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# CFD STUDY OF SMALL-SCALE HYDROPOWER ENERGY RECOVERY AND HYDROGEN PRODUCTION IN THE ATHENS WATER SUPPLY NETWORK

**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 investigates the potential of integrating Small Hydropower Plants (SHPs) into the Athens Water Supply Network (AWSN) to recover otherwise wasted hydraulic energy and support green hydrogen production. Five candidate sites, Evinos, Kirfi, Helicon, Kithairon, and Mandra, are evaluated in terms of their energy recovery potential, economic viability, and contribution to low-carbon hydrogen generation. The proposed approach promotes the sustainable use of existing water infrastructure, reducing energy losses while supporting the

transition to cleaner energy systems. In addition, preliminary Computational Fluid Dynamics (CFD) simulations are presented to examine the hydrodynamic behavior of the proposed installations. Flow-3D results provide initial insights into flow patterns and system performance, highlighting key design considerations. Although the findings are encouraging, further research is needed to fully assess environmental impacts and optimize system integration.

**Keywords:** Hydrogen, CFD, FLOW-3D, AWSN, Renewable Energy, Small Hydro, Environment, Water Supply

## 1. Introduction

Water is conveyed to Athens, the capital city of Greece, mainly through the Evinos–Mornos aqueduct, which constitutes the largest urban water supply system in the country. A schematic representation of the Athens Water Supply Network (AWSN) is provided in Figure 1. The AWSN operates as a gravity-driven, free-flow system, with a design capacity exceeding $2.0\times10^6$ $m^3$/day and a maximum conveyance capacity of approximately 23 $m^3/s$ [1–5].


**Figure 1.** Schematic representation of the Athens Water Supply Network (AWSN).

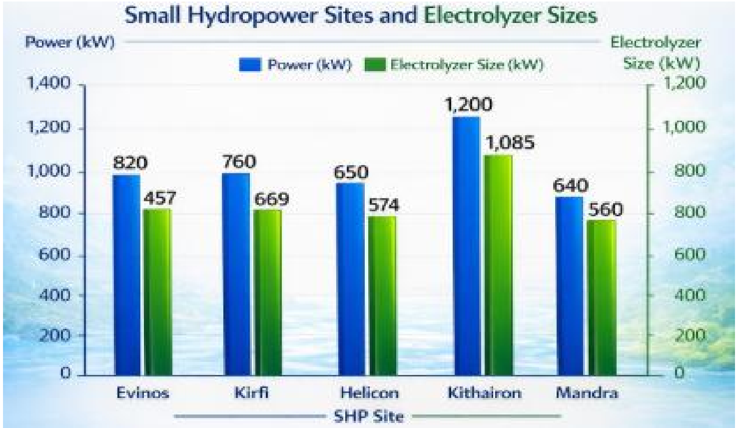
Currently, the hydraulic energy of the 23 $m^3/s$ flow through the AWSN is dissipated via break pressure tanks and energy dissipation devices. By integrating small hydropower systems (SHPs) at these locations, a substantial amount of renewable energy could be recovered. This study assesses the technical feasibility of five potential SHP sites, as well as the potential for hydrogen production via electrolysis.

## 2. Energy Recovery and Hydrogen Production in AWSN

The present study describes the efficient implementation of the multipurpose small hydropower concept for recovering wasted hydraulic energy from the existing break pressure devices and energy dissipation structures of the Athens Water Supply Network (AWSN). Priority is given to the Kirfi, Cithaeron, Helicon, and Mandra energy recovery sites. It was found that, for the AWSN, it is technically and economically feasible to install five small hydropower plants: Evinos SHP, Kirfi SHP, Helicon SHP, Kithairon SHP, and Mandra SHP [1–4]. The installed capacities P (MW) and the annual energy production E (GWh) of the following small hydropower plants depend on the available water discharge Q and net head H, as well as on the type of turbine used:

1. Evinos SHP (Q=1,3 $m^3/s$, H= 70m, P=0.82MW, E= 4 GWh, 1 turbine Francis)
2. Kirfi SHP (Q=11$m^3/s$, H=8.03m, P=0.76 MW, E= 5.86 GWh, 1 turbine Kaplan)
3. Helicon SHP (Q=11$m^3/s$, H=6.84 m, P=0.65MW, E= 5.03 GWh, 1 turbine Kaplan)
4. Kithairon SHP (Q=10.5$m^3/s$, H=16.44m, P=1.20MW, E= 9.50 GWh, 2 Turbines Kaplan)
5. Mandra SHP (Q=10 $m^3/s$, H=8.25m, P=0.63, 0.65 MW, E= 4.9 GWh, 1 turbine Kaplan)

These five cascade small hydropower plants of the AWSN have a total installed capacity of approximately 4.06 MW, producing around 29.3 GWh of electricity per year. Among them, the largest hydropower plant corresponds to the Kithairon break-pressure site. Although the water discharge varies from 5 to 17 $m^3/s$ and the available net head ranges from 13 to 17.8 m, the design point can be characterized by the nominal conditions Q = 10.5 $m^3/s$, H = 11 m, and P = 1.20 MW. Under these conditions, replacing the existing Kithairon break-pressure device with a small hydropower plant would harness approximately 9.5 GWh of hydraulic energy per year. The electricity generated by these five SHPs can be directly utilized for green hydrogen production through water electrolysis. By coupling each hydropower installation with appropriately sized electrolyzers, the recovered energy can be converted into hydrogen, providing a clean and storable energy carrier. In this integrated water–energy–hydrogen system, the cascade of SHPs functions not only as a distributed renewable power source but also as a network of decentralized hydrogen production units. For the five SHP sites, to convert electrical energy into hydrogen, the mass of $H_2$ produced is determined based on the specific electricity consumption per kilogram of hydrogen 55 kWh/kg. Figure 2 present the installed capacity of  the five small hydropower sites and the electrolyser sizes in kW.




**Figur 2**. Installed Capacity of Small Hydropower Sites and Electrolyser Sizes

Given that each SHP installation within the AWSN is relatively small, ranging between approximately 0.6 and 1.2 MW, careful consideration must be given to system configuration, operational strategy, and overall economic performance. The limited scale of these units necessitates particular attention to electrolyser selection, efficient integration with existing infrastructure, and the minimization of the levelized cost of hydrogen, commonly expressed in €/kg $H_2$. Across the five SHP units evaluated, annual hydrogen production is estimated to range from approximately 73 t to 173 t per site, in direction proportion to the available annual electrical output. This relationship is clearly reflected in the hydrogen production versus annual energy plot, which shows a near-linear trend driven by the fixed electrolyser efficiency assumption. Sites with higher utilisation factors, such as Kithairon and Mandra, (both exceeding 85%), convert their electrical output into hydrogen more effectively, reinforcing the importance of stable baseload renewable generation for hydrogen systems. The total hydrogen production across all sites is estimated at 532.5 tonnes per year, while the total installed electrolyser capacity is approximately 3.345 MW. Figure 3 presents the Hydrogen Production and Annual Energy production of the five hydropower plants of the AWSN and highlights the nearly linear relationship between annual hydropower generation and annual hydrogen output. Sites with higher generation (e.g., Kithairon) achieve proportionally larger hydrogen yields, whereas smaller installations (Evinos, Mandra) produce correspondingly lower quantities. This quasi-linear correlation strengthens confidence that energy-based scaling methods can accurately predict hydrogen productivity across the AWSN.

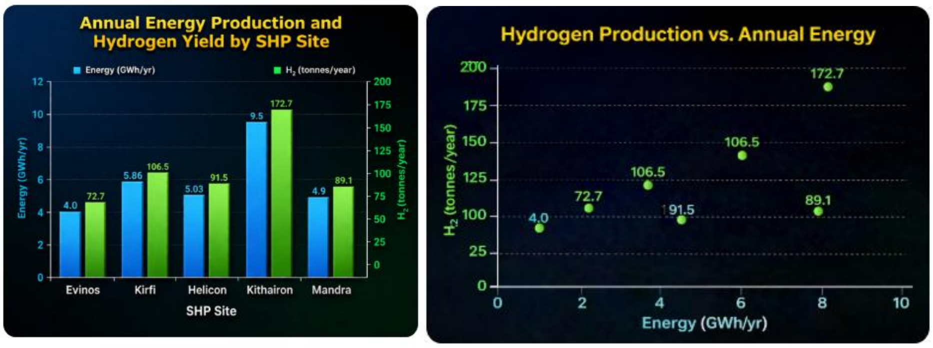



**Figure 3.** Annual Hydrogen and Energy Production and quasi-linear relation of the Hydrogen Production versus Annual Energy

It is estimated that the hydrogen production cost ranges between €5.28/kg and €5.87/kg across all sites.The similarity arises because capital costs scale roughly linearly with electrolyser power size, while the assumed electricity cost and electrolyser efficiency dominate the total cost structure. Consequently, variations in flow rate, head, and turbine technology manifest primarily through differences in total annual energy and thereby total hydrogen output, rather than through significant changes in cost per unit of hydrogen. This makes SHP-to-hydrogen systems relatively predictable from an economic standpoint, provided that capacity factors remain high. The comparison of hydrogen production (t/year) and cost (€/kg) across the five sites is presented in Figure 4 . The bars represent annual $H_2$ production, and the line indicates the corresponding cost per kilogram.

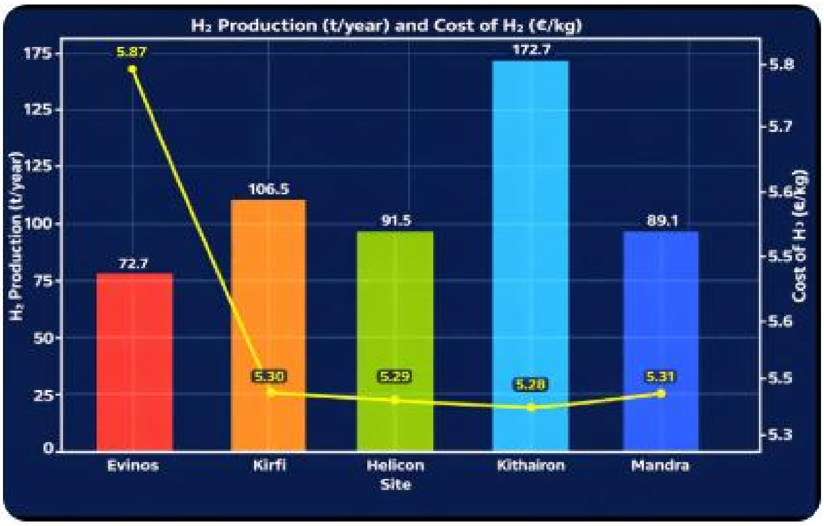



**Figure 4**. Comparison of hydrogen production (t/year) and cost (€/kg) across five sites.

The integration of the five small hydropower (SHP) facilities within the Athens Water Supply Network (AWSN) into a power-to-hydrogen framework demonstrates a robust potential for decentralized renewable hydrogen production. Each SHP site converts hydraulic energy from pressure-reducing locations into electricity, which subsequently drives an electrolyser. While the generation capacities vary across sites, the modelling results reveal consistent techno-economic behaviour due to the common scale range (0.6–1.2 MW) and similar operating patterns. The estimated 29.3 GWh/year of green electricity generation could support more than 530 tons/year of hydrogen production. The calculated levelized cost of electricity is competitive with current market prices (47–60 €/MWh). Importantly, the proposed system enables emission-free hydrogen generation without interfering with water-supply operations. A pilot installation at the Kithairon SHP, the most powerful site (~1.2 MW, 9.5 GWh/year), would provide an effective starting point for implementation. The modelling results across the five small hydropower (SHP) sites of the Athens Water Supply Network demonstrate a consistent techno-economic profile for electricity-to-hydrogen conversion. Despite substantial differences in flow rates, available head, turbine type, and annual operating hours, all sites yield broadly similar hydrogen production costs, typically between €5.2 - €5.8 per kg $H_2$.

## 3. CFD Modeling with FLOW-3D for Energy Recovery and Hydrogen Production in the AWSN

In the present study, the commercial computational fluid dynamics (CFD) software FLOW-3D (version 11.2), developed by Flow Science, Inc., was employed to simulate hydraulic behavior and assess energy recovery potential within the Athens Water Supply Network (AWSN), with particular emphasis on its integration with hydrogen production systems. Software licenses were provided by ASPETE (School of Pedagogical and Technological Education, Athens, Greece) for research and academic use [5]. FLOW-3D solves the Reynolds-Averaged Navier–Stokes (RANS) equations using a finite-volume formulation applied to a structured computational grid. The computational domain is discretized into a network of control volumes, each containing locally averaged values of the dependent flow variables. A staggered-grid arrangement is used, in which scalar quantities are stored at cell centers, while velocity components and fractional face areas are defined at the centers of the cell faces normal to their respective directions [5]. The free-surface dynamics are captured using the Volume of Fluid (VOF) method originally developed in [6], enabling accurate tracking of complex surface deformation. Solid boundaries and internal hydraulic structures are represented using the Fractional Area/Volume Obstacle Representation (FAVOR) method, which embeds obstacles within the fixed mesh by blocking portions of cell volumes and faces. This porosity-based technique assigns a porosity of zero to fully obstructed regions and one to unobstructed regions, with intermediate values representing partially occupied cells [6–9]. The FAVOR methodology enables efficient and geometrically flexible representation of hydraulic structures, such as spillways, stilling basins, and turbine chambers. For turbulence modeling, the RNG model was adopted. To assess numerical uncertainty, a systematic CFD uncertainty evaluation procedure, known as the Grid Convergence Index (GCI), described in [6,10,11], was applied. Details concerning the geometry, mesh configuration, and the initial and boundary conditions used in the Flow-3D simulation of the Evinos Hydropower Plant case study are presented in Figure 5. These modeling parameters form the basis for accurately resolving the hydraulic performance and quantifying the recoverable energy potential of the AWSN system. The resulting flow characteristics and power estimates are subsequently utilized to evaluate the feasibility of coupling the hydropower installation with electrolysis units for green hydrogen production. In particular, the CFD-derived outputs support the assessment of power stability, system efficiency, and the appropriate sizing of electrolyzers to ensure reliable and optimized hydrogen generation.

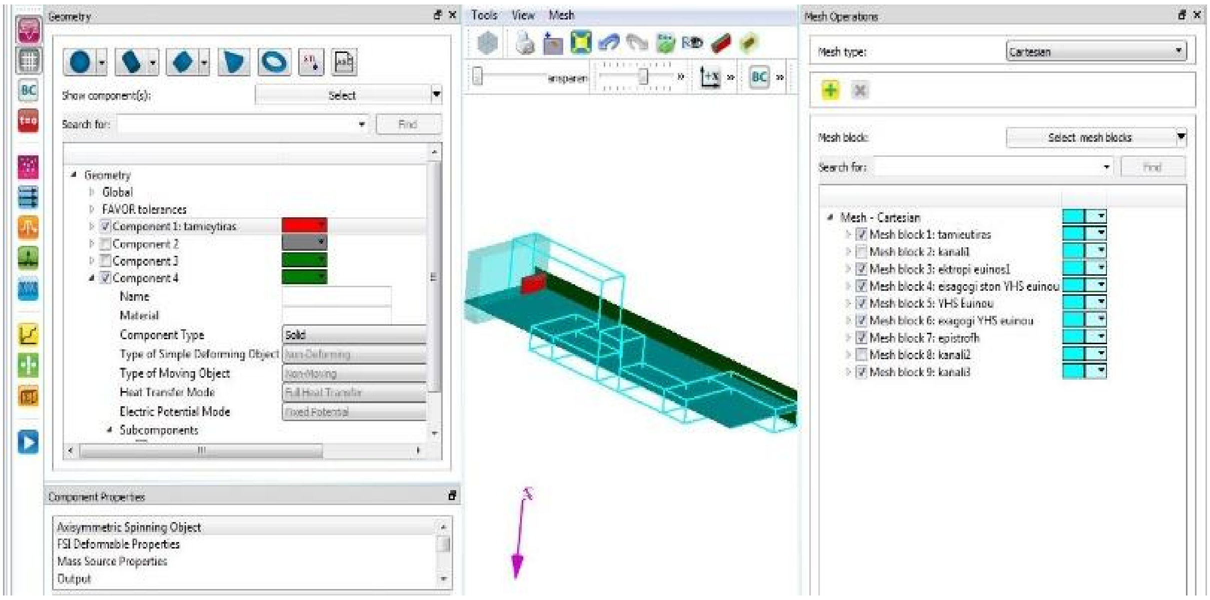


**Figure 5**. Adjustment tab for the simulation geometry of the Evinos hydropower plant, supporting the assessment of energy recovery for subsequent green hydrogen production.

Figure 6 below presents an initial view of the preliminary simulation results tab in the Flow-3D application for the Evinos case, showing the pressure variations at a given time, illustrating pressure variations at a specific time step. These pressure distributions are critical for evaluating hydraulic head availability and energy recovery potential, which directly influence the efficiency and feasibility of downstream green hydrogen production via electrolysis. A simplified CAD model of a small hydropower turbine, represented as a basic water wheel, was created in SolidWorks Premium 2017. In the CFD simulations, this water-wheel geometry is visualized in purple. energy recovery for green hydrogen production. The CAD model was exported in .stl format and subsequently imported into FLOW-3D for preprocessing. Given the available computational resources and the associated time constraints, only the symmetric half of the turbine was included in the analysis.

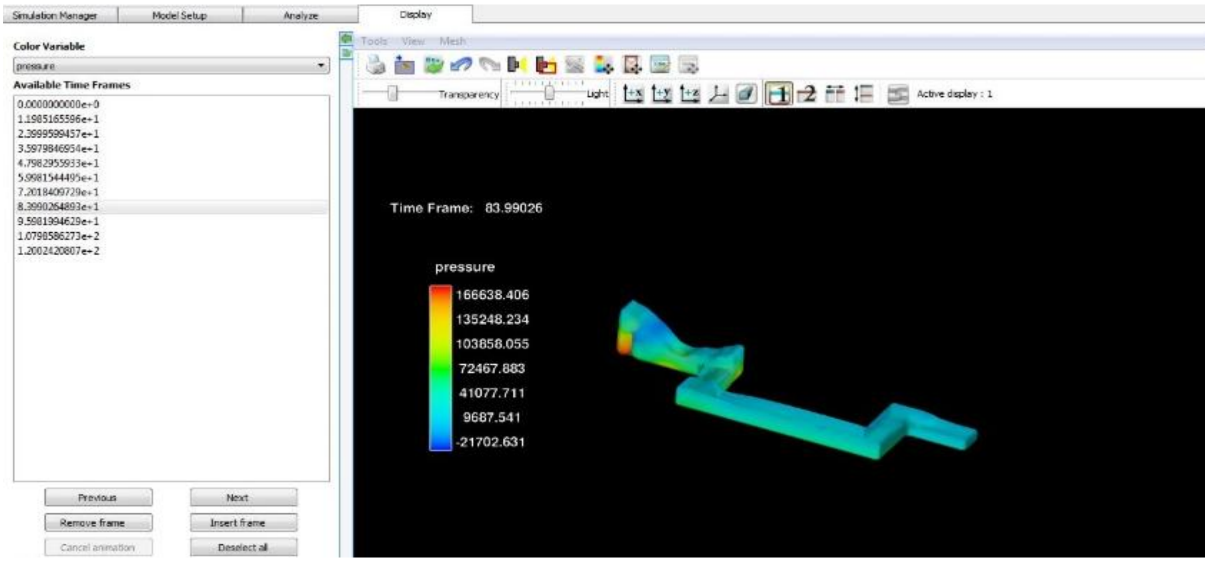



**Figure 6.** Preliminary Flow-3D simulation results tab for the Evinos case, depicting pressure variations used to estimate

The STL geometry was used within the CFD environment to generate the computational mesh. FLOW-3D employs an interactive mesh-generation module and a flow solver capable of resolving the continuity, Euler, and Navier–Stokes equations across all relevant flow regimes.The resulting simulations provide critical insights into turbine performance, including flow behavior, torque generation, and hydraulic efficiency, which are essential for accurately estimating electrical power output. This power output is subsequently evaluated for its direct utilization in water electrolysis systems, supporting the design and optimal sizing of electrolyzers for green hydrogen production. In this context, the CFD-based turbine modeling contributes to ensuring stable and efficient energy supply, which is a key requirement for maximizing hydrogen yield and overall system performance.

$$\frac{\partial \rho}{\partial t} + \vec{\nabla} \cdot \left( \rho \vec{V} \right) = 0$$

$$\rho \frac{D\vec{V}}{Dt} = \rho\left[\left(\vec{V}\cdot\vec{\nabla}\right)\vec{V} + \frac{\partial \vec{V}}{\partial t} + \right] = -\vec{\nabla}p + \rho\vec{F}$$

The input parameters were derived from the turbine design specifications, while the fluid properties were obtained from established literature. The working fluid was defined as water at 20 °C, characterized by a density of 1000 kg/m³ and a dynamic viscosity of 0.001 N·s/m². Uniform pressure distribution and fluid initialization with a prescribed water-surface elevation were applied as initial conditions. The CFD simulations correspond to one of the small hydropower facilities located along the Mornos Athens channel specifically, the Kirfi small hydropower plant, producing green hydrogen.The preliminary FLOW-3D simulation for the Kirfi installation was executed for a total physical time of 120 s. Mean velocity, volume-fraction, and pressure distributions at selected time instances (t = 14.40 s, t = 23.99 s, and t = 116.39 s) were extracted using Flow Sight, the advanced post-processing and visualization module of FLOW-3D. These results are presented in Figures 7, 8, and 9 for the corresponding time steps.

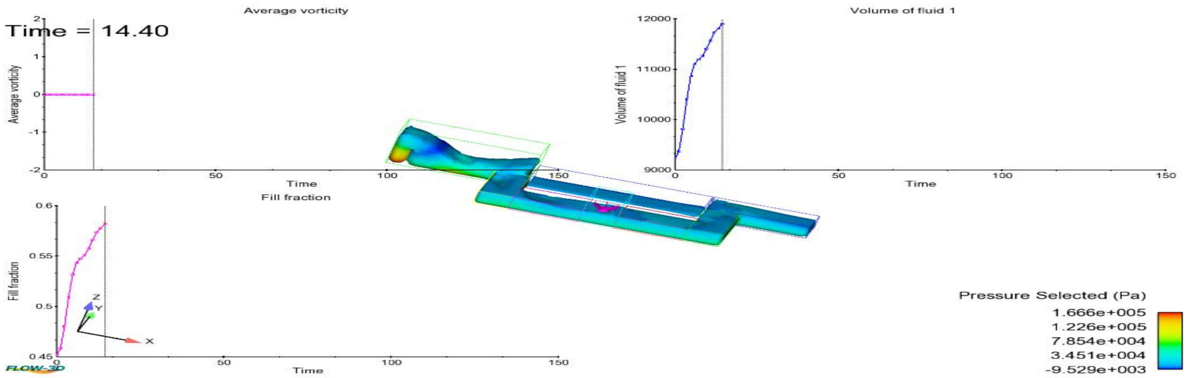



**Figure 7**. Flow-3D simulations and Flow Sight visualizations at the time 14,40 sec for the Kirfi SHP, producing green hydrogen

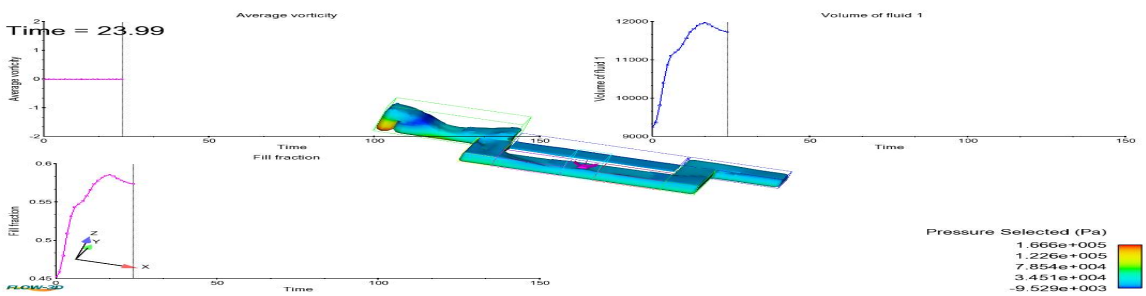



**Figure 8**. Flow-3D simulations and Flow Sight visualizations at the time 24sec for the Kirfi SHP, producing green hydrogen.

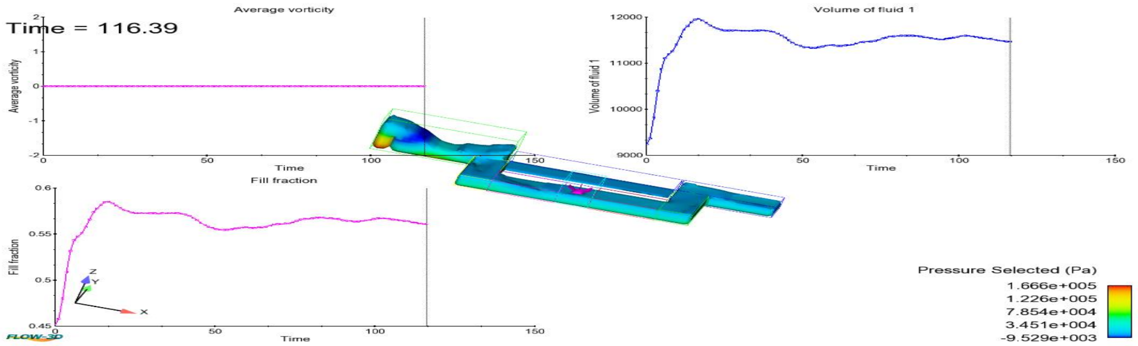



**Figure 9**. Flow-3D simulations and Flow Sight visualizations at the time 116,39 sec for the Kirfi SHP, producing green hydrogen

The first CFD simulation results for the entire Athens Water Supply Network, an open-channel system extending from Lake Mornos to the Mandra plant and including four small hydropower stations, producing green hydrogen,arranged in cascade, are presented below in Figures 10–14. The results were obtained using the post-processing and visualization tool FlowSight of the FLOW-3D code, and correspond to representative time steps of 0, 48, 144, 192, and 384 seconds.

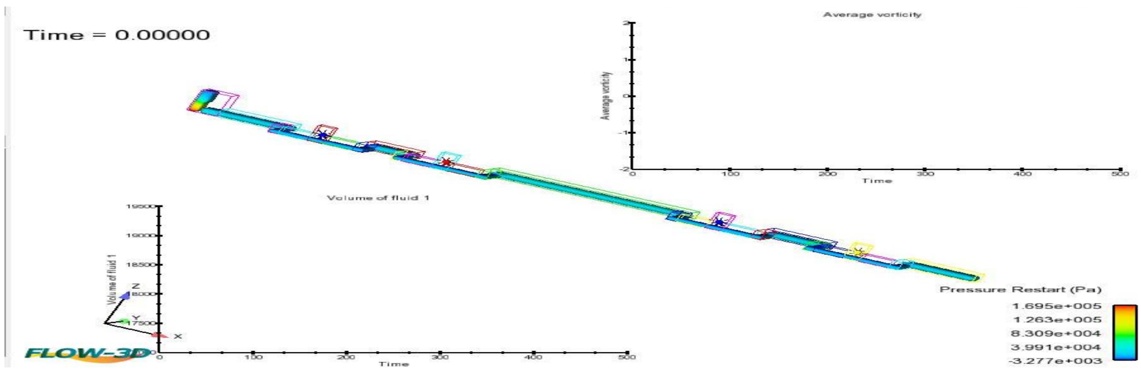



**Figure 10**. AWSN Flow Simulation - Time 0 sec and diagrammatic illustration in Flow Sight application.

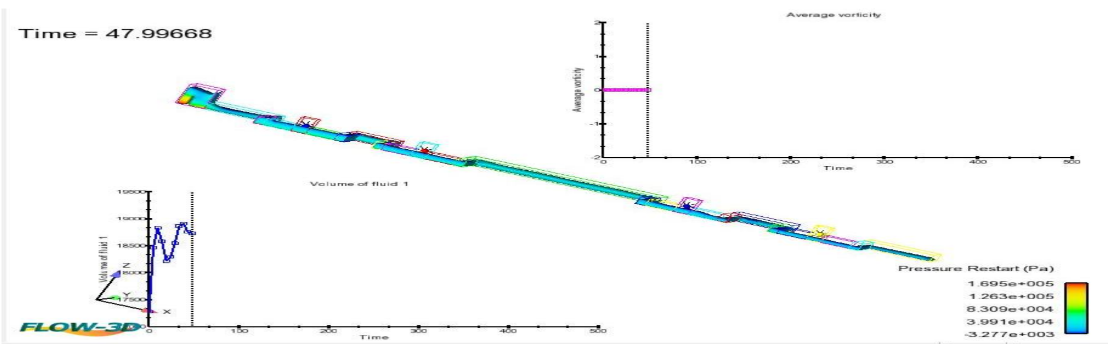



**Figure 11**. AWSN Flow Simulation - Time 48 sec and diagrammatic illustration in Flow Sight application.

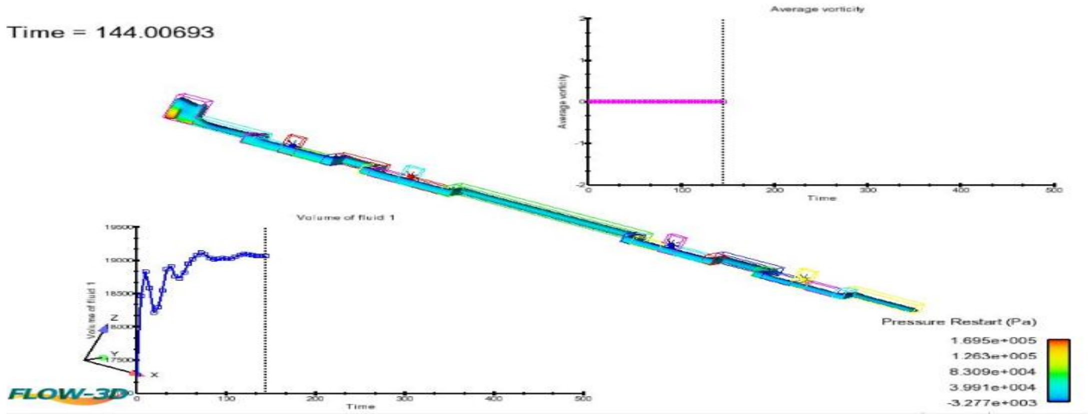



**Figure 12**. AWSN Flow Simulation - Time 144 sec and diagrammatic illustration in Flow Sight application

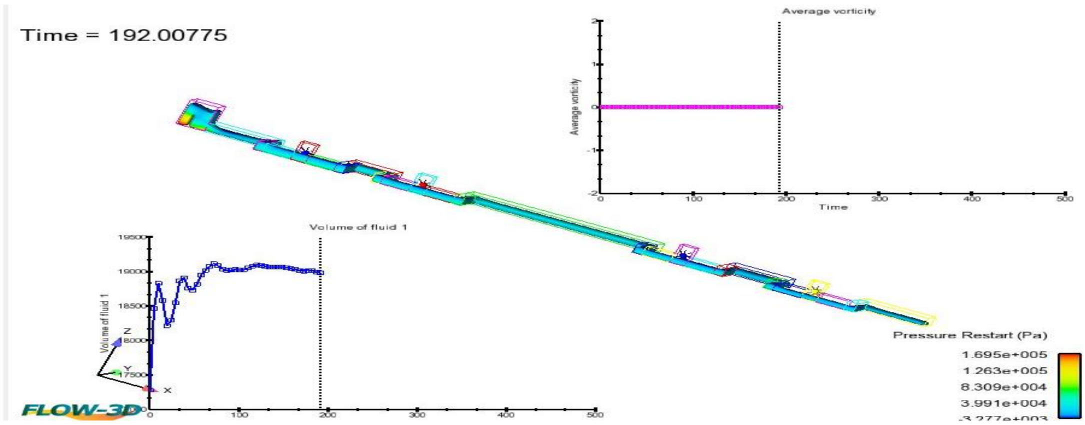



**Figure 13**. AWSN Flow Simulation - Time 192 sec and diagrammatic illustration in Flow Sight application.

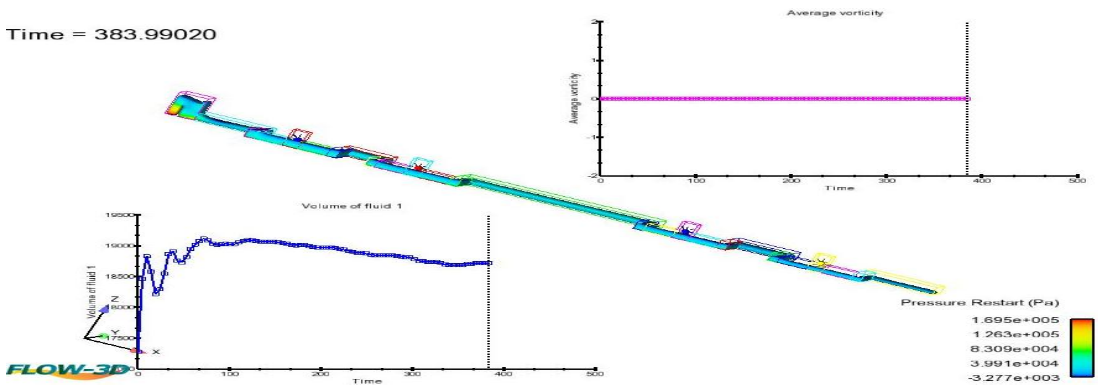



**Figure 14**. AWSN Flow Simulation - Time 384 sec and diagrammatic illustration in Flow Sight application.

## 4. Conclusions & Recommendations

This paper demonstrates that the AWSN, with the sites Evinos, Kirfi, Helicon, Kithairon, and Mandra, holds significant untapped potential for renewable energy recovery about 29.3 GWh/year of electricity and can support >532 tons/year of green hydrogen. The second part of the paper presents key features of CFD simulations and preliminary Flow-3D results assessing the hydrodynamic performance of cascade small hydropower plants. These preliminary simulations indicate the potential for substantial energy recovery from the AWSN, while also highlighting the need for further analysis and optimization to maximize the efficiency of the cascade system. The preliminary CFD simulation results presented here for the five Small Hydropower Plants, designed to harness the wasted hydraulic energy in the dissipation structures of the AWSN, demonstrate significant potential for sustainable energy generation and its direct utilization for green hydrogen production. The findings indicate that the recovered hydropower can provide a reliable renewable energy source to drive water electrolysis processes. However, further detailed investigations are required to optimize both hydropower performance and hydrogen production across the entire AWSN. These include the refinement of turbine design and placement, enhancement of energy recovery efficiency, and improved matching between power output and electrolyzer demand. Such integrated optimization is essential to maximize hydrogen yield, ensure stable system operation, and enhance the overall efficiency of the combined water–energy–hydrogen framework.

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