

# ECOS 2026: Integration of Hybrid Energy-Flexible Technologies in Industrial Processes: Performance Benefits and Implementation Challenges

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## Abstract:

The paper investigates the potential of integrating energy-flexible technologies into industrial processes with the objective of improving energy efficiency, sustainability, and resilience across multiple industrial sectors. It presents the development of three main prototypes designed to support the integration of renewable energy into industrial applications: a heat exchanger prototype intended to optimize thermal management and energy recovery in various industrial processes; a digital energy service (DES) prototype developed to facilitate energy knowledge sharing and enhance storage flexibility; and an advanced hydrothermal reactor prototype for converting biowaste into valuable resources within a circular economy framework. In addition, the study incorporates innovative models for hydrogen utilization and photovoltaic (PV) energy production, together with the evaluation of refined gases and combined heat and power (CHP) systems for simultaneous electricity and heat generation. By integrating renewable energy sources, the proposed approach aims to support sustainable industrial practices that reduce environmental impacts while improving energy autonomy and operational performance. The research addresses industrial processes across several sectors within the framework of the EU-funded TRINEFLEX project, which includes five demonstration cases involving the glass industry in Italy, the aluminium industry in Spain, the copper industry in Greece, and wastewater treatment facilities in both Spain and Greece. To validate the developed prototypes and assess their practical impact, a wastewater treatment plant at ESAMUR in Spain was selected as the main case study, enabling the evaluation of the proposed technologies under real operational

## Keywords:

WWTP; Exergy; Hybrid; Industrial, Sustainability.

## 1. Introduction

The industrial sector plays a central role in global energy demand, accounting for a substantial share of carbon emissions and resource consumption. Traditional fossil-fuel-based energy systems are increasingly constrained by rising energy prices, supply volatility, and growing environmental pressures. As industries pursue strategies to reduce their carbon footprint and enhance operational efficiency, the adoption of hybrid energy-flexible technologies has emerged as a key pathway toward decarbonisation and improved resilience. These technologies enable the flexible and efficient use of renewable energy sources, supporting the transition to more sustainable industrial operations. This paper addresses these challenges by developing and implementing innovative technological solutions aimed at expanding new energy flexibility within industrial processes. The work focuses on the integration of hybrid energy-technologies including heat exchangers, PV technologies, electrolyser and hydrogen utilisation, CHP, Hydromol, waste-to-energy integration system, all

with an advanced digital energy service to support renewable energy learning. The overarching objective is to decrease dependence on non-renewable energy sources, reinforce circular-economy approaches, and strengthen the resilience of industrial energy systems. Three main prototypes were developed combined with multi technologies to advance use of renewable energy and exploiting waste energy in industrial applications:

1-Heat exchangers prototype tailored to improve thermal management across diverse industrial processes.

2-Digital Energy Services (DES) prototype tools for enhanced use and knowledge sharing of distributed energy storage, increasing learning and flexibility of energy use.

3- Hydromol valorisation reactor prototype designed for transforming biowaste into valuable resources hydrochar and volatile fatty acids.

4-An electrolyser and hydrogen utilization models with PV system tailored to the local solar resource, aimed at promoting the adoption of hydrogen as a versatile and clean energy carrier in industrial processes. CO<sub>2</sub> from anaerobic digesters can be converted into biomethane using hydrogen, while the oxygen produced during electrolysis can be applied in aeration and ozonation process.

5- A Combined Heat and Power (CHP) system, using biogas produced from anaerobic digestion of sewage sludge or other organic waste to generate both electricity and heat.

The development of these prototypes and emerging technologies aligns with circular economy objectives by converting waste products into valuable resources, reducing costs, and enhancing flexibility. A Python-based simulation, which integrates all the developed hybrid energy components, is used to evaluate energy autonomy through self-production. Excess electricity generated by photovoltaic systems can be redirected to an electrolyser, producing hydrogen and oxygen, with the latter being valorised in various industrial processes. This paper seeks to advance sustainable industrial practices, reduce environmental impact, and enhance energy resilience. This study is part of the European Union's TRINEFLEX Project, contributing to the development of next-generation, energy-flexible industrial solutions

## 2. Previous work

Incorporating carbon-free renewable energy systems into the global energy mix is essential for combating global warming [1]. This is particularly crucial for the industrial sector, which is one of the largest consumers of energy worldwide. A significant portion of the energy demand in this sector comes from process heating [2]. Therefore, to meet global climate change mitigation targets, it is vital to harvest energy and waste thermal energy solutions that are both technically and economically competitive with fossil fuels for industrial heating applications. Several studies of the integration of renewable energies in industrial process have been discussed in the recent literature, in [3], the authors explained the CO<sub>2</sub> mitigation strategies in selected industrial sectors such as power, cement, iron, and steel as well as the petrochemical industry. Therefore, renewables, including solar, wind, hydropower, biofuels and others, are at the centre of the transition to less carbon-intensive and more sustainable energy system [1]. The authors in [4] suggest a multi-regional power system optimization model to evaluate the impact of various renewable energies flexibility options on reducing carbon emissions in the Chinese power sector, the results suggest that policy efforts should focus on enhancing adaptive regulatory frameworks and investment in renewable technologies, which are crucial for achieving long-term emission reduction goals while maintaining economic resilience in the G7. Several studies [5][6][7] have emphasized the importance of renewable energy in lowering carbon emissions and enhancing energy independence. In [8] highlighted a comprehensive techno-economic-environmental analysis of integrating hydrogen into Dutch heating networks to enhance seasonal storage and reduce CO<sub>2</sub> emissions, a hybrid solar-wind-hydrogen system is proposed, comprising photovoltaic panels, wind turbines, a battery energy storage system, a proton exchange membrane electrolyser, hydrogen compression and storage units, a proton exchange membrane fuel cell, and a water-to-water heat pump, the results show that hydrogen enables seasonal storage, achieving an exergy efficiency of 35.04 %, a total cost rate of 4.84 €/h (5.24 \$/h), annual CO<sub>2</sub> emissions of 63.64 tons, a levelized cost of hydrogen of 6.48 €/kg, and a 42.21 % share of the heat supply mix during cold spells. Renewable energy use in industrial processes can drive decarbonization. Previous studies have explored wastewater treatment plants as a sustainable hydrogen production solution, using renewable energy and treated water as feedstock. This research introduces a decision-making model to optimize capacities of solar, wind, reverse osmosis, electrolysers, storage, and grid imports. The system supports both hydrogen production and wastewater treatment while selling hydrogen and renewable energy certificates. A case study shows that a 120,000 m<sup>3</sup>/day plant with a 5 ton/day hydrogen facility offers a 35.2% gross profit margin and a 7.2-year payback, outperforming scenarios without land and energy constraints [9]. In [10] the authors develop a hybrid green energy-molten salt synergistic system for supplying energy to the

alumina digestion process, based on wind and solar power forecasting. In [11] the study focuses on a twofold power generation system by combining solar and wind energy, which is designed to enhance efficiency and ensure a continuous energy supply, the proposed system employs photovoltaic panels and a wind turbine to harness solar and wind energy even under variable weather conditions. This hybrid approach is particularly effective in regions with fluctuating solar radiation and wind patterns, maximizing energy output throughout the day and year. The authors in [12] study propose and evaluate an AI-optimized solar wind poly generation system that, unlike previous studies, simultaneously integrates 4E with Life Cycle Assessment and reliability modelling within a unified optimization framework. The hybrid configuration combines a steam Rankine cycle, cascaded organic Rankine cycles, wind turbines, PEM electrolyser, PEM fuel cells, thermoelectric generators, and dual storage units for thermal and compressed hydrogen. The AI-based optimization improved energy efficiency reduced total cost rate and decreased environmental impact. In [13], the study explores high-penetration wind-solar-gas hybrid power and hydrogen schemes proposing a novel framework for optimizing power-to-methane systems. In [14], the study evaluates 61 off-grid hydrogen supply chains for a 15 Mt. steel/year plant in 2030, considering renewable energy sources (onshore/offshore wind, solar, and overseas options), transmission technologies (cables, pipelines, trucks, and ships), storage technologies (compressed gaseous hydrogen, liquid hydrogen, ammonia, methanol, and liquid organic hydrogen carriers), and seasonal storage locations (at the energy source or steelmaking plant. In [15] the study explores the integration of a solar-hydrogen hybrid renewable energy system (SHRES) in oil and gas facilities, focusing on its techno-economic and environmental benefits. The SHRES includes Solar PV, hydrogen production and storage, and a gas turbine, aiming to improve energy efficiency and reduce carbon emissions. The analysis highlights the electrolyser system as the main cost driver (57%) and optimises energy sources 45% from PV, 35% from fuel cells, and 20% from gas turbines. The system achieves 80% renewable energy integration, reduces CO<sub>2</sub> emissions by 80%, and results in an annualised cost of \$57,539.85. In this paper, an innovative approach to achieve the decarbonisation of wastewater treatment plant in Spain is explored by the realisation of three prototypes and inclusion of new renewable technologies. The paper is organised as follows: the demonstration site, description of new technologies, simulation and discussion of the impact. Finally, conclusions are drawn.

### 3. Wastewater Treatment Plant ESAMUR

To evaluate the impact of the developed prototypes and digital tools across different industrial processes. A case study of a wastewater treatment plant in Spain was considered. ESAMUR is a regional, publicly owned, non-profit entity responsible for the management and operation of wastewater treatment services in the Region of Murcia, Spain. Alcantarilla WWTP was selected as the reference case study, this facility serves around 47,000 inhabitants, treats approximately 2.7 hm<sup>3</sup> of wastewater annually, and exhibits an electricity demand of about 2 GWh per year. To assess the potential for improving energy self-production, a Python-based simulation model was developed to analyse a hybrid energy system integrating solar photovoltaic (PV) generation, anaerobic digestion with biogas valorisation in combined heat and power (CHP) units, an electrolyser for hydrogen and oxygen production, a Hydromol treatment process, and a heat exchanger for thermal energy recovery. This multi-component configuration enables a coupled management of electrical and thermal energy flows, enhancing overall system efficiency. In this framework, PV provides the primary renewable electricity source, CHP ensures stable energy supply from on-site biogas, and surplus electricity can be converted into hydrogen via electrolysis, while heat recovery and flexible process loads further contribute to improved energy performance and increased self-sufficiency of the WWTP.



Figure 1 ESAMUR WWTP site

### 4. Development of Prototypes

## 4.1. Heat Exchanger Prototype (VENTIVE)

In ESAMUR use-case, TRINEFLEX HPHE was designed to provide extra heat for the sludge during winter as the heat supplied from the current heat exchanger was not sufficient. Therefore, a HPHE was designed to recover heat from the exhaust of the CHP plant and provide heat to the water intermediate heat exchanger as shown in figure 2. The HPHE will operate on variable water inlet temperature depending on the effectiveness of the current heat exchangers. Therefore, the model enables to predict the extra heat recovered by the HPHE and the water outlet temperature at different water inlet temperatures.

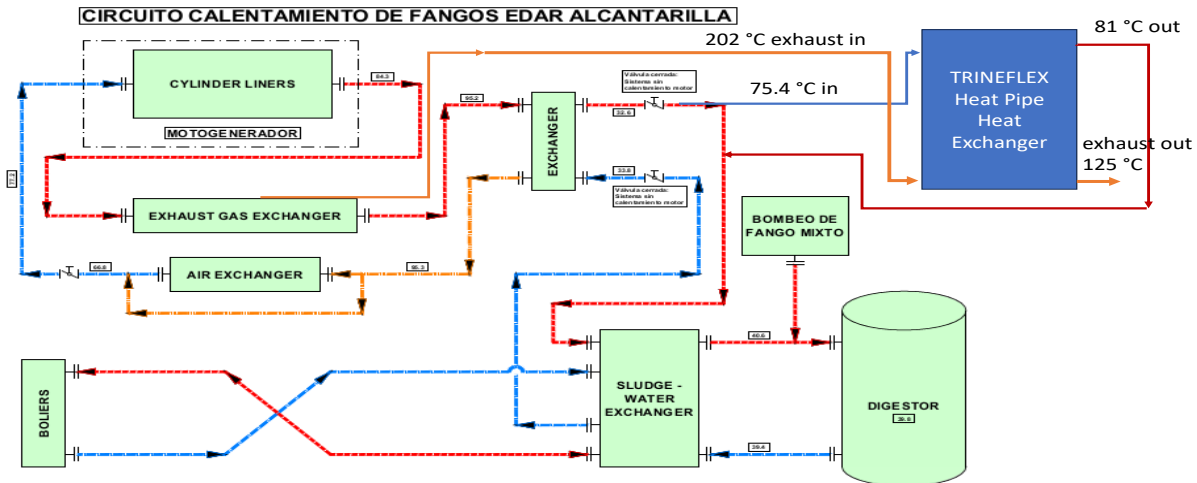


Figure 2 Heat from CHP

The model is performed by designing the heat pipe heat exchanger based on the data collected from ESAMUR WWTP. A HPHE design considers the operating temperature of the actual heat pipe which is dependent on the flow rate and temperature of hot and cold streams. The HPHE is designed to maximise the heat recovery while it is still cost effective. The model was validated based on a HPHE prototype examined experimentally within the project as shown in Figure 3.

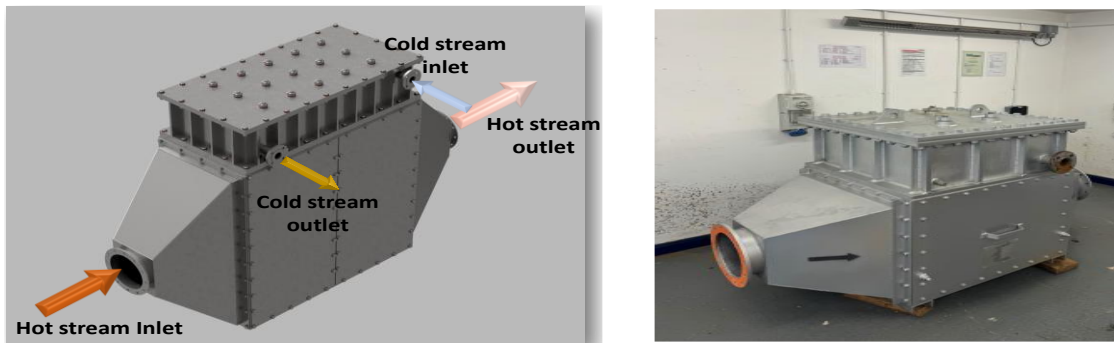


Figure 3 HPHE prototype

The thermal design of ESAMUR HPHE is presented in Table 1. The thermal performance of the designed heat exchanger varies depending on the inlet temperature of the water. i.e. the reported duty is expected to be 35.4 kW for water inlet temperature at 75.4 °C, and the thermal duty will decrease when the water inlet temperature is higher than the design value.

Table 1 ESAMUR HPHE thermal design

| Stream               | Parameter          | Value  | Unit              |
|----------------------|--------------------|--------|-------------------|
| Heat Source: Exhaust | Flow Rate          | 1955.7 | m <sup>3</sup> /h |
|                      | Mass flow rate     | 1464   | kg/h              |
|                      | Inlet Temperature  | 202.3  | °C                |
|                      | Outlet Temperature | 125    | °C                |

|                           |                          |      |                   |
|---------------------------|--------------------------|------|-------------------|
| Heat Sink: Water          | Flow Rate                | 5.6  | m <sup>3</sup> /h |
|                           | Mass Flow rate           | 5440 | kg/h              |
|                           | Inlet Temperature        | 75.4 | °C                |
|                           | Outlet Temperature (max) | 81   | °C                |
| Heat Exchanger Duty (max) |                          | 35.4 | kW                |

The HPHE was designed to recover waste heat from exhaust to provide extra heating, eliminating the need for boiler heating, and reducing energy consumption costs for ESAMUR WWTP as shown in table 2.

*Table 2 Heat exchanger energy savings insights for ESAMUR use-case.*

| Use Case                                                        | ESAMUR |
|-----------------------------------------------------------------|--------|
| Unit Heat Recovery (kW)                                         | 35.4   |
| Working hours per year                                          | 3300   |
| Energy recovery (MWh/yr)*                                       | 117    |
| Primary energy savings (MWh/yr)                                 | 123    |
| Natural gas price (€/MWh)                                       | 40     |
| Reduction of Energy Cost <i>from natural gas savings</i> (€/yr) | 4912   |
| CO <sub>2</sub> emission reduction (t/y)                        | 25     |
| CO <sub>2</sub> trading price (€/t)                             | 65     |
| CO <sub>2</sub> emission saved (€/y)                            | 1628   |
| Total saving (€/yr)                                             | 6540   |

## 4.2. PV and Hydrogen Utilization (TICAS)

Hydrogen plays a central role in the decarbonisation, as energy vector, storage medium, fuel and chemical intermediate. Industrial and research worlds are studying technologies to produce hydrogen with a low environmental impact, also called Green Hydrogen. The basis of these technologies is the production of hydrogen by electrolysis process combined with a renewable source of energy, such as solar or wind power or by biological processes from biomasses. The goal of the Green Hydrogen model, within TRINEFLEX, is to estimate the amount of hydrogen produced based on the power and energy production of PV system plant installed in ESAMUR with a capacity of 209KW. Among different electrolysis cells, polymer exchange membrane (PEM) were chosen because they have been known for over sixty years and, despite the relatively higher investment due to the precious metal used as electrocatalyst, they have a number of advantages, such as high current density, greater energy efficiency, low gas permeability, wider operating temperatures (20–80°C), easy handling and maintenance. In the PEM Water Electrolyser (PEMWE), water is introduced at the anode and decomposed into oxygen, protons and electrons. The protons are driven through the membrane to the cathode under an electric field where they combine with the electrons arriving from the external circuit to form hydrogen gas.

The main chemical reactions involved are:

- Anode:  $\text{H}_2\text{O} \rightarrow 2\text{H}^+ + \frac{1}{2} \text{O}_2 + 2 \text{e}^-$
- Cathode:  $2\text{H}^+ + 2 \text{e}^- \rightarrow \text{H}_2$
- Overall reaction:  $\text{H}_2\text{O} \rightarrow \text{H}_2 + \frac{1}{2} \text{O}_2$

A steady state model was performed using DWSIM ([www.dwsim.org](http://www.dwsim.org)), an Open-Source Chemical Process simulator. The main parts of the green hydrogen model are the PV system and PEMWE. The first one was simulated using a specific DWSIM block, while the simulation of the electrolysis process was performed by a 0-D model using an ad hoc user block written in Python. The process scheme in DWSIM is reported in Figure X. The system is fed with water (WATER) at room temperature (25°C), which is mixed with the water stream (RECY) from the separator after the electrolyser. Subsequently, the stream is heated (HEATING) to process temperature (70°C) and fed to the electrolyser. The latter was simulated by an ad hoc user block written in

Python (PEM). The main outputs of the electrolyser are hydrogen (H<sub>2</sub>), oxygen and unreacted water (O<sub>2</sub>OUT). After a cooling system (COOLING) and a separator (SEPARATOR), the oxygen (O<sub>2</sub>) is separated from the water, and the latter (H<sub>2</sub>ORECY) is recycled at the beginning of the process. The energy required for the electrolytic reactions was provided by the photovoltaic system (PV).

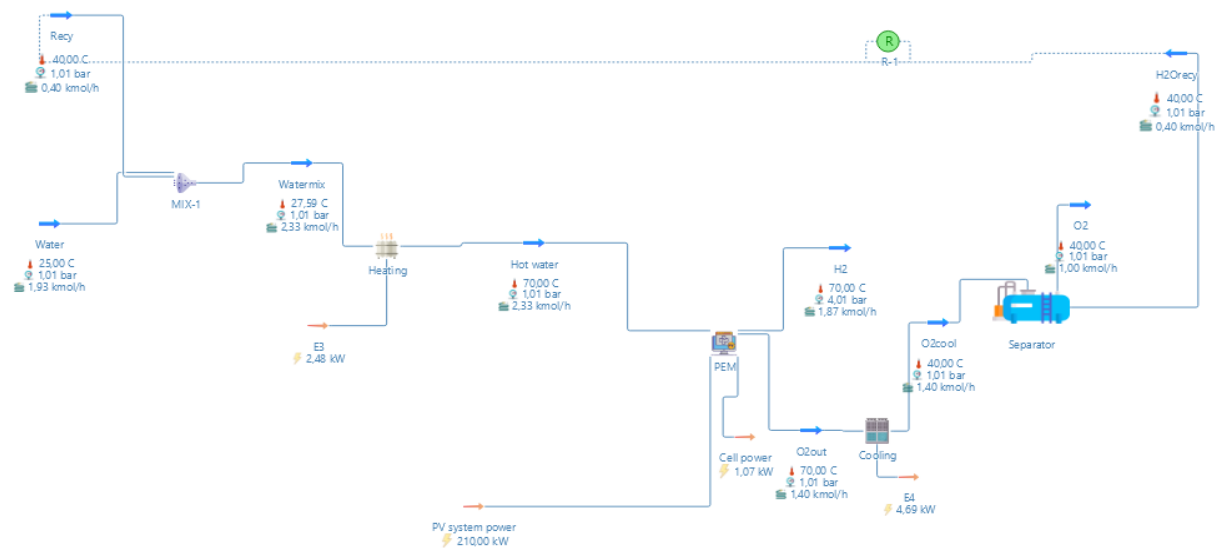


Figure 4 Green Hydrogen Model flowsheet in DWSIM

The model parameters relating to the photovoltaic system (such as the number and area of the panels) were provided by ESAMUR. While many parameters for the thermodynamic and electrochemical analysis of the electrolytic cell were based on literature data [16][17]. The model was validated by comparing it with literature data [18]. The comparison results are good, as shown in Table 3.

Table 3 Model validation by comparison

| Input              |        |            | Output                              |                  |                                     |                  |
|--------------------|--------|------------|-------------------------------------|------------------|-------------------------------------|------------------|
| P at cathode [bar] | T [°C] | Power [kW] | Millet et al., 2010                 |                  | TRINEFLEX model                     |                  |
|                    |        |            | H <sub>2</sub> [Nm <sup>3</sup> /h] | Cell voltage [V] | H <sub>2</sub> [Nm <sup>3</sup> /h] | Cell voltage [V] |
| 1                  | 86     | 1.676      | 0.42                                | 1.68-1.70        | 0.42                                | 1.63             |
| 25                 | 87     | 1.719      | 0.43                                | 1.69-1.71        | 0.43                                | 1.69             |
| 50                 | 85     | 1.711      | 0.42                                | 1.69-1.71        | 0.43                                | 1.70             |

PV panels have been installed in the ESAMUR plant (this is an activity planned within the TRINEFLEX project) The electricity produced by PV system is higher than that used at some times. ESAMUR produces treated water which can be used in the electrolysis process.

The electrolysis process also produces oxygen which can be used on ozone production.

The results obtained through the developed model for the ESAMUR case are reported in Table 4

Table 4 Simulation results applied to ESAMUR case

| Parameter          | Unit | Simulation results |
|--------------------|------|--------------------|
| Power of panels    | kW   | 210                |
| Potential          | V    | 1.82               |
| Power of cell      | kW   | 1.07               |
| Balance of Plant   | %    | 15                 |
| Number of cells    | -    | 170                |
| Water flow (input) | kg/h | 34.75              |

|                              |                      |       |
|------------------------------|----------------------|-------|
| H <sub>2</sub> flow (output) | kg/h                 | 3.76  |
| O <sub>2</sub> flow (output) | kg/h                 | 30.98 |
| Average system efficiency    | kWh/kgH <sub>2</sub> | 55.81 |

To address fluctuations in PV generation, the integration of a battery energy storage system (BESS) is crucial. The battery acts as a short-term buffer, stabilizing power input to the electrolyser and smoothing rapid changes in solar output. This ensures that the electrolyser operates within optimal conditions, improving efficiency and extending equipment lifetime. In parallel, hydrogen storage plays a key role as a medium- to long-term energy buffer. During periods of excess solar generation, surplus electricity is used to produce hydrogen via electrolysis. The battery handles short-term variability, while hydrogen storage compensates for longer-term imbalances between energy supply and demand. Together, these technologies enable a fully renewable, production-driven system capable of maintaining consistent plant performance despite the intermittent nature of solar energy. In a wastewater treatment plant, hydrogen can be effectively used in combination with biogas or, when a biogas upgrading system is already in place, with biomethane. This approach can contribute to reducing CO<sub>2</sub> emissions reducing the fossil fuel consumption. Hydrogen can also react with CO<sub>2</sub> from anaerobic digestion to produce e-fuels such as additional biomethane (via methanation) or bio methanol. The advantages of producing e-fuels from biogas in a WWTP are [15]:

- Both H<sub>2</sub> and CO<sub>2</sub> are required in the methanation process
- CO<sub>2</sub> can also come from anaerobic digestion.

Using biogas, methanation reaction can be performed by adding hydrogen directly to the biogas stream, reducing energy consumption compared to the other solutions. The technical feasibility of direct methanation of biogas was already demonstrated. Compact methanation reactors can be implemented in decentralised installations in waste-water treatment plants. In conclusion, a WWTP considering the installation of photovoltaic systems can gain additional value by using the generated renewable electricity to produce green hydrogen. Although the current cost of green hydrogen remains relatively high (around 7-8 €/kg), this solution offers several strategic and environmental advantages. The hydrogen produced on-site can be utilized in multiple ways and the oxygen, usually a by-product of the electrolysis process, can be directly reused within the wastewater treatment plant, for example to enhance biological treatment processes such as aeration or in the ozonation process. In this way, the integration of photovoltaics and hydrogen production not only enhances energy self-sufficiency but also contributes to a lower environmental impact and a more circular approach to resource management.

### 4.3. Hydrothermal Reactor for Biowaste Conversion (NTUA)

NTUA has developed a compact continuous hydrothermal/solvothermal reactor for the direct conversion of wet biowaste into energy carriers and value-added products. Operating under pressurised subcritical conditions (150–250 °C), the system enables continuous feeding and extraction without prior drying, supporting stable and energy-efficient processing of high-moisture residues. The system is designed for continuous operation and pilot deployment at EYDAP, the national water and wastewater utility of Greece. The integrated reactor configuration allows simultaneous production of hydrochar and liquid fractions enriched in volatile fatty acids, enabling both solid biofuel recovery and chemical valorisation routes. The technology supports circular economy deployment in wastewater treatment and industrial sites by coupling waste reduction with flexible energy and product generation. Hydrothermal and solvothermal treatment generated liquid fractions enriched in volatile fatty acids (VFAs), dominated by acetic, formic and propionic acids at moderate temperatures (~10–40 mg L<sup>-1</sup>), while increased process severity and the use of organic co-solvents promoted the formation of longer-chain compounds and fatty acid methyl esters (FAMES). The resulting hydrochar exhibited increased carbonization and energy density, with high heating values of approximately 20–22 MJ kg<sup>-1</sup>, confirming its suitability for energy recovery and downstream material applications.

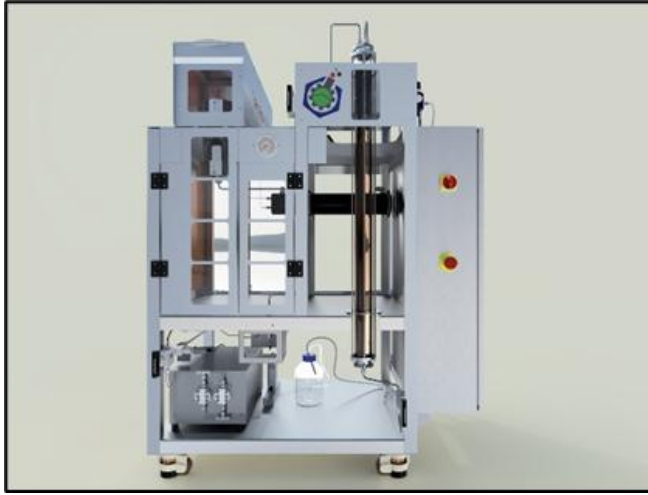


Figure 5 The subcritical HYDROMOL system

#### 4.4 CHP

Combined Heat and Power (CHP) also called cogeneration is a system that produces electricity and useful heat at the same time from a single fuel source. The combined heat and power (CHP) system investigated in this study is a 2G-KWK-190 BGG unit configured for continuous operation with biogas produced via Anaerobic digestion. The supplied fuel consists of approximately 60% Methane ( $\text{CH}_4$ ) and 40% Carbon dioxide ( $\text{CO}_2$ ), representing a typical composition for untreated biogas streams [19]. Combined Heat and Power (CHP) systems are increasingly applied in wastewater treatment plants (WWTPs) as an efficient and sustainable solution for energy recovery and utilization. In these facilities, anaerobic digestion of sewage sludge produces biogas, primarily composed of methane, which serves as a renewable fuel for CHP units and carbon dioxide ( $\text{CO}_2$ ). The CHP unit is based on a spark-ignition gas engine coupled to an electrical generator, with a nominal electrical output of 190 kW. Under steady-state full-load conditions, the electrical efficiency is approximately 38%, resulting in a required thermal fuel input of approximately 500 kW. The relationship between electrical output and fuel input is expressed as:

$n_{el} = \frac{P_{el}}{\dot{Q}_{fuel}}$  (1) where  $n_{el}$  is the electrical efficiency,  $P_{el}$  is the electrical power output, and  $\dot{Q}_{fuel}$  is the thermal input from the fuel. Due to the relatively low lower heating value (LHV) of the biogas, estimated at approximately 6 kWh/Nm<sup>3</sup>, the volumetric fuel consumption at nominal load is in the range of 80–85 Nm<sup>3</sup>/h. The volumetric flow rate can be determined from

$\dot{V}_{gas} = \frac{\dot{Q}_{fuel}}{LHV}$  (2) where  $\dot{V}_{gas}$  is the volumetric gas flow rate and LHV is the lower heating value of the fuel.

In addition to electricity generation, the CHP system incorporates heat recovery from the engine cooling circuit and exhaust gases. This enables a total system efficiency in the range of 80–85%, defined as

$n_{tot} = \frac{P_{el} + Q_{th}}{\dot{Q}_{fuel}}$  (3) where  $Q_{th}$  represents the recovered thermal energy.

The presence of  $\text{CO}_2$  in the fuel gas reduces the calorific value and increases the required volumetric flow rate compared to natural gas. However, within the given methane concentration, stable combustion and nominal engine performance are maintained without significant derating [19].

#### 4.5. Hybrid System Description (NORCE)

To evaluate the impact of the developed prototypes and digital tools, a case study of a wastewater treatment plant in Spain was considered. The integration of photovoltaic (PV) systems, electrolyser, combined heat and power (CHP), heat exchangers, and hydrothermal liquefaction/carbonization (Hydromol/HTC) within a wastewater treatment plant represents a synergistic approach to energy-neutral or energy-positive operation. PV-generated electricity can drive water electrolysis to produce hydrogen, which serves as an energy carrier or can be co-utilized in CHP systems alongside biogas derived from anaerobic digestion. The CHP unit

enhances overall energy efficiency by simultaneously generating electricity and recoverable heat, which is redistributed via heat exchangers to maintain optimal temperatures for biological treatment and thermochemical conversion processes. Integrating Hydromol/HTC enables the conversion of sewage sludge into value-added products such as biochar and bio-crude, improving resource recovery and reducing sludge disposal requirements. This multi-technology integration enhances energy efficiency, reduces greenhouse gas emissions, and supports circular economy principles in advanced wastewater treatment systems as shown in the figure 06.

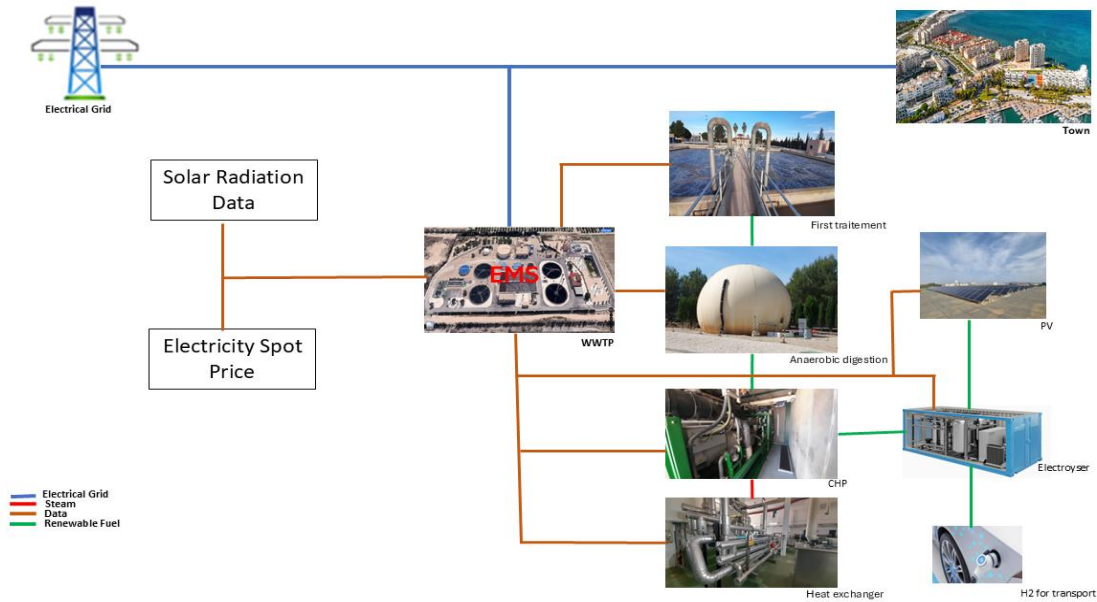


Figure 6 ESAMUR WWTP description

## 4.6. Digital energy service (AUTH)

The digital energy service is a framework introduces a comprehensive suite of digital services designed to address limited awareness and insufficient knowledge sharing regarding technological, financial, and collaborative opportunities for DES adoption, with the industrial sector playing a central role. The framework includes an online energy actors observatory that leverages crowdsourced data analytics to identify trends, innovations, stakeholders, and initiatives in the energy domain; community empowerment and structuring tools based on community detection and network analysis to reveal key communities, influencers, and their interactions within energy markets; an intelligent stakeholder matchmaking and networking system employing recommender technologies to facilitate multi-actor collaboration and synergies; business process optimization mechanisms that utilize business process management techniques to optimize distributed energy resources (DERs) allocation and enhance participation; a powered energy storage services that ensure transparent tracking of energy asset usage and validation of stakeholder roles and cooperation within DES partnerships; and open APIs that enable data exchange and interoperability across energy ecosystems. The tool prototype is accessible at <https://trineflex.csd.auth.gr/>. The prototype was developed by Aristotle University of Thessaloniki.

## 5. Results and Discussion

All results were obtained through simulations developed in Python, where an optimization algorithm was implemented to ensure optimal coordination between energy production and consumption. Under the proposed configuration, which includes 209 kWp of photovoltaic capacity, a 190 kW CHP unit, a 120-kW electrolyser, a 50 kW Hydromol system, an 80 kW heat exchanger, and an annual electrical demand of 2008.4 MWh, the system demonstrates a high level of energy integration and operational efficiency.

### 5.1 Climatic conditions and photovoltaic generation

The climatic conditions of the case study are characterized by the monthly evolution of solar irradiation and ambient temperature, as presented in figure 7 and figure 8. A clear seasonal pattern is observed, typical of Mediterranean climates, with solar irradiation increasing from 101.3 W/m<sup>2</sup> in December to 310.4 W/m<sup>2</sup> in July, while ambient temperature rises from 11.8 °C to 28.3 °C over the same period.

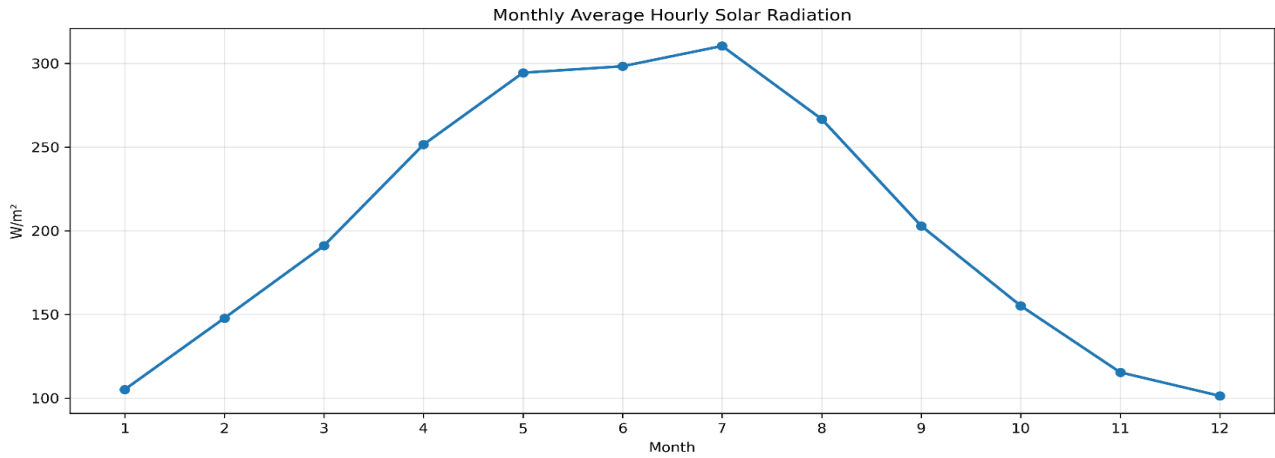


Figure 7 ESAMUR solar radiation

The photovoltaic (PV) generation profile, shown in figure 08, closely follows the solar resource availability figure 07. The system, with an installed capacity of 209 kWp, produces 372.8 MWh/year, with monthly generation ranging between 16.4 MWh and 46.7 MWh. This confirms the reliability of the PV performance model and highlights the significant contribution of solar energy to the local electricity supply. However, the seasonal variability introduces periods of increased generation that may not fully coincide with the plant demand.

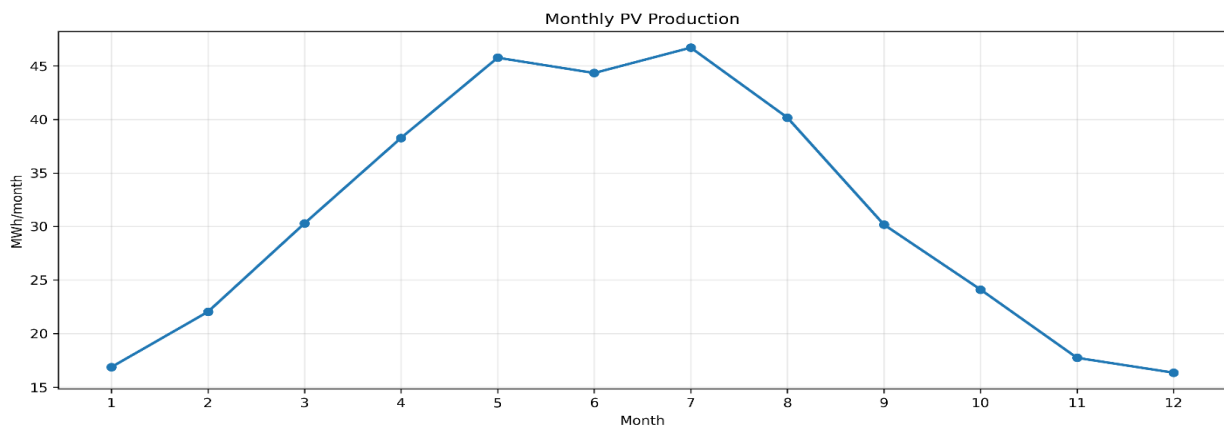


Figure 8 ESAMUR PV production

## 5.2 Electrical balance and WWTP self-sufficiency

The electrical balance of the wastewater treatment plant (WWTP) is governed by a sequential dispatch strategy in which demand is met by PV generation, followed by combined heat and power (CHP), and finally grid imports. The annual base electricity demand is set to 1900 MWh/year, while the inclusion of the Hydromol process increases the total electrical load to 2008.4 MWh/year.

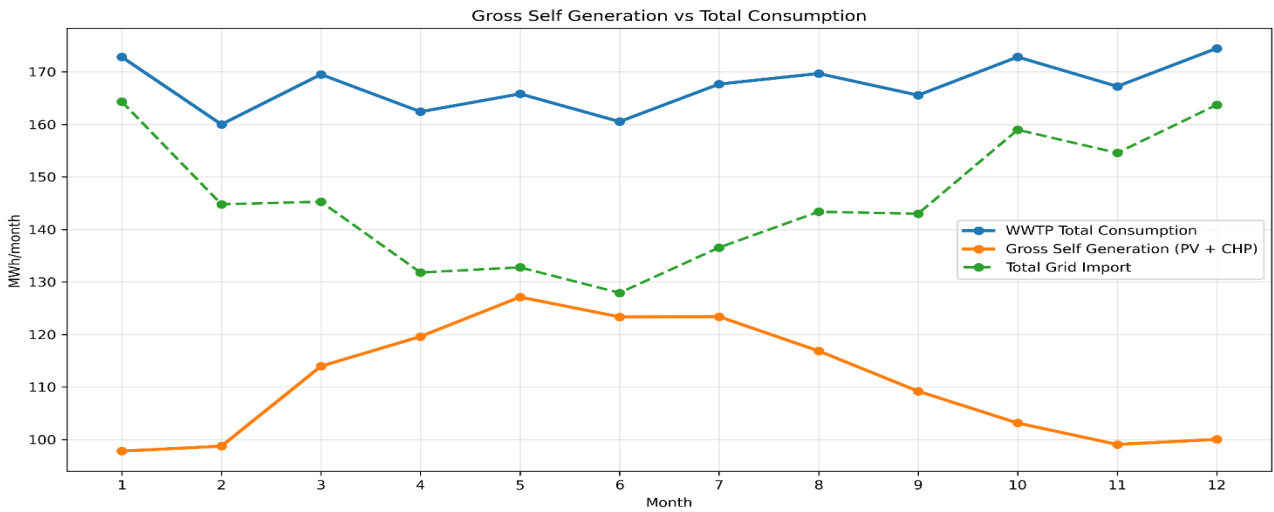


Figure 9 ESAMUR self-production and total consumption

The annual local electricity generation from PV and CHP amounts to 1332.3 MWh/year, of which 1315.5 MWh/year is directly consumed by the WWTP. The remaining demand is supplied by 692.9 MWh/year of grid electricity dedicated to plant operation. The resulting WWTP electrical self-sufficiency is 65.5%, as shown in figure 9 and figure 10.

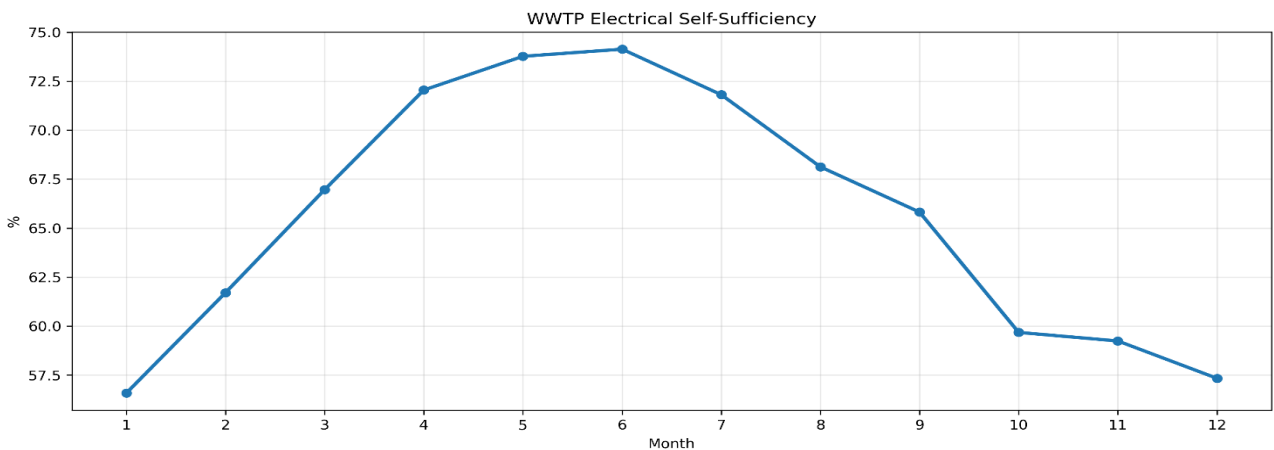


Figure 10 ESAMUR Electrical self sufficiency

This indicator is defined based on the grid electricity used exclusively for WWTP operation, excluding electricity consumed by the electrolyser. This distinction ensures that the metric accurately reflects the energy autonomy of the treatment plant. The comparison between total local generation and plant consumption, shown in figure 09, indicates that local generation occasionally exceeds instantaneous demand, although these occurrences remain limited due to the relatively high base load of the plant.

### 5.3 CHP contribution and biogas valorisation

The CHP unit represents the primary on-site energy source and provides both electricity and thermal energy in a stable and controllable manner. The annual electrical output of the CHP unit is 959.5 MWh, while the thermal output reaches 1060.5 MWh, as illustrated in figure 11. Biogas production, presented in figure. 12, amounts to 420,000 Nm<sup>3</sup>/year, corresponding to an energy content of 2520.0 MWh/year. Nearly the entire biogas energy is utilized by the CHP unit (2525.0 MWh/year), indicating an efficient conversion of waste-derived energy into useful outputs.

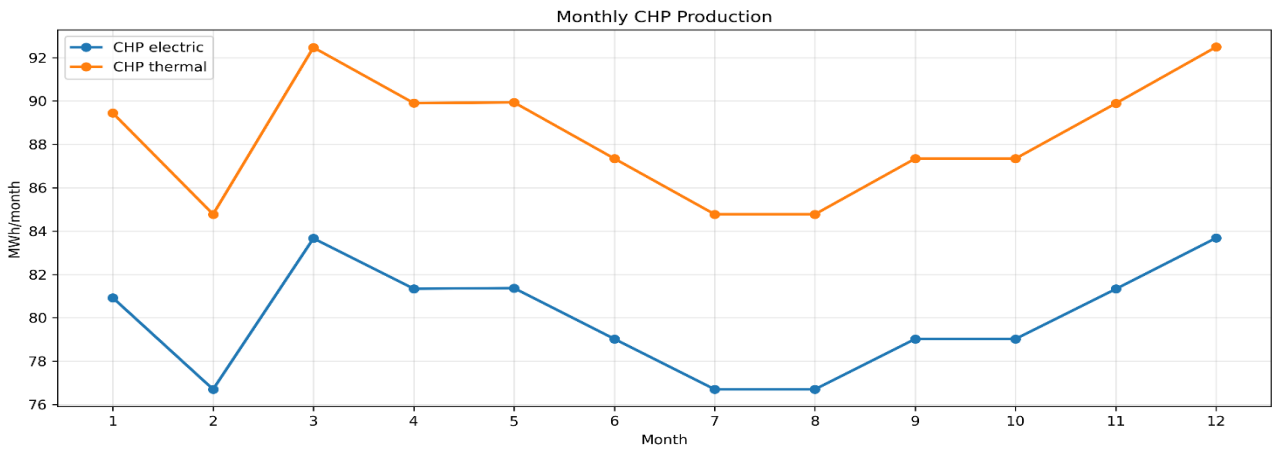


Figure 11 ESAMUR CHP production

The relatively stable biogas production profile enables continuous CHP operation, which compensates for the variability of PV generation and ensures a reliable energy supply throughout the year. This highlights the importance of integrating dispatchable generation technologies within renewable-based systems.

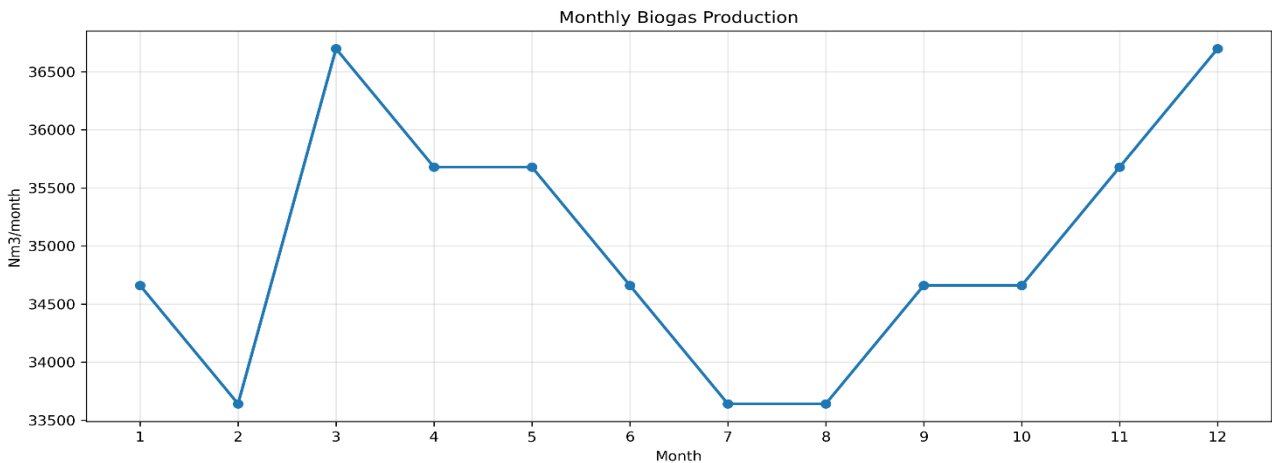


Figure 12 ESAMUR biogas production

## 5.4 Thermal integration and heat recovery

Thermal energy recovery is implemented through a heat exchanger that captures a portion of the CHP thermal output. The recovered heat, shown in figure 13, amounts to 315.5 MWh/year. The total thermal demand of the plant is 570.0 MWh/year, which is entirely covered by the combined contribution of CHP thermal production and recovered heat. Consequently, no backup heat is required, and no unmet thermal demand is observed. These results demonstrate that thermal integration significantly enhances system efficiency by maximizing the utilization of internally generated heat. The coupling of CHP and heat recovery allows the plant to operate without external thermal energy inputs under the simulated conditions.

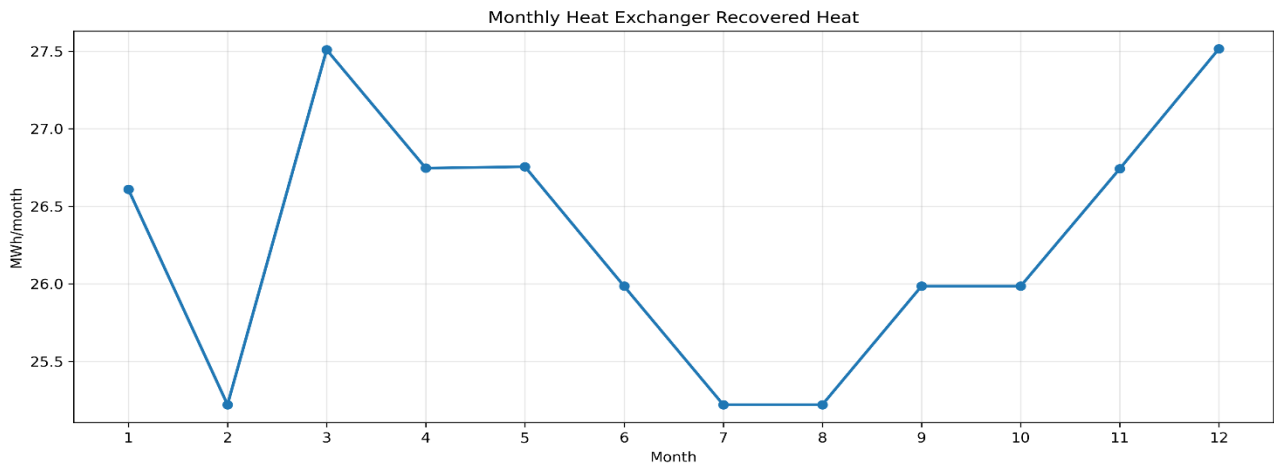


Figure 13 ESAMUR Heat exchanger recovered heat

### 5.5 Hydrogen and oxygen production

The integration of the electrolyser enables the conversion of electrical energy into hydrogen and oxygen. The total hydrogen production, shown in figure 13, reaches 210,816 Nm<sup>3</sup>/year, while the corresponding oxygen production, presented in figure 14, amounts to 105,408 Nm<sup>3</sup>/year. A key outcome of the simulation is the complete dependence of hydrogen production on grid electricity. The results indicate that: Hydrogen from PV: 0 Nm<sup>3</sup>/year and all Hydrogen production is from grid: 210,816 Nm<sup>3</sup>/year

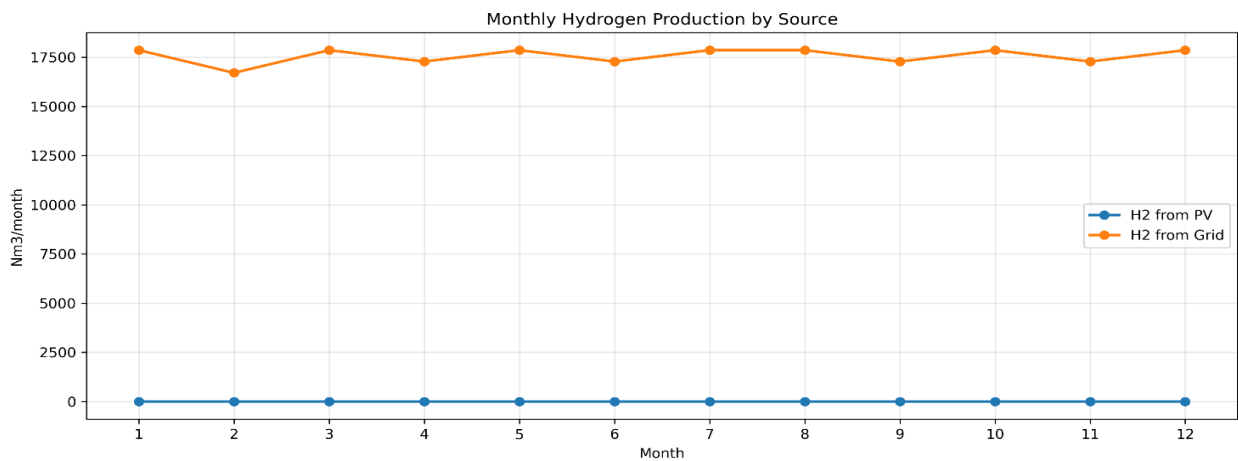


Figure 14 ESMAUR Hydrogen production

Similarly, oxygen production is entirely derived from grid-based electrolysis. The electrolyser consumes 1054.1 MWh/year of grid electricity, while no PV electricity is used for hydrogen production. This behaviour is explained by the high electrical demand of the WWTP, which fully absorbs the available PV generation. As a result, no significant PV surplus is available to supply the electrolyser. The system therefore operates in a mode where electrolysis functions as an additional flexible load rather than a mechanism for renewable energy valorisation.

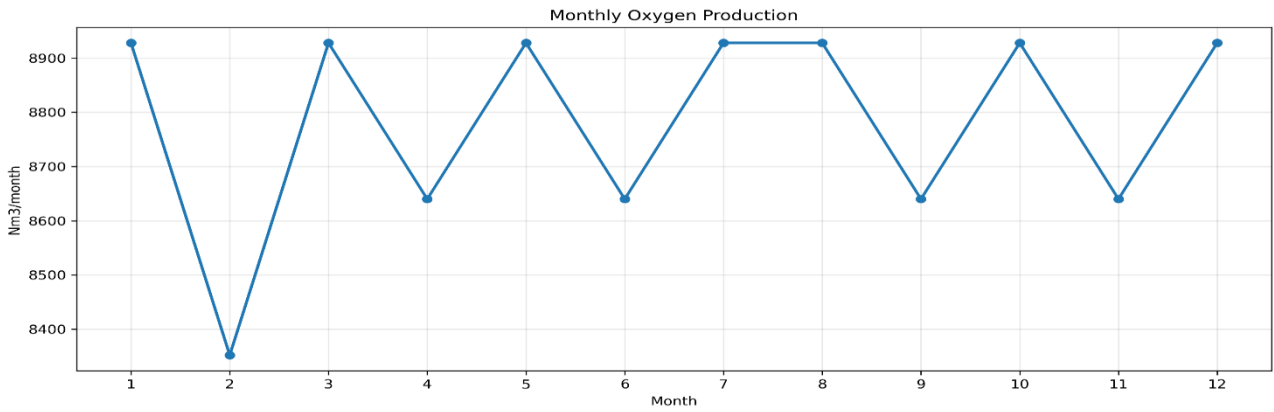


Figure 15 ESMAUR Oxygen production

## 5.6 Energy utilization and flexibility indicators

The performance of the system is evaluated using three key indicators. The WWTP electrical self-sufficiency reaches 65.5% figure 16, indicating that a significant portion of the plant demand is covered by on-site generation which fulfilled the EU regulation requested as least 61 % must be produced on WWTP site.

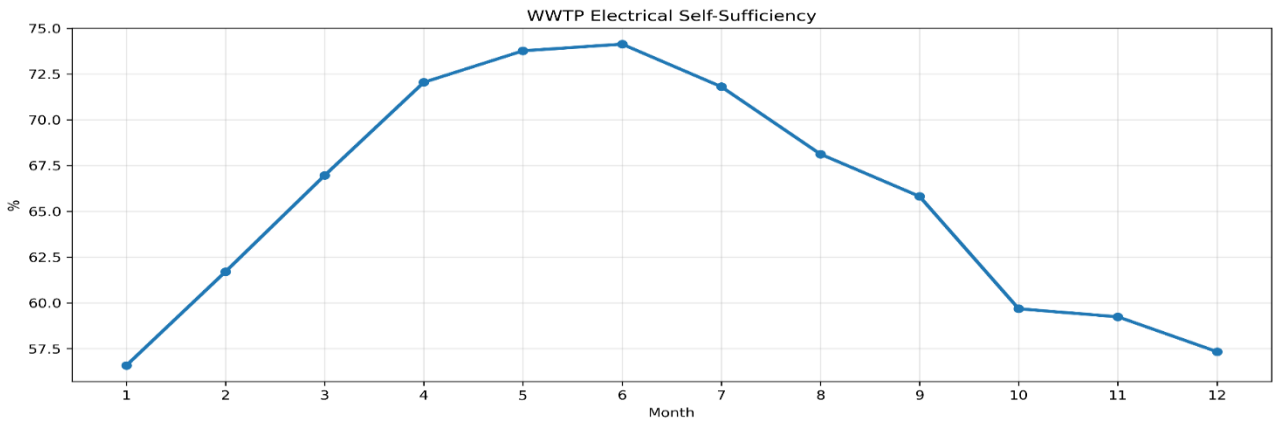


Figure 16 ESAMUR Electrical self sufficiency

The self-consumption ratio, shown in figure 17, is 98.7%, demonstrating that nearly all locally generated electricity is directly consumed by the WWTP. This high value reflects the strong alignment between generation and demand, driven by the dominant role of CHP. These results indicate an efficient use of locally generated electricity but also reveal a limited role of electrolysis in absorbing renewable surplus under the current system configuration.



Figure 17 ESAMUR self-consumption ratio

### 5.7 Process-level integration: Hydromol

The Hydromol process introduces an additional electrical load of 108.4 MWh/year, increasing the total plant demand from 1900.0 MWh/year to 2008.4 MWh/year. The corresponding treatment capacity is presented in Figure 18.

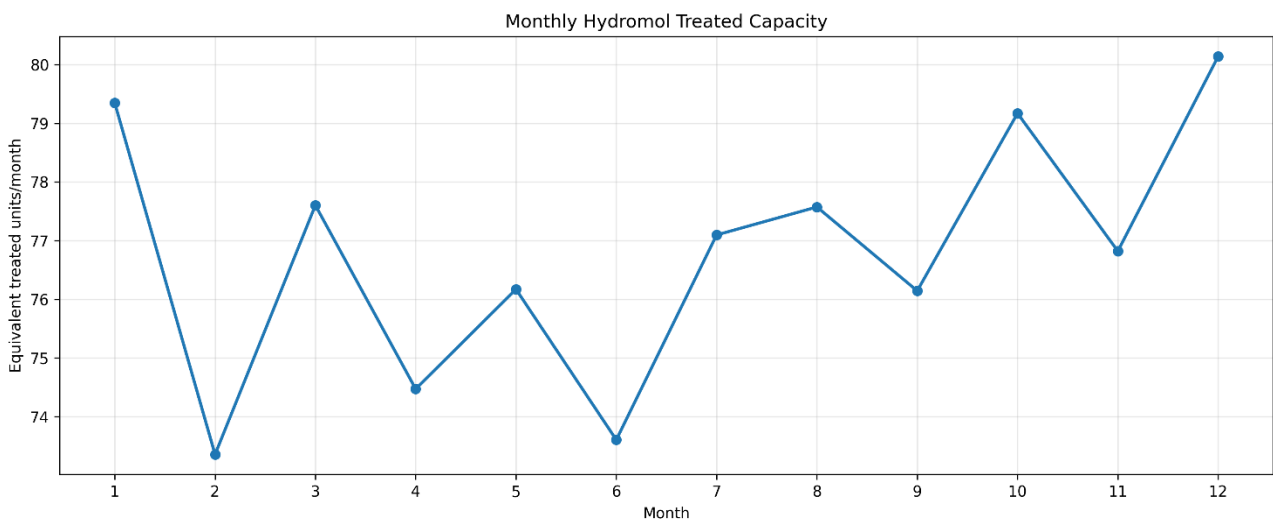


Figure 18 ESAMUR hydromol treated capacity

Although this contribution represents a relatively small share of the total demand, it influences the overall energy balance and system dispatch. The inclusion of process-level technologies is therefore essential for accurately representing the behaviour of industrial energy systems.

### 5.8 Overall system performance

The results demonstrate that the WWTP operates as an integrated multi-energy system combining electrical, thermal, and chemical energy flows. The coordinated operation of PV, CHP, biogas production, heat recovery, and electrolysis enables efficient resource utilization and reduces dependence on external energy sources.

| Indicators                              | Value  | Unit     |
|-----------------------------------------|--------|----------|
| Total electrical consumption            | 2008.4 | MWh/year |
| Local electricity generation (PV + CHP) | 1332.3 | MWh/year |

| Indicators                      | Value   | Unit                  |
|---------------------------------|---------|-----------------------|
| Electrical self-sufficiency     | 65.5    | %                     |
| Local generation utilization    | 98.7    | %                     |
| Recovered heat (heat exchanger) | 315.5   | MWh/year              |
| Hydrogen production             | 210,816 | Nm <sup>3</sup> /year |

The results highlight the dominant role of CHP in ensuring system stability and energy autonomy, while PV contributes renewable electricity with strong seasonal variability. The electrolyser provides additional flexibility but operates primarily using grid electricity under the current conditions.

## 6. Conclusion

The research was carried out within the framework of the TRINEFLEX project, which includes five demonstration cases involving the glass industry in Italy, the aluminum industry in Spain, the copper industry in Greece, and wastewater treatment facilities in both Spain and Greece. Among the developed solutions, three prototypes were physically implemented, namely the heat exchanger, the hydromol system, and the digital energy service platform, while CHP and photovoltaic systems were installed at the wastewater treatment plants in Spain and Greece. In contrast, the electrolyser and hydrogen production system were evaluated through simulation studies only. Focus on this paper was placed on the case study of wastewater treatment plants (WWTPs) to evaluate the new technologies developed, where the simulation results revealed an electrical self-sufficiency rate of 65.5%, exceeding the European Union requirement of at least 61% self-produced energy for WWTPs. The proposed system also achieved a local energy utilization rate of 98.7%, indicating that nearly all generated electricity is effectively consumed on-site. Furthermore, thermal energy recovery considerably improved system efficiency, with 315.5 MWh/year of heat recovered through heat exchangers, allowing the complete coverage of the plant's thermal demand without the need for external heat sources. The CHP unit plays a key role in ensuring the stability and reliability of the energy supply, particularly in balancing the intermittent nature of photovoltaic generation. In addition, the integration of an electrolyser enables the production of approximately 210,816 Nm<sup>3</sup>/year of hydrogen, creating further opportunities for energy storage and sector coupling applications. Beyond energy efficiency improvements, the proposed configuration contributes to environmental sustainability by reducing dependence on grid electricity and fossil-based energy sources, thereby decreasing CO<sub>2</sub> emissions and supporting the transition toward low-carbon and energy-efficient wastewater treatment systems. Overall, the optimized hybrid energy system, supported by advanced simulation represents a robust and scalable solution for enhancing industrial energy autonomy, complying with EU regulatory requirements, and contributing to climate change mitigation objectives.

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