ENERGICA

ENERGY ACCESS AND GREEN TRANSITION COLLABORATIVELY DEMONSTRATED IN URBAN AND RURAL AREAS IN AFRICA

D5.5. Commissioning of the integrated biodigester-photocatalytic reactor

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Deliverable Report

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Nature of the Deliverable		
R	Document, report (excluding the periodic and final reports)	
DEM	Demonstrator, pilot, prototype, plan designs	x
DEC	Websites, patents filing, press & media actions, videos, etc.	
OTHER	Software, technical diagram, etc.	

Dissemination Level		
PU	Public, fully open, e.g. web	
CO	Confidential, restricted under conditions set out in Model Grant Agreement	x
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1. PROJECT SUMMARY

The ENERGICA project (Grant Agreement number: 101037428) has been funded by the European Commission in the Horizon 2020 Green Deal initiative H2020-LC-GD-2020 / H2020-LC-GD-2020-1. The project, gathering 11 African-based partners and 17 Europeans with offices or subsidiaries in Africa, is ambitiously fostering strong collaboration between partners of both continents on energy access and sustainable energy development. The general **objective of the ENERGICA project is to demonstrate the efficient implementation of renewable energy technologies to match local contexts' needs.**

Three demonstration sites will rely upon local Energy Transition Boards to manage community-scale Integrated Community Energy Systems (ICESs). Based on these methodologies and respective innovative technologies, ENERGICA will demonstrate positive social, environmental, technical and economic impacts from the high energy-efficiency and low carbon emission. Specifically, the project will be developed in **three different contexts for energy access**:

- Innovative nano-grids in the rural context of Madagascar.
- Low-tech-efficient biogas systems in the peri-urban/urban context of Sierra Leone.
- Solar-powered e-mobility solutions in the urban context of Kenya.

Eight specific objectives (SO) have been targeted to fit the general aim of the ENERGICA project:

- SO1: Demonstrate integrated productive use systems in innovative nano-grids addressing the Water-Energy-Food (WEF) nexus.
- SO2: Demonstrate water-purification and biogas low-tech cost-effective systems addressing the WEF nexus.
- SO3: Demonstrate urban grid flexibility and decarbonisation through smart battery management for e-mobility.
- SO4: Create dedicated local community-based structures for the uptake of renewable energy technologies.
- SO5: Set up ambitious and tailored replicability strategies.
- SO6: Develop capacity building and knowledge transfer programmes.
- SO7: Develop tailored business models, circular economy models and local value chains.
- SO8: Foster strong EU-AU collaborations.

These SOs were targeted by defining **eleven work packages (WP),** including 3 technical work packages (4, 5 and 6) detailing the development of the demonstration sites in Madagascar, Sierra Leone and Kenya and two thematic work packages on social and environmental activities (Figure 1).

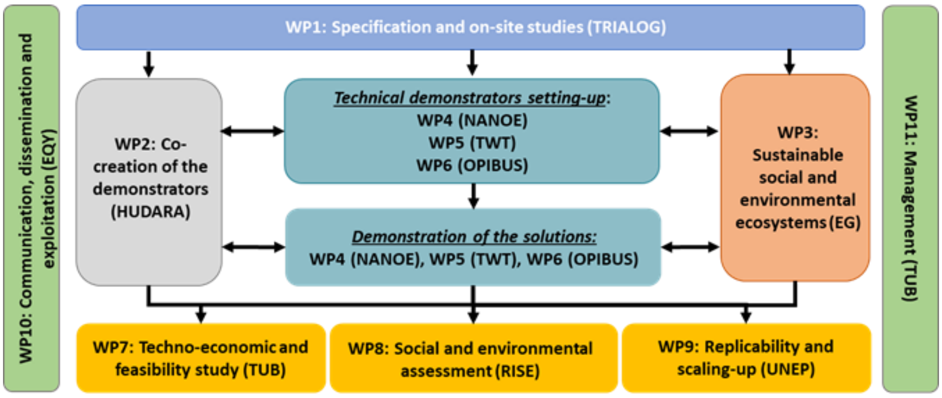


Figure 1: Work Plan structure of ENERGICA project.

The work presented in ***deliverable 5.5 responds to specific objective 2*** and is ***submitted as part of the requirements for completion of WP5 (Frugal and low-tech WEF nexus technologies (Sierra Leone)).***

WP5 (Frugal and low-tech WEF nexus technologies (Sierra Leone))

WP5 focuses on the development of low-tech and frugal technologies in both the biogas and water purification sectors. Two adapted solutions (integrated biogas and water or upscaled biogas system) are tested before an effective integration and demonstration in peri-urban and urban Freetown.

The biogas digester developed in ENERGICA will allow the use of organic waste to produce energy and fertilizer. The Waste Transformers have already developed a prototype of an anaerobic digestion system for organic waste transformation in a Freetown hospital. In this they have worked with their local partner on the operational front, The Freetown Waste Transformers. The first ENERGICA demonstrator will be set up in a peri-urban district of Freetown, and will improve the existing biogas digestor by:

- Optimising and simplifying it,
- Establishing local manufacturing of the plant for scaling up the system,
- **Coupling it with a water purification system based on solar photocatalytic disinfection systems**.

This demonstrator will then be upscaled and tested in the urban context, with a bigger capacity (Figure 2). Freetown´s water-energy-food (WEF) nexus-centred demonstrators are thus aligned with the local policy to tackle the risks and vulnerability of poor waste management systems. Two solutions will be implemented successively in peri-urban Freetown.

On the other hand, in the ***water purification sector***, solar-based technologies for disinfection and decontamination of water will be demonstrated to provide safe treated water for local communities. The solar-based water purification technologies will be developed by the partners TEK, ARENYS and CIEMAT and consist of solar photocatalytic systems (reactors) that promote the collection of solar photons to accelerate the disinfection kinetics of microbial targets and degradation of hazardous chemical compounds in water.

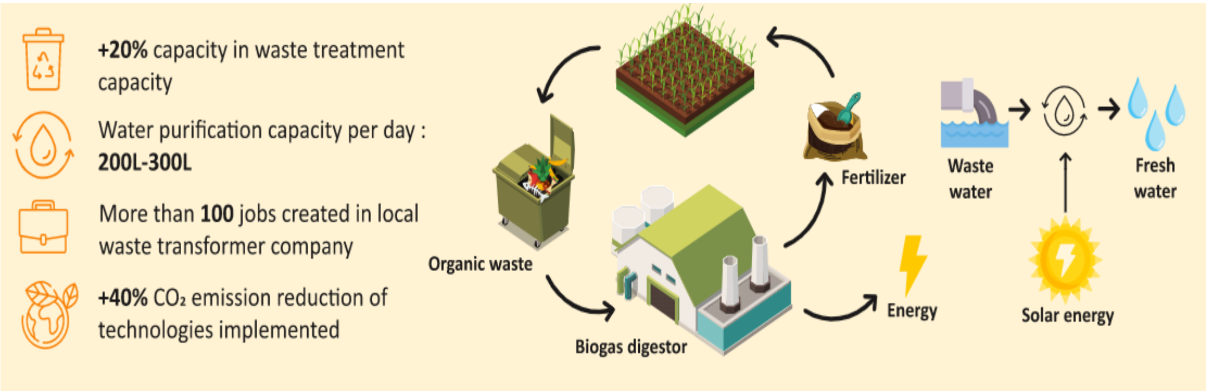


Figure 2: Biodigester and water purification system

Within WP5, four tasks and seven related deliverables were designed to achieve SO2. They are:

Task 5.1: Development and testing of low-tech innovative biogas digester ● Subtask 5.1.1: Setting-up of the local manufacturing of plant components ● Subtask 5.1.2: Optimising day to day operations ● Subtask 5.1.3: Testing and commissioning	D5.1: Biogas plant specifications (TWT, R, PU, M15). This report will provide a list of components for the modular turn-key biogas plant, previously sourced in Europe that can potentially be replaced by locally manufactured components. It will also include the results of the lab-scale ash trial. D5.2: Easy access start-up manual and day-to-day operations instructions (RISE, R, PU, M24). Targeting local plant operators, this report will detail the optimal operation of the plant for easier uptake. D5.5: Commissioning of the integrated biodigester-photocatalytic reactor (TWT, DEM, PU, M24). Integrated plant ready for the demonstration phase, including a full description, construction plan, diagrams and photographs of the prototypes and details of the chosen action plan.
Task 5.2: Development and testing of low-tech solar disinfection systems ● Subtask 5.2.1: New photocatalysts development and testing at lab-scale ● Subtask 5.2.2: Design a solar photocatalytic prototype for water purification ● Subtask 5.2.3: Testing and production of the low-tech water purification technology	D5.3: Development of photocatalytic materials (TEK, R, CO, M18). Synthesis routes and characterisation of new photocatalysts and immobilised photocatalysts, including the main results about their efficiency and optimum operating conditions at the laboratory scale. D5.4: Assessment of photocatalytic pilot plant for solar water treatment (CIEMAT, R, PU, M24). This report will demonstrate the efficacy of the photocatalytic pilot plant against the inactivation of target pathogens and organic chemical contaminants from wastewater under natural sunlight.
Task 5.3: Demonstration in peri-urban Freetown	D5.6: Monitoring results of the sites (TWT, R, CO, M42). The report will provide know-how and best practices for the replicability of the technologies.
Task 5.4: Replication tests in Freetown downtown	D5.7: Monitoring results of the site (FWT, R, CO, M48). The final WP5 deliverable will report on the replication demonstrator during its running period.

2. OBJECTIVE AND EXECUTIVE SUMMARY

The objective of **deliverable 5.5 Commissioning of the integrated biodigester-photocatalytic reactor** is to provide the integrated plant ready for the demonstration phase, including a full description, construction plan, diagrams and photographs of the prototypes and details of the chosen action plan. Besides, the deliverable summarizes the activities, carried out as part of the WP5 of the ENERGICA project, focused on developing low-tech and frugal technologies in both the biogas and water purification sectors to attain an effective integration and demonstration of both technologies in peri-urban and urban areas of Freetown in Sierra Leone.

The activities described in this Deliverable belong to the joint actions of Task 5.1 (Development and testing of low-tech innovative biogas digester) and Task 5.2 (Development and testing of low-tech solar disinfection systems, CIEMAT, TEK, FWT, ARENYS, UAM), and are directly linked with Task 5.3: Demonstration in peri-urban Freetown (TWT, FWT, ARENYS, RISE, CIEMAT, TEK, UAM, ECREEE, TRIALOG), as once D5.5 is available, the first demonstration will start.

The main objective of task 5.1 is to develop and test an adapted version of the bio digester, tailored to the local technical and regulatory constraints and opportunities as found in WP1 as well as the need in lower CAPEX and OPEX. The main objective of task 5.2 is the design and testing of low-tech solar photocatalytic prototypes for water purification, whose previous activities have been detailed in deliverable 5.3 (M18) and deliverable 5.4 (M24), both already submitted. In this regard and very briefly, the framework of solar water treatment context is based on the improvement of the treatment by the combination of solar reactors with photocatalytic materials (photocatalysis), which are very well known to strongly accelerate the water disinfection and decontamination performance by generating powerful oxidative species, mainly hydroxyl radicals ($HO^{\bullet}$). They can destroy a wide variety of pollutants, such as organic acids, oestrogens, pesticides, dyes, microbes (including viruses and chlorine-resistant organisms) or inorganic molecules. Heterogeneous photocatalysis is considered an alternative method for water and wastewater treatment to remove a wide range of pollutants. Moreover, the safety of the process could also be improved if the immobilized catalyst is employed. Therefore, several strategies to implement an immobilized photocatalyst were assessed at the laboratory and the pilot scale, and the best one was selected based on the main results obtained (D5.3 and D5.4). Briefly, it consists of nanocomposites made of TiO_2 nanoparticles incorporated in a sol-gel inorganic formulation, which has been deposited on stainless-steel substrates adapted to multistep cascade reactor designs, assessing their capability performance for water purification by monitoring microbial and chemical compound removal under natural sunlight.

Therefore, **this deliverable reports** the integrated biodigester-photocatalytic plant ready for the demonstration phase. The **different activities** carried out in this task will be explained in detail in the following chapters, and briefly, they consist of the following sections:

- The first section includes an overview of the bio digestor redesign improvements and its specifications.

- The second section focuses on the solar photocatalytic reactors explored for the implementation of solar-assisted treatments in Sierra Leone. This section is divided into the following subsections:
    - ✓ A summary of the framework and activities previously performed in Task 5.2 regarding the design and testing of the pilot scale Multi-Step Cascade Reactor (MSCR).

- ✓ The full description of the prototype of the ENERGICA solar reactor, including design, construction, maintenance action plan and operation plan.

- ✓ The results obtained after the assessment of the MSCR, based on the immobilization of photocatalyst onto stainless steel at the pilot plant scale, through the monitoring of disinfection and decontamination performance under natural sunlight for water and wastewater purification.

- Finally, the integration of the biodigester and the solar photocatalytic pilot plant is described in detail.

3. TABLE OF CONTENT

4. INTRODUCTION

4.1. Bio digestion and the context of organic food waste in Sierra Leone

Mismanaged food waste poses a significant threat to the environment, public health, and economic resources. Without proper disposal, food waste contributes to greenhouse gas emissions, soil and water pollution, and represents a loss of valuable organic resources. When food waste decomposes in landfills it produces methane, a potent greenhouse gas with approximately 28-36 times the global warming potential of carbon dioxide over a century. Leachate from decomposing food waste can pollute soil and water sources, affecting ecosystems and human health. Food waste represents a squandered opportunity to recycle valuable organic matter into beneficial products like digestate or energy.

Some facts:

- Of all food waste generated:
  61% comes from households
  26% from food service
  13% from retail
- Food waste in kg/capita/year, classified by countries:
  High income: 79
  Upper middle income: 76
  Lower middle income: 91
- 70mill T/yr methane is emitted by food waste in landfills (12% of global CH4 emissions)
- Methane has 28x the global warming potential of CO_2 as a GHG

4.2. Solar photocatalytic water treatments and the context of water needs in Sierra Leone

Water is a vital and basic human need, required not only for drinking but also to support proper sanitation and hygiene to sustain life and health. Despite the great efforts made during the last decades to improve this situation, the reality is that over one-third of the world's population lives in water-stressed countries. In African countries, around 70% of the population today still lives without proper access to water and sanitation (WWAP, 2019) and, only 37 % of the sub-Saharan African population have access to safely managed drinking water (WHO, 2021). Sierra Leone also suffers from a lack of safely managed water sources, its current population is higher than 8,500,000 people (World Bank database, 2023), with an estimated steadily growing rate of 2.2% in the next years. This is a challenge for the government and international organizations in the context of providing improved access to safe drinking water to the population to cover their daily water needs, especially in rural areas, where approx. 57% of the total population is living, according to the data presented on the Worldmeter website (data from the United Nations, Department of Economic and Social Affairs, Population Division. World Population Prospects: The 2022 Revision) (Worldmeter, 2023).

As an overview of the situation, and according to the UN that estimates the daily requirements of drinking water per person is 50 L, a daily need of potable water of 425,000 m^3/day in the entire country can be extrapolated to cover the entire population, and ca. 250,000 m^3/day in rural areas. Urban areas generally have better infrastructure and more reliable access to treated water, while rural communities often rely on surface water, unprotected wells, or boreholes. These water sources in Sierra Leone, generally have a high risk of faecal contamination (> 100 *E. coli*/100 mL) (Bain et al., 2021). The Sierra Leone population has a lower percentage of people using safely managed drinking water in comparison with other countries, only 10% of the population has a low risk (< 1 CFU/100 mL) of disease infections transmitted by drinking water (WHO, 2021).

Therefore, the implementation of water technologies to improve the water quality is an important aspect for the future well-being of the population and the economic development of Sierra Leone.

Among the different renewable sources of energy in Sierra Leone, solar radiation is a clear potential option because this country is located near the equator, which ensures consistent sunlight throughout the year. According to the Ministry of Energy of Sierra Leone, the country's solar radiation is ca. 1460 $kWh/m^2/year$ (Conteh et al., 2021). Therefore, the potential implementation of solar technologies for electricity production is clear, but also for other solar applications like the solar treatment of water, thanks to the high availability of natural sunlight irradiance along the different seasons of the year, as even in wet season, direct solar irradiance higher than 50 kWh/m^2 is received.

In this context, in WP5 of ENERGICA project different approaches have been investigated based on TiO_2 immobilization, to maximise the potential of photocatalysis as innovative water treatment to be implemented at pilot plant scale. Deliverable 5.3 (already sent in Month 18) included the different approaches followed in the state of the art for the design of photocatalytic materials as well as their main limitations, and the different strategies followed in ENERGICA for the synthesis of new photocatalysts and their immobilization, including main results about their efficiency and optimum operating conditions at lab scale. And later, D5.4 completes the previous D5.3, focusing on the designs of photocatalytic reactors with the optimization of the photocatalytic process at pilot scale for water purification. The selected reactor design has been described and its performance based on a flat system as a multi-step cascade reactor made of stainless-steel materials, whose stairs are coated with a coating made of TiO_2 dispersed in an inorganic silica matrix as photocatalytic material. The TiO_2 is the material responsible for enhancing the water quality. When it is irradiated with photons of wavelengths < 380 nm, these photons cause excitation of the valence band (VB) electrons of the material (Ahmed et al., 2011), generating catalyst active sites with enough energy to produce positive holes (h^+) in the valence band and electrons (e^-) in the conduction band. The positive holes oxidize either the organic pollutants or H_2O to induce hydroxyl radicals ($HO^\bullet$). Hydroxyl radicals can destroy a wide variety of pollutants, such as dyes, organic acids, pesticides, estrogens, microbes (including viruses and chlorine-resistant organisms) or inorganic molecules (Chong et al., 2010).

The selection of the design for the multi-step cascade reactor (MSCR) in ENERGICA was based on the following aspects as key parameters:

- ✓ Maximizing irradiation throughout the water to promote oxidative reactions.
- ✓ The adequate ratio between illuminated and dark areas.
- ✓ The efficient mass transfer between the catalyst and the contaminants.
- ✓ The good oxygen supply to the reaction solution.
- ✓ The ease of separation of the catalyst after the treatment.
- ✓ Low cost of the system.
- ✓ Easy operation and low maintenance.

In addition, after the analysis of the performance, it was decided to improve the safety of the treatment trough the addition of an oxidant that promotes the microbial inactivation and reduces the possible regrowth of bacteria after the treatment.

5. RESULTS

5.1. Biodigester plant

To provide some background related to the product development cycle of the biodigester plant this chapter starts with a summary of the prototype and findings, elaborating on the findings and its improvements. The paragraph is followed by a description of the new V3 design.

5.1.1. Summary of the prototype + findings

The prototype in this context is known as version 2 (V2) of the engineered bio digestion system called a 'Waste Transformer'. The first version of the system was placed in a European context and was first tested in that context as a proof of concept (V1). In the following years a newer version (V2) was deployed in the Sierra Leone context at a woman's hospital.

As input for the new redesign leading to V3, key findings from operating the V2 Waste Transformer were considered, as well as input from the assessment being part of WP3.

Figure 3 - A Waste Transformer V2 as implemented in Sierra Leone at the Aberdeen Woman's Centre

5.1.1.1 Lessons learned and Design Review

The design philosophy of the bio digestion system, is to create a system that complies with all of the stringent EU health and safety features, whilst simultaneously allowing for adaptation to the local circumstances.

The V2 design is characterized by certain design choices that affect its footprint and operational efficiency. As an example, one of them being the number of containers used to build the system. Many lessons were learnt when operating the V2 Waste Transformers. The lessons were included in the design review to develop V3. The improvements are further discussed below.

Considered product aspects are:

- Feed system
- Pneumatic valves and actuators

- Control system hardware
- Piping and hand valves
- Overall efficiency in design and operations

As part of WP3, an assessment of this site was executed with its advise being reported in D3.1: ENERGICA capacity building needs. The essence of the redesign is to move towards a product that remains to comply with Health and Safety standards, while tailoring it for serial replication in urban context in emerging markets.

The design was assessed using the TEES (Technological, Educational, Economic, and Social) framework, providing insights if the V2 design matches needs for the local context. The outcomes, as presented in D3.1 that effect the design are listed below (sourcing, training or supply chain for example not included):

To consider simplifications or bypasses to the feed system

→ Consider whether PV-001 is necessary and whether it can be removed entirely or at least a by-pass valve installed.
Integrated in new design: no
Remark: The feed system itself was completely redesigned. The root cause of this suggested improvement was eliminated because of it.

To review and simplify use of pneumatic valves

→ Re-consider the balance between automatic and manual closure of valves
Integrated in new design: yes
Remark: The pneumatic actuating of valves has been changed in the new design to electric valves. Both types have their pros and cons which were considered in the initial design but given the experience with V2 the choice was made to change it into electric expecting overall quality and reliability will improve. They can also be manually overridden.

To review the types of piping, hand valves and fittings used

→ Re-consider using threaded fittings rather than Vic-press fittings against the light of the strategy to create Geo-Hubs (given the former are already locally available)
Integrated in new design: no
Remark: Considered but safety / gas tight integrity and overall quality of the system and its subsystems is most important in this choice. A press fit tool is not too expensive and will be made available at a regional hub. Furthermore, threaded fittings more easily wear or can be easily damaged when installed faulty.

→ Improve field tagging of hand valves
Integrated in new design: yes
Remark: Labels included in standardized scope of delivery.

To reduce CAPEX of the system overall to ensure it can be more affordable

→ Find ways to reduce CAPEX by removing redundant equipment
Integrated in new design: yes
Remark: In the redesign the number of containers was reduced significantly. In the V2 design, 2 control containers and 2 tank containers were required i.e. there were 4 containers in total. The updated V3 only has one of each i.e. 2 containers in total.
Furthermore, the compressor is not needed anymore resulting in less moving parts to maintain, however, the higher price of electric actuating valves more or less evens out the capex difference.

To ensure the biodigester system is reliable to maximize probability of adoption
→ Prioritize minimization of down-time in the result of equipment failure Integrated in new design: yes Remark: Several improvements were made to improve this. The feed system is one of the major product aspects that has been improved and impacts the operational effort required as well as the reliability of a properly functioning system. The electrical and automation system has been redesigned as well and provides more options for monitoring and control. Together with the actuator mentioned earlier, these are some key improvements to reduce down-time.

5.1.1.2 Changes between V2 and V3

The redesign of the system was done considering the findings as described in the before mentioned The improved and redesigned Waste Transformer has a slightly different appearance compared to the old design. Some of the key changes are listed in the following table:

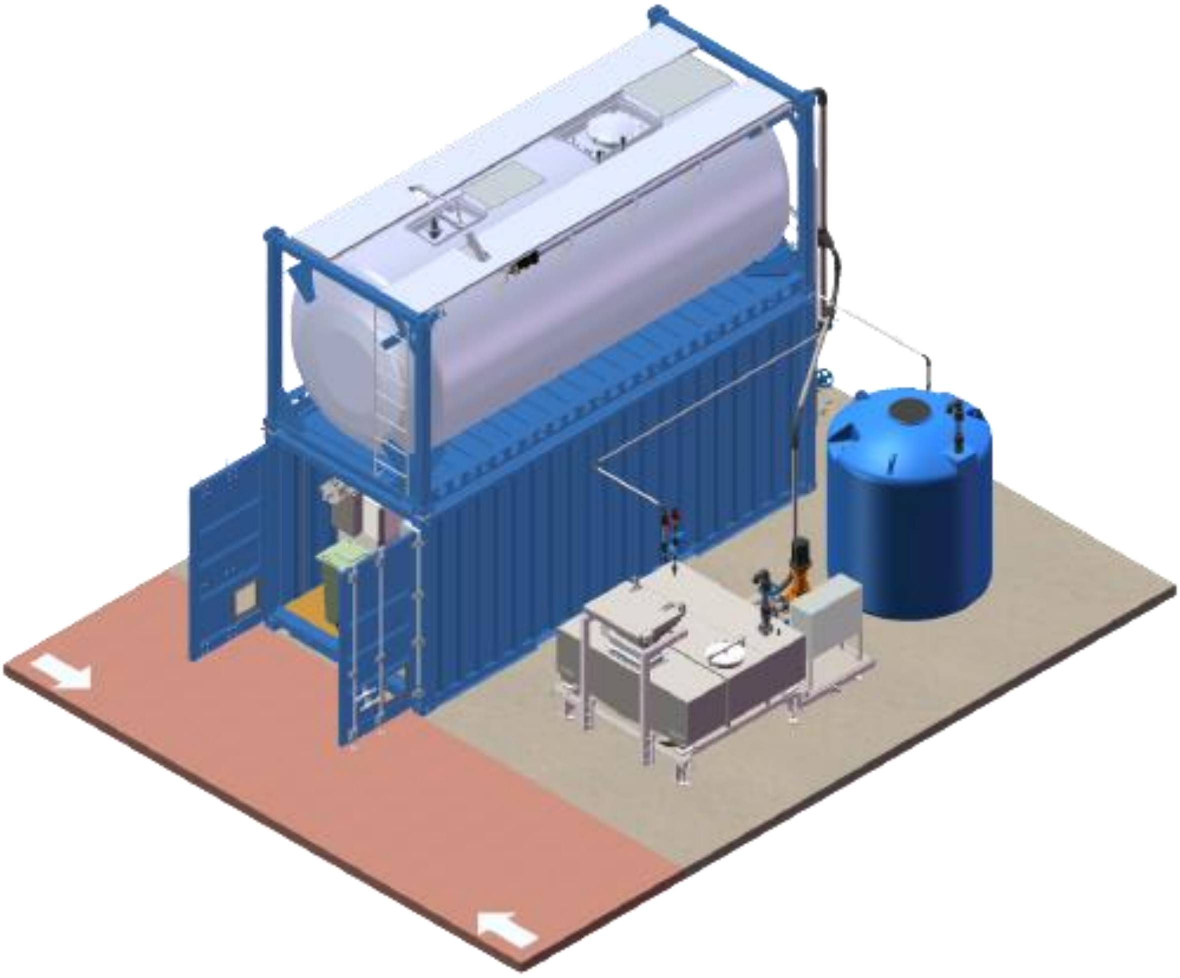
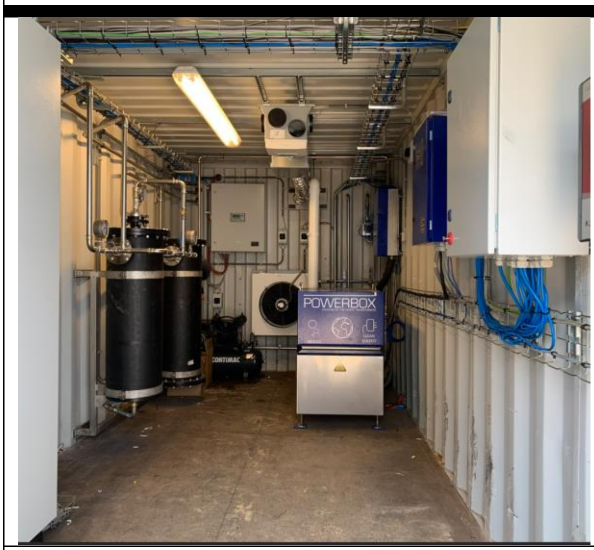


Figure 4: 3D representation of the redesigned V3 Waste Transformer

Design Version 2	Design Version 3
	
Feed system	
- Input of exact amounts to load in the system - Interrupted feeding - Non automated nor scheduled feeding	- 3 day buffer tank introduced - Improved digestion process (hydrolysis in mixing tank)
	
Gas buffer	
	Continuous production of electricity reduces the required buffer volume. Headspace within the digester tank is sufficient

	
Operating method valves	
Pneumatic controlled valves	Electric valves for improved reliability
n.a.	
Redundancy remotely operated valves	
Limited amount of redundancy	All motorized valves can manually be overwritten and in some locations an extra manual valve is added
n.a.	
Structural integrity and protection of piping	
	Added supports to exposed pipework

	
Electrical and automation system	
Individual cables making routing and searching for faults in case of a repair time consuming	Complete redesign of the E&A system Multicore cables with junction boxes
	New software design (increased control)
	
Operational efficiency	
Two control containers needed and not everything was easily serviceable.	One control container that includes general improvements on the layout and location of equipment to improve operation and maintenance as well as reducing the physical space required.

5.1.2 Construction of ENERGICA bio digestor

5.1.2.1. General Description of a Waste Transformer

A Waste Transformer is an anaerobic (absence of oxygen) digestion system to process organic food waste and generate energy. The system is designed to process food waste on-site. It is modular, designed to cope with different capacities starting from 350 kg/day up to 3.000 kg/day. It is a controlled, closed system with reliable safety features and built together from standardized and widely available components.

Anaerobic digestion of food waste results in two outputs; biogas and an effluent. Biogas is used to power a system-integrated CHP (Combined Heat and Power unit). The effluent is called 'digestate' and contains all the rich nutrients from the food waste and can be used as a fertilizer (research ongoing).

Mixed food waste is the preferred feedstock for the Waste Transformer, other types of feedstock are to be reviewed by TWT's R&D team.

A Waste Transformer works as follows: Organic food waste is loaded into the hopper, grinded, diluted and pumped into the digester tank(s). Inside the tank is an inoculum containing bacteria who are transforming the organic food waste into biogas. The gas is cleaned, dewatered and powers the CHP. Heat and electricity are delivered to the local grid and/or systems, with the aim of powering the same building that produced the waste. The slurry that remains in the tank is pumped to a pasteurization tank from where the liquid leaves the system.

An Electrical and Automation system operates the installation based on a specific logic control design. The HMI (Human Machine Interface) allows the operator to control the system and provides remote access for monitoring and control purposes.

Standard product features

- Process food waste producing green energy
- 24/7 remote access
- Full compliance with strict EU Rules
- Ambient temperature 0°C to 40°C
- Low maintenance costs
- Highly efficient CHP (A+++ rating)
- Shredder and dosing system
- Biogas cleaning
- Dedicated safety features
- Alarm and monitoring system
- Troubleshooting and process optimization

5.1.2.2 Expected in- and output

The table below shows the indicative output values from a Waste Transformer. These are design calculations. Daily output values are dependent on local conditions and the type of feedstock.

System Size	**Feedstock amount min-max [kg/day]**	**Electricity [kWh e/day]**	**Heat [kWh th/day]**	**Digestate [Litres/day]**
1AD	300 – 350	65 – 79	121 – 141	279 – 325

5.1.2.3 Design

Over all dimensions of the assembled system:

1AD		
Length	7.5	m
Breadth	5.5	m
Height	5.5	m

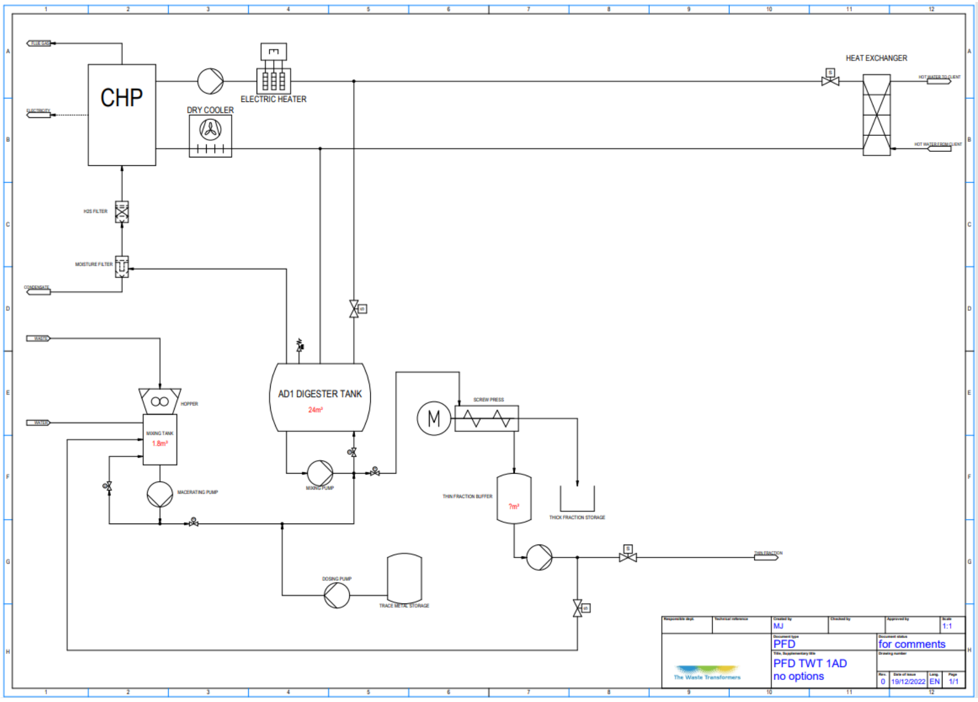


Figure 5: PFD of V3

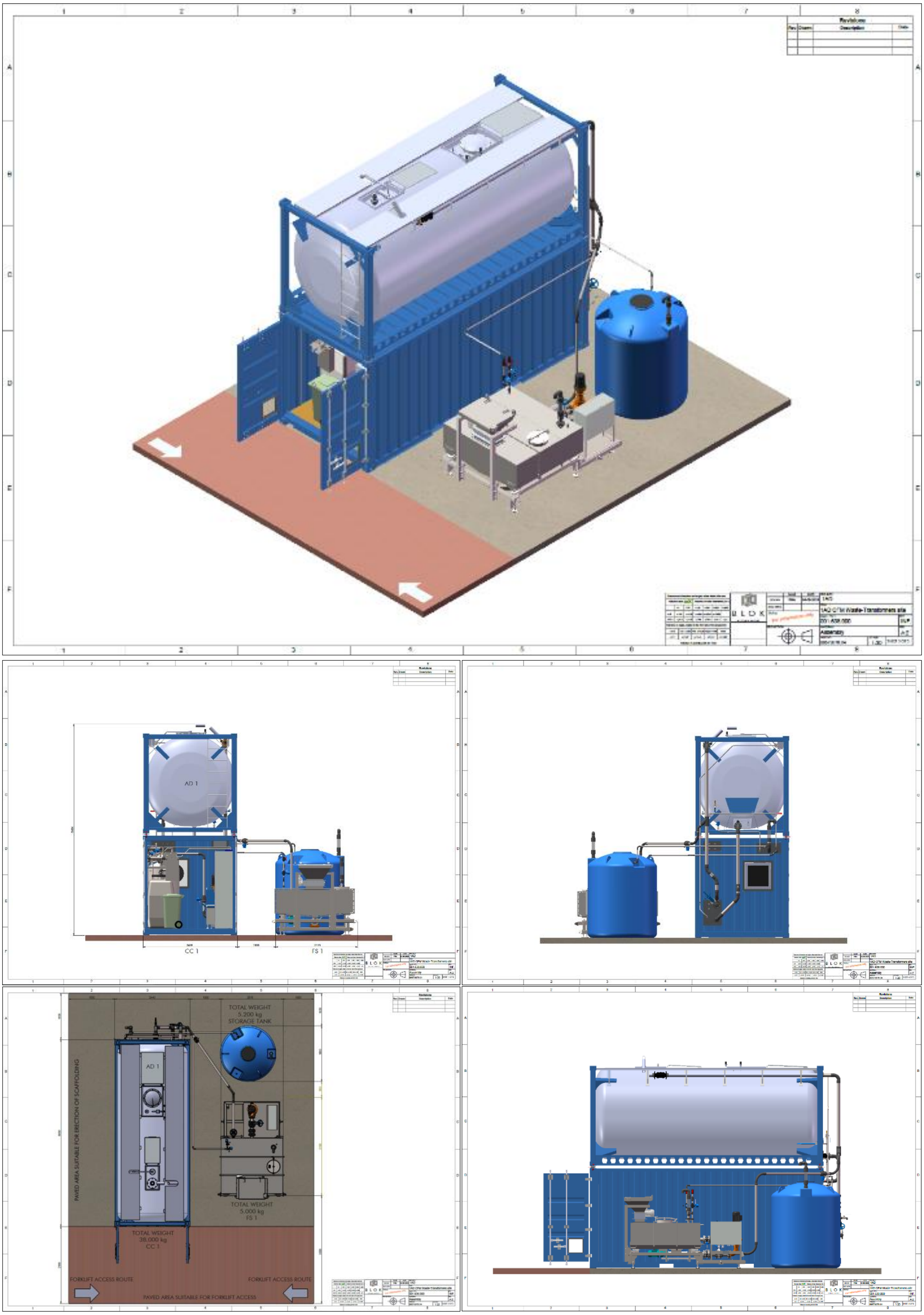


Figure 6: Drawings of the V3 redesign

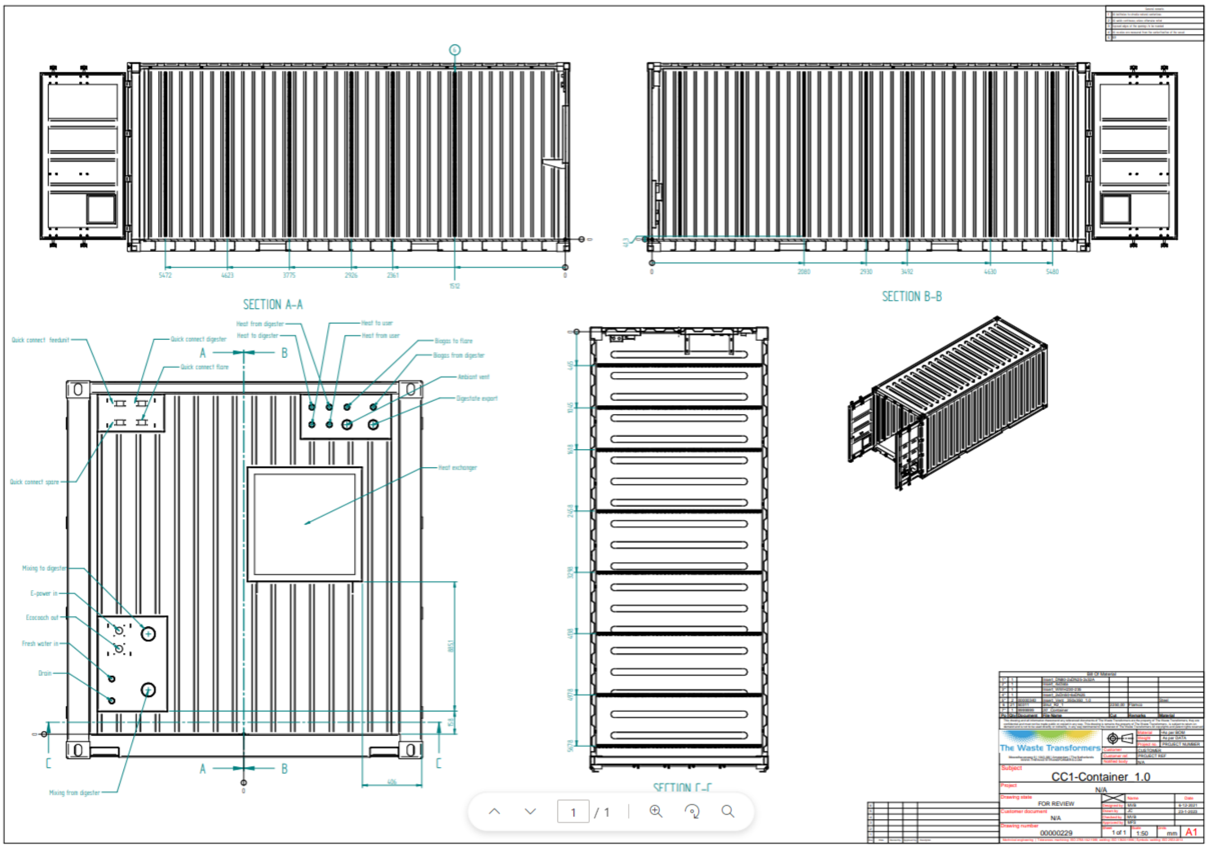


Figure 7: Example of a construction drawing

5.1.2.4. Configuration and main components

The configuration is always adapted to the amount of waste available on-site, optimizing green energy output. Because conditions and local situations change, the scope of delivery is tailored to local conditions for operational efficiency, yield optimization and/or local interface by a number of options.

In the below tables the configuration of the bio digestor for ENERGICA is represented.

Modules	**Quantity**	**Type**
Digester container	1	AD1
Control container	1	CC1
Feed system	1	FS1

Principal equipment	**Quantity**	**Type**
CHP	1	XRGI6
Smart Starter	1	
Hopper/shredder	1	
Trace metal dosing pump	1	Verderflex DS500+
Dewatering screw	1	
Pasteurization tank	1	500 liter
Biogas analyzer	1	Carltech CO2 sensor
Fixed gas detector LEL	1	Honeywell Sensepoint XCL
Fixed gas detector H2S	1	Honeywell Sensepoint XCL
Thin fraction/digestate storage tank	1	5050 liter

5.1.2.5. Site requirements

The site where the Waste Transformer is going to be installed is required to match the following specifications:

Minimum area:	15m x 15m free and levelled area
Capacity:	60 ton point load on each corner of a container
Utility connections:	Electricity Fresh Water Sewage Heat or Cold (optional)

5.1.2.6. Operational description

Pre-sorted organic waste material, also called the feedstock, is loaded into the feed system. Waste segregation at the source is highly recommended since contamination is undesirable: labels, plastic stickers and strings, plastic and metal cutlery, glass and other non-organic solid materials should be carefully removed if found in the feedstock. Bins are manually moved to the feed system and then emptied in the hopper which is located outside of the containers.

The built-in feed system is able to take the pre-sorted organic waste to the shredder from where it is loaded into the holding tank. The batch is weighed and then diluted so it can be pumped into the system. Inside the tank container the digestion process takes place as well as the gas buffering.

Inside the control container most components are located. Gas is cleaned and dewatered before running the CHP (Combined Heat and Power unit). Inside this container the E&A system (Electrical and Automation) is located with an HMI to monitor and control the installation.

Daily operations include feeding of the feedstock, cleaning of the site, monitoring the process and health of the system, unloading digestate and some maintenance tasks on a more prolonged basis.

5.1.2.6. Construction of the demonstrator

Arrival and stacking of the tank container and control container	
Assembly of the feed system	

Installation of the electrical cabinet with the HMI screen	
Finished product	
Finished product	

Finished product	
Finished product	
Finished product	

5.1.2.7. Cost breakdown

V2 was designed and constructed before Covid and before the start of the war in Ukraine. Both events had a considerable impact on the availability and price of raw materials. As a result the components sourced for V2 were considerably cheaper than what they currently are. For example, an Imo tank container, sourced and modified into a digester tank in 2019, cost approximately EUR 10.000,00. The same Imo tank container, sourced and modified into a digester tank in 2024 currently costs approximately EUR 21.000,00. The impact of these global events on the cost of the bio digestion system have been substantial.

The end of Covid and start of the war in the Ukraine, also had a considerable impact on global supply chains. All items sourced for the bio digestion system, were suddenly open to much longer lead times. Specifically the control system – driven by a micro processing chip – became very vulnerable to delays.

During the course of this project, the delivery times related to chips shifted from 4 weeks to 14 months. Currently, these delivery times are between 8 to 12 weeks. Also this has an impact on the cost of the system.

Key differences in the design that influence the cost

V2	ADDING COST	REDUCING COST
2 Imo containers	🟩	
2 tank containers	🟩	
Compressor	🟩	
Pneumatic valves		🟩
Small feed tank		🟩

V3	ADDING COST	REDUCING COST
1 Imo containers		🟩
1 tank containers		🟩
No Compressor		🟩
Electric valves	🟩	
Large feed tank/buffer	🟩	

The net result has been that whilst V3 is more robust, has a smaller physical footprint, has a better output and does not compromise in any way or form on health and safety measures, the actual cost is comparable to to V2.

5.2. Solar photocatalytic pilot plant

In this section, the details of the activities carried out will be explained in the following subsections:

- 5.2.1. Summary of solar photocatalytic prototype: previous findings.
- 5.2.2. Construction of ENERGICA solar pilot plant.
- 5.2.3. Results of the ENERGICA solar pilot plant.

5.2.1. Summary of solar photocatalytic prototype: previous findings

This section summaries the main activities and results obtained within the testing of the developed solar photocatalytic multi-step cascade reactor (spMSCR) for water disinfection and decontamination under natural sunlight and reported in previous D5.4.

Based on the easier implementation of immobilized photocatalytic material and the low cost of construction and maintenance of the flat type of solar reactor, this design was selected as a potential candidate for the ENERGICA project. A multi-step cascade reactor (MSCR) based on a cascade thin-film principal design, where the presence of the steps has the objective of increasing the surface for photocatalyst immobilization, was used for testing the developed immobilization material on stainless steel substrates.

The MSCR pilot plant used is shown in Figure 8. Briefly it consists of a stainless-steel staircase of 0.42 m^2 manufacturing with 5 steps of 7 cm high-depth. The plant is titled 37 degrees against the horizontal and it faces to the South to maximize the solar irradiance on the staircase steps at the location (Almeria, Spain). The plant has a holder tank from which the water is recirculated by a centrifugal pump (maximum flow rate of ca. 6 L/min (340 L/h)). A distribution pipe was made also of stainless-steel material and located in the upper part of the reactor to distribute the water uniformly across the width of the MSCR.

The maximum volume of water is 12 L, and the illuminated water volume is 1.6 L. The immobilization of photocatalyst in stainless steel steps was done by TEKNIKER in inorganic silica formulations incorporating TiO_2_P25_100 g/L and 200 g/L (explained in D5.3). These formulations were employed to be applied as coatings on stainless steel substrates, selected and provided by ARENYS. The substrates were coated by immersing them in each formulation at an immersion rate of 200 mm/min using a KSV NIMA dip-coater. After that, samples were cured in the oven at 150 °C for 2 h.

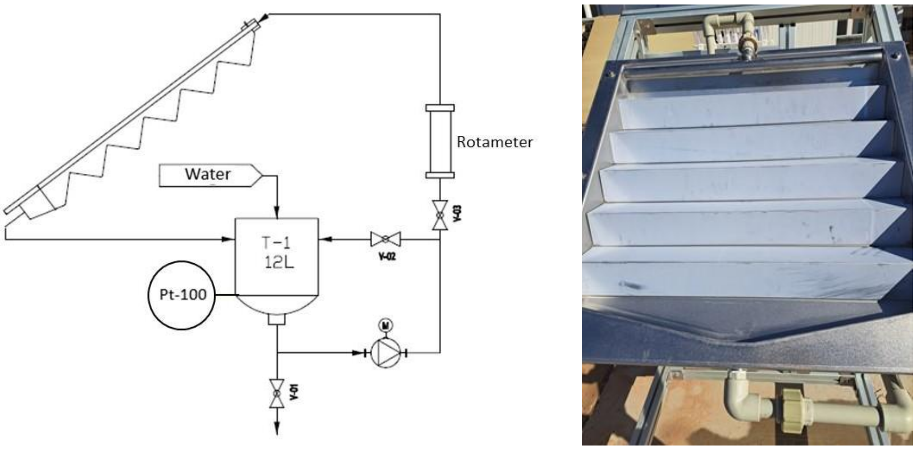


Figure 8: Diagram and images of the pilot-scale MSCR with the TiO2 immobilized for testing in ENERGICA.

The results obtained with MSCR with the immobilized TiO_2 onto the stainless-steel steps showed very promising results for both water disinfection and decontamination in different water matrices: isotonic water, well water and secondary effluents of UWW. The removal of > 80 % of contaminants of emerging concern (CECs) was reached in less than 30 min in isotonic water and 150 min in secondary effluents from UWW. The disinfection results did not show the same good performances, > 5 LRV of *E. coli* inactivation in isotonic water in 180 min and > 3 LRV in UWW in 240 min obtained during the photocatalytic process, which can be mainly attributed to the actions of solar photons (solar only disinfection).

Despite the good results obtained for the degradation of CECs in the photocatalytic MSCR pilot plant, a limitation in the photocatalytic activity for water disinfection has been observed. This aspect could be a potential risk, and therefore the addition of H_2O_2 during the photocatalytic process will be incorporated during the treatment to increase the microbial safety of the treated water. This aqueous oxidant is a low-cost solution and easy to implement in the prototype, and its capability for microbial inactivation under natural sunlight at a very low concentration (< 100 mg/L) is very well-known (Polo-López et al., 2011; Ferro et al., 2015; Abeledo-Lameiro et al., 2017).

5.2.2. Construction of ENERGICA solar pilot plant

5.2.2.1. General description of MSCR

The pilot plant features a cascade-shaped structure made of stainless steel AISI 316L for a total capacity volume of 50 L. Water is distributed in a thin film over this cascade, where it comes into contact with sunlight and a photocatalyst coating the stainless steel structure.

To evenly distribute the water across the width of the reactor, a multiperforated tubular diffuser made of polypropylene has been installed at the top of the reactor.

The water is pumped from a 50 L stainless steel AISI 316L tank to the cascade reactor using an electromagnetic drag pump.

A 50-500 L/h rotameter made of PVC and plastic is included. The flow rate is regulated by two manual valves installed in the pipes (see diagram, ball valve V-02 and V-03).

The supply circuit pipe has an outer diameter of 25 mm and a thickness of 2 mm, made of polypropylene. The drainage pipe system has an outer diameter of 40 mm and a thickness of 2.9 mm to facilitate reactor emptying, also made of polypropylene. The ball valves incorporated in these pipes are made of the same material.

Figure 9: Rear view of the reactor

To control the process, a Kipp & Zonen SUV5 radiometer and a PLC are installed, which will indicate when the operation ends based on the received irradiance.

The structure supporting the reactor and its components is made entirely of anodized aluminium and stainless steel AISI-316L, ensuring resistance to corrosion. The equipment is prepared to remain continuously outdoors.

5.2.2.2. Equipment specifications

The MSCR of the ENERGICA project has the following main characteristics:

Dimensions: 1.6 x 1.6 x 3 m

Approximate weight: 200 kg

Reactor useful surface: 4 m^2

Recommended operation volume: 50 L

Irradiated volume: 10 L

Maximum volume: 70 L

Operating flow rate: 0 – 8.3 L/min

Maximum operating temperature: 55°C

Pump: Pan World NH40PX 220V AC 20W, electromagnetic drive

Operating current: 220V AC

Tank: Stainless steel AISI-316L

Pipes and fittings: Polypropylene and AISI-316L

5.2.2.3. Flow diagram

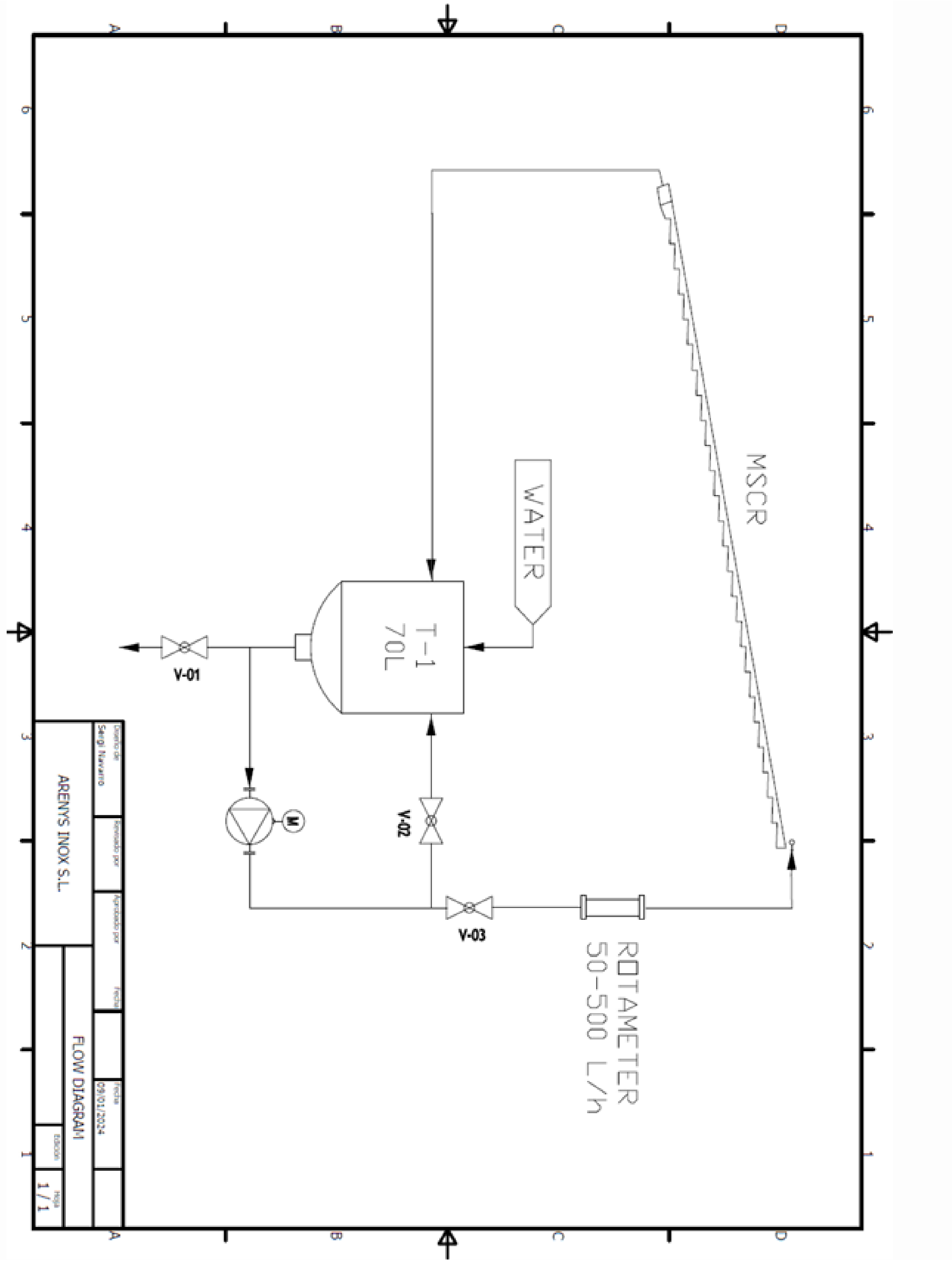


Figure 10: Flow diagram

5.2.2.4. Reactor operation

Below is a summary of the steps to operate the MCSR. For more information, please refer to the user manual.

Step	Summary	Explanation
1	Drainage & levelling	Ensure that there is no water left in the system by opening all polypropylene valves for drainage. Check that the reactor is correctly levelled and that there is a good distribution of water.
2	Tank filling	Fill the recirculation tank with the desired volume of water through the tank lid. The tank is oversized and has a maximum capacity of 70 L. Only 50 L of water is needed to operate the reactor. Keep the drain/sample valve V-01 closed to fill the tank.
3	Reagent mixing	If necessary to use any reagent, configure the valves for water recirculation in the same tank to mix the reagents. Close valves V-01 and V-03, and open V-02. Press the black button of the motor protector of the pump to activate it. See figure 11, how to turn on the pump.
4	Start water disinfection	Configure the valves to carry out the water circulation through the cascade reactor. Valve V-02 must be closed and open V-03 (ever open valves before close). Adjust the flow rate by gradually opening valve V-03.
5	Process controller activation	Activate the process controller, find more information in the user manual. A red LED light will indicate when the process is finished, indicating that the water is disinfected.
6	Reactor emptying	When the water is already treated, turn-off the pump and empty the reactor through valve V-01 by connecting a hose or directly to the ground. ***During the reactor validation phase, avoid using treated water for any activity, and never consider it as certified potable.***
7	Equipment cleaning	Once the process is finished, clean the system using a "piston flow" wash. Perform this operation 2 or 3 times, renewing the water each time for thorough cleaning of the equipment.

Figure 11: Rear view of the reactor, indicating how to turn on the pump

5.2.2.5. Control systems

The solar MSCR operates in batch cycles lasting between 6 and 8 hours under favourable climatic conditions. Due to the need to reduce the time between each water treatment cycle, an integrated control system has been developed to enhance the efficiency of water purification in the solar reactor. This system utilizes a global radiation radiometer and a **Programmable Logic Controller** PLC to indicate when the water has received sufficient solar radiation and has reached the desired purification parameters.

To control this process, a global radiation radiometer is used, which is positioned to match the optimal inclination of the stair-shaped reactor, which is 10 degrees. This radiometer measures the incident solar radiation on the reactor and accumulates this information over time. Once a solar radiation threshold is reached, at which the water should meet the desired standards, a red pilot light is activated as an end-of-cycle indicator. After completing this cycle, the counter is reset manually. It's worth noting that this device incorporates a touchscreen that allows for the modification of the solar radiation threshold to adjust it to the required value based on previous results.

The control system consists of several elements:

1. Global radiation radiometer: The radiometer (SUV5 from Kipp & Zonen, 280 to 400 nm) is responsible for measuring the incident solar radiation on the stair-shaped solar reactor. It is oriented to the same inclination as the reactor (10 degrees) for precise measurements.

2. Display: A touchscreen display shows the accumulated values of solar radiation measured by the radiometer. This provides a visual indication of the progress of the purification process.

3. PLC (Programmable Logic Controller): The PLC serves as the brain of the control system. It is programmed to compare the accumulated solar radiation values with the desired purification parameters, which have been established based on previous tests.

4. LED Indicators: The PLC controls one red LED indicators. When the accumulated solar radiation value reaches the desired purification parameters (not yet defined as the water purification efficiency of the reactor should be assessed in Waterloo-Sierra Leone), the red LED indicator lights up, indicating that the water is treated and ready. If the desired values are not achieved, the red LED indicator remains off, indicating that the water purification process is still ongoing.

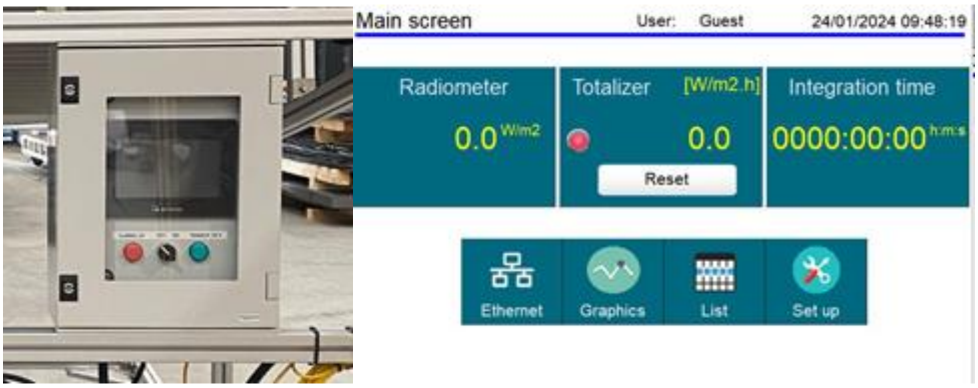

Main screen
User: Guest
24/01/2024 09:48:19
Radiometer 0.0 W/m2
Totalizer [W/m2.h] 0.0
Integration time 0000:00:00 h:m:s

Figure 12 (a) Electrical panel with display and (b) the main display screen

This control system provides several key benefits:

- **Enhanced Efficiency:** It allows for more efficient use of solar radiation by clearly indicating when the water has received enough solar exposure and meets purification standards.
- **Water Safety:** It ensures that treated water complies with established requirements before being considered safe for consumption, improving end-user safety.
- **Automation:** It reduces the need for constant supervision, as the system automates the control and signalling process.

Overall, this integrated control system not only improves process efficiency but also ensures the safety and reliability of the process. This is essential, especially in regions where access to clean water is a critical challenge. Moreover, by optimizing the use of solar radiation and providing clear indications to operators, more effective use of available resources for water purification can be achieved.

5.2.2.6. Electrical panel diagram

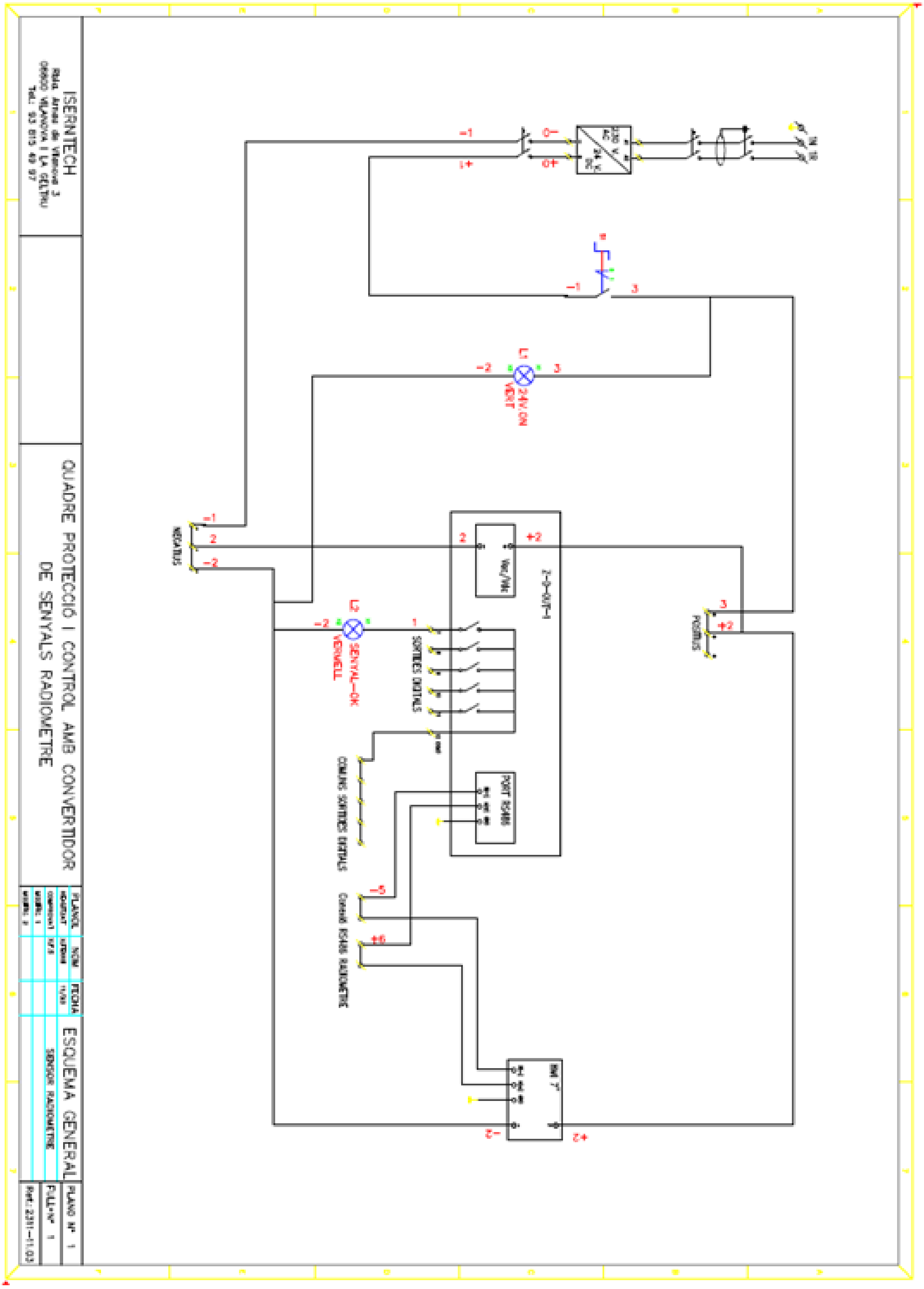


Figure 13: Electrical panel diagram

Figure 14: Image of the electrical panel.

5.2.2.7. Construction of the reactor

A detailed description of the manufacturing process of the Multi Cascade Solar Reactor (MCSR) is provided below, from the initial conception of the design to the completion of construction. This project represents a multidisciplinary effort that combines engineering, design, and manufacturing to create a functional and efficient equipment.

1. 3D Design with Autodesk Inventor: the process began with three-dimensional (3D) design using Autodesk Inventor software. This step allowed for precise visualization and planning of the structure, reactor, and recirculation tank before proceeding with manufacturing.

2. Manufacturing of welded assemblies: once the design was finalized, welded assemblies were fabricated using 316 stainless steel for the cascade and tank. The development of the pieces to be manufactured was calculated, and laser technology was used to precisely cut them.

3. Modelling and Forming of Parts: each cut piece underwent a modelling and forming process to give it the required shape using a sheet metal folder machine. This step ensured that each component fit perfectly into the design and equipment specifications.

4. Welding and finishing: once all the pieces were formed, they were welded together to form the welded assemblies. Subsequently, a polishing process was carried out to ensure a smooth and uniform finish across the entire surface of the equipment.

Figure 15: Image of the welding process for cascade component

5. Pickling and cleaning: welds were pickled using pickling acid to remove contamination caused by welding. Then, all pieces were thoroughly rinsed and cleaned to remove all applied acid.

6. Treatment with passivating soap: the reactor surface was washed with a passivating soap to remove oils and other residues from the manufacturing process. A clean surface means uniform water distribution throughout the reactor. This final step ensured that the equipment was ready for use under optimal conditions.

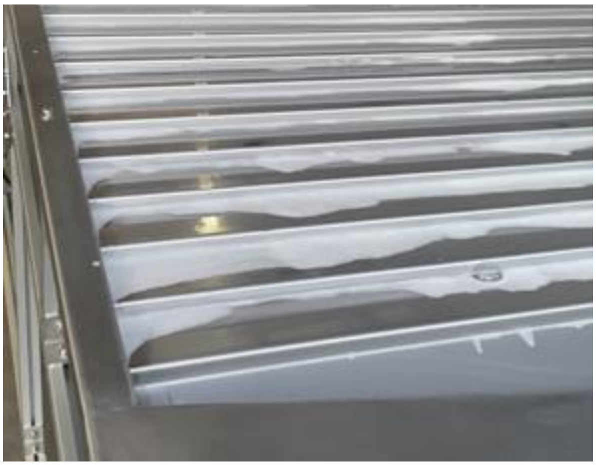


Figure 16: Image of the treatment with passivating soap

7. Cutting and assembly of aluminium structure: once the fabrication of the welded assemblies was completed, the aluminium structure was cut and assembled to serve as support for the equipment. Using A4 quality screws, the structure pieces were joined to guarantee stability and durability.

8. Assembly of all components to the structure: with the aluminium structure ready, all equipment components were assembled onto it. Each component was placed on the structure according to the previously established design.

9. Electrical connection of components: once all components were assembled, electrical connection between them was carried out, ensuring proper coordination and functioning among the different elements of the equipment.

Figure 17: Image of the different electric components

10. Assembly of pipe system and valves: simultaneously with component assembly, the pipe system and valves were assembled according to the design. All components are made of polypropylene and are joined together through heat fusion of their ends.

Figure 18: Image of the different components assembled on the structure

11.Testing and design corrections: upon completion of assembly, comprehensive tests were conducted to verify the correct operation of the equipment. During this phase, potential problems or design deficiencies were identified and promptly corrected to ensure optimal performance of the cascade solar reactor.

Some corrections made in the design are detailed below:

Summary	Description
Failed cascade manufacturing	The manufacturing of the reactor cascade required the construction of 12 pieces welded together. Initially, an attempt was made to manufacture it as a single piece to reduce welding, but this proved problematic. The main piece was too complex to manufacture with the required tolerances. Therefore, it was decided to divide the cascade into smaller pieces that overlap each other. This not only simplified the manufacturing process but also kept the amount of welding constant.
Reinforcement of the aluminium structure	The aluminium structure needed reinforcement because it was deforming in the centre due to the weight of the stainless-steel cascade. A profile truss was installed to provide the additional support needed and prevent deformation.
Pump upgrade	A decision was made to install a higher-power pump because the initially calculated pump had insufficient flow. This resulted in poor water distribution in the upper diffuser, affecting the reactor's performance.
Expansion of Drainage Tube	Because of changing the pump, it was necessary to expand the reactor's drainage tube from DN 32 to DN 40. This was because the original tube couldn't drain all the water from the end of the cascade when the reactor operated at maximum flow.

Figure 19: Side view of MSCR plant

5.2.2.7. Immobilization of the photocatalytic material in the reactor

The inorganic silica formulation incorporating TiO_2_P25_200 g/L has been prepared, as explained in D5.3. Briefly, a silica sol has been prepared using tetraethyl orthosilicate as a precursor of Si in a molar ratio of 1:20 to ethanol under stirring and using nitric acid as a catalyst of the reaction. After 24h of ageing, the photocatalyst, TiO_2 nanoparticles, has been added in a 200 g/L concentration using a dispermat equipment and ultrasound to improve the dispersion of the nanoparticles in the solution. This formulation was employed to be applied as coating on stainless steel substrates, selected and provided by ARENYS. The substrates were coated by immersing them in the formulation at an immersion rate of 200 mm/min using a KSV NIMA dip-coater. After that, samples were cured in the oven at 150 ºC for 2 h. Figure 20 shows the images of the deposition process and the coated substrates. A first batch of 54 stainless steel substrates to be implemented in the demonstrator, were prepared at Tekniker and sent to CIEMAT for characterization. A second batch were also prepared in order to have replacement samples at the Sierra Leone location.

Figure 20: TEOS/TiO2 coatings in stainless-steel preparation procedure at TEKNIKER

The immersion method used until now to obtain the stainless-steel coated substrates of the demonstrator seems not to be the easiest method to implement in the field, when it comes to being able to repair or replace the demostrator stairs. For that reason, TEKNIKER is developing a spraying method for the coating of stainless-steel substrates that can facilitate implementation in the field.

To this end, TEKNIKER is working to find the optimum parameters using an aerographic spray gun (Classic Pro XD from SAGOLA). The work has been focused on the search of the best parameters to obtain a coating comparable to the one obtained by immersion deposition. This includes the selection of the air nozzle, needle and air caps that fulfil the requirements of the solution to be sprayed as well as the product flow and the spray width.

In the figure 21 it is shown the spraying process and the stainless-steel substrates obtained during the first trials. The main problem identified is related to the high solid content that present the inorganic silica formulation, which leads to an excessively dry layer using this deposition method. The activity is ongoing.

Figure 21: Spraying process and the stainless-steel substrate

5.2.2.8. Photocatalytic reactor costs.

Before analysing the detailed costs of manufacturing the MCSR reactor, it is important to consider several considerations that may influence the total cost, especially when considering the manufacturing of a second reactor. Below are the actual manufacturing costs of the MCSR.

CONCEPT	DESCRIPTION	PRICE	TOTAL
Aluminium structure profiles	Anodized aluminium profiles 45x45 mm	1.215,41 €	9.775,15 €
Piping	Polypropylene pipes, ball valves and fittings	277,50 €	
Electrical panel and radiometer	All electronic components, electrical assembly, PLC programming, and radiometer	6.480,80 €	
Stainless steel AISI 316L	Raw sheets metal different thicknesses	780,59 €	
Pump	Pan World NH40PX 220V AC 20W	165,33 €	
Others	Screws, paint, stainless steel accessories, plastic brackets, other…	855,52 €	
Labour (manufacturing and assembly)	2 weeks at €58/hour	4.640,00 €	5.000,00 €
Laser machinery fee	2 hours at €180/hour	360,00 €	
Palletization	Wooden crate with export treatment	775,65 €	775,65 €
		PRICE FOR 1 MSCR	**15.550,80 €**

As can be seen, the components that have the greatest impact on the final price of the equipment are the electrical panel, the radiometer, and labour.

To reduce the cost of the electrical component, it is proposed to acquire a lower-quality radiometer, as oversizing the treatment time for a cycle would address potential measurement errors. On the other hand, it was decided to incorporate a touchscreen to greatly facilitate PLC programming for equipment testing. Instead, the use of a touchscreen could be avoided, and the equipment could be delivered with pre-established accumulated radiation values based on previous tests.

On the other hand, the photocatalytic material should be also included in the cost when considering the system for the photocatalytic water treatment. In the table below the manufacturing cost of the developed inorganic silica formulation. It is worth mentioning that with 1 litre of the formulation can be coated by immersion in a dip-coater the full surface of the photocatalytic reactor.

MATERIAL	DESCRIPTION	PRICE	TOTAL
TEOS	Tetraethyl orthosilicate (CAS num: 78-10-4) as silica precursor	65 €/kg	9.48 €
EtOH	Ethanol (CAS num: 64-17-5) as dispersant phase	20 €/l	16 €
H_2O	Distilled water as catalyst	1.48 €/kg	0.94 €
HNO_3	Nitric acid (CAS num: 7697-37-2) as catalyst	27.9 €/l	0.05 €
TiO_2	Titanium dioxide nanoparticles (CAS num: 13463-67-7) as photocatalyst	220.5 €/kg	44.10 €
PRICE FOR 1 L			70.56 €

The stirring time to carry out the sol-gel homogenization has been 1 h. So, the energy consumption of the Mixer for this process has been 2.4 kWh (for 1 L of sol-gel). The incorporation of the photocatalyst has been 30 min of dispermat equipment (0.55 kW/h) followed by 30 min of ultrasound (0.75 KW/h).

The inventory data for the dip-coating process has been collected on the basis of 1 stainless steel substrate with 750*92.42*11.94 mm dimensions coated with sol-gel in a dip-coater tank of 3.2 L. Each part can be coated in about 5 minutes, so the energy consumption of the dip-coater has been 0.02 kWh (for 1 substrate).

After both coating methods, it is necessary a curing process in an oven at 150 °C for 2 h. Each oven tray has a capacity for about 12 parts, and the dimension of the oven allows to introduce 2 trays at the same time, so curing process data is for 12 parts. All parts must be cured for 2 hours in the oven (9.8 kWh), so the energy consumption of the curing process has been 1.63 kWh (for 1 substrate).

Regarding labour, it is worth mentioning that manufacturing a piece of equipment for the first time always requires more work. Once the manufacturing process is defined and tested, everything becomes more streamlined.

To assess how the price would be affected by manufacturing more reactors, this possibility has been estimated. Below are the costs for the simultaneous manufacturing of two reactors that would operate together.

CONCEPT	DESCRIPTION	PRICE 1st	PRICE 2nd
Aluminium structure profiles	Anodized aluminium profiles 45x45 mm	1.215,41 €	1.215,41 €
Piping	Polypropylene pipes, ball valves and fittings	277,50 €	277,50 €
Electrical panel and radiometer	All electronic components, electrical assembly, PLC programming, and radiometer	6.480,80 €	- €
Stainless steel AISI 316L	Raw sheets metal different thicknesses	780,59 €	780,59 €
Pump	Pan World NH40PX 220V AC 20W	120,00 €	120,00 €
Others	Screws, paint, stainless steel accessories, plastic brackets, other…	500,00 €	500,00 €
Labour (manufacturing and assembly)	1.3 weeks at €58/hour	3.286,00 €	3.286,00 €
Laser machinery fee	1.5 hours at €180/hour	270,00 €	270,00 €
Palletization	Not applicable - Shipping in 20 ft container	- €	- €
	PRICE FOR EACH ONE	**12.666,30€**	**6.179,50 €**

With the manufacturing of multiple reactors, a substantial reduction in labour and laser cutting costs can be expected due to process optimization and economies of scale. This could result in lower prices for materials and more efficient and economical labour.

Furthermore, when considering the manufacturing of a second reactor, it is important to note that elements, such as the radiometer and electrical panel, would not need to be duplicated, as both reactors could be connected to the same electrical panel and share these components, thus reducing associated costs.

In terms of shipping, manufacturing multiple reactors could also lead to considerable savings in shipping costs. Instead of individual palletization, the additional reactors could be shipped in a 20 ft container or similar, resulting in a more economical shipping cost.

It's worth highlighting that the cost for one reactor is €15,550.80, while fabricating two amounts to €18,845.80. Therefore, adding a second reactor would increase the total cost by €3,295.00 compared to having just one.

In summary, manufacturing two reactors simultaneously represents an economically favourable option, offering the possibility of obtaining a high-quality product at a more competitive price in the market. Moreover, if the operation required more reactors, the price would decrease even further.

Finally, it is worth mentioning that the costs used herein are based on the first prototype developed in the project and based on the results obtained under controlled conditions in CIEMAT. The efficiency and behaviour of the reactor in the field should be assessed once installed in Waterloo in Sierra Leone, and therefore, some modifications can be needed to address to fit well the local context needs.

5.2.3. Results of the ENERGICA photocatalytic pilot plant.

The ENERGICA photocatalytic pilot plant has been tested for validation of the preliminary results obtained in D5.4 and before to send it to Sierra Leone. To do so, the reactor was shipped from ARENYS (Barcelona, Spain) to CIEMAT-PSA (Almería, Spain). The assessment of the reactor performance was done following similar methodologies described and used in D5.4, briefly summary below, and monitoring the simultaneous disinfection and removal of CECs from natural well water.

Experimental procedures and set-up

All the assays were carried out to treat natural well water obtained from a bore hole located at Plataforma Solar de Almería (CIEMAT). This matrix was selected to analyze the performance of the photocatalytic reactor in the absence of organic content. The physicochemical characterization of the water is shown in the table below. The analyzed parameters and the correspondent instruments were: Total Organic Carbon (TOC analyzer, Model 5050, Shimadzu, Japan), pH (pH meter multi720, WTW, Germany), conductivity (conductivity meter GLP31, CRISON, Spain), and ionic content (ion chromatograph (Model 850, Metrohm, Switzerland; Column METROSEP C4-250/4.0 (250 mm X 4.0 mm ID)) and turbidity (turbidimeter Model 2100N, Hach, USA).

For this purpose, natural well water was artificially spiked with *E. coli* K12 (from the Spanish Culture Collection, CECT 4624) at an initial concentration of 10^6 CFU/mL and a mix of three CECs (Imidacloprid, Sulfamethoxazole and Trimethoprim) at an initial concentration of 100 µg/L per each. Bacteria inactivation was monitored by standard plate counting method with Endo Agar (Detection Limit 2 CFU/mL) and CECs concentration was followed by Ultra Performance Liquid Chromatography with UV-DAD detection (Agilent Technologies, Series 1260) and a C-18 column (XDB-C18 Agilent; 4.6 mm x 50 mm; particle size 1.8 µm) following the procedure described in other studies (Berruti et al., 2023).

Parameter	WW
DOC (mg/L)	1.9±1.0
$[HCO_3^-]$ (mg/L)	105.4±13.2
Turbidity (NTU)	0.2±0.1
pH	7.4±0.1
Conductivity (mS/cm)	0.3±0.1
Cl^- (mg/L)	31.6±6.5
NO_3^- (mg/L)	1.5±1.1
NO_2^- (mg/L)	0.2±0.1
SO_4^{2-} (mg/L)	20.0±6.1
Na^+ (mg/L)	49.9±1.9
Ca^{2+} (mg/L)	9.4±1.8
Mg^{2+} (mg/L)	6.0±0.9

Experimental Procedure for the assessment of the ENERGICA MSCR

(i) *The effect of solar only radiation on target removal*

Experiments with only solar were performed following the subsequent methodology. Well water was poured into the MSCR tank, and the necessary volume of resuspended bacteria stock and CECs was added to achieve the concentrations previously mentioned. To guarantee the homogenization of all water conditions, it was recirculated at dark conditions on the reactor hold tank for 15 min at a flow rate of 500 L/h (8.3 L/min). An aliquot was taken after this period corresponding to the initial sample (time 0). Then, water started to flow through the reactor during 180-240 min. Assays started around 10:30-11:30 a.m. Aliquots were taken out to follow the kinetics of bacteria inactivation and CECs degradation. Moreover, water temperature and UV-A irradiance were monitored during the experiment.

(ii) The immobilized TiO_2

The followed procedure to assess the immobilized substrate coated with TiO_2 (200 g/L solutions) for the simultaneous disinfection and decontamination of well water was the same as the previously described for the solar treatment (i). However, the immobilized set of steps was collocated onto the stainless-steel staircase of the reactor before recirculating water on it, as it is shown in figure 22.

Figure 22: Immobilized TiO2 onto the stainless-steel staircase of the ENERGICA MSCR at CIEMAT-PSA facilities

(iii) Combination of immobilized TiO_2 and H_2O_2

Two concentrations of hydrogen peroxide (25 and 50 mg/L) were tested to determine the effect of hydrogen peroxide (H_2O_2) on the photocatalytic treatment of well water. The experimental procedure was almost the same as the one previously described; however, after the homogenization, the necessary amount of H_2O_2 was added and recirculated for another 15 min in the MSCR tank. Then, a new sample was taken under dark conditions to ensure there were not interactions between *E. coli* / CECs and H_2O_2. Moreover, the H_2O_2 concentration was monitored by spectrophotometry at 410 nm using titanium (IV) oxysulfate in accordance with the DIN 38402H15 method.

Results of the ENERGICA photocatalytic plant

Solar experimental tests:

The performance of the ENERGICA reactor at plant scale was evaluated based on the removal of the sum of three CECs and the inactivation of *E. coli*, as a model pathogen. Temperature and UV-A radiation were monitored along all the assays as it is shown in figure 23. Data demonstrated that water temperature did not suffer any significant change during experimentation, being almost constant at 22.5 °C. Similarly, in the case of UV-A radiance, it can be observed that assays were performed under similar irradiance conditions, ranging between 20 to 45 W/m^2 of solar UV-A dose measured by the radiometer installed in the reactor.

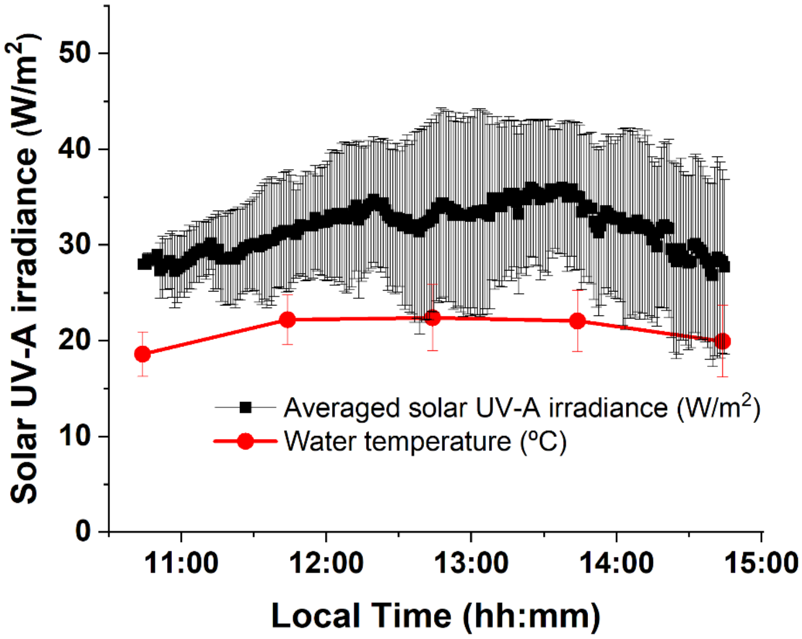


Figure 23: Average water temperature and solar UV-A irradiance measured along the solar treatments in the ENERGICA MSCR during the testing at CIEMAT-PSA facilities

The presence of carbonates could affect the removal of CECs and disinfection rate since they can present a hydroxyl radical (•OH) *scavenger* effect (Saggioro et al. 2015). For this reason, Dissolved Organic Carbon (DOC) and bicarbonates (HCO_3^-) concentrations were monitored at the beginning and at the end of the experimentation as shown below. It can be implied that the initial concentration of bicarbonates varied from 65 mg/L to 115 mg/L. It was observed that the final concentration of bicarbonates increased slightly in all the experiments (between 69 and 131 mg/L). It might be suggested that the variation on bicarbonates concentration did not exert a strong influence in the removal of CECS or *E. coli* inactivation.

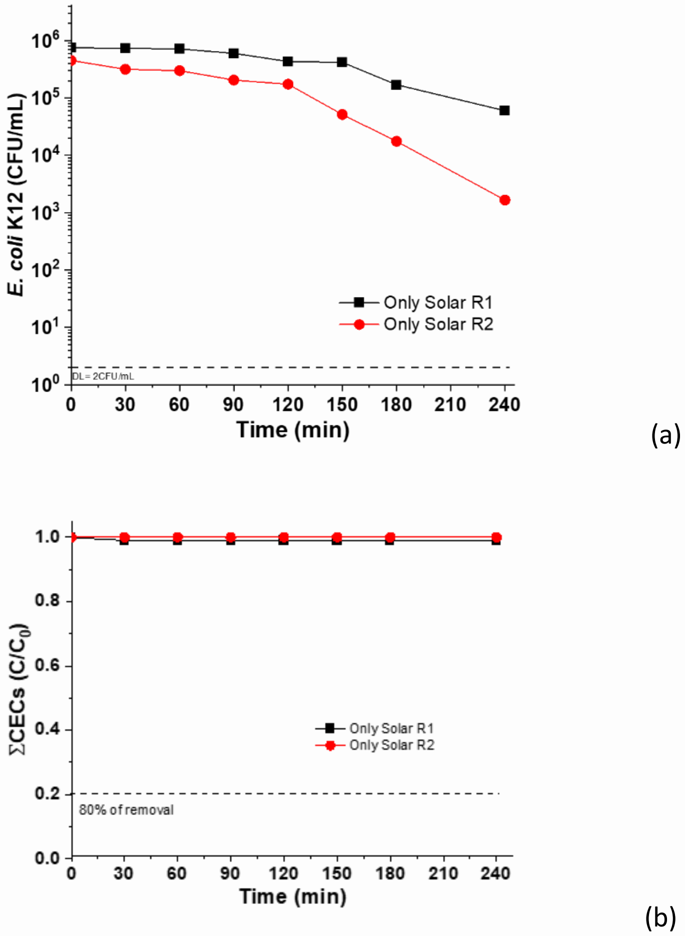
Table X. Dissolved Organic Carbon (DOC) and bicarbonates concentration measured at the start and at the end of the solar treatments in the ENERGICA MSCR during the testing at CIEMAT-PSA facilities.

Treatment	Date	DOC (mg/L)		HCO_3^- (mg/L)	
		t_o (min)	t_f (min)	t_o (min)	t_f (min)
Only Solar R1	10/01/2024	1.1	2.8	90.3	93.6
Only Solar R2	16/01/2024	1.3	3.0	106.0	119.8
Immobilized Catalyst R1	02/02/2024	1.7	2.2	110.6	125.9
Immobilized Catalyst R2	07/02/2024	1.6	2.7	71.3	71.8
Immobilized Catalyst + H_2O_2 (25 mg/L)	13/02/2024	1.1	1.3	98.4	118.6
Immobilized Catalyst + H_2O_2 (50 mg/L)	08/02/2024	2.8	2.3	64.7	69.2
Immobilized Catalyst + H_2O_2 (50 mg/L)	20/02/2024	0.5	1.0	113.4	131.0

Immobilized Catalyst + H_2O_2 (50 mg/L)	21/02/2024	2.0	3.2	114.6	126.4

(i) The effect of solar only radiation on target removal

The effect of solar only radiation for the treatment of 50 L of well water was evaluated, and the results are depicted in figure 24. For this purpose, two replicates were carried out and it was demonstrated that the total inactivation of *E. coli* was not achieved after 240 min of treatment or at high solar UV-A doses (308 kJ/m^2) (Figure 24(a)). In the case of CECs, they neither can be removed by the isolated solar action as it is shown in Figure 24(b), demonstrating that it is required to include an oxidative additional photocatalytic process to reach a safe treated water.



(a)

(b)

Figure 24: (a) Inactivation profiles of E. coli and (b) removal of ΣCECs under solar only radiation in well water in ENERGICA MSCR.

(ii) The immobilized TiO_2

The results obtained with the immobilized catalyst onto the stainless-steel stairs are shown in Figure 25. Two replicates were carried out to determine the water purification efficiency of the immobilized TiO_2 (200 g/L) onto the stainless-steel stairs of the reactor. Both replicates showed similar results, with a 3 Log Reduction Value (LRV) of *E. coli* after 240 min of treatment (equivalent to 474 and 482 kJ/m^2), while total inactivation to the detection limit was not attained.

In the case of CECs, it could be inferred that removal percentages > 80 % were achieved at both experiments after 75 and 90 min (136 and 163 kJ/m^2) of treatment. This can be attributed to the formation of hydroxyl radicals ($^{\bullet}OH$), which are non-selective and high reactive species. These results agree with the previously obtained in the preliminary analysis carried out at pilot scale, shown in D5.4. And it clearly states the need to add an oxidant (at low concentration) with the aim of increasing the disinfection capability of the treatment and of enhancing the safety level of the treated water in the field.

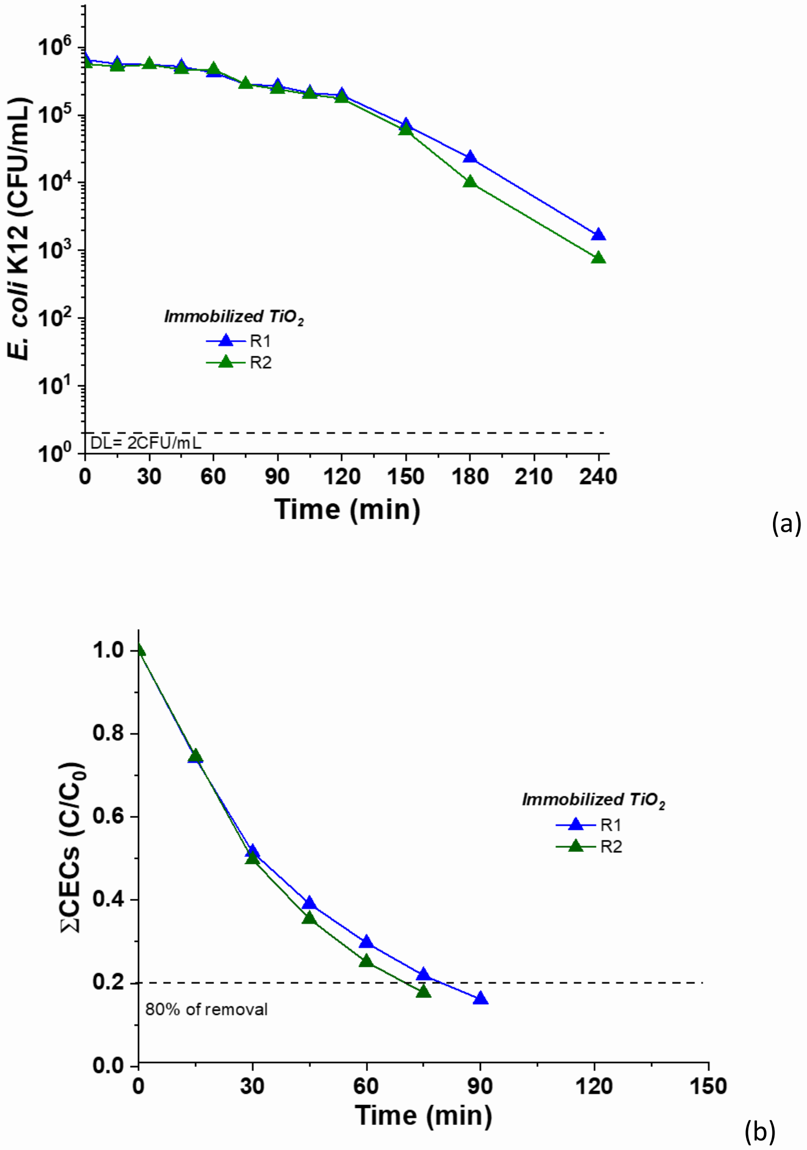


Figure 25: (a) Inactivation profiles of E. coli and (b) removal of ΣCECs in well water under solar radiation with immobilized TiO2 (200 g/L) in the ENERGICA MSCR

(iii) <u>The effect of the immobilized TiO_2 combined with H_2O_2</u>

To increase the treatment capability of the MSCR containing the immobilized TiO_2 onto the surface of the stainless-steel stairs, the addition of H_2O_2 as an oxidant at a very low concentration was assessed. The addition of this oxidant will have a dual effect during the photocatalytic treatment, from one hand a direct effect onto the inactivation kinetics, and on the other hand, as promoter of hydroxyl radicals in the surface of the catalyst, two very well-known processes.

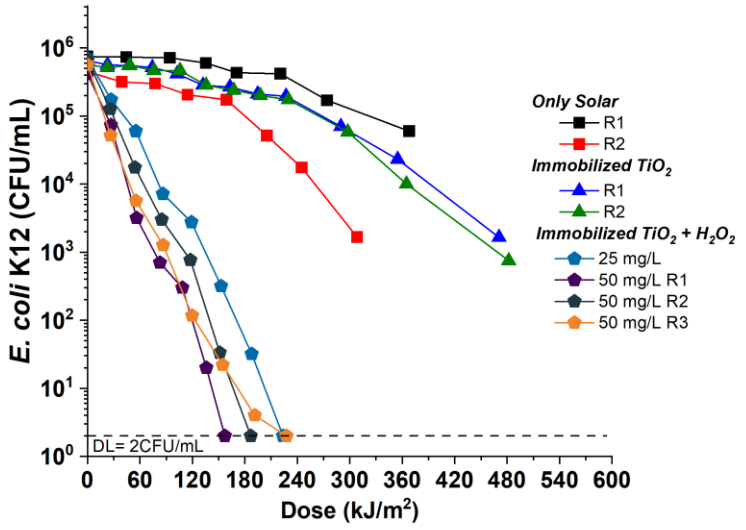
Therefore, two concentrations of H_2O_2 (25 and 50 mg/L) were tested to establish the influence of the oxidant in sun-driven immobilized photocatalysis in the MSCR.

Figure 26 shows that the addition of H_2O_2 at both concentrations (25 and 50 mg/L) allowed the complete inactivation of *E. coli* (6 LRVs). In the case of CECs, it can be implied that the degradation efficiency did not improve in the presence of H_2O_2. CECs removals presented a similar tendency as the one presented in the treatments with immobilized catalysts without oxidant. Removal percentages > 80 % were achieved after 75 and 90 min of treatment (UV-A doses of 136 and 163 kJ/m^2, respectively).

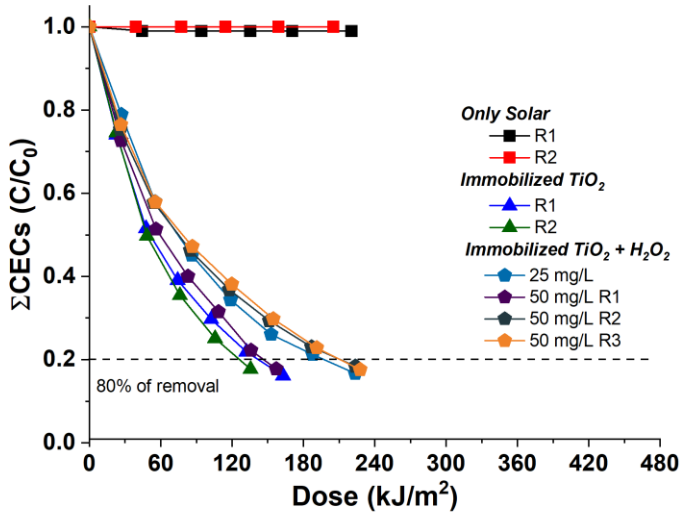
The improved *E. coli* inactivation kinetic in this case is attributed to the synergistic effect of TiO_2, sunlight and H_2O_2. This can be explained since the presence of hydrogen peroxide could improve the sensitivity of *E. coli* to sunlight. Moreover, the oxidative action of H_2O_2 by itself could increase the photolytic effect (Rincón and Pulgarín, 2004). It can also be due to the generation of hydroxyl radicals ($^{\cdot}OH$) by the internal Haber-Weiss reaction, as it is shown in the equation below.

$$O_2^{\cdot -} + H_2O_2 \rightarrow {}^{\cdot}OH + OH^- + O_2$$

Moreover, the addition of H_2O_2 prevented the regrowth of *E. coli* after 24, 48, 72 and 168 hours of treatment.



(a)



(b)

Figure 26: Comparison of the inactivation profiles of E. coli (a) and ΣCECs removal under solar irradiation in well water with immobilized TiO2 (200 g/L) combined with H2O2 in the ENERGICA MSCR.

Two initial concentrations of H_2O_2 (25 and 50 mg/L) were tested, and the influence of the subsequent additions of the oxidant was also evaluated to assess its effect on the treatment. The criterion considered for H_2O_2 addition was reaching a concentration lower than 90 % of the initial one. Four assays were carried out adding the oxidant. In the experiment performed with 25 mg/L of H_2O_2 on 13th February 2024, the oxidant was added four times with a total dose of (100 mg/L), as depicted in Figure 27(a). The other three experiments were conducted with an initial concentration of 50 mg/L of H_2O_2. The first assay, performed on 8th February 2024, in which a second amount of H_2O_2 was added after 90 min of treatment; resulting in a total dose of oxidant added of 100 mg/L (Figure 27(b)). The subsequent assay was conducted on 20th February 2024, involving three additions of H_2O_2 (50 mg/L) and the total amount of oxidant was 150 mg/L as shown in Figure 27(c). The last test was carried out on 21st February 2024, in which only one dose of oxidant was added Figure 27(d) with a global dose of 50 mg/L. Results showed that an initial addition of H_2O_2 (50 mg/L) allowed to obtain a similar tendency in the behaviour of *E. coli* as the obtained after several addition of this oxidant. The same tendency was observed in the case of CECs; subsequent additions of the oxidant did not allow higher removals. Therefore, it was concluded that a single initial addition of H_2O_2 could improve the disinfection rate, which could bring a decrease in the associated costs.

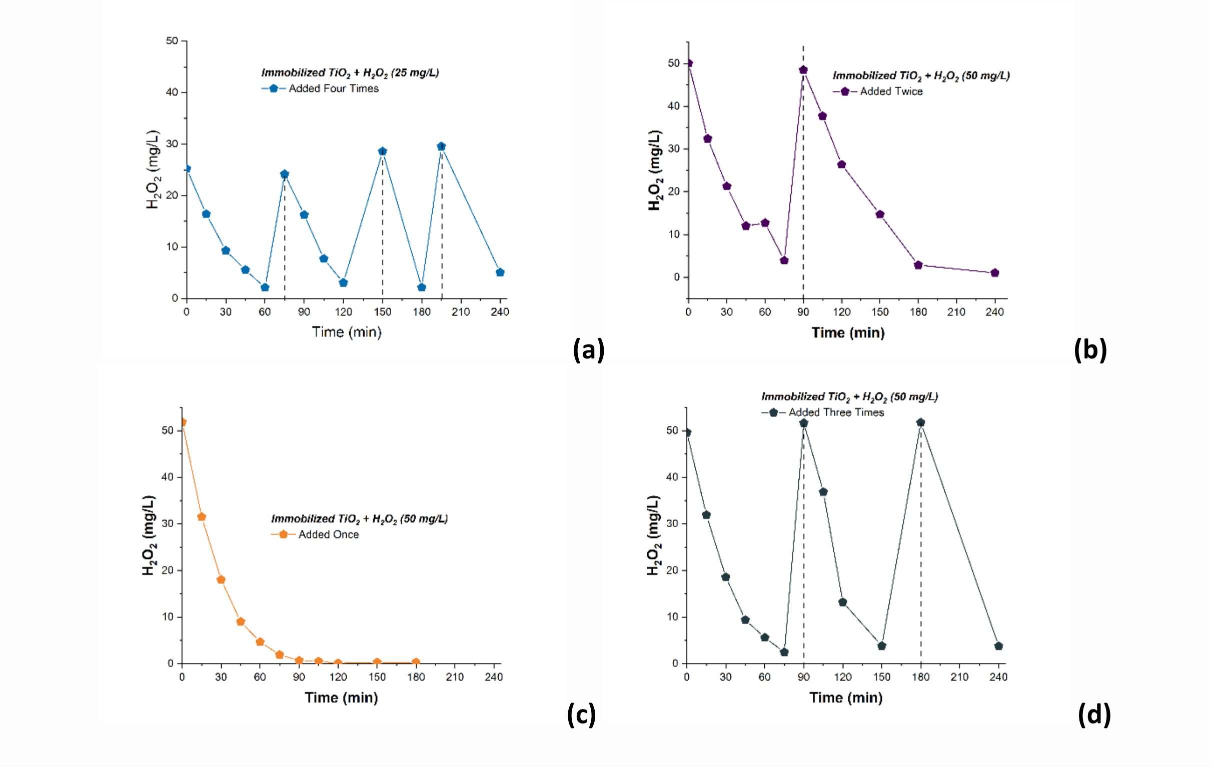


Figure 27: Hydrogen peroxide consumption during the experiments under solar irradiation in well water with immobilized TiO2 (200 g/L) combined with H2O2 in the ENERGICA MSCR.

The behaviour of each CEC during all the experiments performed under solar radiation in well water in ENERGICA MSCR are shown below. It was determined in previous studies that solar only treatment did not allow the removal of CECs; nevertheless, they were monitored during all the assays.

Table X. CECs removal in ENERGICA MSCR under natural sunlight compared to the immobilized TiO_2 and to the combination of the immobilized steps with H_2O_2 at different concentrations and additions.

Treatment	Date	Time (min)	Dose (kJ/m^2)	CECs Removal (%)			
				Imidacloprid	Sulfamethoxazole	Trimethoprim	ΣCECs
Only Solar R1	10/01/2024	60	94	-	-	-	-
		120	171				
		180	274				
		240	368				
Only Solar R2	16/01/2024	60	77	-	-	-	-
		120	159				
		180	245				
		240	308				
Immobilized Catalyst R1	02/02/2024	60	102	57	71	74	67
		120	227	85	94	93	91
		180	355	95	99	98	97
		240	474	97	> 99	> 98	> 97
Immobilized Catalyst R2	07/02/2024	60	106	65	77	75	72
		120	230	89	96	94	93

		180	365	97	> 99	> 98	> 97
		240	482	> 97	> 99	> 98	> 97
Immobilized Catalyst + H_2O_2 (25 mg/L) Added Four Times	13/02/2024	60	119	48	73	67	62
		120	260	75	94	89	86
		180	407	89	99	97	95
		240	540	94	> 99	98	97
Immobilized Catalyst + H_2O_2 (50 mg/L) Added Twice	08/02/2024	60	109	53	71	71	65
		120	206	77	92	92	87
		180	277	87	97	97	94
		240	314	92	98	98	96
Immobilized Catalyst + H_2O_2 (50 mg/L) Added Three Times	20/02/2024	60	118	45	72	64	60
		120	262	72	94	87	84
		180	417	87	99	95	93
		240	565	93	> 99	98	97
Immobilized Catalyst + H_2O_2 (50 mg/L) Added Once	21/02/2024	60	120	43	72	62	62
		120	265	74	96	88	86
		180	421	90	> 99	97	96

5.3. Integration Biodigester-Solar photocatalytic pilot plant

5.3.1. Potential synergies between both systems

After introducing both technologies to the work package team members, a few synergies were identified: Local needs, electricity and water. Local needs in this context explains itself as a need to change the status quo. Food waste is generally going to landfills where it contributes to local pollution of soil and groundwater and eventually emits in the air generating harmful greenhouse gasses. Diverting the food waste, not going to landfill but being utilized in the digester is a great opportunity to improve these conditions. Furthermore, the biodigester's effluent can potentially act as a natural fertilizer, growing crops locally. Both the biodigester and solar purification systems combined can make an impact on local needs and contributes to ENERGICA's main objective to implement renewable energy technologies to match local contexts' needs.

Purification of water is the more obvious need, because water is a vital and basic human need. A potential synergy here is to clean the effluent from a Waste Transformer by using the solar reactor plant. However, this approach doesn't seem feasible because the effluent contains too many solid parts to process it. Secondly, using the effluent as a natural fertilizer makes more sense given the nutrient contents of the fluid. Therefore, the water purification system will be employed to improve well water for potable purposes.

By processing food waste, the Waste Transformer generates electricity which is supplied to local consumers as an alternative or -in most cases- to reduce dependency from the local grit. In most cases, the location where it is placed is the same location where the food waste originates. In some cases, a distributed waste collection approach is chosen if for example ample space is available at a site with electricity needs. In both cases, electricity will be generated.

5.3.2. Pilot plant setup

The biodigester and the solar photocatalytic pilot plant will be integrated with the aim to exploit a portion of the electricity generated by providing the required electricity to the solar plant. The electricity is used for running its electrical devices like the water pump, PLC and radiometer.

Figure 28: The combined setup of the pilot plant

5.3.2. Integration

According to the results shown in section 5.2.3 (Performance of the solar photocatalytic reactor) and obtained under controlled conditions in CIEMAT-PSA facilities, it can be estimated that a batch of 50L of surface contaminated water can be treated (with safety margins) in two hours of full sunshine. Based on the actual electricity consumption by the equipment's of the reactor, a total of 43 Wh e/batch (50 L) is needed and should be supplied by the biodigester.

The solar reactor has a need for electricity as described above, which can be supplied by the Waste Transformer by using a standard 220V plug from the reactor and socket from next to the entrance of the technical container. The amount of electricity generated is sufficient (as stipulated in 5.1.2.1. General Description of a Waste Transformer).

Figure 29: Assembly of photos showing the connection of the integrated pilot plant

6. CONCLUSIONS

6.1. General conclusions

Deliverable 5.5 reports the development, construction and testing of the final design of the biodigester unit and the solar photocatalytic pilot plant (solar MSCR) developed in WP5, as well as the integration of both systems with the aim of reusing the electricity generated by the biodigester as an electricity supplier for the MSCR (running). Both systems will be implemented in Freetown (Sierra Leone), where the correct functioning, potential limitations and drawbacks will be analysed till the end of the ENERGICA project.

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