# Investigation of energy, water, and electromobility through the development of a hybrid renewable energy system on the island of Kos

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*Abstract*: The lack of fresh water and energy independence in remote islands leads to the investigation of Hybrid Systems (HS). In this paper, the implementation of wind energy for meeting energy, water, and electromobility demands on a Greek island is examined. The stochastic nature of wind potential leads to the introduction of energy storage units. Energy storage can be achieved through the HS, which utilizes the rich wind potential of the island of Kos, stores excess energy through pumping to an upper reservoir, and produces hydropower in order to cover the energy deficit. The HS in this study consists of a wind farm with a total capacity of 9.4 MW, which is composed of 4 wind turbines of 2.35 MW, two desalination units with a total capacity of 2275 $m^3$/day a 10 kW power pump for pumping the desalinated water to the drinking water reservoir with a capacity of 180000 $m^3$. It also consists of a hydro turbine of 5 $m^3$/s and an upper reservoir with a capacity of 400000 $m^3$ at a height of 176 m above the hydroelectric station. The first operated scenario aims to meet the energy and water needs of Pyli (3500 inhabitants). The second scenario aims to cover the electromobility and water needs of 20000 inhabitants, which is equivalent to the entire city of Kos. The simulation models operate with hourly meteorological and demand data for the period 2016-2020, results about $CO_2$ emissions, before and after the integration of the HS are presented, and a cost-benefit analysis is performed for the first scenario.

*Key-Words:* Hybrid system, Wind power, Electricity, Water management, Desalination, Electromobility, Kos island

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## 1 Introduction

For many years, the majority of power generation systems around the world have relied on non-environmentally friendly thermal power plants. In modern societies, the use of environmentally friendly energy sources and the awareness of the environmental impact of polluting fossil fuels is getting attractive. Today the focus is both on the adequacy of energy supply and on the environmental impact of specific sources. In this context, the European Union (EU) has launched a series of actions and support measures for the further expansion of Renewable Energy Sources (RES).

In Greece, there is a special interest in the development of RES, especially in its island sector, as most of the islands are not connected to the energy network of the mainland [1]. Also, during the summer months, there are high energy requirements due to the tourist traffic. The electricity needs of these islands are usually met either by autonomous power plants based on fossil fuels or through their interconnection with the mainland, which leads to energy dependence and poor quality of electricity [2,3]. With the development of RES units, an island becomes more autonomous, the dependence on fossil fuels is reduced and the fares to the EU are reduced [4]. Greek islands in general are suitable for the installation and operation of wind farms, due to their very high wind potential. Today, more and more studies serve the energy supply for islands in the world [5-9].

In the same direction as RES units, the replacement of vehicles with electric vehicles is in progress. In the next years, the number of electric vehicles will increase significantly, both internationally and nationally [10,11] Also, with the horizon of green growth, an additional goal is the supply of recharging infrastructure, to come exclusively from electricity production through RES [12,13]. Already, with the development of tax incentives, it is becoming more attractive to install recharging infrastructures that operate with energy from alternative sources, thus making charging 100% green. In recent years, the share of $CO_2$ emissions from the transport sector has risen in the EU from 32% in 1990 to 45% in 2015. Furthermore, road transport accounts for 92% of $CO_2$ emissions from the transport sector, and between 1990 and 2015 $CO_2$ emissions from cars accounted for half of the road transport emissions. This means that transportation is a key sector for the goal of minimizing $CO_2$ emissions [14].

At the same time, the lack of water resources worldwide is worrying. This problem affects also Greece, where most of the islands have limited water resources. Many Greek islands face water scarcity problems. Current practices to ensure water supply in small dry islands in Greece are not sustainable and environmentally friendly, especially during the tourist period, where water needs increase significantly [15]. Meeting the water needs of the islands takes place in two ways, either by transporting drinking water by tankers, a process that is quite expensive, or by dams (where possible), or by costly energy-intensive drilling from underground water. In the case of the Greek islands, which are surrounded by the sea, the development of seawater desalination systems is a solution for the water needs [15,16]. Restrictions of groundwater pumping will reduce the problem of salinization of the aquifers and will increase the groundwater table.

In order to meet the energy and water demands of the islands and to deal with the stochastic nature of wind energy, it is necessary to introduce energy storage units [17,18] in autonomous island systems [19]. Today, numerous researchers studied a solution that includes energy storage [21-26]. Energy storage can be achieved through a HS, which utilizes the rich wind potential of an island and uses excess energy to pump seawater to the upper reservoir [27,28]. Respectively, when there is an energy deficit, the hydroelectric station is activated and energy is produced. This is achieved by converting the gravitational potential or kinetic energy of the stored water for energy production [29]. A significant number of previous research works have already studied the introduction of HS on non-interconnected islands. Groppi et al. [5] present solutions that address the stochasticity of RES through the improvement of network capacity, such as energy storage technologies. In addition, Alves et al. [6] investigate the interconnection between islands, in order to reach 100% renewable energy systems in isolated islands. Petrakopoulou et al. Al [18] estimate the cost of HS on a Greek island and compare it to the cost of a local fossil fuel power station. Icaza-alvarez et al. [21] present, regarding 2050 targets, a zero-emission system coupling with RES for the fragile ecosystem of the Galapagos Islands of Ecuador. Segurado et al. [24] promote a methodology for optimizing the size and operation of a desalination unit powered by wind and hydroelectric energy. Jurasz et al. [25] develop a new mathematical model for planning the operation of the HS 25 to 48 hours ahead, according to meteorological forecasts. Liu et al. [30] study an optimal capacity planning method for an HS with a desalination unit using linear programming. Tsai et al. [31] use a Philippine offshore island to optimize the capacity planning of an HS using the Hybrid Optimization Models for Energy Resources (HOMER) software. Hamanah et al. [32] investigate the sizing of an HS using the annual cost as an objective function. Finally, Abdul-Wahab et al. [33] investigate solutions for supplying electricity to consumers in an off-grid remote area using the HOMER software.

The object of the present research is the simulation of an HS to meet the desalinated water, energy, and electromobility needs on the island of Kos. The project includes four wind turbines, a hydroelectric station, a desalination unit, a pumping station, a seawater reservoir, and finally, a drinking water reservoir. Two scenarios are implemented based on different priorities for on-demand coverage. Also, results about $CO_2$ emissions are presented, and a cost-benefit analysis is performed for the first scenario. The paper's contribution is summarized in the methodology for the assessment of an HS for the water and energy demands fulfillment and, also, the estimation of $CO_2$ emissions before and after the application of HS on the island of Kos, which is used as a case study. The savings from the reduction of the $CO_2$ emission costs are then calculated, based on European Union's taxes. Extensive historical data is used for the water and energy needs of the island. In addition, the contribution of each energy source to the island's energy mix per month and the monthly coverage of energy needs by the HS is presented. Moreover, the penetration of electromobility on the island and its connection to the HS is investigated. The estimation of the number of vehicles and their hourly demands per day, in line with the national target of Greece [34] for a green transition in the transport sector, is examined. Finally, a cost-benefit analysis is conducted for the economic feasibility of the proposed system and the profitability of the investment.

# 2 Problem Formulation

## 2.1 General Description of the Study Area

Kos is a Greek island, part of the Dodecanese island chain group in the southeastern Aegean Sea. It is the third-largest island of the Dodecanese after Rhodes and Karpathos. The surface of the island is 295.3 sq. km. with a coastline of 112 km. The capital of the island is Kos, which is the main port of the island. It is 200 nautical miles from the port of Piraeus. The island also has an airport which is located 27 km southwest of the city of Kos, near the village of Antimacheia. The population of the island according to the 2011 census amounts to 33388 permanent residents. The island has tourist traffic during the whole year. The population, especially during the summer months, is double. The climate of Kos is the Mediterranean, characterized by mild winters, with plenty of rain, strong winds, and periods of relatively high sunshine. The dry or hot season lasts from the end of April until mid-September. In terms of temperature, according to Kos' meteorological station of the National Meteorological Service (NMS), the lowest average minimum appears in February (8.32 °C) with an average absolute minimum temperature of 2.75 °C, while the highest average maximum temperature appears in July (30.67 °C) with an average absolute maximum temperature of 35.75 °C. As for the precipitation, it should be noted that the average rainfall is 559.54 mm with December appearing with the highest average monthly rainfall of 121.96 mm. January is the month with the highest maximum daily rainfall (134.90 mm). In terms of winds, the prevailing winds are North with an average annual number of days that show an intensity above 8 Beaufort at 18, most of them appear from December to March.

## 2.2 Electricity and Water Needs in Kos

The energy needs of the island are served by an autonomous power station of 138.74 MW located in the area of Mastichari, west of the island. It supplies electricity to the island of Kos, Kalymnos, Tenedos, Leros, Lipsi, Gyali, Nisyros, Tilos, and Pserimos. The main source of energy is the thermal power plant that is installed on the island.

The water needs of the island are covered mainly by groundwater and natural springs. The available water covers completely the water supply needs. The tourism sector consumes very high quantities, as a result of which it operates in competition with the agricultural sector. However, there are water supply projects aimed at meeting both irrigation and household water needs. The monthly variations of water and electricity needs are shown in Fig.1 and Fig. 2.

According to the national target of Greece [34], electric vehicles will be 82422 by 2030 and will correspond to 1.39% of the total amount. The estimated total fleet of 12518 vehicles corresponds to 174 electric vehicles on Kos. According to published papers [35,36], about 68% of vehicles are expected to be charged during the night hours (8 pm to 8 am) when vehicle owners have returned home, and 27.5% are expected to charge during the day (from 10 am to 5 pm) at other charging points, such as publicly accessible points located on the road, or in workplaces. Based on the above, the hourly load distribution by the fleet of electric vehicles is shown in Fig.3

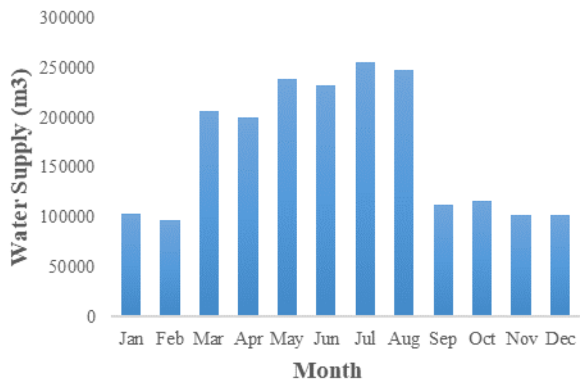


Fig. 1: Mean monthly demand for water supply

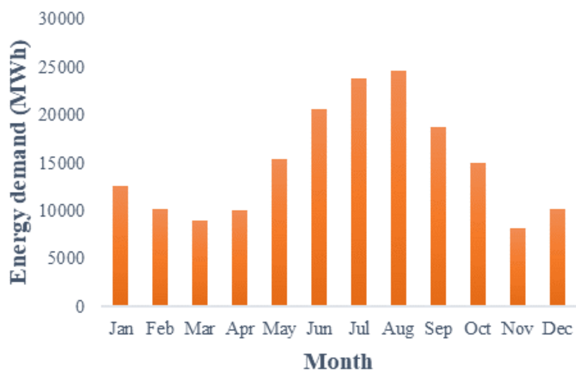


Fig. 2: Mean monthly energy demand

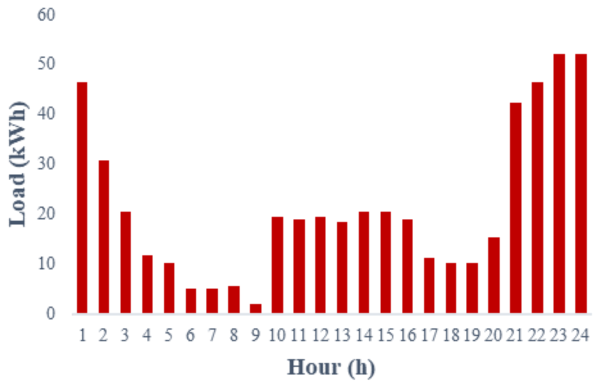


Fig. 3: Hourly load distribution by the fleet of electric vehicles

### 2.3 Technical Description

The HS in this study consists of a wind farm with a total capacity of 9.4 MW, which is composed of 4 wind turbines Enercon E-92 of 2.35 MW. The wind farm is located at an altitude of 303 m. In addition, the HS consists of two desalination units with a total capacity of 2275 $m^3$/d and a capacity of 6.5 kW/$m^3$, in order to produce drinking water. The desalination unit is accompanied by a 10 kW power pump to pump the produced desalinated water to the drinking water reservoir with a capacity of 180000 $m^3$. The drinking water reservoir is located next to the desalination unit. The HS also consists of a hydro turbine of 5 $m^3$/s, in order to produce hydroelectric energy. The seawater reservoir with a capacity of 400000 $m^3$ is located at a height of 176 m above the hydroelectric station. The existing local power station meets the demand when the required energy is not produced by the HS. The schematic representation of the HS is shown in Figure 4.

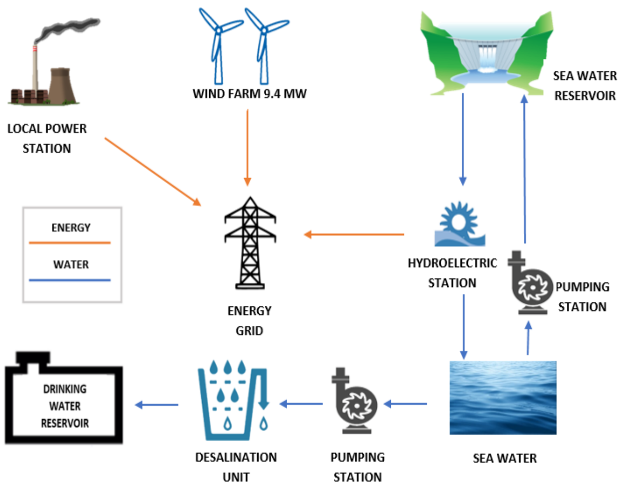


Fig. 4: Schematic representation of the HS

## 3 Problem Solution

### 3.1 Methodology

In order to calculate the estimated wind energy production, wind speed measurements are collected from the local meteorological station of the National Observatory of Athens Automatic Network (NOANN) [37]. The time series processing is carried out using the free software application Hydrognomon [38]. The wind speeds measured at the meteorological station are converted according to the height at which the wind turbines are installed. Using the altitude of the meteorological station, which is 42 m, and the height of the wind turbine rotor, which is 303 m, the conversion of the time series of the wind data is made. As mentioned above, the Enercon E-92 wind turbine model is selected. Based on the power curve, provided by the manufacturer, the generated wind energy is calculated. Fig. 5 shows the average hourly wind energy produced per month. If the produced wind energy does not adequately cover the needs, the water of the seawater reservoir supplies the hydroelectric power station, which covers the energy deficit. If the electricity demand cannot be met by the produced hydro energy, then the deficit is covered by the local power station. Two operating scenarios are simulated for the management of the produced energy. In Scenario 1 the priority is to meet the electricity load and in Scenario 2 the priority is to meet the electromobility and desalination energy needs. The developed methodology can be adapted by other islands, interconnected or not, by importing the respective data, thus, leading to the energy and water independence, the increase of the penetration of RES, and the reduction of $CO_2$ emissions.

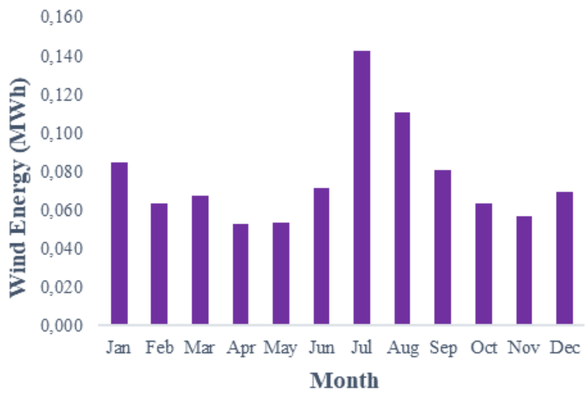


Fig. 5: Average hourly wind energy produced per month

### 3.2 Scenario 1: Energy Coverage as a Priority

The operating scenario aims to meet the energy and water needs of Pyli (3500 inhabitants) on the island of Kos. The priority is to cover the energy needs and then the water needs. From the produced energy from the wind turbines, 30% is distributed directly to the grid, while the remaining 70% goes is used firstly to the pumping station for pumping seawater and secondly to the desalination unit for drinking water production. The wind energy is primarily allocated to the pumping station for pumping water to the upper reservoir, in order to be stored and released to the hydro turbine when there is an energy deficit. The energy that cannot be implemented by the pumps, due to their capacity, is used for the desalination of seawater. The pumping of seawater in the upper tank in case of excess energy and the operation of the hydroelectric power station in case of deficit smooths out the sharp fluctuation of the produced energy. Thus, with the presence of the HS instead of an individual wind farm, much higher percentages of reliability in meeting the needs for energy and water supply are achieved. The system is simulated for 5 years with an hourly step. Fig. 6 shows the management of the total wind energy for each month. The strong fluctuation of the wind is reflected in the generated wind energy per month. Fig. 7 shows the monthly coverage of energy needs by the HS and the coverage ranges from 58% in August to 81% in July. Fig. 8 and 9 show the energy production per month and how energy needs are met. It is observed that the maximum monthly energy production occurs in July and exceeds 3000 MWh, due to high wind energy production. Demand in August is high, due to tourism, but due to lower wind energy production, the LPS operates more than in other months.

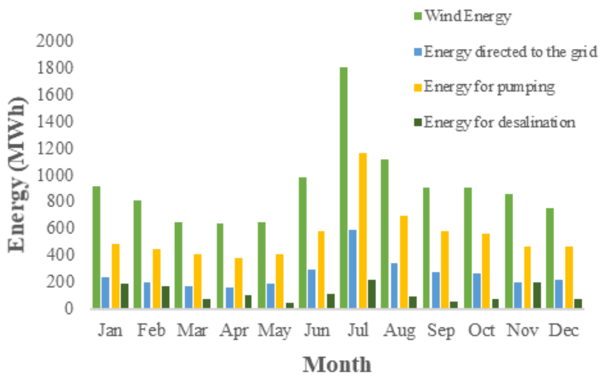


Fig. 6: Wind energy management

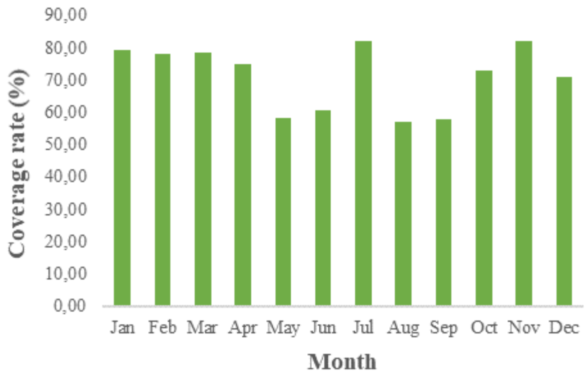


Fig.7: Monthly coverage of energy requirements by the HS

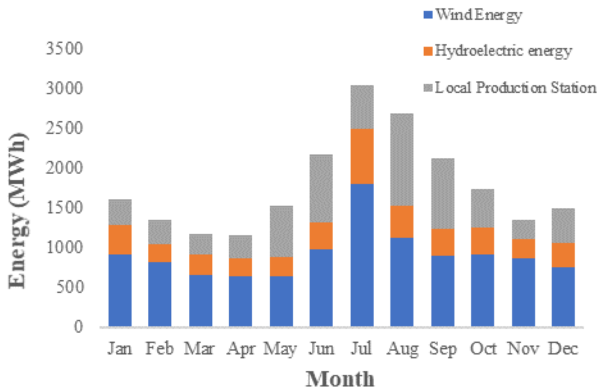


Fig. 8: Energy production per month

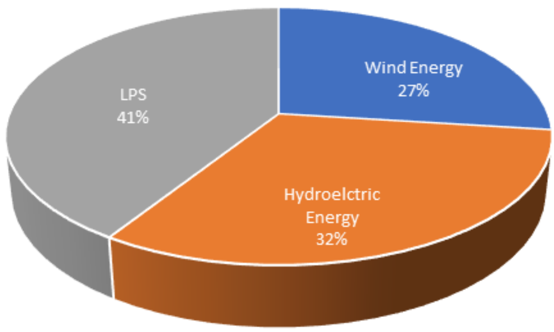


Fig. 9: Covering energy needs

Drinking water production per month is shown in Fig. 10. The volume of desalinated water produced is stored in a reservoir and is used to meet water supply needs.

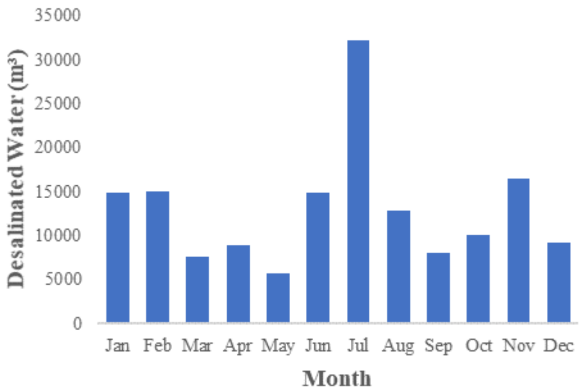

Fig. 10: Production of desalinated water per month

For the population of 3500 inhabitants, the percentage of coverage of energy demand by the desalination unit is 95% from the HS, as shown in Fig. 11. At a rate of 5% that the HS is unable to meet demand, water is supplied by the natural springs of Kos.

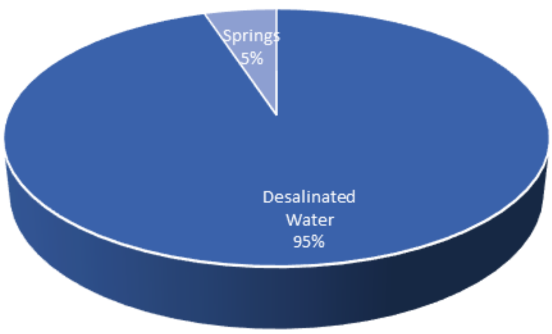

Fig. 11: Covering water needs

### 3.3 Scenario 2: Coverage of Energy Requirements for Electro-Mobility and Desalination as a Priority

In Scenario 2 the priority is to cover the energy requirements of the electric vehicles and then the energy requirements of the desalination unit. Like in Scenario 1, 30% of the energy produced by the wind farm is given directly to the grid. The remaining 70% is distributed at a rate of 75% to cover the needs of the electric vehicles in priority, and then the energy requirements of the desalination unit. The remaining 25% is used to pump water to the upper reservoir for energy storage. The priority in this scenario is coverage of water and electromobility demands of the city of Kos, with a population of 20000 inhabitants, and secondly the coverage of the energy requirements of the households. In Fig. 12 it is shown that the energy for the electrification of the vehicles of the island is consistently much smaller than the generated wind energy, so the percentage of reliability of its coverage with "green energy" from the HS reaches 100%. This fact is quite encouraging and even if the forecasts for the penetration of electric propulsion are exceeded, the HS will still be able to respond. Furthermore, the fact that electric vehicles do not consume much energy is encouraging, as, in the societies of the future, electric vehicles will have to be charged with energy from RES and not from fossil fuels. In addition, it can be seen that in July, the month with the highest wind potential, the highest production of drinking water takes place and the largest monthly volume of water is pumped.

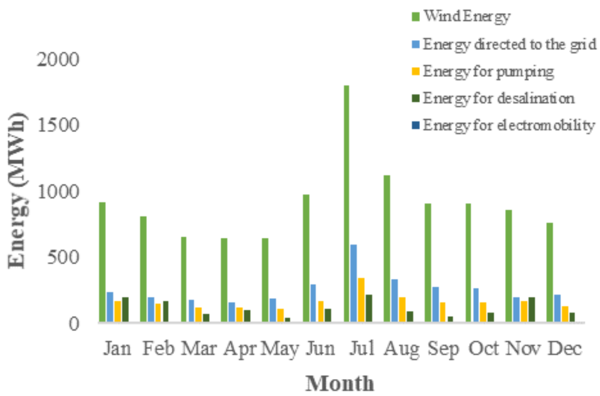

Fig. 12: Wind energy management

Fig. 13 shows the monthly coverage of energy requirements by the HS. The percentages are reduced, compared to Scenario 1, which has energy coverage as a priority. Nevertheless, they are still satisfying, as they range from 46% in May to 70% in November.

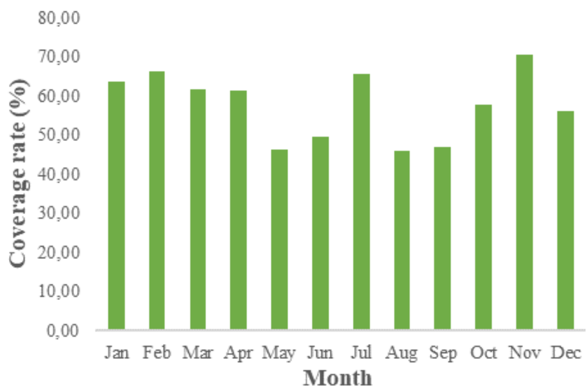

Fig. 13: Monthly coverage of energy requirements by the HS

Fig. 14 and 15 show the percentage of energy demand coverage as well as the average monthly energy production from each of the respective energy sources. The percentages of hydroelectric energy are reduced, compared to Scenario 1, because smaller amounts of energy are available for energy storage in the upper reservoir.

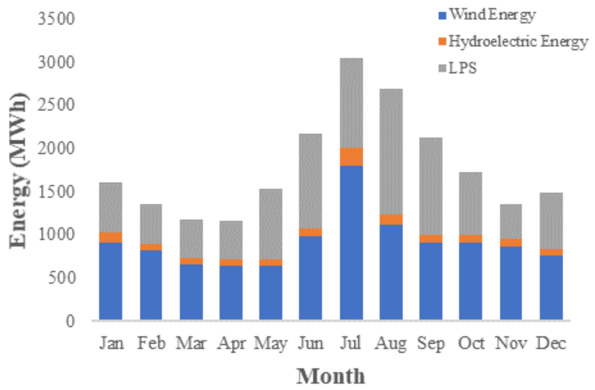


Fig. 14: Energy production per month

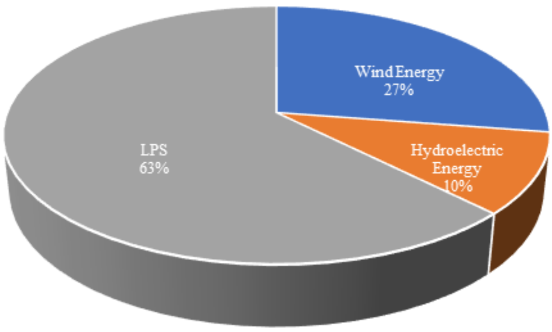


Fig. 15: Covering energy needs

Fig. 16 shows the average monthly production of desalinated water. It is obvious that in Scenario 2 much larger amounts of water are desalinated since the water supply is a priority. The production of drinking water in Scenario 2 can cover the water needs of the entire city of Kos, at a rate of 92%, as it is shown in Fig. 17. The use of HS for drinking water supply will improve groundwater quality and quantity. In particular, the level of the aquifer will rise and the risk of salinization of groundwater will be minimized.

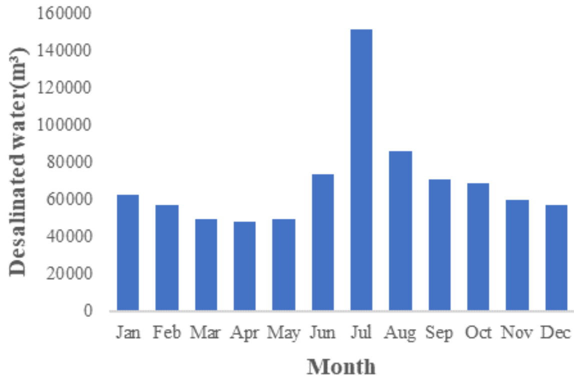


Fig. 16: Production of desalinated water per month

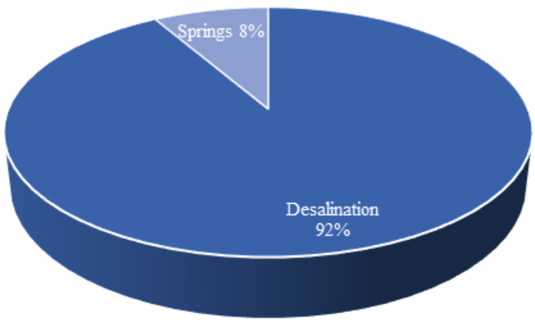


Fig. 17: Covering water needs

### 3.4 Comparison of $CO_2$ Emissions before and after the Integration of the Hybrid System

This subchapter presents data depicting the total $CO_2$ emissions from the operation of the LPS and the number of conventional vehicles on the island. The purpose is to compare the pollutants emitted before and after the integration of HS and electric vehicles. For the calculations, it is assumed that the $CO_2$ emissions for conventional vehicles are 120 g/km [39,40]. The $CO_2$ emissions of the LPS are considered about 0.92 kg $CO_2$/kWh [41]. Emission reductions are estimated to be 9720 tons of $CO_2$ per year in Scenario 1 and 6290 tons of $CO_2$ in Scenario 2. It is considered that the price is 60 € per ton for the first 10 years of operation [42]. In Fig. 18 the annual cost of the LPS before and after the inclusion of HS for each operating scenario is shown.

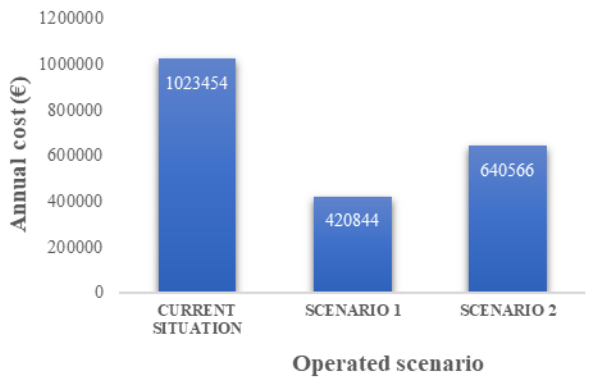


Fig. 18: Annual cost per case of operation

### 3.5 Cost-Benefit Analysis

The cost-benefit analysis [43,44] is based on the results of Scenario 1. The total amount of the investment amounts to 11333600 €, based on prices presented in [45]. The following financing scheme is provided for this investment: grant, bank loan, and own capital investment. The grant is given by an operational program for the promotion of RES in the islands and is set at 40% of the total cost [45], which is 4533440 €. The bank loan is taken for 40% of the investment, namely 4533440 € and finally, the same participation amounts to 20%, which corresponds to 2266720 €. Based on the assumptions mentioned above, the Net Present Value (NPV) of the investment is zeroing for a sale price of desalinated water at 2.18 €/$m^3$ and a fixed sale price of energy of 0,0875 €/kWh [46]. For this price, the Internal Rate of Return (IRR) is equal to the discount rate and the investment is marginally profitable [47]. Fig. 19 shows the efficiency of the project depending on the selling price of water through the NPV and IRR diagram for different water prices. Likewise, Fig. 20 shows the efficiency of the project depending on the selling price of energy through the NPV and IRR diagram for different energy prices. It is observed that for an extremely small increase in the selling price of either water or energy, NPV is increasing significantly because annual cash inflows are increasing. Specifically, an increase of NPV by approximately 400000 € corresponds to an increase in energy of just 0,00345 €/kWh discounts. Similarly, for the same increase in NPV, an increase in a water price of at least 0,07 €/m3 is required. In addition, it is worth noting that compared to the selling price of water; small changes in the selling price of energy have a greater effect on the NPV.

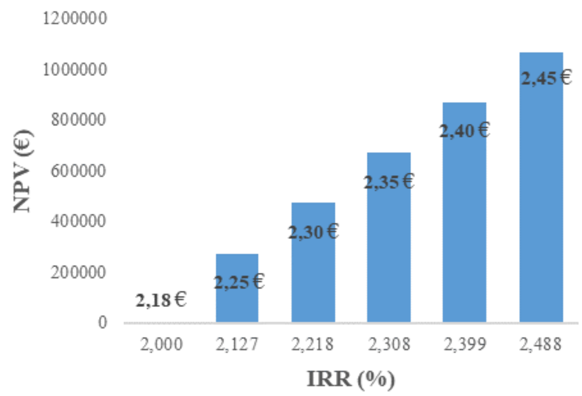


Fig. 19: NPV and IRR for different selling prices of desalinated water

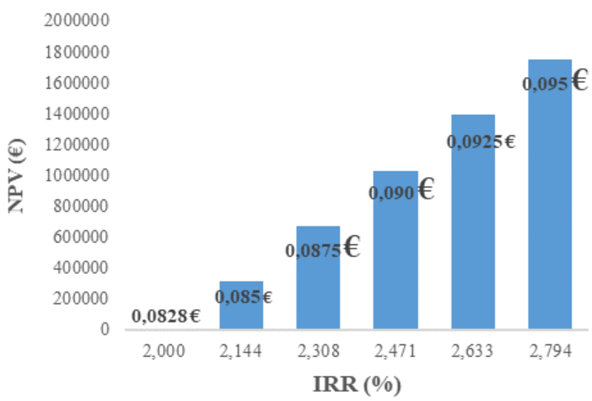


Fig. 20: NPV and IRR for different selling prices of energy

## 4 Discussion

This research work presents the assessment of an HS on the Greek island of Kos, to promote its contribution to local sustainability and energy independence. Data about the island's population and data on water and electricity consumption are collected, as well as data from the meteorological station of the island. In addition, based on the national plan of Greece, an estimation is made for the number of electric vehicles on the island of Kos and their energy requirements. Then, based on the processed data, two different operating scenarios are evaluated. The first scenario aims to meet the energy and water needs of Pyli (3500 inhabitants). The second scenario aims to cover the electromobility and water needs of 20000 inhabitants, which is equivalent to the entire city of Kos. The simulation uses hourly meteorological and demand data for the period 2016-2020. Also, results about $CO_2$ emissions, before and after the integration of the HS are presented and a cost-benefit analysis is performed for the first scenario.

Monthly energy production is maximized during the tourist months of July and August and minimized during March and April. In Scenario 1, in which energy demand is a priority, the requirements are covered by 60% by the HS on average. Specifically, 28% of the demands are covered by wind turbines and 32% by the hydroelectric station. This participation significantly reduces the emitted pollutants, as a result, the Greek state spares an estimated 600000 € per year, due to the reduction of the cost of $CO_2$ emission allowances. The HS's monthly coverage of energy requirements ranges from 58% in August to 82% in July. Also, the water demands of 3500 inhabitants are covered by 96% with drinking water from the desalination unit.

In Scenario 2, in which energy demand is a priority, the priority is to cover the energy needs of desalination and electromobility. The requirements are covered by 37% by the HS on average. Specifically, 27% of the demands are covered by wind turbines and 10% by the hydroelectric station. This participation significantly reduces the emitted pollutants, as a result, the Greek state spares an estimated 380000 € per year, due to the reduction of the cost of emission allowances. The HS's monthly coverage of energy requirements ranges from 46% in August to 71% in November. Also, the water demands of 20000 inhabitants are covered by 96% from the desalination unit. In addition, Scenario 2 covers 100% of the projected penetration of electromobility on the island of Kos until 2030 from the HS. In particular, the need for 174 electric cars, which are part of the national target, is adequately met. Even if the progress of the electric vehicles is made at a faster pace, the HS will be able to meet with 100% adequacy the needs of all vehicles, due to the energy storage that takes place.

# 5 Conclusions

Scenario 1 is more cost-effective and more environmentally friendly. However, in the future, when more electric vehicles will be used, increased amounts of energy will be required and Scenario 2 will be preferred for covering the required needs. The system seems to meet to a large extent the energy and water demands of the island of Kos. At the same time, the emitted pollutants are minimized and the groundwater table is increased. Thus, the problem of groundwater salinization will be addressed. In addition, the island becomes autonomous and self-sufficient, by producing drinking water and energy for all its annual needs. The area of the reservoir can be a place of recreation and green spaces can be developed around it. Electromobility will reduce pollution in the busy, tourist city of Kos, and noise pollution will be minimized since electric vehicles do not emit pollutants and are noiseless. Thus, the HS will make a significant contribution to the development of the area and improvement of the quality of life. The application of this methodology is suggested in other islands of Greece, interconnected and not, contributing to the local independence from the electrical network, increasing the contribution of RES, and reducing $CO_2$ emissions.

Based on this research work and its results, further research is proposed on the optimization of the HS. Also, the production of stochastic time series for the prediction of the future response of the HS would provide an overall picture for the optimization of the system. Finally, a multi-criteria analysis for the installation of each subsystem could enhance the minimization of the environmental impact of the HS.

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**Contribution of Individual Authors to the Creation of a Scientific Article (Ghostwriting Policy)**

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