

Article

Impact of Air Temperature Variation on a Wind-Driven Desalination System with Pumped-Hydro Storage: A Case Study of the Regional Unit of Rethymno, Crete, Greece

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Abstract

Water scarcity and increasing energy demand are critical challenges that often characterize Mediterranean regions, especially islands such as Crete. A sustainable solution for a combined water and energy supply lies in the domain of hybrid renewable energy systems. This research study evaluates a large-scale wind-driven desalination system with pumped-hydro energy storage for the Regional Unit of Rethymno, Crete, focusing on climate-driven demand and air temperature variation. The proposed system integrates wind energy production, seawater desalination, pumped-hydro storage, and water supply both for domestic and for irrigation purposes. Four scenarios, each with increasing air temperature, are examined in order to assess their effect on water demand and system performance. The analysis evaluates electricity allocation, the production of desalinated water, domestic and irrigation coverage, as well as the economic performance of the system. The results indicate that domestic water demand is almost fully covered in all four scenarios, reaching nearly 99.9%, while irrigation water coverage decreases from 82% under present conditions to 67% under higher-temperature scenarios. Wind-generated electricity is mainly used for water-related processes, with a constant share supplied to the grid. The economic assessment indicates that the system can operate under break-even conditions using realistic water and electricity prices.

Keywords: air temperature variation; climate change; Crete Island; desalination; pumped-hydro storage; Rethymno; water demand

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1. Introduction

Global electricity consumption has been steadily rising in recent years [1]. The main factors associated with this increase are population growth and rising living standards [2]. This trend underlines the necessity for cleaner and more sustainable methods of energy production [3]. The continuous reliance on fossil fuels as the main source of energy for numerous decades has been identified as a major contributor to greenhouse gas emissions in the European Union [4]. At the same time, the long-term availability of these finite resources has been proven questionable, thus raising further concerns [5].

The extensive use of fossil fuels has brought about climate change, which, in turn, has had a wide-ranging impact both on human activities and on natural systems [6]. Strik-

ing examples include the rise in the sea level due to ice melting [7], more frequent extreme weather phenomena and patterns, heavier rainfall in some areas, and more intense heat-waves and droughts in others, to name but a few [8]. Beyond the aforementioned environmental damage, these climatic changes have also taken their toll on human health, social stability and economic development [9].

Renewable energy sources, such as wind, solar, hydro, biomass, ocean, and geothermal energy, seem to be paving the way for the transition towards a more sustainable system of energy production [10]. These sources make use of naturally available energy flows, while reducing dependence on fossil fuels [11]. Their primary limitation, however, lies in their stochastic and variable nature [12], which affects the stability of energy supply [13]. A promising way to address this challenge is through the application of hybrid renewable energy systems [14]. In regions with high renewable potential, such as Crete, hybrid renewable energy systems can improve the reliability of the system, thereby supporting energy independence and self-sufficiency [15].

Hybrid renewable energy systems have become the focus of numerous studies that place an emphasis on the integration of renewable energy sources, desalination, and energy storage technologies. Babatunde and Olanrewaju [16] studied a solar-based system with hydrogen storage for seawater desalination in four coastal areas of South Africa; their findings suggest that the system can provide nearly total coverage of all water demand (99–100% reliability). They also showed minimal use of the fuel cell (<1%) and highlighted the need for extra water for the production of hydrogen (5504–8123 L/year). Consequently, hydrogen storage may be larger than needed unless its cost drops. Abbas et al. [17] investigated standalone solar, wind, and hybrid solar–wind systems combined with pumped-hydro storage for seawater desalination in coastal Saudi Arabia. Their study concluded that pumped-hydro storage leads to lower electricity costs (0.173–0.179 \$/kWh) and competitive water costs (0.787–0.899 \$/m³) compared to battery-based configurations. Asaduz-Zaman et al. [18] examined an autonomous renewable energy microgrid intended for seawater reverse osmosis desalination. They found that the combination of solar power, wind power, battery storage, and water tanks can lead to a reduction in the Levelized Cost of Water to 1.2004 \$/m³; the system, at the same time, ensures a reliable freshwater supply under conditions of variable demand. Papadaki et al. [19] studied hybrid renewable energy systems on European islands, making use of a literature review and a survey of 50 experts. They concluded that faster and simpler permits are the most important factor for the implementation of more projects (4.6/5); also, better policies and planning can improve energy security and reduce carbon emissions by up to 40%. Kim et al. [20] proposed a stochastic optimization framework for atmospheric water extraction under climate variability, highlighting the significance of meteorological conditions in system design.

Despite the existence of extensive literature on hybrid renewable energy systems and desalination, only a limited number of studies has integrated large-scale wind-driven desalination with pumped-hydro storage at a regional level in Mediterranean coastal areas; even fewer have considered the climate-driven demand, including the effect of increasing air temperature on water demand. Furthermore, most existing studies have carried out an evaluation of hybrid systems under fixed or average demand conditions, without explicitly incorporating a temperature-driven variability in regional water demand. This limitation reduces the realism of performance assessments in Mediterranean coastal regions, where irrigation water demand is highly sensitive to climatic fluctuations.

Given the limited research on this topic, the present research study considers the effect of increasing air temperature on water demand during the evaluation of the proposed hybrid renewable energy system.

Specifically, the study examines a hybrid renewable energy system for the Regional Unit of Rethymno. A literature review was carried out on renewable energy sources, de-

salination technologies, energy storage systems, and their integration within hybrid energy systems, both on an international and on a national level. Based on the analysis of regional data, a comprehensive proposal was drafted, aimed at the improvement of the local water and energy system. The main objectives were to achieve full coverage of domestic and irrigation water demand without increasing costs for residents, to support energy autonomy, and to promote the Regional Unit of Rethymno as an example of sustainable development. The proposed system is composed of a wind farm, a hydroelectric power plant, a desalination unit, and an integrated energy storage system.

The novelty of this research study lies in the explicit assessment of climate variability, focusing on changes in air temperature, in the design and evaluation of a hybrid wind-driven desalination system with pumped-hydro storage for the island of Crete and the Regional Unit of Rethymno. Unlike most existing studies that examine hybrid systems under fixed demand conditions, this research study evaluates how temperature-driven changes in water demand affect the operation of the system, the coverage of the water supply, and the distribution of energy at a regional scale. Rethymno can be described as a water-stressed coastal region of the Mediterranean, with strong seasonal demand. By applying the proposed framework to its Regional Unit, the research study provides a realistic and location-specific assessment that can support the sustainable planning of water and energy production and distribution. The aspect that makes the present research study unique is the combined assessment of climate variability, hybrid renewable energy integration, energy storage, and economic performance. In addition, the application of the proposed framework to Crete proves its suitability for a representative Mediterranean region facing significant water and energy challenges. This proposed methodological framework can be applied to any other region by incorporating site-specific climate change scenarios, meteorological data, renewable energy resources, and infrastructure characteristics.

The paper is organized as follows: Section 2 (Materials and Methods) describes the study area, the proposed hybrid energy system, and the examined climate-related scenarios. Section 3 (Results) presents the technical and economic results of the system under the different scenarios. Section 4 discusses the main findings in the context of the existing literature. Section 5 concludes the paper.

2. Materials and Methods

2.1. Study Area

The Regional Unit of Rethymno is located in central Crete, bordered by the Regional Unit of Chania to the west and Heraklion to the east. The Cretan Sea lies to its north and the Libyan Sea to its south. The region had a permanent population of 84,866 inhabitants in 2021, as indicated by the Population and Housing Census carried out in the same year [21], and covers a total area of 1494 km². During the summer months, the population rises significantly as a result of increased tourist presence [22]. The administrative capital is the city of Rethymno, situated along the northern coastline.

The climate of Rethymno lies under the classification of a “mild Mediterranean climate”, characterized by relatively mild winters and warm summers. Coastal areas benefit from maritime influence, therefore experiencing moderate summer temperatures. On the other hand, inland and mountainous regions exhibit characteristics similar to those of the mainland, including lower winter temperatures and increased thermal variability. Overall, the climate remains mild across the whole region throughout the year [23].

Meteorological data on air temperature, precipitation, and wind conditions for the Regional Unit of Rethymno were obtained from the Hellenic National Meteorological Service station in Souda [24]. The mean annual air temperature is 20.7 °C. The highest mean

monthly precipitation is observed in December (156 mm), whereas precipitation is negligible during the summer months, reaching 0 mm. Wind data cover the period 2015–2024.

Water demand in the study area is calculated based on per capita consumption and is estimated at 0.2 m³ per inhabitant and 0.3 m³ per tourist on a daily basis [25]. This is a typical value for domestic water use in Mediterranean regions [26]. This assumption accounts for daily household demand and provides a realistic basis for calculating total water demand at a regional level. The total domestic water demand amounts to 9,000,000 m³ on an annual basis, including tourists. The electrical energy required to desalinate this volume of water is 27,000,000 kWh annually, operating at a specific energy consumption of 3 kWh/m³ [27]. Figure 1 depicts the monthly variation in domestic water demand in the Regional Unit of Rethymno, which is used as input for the simulation model.

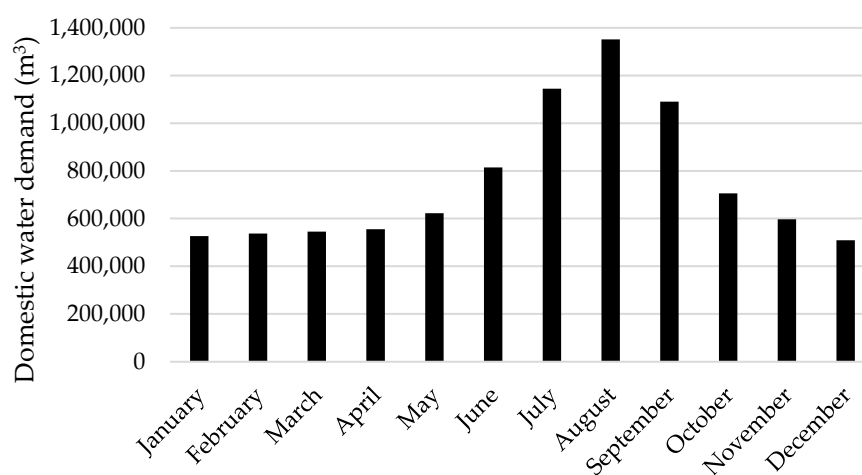


Figure 1. Monthly domestic water demand in the Regional Unit of Rethymno.

The Regional Unit of Rethymno is a diverse landscape, consisting of vast agricultural, forested, and semi-forested areas, as well as grazing land [28]. For the calculation of the volume of water required to meet the irrigation demand of local crops, the Blaney–Criddle method was applied, as shown on Equation (1) [29]. Evapotranspiration is determined using the sum of the products of the mean monthly temperature and the percentage of daylight hours for each month, under conditions of crops with adequate soil moisture.

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

where ET (mm/month) stands for the monthly potential evapotranspiration (mm), k for the crop coefficient, T for the mean monthly temperature (°C), and p (%) for the percentage of daylight hours for each month.

The total annual irrigation water amounts to 37,518,133 m³, which, in turn, corresponds to an energy requirement of 112,554,000 kWh for desalination.

2.2. Methods

The proposed system of renewable energy is mainly made up of a wind farm with a total installed capacity of 75,900 kW. It consists of 33 wind turbines rated at 2300 kW each. A seawater desalination unit is also incorporated into the system, with freshwater production of 39,600,000–42,100,000 m³ on an annual basis, corresponding to the capacity required in order to achieve maximum coverage of the water supply that corresponds to the examined demand conditions. In addition, a pumping station is included, featuring two main pumps at 25,000 kW as well as one auxiliary pump rated at 5000 kW. Seawater is first treated through desalination. Following this procedure, it is pumped to the upper reservoir, thereby enabling both water supply coverage and energy storage. During the

discharge phase, the stored water generates electricity by means of a hydro turbine while, at the same time, water is supplied directly to the distribution network.

Since the available wind speed data were measured at a height of 10 m, they had to be adjusted to the wind turbine hub height of 85 m using Equation (2) [30]. This correction was applied to obtain a more realistic estimation of the wind energy available for electricity generation.

$$V_2/V_1 = (y_2/y_1)^a, \quad (2)$$

where V_2 (m/s) is the wind speed at the turbine hub height (85 m), V_1 (m/s) is the measured wind speed at 10 m, y_2 and y_1 are the corresponding heights, and a is the surface roughness exponent, assumed to be equal to 0.20 for natural terrain.

Wind energy output was estimated based on the manufacturer's power curve of the selected wind turbine. Equation (3) describes a polynomial approximation of this curve. It is implemented in the simulation for wind speeds ranging from 1 to 14 m/s. In the cases where the wind speed drops below 1 m/s, the turbine remains inactive. For wind speeds ranging between 14 and 25 m/s, the turbine delivers its nominal capacity of 2300 kW, whereas for wind speeds exceeding 25 m/s, the operation of the turbine halts due to cut-out conditions. Equation (3) is expressed as follows:

$$P_{\text{wind}} = (0.0127 \cdot V^6 - 0.5432 \cdot V^5 + 8.4781 \cdot V^4 - 60.271 \cdot V^3 + 220.74 \cdot V^2 - 362.15 \cdot V + 196.69), \quad (3)$$

where V (m/s) describes the wind speed and P_{wind} stands for the electrical power output of the wind turbine (kW). A wind turbine availability of 97% was assumed throughout the simulation [31].

The system also includes a hydroelectric power plant. This functions by means of a Pelton-type turbine, designed to operate under water flow rates which range between 1 and 7 m³/s. The system features an existing upper reservoir with a total storage capacity of 1,200,000 m³, situated at an altitude of 450 m above sea level. During pumping operation, water is transferred to the upper reservoir with a pump efficiency of 90% [32]. When the upper reservoir reaches its storage limit of 1,200,000 m³, pumping ceases and surplus energy is not stored. During discharge, the electrical power output of the Pelton turbine (P_{hydro}) is calculated as described in Equation (4) [33]:

$$P_{\text{hydro}} = \rho \cdot g \cdot H \cdot Q \cdot n/1000, \quad (4)$$

where ρ stands for water density (1000 kg/m³), g for the gravitational acceleration (9.81 m/s²), H for the hydraulic head (m), Q for the turbine flow rate (m³/s), and n for the turbine efficiency (assumed equal to 0.85). P_{hydro} shows the electrical power output (kW), calculated as described in Equation (5).

The energy production (E), expressed in kWh, at each time step was calculated by applying

$$E = P \cdot t, \quad (5)$$

where P stands for the electrical power output (kW) and t for the simulation time step (3 h). The present analysis does not account for electrical losses in the system.

Electricity is produced by means of the wind turbines. Energy storage takes place through a pumped-hydro storage system, which converts the potential energy of stored water into electrical power. When local energy demand—associated with domestic and irrigation water—exceeds the wind power generated, then the stored energy is released to compensate for the deficit. Therefore, a stable and reliable energy supply for the region is ensured.

The simulation was performed in Microsoft Excel using historical data. Regarding the implementation of this model, a number of quality control routines were developed for the analysis and processing of the raw input data. A deterministic model was devel-

oped to support the verification and reproducibility of the simulation. Calculations were carried out using formulas and built-in data analysis tools. The operational behavior of the system was simulated using a 3 h temporal resolution. The reference period studied was 2015–2024. At each time step, five parameters were evaluated: namely, wind generation, desalination operation, pumping activity, storage charging and discharging, and demand coverage. This process allows for a realistic representation of short-term renewable variability and storage response.

Figure 2 depicts the energy flow from wind power to electricity supply, to desalination, to water demand, and, finally, to the pumped-hydro storage operation during excess and insufficient energy conditions. At each simulation time step, 30% of the wind-generated electricity is supplied directly to the power grid, while the remaining 70% is used by the proposed system. The available energy is first used for the desalination process to cover domestic water demand. Subject to sufficient water availability, irrigation demand is then addressed. In the case of excess electricity, water is pumped to the upper reservoir for energy storage. In the case of insufficiency in wind generation, the stored water is used to produce electricity by means of the hydro turbines.

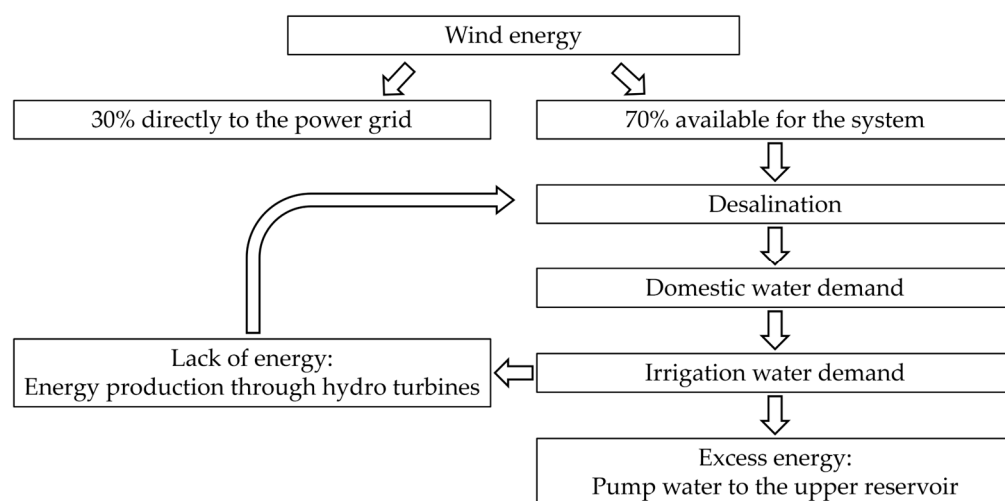


Figure 2. Flow chart illustrating the energy flow of the proposed hybrid system.

Four scenarios were analyzed, each under different climatic conditions, in order to deliver a robust assessment of the proposed hybrid energy system. All scenarios take the year 2050 as a point of reference. They differ solely in air temperature, thus reflecting varying levels of projected greenhouse gas emissions.

The climate scenarios applied in this research study are aligned with temperature change ranges, as these were reported in recent IPCC assessment reports for Mediterranean regions [34]. The selected temperature increments correspond to low-, medium-, and high-emission conditions, represented by the IPCC SSP1-2.6, SSP2-4.5, and SSP3-7.0 pathways [35]. These temperature increments fall within the IPCC-projected temperature ranges by the year 2050 for Mediterranean regions and were selected as representative values close to the central part of each range. The IPCC projects temperature increases relative to the present climate, specifically of 0–1.7 °C under SSP1-2.6, 0.2–2.0 °C under SSP2-4.5, and 0.5–2.6 °C under SSP3-7.0 for Mediterranean regions in 2050. Accordingly, representative temperature increases of +0.5 °C, +1.0 °C, and +1.5 °C relative to the present climate were selected for the examined scenarios. Air temperature is selected as the climatic variable for defining the examined climate scenarios, and the analysis applies incremental air temperature increases to examine their effect on water demand and system performance.

Scenario 1 depicts present-day air temperature conditions, while Scenarios 2, 3 and 4 correspond to low, medium, and high emission levels, respectively. As shown in Table 1, there is a 0.5 °C increase in air temperature in each scenario. Increasing temperature results in higher water demand, consequently highlighting the direct relationship between climatic conditions and the region's hydrological requirements.

Table 1. Definition of the climate scenarios considered in the analysis, based on incremental increases in air temperature relative to present-day conditions.

Scenario	Air Temperature
1	Present conditions
2	+0.5 °C
3	+1.0 °C
4	+1.5 °C

3. Results

3.1. Scenario Analysis

The use of multiple climate scenarios enables a systematic comparison of the model outcomes. This, in turn, allows for a comprehensive assessment of the operational performance of the proposed hybrid energy system. In addition, there is an evaluation of the effect of increasing air temperature on the coverage of regional water supply demand in the wider Rethymno area.

Table 2 describes the allocation of electricity generated by the wind turbines across the four examined scenarios. In all cases, 30% of the produced electricity is supplied directly to the grid, while the remaining 70% is used within the system for water-related processes. The 30% rate of electricity export to the grid was adopted following the results of previous research, where this percentage was found to reduce non-utilized energy while ensuring efficient system operation [36]. The percentage of electricity designated to desalination gradually increases from 33% in Scenario 1 to 37% in Scenario 4. This reflects an increase in water demand as air temperature increases. At the same time, the energy required for pumping drops from 14% to 11%, indicating a shift in the operation of the system. The percentage of non-utilized energy remains relatively stable in all four scenarios, with minimal fluctuations between 22% and 23%.

Table 2. Distribution of wind-generated electricity among grid supply, desalination, pumping, and non-utilized energy under the examined scenarios.

Scenario	Grid	Desalination	Pumping	Non-Utilized
1	30%	33%	14%	23%
2	30%	35%	13%	22%
3	30%	36%	12%	22%
4	30%	37%	11%	22%

The volume of desalinated water amounts to 39,600,000 m³ on an annual basis. This requires an annual input of electrical energy of 118,680,000 kWh. Seawater is drawn directly from the sea for desalination, and the available energy is used to produce the maximum possible volume of freshwater in order to meet regional water demand.

Figure 3 depicts the coverage of both domestic and irrigation water demand under each of the four examined scenarios, expressed as a percentage. In all cases, the system achieves almost a complete coverage of domestic water demand, reaching 99.9%, as water supply for domestic use is always prioritized over other uses.

Figure 3 also illustrates the coverage of irrigation water demand, which is directly linked to the availability of desalinated water. As air temperature increases, a gradual decrease in irrigation water demand coverage is observed. This reflects the corresponding rise in irrigation water requirements under warmer climatic conditions. Specifically, irrigation water demand coverage in Scenario 1 drops from 82% to 76%, 71%, and 67% for Scenarios 2, 3, and 4, respectively.

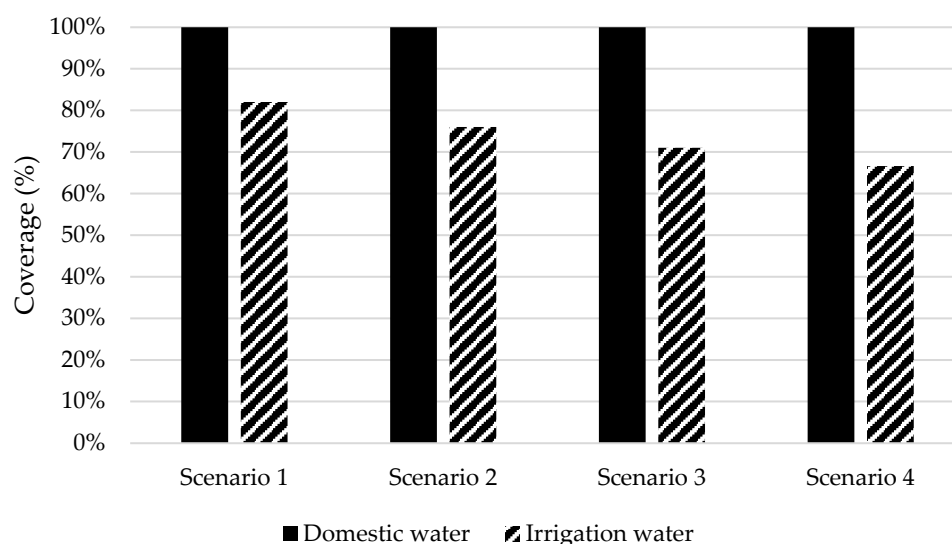


Figure 3. Percentage coverage of domestic and irrigation water demand under the four examined climate scenarios. Solid black bars represent domestic water coverage, while hatched bars indicate irrigation water demand coverage.

Table 3 depicts the coverage levels of domestic and irrigation water demand across the four examined scenarios. Domestic water demand is almost fully met in all scenarios, reaching 99.9%. Coverage of irrigation water demand gradually drops from 82% in Scenario 1 to 67% in Scenario 4 as water requirements increase. Despite the availability of surplus wind energy during certain periods, this does not always coincide with irrigation demand. In addition, the pumped-hydro storage system has a finite storage capacity, thereby limiting the amount of energy that can be stored and later used for irrigation.

Table 3. Percentage coverage of domestic and irrigation water demand under the four examined scenarios.

Scenario	Domestic Water Demand	Irrigation Water Demand
1	99.9%	82%
2	99.9%	76%
3	99.9%	71%
4	99.9%	67%

Figure 4 illustrates the annual volume of desalinated water produced and annual water demand for each examined scenario. The reported values refer to the total production of desalinated water annually, including both domestic water and water used for irrigation. The volume of desalinated water increases progressively and correspondingly with rising air temperature. This reflects higher water demand under warmer climatic conditions. Specifically, the production of desalinated water on an annual basis increases from 39,600,000 m³ in Scenario 1 to 40,200,000 m³ in Scenario 2, then to 41,200,000 m³ in Scenario 3, and reaches a maximum value of 42,100,000 m³ per year in Scenario 4. Overall,

this corresponds to an increase of 2,500,000 m³, or 6.5%, between present-day conditions and the high-emission scenario (Scenario 4). Despite the increase in desalinated water production under warmer climate scenarios, the gap between water demand and water production increases as well, as there is, also, a rise in annual water demand.

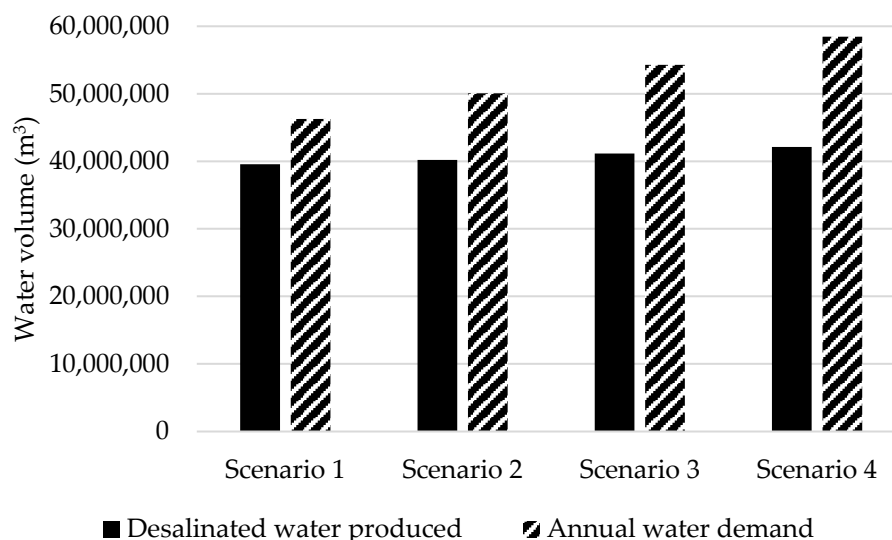


Figure 4. Annual volume of desalinated water produced and annual water demand under the four examined climate scenarios.

The efficiency of the pumped-hydro storage system is described as the ratio between the electrical energy generated during turbine operation and the electrical energy required for pumping. The overall efficiency amounts to 67%.

A sensitivity analysis was performed to evaluate the influence of precipitation and wind speed variability on the water coverage of irrigation for Scenario 1 (present conditions). As presented in Table 4, decreasing precipitation progressively reduced irrigation water coverage because of the lower availability of water resources, whereas increasing precipitation improved system performance. Similarly, the reduced availability of wind speed decreased renewable energy production and, consequently, the energy available for desalination and pumped-hydro storage, leading to lower water coverage meant for irrigation. Conversely, higher wind speed resulted in an improvement in system performance. The results indicate that the water coverage of irrigation is more sensitive to changes in wind speed than to changes in annual precipitation.

Table 4. Effect of precipitation and wind speed variations on irrigation water coverage for Scenario 1.

Change	Annual Precipitation (mm)	Irrigation Water Coverage	Annual Average Wind Speed (m/s)	Irrigation Water Coverage
−20%	360	73%	6.5	65%
−10%	405	78%	7.3	74%
0	450	82%	8.1	82%
+10%	495	86%	8.9	90%
+20%	540	90%	9.7	96%

An additional uncertainty analysis was performed for Scenario 1 (present conditions) to measure the effect of variations in key technical parameters on the proposed system. Wind turbine availability, desalination energy consumption, irrigation coefficient, and

storage efficiency were examined within representative operating ranges, while all other model parameters were kept constant. The corresponding changes in irrigation water coverage are presented in Table 5. The uncertainty analysis indicates that the proposed system maintains a high level of irrigation water coverage under all examined parameter ranges, ranging between 77% and 87%. Among the investigated parameters, desalination energy consumption and the irrigation coefficient exhibit the largest influence on irrigation water coverage, whereas wind turbine availability and storage efficiency have a comparatively smaller impact.

Table 5. Uncertainty analysis of wind turbine availability, desalination energy consumption, irrigation coefficient, and storage efficiency for Scenario 1, showing their effect on irrigation water coverage.

Parameter	Range	Irrigation Water Coverage
Wind turbine availability	90–99%	80–83%
Desalination energy consumption	2.5–3.5 kWh/m ³	86–77%
Irrigation coefficient	0.7–1.0	77–85%
Storage efficiency	60–75%	81–83%

3.2. Cost Analysis

To carry out the economic assessment of the system, it is first necessary to define the project time horizon, which corresponds to the operational lifetime of the installed technical components. The service life of the proposed system is assumed to be 25 years, as inferred by previous comparable large-scale infrastructure projects on renewable energy and water. The desalination unit is designed to meet the maximum water demand among the examined scenarios. Therefore, the installed capacity, investment cost, and operation cost remain unchanged. The annual desalinated water production varies according to the water demand of each scenario, while the estimated water selling price changes accordingly. The implementation of the system requires a total investment of 94,364,000 € as capital. The costs of the individual project components, presented in Table 6, are based on cost estimates derived from equipment and installation data of similar projects [37,38].

Table 6. Estimated equipment supply and installation costs of the project.

No.	Work Description	Cost (€)
1	Studies–supervision–permits	100,000
2	Desalination unit	12,000,000
3	Pumping station, pressure pipeline, transmission pipelines, automation	1,000,000
4	Upper reservoir construction	5,000,000
5	Hydroelectric power plant	8,000,000
6	Wind farm	50,000,000
	Total	76,100,000
	VAT (24%)	18,264,000
	Total including VAT	94,364,000

The annual operation and maintenance cost was estimated at 1,600,000 € per year based on previous studies [39,40]. This includes the operation and maintenance of all system components, while the desalination membranes were assumed to be replaced every 2 years [41]. The financing structure assumes a repayment period of 10 years for the loan, with debt servicing carried out through the annuity method, resulting in equal annual installments. Asset depreciation is applied at a rate of 10%. This is distributed over the first 10 years of system operation. For the purposes of the financial evaluation, a discount

rate of 2% is assumed. The main economic parameters used in the financial analysis are depicted in Table 7.

Table 7. Main economic parameters used in the financial analysis.

Parameter	Value
Total investment	94,364,000 €
Operation and maintenance cost	1,600,000 €
Discount rate	2%
Tax rate	35%
Project lifetime	25 years
Loan period	10 years
Membrane replacement	2 years

During the operational phase, project revenues are derived from the sale of both electricity and desalinated water. Table 8 reports the annual production volumes of desalinated water (m³) and electrical energy (kWh) corresponding to each examined scenario. It is assumed that 30% of the total electricity generated is directly exported to the power grid. The total production of desalinated water is distributed between domestic and irrigation uses. Table 8 presents these volumes separately.

Table 8. Annual volumes of desalinated water allocated to domestic and irrigation use, and electricity available for sale under the examined scenarios.

	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Domestic water (m ³ /year)	9,000,000	9,000,000	9,000,000	9,000,000
Irrigation water (m ³ /year)	30,600,000	31,200,000	32,200,000	33,100,000
Electrical energy (kWh/year)	54,600,000	54,600,000	54,600,000	54,600,000

For each examined scenario, a specific combination of selling prices for desalinated water and electricity results in a Net Present Value (NPV) equal to zero. Under such conditions, the Internal Rate of Return (IRR) coincides with the applied discount rate (ϵ). This indicates that the investment is marginally profitable.

The selling price of desalinated water in Greece generally ranges from 0.24 €/m³ to 2.00 €/m³ [42]. Within this range, the present analysis adopts a selling price of 0.26 €/m³ for domestic water and 0.050 €/m³ for irrigation use. A 35% tax rate is applied to net profits, which are calculated after accounting for annual operation and maintenance costs, depreciation, and interest payments.

Table 9 depicts the selling prices of desalinated water and electricity required to satisfy the zero-NPV condition for each examined scenario, following the aforementioned economic assumptions. The selling price of desalinated water was defined a priori, while the corresponding electricity selling price was subsequently calculated so that the NPV of the investment equals zero.

Table 9. Water and electricity selling prices for the zero-NPV condition.

	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Domestic water price (€/m ³)	0.26	0.26	0.26	0.26
Irrigation water price (€/m ³)	0.050	0.049	0.048	0.046
Electrical energy price (€/kWh)	0.05	0.05	0.05	0.05

In addition, the Levelized Cost of Water (LCOW) and the Levelized Cost of Energy (LCOE) were both calculated to provide additional indicators of economic performance for the proposed integrated water–energy system. The LCOW and LCOE represent the

average unit costs of water and electricity production over the lifetime of the project, taking into account the investment and operational costs. Based on this approach, the LCOW and LCOE were calculated as 0.08 €/m³ and 0.04 €/kWh, respectively. Furthermore, the payback period was calculated as 19 years, indicating the time required to redeem the initial investment. The profitability index was calculated as 1.00, corresponding to the break-even condition (NPV = 0) adopted in the present economic assessment.

To justify the selected wind farm capacity, alternative wind farm configurations were evaluated by comparing the corresponding investment cost, the energy utilized on an annual basis, and the investment cost-to-utilized annual energy ratio. This assessment was carried out in order to identify the most cost-effective wind farm configuration. The results are depicted in Table 10.

Table 10. Comparison of alternative wind farm capacities based on investment cost, utilized annual energy, and the investment cost-to-utilized annual energy ratio.

Number of Wind Turbines	Installed Capacity (kW)	Investment Cost (€)	Utilized Annual Energy (kWh/year)	Investment Cost-to-Utilized Annual Energy Ratio (€/kWh)
31	71,300	47,000,000	51,000,000	0.922
32	73,600	48,500,000	52,800,000	0.919
33	75,900	50,000,000	54,600,000	0.916
34	78,200	51,500,000	54,700,000	0.941
35	80,500	53,000,000	54,750,000	0.968

As presented in Table 10, the 75,900 kW wind farm provides the lowest investment cost-to-utilized annual energy ratio among the examined configurations. An increase in the installed capacity beyond this value will result in only a marginal increase in utilized annual energy, while the investment cost continues to rise. Therefore, the selected 75,900 kW configuration represents the most cost-effective solution among the examined alternatives.

A sensitivity analysis is also carried out for Scenario 1 (present conditions) to evaluate the effect of changes in the main economic parameters on the financial performance of the proposed system. Specifically, the discount rate, domestic water price, irrigation water price, electrical energy price, and total investment cost were varied by ± 10 and 20%, while all other variables were held constant. The results are depicted in Table 11.

Table 11. Sensitivity analysis of the discount rate, domestic water price, irrigation water price, electrical energy price, and total investment cost on the NPV of Scenario 1.

Change	Discount Rate	NPV (€)	Domestic Water Price (€/m ³)	NPV (€)	Irrigation Water Price (€/m ³)	NPV (€)	Electrical Energy Price (€/kWh)	NPV (€)	Total Investment Cost (€)	NPV (€)
−20%	1.6%	4,350,000	0.21	−8,678,000	0.040	−5,674,000	0.040	−10,124,000	75,491,000	18,503,000
−10%	1.8%	2,135,000	0.23	−4,339,000	0.045	−2,837,000	0.045	−5,062,000	84,928,000	9,251,000
0	2.0%	0	0.26	0	0.050	0	0.050	0	94,364,000	0
+10%	2.2%	−2,058,000	0.29	4,339,000	0.055	2,837,000	0.055	5,062,000	103,800,000	−9,251,000
+20%	2.4%	−4,043,000	0.31	8,678,000	0.060	5,674,000	0.060	10,124,000	113,237,000	−18,503,000

The results indicate that the financial performance of the proposed system is sensitive to changes in all five economic parameters. As expected, higher water and electricity prices improve the NPV, whereas increases in the discount rate and total investment cost

reduce the project's economic performance. Among the examined parameters, total investment cost has the highest impact on the NPV.

An inflation sensitivity analysis was also performed by applying annual changes of −2%, −1%, +1% and +2% to operation and maintenance costs, while selling prices were kept constant. Under these assumptions, the 25-year NPV increases from zero in the baseline case to 6,000,000 € and 3,200,000 € for the −2% and −1% cases, respectively, and to −3,700,000 € and −8,000,000 € for the +1% and +2% cases, respectively. The analysis shows that long-term changes in operating costs affect the economic performance of the proposed system.

An electricity market volatility analysis was performed by applying annual changes of −2%, −1%, +1%, and +2% to the electricity selling price, while all other parameters were kept constant. The corresponding 25-year NPVs were −10,200,000 €, −5,400,000 €, 6,300,000 €, and 13,600,000 €, respectively. The analysis demonstrates that long-term electricity price fluctuations influence the economic performance of the proposed system.

In addition to the economic indicators presented, the environmental benefit of the proposed system was also quantified. Based on the average Greek electricity emission factor (0.4085 kgCO₂/kWh) [43], the renewable electricity generated by the proposed system is estimated to prevent the release of 22,300 tones of CO₂ annually, compared to electricity supplied by the Greek power system. Assuming a carbon price of 80 €/tonCO₂ [44], the corresponding avoided carbon cost is 1,780,000 € per year.

Future improvements in desalination technologies are expected to further enhance the economic performance of the proposed system. Assuming reductions of 10% and 20% in the specific energy consumption of the desalination process (from 3.0 to 2.7 kWh/m³ and 2.4 kWh/m³, respectively), the corresponding annual electricity cost savings are estimated at 594,000 € and 1,190,000 €, respectively. These improvements would reduce the operating costs and enhance the economic viability of the proposed integrated water–energy system in the long term.

4. Discussion

The results demonstrate that the water requirements of the Regional Unit of Rethymno are directly affected by increasing air temperature, and, consequently, so is the operation of the proposed hybrid renewable energy system. Although the system maintains a high level of domestic water supply coverage under all examined scenarios, the increasing irrigation demand gradually reduces the coverage of the water used for irrigation. This trend indicates that higher air temperatures primarily increase water demand meant for irrigation, while the adopted operational strategy successfully prioritizes domestic water supply. These findings are consistent with those reported by Xiao et al. [45], who also indicated that increasing air temperature significantly influences water use under future climate scenarios.

The proposed methodology was validated through a comparison with previously published studies that involve similar hydrometeorological conditions, topography relief, hybrid renewable energy and desalination systems. Allouhi and Almohammadi [46] reported renewable energy fractions ranging from 31% to 36% and a cost of energy between 0.0700 and 0.0783 \$/kWh for hybrid renewable energy-powered reverse osmosis desalination systems. These values are aligned with the results obtained in the present research study and further support the reliability of the proposed methodology. Jones et al. [47] reported a renewable fraction of 74.84% and an overall system efficiency of 60.15% for an integrated renewable energy system that combines electricity, desalination, and green hydrogen production. These findings are consistent with the present research study and further support the reliability of the proposed methodology. Similar findings have been reported by Skroufounta et al. [48], who proposed a hybrid renewable energy system com-

binning wind energy, reverse osmosis desalination, and seawater-pumped storage hydropower for Karystos, Greece. Their system achieved 99% drinking water reliability and 86% energy coverage. These findings are also consistent with the present research study and further support the applicability of the proposed methodology under Mediterranean conditions.

The reduction in the water coverage of irrigation highlights the lower capacity of the agricultural sector when it comes to coping with increasing water stress under warmer climate conditions. This finding underscores the importance of adaptive water management strategies to enhance agricultural resilience and improve the long-term sustainability of agricultural water management in Mediterranean regions that are faced with increasing frequency of drought [49]. The reduction observed in irrigation water coverage also indicates that additional adaptation measures may become essential under warmer climate conditions. In Mediterranean regions, increasing pressure on water resources highlights the necessity for improved irrigation management and, where necessary, the expansion of water supply infrastructure to maintain reliable water supply for the purpose of agriculture [50]. The present findings are also consistent with recent reviews on renewable energy-powered desalination for island systems, which identify hybrid wind-powered desalination as a promising approach for improving water supply resilience while supporting the transition towards integrated water–energy management [51]. Furthermore, recent studies on Mediterranean islands report that increasing temperatures intensify both drought conditions and water scarcity, highlighting the necessity of adopting integrated adaptation strategies, including desalination, water storage, and improved water management to enhance long-term water security [52].

The reduction in irrigation water coverage may affect agricultural productivity, particularly during periods of high water demand, as crops may not receive an adequate amount of irrigation water [53]. It may also increase pressure on regional water resources, highlighting the importance of efficient water allocation under warmer climate conditions [54]. These findings underline the necessity of adopting climate adaptation measures, such as improved irrigation management [55] and water-saving practices, to maintain reliable water supply under future climate conditions [56].

The economic results obtained in the present research study are consistent with previous techno-economic studies carried out on renewable energy-powered desalination systems. A domestic water price of 0.26 €/m³ and an irrigation water price of 0.046–0.050 €/m³ were estimated, while Martínez and Martín [57] reported desalinated water production costs ranging from 0.60 to 1.00 €/m³ for reverse osmosis systems. Similarly, Kuralov et al. [58] reported water production costs ranging from 0.59 to 2.81 €/m³ for hybrid renewable energy desalination systems. The estimated water prices are lower than the values reported in previous studies, as they represent the minimum selling prices required to achieve the zero-NPV condition. The selling price of electricity, estimated at 0.05 €/kWh, is similar to values reported in previous studies. Kaygusuz and Kolay [59] reported electricity costs between 0.02 and 0.19 USD/kWh for hydropower projects, while the estimated selling price of electricity in the present study is 0.05 €/kWh.

The comparison with previously published studies revealed both similarities and differences. The observed similarities confirm the reliability and consistency of the proposed methodology, while the differences are mainly attributed to variations in climatic conditions, renewable energy resource availability, and water demand.

Although the present research study focuses on the Regional Unit of Rethymno, the proposed framework can also be applied to other Mediterranean and water-stressed regions facing similar climatic conditions. The simulation methodology, system operation, and economic evaluation are transferable, whereas input data such as renewable energy resources, water demand, climate conditions, and economic parameters should be

adapted to reflect the characteristics of each study area. Therefore, the proposed framework provides a useful tool for supporting the planning of sustainable water and energy systems under different regional conditions.

5. Conclusions

This research study elaborates on an integrated methodology for the design, construction, and implementation of a hybrid renewable energy system which combines wind energy, desalination, and pumped-hydro storage in the Regional Unit of Rethymno. The applied framework examines climate-driven scenarios for the year 2050: stepwise air temperature increases of 0.5 °C define each scenario, and system performance is evaluated in terms of water supply coverage, energy production, and economic viability.

The analysis of electricity allocation shows that the proposed system consistently prioritizes water-related uses. In all four scenarios, 70% of the wind-generated electricity is utilized within the system, while a stable share of 30% is supplied directly to the grid. As air temperature increases, a gradually larger fraction of electricity is used for the purpose of desalination. This percentage rises from 33% to 37%, while the energy required for pumping decreases from 14% to 11%. At the same time, non-utilized energy remains limited and relatively stable, thereby indicating an efficient redistribution of available renewable energy to meet increasing water demand.

Almost full coverage of domestic water demand (99.9%) is ensured across all four scenarios, as desalination is applied to respond to water demand. Irrigation water demand is not fully satisfied in any of the four scenarios. As water requirements increase, coverage of irrigation demand decreases from 82% in Scenario 1 to 76%, 71%, and 67% in Scenarios 2, 3 and 4, respectively.

The economic assessment indicates that the proposed hybrid system is financially viable under realistic assumptions. For a project lifespan of 25 years and a total investment cost of 94,364,000 €, break-even conditions are achieved in all examined scenarios. Specifically, a combination of selling prices for desalinated water and electricity results in an NPV equal to zero, with the IRR matching the applied discount rate of 2%. By estimating water selling prices at 0.26 €/m³ for domestic use and at 0.050 €/m³ for irrigation, the required electricity selling price is calculated at 0.05 €/kWh. These results indicate that the system can meet water and energy demands while remaining economically balanced, even in the event of increased water demand conditions associated with higher air temperatures.

There are certain limitations mainly related to climate projections, economic parameters, and system operation, which are accounted for in the present analysis. Climate variability is represented solely through incremental changes in air temperature. Therefore, other climatic factors are not explicitly taken into consideration. In addition, the analysis does not account for potential future changes in the availability of wind resources or technological performance. These factors could reduce the water coverage and affect the economic performance of the proposed system under future climate conditions. The economic evaluation is based on current cost assumptions and fixed selling prices. Although sensitivity analyses of operation and maintenance cost escalation and electricity price volatility are included, a fully dynamic representation of future market conditions and broader economic impacts of climate change is not considered. Similarly, the system operation is based on the assumptions adopted in the present research study and does not account for possible future changes in operating conditions.

However, future research could incorporate more comprehensive climate projections, dynamic economic conditions, and different system operation, while focusing on the application of the proposed methodology to other Greek islands as well as to small, water-stressed regions, both interconnected and non-interconnected. This will allow for

the assessment of its wider applicability and scalability. Further work may also include a more detailed spatial analysis for the optimal siting of desalination units, reservoirs, and pumping infrastructure, as well as the optimization of seawater intake, water distribution, and energy transmission networks. In addition, the accuracy of the results could be improved by making use of higher-resolution data on population, tourism activity, and energy demand, together with the installation of additional meteorological stations. Finally, the development of long-term time-series simulations would allow for a more detailed evaluation of the performance of the system under future climatic conditions and increasing water demand.

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Abbreviations

The following abbreviations are used in this manuscript:

IPCC	Intergovernmental Panel on Climate Change
IRR	Internal Rate of Return
LCOE	Levelized Cost of Energy
LCOW	Levelized Cost of Water
NPV	Net Present Value

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