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A NATIONAL INVENTORY OF HYDROGEN PRODUCTION POTENTIAL FROM ARCHIMEDEAN SMALL HYDROPOWER SYSTEMS IN GREECE

Alkistis Stergiopoulou [1], Vassilios Stergiopoulos [2,*]

[1] Institut für Wasserwirtschaft, Hydrologie und Konstruktiven Wasserbau, B.O.K.U. University, Muthgasse 18, 1190 Vienna, (actually Senior Process Engineer at the VTU Engineering in Vienna, Office Campus Gasometer, Guglasse 15/4a/1.OG, 1100 Vienna), Lindengasse 15, 1070 Vienna, Austria

[2] Professor, ASPETE, School of Pedagogical and Technological Education, Department of Civil Engineering Educators, ASPETE Campus, Eirini Station, 15122 Amarousio, Athens, Greece

*Corresponding author: e-mail: bstergiopoulos@aspete.gr, tel: +30-6937972940

Abstract

This paper presents a comprehensive inventory of the potential for green hydrogen production derived from the Archimedean small hydropower resources of Greece. The assessment is based on hydrological and geographical data from the country's 14 Water Districts and adopts a holistic methodology to estimate the total theoretical hydropower potential exploitable through Archimedean Screw Turbines (ASTs). The theoretical Archimedean hydropower potential is estimated to reach several TWh per year, corresponding to an installed AST capacity in the order of several thousand megawatts, with notable values of specific capacity and capacity density. Building upon this energy assessment, the study evaluates the associated hydrogen production potential through water electrolysis under different efficiency and operational scenarios. The results highlight the significant, yet largely untapped, opportunity for coupling environmentally friendly small-scale hydropower with green hydrogen production in Greece.

Keywords: Hydrogen Production, Archimedean Screw Turbines, Renewable Energy, Small Hydro, Greek Hydropotential

1. Introduction

Greece possesses an extensive and diverse hydrological network comprising numerous small and large watercourses, characterized by wide variations in catchment size, flow regimes, and precipitation levels resulting from the country's mountainous topography and spatially non-uniform rainfall distribution. These characteristics create favorable conditions for the exploitation of low-head hydropower resources, particularly through the deployment of Archimedean Screw Turbines (ASTs). AST technology enables electricity generation from low-head and low-flow sites with minimal environmental impact, offering a suitable and environmentally compatible solution for decentralized renewable power generation. Such systems are especially well suited for coupling with water electrolysis units, enabling localized and small-scale green hydrogen production.
Archimedean hydro technology has a long historical background, originating from the classical Archimedean screw, while its modern application in hydropower generation represents a relatively recent advancement in small-scale renewable energy systems. Contemporary Archimedean Screw Turbines constitute an emerging class of low-head small hydropower plants that can be installed in a wide range of natural and artificial watercourses, including sites unsuitable for conventional turbines. In recent years, a global resurgence in the development of renewable energy systems has driven increased interest in low-head small hydropower applications, highlighting the role of ASTs as a viable and mature technology [1-4]. ASTs provide clean and renewable electricity, exhibit high operational reliability, and demonstrate superior environmental performance, particularly with respect to fish passage and aquatic ecosystem protection, compared to other traditional hydropower technologies.
As a result, Archimedean small hydropower has attracted growing attention from the research community and industry alike, with several European companies actively deploying AST-

based installations [5–10]. Within this context, the present study addresses the need for a systematic assessment of the hydrogen production potential associated with Archimedean small hydropower in Greece. By quantifying the theoretical hydropower resource and its conversion into green hydrogen through water electrolysis, this work contributes to the development of a national-scale hydrogen production inventory, supporting Greece’s transition toward a low-carbon and hydrogen-enabled energy system. Figure 1 illustrates a representative inclined-axis Archimedean small hydropower installation [11]. The renewed interest in Archimedean screw technology in Greece, applied as a modern low-head hydropower solution, offers the potential to satisfy the energy requirements of a large number of dispersed sites across the country. The deployment of multiple small-scale Archimedean Screw Turbines within natural and engineered watercourses can be achieved with relatively simple installation procedures, competitive energy conversion efficiencies comparable to or exceeding those of conventional small hydropower plants, and reduced investment costs, particularly at low-head locations [3–10]. These characteristics make AST-based systems especially attractive for decentralized renewable energy generation. ASTs are well suited for hydraulic heads typically ranging from 1 to 5 m, with operating flow rates between approximately 0.1 and 50 m^3/s, and are commonly installed at inclination angles between 22° and 33° relative to the horizontal [4,6,9]. For sites with larger available heads, cascaded configurations comprising two or more AST units in series can provide efficient hydropower exploitation, while parallel arrangements of multiple turbines are appropriate for accommodating higher discharge conditions. Such modular and scalable configurations enhance the adaptability of AST technology to a wide range of hydrological settings. From the perspective of renewable hydrogen production, the distributed and flexible nature of AST installations enables their direct coupling with water electrolysis systems. The electricity generated by single or cascaded AST configurations can be utilized to supply electrolyzers operating under steady or variable load conditions, thereby supporting localized green hydrogen production. Consequently, the widespread application of Archimedean small hydropower across Greece forms a robust basis for developing a national inventory of hydrogen production potential, linking low-head hydropower resources with emerging hydrogen energy infrastructures. Representative configurations of Archimedean hydropower plants featuring turbines arranged in series and in parallel are illustrated in the right part of Figure 1 [11].

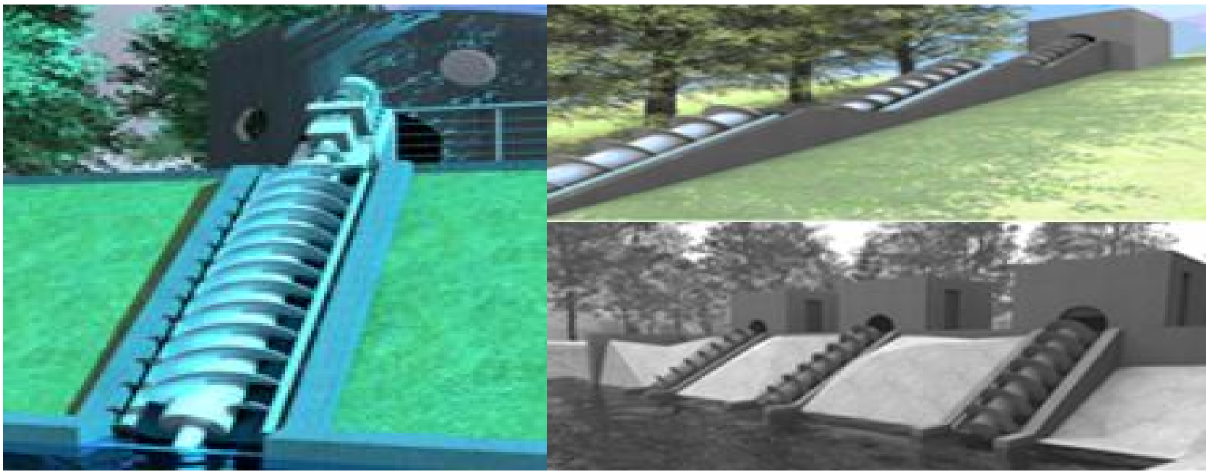


Figure 1. Photorealistic views of one AST and of ASTs having three screw rotors in series and in parallel.

A large number of watercourses in Greece present favorable conditions for the deployment of small hydropower plants based on Archimedean Screw Turbines (ASTs). The availability of small-scale hydropower resources across the country is considerable and characterized by diverse hydrological and geomorphological conditions. Given that modern AST technology enables the efficient exploitation of low-head hydropower sites that have remained largely untapped to date, there is a clear need for a systematic assessment of this renewable energy resource. In this context, the development of a national inventory of the Archimedean small hydropower potential of Greece is essential, not only to quantify the available renewable electricity generation but also to evaluate its potential contribution to green hydrogen production. By coupling AST-based hydropower systems with water electrolysis, these low-head resources can be transformed into a decentralized and environmentally sustainable source of renewable hydrogen. Such an inventory provides a necessary foundation for assessing the role of Archimedean small hydropower in supporting Greece's long-term hydrogen strategy and broader energy transition objectives [11].

2. Some Basic Greek Hydraulic Data

Greece, with a total surface area of 131,913 km², is characterized by an extensive network of small and large watercourses distributed across diverse catchment areas. The country's complex geomorphology, marked by rugged terrain, steep slopes, and highly uneven precipitation patterns, strongly influences its hydrological behavior . For water management and planning purposes, Greece is divided into 14 Water Districts, as shown in Figure 2: (01)

Western Peloponnese, (02) Northern Peloponnese, (03) Eastern Peloponnese, (04) Western Central Greece, (05) Epirus, (06) Attica, (07) Eastern Central Greece, (08) Thessaly, (09) Western Macedonia, (10) Central Macedonia, (11) Eastern Macedonia, (12) Thrace, (13) Crete, and (14) Aegean Islands. A general idea concerning the map of the annual isoyetial curves of Greece in mm is given in the same Figure 2 [11,12].

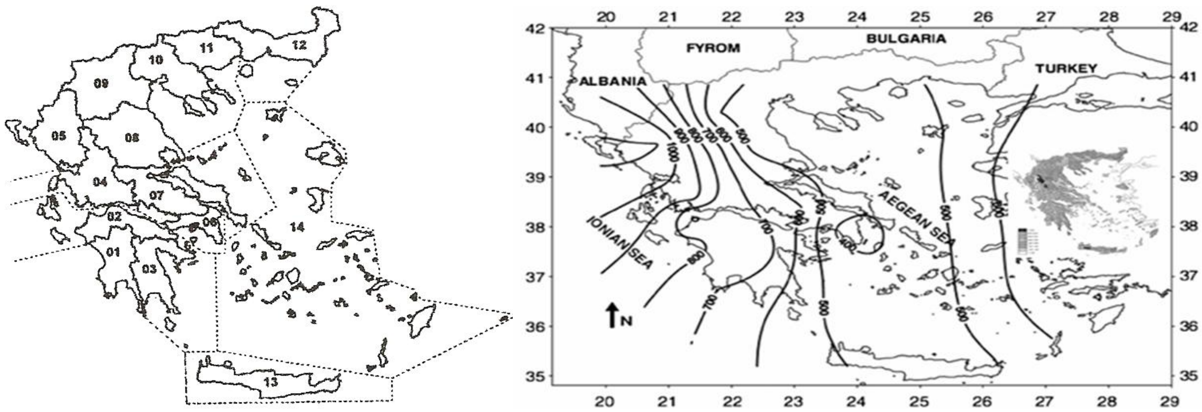


Figure 2. Greek Water Districts and map of the isoyetial curves of Greece, in mm

The values adopted for catchment areas, watercourse lengths, and available hydraulic heads were derived from topographic and hydrological maps provided by the Hellenic Military Geographical Service at scales of 1:50,000 and 1:400,000. The Archimedean small hydropower inventory developed in this study focuses exclusively on natural watercourses and does not include existing artificial open channels, hydraulic conveyance systems, or the kinetic energy potential of medium and large rivers. This scope ensures consistency with the low-head hydropower applications relevant to Archimedean Screw Turbine (AST) technology and its coupling with decentralized hydrogen production systems. Greek water resources are characterized by pronounced spatial and temporal variability, exhibiting strong seasonal and interannual fluctuations in flow regimes. To address these challenges, flow discharges were estimated using a combination of: (a) available hydrometric measurements, ranging from systematic records to sporadic and incomplete datasets; (b) theoretical hydrological calculations; and (c) comparative analyses and interpolations between adjacent catchment areas with similar geological, geomorphological, and hydrological characteristics. These approaches were adopted to ensure robust estimation of representative flow conditions suitable for small hydropower and hydrogen production assessments.

The evaluation of Archimedean small hydropower potential was based on the analysis of flow time series and the derivation of representative discharge values, Q, from Flow Duration Curves. In cases of limited data availability, simplified linear transpositions of discharge between catchments were applied, using ratios of drainage areas A1/A2 and, where necessary, precipitation ratios P_1/P_2 according to:

$$Q_1/Q_2 = (A_1/A_2).P_1/P_2 \qquad (1)$$

When precipitation patterns between two basins were comparable, the rain–runoff transposition was performed solely on the basis of catchment area ratios:

$$Q_1/Q_2 = (A_1/A_2) \qquad (2)$$

The resulting discharge estimates form the basis for calculating the theoretical Archimedean hydropower potential, which is subsequently converted into hydrogen production potential through water electrolysis. In total, the study investigated an area of approximately 45,915 km², corresponding to nearly 35% of Greece's land surface. Figure 3 presents the distribution of the investigated areas across the country's 14 Water Districts, providing the spatial framework for the national hydrogen production inventory derived from Archimedean small hydropower resources and the number of the examined watercourses per Water District 01, 02, 03,…014.

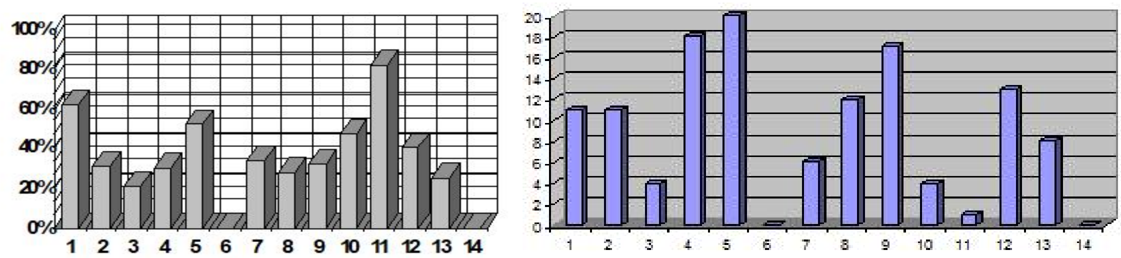


Figure 3. Percentage of the 14 Water Districts investigated areas and the number of the examined watercourses per Water District.

3. Looking for the Greek Archimedean Small Hydropower Inventory

The investigated area of approximately 45,915 km² was assessed using a holistic evaluation methodology that incorporates simple quasi-linear formulations, representative water-discharge values, and hydrological parameters derived from precipitation and evapotranspiration data. This approach enabled a first-order estimation of the theoretical Archimedean hydropower potential for each Greek watershed, basin, and Water District, expressed as a function of mean water flow and gross head $(Q.\Delta H)_{mi}$ across the 14 Water Districts of Greece. The theoretical hydropotential $E_i(kWh)$ and corresponding hydropower $P_i(kW)$ depend primarily on the available discharge Q and the topographical head ΔH.

Additional controlling factors include the catchment area A, watercourse length L, time t, and the efficiency of Archimedean screw turbine installations, all of which influence the determination of E_i and P_i.

$$E_i = f_1 \quad (Q, H, A, \quad L, t, \eta) \tag{3}$$

$$P_i = f_2 \quad (Q, H, A, \quad L, t, \eta) \tag{4}$$

Ideally, Archimedean Screw Turbines (ASTs) can enable hydropower generation in virtually any location where flowing water is available. In areas characterized by low discharge but relatively high head, this approach can be extended by installing a theoretical series of AST units, as illustrated in Figure 4. Conversely, in locations with larger flows and significant head, the concept may be expanded into more complex cascades, comprising both parallel and series configurations, to maximize energy extraction under varying hydrological conditions. Figure 4 provides schematic representations of such cascades. These include multiple ASTs arranged in series to exploit the total available head along an extended watercourse, as well as parallel configurations designed to accommodate higher flow volumes. These layouts demonstrate how AST cascades could be strategically deployed within the watercourses of Greece's Water Districts to harness their distributed hydropower potential [11,12]. We used for each catchment area a quasi linear variability of the flow Q_i, alongside a watercourse i, as illustrated in the right part of the same Figure, with a mean value flow discharge-height $(Q.\Delta H)_{mi}$ obtained

$$(Q.\Delta H)_{mi} = (Q_i . H_i)/2 \tag{5}$$

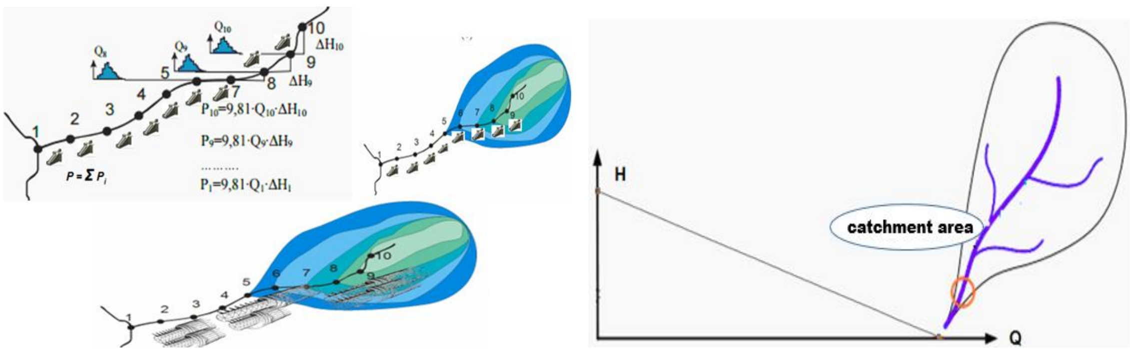


Figure 4. Schematic representations of several ASTs in series and in parallel (left) and representation of linear flow discharge variation of each watercourse (right)

For a typical watercourse i the theoretical Archimedean hydropower potential is calculated by using the linear formula

$$E_i\,(kWh)=9.81\,.\,(Q.\Delta H)_{mi}\,.\,8760 \qquad (6)$$

with Qi(m3/s), as the representative value from the flow duration curve water discharge and ΔHi (m), as the available constant over the year head in watercourse. Figure 5 gives the estimated theoretical Archimedean hydropotential, E_{th} in in GWh, per Water District [12].

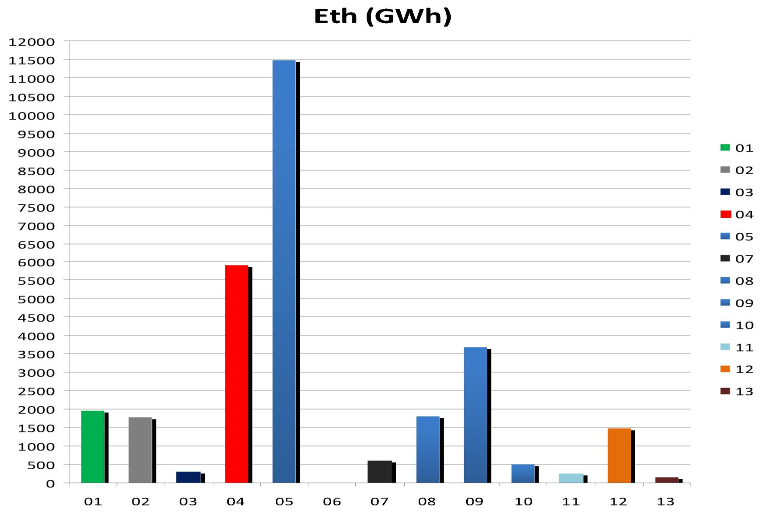


Figure 5. Theoretical Archimedean hydropotential per Water District in GWh.

The total theoretical Archimedean hydropower potential of the natural watercourses within the evaluated Greek area is estimated at approximately $E_{th} \approx 30$ TWh. The corresponding theoretical Archimedean small hydropower capacity is on the order of 3,500 MW. This inventory does not include the substantial kinetic small-hydropower potential of natural streams, the hydraulic energy available in water-supply and irrigation networks, or the promising potential of coastal and tidal currents. Based on the present assessment, the equivalent national energy savings are estimated to exceed 2.57×10^6 T.O.E. and 5.14×10^6 T.C.E., respectively. The theoretical specific Archimedean small hydropower capacity (kW/km²) was derived directly from the calculated energy output, yielding an average value of 74.7 kW/km² for the entire investigated area. Likewise, the theoretical small-hydropower density, or specific small-hydropotential of Greece as a whole, is approximately 0.651 GWh/km². The preliminary Archimedean small-hydropower assessment highlights the clear predominance of the Water Districts of Epirus and Macedonia, which together exhibit the highest theoretical hydropotential in Greece. Their combined theoretical small-hydropower potential is approximately 20 TWh with an estimated capacity of 1,500 MW, while their specific hydropotential reaches 2 GWh/km² and 250 kW/km². This dominance is strongly influenced by the Pindos Mountain Range, which governs the pronounced rainfall gradient between northwestern Greece (approximately 1,000 - 2,000 mm/year) and eastern regions (approximately 400–500 mm/year). Notably, although the Epirus Water District covers only 7.55% of Greece's total area, it accounts for more than 38% of the total theoretical Archimedean small-hydropower potential identified in this study. Its theoretical potential reaches 11.48 TWh and 1,310.6 MW, with corresponding specific values of 2.25 GWh/km² and 257 kW/km². Beyond the dominant influence of the Pindos range, several other major mountain systems, such as Vermion, Olympos, Athos, and Taygetos, also contribute significantly to the regional small-hydropower potential. Overall, the mean specific theoretical hydropotential for the Epirus–Macedonia region is estimated at 2 GWh/km² and 250 kW/km², underscoring its exceptional suitability for Archimedean small hydropower development.

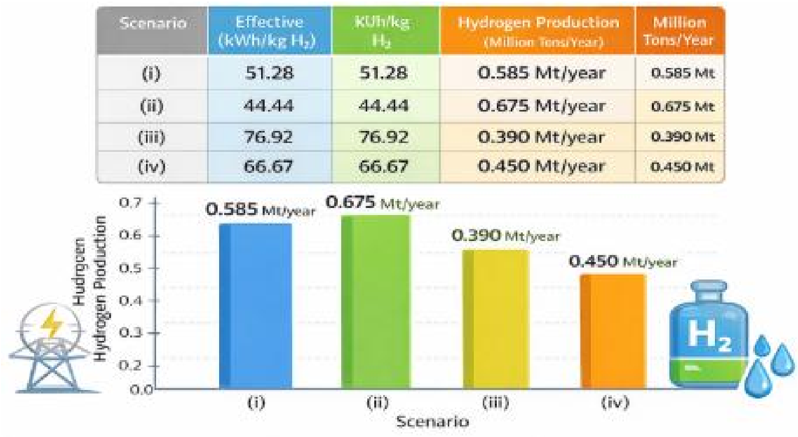
4. Towards a first Greek Archimedean Hydrogen Inventory

An initial approach to the Greek Archimedean Hydrogen Inventory is presented below, based on the estimated hydrodynamic electricity potential (30,000 GWh/year across all Water Districts) and assessed under four electricity-to-hydrogen conversion scenarios. To convert electrical energy into hydrogen, the mass of H_2 produced is determined based on the specific electricity consumption per kilogram of hydrogen. Scenarios (i) and (ii) adopt a baseline value of 33.33 kWh/kg (lower heating value, LHV), whereas scenarios (iii) and (iv) assume a higher consumption of 50 kWh/kg. Conversion efficiency directly influences the actual electricity required for hydrogen production. The following Figure 6 summarizes the four scenarios, including the baseline specific energy consumption (kWh/kg H_2), the assumed efficiency, and the resulting effective specific energy consumption (kWh/kg H_2).

Scenario	Baseline (kWh/kg H_2)	Efficiency	Effective Consumption (kWh/kg H_2)
(i)	33.33	65%	33.33 / 0.65 = 51.28
(ii)	33.33	75%	33.33 / 0.75 = 44.44
(iii)	50.00	65%	50.00 / 0.65 = 76.92
(iv)	50.00	75%	50.00 / 0.75 = 66.67

Figure 6. The four scenarios, including the baseline specific energy consumption (kWh/kg H_2), the assumed efficiency, and the resulting effective specific energy consumption (kWh/kg H_2).

The Figure 7 below presents the total hydrogen production potential for Greece across the four scenarios, expressed in million tonnes per year.



Scenario	Effective (kWh/kg H_2)	KUh/kg H_2	Hydrogen Production (Million Tons/Year)	Million Tons/Year
(i)	51.28	51.28	0.585 Mt/year	0.585 Mt
(ii)	44.44	44.44	0.675 Mt/year	0.675 Mt
(iii)	76.92	76.92	0.390 Mt/year	0.390 Mt
(iv)	66.67	66.67	0.450 Mt/year	0.450 Mt

Figure 7. The total hydrogen production potential for Greece across the four scenarios, expressed in million tonnes per year

The estimated hydrogen production potential in Greece amounts to approximately (i) 585 thousand tons H_2/year, (ii) 672 thousand tons H_2/year, (iii) 390 thousand tons H_2/year, (iv) 450 thousand tons H_2/year. These values are derived from the theoretical hydrogen production potential of each Water District, based on the available hydropower-generated electricity. Hydrogen production is assumed to occur via electrolysis under four distinct scenarios, reflecting different combinations of system efficiency and specific energy consumption: (i) 65% efficiency with 33.33 kWh/kg H_2 (LHV), (ii) 75% efficiency with 33.33 kWh/kg H_2 (LHV), (iii) 65% efficiency with 50 kWh/kg H_2, and (iv) 75% efficiency with 50 kWh/kg H_2. The resulting hydrogen production potentials are illutrated in Figure 8.

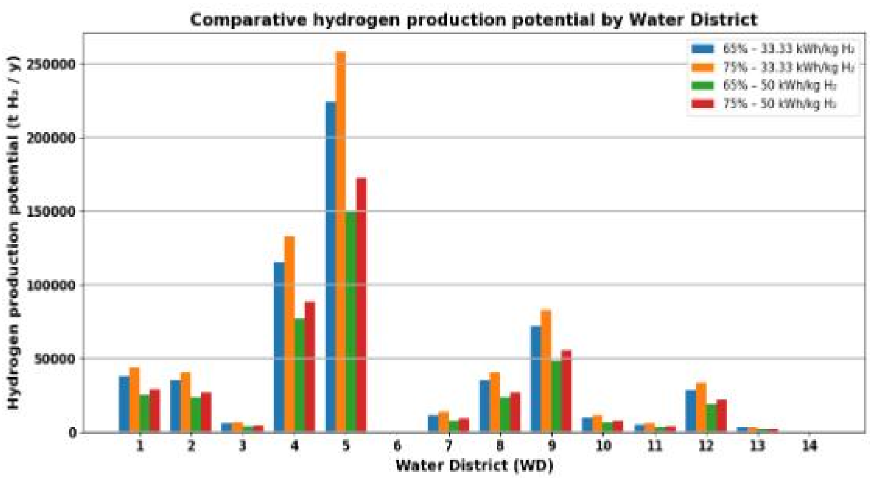


Figure 8. Corresponding theoretical hydrogen production potential by Water District, derived from the hydrodynamic electricity potential assuming electricity-to-hydrogen conversion via

electrolysis under four scenarios: (i) 65% efficiency with 33.33 kWh/kg H_2 (LHV), (ii) 75% efficiency with 33.33 kWh/kg H_2 (LHV), (iii) 65% efficiency with 50 kWh/kg H_2, and (iv) 75% efficiency with 50 kWh/kg H_2.

5. Conclusions

This study presents a national-scale inventory of hydrogen production potential derived from the theoretical Archimedean small hydropower resources of Greece. By analyzing the fundamental data from the 14 water regions of Greece and adopting a holistic methodology for assessing the country's total theoretical hydropower potential, this study compiles a comprehensive inventory of Greek Archimedean small hydropower resources. These resources, exploitable through Archimedean Screw Turbines (ASTs), correspond to an estimated total theoretical hydrodynamic energy potential of approximately 30 TWh/year. Based on this potential, the corresponding inventory of the theoretical Archimedean hydrogen potential of the country, is evaluated under four electrolysis scenarios: (i) 65% efficiency with 33.33 kWh/kg H_2 (LHV), (ii) 75% efficiency with 33.33 kWh/kg H_2 (LHV), (iii) 65% efficiency with 50 kWh/kg H_2, and (iv) 75% efficiency with 50 kWh/kg H_2. The resulting hydrogen production potentials are estimated at approximately (i) 585 thousand tons H_2/year, (ii) 672 thousand tons H_2/year, (iii) 390 thousand tons H_2/year, (iv) 450 thousand tons H_2/year, respectively.

The present hydrogen inventory suggests that Greece could produce between approximately 390,000 and 672,000 tons of green hydrogen annually from its theoretical Archimedean small hydropower potential, depending on technological efficiencies and operational factors. This highlights the significant opportunity to integrate small hydropower-based green hydrogen production into Greece's sustainable energy landscape.

Pleiades of promising small hydrogen production sites in Greece for ASTs installation are presented in Figure 9, in which is also given a "2 Archimedean Hydrogen Spears (AHS)" representation, with the important small hydroelectric hydrogen role of Pindos mountain range, along the first AHS, from Epirus, Thessaly, Central Greece, Peloponnesus, and the role of the mounts of Vermion, Voras, Paikon, Rodope of Northern Greece, Macedonia and Thrace, along the second AHS.

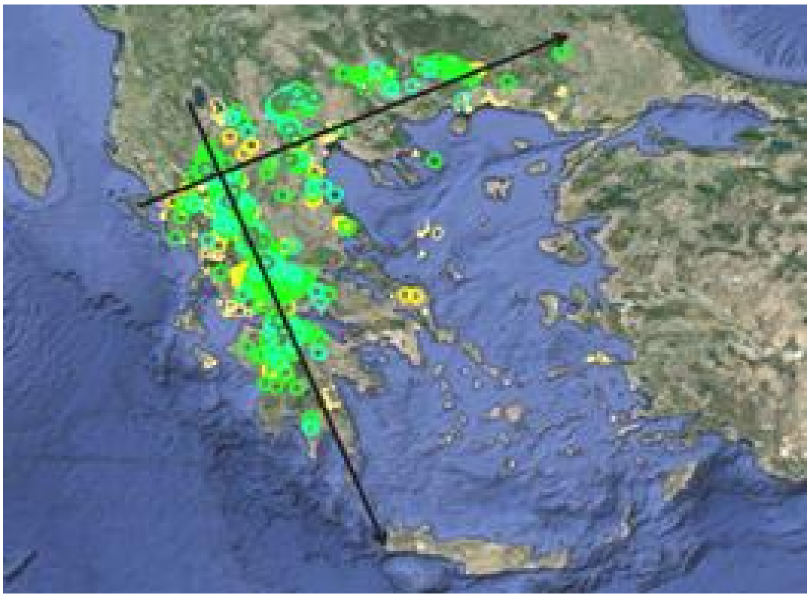


Figure 9. The two Archimedean Hydrogen Spears of Greece

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