

Original Research

Restoring the Resilience of Water-Energy-Food Nexus Based on Desalination through Biomass Management: Case Study West Mani, Greece

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Abstract

Mediterranean regions like West Mani, Greece, face escalating water scarcity exacerbated by climate variability and seasonal tourism peaks, straining the water-energy-food (WEF) nexus. Olive cultivation, central to the region's economy and culture, generates substantial underutilized biomass residues that increase wildfire risk if left unmanaged. At the same time, water supply increasingly relies on energy-intensive desalination and pumping. This study addresses the gap in integrated, place-based WEF nexus applications by quantifying the potential of local olive biomass (pruning, grasses, and pits) to power desalination and water distribution. Using remote sensing for olive grove mapping, field data validation, village-level water demand modelling (including tourism scenarios), and energy system analysis, we assessed biomass availability and conversion feasibility. Results show that approximately



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2,900-3,800 tonnes of recoverable dry biomass per year can generate 2.8-3.6 GWh of electricity annually, sufficient to fully cover the required energy for multi-site desalination (brackish and seawater reverse osmosis) and elevation-specific pumping under high-demand tourism conditions. This novel contribution lies in closing the resource loop through a replicable, community-scale framework that simultaneously achieves energy autonomy for water security, reduces wildfire risk via managed pruning (creating firebreaks), and enables ash reuse as soil amendments, offering a practical model for other tourism-dependent Mediterranean areas seeking resilient, synergistic resource management.

Keywords

Water-energy-food nexus; water scarcity; biomass; desalination; wildfire protection

1. Introduction

1.1 Prolegomena

The water-energy-food (WEF) nexus framework has emerged as a critical approach for understanding and managing the interdependencies between water, energy, and food systems, particularly in regions facing resource scarcity and environmental challenges [1, 2]. In Mediterranean regions like West Mani, Greece (Figure 1), these challenges are exacerbated by climate variability, water scarcity, and increasing demands from tourism [3].

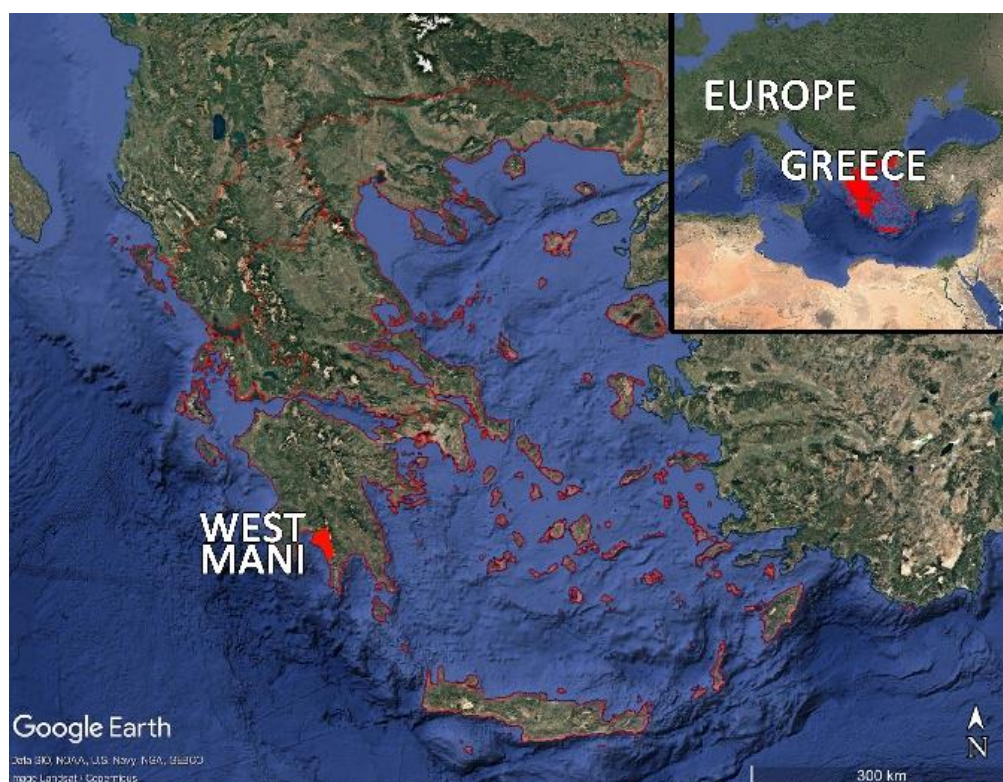


Figure 1 Map of Greece with the location of West Mani indicated in red [4].

The climate is characterized by pronounced rainfall seasonality, with wet winters (peak in January at ~90 mm monthly average) and dry summers (minimal in August at ~10 mm), resulting in annual precipitation of 575 mm concentrated from October to March. This pattern exacerbates summer water shortages, particularly during tourism peaks (Figure 2).

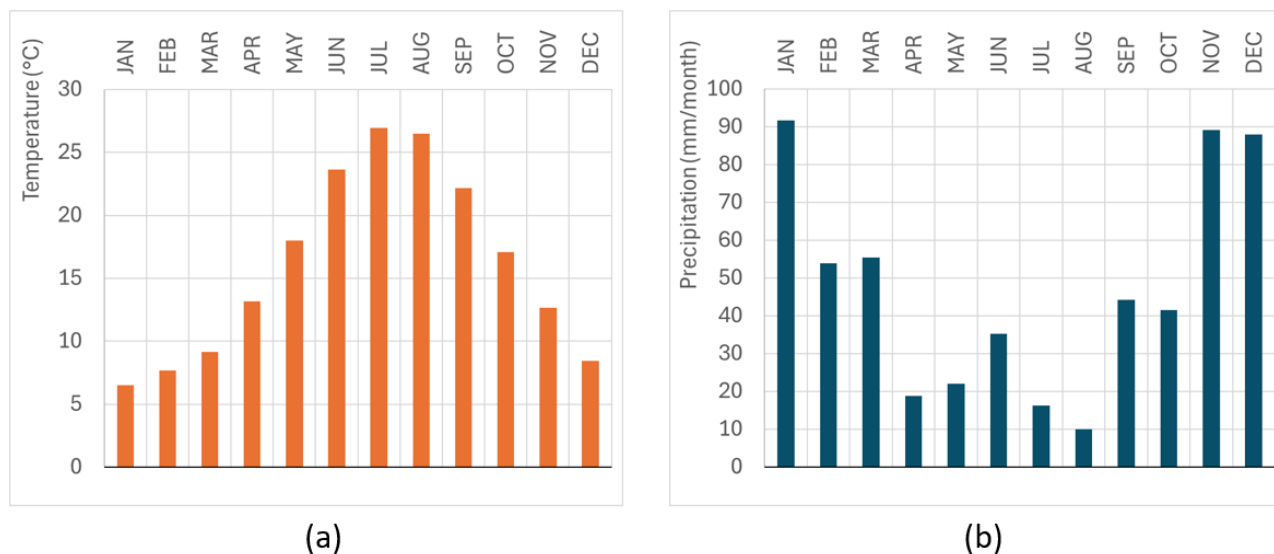


Figure 2 Average monthly climate profiles in West Mani [5] (a) Temperature (b) Precipitation.

Hydrogeologically, the region features karstic limestone formations with coastal aquifers prone to seawater intrusion due to overexploitation. The existing brackish aquifer near Agios Nikolaos has depths of 100-140 m and moderate salinity (estimated 5-10 g/L TDS, lower than seawater's ~35 g/L).

Topographically, West Mani's rugged terrain includes steep slopes from shoreline to inland villages, with elevations ranging from sea level to 50-650 m (e.g., coastal hubs like Stoupa at ~50 m, upland villages like Milea at ~650 m). Existing water infrastructure includes a BWRO unit in Agios Nikolaos producing 1,000 m³/day, supplemented by limited rainwater harvesting and grid-supplied pumping [6]; however, seasonal demands require expansion.

West Mani, a region characterized by its extensive olive groves, rugged terrain, and reliance on tourism (Figure 3), exemplifies the complexities of balancing resource use with sustainability [7-9]. Olive cultivation, a cornerstone of the region's cultural heritage, contributes significantly to food production (olives and olive oil) while generating substantial biomass through pruning, grasses, and olive pit residues. However, the region faces pressures from water scarcity, necessitating energy-intensive desalination [10].

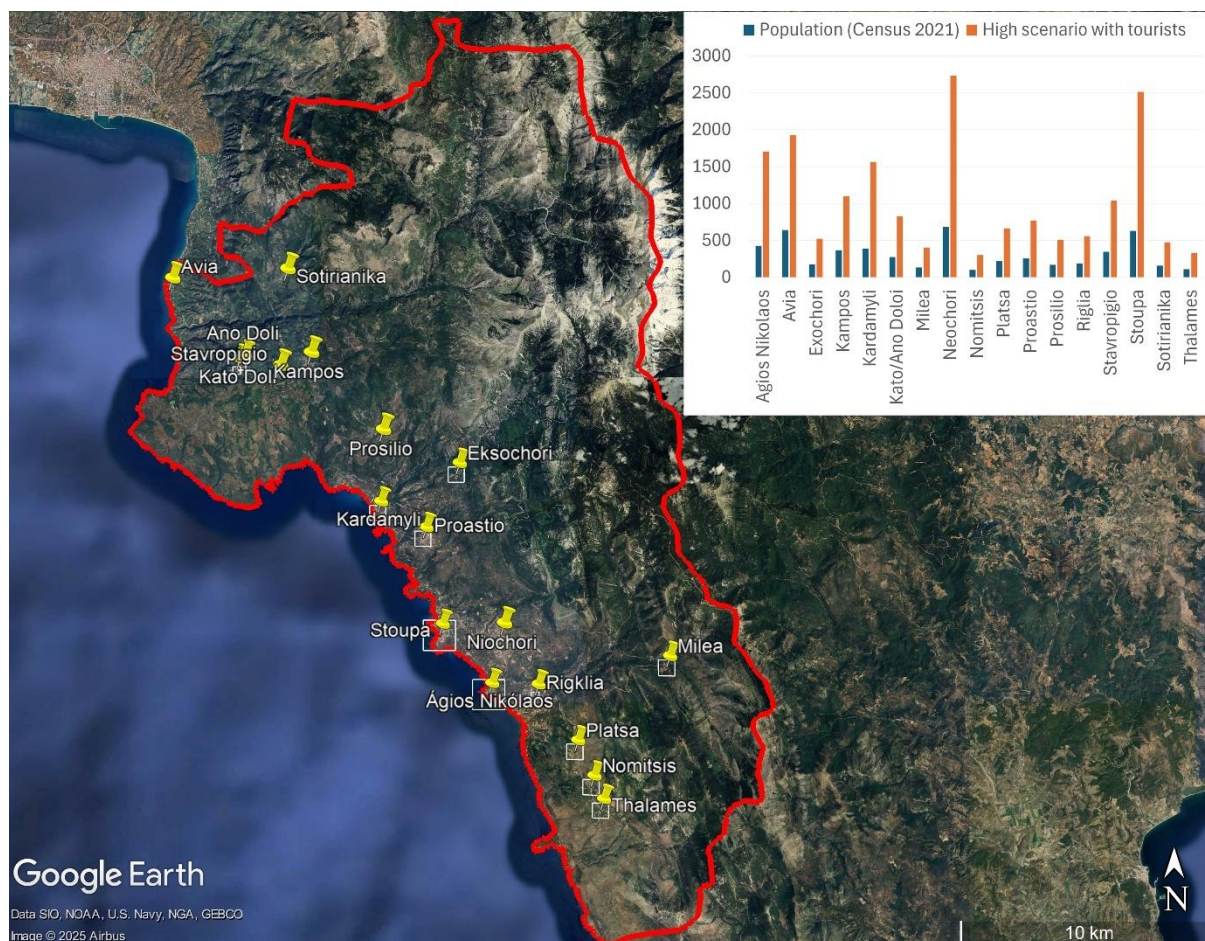


Figure 3 Map of West Mani indicating the main villages with more than 100 inhabitants. The diagram shows the inhabitants and the high scenario with tourists [4].

The WEF nexus approach promotes integrated resource management to optimize synergies and minimize trade-offs across sectors [11]. In West Mani, the nexus is particularly relevant due to the interplay between olive-based agriculture, energy demands for water desalination, and the potential for biomass to serve as a renewable energy source [12]. Olive trees, approximately 50 years old on average in this region, produce not only food but also biomass, which is so far largely unutilized. This biomass can be harnessed for electricity generation, potentially offsetting the energy demands of the necessary water infrastructure of the region, like desalination and water pumping [13]. Additionally, biomass management, including pruning and grass clearing, also serves as a critical fire prevention strategy, reducing fuel loads compared to unmanaged cultivations, which are more susceptible to wildfires [14, 15].

Desalination is increasingly adopted in water-scarce regions like West Mani to meet water needs, particularly during the summer tourist season [16]. However, desalination is an energy-intensive process, producing water at sea level, with additional energy for pumping to elevated villages [17]. The reliance on the energy grid for desalination underscores the need for renewable energy integration [18]. The dual role of biomass in energy generation and fire risk reduction aligns with sustainable development goals, particularly those related to clean water, affordable and clean energy, and zero hunger [19].

1.2 Literature Review

The water-energy-food (WEF) nexus has been extensively explored as a framework for addressing interconnected resource challenges, particularly in water-scarce regions like the Mediterranean. This review synthesizes prior work into key themes: conceptual foundations of the WEF nexus, applications in Mediterranean contexts, integration of biomass for energy production, desalination's role in water security, and synergies with environmental risk management, such as wildfire prevention.

- **Conceptual Foundations and Methodological Approaches:** Early studies established the WEF nexus as a tool for understanding trade-offs and synergies among water, energy, and food systems, emphasizing the need for integrated assessments to achieve sustainable development goals [20, 21]. Systematic reviews have highlighted methods for nexus evaluation, including system dynamics modeling and quantitative frameworks that assess resource interdependencies, often revealing gaps in linking theoretical models to practical implementation [22-24]. These approaches underscore the importance of multi-stakeholder involvement to balance competing demands, particularly under climate pressures.
- **Applications in Mediterranean and Arid Regions:** In the Mediterranean basin, the nexus is critically influenced by climate variability, seasonal tourism, and agricultural demands, with studies focusing on policy reviews [25, 26]. Research in Southern Europe and North Africa has examined how nexus thinking can transition to actionable strategies, addressing water scarcity in arid coastal areas through context-specific interventions [27]. Policy analyses across Mediterranean countries reveal institutional barriers and opportunities for cross-sectoral coordination, often incorporating ecosystem services to enhance resilience [28].
- **Biomass Integration for Energy in the Nexus:** Biomass from agricultural residues, such as olive byproducts, has been investigated as a renewable energy source within the WEF framework, particularly for offsetting energy-intensive processes in food-producing regions [29]. Studies in arid zones highlight the multi-benefit synergies of biomass utilization, including energy generation and waste reduction, while emphasizing challenges like spatial heterogeneity and collection logistics in small-scale farming systems [30].
- **Desalination's Role in Water-Energy Linkages:** Desalination emerges as a key technology for water security in nexus studies, with analyses quantifying its energy footprint and potential integration with renewables to mitigate trade-offs [20, 25]. In Mediterranean settings, research explores how desalination can support food production amid rising demands, though it often stresses the need for energy-efficient designs to avoid exacerbating energy scarcity [26].

Overall, prior work identifies persistent gaps in place-based, multi-benefit applications, not particularly linking biomass-derived energy to desalination while addressing wildfire risk areas, which this study aims to advance through quantification in West Mani.

1.3 Research Gap and Contributions

The study examines water consumption patterns across West Mani's villages, accounting for both residents and seasonal tourists, to calculate the energy required for water supply by desalination and pumping. By estimating olive tree density, biomass accumulation [14], and food production, we provide a comprehensive analysis of resource availability. Through this integrated

approach, we propose a renewable energy source (biomass) to meet water and energy demands while enhancing fire resilience and supporting sustainable agriculture [31]. To the existing WEF nexus literature [32-34] is added a more targeted contribution through the development of a locally adapted and practical framework for resource management in the Mediterranean context. While the water-energy-food (WEF) nexus framework has been widely applied to analyze interdependencies in resource-scarce regions, and olive biomass residues (from pruning, pits, and grasses) have been extensively studied for bioenergy production in Mediterranean contexts, several key gaps remain in the literature:

- Lack of integrated place-based applications linking biomass to desalination energy demands.
- Limited consideration of spatial heterogeneity.
- Under-explored multi-benefit synergies, particularly wildfire risk reduction.
- Absence of replicable frameworks for small-scale Mediterranean communities.

This paper addresses these gaps through the following concrete contributions:

- Provides a place-based quantification for West Mani, Greece, demonstrating that 2,900-3,800 tonnes/year of recoverable olive residues can generate 2.8-3.6 GWh of electricity, sufficient to fully power local desalination (brackish and seawater RO) and elevation-specific pumping needs under high tourism demand scenarios.
- Develops an integrated spatial model combining remote sensing-derived olive grove mapping, village-level water consumption (including tourist peaks and swimming pools), clustered multi-site desalination design, and amortized capital costs.
- Explicitly incorporates wildfire risk reduction as a nexus co-benefit, comparing managed vs. unmanaged groves and highlighting how pruning/residue removal creates firebreaks while supplying energy.
- Offers a replicable framework for other Mediterranean communities, emphasizing resource synergies (energy autonomy, ash reuse as soil amendments, community self-sufficiency) and practical implementation considerations (e.g., biomass collection from small holdings, ORC or gasification technologies).

These advancements provide a targeted, practical contribution to WEF nexus literature by closing the loop between olive agriculture, tourism-driven water stress, renewable energy, and landscape fire resilience in a specific Mediterranean context.

2. Methodology

To address the objectives of restoring the stability of the water-energy-food nexus in West Mani, this study employs a multi-step, integrated approach combining remote sensing, field data analysis, and modelling. The methodology is structured to quantify olive tree biomass, food production, energy generation potential, water consumption, and energy requirements for desalination and pumping, while proposing a sustainable energy mix. Below, we outline the key steps. The studied issues are presented symbolically in Figure 4, and the interactions between the issues are analyzed using the methodology and are visualized with arrows.

1. Water Consumption Estimation:

- Population and Tourism Data: Census data for West Mani villages will provide resident populations. Tourist numbers will be estimated based on regional tourism statistics, assuming a population increase during summer months [29].

- Domestic Water Demand: It is estimated that the average Greek consumes 63 m³ of water per year (which corresponds to 173 L/day) [35, 36]. The minimum water needs are estimated at 18.5 m³ per year (which corresponds to 50 L/day) [37]. The estimated water consumption by tourists is 200-300 L/day. As olive trees are on average 50 years old, no irrigation needs are considered [38, 39].
2. Energy Requirements for Desalination and Pumping; Identification of infrastructures:
- Desalination Energy: Reverse osmosis desalination energy requirements will be assumed at 5 kWh/m³ at sea level, based on standard systems [32].
 - Pumping Energy: Energy (in MJ) for pumping water to villages will be calculated using the formula (equation 1):

$$E = \frac{\rho(kg\ m^{-1})g(m\ s^{-1})V(m^3)H_M(m)}{3600n} \quad (1)$$

where: ρ = density of the water; g = gravity constant; H_M = manometric height; n = efficiency coefficient.

Elevation data for each village will be sourced from topographic maps.

Friction losses were calculated using the Darcy-Weisbach (equation 2):

$$h_f = \frac{f * V^2}{D * 2 * g} * flow_{length} \quad (2)$$

where: f is the Darcy friction factor; L is pipe length (m); D is pipe diameter (m); V is flow velocity (m/s); $g = 9.81\ m/s^2$.

- Depending on local demand, the geographical clusters of villages are delineated so that they can be served by desalination units. The capacity of these units is determined, along with the main infrastructure components required for their operation.
3. Estimation of CAPEX:
- To estimate the CAPEX, we convert monetary capital into kilowatt-hours (kWh), which constitute a stable and invariant measure, given that money is an unstable metric that varies over time and space. This approach enables an objective comparison that is, to a large extent, independent of both geographical location and temporal context.
4. Olive Tree Density Estimation and Biomass Quantification:
- Remote Sensing Analysis: High-resolution satellite imagery will be used to map olive groves in West Mani. A supervised classification will identify olive trees based on canopy size.
 - Ground Truthing: Field surveys in selected plots will validate satellite data, estimating tree density per hectare.
 - Managed Biomass: Annual biomass from olive tree pruning, grass clearing, and olive pit residues will be calculated.
 - Energy Sufficiency: Total energy from biomass will be compared to desalination and pumping energy demands.
5. Electricity Generation from Biomass:
- Biomass Conversion: Standardized biomass-to-energy systems [28].
 - Energy Yield Calculation: Total annual biomass per hectare will be converted to electricity, accounting for system losses and regional conditions.

6. Food Production Assessment:

- Olive and olive oil yields will be estimated using regional data. Caloric content will be calculated (olives: ~1.150-1.450; olive oil: ~8,840 kcal/kg) [40] to quantify food contributions to the WEF nexus.

7. Fire Risk and Sustainability Assessment:

- Unmanaged Biomass: Biomass accumulation without pruning or clearing will be estimated by field research.
- Biomass management's role in fire prevention will be quantified by comparing fuel loads in managed vs. unmanaged olive groves and pine forests to assess fire prevention benefits.

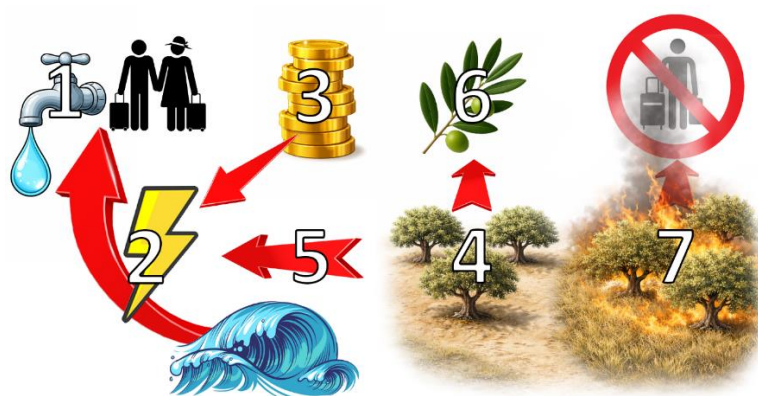


Figure 4 The numbers correspond to the steps described in the methodology, and the arrows symbolize the interactions of the issues.

3. Water Consumption Estimation

The inhabitants in West Mani are estimated by the 2021 Census to 5.875 people [41]. The villages with more 100 inhabitants, are estimated with 5.267 people. In the following paragraphs, we quantified water consumption in the villages of West Mani under two contrasting scenarios, and we will design the hybrid system of the main villages, estimating the associated energy needs, in order to capture a full range of seasonal conditions:

1. “Moderate” Scenario: A baseline hypothesis, assuming 100% of the average local population plus an additional +50% during the tourist season. Per capita water consumption is assumed to be standard, approximately 173 L/day, which reflects the national average in Greece and represents typical usage levels [35].
2. “High” Scenario: In the high-demand scenario, it is assumed that there are twice as many tourists as the local population in the area, and in high touristic areas (Neochori, Stoupa, Agios Nikolaos), the number of tourists is estimated to be three times that of the local population. Individual consumption values are deliberately high: 173 L/day per inhabitant (same as in the moderate scenario), and up to 300 L/day per tourist to account for increased water use linked to accommodation, leisure activities, and services. This “high” scenario reflects maximum estimated demand and is used to ensure a cautious assessment of water and thus energy requirements.

Permanent population figures for each village served as the reference point for both scenarios, and seasonal increases due to tourism were applied using the percentages above. It is assumed that

the additional tourist population is present for approximately three months each year, which allows for the calculation of annual water consumption, including seasonal variation [42, 43]. The 173 L/day per capita value used here is well above the theoretical minimum requirement (50 L/day [37]), ensuring that the estimates do not underestimate demand. Using high-end assumptions for both occupancy and consumption allows the energy system to be sized with a safety margin, ensuring that desalination and pumping infrastructure can meet demand even during the summer peak.

The Neochori, Stoupa, and Agios Nikolaos stand out as the highest consumers of water. Under the high scenario, their annual consumption reaches approximately 71,000 m³, 65,000 m³, and 44,000 m³, respectively, reflecting both their population size and tourist appeal. During peak season, daily water demand can reach around 270 m³/day in Neochori, 250 m³/day in Stoupa, and 167 m³/day in Agios Nikolaos. These peaks confirm that seasonal population increases are primarily concentrated in the major coastal tourist hubs.

In Figure 5, a graphical representation is used to express the water consumption in each village. The bubbles have been placed at the locations of the villages, which are presented in Figure 3. Bubble size proportional to annual water consumption (m³/year) highlights the spatial systems' demands.

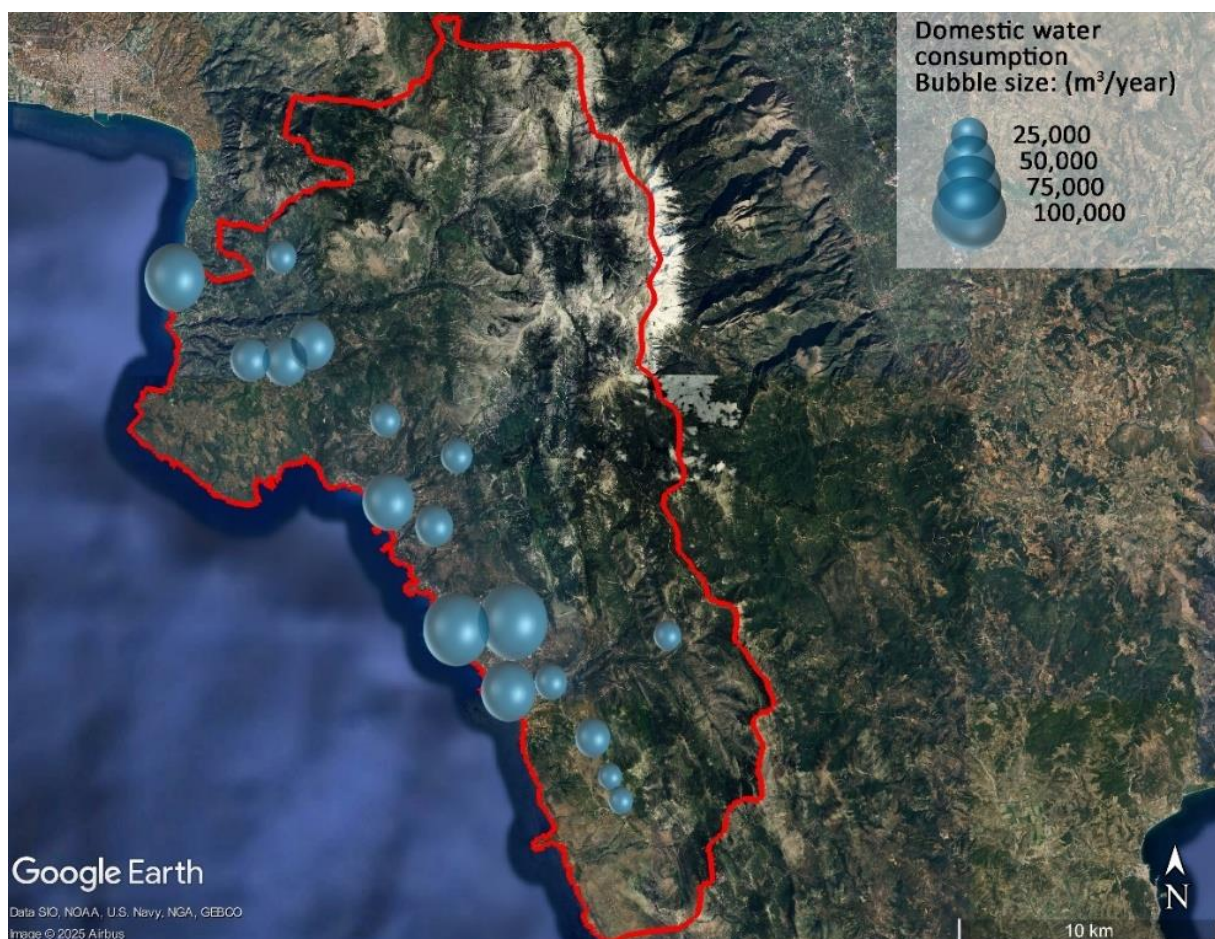


Figure 5 The worst-case scenario of water consumption by villages in West Mani in a bubble chart. Each bubble indicates the village's (more than 100 inhabitants) water consumption [4].

In summary, adopting high-end assumptions in the reference scenario provides an upper bound for water needs, ensuring that the bioenergy system is sized to handle the most demanding conditions. These water consumption estimates form the basis for the energy calculations developed in Section 4, where the required desalination and pumping capacities are evaluated to ensure a continuous water supply for all villages, even during periods of high tourist inflow.

According to the 2021 Census, and assumptions described above, the total annual water consumption for the villages (more than 100 inhabitants) of West Mani is approximately 330,000 m³/year, while under moderate scenario is 545,000 m³/year, and to the high scenario, it rises to about 734,000 m³/year. In the high scenario, nearly 48% of the annual volume is attributed to tourist use, concentrated within just three months of the year.

This highlights the significant impact of seasonal tourism on water demand, which is also impacted by swimming pools, with estimate water use consumption of 40,000 to 50,000 m³, nearly 13% of the water needs of inhabitants or 7% of total annual volume of water in high demand scenario [44]. Since the pools are mainly located along the coastline, we assume an average elevation of 100 m.

4. Energy Requirements for Desalination and Pumping

To address the rugged topography and dispersed settlement pattern of West Mani, a multi-site desalination strategy is proposed, dividing the 17 villages into four coastal clusters based on topographic and distance criteria (Figure 6) [45]. Each cluster is supplied by its dedicated desalination station, positioned optimally at sea level to minimize pumping distances.

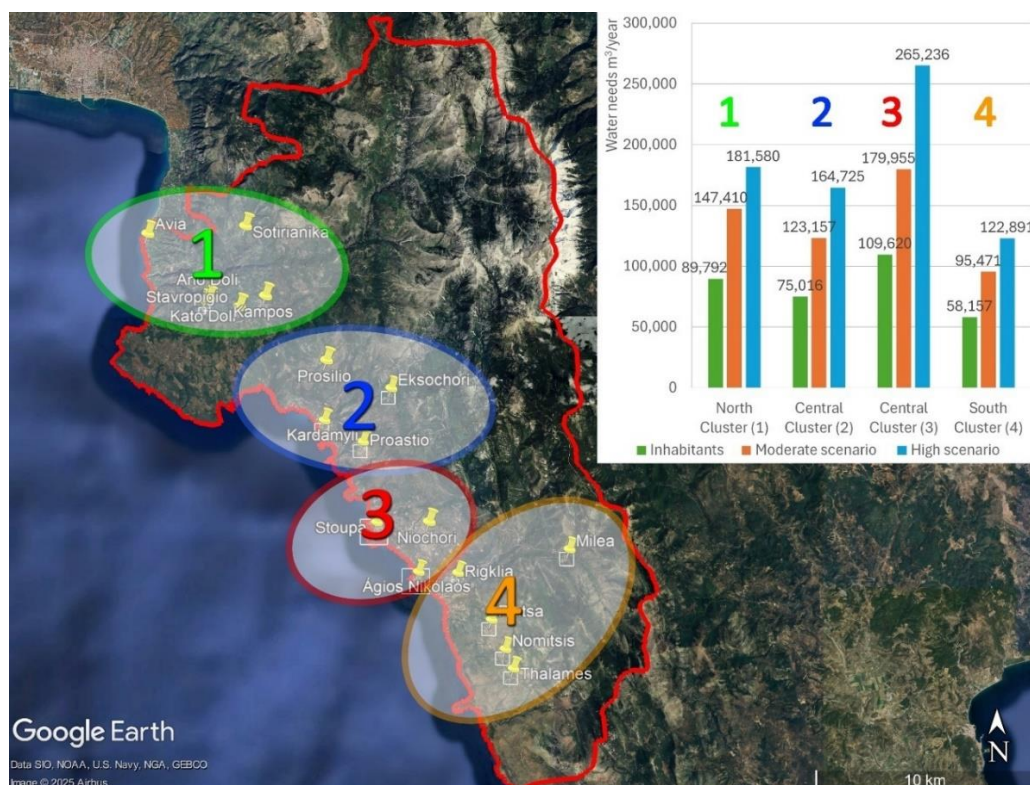


Figure 6 Regional Clustering of West Mani for Multi-Site Energy-Water Infrastructure Design. The diagram shows annual Water Consumption by Cluster in West Mani under Moderate and High Scenarios (m³/year) [4].

This approach, supported by field research, better accommodates the region's challenging geography. In order to separate the clusters, the maximum daily water needs in tourist season for Clusters 1, 2, 3 and 4 are ≈ 497 , 451, 726, and 753 m³/day of water.

The central Cluster (3), comprising the highly touristic coastal villages (Neochori, Stoupa, Agios Nikolaos), benefits significantly from an existing brackish-water resource (aquifer depth: approximately 100-140 m), considerably reducing energy consumption for desalination. From the operation of the existing desalination plant in the central Cluster 3 (Agios Nikolaos), it has been determined that the Specific Energy Consumption (SEC) for this brackish resource is conservatively 1.5 kWh/m³. Seawater reverse osmosis for the northern and central clusters requires approximately 5 kWh/m³ [46] due to higher salinity (~ 35 g/L dissolved solids). The Agios Nikolaos Brackish-Water Reverse Osmosis (BWRO) desalination unit produces 1000 m³/day, while the maximum daily demand for all villages in the summer period is 2,260 m³/day in the high-demand scenario. Thus, multiple stations remain essential to sustainably fulfil present and future water demands under peak scenarios, ensuring resilience, modularity, and energy optimization. Therefore, in our calculations, we consider a system with three more similar Salt-Water Reverse Osmosis (SWRO) desalination units.

To organize water production, we consider four clusters of villages, each of which, in aggregate, is served by its own dedicated desalination facilities. The elevations and distances of the villages from the coastline are presented in Table 1. The gross static head is based on village elevations. To ensure reliable delivery and system operation, a minimum delivery pressure head of 15 m (≈ 1.5 bar) is specified.

Table 1 The clusters, the population and the elevations of villages, the distance from the coastline and the total manometric height (including the friction losses and delivery pressure).

	Village	Population (Census 2021)	Tourist multiplier used in high demand scenario	Altitude (m)	Village-Sea (km) (straight-line)	Total manometric height (with friction loses)
Cluster 1	Avia	642	2	15.0	1.0	70.0
	Stavropigio	347	2	325.0	5.0	540.0
	Sotirianika	158	2	395.0	8.6	754.0
	Kato/Ano Dolo	275	2	311.0	1.0	367.2
	Average			261.5	3.9	432.8
Cluster 2	Kardamyli	391	2	30.0	0.8	76.2
	Exochori	174	2	277.0	1.2	339.6
	Proastio	256	2	220.0	1.4	291.0
	Kampos	367	2	300.0	1.4	369.8
	Average			206.8	1.2	269.2
Cluster 3	Neochori	683	3	240.0	3.0	375.0
	Stoupa	628	3	30.0	1.0	85.0
	Agios Nikolaos	425	3	15.0	1.0	70.0
	Average			95.0	1.7	176.7
Cluster 4	Riglia	186	2	194.0	1.2	257.0
	Thalames	110	2	483.0	1.2	546.0
	Platsa	221	2	273.0	1.1	332.0
	Prosilio	170	2	425.0	2.6	544.0
	Nomitsis	100	2	501.0	1.4	572.0
	Milea	134	2	650.0	6.5	925.0
	Average			421.0	2.3	529.3

Flow length has been determined by doubling the straight-line distance of each village from the coastline, and a design velocity of $V = 2.0$ m/s is selected, ensuring losses remain within acceptable limits. Given the turbulent flow regime in closed conduits, the Colebrook-White equation is employed to determine the Darcy friction factor [47].

High-density polyethylene (HDPE) pipes were assumed, with low roughness (typical absolute roughness $\epsilon \approx 0.0015$ - 0.007 mm for new HDPE). This yields a conservative estimate of approximately 4.9 m of head loss per km of pipeline.

Local losses due to bends, fittings, valves, and direction changes were conservatively estimated as double the friction losses per km. Overall, friction and local losses were considered acceptable in favor of safety, with a worst-case limit of 20 m/km [48-50]. According to the above assumptions, the clusters, the population, and the elevations of villages, the distance from the coastline and the total manometric height (including the estimated friction losses) are presented in Table 1. A conservative overall pump efficiency of $\eta = 70\%$ was used for energy calculations across all sites.

Since the value of money is subjective [51], changes over time, and has no fixed basis for planning infrastructure - being dependent on financial [52] and geopolitical uncertainties [53-55] - all investment capital of a desalination plant is converted below into energy units. For the central cluster of West Mani served by the Agios Nikolaos brackish-water desalination station, the Capital Expenditures (CAPEX) are set at €872,400, covering the containerized BWRO, site preparation, a 300 m³ reservoir with additional pumps, and network connection, plus a 20% allowance for indispensable but non-itemized costs. Assuming that an average price per kWh is €0.15 [56], this investment corresponds to 5,816,000 kWh.

We assume three additional similar SWRO units of 1,000 m³/d each in Cluster 1, Cluster 2, and Cluster 4, with a realistic median CAPEX of €900,000 per unit, corresponding to 6,000,000 kWh over the lifetime. The desalinated water required by Clusters 1, 2, 3, and 4 is $\approx 181,580$, 164,725, 265,236, and 122,891 m³/year, respectively, for covering the needs of the high-scenario needs. Therefore, the investment corresponds to 1.3, 1.5, 0.9, and 2.0 kWh/m³, respectively (Table 2).

Table 2 Water needs, correlated to pumping and desalination needs for different clusters.

	Operational needs			CAPEX equivalent to €/kWh	
	Maximum water needs (m ³ /day)	Energy (average pumping) kWh/m ³	Energy desalination kWh/m ³	Investment of the unit in kWh	Amortized investment in kWh/m ³ (25 years)
Unit with maximum production	1,000	~1.09 (average to all villages)	1.5 (brackish water)	5,816,000	0.60
Cluster 1	497	~1.17	5.0	6,000,000	1.3
Cluster 2	451	~0.88	5.0	6,000,000	1.5
Cluster 3	726	~0.74	1.5	5,816,000	0.9
Cluster 4	753	~1.74	5.0	6,000,000	2.0

If calculated instead against the maximum 1,000 m³/d supply capacity, the investment energies fall to about 0.6-0.7 kWh/m³. This dual perspective based on actual demand versus technical maximums illustrates the sensitivity of investment amortization to system utilization rates and highlights the importance of sizing and operational planning for the long-term energy costs of desalinated water.

The Table 2 shows the average daily water needs (m³/day) of each cluster, the specific pumping energy (kWh/m³), averaged across villages according to their elevation, the desalination energy depending on the water source (1.5 kWh/m³ for brackish water in Cluster 3, 5.0 kWh/m³ for seawater in Clusters 1, 2 and 4), the CAPEX and the amortized CAPEX expressed as total kWh over the plant's lifetime and as kWh per m³ when distributed over the actual demand.

This combined view highlights how pumping, desalination, and capital amortization contribute jointly to the final energy cost per cubic meter of water.

The total energy needs for desalination and pumping are 2.8 to 3.6 GWh/year. Figure 7 presents the annual energy needs (MWh/year) required for desalination and pumping by cluster under the Moderate and High demand scenarios.

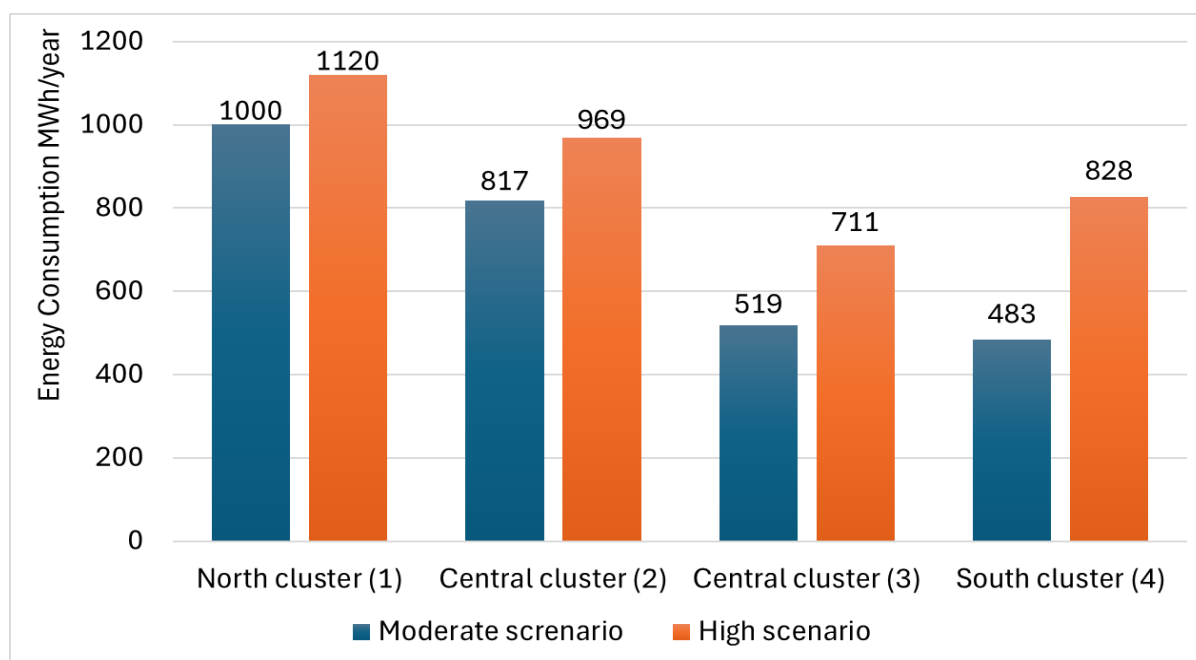


Figure 7 Annual energy consumption for desalination and pumping (MWh/year) by cluster under Moderate (blue) and High (orange) scenarios.

Figure 8 depicts the settlements of West Mani, showing their daily water consumption (m³/day) in the high-demand scenario plotted in correlation with pumping energy (kWh/m³). Bubble size and the numeric labels represent the theoretical value of total energy cost per cubic meter (CAPEX, desalination, and pumping) in kWh/m³.

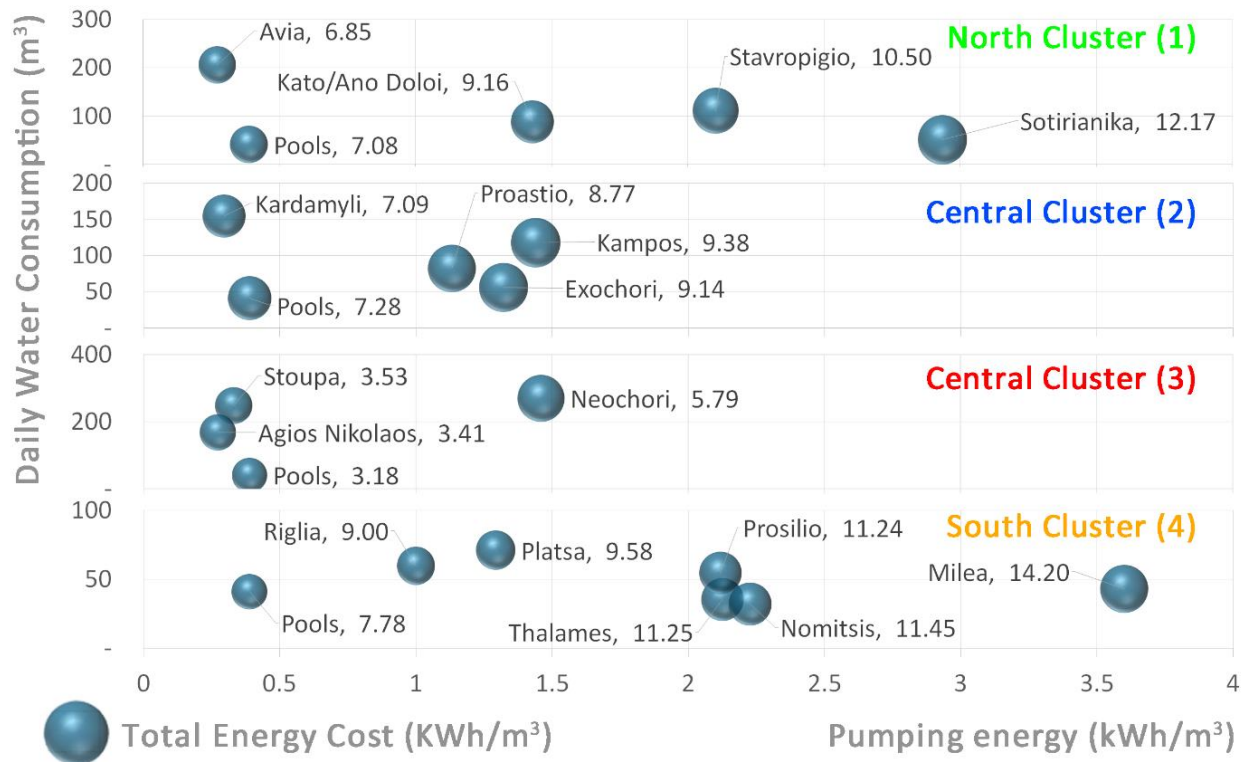


Figure 8 Daily water consumption, correlated with pumping energy. Total energy cost (CAPEX, desalination and pumping) is depicted in bubbles.

A sensitive issue that must not be overlooked is that infrastructure should be designed and implemented without disrupting the landscape [57-59]. The area's scenic landscape supports the tourism product. For this reason, even though the infrastructure is limited in scale, it must be placed in locations that will not alter it.

5. Olive Tree Density Estimation

The olive grove area in West Mani was reassessed using manual mapping from Google Earth [4] and estimated at 5,121 ha. These areas have been cross-referenced with Corine Land Cover (CLC) 2018 data [60, 61], 5,871 ha (Figure 9).

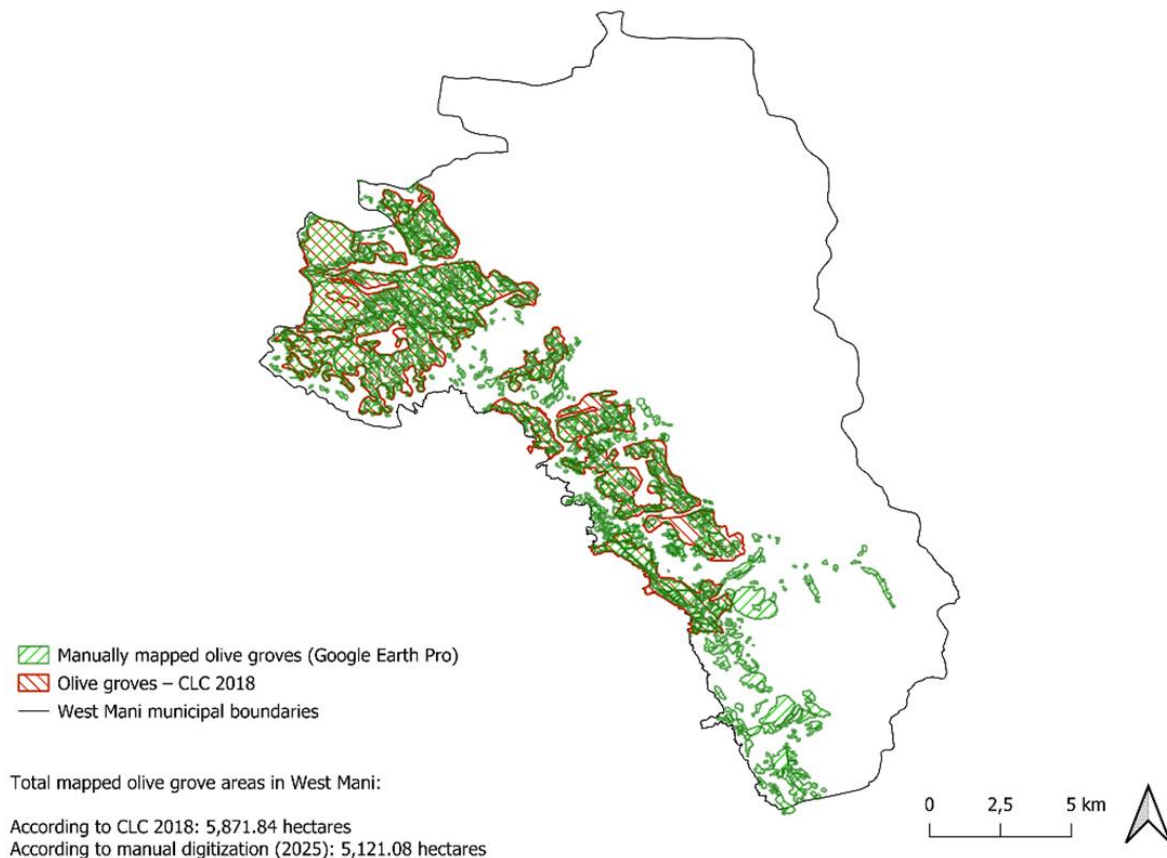


Figure 9 Mapped Olive Grove Extent in West Mani: Manual Digitization (2025) Google Earth [4] vs CLC 2018 Layers [60, 61].

The manual mapping value of 5,121 ha (conducted in 2025) using high-resolution imagery provided from Google Earth (February 2025) is original to this study and represents a detailed, ground-truth reassessment (scale accuracy 1:100 or ~0.5 m/pixel [62]) that excludes or reclassifies some abandoned areas misidentified in CLC 2018. The approximately 700 ha difference between the two methods is partly due to abandoned olive groves, which were classified as forest in the manual mapping. The manual mapping data from Google Earth is provided as supplementary material.

To highlight the noted differences, drone-based field surveys were conducted to validate remote sensing data and estimate biomass. Ten plots (about 1 ha each), selected using stratified random sampling to represent managed and abandoned olive groves, based on remote sensing classification. From the samples, we select a property with a known history of cultivation, where one part has been abandoned, and the other is still cultivated. In Figure 10, we see an olive grove originally planted around 1995, now visibly divided into two. Until 2010, the entire field was cultivated. After that point, the section shown on the left side of the image was abandoned, while the section on the right continued to be actively managed. The image highlights the significant accumulation of biomass in the abandoned area, demonstrating its considerable potential. In contrast, the cultivated section clearly shows a reduced amount of available biomass, which may limit its ability to act as a natural barrier in the event of a wildfire. Figure 11 shows the closer, angled views for more detailed observation.



Figure 10 Olive grove. The section shown on the left side of the image was abandoned in 2010, while the section on the right continued to be actively managed.



(a)



(b)

Figure 11 Closer, angled views of the olive grove shown in Figure 10. (a) Abandoned olive grove section with dense understory vegetation, showing higher biomass accumulation and increased fire hazard. (b) Managed olive trees with cleared understory, illustrating reduced biomass and lower fire risk.

Average olive tree density in Mediterranean regions (100-200 trees/ha) [63, 64], and in West Mani, the estimated density is about 180 trees/ha.

6. Biomass Quantification

The expected biomass from cultivated pine forests, olive trees, and annual pruning is illustrated in Figure 12 and could be considered maximum at a tree density of 200 trees/ha and minimum at 100 trees/ha.

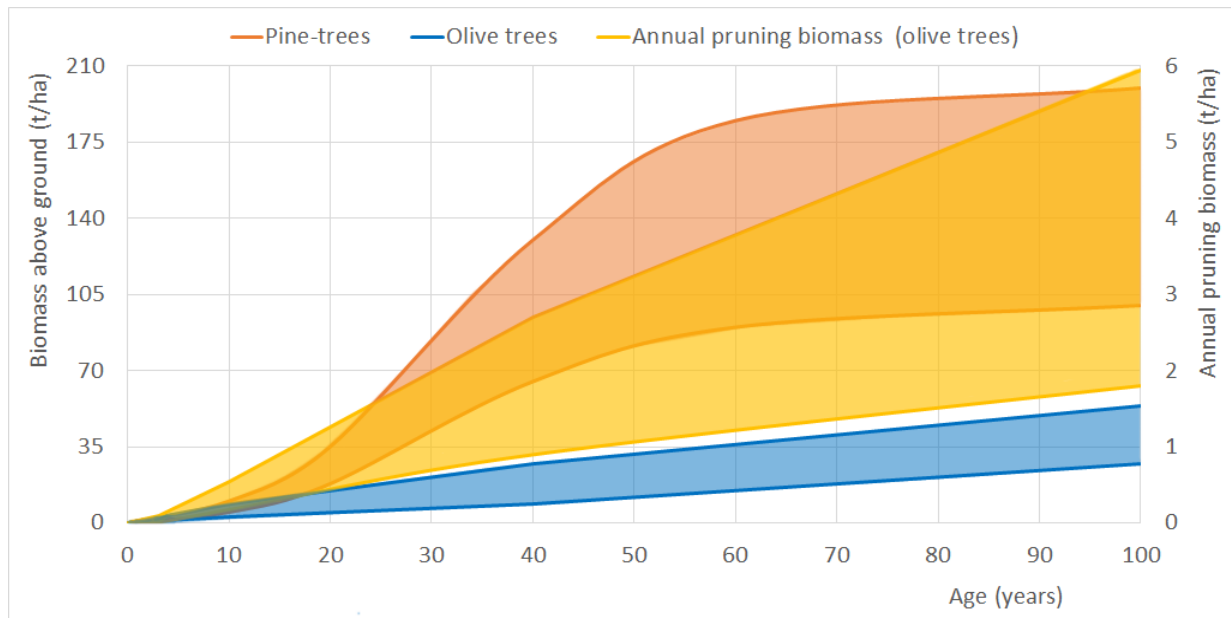


Figure 12 The estimated above-ground biomass for a pine-tree forest, olive tree cultivation, and the annual pruning biomass [65-67].

The average age of olive trees in the area is about 50 years old. The expected pruning yields are estimated at about 3 tons/ha/year (dry weight with Lower Heating Value (LHV) 19 MJ/kg), grasses at 0.5-1 ton/ha/year (LHV 18 MJ/kg), and olive pits 0.8-1.2 tons/ha/year (LHV 19.7 MJ/kg) based on regional studies [68, 69]. Therefore, the energy contained in the annual olive biomass residues in West Mani is estimated between 116 and 140 GWh, as reconciled using a manual mapping area of 5,121 ha for consistency with the reassessed cultivable extent. Calculations assume dry basis (moisture content $\approx 0\%$, as residues are typically air-dried post-pruning). Accessibility factor for gross potential: 100% (theoretical; no deductions for unharvested or inaccessible areas).

Velázquez et al. [70] estimate that the correlation between the time per ha taken for manual pruning versus residual biomass productivity follows the equation:

$$y = 20.2x + 28.2 \quad (2)$$

where x is residual biomass (t/ha) and y is labour (h/ha).

7. Technical Design of Olive Bioenergy System

The optimal technology for converting olive biomass depends on the scale of operation, specific energy demands, and practical objectives. Potential solutions include combustion coupled with Organic Rankine Cycle (ORC) cogeneration [36, 71] and biomass gasification systems [36, 72].

Considering the identified energy requirements of ≈ 2.8 -3.6 GWh/year (which corresponds to an average continuous electrical load of ≈ 320 -410 kW_e), two optimal configurations emerge for West Mani: a biomass combustion-ORC micro-cogeneration plant (in the ~ 350 -450 kW_e class) prioritizing reliability and robustness, or a biomass-gasification system coupled with an internal-combustion engine, suitable for modularity, flexibility, and economic viability.

At $\sim 20\%$ net electrical efficiency [73-75], meeting an average continuous output of 320-410 kW_e requires roughly 1,650-2,175 kW_{th} of thermal biomass input. Converted to annual biomass demand

(based on the stated annual electrical energy of 2.8-3.6 GWh), the plant would consume roughly 2,900-3,800 tonnes of dry biomass per year.

To supply 2,900-3,800 t/year from local olive-grove residues (estimated 2-3 t/ha·yr), ~970-1,900 hectares of olive groves are needed (best case at 3 t/ha $\approx$ 970-1,270 ha; worst case at 2 t/ha $\approx$ 1,450-1,900 ha). These values incorporate the gross potential, adjusted for 10-20% accessible area (due to rugged terrain and smallholder fragmentation) and 85% recovery efficiency (collection and processing losses).

This accessible fraction accounts for:

- Terrain and accessibility: Rugged Mani topography restricts mechanical harvesting/chipping to flatter coastal areas; steep inland groves rely on manual labor, increasing costs and reducing recovery rates.
- Smallholder constraints: Fragmented ownership (common in Greece) hinders coordinated collection; cooperatives or incentives are essential for aggregation.
- Seasonal logistics: Pruning residues available January-March (post-harvest); pits from mills (November-February). Collection must occur promptly to avoid degradation, with natural drying in the fields before chipping/transport (average distances 5-15 km to central plant). Storage buffers (1-3 months) mitigate seasonality, but wet winters risk moisture reabsorption (>20% wet basis reduces LHV).

8. Fire Risk and Sustainability Assessment

Abandoned olive groves accumulate substantial dry biomass on the ground. Without maintenance, over 8-10 t/ha of residues (branches, dry leaves, dead grasses) can accumulate within a few years [76] (Figure 10, Figure 11). Such combustible material creates highly flammable conditions. Sparks et al. note that unmanaged Mediterranean olive groves are “readily receptive to fire spread.” [77]. Therefore, without pruning and clearing, olive grove understories become significant fire risks. Fine leaves and twigs, rich in minerals, tend to form tar during combustion, while denser pruning wood and olive stones burn more slowly, making them suitable as biofuel. Woody branches have a high calorific value (~18 MJ/kg dry) and low ash content, making excellent fuel, unlike leaves (~12 MJ/kg, 8-10% ash) [29].

Mediterranean pine forests pose even higher risks. Pine litter typically accumulates 8-15 t/ha [29], with a comparable calorific value (~18 MJ/kg, ~5 kWh/kg). Simultaneous combustion of these loads creates intense canopy fires: rapid spread (several km/h) [78-80] and tall flames (10-30 m) under strong winds [81]. Olive grove fires, by contrast, usually propagate as moderate surface fires; however, without management, plant biomass significantly increases fire hazards. Conversely, controlled biomass utilization reduces the availability of fire fuels. Properly maintained olive groves can serve as firebreaks, whereas unmanaged groves become fire sources [82].

Using olive biomass for energy simultaneously reduces fire risks and generates renewable electricity. This dual logic, which controls fuel use to prevent fires while enhancing local energy autonomy, is highlighted by Rigolot [81]. Such integrated approaches (energy pruning, local logistics support, agricultural cooperation) significantly enhance sustainability, promoting energy independence, local employment, and Mediterranean landscape resilience to wildfires [83, 84].

Furthermore, tourism constitutes a fragile economic pillar in West Mani, highly vulnerable to stochastic shocks (e.g., pandemics or wildfires) [15]. A major wildfire would irreversibly alter the

characteristic Mediterranean landscape-destroying the visual and experiential appeal that underpins the tourist product for decades-while many tourism facilities (hotels, rentals) built within or adjacent to abandoned, overgrown olive groves face heightened direct exposure to fire spread due to increased fuel continuity and load. Recent Mediterranean examples, such 2021 Euboea fire in Greece [15], the 2023 fire in Rhodes [85] illustrate how such events lead to mass evacuations, prolonged booking cancellations, and multi-year economic losses in visitor numbers and regional income, underscoring the necessity of proactive biomass management for preserving both environmental integrity and long-term economic viability.

9. Sensitivity Analysis and Robustness of Energy Coverage

To assess the robustness of the study's conclusion that local olive residues can fully cover the energy needs for desalination and pumping, we varied key parameters by $\pm 20\%$. The results show the conclusion is robust: even in worst-case variations (e.g., +20% tourist demand or -20% biomass accessibility), coverage of water needs will be complete as the SWROs in clusters 1 and 2 according to high scenario work with 50% of their capacity, BWRO in clusters 3 and SWRO in clusters 4 works with 75% of their capacity. Supply shortfalls could be addressed by expanding the accessible area or by improving efficiency, as the required area for biomass harvesting is 20% of the total available biomass.

Cluster-level differences are pronounced: Cluster 3 (central, brackish RO at 1.5 kWh/m^3) shows the lowest specific energy consumption ($\text{SEC} \sim 2.24 \text{ kWh/m}^3$) due to lower salinity and elevation (avg. 177 m), accounting for only 16% of total energy despite 36% of water volume; seawater RO clusters (1, 2, 4) exhibit higher SEC ($5.88\text{-}6.74 \text{ kWh/m}^3$) from salinity and rugged topography (up to 529 m head).

10. Discussion

Tourism can be a profitable investment, but it introduces significant challenges and uncertainties to the local water-energy-food nexus [86-92]. Therefore, while it is appropriate to consider how to meet its demands due to the abundance of water, it is even more important to focus on how to ensure the resilience of society [93, 94]. In this context, agriculture, which today appears to be neglected, and particularly olive cultivation, has the potential to support the self-sufficiency of the community.

Thus, the maintenance and pruning of olive trees - which, if harvested, could realistically provide a conservative exploitable energy potential of about 2.8 to 3.6 GWh per year under the assumptions of 10-20% accessible area, 85% biomass recovery efficiency, and 15% conversion efficiency - is a process that is essential.

An olive grove produces 2.000-5.000 kg/ha and olives contain $\sim 1.150\text{-}1.450 \text{ kcal/kg}$. In calorific terms, this corresponds to 33-42 billion kilocalories, which could theoretically cover the annual dietary energy needs of approximately 45,000 to 57,000 residents [95].

By adopting this realistic scenario, rather than the theoretical gross biomass potential (125-150 GWh/year), the estimation acknowledges the spatial, technical and operational constraints that strongly reduce the fraction of biomass that can actually be mobilized. Even so, the magnitude remains significant: the recovered energy could supply a non-negligible share of the local population's energy demand, reinforcing community self-sufficiency.

An important aspect of biomass utilization concerns the management of residues after energy conversion. Combustion or gasification of olive biomass generates carbon dioxide (CO₂), but this emission is considered carbon-neutral, as it corresponds to the CO₂ previously absorbed by the trees during their growth. Indicative emission factors for olive biomass combustion (dry basis) include: CO₂ ~1.8 kg/kg fuel (biogenic), CO ~0.5-1.5 g/kg, NO_x ~1-3 g/kg, SO₂ ~0.1-0.5 g/kg, and particulate matter (PM) ~0.5-0.6 g/kg. These align with compliance under the EU Medium Combustion Plant Directive [96]. For the proposed ~2 MW system (1-5 MW category), Emission Limit Values (ELVs) for new plants are: dust (PM) 50 mg/Nm³, NO_x 500 mg/Nm³, SO₂ 200 mg/Nm³, and CO 200 mg/Nm³. To meet these limits, flue-gas cleaning includes Electrostatic Precipitators (ESPs) or baghouse filters for PM removal (>99% efficiency), Selective Non-Catalytic Reduction (SNCR) for NO_x (50-70% reduction via urea injection), and dry sorbent injection for SO₂ if needed (though low sulfur in olive biomass typically suffices). Particulate emissions can be further mitigated by pre-boiler cyclone separators.

In addition, ash generation varies with residue type: wood and olive stones typically leave only 1-3% of the dry input mass as ash, whereas leaves and fine residues may reach 8-10%. These ashes are rich in potassium, calcium, magnesium, and phosphorus, and can be recycled as soil amendments in olive groves or other crops. Ash return protocols involve: (1) collection from boiler/ESP (bottom and fly ash separated); (2) laboratory analysis for nutrient content and heavy metals (e.g., Cd < 1.5 mg/kg, Pb < 150 mg/kg, per EU Fertilizing Products Regulation (EU) 2019/1009 [97]); (3) dilution/blending if concentrations exceed limits (olive ash typically low in heavy metals like Cd, Cr, Pb due to minimal soil contamination, but checks for Zn/Fe from pruning tools); and (4) field application at 1-5 t/ha/year, incorporated into soil to avoid runoff. If heavy metals exceed thresholds (e.g., >10 mg/kg Cd), ash is disposed of as non-hazardous waste per Directive 2008/98/EC [98].

Overall, the environmental footprint of olive biomass conversion remains low if ashes are properly managed and modern emission control systems are applied. This strengthens both the environmental performance of bioenergy and its role in an integrated water-energy-food (WEF) nexus strategy.

Moreover, the maintenance and pruning of olive trees also protects the local community from wildfires. A wildfire, if it were to occur, could both significantly impact the water-energy nexus and devastate the landscape for many years, weakening the area's tourism appeal as well.

Although desalination is a viable solution for addressing water scarcity in regions like West Mani, it demands a substantial energy investment that cannot be overlooked. For instance, assuming an average Greek consumes approximately 6,000 kWh of electricity annually [56] and requires around 63 m³ of water per year (equivalent to 173 liters per day), the energy required to produce this volume of water through desalination can represent a notable portion of individual energy consumption. Using a conservative estimate of 6-10 kWh per cubic meter for desalination (including operational costs for reverse osmosis and pumping, plus amortized capital expenditures), this translates to roughly 380-630 kWh per person annually for water production alone. This equates to approximately 5-10% of the average Greek's yearly electricity use, underscoring how desalination, while effective, intensifies energy demand and highlighting the need for more efficient alternatives to avoid overburdening local energy systems.

For this reason, prioritizing the utilization of rainwater resources should precede the widespread adoption of desalination infrastructure. Rainwater harvesting offers a lower-energy pathway to water security, leveraging natural precipitation to meet demand without the high electrical

footprint of desalination. In Mediterranean contexts, where rainfall is seasonal but often abundant during winter months, integrating rainwater collection can reduce reliance on energy-intensive methods, promote sustainability, and align better with the water-energy-food nexus by conserving resources across sectors.

In West Mani specifically, the steep terrain, permeable soils, and complex geomorphology limit the feasibility of large-scale rainwater collection projects, such as extensive reservoirs or dams, which could otherwise capture significant runoff. Nevertheless, given the dispersed nature of the villages, it is reasonable and practical to support smaller settlements by enhancing the existing network through small-scale rainwater utilization infrastructure. These could include decentralized systems like rooftop harvesting, micro-dams, or infiltration galleries tailored to local topography, providing supplemental water to reduce desalination loads during peak seasons and enhancing overall resilience without requiring massive investments.

However, with this approach, we achieve full energy autonomy for desalination while integrating wildfire risk reduction and ash reuse, absent in prior place-based WEF studies. Application elsewhere requires minimal data: census/tourism statistics for demand modeling, remote sensing for olive grove mapping (tree density and area), topographic data for pumping calculations, and regional biomass yield factors. These data enable the adaptation of the methodology to other tourism-dependent areas with fragmented small holdings [99].

11. Conclusions

This study demonstrates the potential of olive biomass management to restore resilience in the water-energy-food (WEF) nexus in West Mani, Greece, and similar remote, tourism-dependent Mediterranean areas facing water stress alongside traditional, low-intensity agricultural production (primarily olive cultivation). By quantifying local biomass resources and proposing an integrated system, the work demonstrates how renewable energy generated from olive residues (pruning, grasses, and pits) can power desalination and water distribution, addressing seasonal scarcity exacerbated by tourism peaks while delivering co-benefits, such as reduced wildfire risk and soil enhancement through ash reuse.

Realistic estimates of energy requirements 2.8-3.6 GWh/year for desalination and pumping in West Mani suggest that available olive residues, which are estimated to contain 125-150 GWh, could effectively meet these demands. However, these preliminary findings require further refinement with more precise field data on actual biomass availability, logistical accessibility, and qualitative characteristics of the residues.

Additionally, more detailed research is necessary to accurately determine optimal conversion technologies, taking into account the current local context as well as future growth in West Mani, particularly tourism expansion, which causes inequalities inside the social structure. A significant challenge to be addressed is the societal and political structures that will allow for the efficient collection of the necessary biomass from multiple small to medium-scale agricultural units.

By incorporating these elements into subsequent research phases, it will be possible to develop a genuinely tailored and sustainable strategy capable of efficiently managing local resources while preserving the environment, ensuring energy security, and protecting the region's agricultural heritage, thereby reinforcing the sustainability and overall resilience of the region.

In closing, this work directly addresses the identified research gaps through the following targeted contributions, offering a novel, replicable framework for Mediterranean communities:

- Integrated place-based application: Quantifies how 2,900-3,800 tonnes/year of olive residues in West Mani generate 2.8-3.6 GWh to fully power desalination and pumping, linking biomass to energy demands in a tourism-stressed context.
- Spatial heterogeneity consideration: Develops a model incorporating remote sensing for olive mapping, village-specific water demands (with tourist peaks and pools), clustered desalination, and amortized costs, accounting for topographic and hydrogeologic variations.
- Multi-benefit synergies: Explicitly integrates wildfire risk reduction (managed groves vs. unmanaged areas, creating firebreaks) as a co-benefit, alongside ash reuse for soil enhancement.
- Replicable framework: Provides practical guidance for small-scale communities, emphasizing synergies like energy autonomy, community self-sufficiency, and implementation (e.g., smallholder collection, ORC/gasification), and is adaptable with minimal data inputs.
- Fire protection safeguards tourism investment: Tourism constitutes a fragile economic pillar in West Mani, highly vulnerable to random shocks. A major wildfire would irreversibly alter the characteristic Mediterranean landscape, destroying the visual and experiential appeal that underpins the tourist product for decades, while many tourism facilities (hotels, rentals) built within or adjacent to abandoned, overgrown olive groves face heightened direct exposure to fire spread due to increased fuel continuity and load.

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Author Contributions

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Competing Interests

The authors have declared that no competing interests exist.

Data Availability Statement

This research creates new databases by detail inspection of satellite images. The data sets are uploaded as supplementary material.

AI-Assisted Technologies Statement

Artificial intelligence (AI) tools were used solely for basic grammar correction and language refinement in the preparation of this manuscript. Specifically, OpenAI's ChatGPT was employed to improve the readability and linguistic clarity of the English text. All scientific content, data interpretation, and conclusions were developed independently by the author. The authors have thoroughly reviewed and edited the AI-assisted text to ensure its accuracy and accept full responsibility for the content of the manuscript.

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