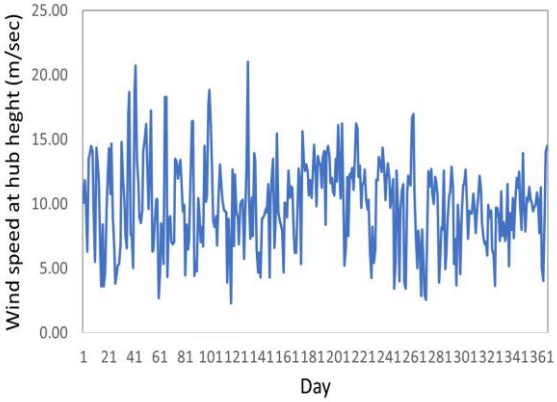


Figure 6 Wind speed at hub height

Each time step the energy that is required by the desalination system to provide residents with desalinated water is calculated. At the same time, the energy produced by the W/T is also calculated. If W/T energy is sufficient and there is excess energy, then this excess amount is used by the pumping station to raise water to the upper tank. In case that the W/T energy generation is not enough to cover the demand then the turbine operates to generate hydro energy in order to be used by the desalination system to meet the required needs in desalinated water. Drinking water is a priority at every time step, and if this is covered then energy is also given to desalinate irrigation water.

III. RESULTS AND DISCUSSION

A. Drinking and irrigation water

The annual coverage and deficit of drinking and irrigation water demand is shown in Fig. 7. The annual coverage of drinking and irrigation water is 97.84% kai 91.85% respectively.

The monthly coverage and deficit of drinking water demand is shown in Fig. 8. From January to April and from September to December the island is autonomous in meeting its drinking water needs through the operation of the proposed HRES. The remaining months the coverage of drinking water demands range between 92.2% and 98.9%, a very satisfactory result.

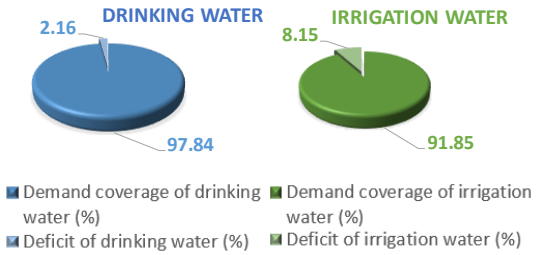


Figure 7 Annual coverage and deficit of drinking and irrigation water demand

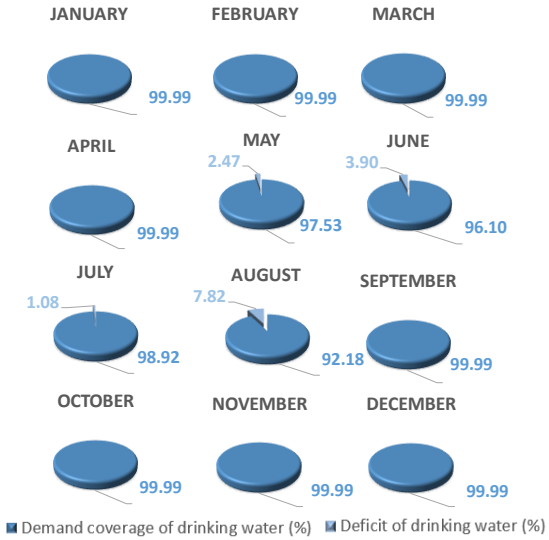


Figure 8 Monthly coverage and deficit of drinking water demand

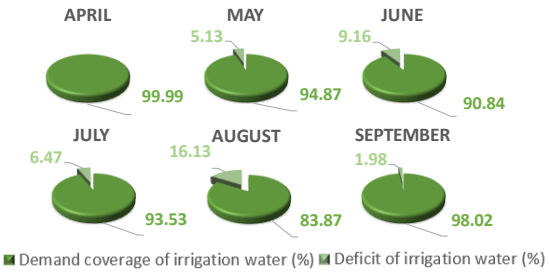


Figure 9Monthly coverage and deficit of irrigation water demand

The monthly coverage and deficit of irrigation water demand is shown in Fig. 9. The island is autonomous in meeting its irrigation needs only in April. This is explained, since the quantities required are greater and since irrigation water is not the priority in the system design. The coverage of irrigation water demands for the remaining months range between 83.87% and 98.02%, a satisfactory result as well.

B. Energy distribution

The proposed HRES consumes energy through the pump in order to raise water to the upper reservoir (C-1). Also, energy is consumed for the desalination of drinking and irrigation water quantities (C-2 and C-3 respectively). On the other hand, the proposed HRES generates energy by two different sources. The first is the two wind turbines (G-1) and the second source is the hydro turbine (G-2).

Fig.10 represents these five different sources of energy consumption and generation over the year. C-1 is thedominant source of consumed energy and is necessary in order to store the excess energy. C-2 is lower than C-3 during the irrigation period (April to September), while the required quantities of irrigation water are greater than required quantities of drinking water. G-1 is thedominant source of generated energy, while G-2 is necessary for peak hours and represents the storage of the excess W/T energy (G-1)

The monthly amount of C-1, C-2, C-3, G-1 and G-2 is shown in Fig. 11. Maximum C-2 and C-3 is observed in July and August, as the demand of drinking water is increased due to tourism and demand of irrigation water is also increased due to higher temperatures. Maximum G-1 isobserved in July, due to continuously high wind speeds. Maximum G-2 isobserved in November, due to lower wind speeds. Low wind speeds result in insufficient amount of produced W/T and therefore hydroelectric station is necessary to operate more tomeet the electrical needs for the desalination.

Fig. 12 depicts the energy demand for pumping and the produced hydroelectric energy over the year.As expected, produced hydroelectric energy is less than the energy required for pumping. However, the first enables to meet demand at peak hours, when there is no alternative for desalinating water.

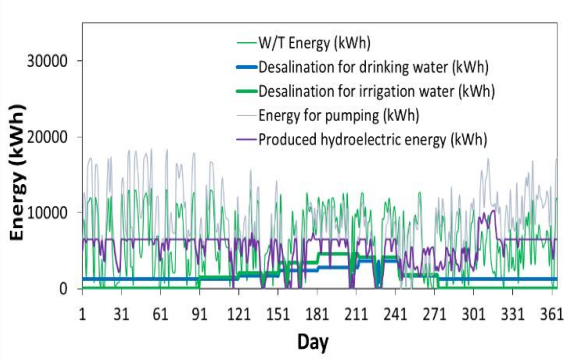


Figure 10 Produced W/T and hydroelectric energy and energy demand for pumping and desalination

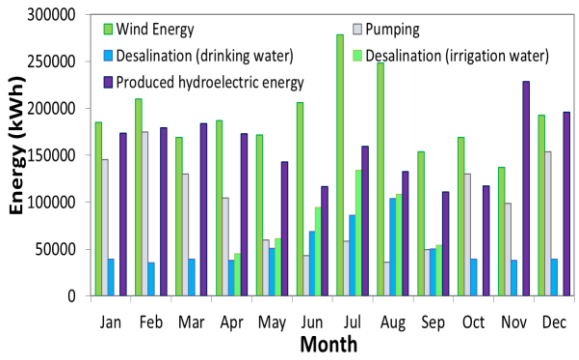


Figure 11 Monthly produced W/T and hydroelectric energy and energy demand for pumping and desalination

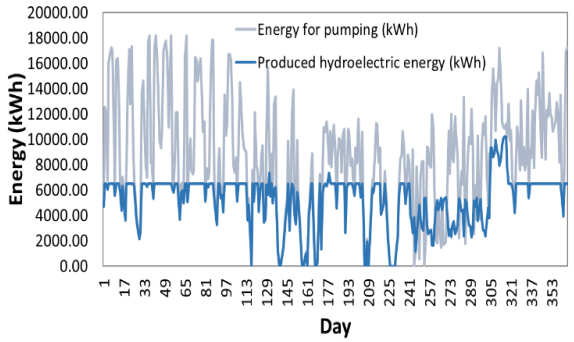


Figure 12 Energy demand for pumping and produced hydroelectric energy

IV. CONCLUSIONS

In this research work an evaluation of a wind-powered desalination system combined with a PHES is implemented to provide drinking and irrigation water in Fournoi island. The proposed methodology is designed for dry islands, in order to cover electricity needs for the desalination of the demanded drinking and irrigation water through a desalination plant operation. Results are concentrated on the percentage of the covered water demands and on the energy distribution of the proposed system. Collection of hydrometeorological data, population variation and drinking water needs is performed. Analysis of wind data and conversion to the height of the wind turbine is evaluated. Evapotranspiration is calculated for the estimation of the irrigation needs. For every time step energy produced by the W/T, water volume in the upper reservoir and the hydroelectric energy production is estimated.

It is found that the annual coverage of drinking and irrigation water is 97.84% kai 91.85% respectively. Also, from January to April and from September to December the island is autonomous in meeting its drinking water needs through the operation of the proposed HRES. As far as irrigation water is concerned, the island is autonomous in meeting its irrigation needs only in April, while the remaining months the coverage range between 83.87% and 98.02%.

Energy for the pump station is thedominant source of consumed energy. Energy for desalinated drinking water is lower than that for irrigation water with maximum values for both observed in July and August. W/T energy is thedominant source of generated energy and its maximum values is observed in July. Produced hydroelectric power is necessary for peak hours, represents the storage of the excess W/T energy and its maximum values is observed in November. Based on the encouraging results, further research is needed in the direction of uncertainty analysis of the hydrometeorological and demand input data. Also, a cost – benefit analysis is recommended in order to evaluate the advantageous operation mode of the hybrid system.

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