iWAYS
innovative water recovery solutions

Water-Waste-Energy Nexus model

Circularity modelling and assessment

[31/05/2023]

Authors:
BUL

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Technical References

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Project Coordinator	Prof. Luca Montorsi – University of Modena and Reggio Emilia
Scientific and Technical Director	Prof. Hussam Jouhara – Brunel University London
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[1] PU = Public
PP = Restricted to other programme participants (including the Commission Services)
RE = Restricted to a group specified by the consortium (including the Commission Services)
CO = Confidential, only for members of the consortium (including the Commission Services)

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V0.6	19/05/2023	TTI	Gorka Bilbatua
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Summary

Summary of Deliverable

Deliverable D3.9 describes the methodology employed and results of Water-Waste-Energy (WWE) Nexus modelling exercise. The approach considers a stepwise analysis where the baseline scenario is identified and characterised for each use-case, then incrementally iWAYS technologies are considered in the model and its relative impact translated into indicators.

This approach includes the development of a unified cross-sectorial circularity modelling approach in order to evaluate circular economy potentials of the industrial value chains, as well presenting information to engage potential different industrial actors and stakeholders on circularity and sustainability. The circularity analysis also indicates the distance that the three use-cases are from closing resource loops under the current context.

This is a public version of the deliverable, suited for public consultation.

The main conclusions based on the assessment methodology applied for each use-case are are below. General comments for all use-cases regarding the economic benefits shows that the results from the assessment indicate that the integration of iWAYs solutions (i.e. iWAYS HPCE, iWAYS water treatment plant and rainwater harvesting process) can bring significant financial savings.

ATLAS CONCORDE

The integration of the HPCE increases renewable energy contribution by 405 times by using wasted emissions. However, no significant increase in water circularity is observed due to the potential low amount of water recovered. This scenario changes when rainwater is potentially harvested, further increasing water circularity. Moreover, the assessment of the scenario with rainwater harvesting shows that it has the potential to cover freshwater demand of the industry.

ALUFLUOR

The integration of the HPCE potentially increased renewable energy utilisation through the utilisation of emissions, however it does not reflect on the increase of water circularity of the system as the recovered condensate does not contribute to an increase in recovered water volume, as the water treatment process will treat the effluent of onsite water treatment plant. The rainwater harvesting exercise did not reveal potential significant increase on water circularity.

TUBACEX

As the integration of the HPCE is at an experimental scale due to its novel design, it did not promote significant increases regarding the 3 nexuses (Water-Waste-Energy), as it will only

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recover energy and not condensate. Water circularity is increased by treating one of the water lines which produces sludge in the industry, reducing produced waste. However, if rainwater is harvested, it can potentially of cover industrial freshwater demand.

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Table of contents

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N°958274

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N°958274

Table of tables

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N°958274

Table of figures

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Acronyms

ALU AB	Alufluor
BaF_2	Barium Fluoride
CaF_2	Calcium Fluoride
CE	Circular Economy
CEF	Circular Economy Framework
CON	Atlas Concorde
CWF	Circular Water Flow
CWI	Circular Water Input
CWO	Circular Water Output
D waste	Dangerous waste
DX.Y	Deliverable X.Y – X: Work Package; Y: Task.
EUI	Emission Utilisation Index
F	Fluoride
GA	Grant Agreement
HF	Hydrogen Fluoride
HPCE	Heat Pipe Condenser Economiser
H_2SiF_6	Hexafluorosilicic acid
iWAYS	Innovative Water recoverY Solutions
LE	Linear Economy
MFA	Mass Flow Analysis
ND waste	Non-Dangerous waste
NF	Nanofiltration
NG	Natural Gas
NRE	Non-renewable Energy
OWC	Onsite Water Circularity
PW	Processed Waste
RE	Renewable-energy
REC	Renewable Energy Contribution
RFW	Reducing Freshwater Withdrawal
RNGD	Reducing Natural Gas Dependency
$ROCO_2F$	Reducing Overall CO_2 Footprint
RRCR	Reusing and Recycling Condensate and Rainwater
TTI	Tubacex Tubos Inoxidables
UF	Ultrafiltration
UW	Unprocessed Waste
URW	Upcycling the Recovered Water
WP	Work Package
WUI	Waste Utilisation Index
WWE	Water-Waste-Energy
WWR	Water Withdrawal Reduction
WWTP	Wastewater Treatment Plant

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1 Introduction

1.1 Motivation and objectives

1.1.1 Deliverable

The goal of Deliverable 3.8 (D3.8) of the iWAYS WP3 is to provide a confidential report on the Water-Waste-Energy Nexus modelling exercise for each of the three Use-cases. This corresponds to Task 3.5 – *Water-Waste-Energy Nexus model*, scheduled between M4 – M30 of the project calendar, and reporting in M30. The task was led by Brunel University London (BUL). To create the context of this task, listed below is WP3's other tasks (five (5) in total):

Task 3.1: Design of sustainable water sourcing as replacement for industrial water;
Task 3.2: Integration of the monitoring solutions;
Task 3.3: Data security, clarity and reliability;
Task 3.4: Sustainable water source assessment framework;
Task 3.5: Water-waste-energy nexus.

According to the Grant Agreement and the objectives of WP3, the goal of WP3 is to utilize the outputs of WP2 and deliver efficient designs of sustainable water sourcing as replacement for industrial water, focusing on:

- Design and implement monitoring and control modus operandi, hardware and the associated software tools, for integrated sustainable water source systems;
- Create a safe, secure and reliable knowledge and data engineering platform to guarantee accurate and representative performance measures of the loops – demonstrated in the form of software application that communicates the key performance indicators of the system;
- Build the prescriptive models for the optimisation of the loops' performances e.g. operational cost, quality, energy efficiency, and sustainability; subject to technical and environmental constraints – demonstrated by operations research inspired decision support models;
- **Develop the Circular Economy models to demonstrate the circularity and economic merits of the solutions within the water-waste-energy nexus – demonstrated in the form of an interactive software application, serious game, where users will be able to instigate events and visualise the circularity and economic impact on the nexus.**

The highlighted bullet point indicates the expected outcome of task 3.5. In order to proceed with the completion of the highlighted bullet point, the section related with the demonstration through an interactive software application will be reported in D3.6 (confidential) and D3.7 (public): T3.4 – Sustainable water source assessment framework. The justification for the slight change in reporting is that the timing of delivering the interactive software application does not align with the inputs from the other tasks, as the water-waste-energy nexus model (T3.5), the cloud data management system (T3.1) and the digital models (T3.3, T3.4) will serve as a basis for the development, and all the formers finish in M36 of the project (November 2023). Therefore, this would be the only change required – reporting of the serious game in the deliverables of T3.4 (D3.6 and D3.7 – due in November this year (M36)) instead of in T3.5 (D3.8 and D3.9 – both due by the end of this month).

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1.1.2 Report objectives

The current deliverable is to report the Water-Waste-Energy (WWE) Nexus modelling approach and circularity and economic indicators. Inputs from partners, D2.2, D4.1 and D4.2 were useful to perform the modelling procedure. A unified cross-sectorial circularity modelling approach was developed, applied and tested to the three Use-Cases part of the iWAYS project. The results decree the level of circularity and economical gains and trade-offs identified from the exercise, therefore scoring how close the gaps are to closing the loops on water, energy and waste circularity (e.g. decarbonisation – energy).

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1.2 Structure of the report

Following the objectives, the deliverable is divided into two main sections, methodology and results & discussion (per case-study). The sections are divided into subsections per use-case, in line with the deliverable's objectives:

- Methodology
    - System development;
    - Indicators selection;
    - Circularity measurement;
    - System testing;
    - Circularity assessment.
- Results & discussion
    - System development;
    - Indicators selection;
    - Circularity measurement;
    - System testing;
    - Circularity assessment:
        - Benchmark assessment;
        - Dynamic assessment (when possible).

1.3 Overall description and general concepts

The following three (3) sections describe the three (3) Use-Cases and the general idea behind the water recovery from the steam sources.

The Innovative WAter recoverY Solutions (iWAYS) through recycling of heat, materials and water across multiple sectors is a take on optimising, circularising and increasing overall sustainability for the industrial sector. The approach is to be applied to three distinct industrial sectors with the aim of demonstrating the feasibility and flexibility of the bespoke implementations for vapour / condensate recovery, increased water circularity and thermal energy recovery in the targeted industries. Overall, the iWAYS project is bridging the gaps to closing the loops on water and energy circularity.

To design, develop and implement the Water-Waste-Energy (WWE) Nexus in the context of the iWAYS project, several datasets regarding operations at the three use-cases was supplied by the partners. The datasets included information on fresh and non-fresh water sourcing and use, energy sourcing and use, and overall waste production. This information was acquired to build the models for the baseline or benchmark scenario. Additional information such as the current operations of onsite wastewater treatment plants (WWTP) was also supplied by the use-case partners. The underlining working intricacies of the Heat Pipe Condenser Economiser (HPCE) were supplied by respective partners in charge of its development and by consulting D2.1 in order to approximately simulate its operation (heat and condensate recovery) – real data not available because the HPCE will only be installed in the use-cases from M36 (November 2023). Operational information and modelling of the iWAYS solutions for treating condensate and water was retrieved from D4.2, and also by consulting with partners that developed the technologies. D4.1 was consulted for steam condensate characteristics, while D2.2 was consulted for the rainwater harvesting exercise, as well as to perform a dynamic assessment of the potential water loops.

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1.3.1 Demo case 1 – Ceramics: Atlas Concorde (Ceramiche KEOPE Facility)

The KEOPE facility (Gruppo Atlas Concorde – CON) industrial partner is located in Casalgrande, in the Reggio Emilia region in northern Italy, bordering municipalities such as Castellarano, Modena and Sassuolo. According to the Köppen-Geiger for climate classification, the facility's location is classified as Cfa – humid subtropical climate or mild temperate - frequent thunderstorms.

The facility is a full cycle ceramic company, meaning that it includes the spray drying process for tile manufacturing, therefore promoting the production of a multitude of different ceramic products such as wall and floor ceramics. The ceramic process begins with selecting the raw materials (mainly clays, feldspars, sands, and kaolins) and then mixing them. After this step, continuous milling with the addition of water occurs, therefore resulting in a ceramic suspension, or ceramic slip. Part of the water contained in the slip is removed by exposing it to the spray dryer process, resulting in a product with a moisture content between 5 - 7% to be used in the next process. The resulting vapour / gas from the spray drying process, is lost to the atmosphere through the chimney stack.

The Atlas Concorde Cermiche Keope (CON) facilities uses two different types of water in the product manufacturing steps:

- Fresh (e.g. wells) or good quality water (e.g. treated water) is used (D2.2) primarily for the glazing process;
- Treated water from the onsite water treatment plant (onsite WWTP) and freshwater (and other water sources) are also sourced for the grinding process (ceramic milling), and the type of water used depends on the quality of the required slip – D2.2.

Overall, the CON facilities do not discharge their generated wastewater to the public sewage line, instead each waste stream is collected into a sludge recovery basin and used in the milling process (e.g. for darker slips). The water recovered from the milling process is sent to an onsite WWTP to remove pollutants and suspended solids, and reused in the milling process, reducing freshwater consumption when possible. In some cases, treated water quality from the existing WWTP (physical-chemical treatment) is adequate to be reused also in the glazing section, but this is rare.

Condensate is recovered by the iWAYS solution, i.e. the Heat Pipe Condenser Economiser (HPCE) and treated in order to be reused in the glazing process. The iWAYS solution will enable the recovery of a substantial amount of the water discharged by the spray dryer as exhaust gases along with the generated sensible and latent heat. It will be installed downstream the spray dryer, after the baghouse filter (D2.1). The resulting condensate (D2.2 – characteristics) will be treated by the iWAYS wastewater treatment plant (WWTP) solution.

The objective of installing the iWAYS solutions is to reduce freshwater sourcing in the system which generally originates from the wells and industrial aqueduct. However, due to the low recovery rate of condensate by the HPCE (500 l/h), and to reach the targeted values defined by the iWAYS project, a solution was proposed by introducing the treated water from the onsite plant with the recovered condensate from the HPCE to the iWAYS WWTP solution. This will allow compliance with what was defined in the Grant Agreement and resulted in an operational output of 10,000 t/y. However, this was not modelled as described above in scope of the WWE nexus, as the objective of this exercise is to account for recovered wasted water, and not to achieve the volumes stipulated in the GA.

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1.3.2 Demo case 2 - Chemical – Alufluor

The Alufluor AB (ALU) industrial facility is located in Helsingborg, in the Scania province in southern Sweden. According to the Köppen-Geiger for climate classification, the facility's location is classified as Cfb – oceanic climate – cloudy conditions with precipitation.

ALU is a major actor on a global scale regarding Aluminium Fluoride (AlF_3) production. Generally, AlF_3 is employed as a flux in the primary aluminium production process, as it lowers energy consumptions and consequently reduces overall production costs. However, the production of AlF_3 generates anhydrous hydrofluoric acid / hydrogen fluoride (HF) emissions, which apart from toxic, fluoride (F) precipitates quickly as calcium fluoride (CaF_2) or Barium Fluoride (BaF_2) in the sea.

The exhaust gases contain gaseous fluorine (HF) from producing AlF_3 and is treated by a gas purification scrubber unit to wash and condense the exhaust with clean water in a continuous fashion. A mixture of water and condensed exhaust gases flows from the scrubber unit to the onsite water treatment plant for purification. Precipitation with lime is added to the acidic water to recover calcium fluoride which is then sold to the construction industry. The treated effluent is discharged into the sea. Even though the scrubber unit is present, exhaust emissions in the form of gaseous fluorine compounds, as well as water vapour are lost through the stack chimney to the environment.

Water is used in the following processes at the ALU facility:

- Production of aluminium fluoride;
- Pure and clean water from the tap is heated to 65° C to wash the centrifuges and reactors;
- Pure and clean water from the tap is used in the scrubber to wash and condense the exhaust gases from process, resulting in an acidic effluent stream.

All water after use is flowed to the onsite water purification plant.

In general, the water treatment scheme of the iWAYS project was evaluated in detail and reported in D2.1 and D2.2, the configuration of ALU facilities, as well as the characteristics of the water to be treated (D2.2) and the specific requirements for the possible re-use requested by ALU itself were considered (D4.2).

Two HPCE are going to be installed upstream and downstream the gas purification scrubber unit that cleans the generated process exhaust. The HPCE's will recover condensate and sensible and latent heat. More information is available in D2.2.

Due to the characteristics of the condensate and in particular the impossibility to recover the condensate directly from the Heat Pipe Condenser Economiser (HPCE), a decision was taken to treat the recovered condensate from both HPCE firstly in the existing water purification treatment plant. Following the onsite water purification plant, the iWAYS water treatment plant will treat a portion of the water stream that is currently discharged into the sea. The effluent treated by the iWAYS WWTP will consequently present a water quality that complies with the standards required by ALU for (re)use in its processes, therefore reducing the quantity of water discharged to the sea, saving on freshwater sourcing (i.e. tap water), and also recovering wasted heat to be used in heating processes. In fact, the amount of recoverable water is expected to 60,000 t/y, nearly double the target described in the GA (33,000 t/y).

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1.3.3 Demo case 3- Steel – Tubacex

The Tubacex Tubos Inoxidables (TTI) industrial park is located in Amurrio, in the Álava province, Basque Country, northern Spain. According to the Köppen-Geiger for climate classification, the industrial park's location is classified as Cfb: oceanic climate – cloudy conditions with precipitation.

TTI is part of the Tubacex Group and a world leader in the production of seamless stainless-steel tubes and high-nickel alloys, as well as both hot and cold finishing of the tubes. Additionally, the manufacturing of tubes for oil and gas (oil country tubular goods – OCTG) extraction and production in critical conditions (offshore deep waters) also takes place at the facility, as well as tubes for heat exchangers, condensers, boilers, refinery piping and equipment, and high-performance tubes that can withstand high and low temperatures, pressures and corrosion.

The TTI chain of industrial processes operates with three independent water circuits (D4.2). Water circuit 1 is connected to industrial processes consisting of (i) pilgering, (ii) degreasing and (iii) rinsing of steel tubes; it has an onsite wastewater treatment system (decantation and LAMIK systems), but still generates on average 50m^3 of wastewater per week. Water circuit 2 is connected to the heat treatment process and does not generate wastewater. Water circuit 3: industrial processes consisting of (i) pickling, (ii) rinsing and (iii) washing of steel tubes. This water circuit 3 already has its own water treatment system implemented allowing to close the loop in terms of water reuse in this circuit and does not generate wastewater.

Regarding the HPCE, and as explained in D2.2, a screening experimental campaign was performed to identify the best location to install an experimental HPCE. Three potential locations where identified: stack from the kiln HH1, stack from the kiln HH2 and a gap between the heating and cooling zone in the kiln HH3. As the recovery rate of condensate is very low for the current use-case in all identified locations, it will not be considered in the current assessment, only sensible and latent heat recovery was evaluated.

The requirement of the industrial partner and within the scope of the iWAYS project is to close the loop (D4.2) of water circuit 1, hence the iWAYS water treatment solution will target this circuit. Here, the production of wastewater (up to 50m^3 / week) is relatively small compared to the other use case sites. However, the wastewater characteristics present:

- Quality posing challenges for standard treatment processes (receiving the mineral greases and solvent from water circuit 1);
- High environmental footprint of its current operations, characterised by high energetic costs and GHG emissions for treatment (the wastewater is transported by a third party for incineration), and;
- High economical value (80 euros / m^3 of transported sludge).

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1.4 Objective of the document

The objective of this document is to provide a comprehensive report on the Water-Waste-Energy (WWE) nexus for each of the Use-Cases in terms of baseline scenario (current practice) and incremental addition of the different iWAYS solution scenarios in each use case (i.e., iWAYS HPCE, iWAYS WWTP, and iWAYS rainwater harvesting). It covers the methodology developed (a unified cross-sectorial circularity modelling approach through a WWE nexus lens), models used for each use case, indicator selection, indicator testing, considerations, dynamic simulations, and assessment of the results (to close resources loops). The assessment results demonstrate the gains and trade-offs of each of the different iWAYS solutions which are measured in terms of circularity, carbon footprint and economic indicators (engagement and information to different industrial actors and other stakeholders about the sustainability challenges). The indicators inform on the progression of each Use Case towards circular economy from a high-level observation point, highlighting sections where there is still ground for improvement.

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2 Methodology

2.1 Circular economy framework

Numerous attempts have been made to define Circular Economy (CE) and contextualise it for given eras. To understand circular economy, there is need to understand what it proposes to substitute in current practices, i.e., “Linear Economy” (LE), which essentially has driven the world economy during much of the XX century, and still strong in the XXI century. LE consists in employing raw virgin materials to make a product, which after it has served its purpose during the use phase, becomes a waste and is subsequently disposed of. This brings about several factors and concerns (Morganti and Coltelli, 2021):

- Generation of waste;
- Exposure to economic risks;
- Availability of resources;
- Degradation of the natural capital and;
- The evolution of regulations.

The above list indicates increasing challenges for the LE model for the current context in which it operates, signalling that deep changes are required on an operational level regarding XXI century economies. By contextualising the above, the CE model aims to dissociate economic growth regarding the consumption of limited resources, therefore leading to a less vulnerable economic system in regard to crises (Morganti and Coltelli, 2021). In a CE, by contrast, waste production is reduced or eliminated (Ellen MacArthur Foundation), therefore promoting a model that focus also on production and consumption, however following the guidelines that involves sharing, leasing, reusing, repairing, refurbishing and recycling existing materials and products as long as conceivable – extending the life cycle of products[1].

To accomplish the above, the Ellen MacArthur Foundation has established three principles which are widely accepted and driven by design:

- Eliminate waste and pollution;
- Circulate products and materials (at their highest value);
- Regenerate nature.

Therefore, to measure the transition of from a LE to a CE in the iWAYS project, a circular economy framework (CEF) was employed that covers and considers the three CE principles proposed by the Ellen MacArthur Foundation. This way, the assessment results would demonstrate the progression of a system towards a CE model from its current state. The CE assessment method would require tuning and adaptation to the Water-Waste-Energy (WWE) Nexus context, therefore resulting in a higher-level assessment of the system.

In this context, the method developed and adapted to measure the circularity level introduced by integrating the iWAYS solutions in each industrial Use Case was formulated from the circularity framework presented by Nika et al., 2022 which followed the new (still draft) ISO 59020 on circularity measurement and assessment (Figure 1). The framework proposal and approach are an effort to provide a standardised methodology for assessing systems through a circular economy lens. It encompasses five steps:

- System development;
- Indicator selection;
- Circularity measurement;
- System testing and;

1 https://ec-europa-eu.libguides.com/circular_economy/intro

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- Circularity assessment.

The framework adapted from Nika et al., (2022) encourages a CE assessment practice of complex systems like industrial sectors, by considering the interdependencies of resources under the WWE nexus umbrella.

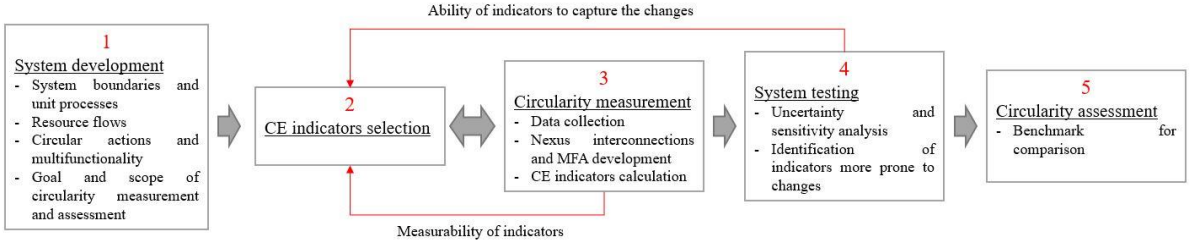

Figure 1 - WWE nexus intersection with Circular Economy framework (Adapted: Nika et al., 2022).

Each step of the methodology is described in the following subsections.

2.1.1 System development

The ***system development*** step (Figure 1) is the first step of the proposed methodology and essentially defines the system under evaluation, by describing the targeted situations addressed by the system, defining system boundaries and unit processes, corresponding resources flows (i.e. renewable and non-renewable) with the goal of comparing the incremental inclusion of the iWAYS solutions in the scope of the WWE nexus. After these initial points, circular actions and multifunctionality (if present) are identified. Circular actions indicate what actions regarding the scenarios are achieved through the implementation of solutions to enable the transition to a CE model by considering the three principles of CE. By identifying the circular actions of the system, these allow to identify what resource flows need to be measured and assessed, therefore allowing to select targeted circularity indicators that can translate those flows into meaningful information – i.e. second step of the developed framework.

2.1.2 CE indicators selection

For this step, ***indicator selection*** (Figure 1) considering the WWE nexus umbrella and CE principles is performed. Additional economic indicators are considered to translate the value added into monetary units for stakeholders. The indicators must consider the identified circular actions and circular economy principles, and the system specificities (e.g. boundaries, unit processes, resource flows). As one of the objectives is to measure the economic and environmental merits of integrating the iWAYs solution and consequent circular actions, economic and environmental indicators were considered to aid in monitoring and tracking iWAYs solutions performance. Each nexus is defined by the goal of the indicators and their relating purpose. Finally, the coverage (relating to the identified circular actions) of the chosen indicators is also identified.

2.1.3 Circularity measurement

Following the identification of indicators in the previous step, the ***circularity measurement*** step (Figure 1) is conducted and includes:

- Primary data acquisition – the data required to measure the resource flows identified;

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- Model development for the system: baseline and iWAYS scenarios, as well as the generation of secondary data and finally;
- CE indicator calculation and other indicator calculations.

In setting the scope during the 1st step for circularity measurement and assessment, specific primary data needs are identified and collected from partners, as well as the development of the required models – models that mimic the underlining of certain processes in the system, including those considered for the iWAYS solutions, and integrating the main and complementary assessment methods and tools. As the units are already at an industrial scale, upscaling techniques were not considered in this step.

The purpose of this step is to enable indicator measurement, and to act in case of a lack of data that hinders the calculation of the selected indicators, which include but are not limited to:

- Investigation of alternative acquisition approaches (e.g. modelling procedures);
- Alternative ways to measure the indicators;
- Proxy values;
- Assumptions, or as a last resort the;
- Selection of alternative indicators that are similar and can be measured with the available data (step 2 – Figure 1).

2.1.4 System testing

In the ***system testing*** step, an uncertainty and sensitivity analysis are conducted. For this step, different scenarios (e.g. maximum, minimum and average operational input and output) are selected, assessed and validated. The purpose of this step is to investigate the effectiveness (stiffness vs elasticity) of the selected indicators in capturing changes in the system – occurred from the implementation of circular actions – and consequently, to identify the main operational variables that affect the system's performance. If the indicators are not able to capture system changes, alternative indicators need to be selected (back to step 2 – Figure 1).

2.1.5 Circularity assessment

The last methodological step of the framework (Figure 1) consists in the ***circularity assessment*** step. This step presents the results of the assessment and consequent interpretation of the indicator regarding both the baseline scenario and iWAYS scenarios (i.e. benchmarking the assessment) but it can further incorporate the indicator results of the selected scenarios of the previous step (i.e. dynamic assessment) to investigate potential improvements or deteriorations of circularity performance, or even circularity risks that would require mitigation measures.

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3 Results and Discussion

3.1 Ceramics – Atlas Concorde (Ceramiche KEOPE Facility)

3.1.1 Process description

As mentioned in section 1.3.1, the slip (mixture of water and clay), is dried in the Spray Dryer. The resulting powder is processed and proceeds to the next step in the industrial line and the resulting water vapour from drying the slip is lost to the environment through the chimney stack. This is where the iWAYS solution for condensate recovery comes into play, by employing a Heat Pipe Condenser Economiser (HPCE) – WP2 – to condense the vapour and consequently recover it. The condensate will be treated by the iWAYS wastewater treatment plant (WWTP) – WP4 – and storing the high quality, recovered and treated, condensate to be used in a multitude of different processes (including glazing and other processes requiring a high-quality source of water), therefore potentially reducing freshwater consumption by potentially 50% (GA).

3.1.2 Circular Economy (CE) framework

3.1.2.1 System development

In the CON Use-Case, three scenarios were considered: a baseline scenario, and scenarios A and B. The goal of the assessment consists in comparing the baseline scenario with the other two proposed scenarios. The scope of the assessment considers the Water-Waste-Energy (WWE) Nexus of the industrial system, which encapsulates the amount of onsite water available from different sources, the onsite wastewater treatment process, industrial milling step and spray dryer (i.e., Industrial - Figure 2). The inputs to the system, as enclosed by the boundary, are the source of water, source of energy, i.e. Renewable Energy (RE) and Non-Renewable Energy (NRE). Outputs considered are emissions to the environment in the form of exhaust gas (vapour), and corresponding products (however the latter is not presented or characterised).

3.1.2.1.1 Baseline scenario

Figure 2 presents a high-level overview of the current baseline of operations, where a boundary circles the processes (Industrial and onsite WWTP) with inputs regarding the water cycle, energy sources, and outputs regarding exhausted gas emissions and products (the latter is not accounted for in the assessment). The external water sources are dirty and fresh water, where dirty water originates from internal cycling and from other industries (transported to the facility via trucks). As virtually no water is discharged from the industry (internal recycling), it was considered that there is a zero-liquid discharge (ZLD) practice already in place. Detailed information on the characteristics of the water sources and emissions can be consulted in D2.2 and D4.1.

Dirty water can essentially be used in two processes: directly in the milling process to produce the slip with a medium-to-lower quality, or it can be fed directly to the onsite wastewater treatment plant (WWTP). Wastewater or dirty water resulting from the onsite processes (e.g. during milling) can also be directly fed to the onsite WWTP. When the onsite WWTP is fed with dirty or process wastewater, it produces two sources of water: purified water and sludge water,

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which are then used by the industrial processes (e.g. milling). Fresh water is obtained directly from an industrial aqueduct or from boreholes located in the vicinity.

Energy consumed by the industry is obtained from four (4) different sources of renewable energy (RE) and non-renewable energy (NRE) (Figure 2). NRE is obtained from three (3) of the four (4) sources:

- Cogeneration plant burns natural gas to produce electricity for the industry and also power the cogeneration unit;
- Electricity sourced from the grid;
- Natural gas used for heating (e.g. spray dryer).

RE is obtained from photovoltaic panels located onsite.

In the Industry's production department, there is a sector with a spray dryer that uses water and heat gas in its process, and essentially blasts the slip with the heat mixture of gas and water to evaporate the water present in the slip (i.e. from mixing in the milling phase) and consequently emits an exhaust gas that is ejected to the environment through the chimney stack. The exhaust gas is a mixture of various elements, including water vapour – its composition can be found in D4.1.

Regarding waste and emissions, as the focus is primarily on the water and energy cycles, solid waste produced by the industry was not modelled.

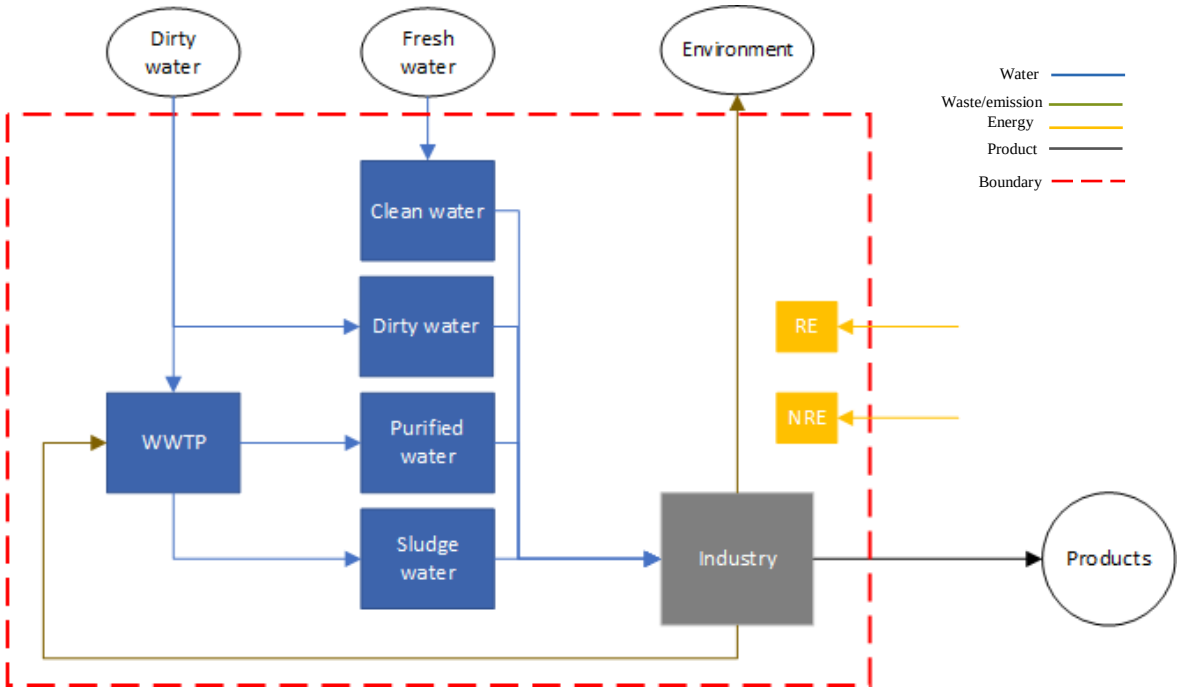

Figure 2 - Baseline: Water cycle of the CON industry, and types of water sources and flows; Renewable and non-renewable energy sources and flows of CON; CON's wastewater and exhausted gas emissions flows. RE: Renewable Energy; NRE: Non-renewable Energy.

3.1.2.1.2 Scenario A – Condensate and energy recovery

Scenario A considers the integration of the proposed iWAYS solution, consisting of the Heat Pipe Condenser Economiser (HPCE) and the water treatment system (Figure 3) – within the defined boundary. The objective of the iWAYS solution integration is to increase the internal circularity level of the industry (i.e., increase water and energy recovery). Scenario A builds

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upon the baseline (see description in section 3.1.2.1.1), and considers the integration of the HPCE just after the baghouse filter in order to promote heat transfer for thermal energy recovery and to condense the exhausted vapour gas.

The HPCE achieves vapour condensation through temperature differences, i.e. the HPCE is essentially divided into two sections, one where the vapour passes through in a series of channels and progressively cools down. A coolant liquid (insulated) flows through the HPCE to cool down the vapour as it flows through the different channels while never in direct contact with the exhaust vapour gas. This thermal exchange between the exhaust vapour gas with the coolant liquid captures thermal energy by heating up the coolant liquid which can then be reused to heat boilers or other purposes that require heating (e.g. pre heat the water for the spray dryer). The recovered condensate after treatment can be reused in the industry, for milling or glazing activities.

The iWAYS condensate / water treatment system which essentially treats the recovered condensate from the HPCE is composed of an Ultrafiltration (UF) unit and a Nanofiltration (NF) unit in series (D4.2), with the resulting treated water stored in the clean water storage tank, and the concentrate in the sludge water storage tank.

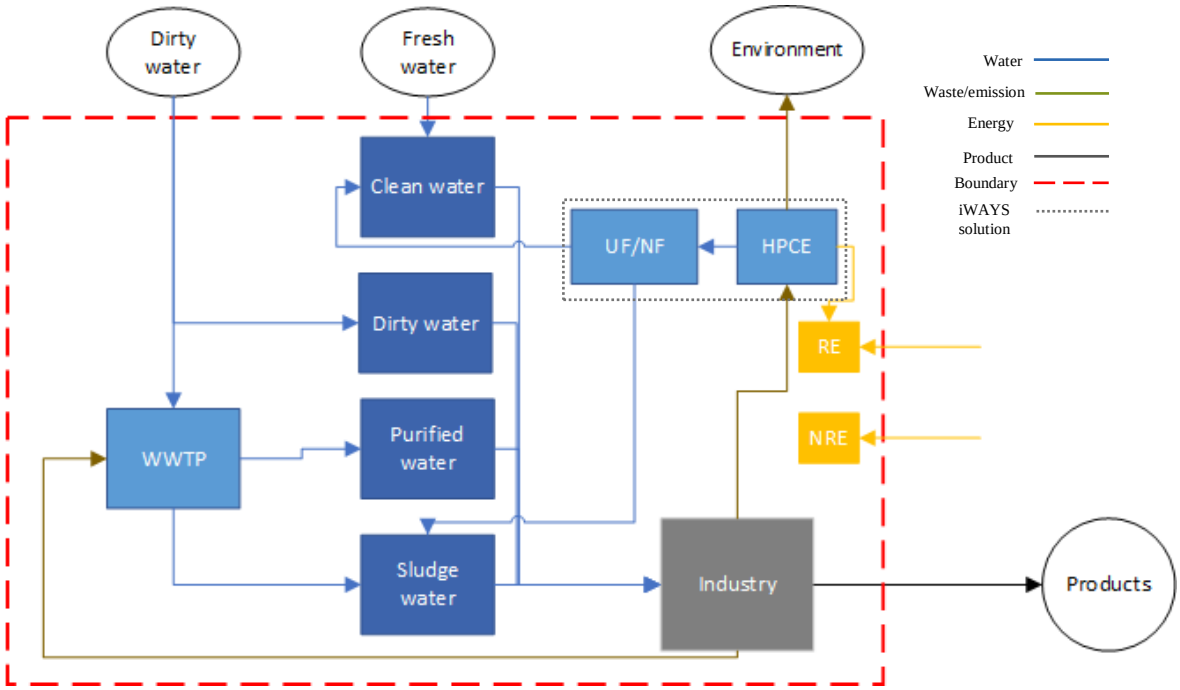

Figure 3 – Scenario A: Water cycle of CON, and types of water sources and flows with the HPCE and water treatment system; Renewable and non-renewable energy sources and flows of CON; CON's wastewater and exhausted gas emissions flows. RE: Renewable Energy; NRE: Non-renewable Energy; HPCE: Heat Pipe Heat Economiser; NF: Nanofiltration; UF: Ultrafiltration.

3.1.2.1.3 Scenario B – Scenario A + Rainwater harvesting

The third scenario (scenario B – Figure 4) builds on scenario A and expands it to include rainwater rooftop harvesting which is treated by the iWAYS water system and then stored as clean water, with concentrate stored in the sludge tank. Annual precipitation in the industrial area and the roof-top area were considered in order to estimate the potential volumes of harvested rainwater (for further details consult D4.1) – including the first flush practise.

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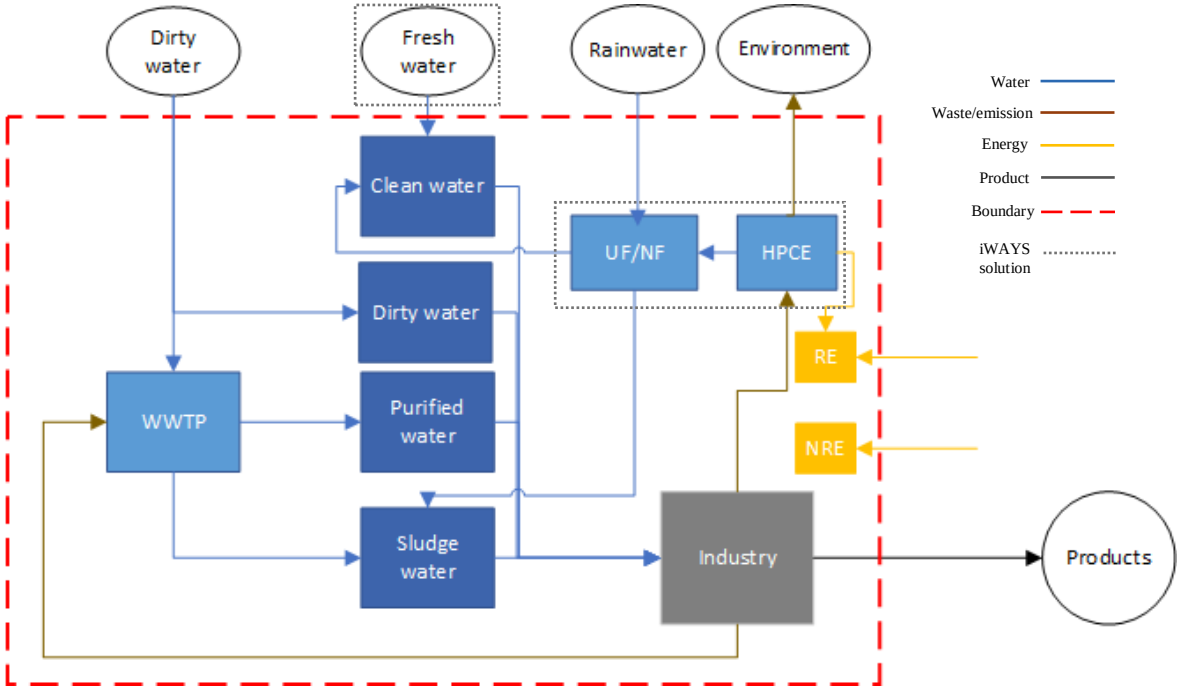

Figure 4 - Scenario B: Water cycle of the CON, and types of water sources and flows with the HPCE, water treatment system and rainwater harvesting integration; Renewable and non-renewable energy sources and flows of CON; CON's wastewater and exhausted gas emissions flows; RE: Renewable Energy; NRE: Non-renewable Energy; HPCE: Heat Pipe Heat Economiser; NF: Nanofiltration; UF: Ultrafiltration.

3.1.2.1.4 Identification of the circular actions

The incremental integration of the iWAYS solutions intends to address the following identified circular actions:

- Reducing the withdrawal of freshwater sourced from the industrial aqueduct and wells, by recovering condensate and rainwater from the exhaust gases and rooftop run-off, respectively;
- Upcycling the recovered water by treating it in the iWAYS water treatment system;
- Reusing and recycling condensate and rainwater from the exhaust gases and rooftop run-off, respectively;
- Reducing natural gas consumption (dependency) for heating boilers by recycling the wasted heat captured by the HPCE from the exhausted vapour gas;
- Reducing the overall CO_2 footprint from natural gas consumption.

Therefore, the methodology coined by Nika et al. (2022) was adapted to measure the circularity level of relating to 5 circular actions identified in the industrial Use Case within the WWE nexus framework, for the industry before (scenario - baseline) and after (scenario – A and B) the integration of the iWAYS solutions.

Additionally, complementary economic indicators to measure the potential economic value gained in each scenario, in line with the identified circular actions, were considered in the assessment:

- Reducing overall costs associated with water withdrawal, energy and CO_2.

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3.1.2.2 Indicators selection

Table 1 presents the Indicator selection process method, consisting in utilising the information gathered during the *System Development* step. This identifies the category (Nexus) of the indicators, the purpose of the category, the overall goal of the category, and finally the indicators selected to represent each category. Complementary columns indicate the coverage (i.e. circular action) of the indicators: Reducing Freshwater Withdrawal (*RFW*), Reducing Natural Gas Dependency (*RNGD*), Upcycling the Recovered Water (*URW*), Reusing and Recycling Condensate and Rainwater (*RRCR*), and Reducing Overall CO_2 Footprint (*ROCO₂F*). Indicators were proposed and selected from a collection of indicators as the most appropriate for the identified circular actions (coverage).

Table 1 – Indicator selection process CON: CE – Water, energy and waste CE indicators; and economic indicators.

Nexus	Purpose	Goal	Indicator(s)	Coverage (Circular actions)				
				RFW	RNGD	URW	RRCR	ROCO₂F
Water nexus	Close the loops / reduce environmental impact	Water circularity	Circular Water Inflow (CWI); Circular Water Outflow (CWO); Circular Water Flow (CWF); Onsite Water Circularity (OWC); Water Withdrawal Reduction (WWR).	X		X	X	
Energy nexus	Close the loops / reduce environmental impact / reduce non-renewable energy requirements	Energy circularity / sustainability	Renewable Energy Contribution (REC).		X			X
Waste nexus	Close the loops / reduce environmental impact	Waste circularity	Emission Utilisation Index (EUI).	X		X		
Economic coverage	Added value	Value gained with circular actions	Fuel Cost Saving; Total CO_2 Cost Saving; Water Cost Saving; Total Saved Cost.	X	X	X	X	X

RFW: Reducing Freshwater Withdrawal; RNGD: Reducing Natural Gas Dependency; URW: Upcycling the Recovered Water; RRCR: Reusing and Recycling Condensate and Rainwater; and ROCO₂F: Reducing Overall CO_2 Footprint.

In the **Water nexus**, the purpose of the assessment as identified in the *system development* step is to measure the Reduction of Freshwater Withdrawal, Upcycling the Recovered Water and, Reusing and Recycling Condensate and Rainwater. Five (5) indicators were identified and selected to cover three (3) of the identified circular action:

- *Circularity Water Inflow* (*CWI*), *Circular Water Outflow* (*CWO*) and *Circular Water Flow* (*CWF*) inform on the changes that occurred to the water resource flows, as they indicate the level of fresh water demand (i.e. *CWI*) and the water resource availability for all users and the environment (i.e. *CWO*) (WBCSD, 2022). The three indicators

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further impact the *Water Withdrawal Reduction* (*WWR*) (Nika, et al., 2022) as the *CWI* considers the volume intake of non-circular water withdrawal which in this case is consumed freshwater;

- The *WWR* indicates exactly how much fresh water withdrawal is reduced;
- The *Onsite Water Circularity* (*OWC*) indicator was selected to measure the level of water recycled and reused onsite by estimating the number of times the industry uses, on average, a drop of water before leaving the facility as outflow (WBCSD, 2022).

The **Energy nexus** relates to heat recovered by the HPCE, by reducing wasted energy and CO_2, and increasing energy circularity. One (1) indicator was identified and selected for this nexus to cover two (2) of the identified circular action:

- Renewable Energy Contribution (REC), indicates how much the integration of the HPCE improves the transition to renewable energy as a CE requirement (WBCSD, 2022).

In regard to the **Waste nexus**, focus was targeted exclusively to water vapour (i.e. exhausted vapour gas) loss through the stack chimney, therefore neglecting solid waste for the assessment (although data is available, but no impact occurs to the solid waste). Waste in this context is thus classified as the water vapour lost in the process, which results in one (1) indicator that has a coverage of two (2) circular actions:

- Emission Utilisation Index (EUI), indicates the amount of water recovered as condensate from the exhaust gas by the HPCE.

The economic indicators cover all (5) circular actions, as shown in Table 1. The economic benefit of transiting to more sustainable renewable energy is calculated in terms of:

- Fuel Cost Savings and;
- CO_2 savings.

The economic benefit for transiting closer to water circularity is measured by:

- Water Cost Saving indicator.

The total saved cost aggregates all circular actions. The equations of the selected indicators can be found in the Annex.

3.1.2.3 Circularity measurement

3.1.2.3.1 Material Flow Analysis and Data collection – Water, Waste and Energy

After identifying the circular actions and selecting indicators, the resource flows through a Material Flow Analysis (MFA) were identified. Since the CE assessment is performed within the WWE nexus framework, data regarding the industry's monthly and annual operations for water use, waste (solid) production and energy consumption supplied by the Use Case partners, as well as details relating to the nexus (e.g. source of energy, source of water, etc) were provided by partners. The data spanned operations between 2018 and 2021. The year 2020 was excluded from the analysis due to the COVID-19 pandemic, as operations during this year did not reflect normal industrial operations.

WATER

The Water nexus consists in measuring linear and circular water flows of the system.

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Monthly and annual freshwater consumption was supplied by the partners, while dirty water and sludge water consumption was lumped summed in annual consumption. Table 2 presents monthly average, minimum and maximum values of freshwater consumption, and Table 3 presents annual average, maximum and minimum freshwater consumption.

Table 2 - Monthly Freshwater Consumption CON (2018, 2019, 2021).

Monthly Freshwater Consumption (m^3 / month): 2018, 2019 & 2021			
Month	Average	Maximum	Minimum
January	6 212	6 787	5 229
February	8 201	8 371	7 901
March	9 177	9 559	8 688
April	7 094	7 712	6 373
May	8 778	9 770	7 928
June	10 092	10 513	9 373
July	9 607	10 626	8 771
August	2 582	3 928	1 590
September	10 370	10 870	9 904
October	9 741	10 289	9 453
November	8 644	9 264	8 041
December	5 569	8 106	3 369
Monthly	**8 006**	**10 870**	**1 590**

Table 3 - Annual Freshwater Consumption CON (2018, 2019, 2021).

Annual Freshwater Consumption (m^3 / year)			
Years	Average	Maximum	Minimum
2018, 2019 & 2021	**96 066**	**98 958**	**93 356**

In terms of Dirty and Sludge water internal use, annual consumption is shown in Table 4.

Table 4 - Annual Dirty and Sludge Water Consumption CON (2018, 2019, 2021).

Annual Dirty and Sludge Water Consumption (m^3 / year)			
Years	Average	Maximum	Minimum
2018, 2019 & 2021	**45 905**	**61 127**	**28 586**

For the WWE nexus modelling exercise, and to ensure operation is current, only datasets from 2021 were considered. The above information is to contextualise operations in 2021 with past operational trends. Water consumption for 2021 is shown in Table 5 and Table 6, on a monthly and annual basis, respectively.

Table 5 - Monthly Freshwater Consumption CON (2021).

Monthly Freshwater Consumption (m^3 / month): Year 2021				
Month	Value	Average	Median	Standard Deviation
January	6 620	**8 247**	**8 699**	**2 288**
February	7 901			
March	9 559			
April	7 712			
May	9 770			
June	10 513			
July	8 771			
August	1 590			
September	10 337			
October	9 453			
November	8 626			
December	8 106			

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It is worth noting that Table 5's average and median values are within the same order of magnitude as the values in Table 2, therefore year 2021 can be considered as a good representation of the last previous years of operation (excluding 2020).

Table 6 - Annual Fresh and, Dirty and Sludge Water Consumption CON (2021).

Annual Fresh and, Dirty and Sludge Water Consumption (m^3 / year): Year 2021		
Source	Value	Total Water Consumption
Freshwater	98 958	**127 544**
Dirty and Sludge Water	28 586	

Freshwater consumption is higher in Table 6 compared to the average yearly value in Table 3. However, it falls within the 95% of observations under a normal distribution considering 2 x standard deviation from the average. The same conclusion can be obtained for the Dirty and Sludge water, therefore also representative of normal operations. It must be noted that Dirty and Sludge water use have decreased in use over the years (data not shown) at the industrial case.

The onsite WWTP at the industrial use-case treats dirty water to produce purified water and as a by-product, sludge water. Efficiency for this process was supplied by partners and is considered to have a recovery rate of 40% for purified water and the remaining 60% for sludge production. In terms of total water use at the CON use case facility, this is divided up as freshwater (78%), purified water (9%) and sludge water (13%) (Figure 5), leading to the conclusion that over 3/4 of total water sourced by the facility is from a non-renewable source (freshwater).

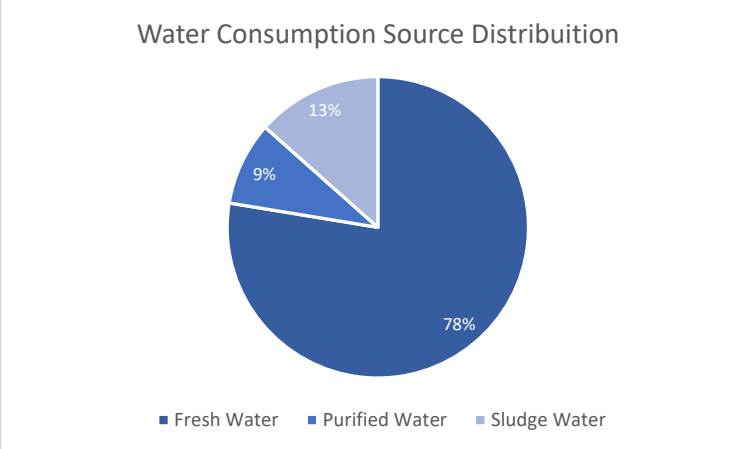

Figure 5 - Water Consumption Source Distribution CON (2021).

ENERGY / ELECTRICITY

As with the Water nexus, the energy nexus consists in measuring linear and circular energy flows of the system.

Monthly and annual energy / electricity consumption from 2018 to 2021 was supplied by the partners. Energy in the industrial use-case is sourced from four (4) sources, three (3) Non-Renewable (NRE) sources and one (1) Renewable (RE) source. The NRE sources include electricity from the grid, electricity generated by the burning of Natural Gas (NG) by the onsite Cogeneration system (the cogeneration consumes NG to run) and the amount of gas required to burn to produce thermal energy. Energy not used by the industry is returned back to the grid. Table 7 presents monthly average, median, minimum and maximum values regarding

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energy / electricity consumption, and Table 8 the annual average, median, maximum and minimum energy / electricity consumption.

Table 7 – Total Monthly Energy / Electricity Consumption CON (2018, 2019, 2021).

Total Monthly Energy / Electricity Consumption (MWh / month): 2018, 2019 & 2021			
Month	Average	Maximum	Minimum
January	19 784	21 669	16 998
February	24 416	24 633	24 212
March	25 953	26 839	25 353
April	21 644	23 092	19 669
May	25 549	26 853	24 079
June	24 952	25 066	24 799
July	23 664	24 753	23 034
August	6 124	11 130	1 743
September	25 368	26 196	24 397
October	26 120	28 489	23 078
November	25 406	27 499	24 328
December	15 753	23 983	8 336
Monthly	**22 061**	**28 489**	**1 743**

Table 8 - Total Annual Energy / Electricity Consumption CON (2018, 2019, 2021).

Total Annual Energy / Electricity Consumption (MWh / year): 2018, 2019 & 2021			
Years	Average	Maximum	Minimum
2018, 2019 & 2021	**264 733**	**279 034**	**249 380**

As with water consumption, energy / electricity consumption regarding the WWE nexus modelling exercise considered only datasets from 2021 to ensure that the data is current. The above information (Table 7 and Table 8) is to contextualise operations in 2021 with past operational trends.

Table 9 shows the monthly consumption of energy / electricity, as well as the average, median and standard deviation of total energy / electricity consumption for 2021 on a monthly basis. The overall annual consumption is also presented.

Table 9 – Monthly and Monthly Average, Median and Standard Deviation Energy and Electricity Consumption; Annual Energy and Electricity Consumption CON (2021).

Total Monthly Energy / Electricity Consumption (MWh / month): Year 2021				
Month	Value	Average	Median	Standard Deviation
January	21 669	**23 253**	**24 734**	**6 772**
February	24 401			
March	26 839			
April	23 092			
May	26 853			
June	25 066			
July	23 204			
August	1 743			
September	26 196			
October	28 489			
November	27 499			
December	23 983			
Total (MWh / year)	**279 034**			

It is worth noting that the average and median values in Table 9 are within the same order of magnitude as the values in Table 7, therefore year 2021 can be considered as a good representation of the last previous years of operation (excluding 2020). Energy / electricity consumption is higher in Table 9 compared to the average yearly value in Table 7. Performing the same analysis as for freshwater consumption, it is possible to observe that it falls within the 95% of observations under a normal distribution considering 2 x standard deviations from

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the average value. Therefore, the year 2021 is representative of normal operations (same as for monthly average value).

The source of the energy / electricity consumed in the industry in terms of percentage is shown in Figure 6. It is possible to observe that an overwhelming amount of energy is consumed through burning of Natural Gas (~89%) and the Cogeneration unit (~8%), resulting in up to ~97% of total energy and electricity requirements of the industry sourced exclusively from NG. Around ~3% of electricity is sourced from the grid, therefore totalling up all NRE use for the industrial use case. RE from photovoltaic panels (PV) makes up an insignificant amount of total electricity use (~0.05%). Unused electricity is sold back to the grid and in 2021 this corresponded to around ~0.2% of total energy requirements.

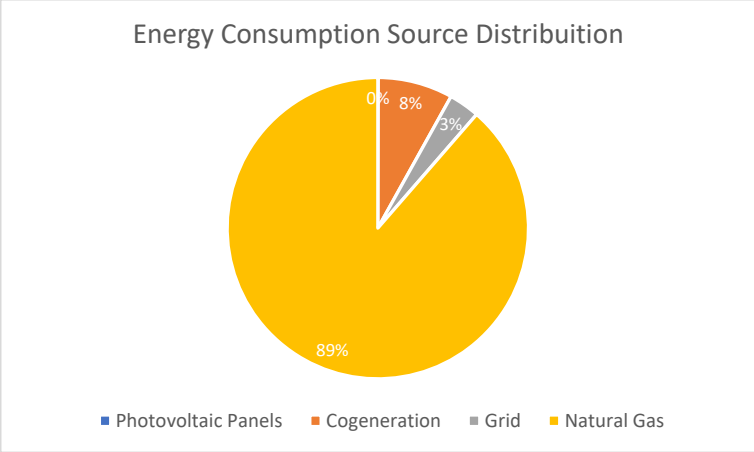

Figure 6 – Energy / Electricity Consumption Source Distribution CON (2021).

WASTE

As with the previous two nexuses, the waste nexus consists in also measuring linear and circular waste flows of the system. However, as it is expected that the volume of solid waste will not change with the iWAYS interventions, this was not accounted for in the assessment step, although it is reported here. For the current context, waste was considered as exhaust vapour gas emitted by the spray dryer, and thus accounted for in the assessment.

The annual solid waste production from 2018 to 2021 was supplied by the partners (Table 10). Solid waste is divided into Unprocessed Waste (UW) and Processed Waste (PW), where UW is further divided into dangerous (D) and non-dangerous (ND) waste. Processed waste is a mixture of sludges and other non-specified wastes.

Table 10 - Total Annual Solid Waste Production CON (2018, 2019, 2021).

Total Annual Solid Waste Production (ton / year): 2018, 2019 & 2021				
Source	Type	Average	Maximum	Minimum
UW	D	49	53	47
	ND	4 383	4 739	4 033
	Total	4 432	4 792	4 079
PW	Total	13 948	14 817	12 298
Total Solid Waste		**18 380**	**19 609**	**16 723**

*UW – Unprocessed Waste; PW – Processed Waste; D – Dangerous; ND – Non-Dangerous.

As with Water Consumption and energy / electricity consumption, solid waste regarding the WWE nexus modelling exercise considered only datasets from 2021 to ensure that the data is current. The above information (Table 10) is to contextualise operations in 2021 with past operational trends. Table 11 shows the annual solid waste production for 2021.

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Table 11 - Total Annual Solid Waste Production CON (2021).

Total Annual Solid Waste Production (ton / year): 2021		
Source	Type	Value
UW	D	53
	ND	4 739
	Total	4 792
PW	Total	14 817
Total Solid Waste		**19 609**

*UW – Unprocessed Waste; PW – Processed Waste; D – Dangerous; ND – Non-Dangerous.

The majority of produced solid waste in the industry originates from PW, accounting for ~76% of total solid waste. UW (D and ND) totals up to just over 24% of total produced solid waste – Figure 7.

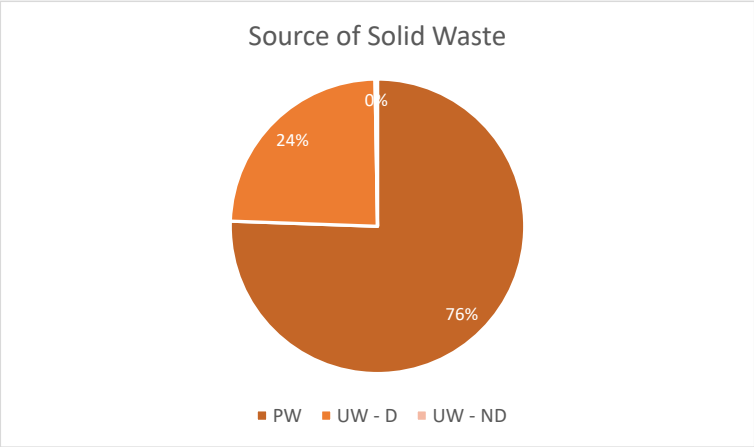

Figure 7 – Source of Solid Waste CON (2021).

The volume of theoretical emissions from the spray dryer in the form of exhaust vapour gas was determined from onsite measurements performed by ITC-AICE partners performed in 2021 (D2.2). The measurements (D2.2), calculations and assumptions for modelling the exhaust vapour gas that flowed through the stack chimney and into the environment are shown in Table 12. The pollutant load in the exhaust vapour gas is shown in Table 13 – calculated based on the concentrations measured in the condensate and reported in D4.1. It considers the amount of water in the vapour and respective concentration from sampling condensate.

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Table 12 - Spray dryer operational characteristics and exhaust gas and vapour calculation CON (2021).

Parameter	Value	Unit	Comment
Vapour (dry + wet)	64 124	Nm^3 / h	D2.2
% wet in vapour	21.1	%	D2.2
Total water content in vapour	13 594	Nm^3 / h	Calculated
Dry air in vapour	50 530	Nm^3 / h	Calculated
Total flow rate of wet vapour (at T)	9 717	m^3 / h	Calculated
Total flow rate of water weight (at T)	7 812	Kg / h	Calculated
Total flow rate of water (at T)	7.8	m^3 / h	Calculated
Operational Time	5 188	h	Calculated
Total operation days	216	days	Calculated
Total water volume produced (out chimney stack)	40 528	m^3 / year	Calculated
Dry gas density	1 294	Kg / m^3	Assumed
Temperature of exhaust	109	^oC	D2.2
Water vapour density	804	Kg / m^3	Assumed
% of total water requirements to milling	33.5	%	CON
% of water left in product (dry powder)	5	%	CON
Water input from milling	42 661	m^3 / y	Calculated

Observing Table 12 indicates that the CON facility potentially emits up to 40 528 m^3 / year of water vapour from spray drying operations, corresponding to 217 days of operation from a total of 42 661 m^3 / year of water used in the milling operations (around 34% of total water needs). The final powder still contains a small fraction water (around 5%) which is considered in the assessment. The volume of emitted exhaust vapour gas results in an emission load of the parameters monitored in D4.1 as shown in Table 13 – not all parameters were calculated as some were below the detection limit, and therefore insignificant. With the iWAYS HPCE solution, the emitted load to the environment will decrease as water vapour / condensate is recovered.

Table 13 - Exhaust gas and vapour potential load to the environment CON (2021).

Parameter	Value	Unit
BOD	486	kg / y
COD	2 472	kg / y
TSS	1 418	kg / y
NH4+	16	kg / y
NO-2	315	kg / y
NO-3	164	kg / y
TN	208	kg / y
TP	0.75	kg / y
Sulphates	223	kg / y
Bicarbonates	2 432	kg / y
Carbonates	734	kg / y
Anionic surfactants	2.07	kg / y
Cationic surfactants	12	kg / y
Non-ionic surfactants	21	kg / y
Total surfactants	24	kg / y
Animal / vegetable fats and oils	405	kg / y
Chloride	203	kg / y
Fluoride	12	kg / y
Aluminium	1.82	kg / y
Antimony	0.01	kg / y
Arsenic	0.02	kg / y

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Barium	0.70	kg / y
Cadmium	0.01	kg / y
Cobalt	0.01	kg / y
Mercury	0.00	kg / y
Nickel	0.53	kg / y
Lead	0.08	kg / y
Strontium	0.62	kg / y
Copper	0.25	kg / y
Selenium	0.01	kg / y
Titanium	0.10	kg / y
Vanadium	0.01	kg / y
Zinc	10	kg / y
Boron	1.26	kg / y
Calcium	1 093	kg / y
Iron	1.66	kg / y
Magnesium	127	kg / y
Manganese	1.58	kg / y
Potassium	32	kg / y
Silica	490	kg / y
Sodium	72	kg / y
Total Hydrocarbons	6	kg / y

Table 13 specifies potentially which pollutant are emitted in higher quantities to the environment in terms of load, highlighting the highest contribution from COD, TSS and Bicarbonates.

Models

The WWE nexus was modelled according to the data supplied by CON, and consequent mass balance. The spray drier was modelled also according to measurements (D2.2) to calculate the volume of potential water / condensate (Table 12). Energy consumption models were based on the information in D4.2 regarding the iWAYS water treatment plant (designed for CON) and operational time (Table 12), and the iWAYS HPCE thermal and condensate efficiency was modelled according to conversations with the partners in charge of commissioning (BUL). The HPCE was modelled considering that 100% efficiency in terms of operation corresponds to 1.3 MWh / h for energy recovery and 500 l / h for condensate recovery (Figure 8), and this will vary depending on the input temperature of vapour gas to the HPCE which ultimately affects its operational dynamics.

In this step, the selected efficiency levels of the HPCE ranged from 0 through 40, 60, 80 and 100%, with the corresponding condensate recovery efficiency, but limited to a maximum 1.3 MWh (exponential equation in Figure 8 but capped at 1.3 MWh). Even if no thermal energy is recovered, it is still expected that residual condensate recovery will occur (very low).

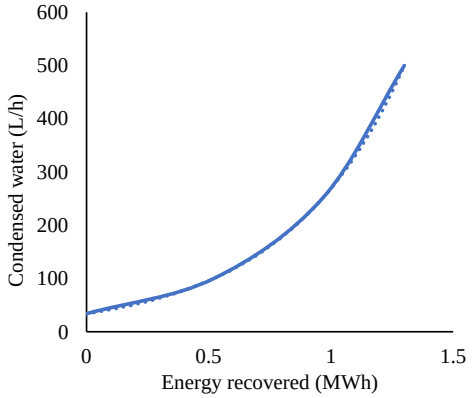

Figure 8 - HPCE efficiency correlation curve (condensed water recovery vs thermal energy recovery) CON.

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Economic coverage

Monetary values were acquired and assumptions were made to calculate the economic indicators for (Table 14).

Table 14 - Price assumptions for economic coverage indicator calculation CON.

Parameter	Value	Unit	Source
Natural Gas	0.0782	€ / kWh	https://www.statista.com/statistics/785605/natural-gas-prices-for-household-consumers-in-italy/
Emissions Allowances	85.22	€ / ton CO_2	https://www.statista.com/statistics/1322214/carbon-prices-european-union-emission-trading-scheme/
Tap / Freshwater	1.05	€ / m^3	https://www.waternewseurope.com/water-prices-compared-in-36-eu-cities/

3.1.2.4 System testing

The system testing describes if the selected indicators are resilient to data and system changes. Due to the fact that scenario B considers the integration of both iWAYS processes, i.e. HPCE, water treatment plant and rainwater harvesting process, it was selected for the reference system to perform the system testing step. This exercise consists in calculating the indicators regarding different energy recovery efficiencies of the HPCE, as this will vary depending on the input temperature of vapour gas to the HPCE and ultimately affect operational dynamics. On the other hand, condensate recovery rate of the HPCE will be affected, varying according to the model (Figure 8). In this step, efficiency levels of the HPCE ranged from 0 through 40, 60, 80 and 100%.

The indicator results of the system testing can be seen in Figure 9 considering the variation in potential energy and condensate (Figure 8) recovery by the HPCE. This crucial step allows to observe the sensitivity of the selected indicators that represent the circular actions. Regarding the water nexus, no significant changes in the indicators were observed due to variation in the HPCE operation, therefore indicating that water recovery through a circular lens for the current technology will not impact significantly the circular actions targeting water, as the main contribution of a renewable source of water is from rainwater. The CWF, OCW and WWR indicators showed that when comparing the maximum capacity of operation, 100% efficiency, with 0% efficiency, there was difference of 2.4%, 1.2% and 9.0%, respectively. On the other hand, regarding the energy and waste nexus, the REC and EUI varied significantly. Comparing with 100% efficiency scenario, the reduction effect on the REC is 19.8% (80%), 39.5% (60%), 59.3% (40%) and 98.8% (0%), and on the EUI is 41.6% (80%), 65.8% (60%), 80.0% (40%) and 93.2% (0%). Regarding the economic indicators (encompass all circular actions), the trajectory of the indicators was expected because the economic indicators related to the energy nexus show a larger decline with decreasing efficiency, corresponding to less savings, and therefore the indicators are consequently more sensitive than indicators related to the water nexus.

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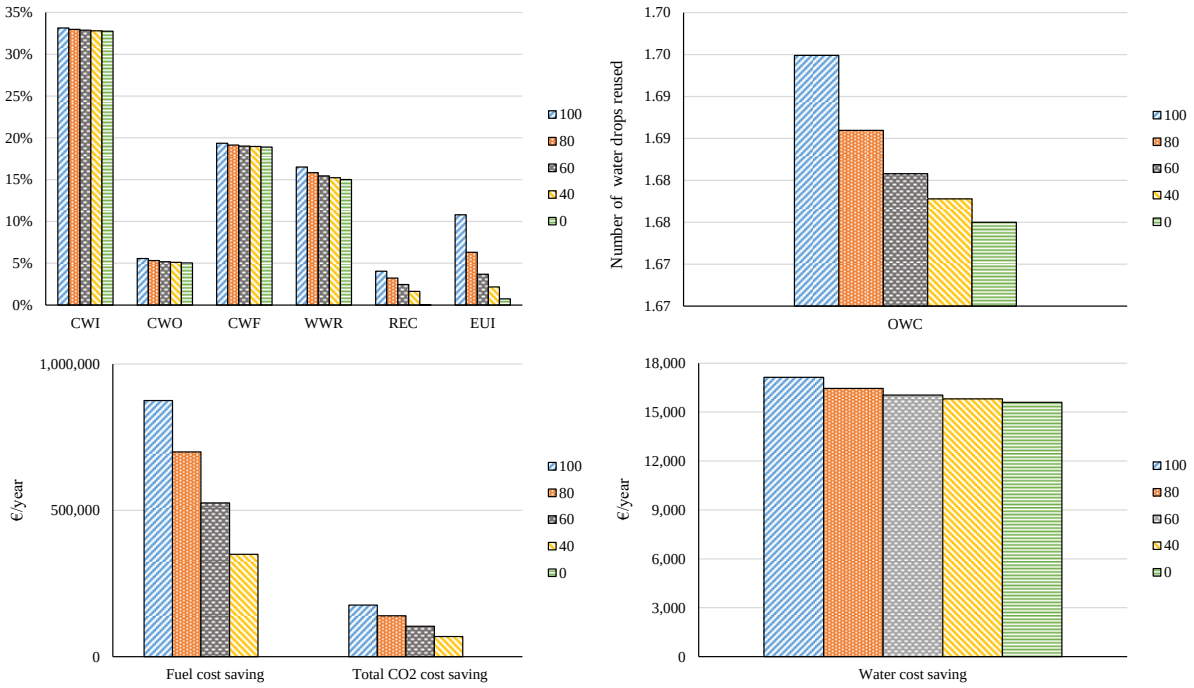

Figure 9 – Results of the system testing by varying the HPCE energy efficiency CON (CWI – Circular Water Inflow; CWO – Circular Water Outflow; CWF – Circular Water Flow; OWC – Onsite Water Circularity; WWR – Water Withdrawal Reduction; REC – Renewable Energy Contributions; EUI – Emissions Utilisation Index). The y-axis of the first image is in % as it indicates the units from indicator calculation.

As demonstrated by the system testing step, it was possible to confirm that the selected indicators were indeed sensitive to operational variations of the HPCE (with focus on the energy side, while water indicators did vary, but not as much due to the volume that is recovered by varying the HPCE's efficiency), therefore confirming the ability for them to be used for the assessment step. Further changes in water indicators would be expected if different precipitation events for rainwater harvesting were considered in the system testing step, and consequently feedback to the water nexus economic indicator. However, for this exercise, rainwater harvesting variation was not considered in the system testing step, only a constant volume of potentially harvested rainwater was considered. Nevertheless, the variation in rainwater harvesting is measured in the circularity assessment step for benchmarking the solutions and for dynamic modelling.

3.1.2.5 Circularity assessment

Two types of circularity assessments are applicable: benchmarking the scenarios against the baseline scenario and proceeding with the assessment (benefits and trade-offs), and performing a dynamic simulation with historical rainfall data and assessing the results. To perform the benchmark assessment, the identified circular actions indicators are assessed and compared with the baseline scenario. Regarding the dynamic assessment, the objective is to understand what changes (if any) occur to the indicators and consequent circular actions concerning potential freshwater consumption, through a circular lens, and its impact on economic performance.

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3.1.2.5.1 Circularity measurement and assessment: Baseline vs scenario A vs B (benchmark assessment)

Table 15 shows the circular economy (CE) and economic indicators scores for the baseline, scenario A and B. Each nexus is discussed in detail below.

Table 15 – Circularity assessment results for the baseline and scenario A and B, CON.

Category	Indicator	Unit	Baseline	Scenario A	Scenario B
Water	CWI	%	0.00	0.00	33.15
	CWO	%	5.00	5.57	5.57
	CWF	%	2.50	2.79	19.36
	OWC	Number of drops	1.29	1.31	1.70
	WWR	%	0.00	1.59	16.50
Energy	REC	%	0.05	4.05	4.04
Waste	EUI	%	0.00	10.81	10.81
Economic	Fuel Cost Saving	€/year	-	875 678	875 678
	Total CO_2 Cost Saving	€/year	-	176 272	176 272
	Water Cost Saving	€/year	-	1 655	17 137
	Total Saved Cost	€/year	-	1 053 606	1 069 088

CWI – Circular Water Inflow; CWO – Circular Water Outflow; CWF – Circular Water Flow; OWC – Onsite Water Circularity; WWR – Water Withdrawal Reduction; REC – Renewable Energy Contributions; EUI – Emissions Utilisation Index.

3.1.2.5.2 Water nexus

Assessing the WWE nexus of the baseline scenario shows that freshwater input for the industry was 98 958 m^3/year, dirty water was 28 586 m^3/year, resulting in a total water consumption of 127 544 m^3/year. Around 34% of the total freshwater requirements are used in the milling operations resulting in potentially 40 528 m^3/year lost to the environment as exhausted vapour (Table 12). Interpreting the *baseline scenario*'s indicators shows that withdrawal of non-renewable water (freshwater) is 100% and that no water is recovered as it is exhausted as vapour gas and discharged (WWR = 0.00%). By assuming that exhausted vapour gas does not return back to its origin (aquifer or dam), and that only some of the water remains in the products and by-products, hence the CWO score of 5.00%, the resulting CWF score therefore indicates that water use for the current system is 2.50% circular. As CWO is an intermediate step to calculate CWF (Annex), it also requires contribution from CWI, which yielded a value of 0.00%. Therefore, CWF's scores exclusively from CWO (Annex). This score was obtained due to the loss of water that occurs through the chimney stack to the environment and discharged from the water treatment to the sea, while the remaining volumes of water end up in the products and by-products (circular water until the boundary of the system). OWC presented a value of 1.29 due to % of the water remaining in the products and by-products.

Scenario A consisted in the integration of the iWAYS HPCE and water treatment plant to the baseline scenario. The maximum recovery rate of condensate by the HPCE is 500 l/h (100% efficiency) corresponding to potentially 2 594 m^3/year of recovered water condensate from potentially 40 528 m^3/year of exhausted vapour gas. The iWAYS water treatment system's total recovery efficiency was calculated as 61% (D4.2), with the remaining 39% flow to the sludge tank. However, this did not yield significant changes to the system in terms of water as demonstrated by the CWF indicator (2.79%) because the CWI indicator scored equal to the baseline scenario (0%), and as internal circular water input to the system is not accounted for in this indicator (CWI), only external sources from the boundary. The small increase in the CWO (5.57%) is due to the HPCE's potential of recovering a maximum of 4 380 m^3/year of water condensate from potentially 40 528 m^3/year of exhausted gas vapour. The WWR indicator increased to 1.59%, suggesting a slight decrease in fresh water withdrawal was

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promoted. This led to a negliable increase in water reuse and recycling as demonstrated by the OWC score of 1.31 over 1.29 (baseline).

Scenario B consisted in extending scenario A with the rainwater harvesting solution. This scenario assumes that rainwater is treated onsite by the iWAYS WWTP before use. By analysing D2.2, it was possible to assume that on average 40 981 m^3/year of rainwater can potentially be harvested from a rooftop area of 63 000 m^2 and combined with condensate recovery, this can reach 45 361 m^3/year. This extension reflected a potential increase in water circularity, with a potential CWF increase of up to 19.36%, which also reflects by the score demonstrated by the WWR indicator of 16.50% over scenario A. The increase in CWF is credited with the increase of the CWI (9.49%) from potential harvested rainwater. The CWF indicator's overall value increases because rainwater harvesting is considered a form of water withdrawal from a circular input (OECD, 2023). Additionally, the OWC increased from 1.31 to 1.70 indicating a moderate increase (~ 30%) on the reused and recycled water by the industry.

3.1.2.5.3 Energy nexus

By introducing the HPCE, thermal energy is captured from wasted heat which can potentially be used to preheat processes in the industrial system (e.g. evaporator). To quantify current (baseline) and potential changes induced by incorporating the HPCE in scenario's A and B, the Renewable Energy Contribution (REC) indicator was selected. The REC indicates the transition of the industry to becoming more sustainable and carbon neutral, i.e., the amount of RE sourced and therefore the transitional progress of the system to a more sustainable and carbon neutral reality. By calculating the REC for the three scenarios, it is possible to conclude for the baseline scenario the indicator scored 0.05%, due to a small contribution of renewable energy from the PV panels. With the integration of the HPCE, the REC increased its value to 4.05% and 4.04% in scenarios A and B, respectively. Rainwater harvesting will not impact the results and the decrease in REC by 0.01% (scenario B) was due to the energy consumption of the water system from the electricity grid to pump the rainwater to the water treatment system. In comparison with the baseline scenario, there is an increase in renewable energy use by 405 times, and indicates a positive step towards decarbonisation.

3.1.2.5.4 Waste nexus

As the assessment does not cover solid waste because the iWAYS solutions will not impact overall production of solid waste, this was not accounted for the modelling exercise of the WWE nexus model. However, as shown in section 3.1.2.3.1, solid waste produced by the facility originates as UW and PW, resulting on average 18 380 tons which will not change due to the incorporation of the iWAYS solutions. Therefore, in the current context, waste was assumed as exhausted vapour gas lost through the chimney stack and the Emission Utilisation Index (EUI) was selected to represent the % of emissions used or recycled that would otherwise be lost, back into the system. For the baseline scenario, the EUI was calculated and represented 0% contribution, as the emissions in the form of exhausted vapour gas are completely lost through the chimney. For both scenario A and B, as rainwater will not affect the volume of recovered condensate or thermal heat, both presented a value of 10.81%. This value indicates that out of total waste in the form of gas vapour, not accounting for solid waste, potentially 10.81% of total emissions are recovered by the HPCE. This also translates in a reduced pollution load to the atmosphere and energy recovery, therefore contributing to closing the loops in terms waste.

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3.1.2.5.5 Economic coverage

Economic indicators were selected to cover the identified circular actions to indicate the value added by the interventions, therefore they indicate what potential annual economic savings are potentially achieved in regard to water and energy resources, as well as emissions (i.e. monetary CO_2 savings for society). Therefore, economic indicators were selected to demonstrate their economic coverage of the identified circular actions (Table 15 – proposed in D6.1 / D6.2). Therefore, several economic indicators were selected to demonstrate their economic coverage of the identified circular actions (Table 1). The circular action of reducing natural gas consumption by integrating the HPCE (scenario A) indicates a fuel cost and CO_2 cost saving of 875 678 € and 176 272 € per year, respectively. The identified reduction of fresh water circular actions, shows that scenario A contributes by saving 1 655 €/year due to the water recovery from exhausted vapour gas compared to the baseline scenario. However, scenario B results demonstrates that an increase in the water cost saving by 9.66% (17 137 €/year), relative to the baseline scenario. Consequently, the circular actions indicate a potential total cost saving due to the iWAYS solutions of 1 053 606 €/year for scenario A and 1 069 088 €/year for scenario B is possible (direct and indirect). The main contribution to the monetary savings is attributed to the decrease in non-renewable energy requirements and consequent decarbonisation, and wasted heat as a source of renewable energy, achievable with a slight increase in value, but significant, as identified by the REC indicator.

3.1.2.5.6 Dynamic assessment – Annual rainwater variation impact

For the water circularity assessment, a potential scenario analysis was performed by considering the historical annual precipitation in Modena region in Italy between the year 2006 and 2021, retrieved from D2.2. Considering a potential harvesting rooftop area of 63 000 m^2 – D2.2 – the potential rainwater harvesting volumes were calculated for the past 15 years (Table 16). The rainwater harvesting potential considers maximum, minimum, average and median rainfall volumes for the industry, therefore demonstrating significant differences in potential. Considering the dynamic modelling exercise for rainwater harvesting, indicators regarding Water Withdrawal Reduction (WWR) and the associated economic coverage indicator for total potential water recovery (condensate and rainwater) were calculated.

Table 16 - Potential rainwater harvesting volume (2006 - 2021) CON.

Month	Average (m^3)	Median (m^3)	Max (m^3)	Min (m^3)
January	2 428	1 978	7 069	126
February	4 296	3 641	9 778	315
March	3 624	3 427	8 921	176
April	3 389	3 352	7 472	25
May	4 052	3 818	12 323	1 058
June	4 229	3 856	11 416	441
July	1 649	1 121	6 023	0
August	2 265	2 180	6 728	0
September	3 607	4 045	8 921	491
October	4 171	4 662	9 387	529
November	5 045	4 927	10 760	1 184
December	2 227	1 531	7 459	0
TOTAL	**40 981**	**38 537**	**106 256**	**4 374**

Figure 10 presents (a) the calculation of the WWR indicator considering the potential average, maximum and minimum rainwater harvested and the relating (b) average, maximum and minimum monetary value of the total water recovered (condensate and rainwater), respectively. The analysis shows that for May and June, a WWR score above 50% is potentially achievable (maximum rainwater harvesting) which represents a potential monetary saving in regard to freshwater of 4 796 € and 4 453 €, respectively. For average values these

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savings are potentially close to 2000 € (potential average savings per month are above a 1000 € throughout the year). On the other hand, Figure 10 also shows that, the months with potentially lower minimum harvested rainwater (WWR = 1.59%) are July, August and December, which can be considered the drier months for the region and therefore result in insignificant water savings (~138 €) due to no precipitation and only condensate recovery (Table 16).

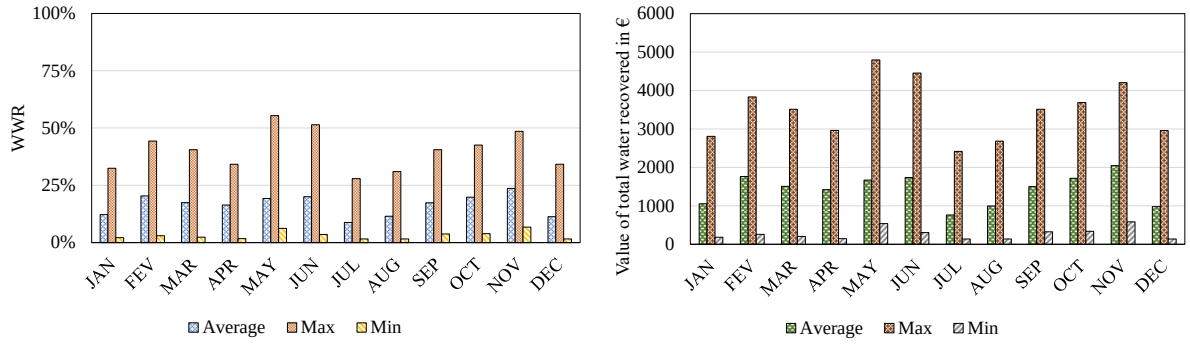

Figure 10 – (a) Average, maximum and minimum for the WWR indicator and (b) the monetary value of the recovered water (condensed and rainwater) monthly, CON.

Another option to increase the WWR indicator value and consequent water saving would consist in not feeding the harvested rainwater to the iWAYS water treatment system. The UF and NF units recovery efficiencies are 72% and 50% (D4.2), respectively, therefore lowering the WWR value because the generated concentrate does not serve as a substitute for freshwater. However, the concentrate can still be used in milling operations. The decision to feed the harvested rainwater to the iWAYS water treatment plant is mainly to remove algae that may grow in the harvesting storage tanks, however the rainwater composition was analysed and it has a good quality compared with the freshwater (D4.1). Therefore, 2 scenarios were studied:

i) Only the UF unit was considered for water treatment and;
ii) No unit from the iWAYS water treatment plant was considered for water treatment, resulting in direct use of the harvested rainwater in the system (Figure 11).

Under the scenario i), the average annual WWR indicator more than doubled (average = 36%) when compared to scenario B (Table 15 and Figure 11a) and the analysis potentially demonstrates that a score greater than 50% for all the months regarding the WWR indicator is achievable when maximum precipitation events occur (for average precipitation events, this value is 36%). Moreover, from historical data, it is possible to see that there is a potential for the maximum recorded rainfall during the months of May and June covering all fresh water demand by the recovered water – negative values – therefore promoting water storing or potential selling (industrial symbiosis).

Considering scenario ii), harvested rainwater is directly used in the industrial processes, the WWR indicator increased to an average annual value of 43% (covering of water needs), and consequently the potential of fully covering freshwater requirements with recovered water is extended to months February, March, September, October and November (Figure 11b), while also including May and June – maximum harvested volumes of rainwater.

Economically, scenario i) and ii) could lead to average savings of 34 869 € and 44 685 € regarding water consumption per year, respectively (Figure 11c and d). The water recovered that exceeds the industries water demand, could be stored for further use, maintaining and potentially increasing prospective industrial water circularity. An option of selling water to another industry in the vicinity could be a scenario (industrial symbiosis), however further research would be required to increase the systems boundaries and additional information for

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the assessment is required, such as considering supplementary circular actions and economic performance indicators (e.g. how water is returned to the environment after being used by another industry and related costs).

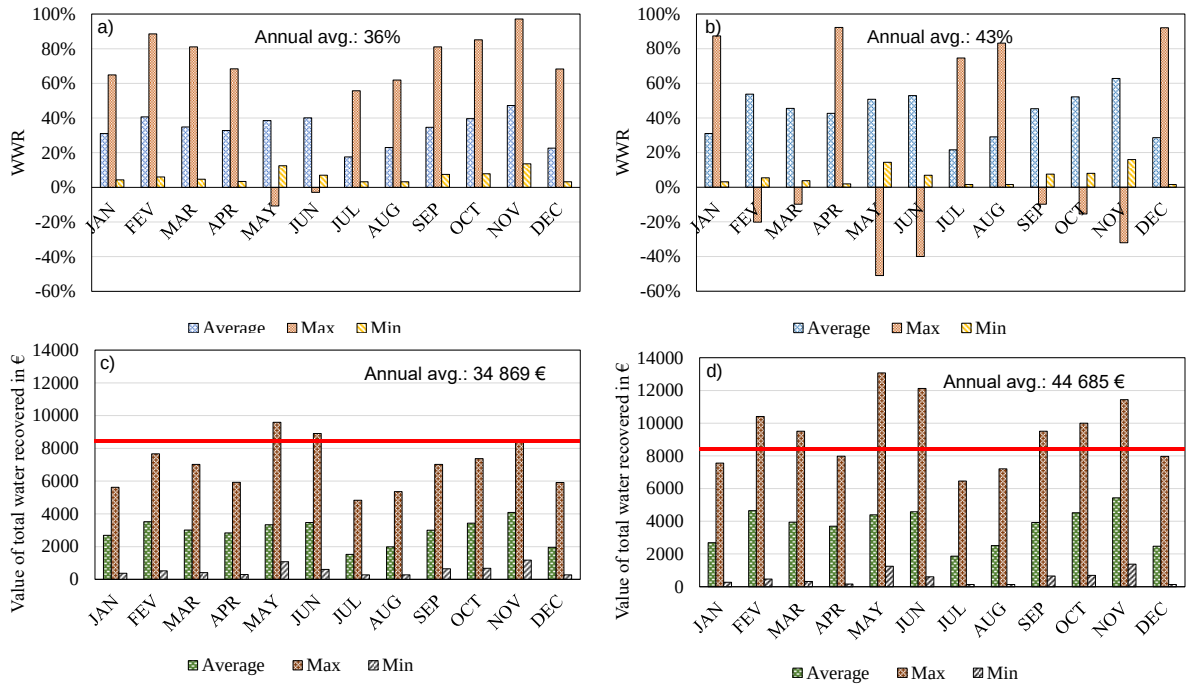

Figure 11 - Average, maximum and minimum for the WWR indicator and the monetary value of the recovered water (condensed and rainwater) in all the annual months. Scenario no NF use (a and c) and scenario no UF and NF use (b and d). The red line in the charts c and d indicates when the recovered water exceeds fresh water demand.

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3.2 Chemical – Alufluor AB

3.2.1 Process description

As mentioned in section 1.3.2, the resulting exhaust gases (contains HF) from AlF_3 production enter a scrubber unit to be washed, partially removed and condensed with a continuous flow of clean water (~7.0 – 10 m^3 / h). However, remaining exhaust vapour gases still escapes through the stack chimney and lost to the environment. This is where the iWAYS solution Heat Pipe Condenser Economiser (HPCE) contributes – WP2 – to condense and recover the highly acidic vapour. Two HPCE's are to be installed, one before the scrubber unit and one after the scrubber unit (before the chimney stack). The condensate recovered from both HPCE's will be treated by the onsite WWTP and a portion of the effluent will be treated by the iWAYS wastewater treatment plant (WWTP – WP4). The iWAYS WWTP can operate without receiving the condensate from the HPCE's, as it will receive the effluent from the onsite WWTP which treats effluent from the scrubber unit and from other processes of the industrial system.

The recovered and treated effluent will be recirculated and reused in the scrubber unit for treating the corrosive exhaust vapour gases, therefore covering freshwater requirements and consumption of the scrubber unit. The iWAYS solution will reduce the amount of exhaust vapour gas discharged in the environment and increase the overall water and resource circularity of the Alufluor (ALU AB) industry.

3.2.2 Circular Economy (CE) framework

3.2.2.1 System development

In the ALU AB Use-Case, three scenarios were considered: a baseline scenario, and scenarios A and B. The goal of the assessment consists in comparing the baseline scenario with the other two proposed scenarios. The scope of the assessment considers the Water-Waste-Energy Nexus of the industrial system, which considers the onsite wastewater treatment process and industrial processes. The inputs to the system, as delimited by the boundary, are freshwater and energy, i.e. Non-Renewable Energy (NRE). Outputs considered are emissions to the environment in the form of exhaust gas (vapour), and corresponding products and by-products (presented but not characterised).

3.2.2.1.1 Baseline scenario

Figure 12 presents a high-level overview of the current baseline of operations, where the boundary defines the processes (industrial and onsite WWTP) and inputs regarding the water cycle, energy sources and outputs regarding exhausted gas emissions, products and by-products (the former and latter are not accounted for in the assessment). Around 4% of the freshwater is left in the products, with the remaining 96% is lost as exhausted emissions or discharged into the sea. This makes the current operations of the use case water intensive as it requires freshwater with low impurities for operations. Detailed information on the characteristics of the water source and emissions can be consulted in D2.2 and D4.1.

Freshwater is used in all parts of the system processes: directly in the production phase of aluminium fluoride, in the scrubber unit and also for the onsite WWTP. No other sources of water are used in the current industrial system.

Energy consumed by the industry is obtained from 2 different sources of non-renewable energy (NRE) (Figure 12). NRE is obtained from 2 sources:

- Electricity sourced from the grid;

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- Natural gas used for heating (e.g. drum dryers, steam boiler).

Renewable energy (RE) is currently employed in the industrial system by recovering heat which is used to heat up water for washing purposes.

Exhaust vapour gas flows to the scrubber unit from the drum driers and crystallisers used in the production of AlF_3, where the scrubber requires water to essentially cleanse the exhaust gas to acceptable values before flowing out through the chimney stack. The water used in the scrubber unit flows at a constant rate and is then sent to the onsite WWTP. Other contributions from the industry are also flowed to the onsite WWTP. Exhaust and heat still are present in the exhaust vapour gas after the scrubber unit. The exhausted vapour gas is a mixture of various elements, including water vapour – its composition can be found in D2.2 and D4.1.

Regarding waste and emissions, as the focus is primarily on the water and energy cycles, solid waste produced by the industry as well as by-products were not considered.

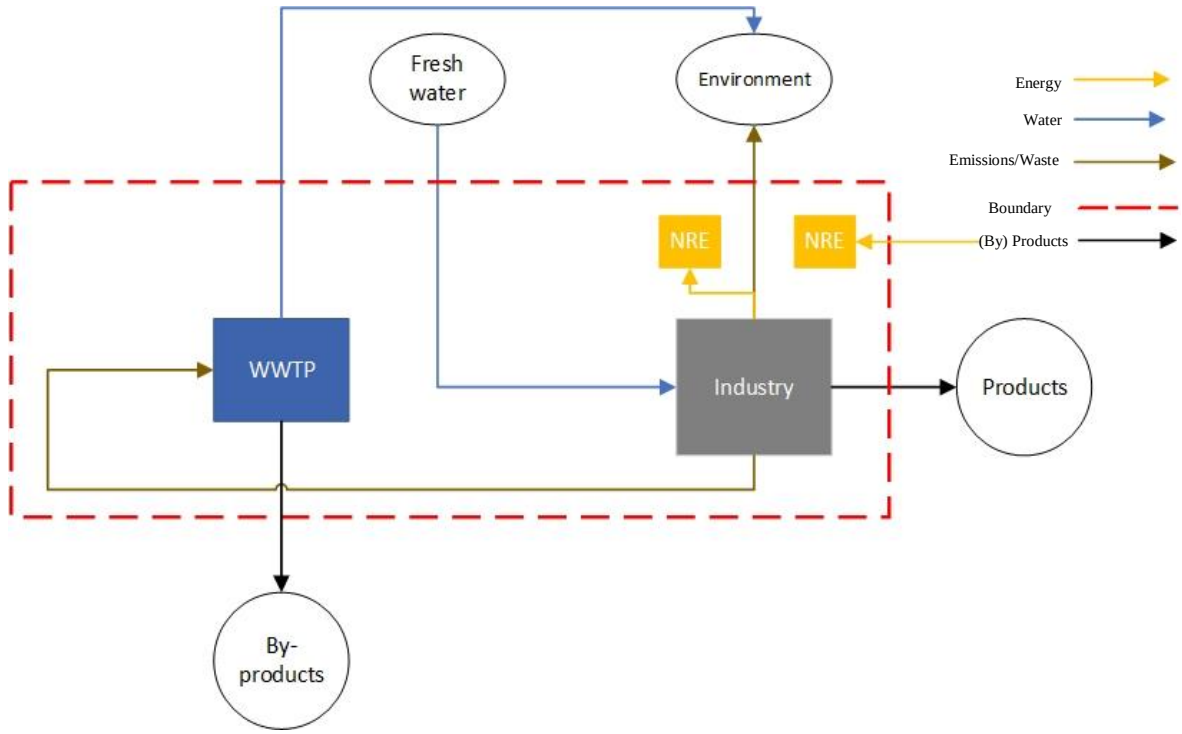

Figure 12 - Baseline: Water cycle of the ALU AB industry and water source and flows; Non-renewable energy sources and flows of ALU AB; ALU AB wastewater and exhausted gas emissions flows; NRE: Non-renewable energy.

3.2.2.1.2 Scenario A – Condensate and energy recovery

Scenario A considers the integration of the proposed iWAYS solution, consisting of two Heat Pipe Condenser Economiser (HPCE) and the water treatment system (D4.2) (Figure 13) – within the defined boundary. The objective of the iWAYS solution integration is to increase the internal circularity level of the industry (i.e. increase water and energy recovery). Scenario A builds on the baseline (see description in section 3.2.2.1.1), and considers the integration of the first HPCE (HPCE#1) just before the scrubber unit and the second HPCE (HPCE#2) just after the scrubber unit in order to promote heat transfer for thermal energy recovery and to condensate the vapour. The condensate recovered by HPCE#1 will flow directly to the onsite WWTP, while the condensate recovered by HPCE#2 will first flow into the scrubber unit and then to onsite WWTP (D4.2). This solution was the best and easiest to implement.

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The HPCE's achieve vapour condensation through temperature differences, i.e. the HPCE is essentially divided into two sections, one where the vapour passes through in a series of channels and progressively cools down. A coolant liquid (insulated) flows through the HPCE's to cool down the vapour as it flows through the different channels while never in direct contact with the vapour exhaust. This thermal exchange between the vapour exhaust with the coolant liquid captures thermal energy by heating up the coolant liquid which can then be reused to heat boilers or other purposes that require heating (e.g. pre heat the water for boilers). This exchange can translate in a reduction of sourcing natural gas for heating purposes and a source of renewable energy (RE) – Figure 13. The recovered condensate is flowed to the onsite WWTP to be treated.

The iWAYS water treatment system which treats a portion of the effluent from the onsite WWTP is composed of a sand filter unit and a softner unit in series (D4.2), with the resulting treated water flowed directly back to the scrubber unit, and the concentrate from treatment flowed to the sea.

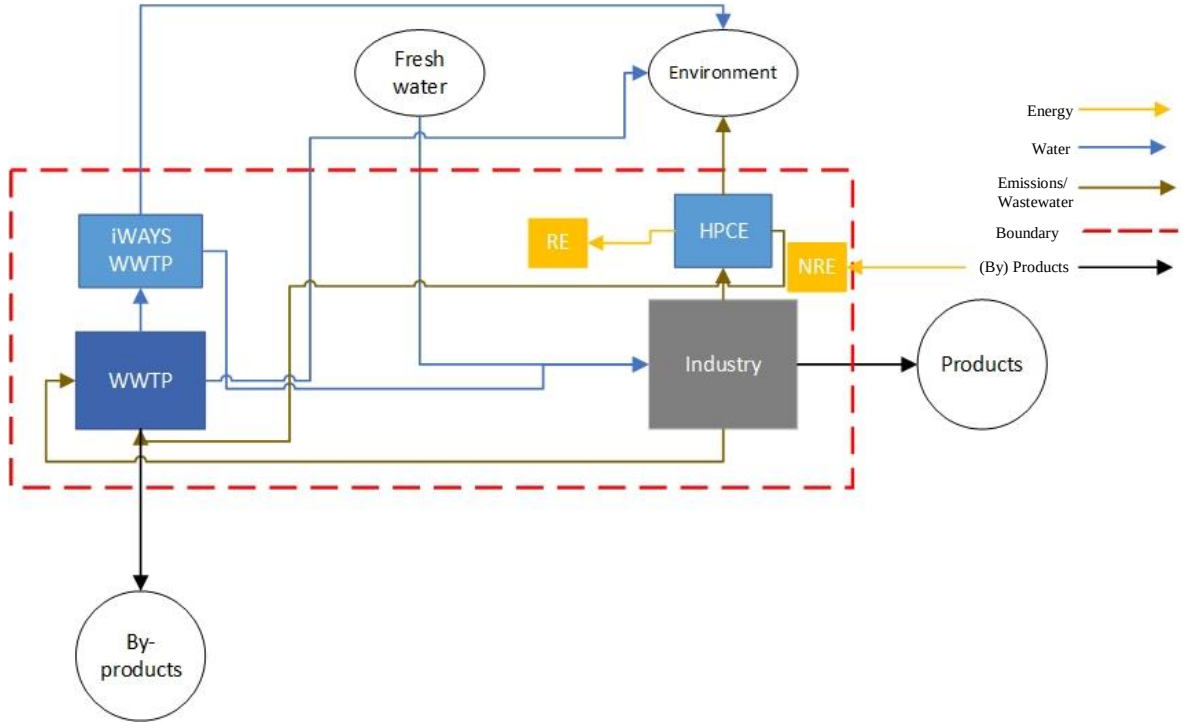

Figure 13 – Scenario A: Water cycle of ALU AB, and types of water sources and flows with the HPCE and water treatment system; Renewable and non-renewable energy sources and flows of ALU AB; ALU AB wastewater and exhausted gas emissions flows; NRE: Non-renewable energy; RE: Renewable energy.

3.2.2.1.3 Scenario B – Scenario A + Rainwater harvesting

The third scenario (scenario B) includes the interventions made in scenario A and extends it by including rainwater rooftop harvesting (Figure 14). The recovered rainwater is treated by the iWAYS water system and then stored as clean water, with concentrate discharged in the sea. Annual precipitation in the industrial area, and the roof-top area were considered in order to estimate the potential volumes of harvested rainwater (for further details consult D4.1) – including the first flush practise.

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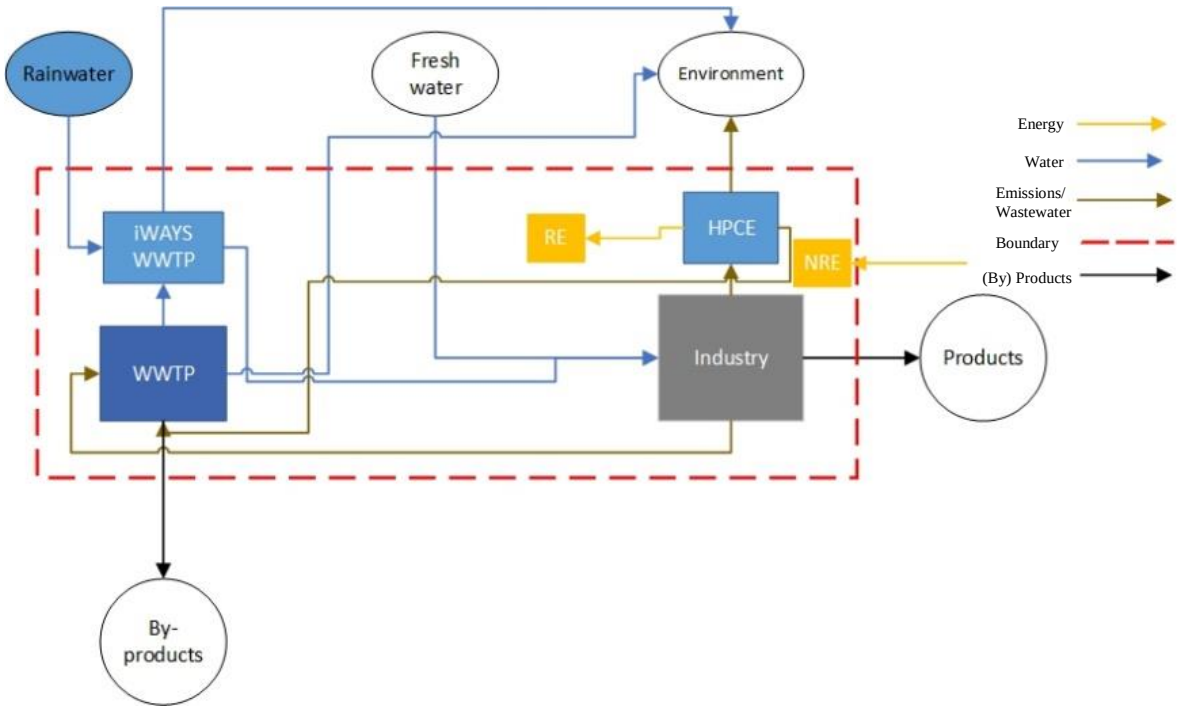

Figure 14 – Scenario B: Water cycle of the ALU AB, and types of water sources and flows with the HPCE, water treatment system and rainwater harvesting integration; Renewable and non-renewable energy sources and flows of ALU AB; ALU' s wastewater and exhausted gas emissions flows; NRE: Non-renewable energy; RE: Renewable energy.

3.2.2.1.4 Identification of the circular actions

The integration of the proposed iWAYS solutions intends to address the following identified circular actions:

- Reducing the withdrawal of freshwater from the mainline by recovering wastewater that contains condensate, wastewater and rainwater from the exhaust gases, industrial proceses and rooftop run-off, respectively;
- Upcycling the recovered water by treating it in the onsite wastewater treatment plant and the proposed iWAYS water treatment system;
- Reusing and recycling condensate, wastewater and rainwater from the exhaust vapour gases, wastewater from industrial processes and rooftop run-off, respectively;
- Reducing natural gas consumption (dependency) for heating boilers by recycling the wasted heat captured by the HPCE from the exhaust vapour gas;
- Reducing overall CO_2 footprint from natural gas consumption.

This resulted in an adaptation of the proposed by Nika et al. (2022) to measure the circularity level relating to 5 circular actions identified in the industrial Use Case within the WWE nexus framework: considering before (scenario - baseline) and after (scenario – A and B) the integration of the iWAYS solutions.

Furthermore, economic indicators were proposed to measure the potential economic performance of each scenario and aligned with the identified circular actions:

- Reducing overall costs associated with water withdrawal, energy and CO_2.

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3.2.2.2 Indicators selection

Table 17 presents the *Indicator selection* process method, consisting in utilising the information gathered during the *System Development* step. This allows to identify the category (i.e. Nexus) of the indicators, the purpose of the category, the overall goal of the category, and finally the indicators selected to represent each category. Complementary columns indicate the coverage (i.e. circular action) of the indicators: Reducing Freshwater Withdrawal (*RFW*), Reducing Natural Gas Dependency (*RNGD*), Upcycling the Recovered Water (*URW*), Reusing and Recycling of Recovered Water, Condensate and Rainwater (*RRRWCR*), and Reducing Overall CO_2 Footprint (*ROCO$_2$F*). Indicators were proposed and selected from a collection of indicators as the most appropriate for the identified circular actions (coverage).

Table 17 – Indicator selection process ALU AB: CE – Water, energy and waste CE indicators; and economic indicators.

Nexus	Purpose	Goal	Indicator	Coverage				
				RFW	RNGD	URW	RRRWCR	ROCO$_2$F
Water nexus	Close the loops / reduce environmental impact	Water circularity	Circular Water Inflow (CWI) Circular Water Outflow (CWO) Circular Water Flow (CWF) Onsite Water Circularity (OWC) Water Withdrawal Reduction (WWR)	X		X	X	
Energy nexus	Close the loops / reduce environmental impact / reduce non-renewable energy requirements	Energy circularity / sustainability	Renewable Energy Contribution (REC)		X			X
Waste nexus	Close the loops / reduce environmental impact	Waste circularity	Emission Utilisation Index (EUI)	X		X		
Economic coverage	Added value	Value gained with circular actions	Fuel Cost Saving (FCS) Total CO2 Cost Saving Water Cost Saving Total Saved Cost	X	X	X	X	X

RFW: Reducing Freshwater Withdrawal; RNGD: Reducing Natural Gas Dependency; URW: Upcycling the Recovered Water; RRRWCR: Reusing and Recycling of Recovered Water, Condensate and Rainwater; and ROCO$_2$F: Reducing Overall CO_2 Footprint.

Water nexus: the purpose of the assessment as explained in the system's development step focuses on the Reduction of Freshwater Withdrawal, Upcycling the Recovered Water and, Reusing and Recycling Wastewater, Condensate and Rainwater. Therefore, five (5) indicators were identified and selected to assess and cover three (3) of the identified circular action.

Energy nexus: relates to the heat recovered by the HPCE, resulting in a reduction of emitted emissions and wasted energy, consequently increasing energy circularity. Therefore, two (2) of the identified circular actions are covered by one (1) selected indicator.

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Waste nexus: exclusively regarding water vapour loss through the chimney stack, therefore neglecting solid waste for the assessment (although data is available, but no changes to solid waste production occurs). Waste in this context is classified as water vapour and lost in the process – one (1) indicator was selected to cover two (2) circular actions.

Economic indicators: after selecting the circular indicators that cover all identified circular actions, as shown in Table 17, the economic indicators must therefore inform on the economic benefits of the transition to sustainable renewable energy and water circularity. Total saved costs are aggregated to cover all identified circular actions.

More information on the description of the indicators can be found in section 3.1.2.2 and Annex. The indicators selected to assess the ALU AB are the same as the indicators selected for CON, therefore resulting in a direct form of comparison between both industries and the proposed interventions.

3.2.2.3 Circularity measurement

3.2.2.3.1 Material Flow Analysis and Data collection – Water, Waste and Energy

With the identification of the circular actions and consequent indicator selection process complete, a Material Flow Analysis (MFA) was performed to identify flows and required data sets. As the CE assessment is performed within the WWE nexus framework, data requirements included ALU AB's monthly and annual operations regarding water use, waste (solid) production and energy consumption, as well as details relating to the nexus (e.g. source of energy, source of water, etc). The data supplied by ALU AB partners spanned from 2016 to 2021. The year 2020 was not excluded from the analysis due to the COVID-19 pandemic, as operations during this year did not deviate from normal industrial operations.

WATER

The Water nexus comprised of measuring linear and circular water flows identified in the system.

Monthly and annual freshwater consumption was supplied by the partners. Table 18 presents monthly average, median, minimum and maximum values of freshwater consumption, and Table 19 presents annual average, median, maximum and minimum of freshwater consumption. Hexafluorosilicic acid (H_2SiF_6) is used in the process and added at the head of the system, however only data for 2021 is shown (Table 21).

Table 18 – Monthly Freshwater Consumption ALU AB (2016 – 2021).

Monthly Freshwater Consumption (m^3 / month): 2016 – 2021					
Month	Average	Median	Standard Deviation	Maximum	Minimum
January	15 865	16 180	1 926	18 384	12 541
February	13 364	14 553	2 774	15 683	7 570
March	16 504	16 109	1 566	19 288	14 577
April	14 315	14 693	1 460	16 420	11 975
May	14 286	14 866	2 492	16 819	9 591
June	15 401	15 175	2 046	19 183	12 463
July	13 272	14 409	3 266	16 259	6 584
August	14 184	13 257	2 211	17 324	12 041
September	11 064	10 540	3 263	17 018	6 814
October	15 369	16 005	2 130	17 585	11 417
November	16 817	16 302	3 041	23 191	13 676
December	14 445	14 349	1 882	17 668	12 000
Monthly	**14 574**	**14 788**	**2 850**	**23 191**	**6 584**

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Table 19 – Annual Freshwater Consumption ALU AB (2016 – 2021).

Annual Freshwater (m^3 / year): 2016 – 2021					
Parameter	Average	Median	Standard Deviation	Maximum	Minimum
Freshwater	**174 884**	**180 911**	**13 792**	**188 765**	**164 361**

For the WWE nexus modelling exercise, and to ensure operation is current, only datasets from 2021 were considered. The above information is to contextualise operations in 2021 with past operational trends. Water consumption for 2021 is shown in Table 20 and Table 21, on a monthly and annual (including acid consumption) basis, respectively.

Table 20 - Monthly Freshwater Consumption ALU AB (2021).

Monthly Freshwater Consumption (m^3 / month): Year 2021				
Month	Value	Average	Median	Standard Deviation
January	15 692	**15 730**	**15 684**	**3 600**
February	15 285			
March	19 288			
April	15 154			
May	15 732			
June	14 404			
July	16 259			
August	14 043			
September	6 814			
October	17 228			
November	23 191			
December	15 675			

Table 21 - Annual Freshwater and H_2SiF_6 Consumption ALU AB (2021).

Annual Fresh Water and Hexafluorosilicic Acid Consumption (m^3 / year): Year 2021		
Source	Value	Total Water and H_2SiF_6 Consumption
Freshwater	188 765	**207 008**
H_2SiF_6	18 243	

Freshwater consumption is higher in 2021 (Table 21) compared to the average yearly value in Table 19 – maximum observed. However, it falls within the 95% of observations under a normal distribution considering 2 standard deviations from the average. The percentage of liquid input to the system of freshwater and H_2SiF_6 (year 2021) are shown in Figure 15. All of liquid input to ALU AB are from a non-renewable source (freshwater).

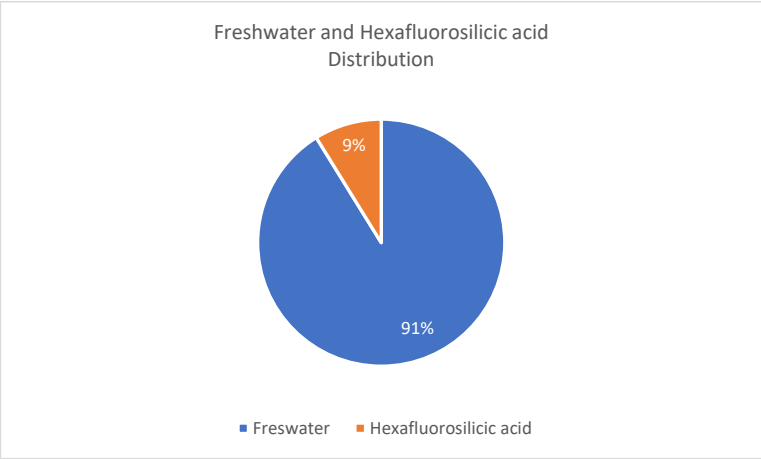

Figure 15 – Freshwater and Hexafluorosilicic Acid Consumption Source Distribution ALU AB (2021).

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ENERGY / ELECTRICITY

The Energy nexus also consists in measuring linear and circular energy flows of the system.

Monthly and annual energy / electricity consumption from 2016 to 2021 was supplied by ALU AB partners. Energy in is obtained from two (2) Non-Renewable Energy (NRE) sources and one (1) Renewable Energy (RE). The NRE source includes electricity from the grid and Natural Gas to burn to produce thermal energy, and the RE is recovered from onsite heat exchangers that recover 200 – 250 kWh/day. A conservative value was calculated for RE, resulting in contribution of 73 MWh/year (maximum = 91 MWh/year). Table 22 presents monthly average, median, minimum and maximum values regarding energy / electricity consumption, and Table 23 presents annual average, median, maximum and minimum of energy / electricity consumption.

Table 22 – Total Monthly Energy / Electricity Consumption ALU AB (2016 – 2021).

Total Monthly Energy / Electricity Consumption (MWh / month): 2016 – 2021					
Month	Average	Median	Standard Deviation	Maximum	Minimum
January	3 883	3 878	301	4 242	3 320
February	3 362	3 572	682	3 925	1 917
March	4 139	4 282	309	4 482	3 701
April	3 519	3 618	477	4 240	2 831
May	3 235	3 075	576	4 115	2 333
June	3 527	3 619	360	4 030	3 005
July	3 024	3 268	641	3 563	1 698
August	3 121	2 922	469	3 874	2 515
September	2 470	2 602	777	3 658	1 306
October	3 571	3 829	564	3 994	2 390
November	3 462	3 525	245	3 764	3 117
December	3 524	3 519	613	4 286	2 686
Monthly	**3 403**	**3 566**	**665**	**4 482**	**1 306**

Table 23 – Total Annual Energy / Electricity Consumption ALU AB (2016 – 2021).

Total Annual Energy / Electricity Consumption (MWh / year): 2016 – 2021					
Years	Average	Median	Standard Deviation	Maximum	Minimum
2016 – 2021	**40 837**	**40 891**	**2 654**	**44 388**	**36 912**

As with water consumption, energy / electricity consumption regarding the WWE nexus modelling exercise considered only datasets from 2021 to ensure that the data is current. The above information (Table 22 and Table 23) is to contextualise operations in 2021 with past operational trends. Table 24 shows the monthly consumption of energy, as well as the monthly average, median and standard deviation of Total Energy / electricity consumption for 2021. Overall annual consumption is also shown.

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Table 24 – Monthly Energy and Electricity Consumption and Monthly Average, Median and Standard Deviation Energy and Electricity Consumption; Annual Energy and Electricity Consumption ALU AB (2021).

Total Monthly Energy / Electricity Consumption (MWh / month): Year 2021				
Month	Value	Average	Median	Standard Deviation
January	3 864	**3 254**	**3 270**	**711**
February	3 349			
March	4 255			
April	3 606			
May	3 053			
June	3 005			
July	3 530			
August	2 874			
September	1 306			
October	3 898			
November	3 117			
December	3 191			
Total (MWh / year)	**39 121**			

It is worth noting that the average, median and total values in Table 24 are within the same order of magnitude as the values in Table 22 and Table 23. Energy / electricity consumption is lower in Table 24 compared to the yearly average value in Table 23. The value from 2021 falls within the 95% of observations under a normal distribution considering 2 standard deviations from the average value. Therefore, the year 2021 is representative of normal operations (same as for monthly average value).

The source of the energy and electricity consumed by ALU AB is represented in Figure 16. It is possible to observe that an overwhelming amount of energy is consumed through burning of Natural Gas (~84%) and around ~16% of electricity is sourced from the grid. Around 0.20% is in the form of RE.

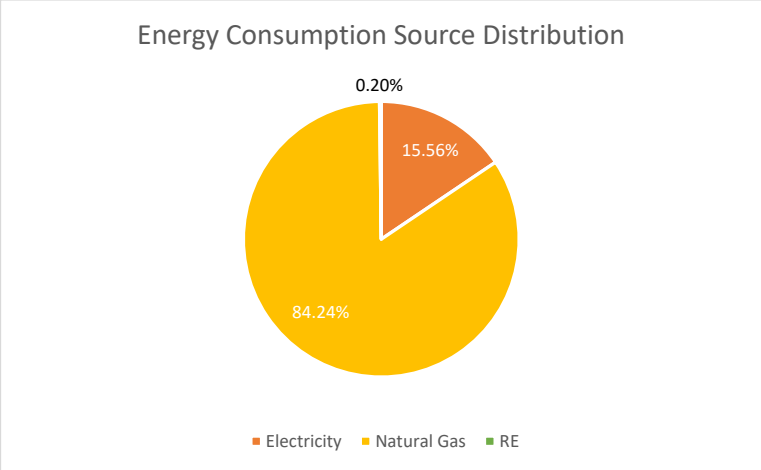

Figure 16 – Energy / Electricity Consumption Source Distribution ALU AB (2021).

WASTE

The waste nexus also consists in measuring linear and circular waste flows of the system. However, as solid waste is valorised as by-product and resold to the construction market, it is out of the scope of this assessment as it will not be affected or changed by the iWAYS interventions. On average 3 177 tons of Calcium Fluoride (CaF) is recovered per year and sold to the construction market. Therefore, in the current context of the WWE nexus, waste was considered as exhaust vapour gas emitted by ALU AB.

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Emissions from the stack chimney in the form of exhaust vapour gas was determined from onsite measurements performed by ITC-AICE partners performed in 2021 (D2.2). Additionally, measurements performed by ALU AB partners were also provided. Only the measurements performed by ALU AB partners is presented in Table 25. Fourteen (14) sampling campaign were conducted from June 2021 to November 2021. Data is presented for each sampling campaign, as well as calculated as an hourly average flow rate, and average and median flow rates (converted into annual flow rates). The pollutant load in the exhaust vapour gas is shown in Table 26 which was calculated based on the concentrations measured in the condensate reported in D4.1. It considers the amount of water in the vapour and respective concentration from sampling the condensate.

Table 25 – Chimney stack exhaust gas and vapour monitoring campaign and calculations ALU AB (2021).

Date	Parameter	Value	Unit	Comment
22/06/2021	Water out of chimney at T	1 908	kg / h	Measured by Alufluor AB partners
01/07/2021		2 235	kg / h	
08/07/2021		2 736	kg / h	
13/07/2021		2 490	kg / h	
20/07/2021		2 648	kg / h	
22/07/2021		2 526	kg / h	
27/07/2021		681	kg / h	
28/07/2021		2 708	kg / h	
17/08/2021		2 241	kg / h	
12/10/2021		2 375	kg / h	
19/10/2021		2 399	kg / h	
26/10/2021		2 671	kg / h	
02/11/2021		1 776	kg / h	
09/11/2021		2 845	kg / h	
Average		**2 303**	**kg / h**	Calculated
Average		**20 172**	**ton / y**	
Median		**21 413**	**ton / y**	
Standard Deviation		**4 723**	**ton / y**	

Table 25 indicates that the ALU AB facility potentially emits up to 20 172 ton / year (or ~ m^3 / year) of water vapour from operations, considering 365 days of continuous operation and 188 765 m^3 / year of freshwater. The volume of emitted exhaust gas and vapour results in an emission load of the parameters monitored in D4.1, as shown in Table 26. With the iWAYS HPCE solution, the emitted load to the environment will decrease as water vapour / condensate is recovered and treated.

Table 26 - Exhaust vapour potential load to the environment ALU AB (2021).

Parameter	Value	Unit
TSS	2.26	ton / y
AL	605.15	kg / y
Si	100.86	kg / y
F	10.91	ton / y
Cl	201.72	kg / y
Ca	86.74	kg / y
Na	15.53	kg / y

Table 26 specifies potentially which pollutants are emitted in higher quantities to the environment in terms of load, highlighting the highest contribution from TSS and Fluoride (carry through).

Models

The WWE nexus was modelled according to the data supplied by ALU AB partners (input and output), and a consequent mass balance. The amount of exhaust vapour and water volume

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flowing out the chimney stack was modelled according to measurements performed by the industrial partners (Table 25). Energy consumption models for the iWAYS water treatment plant solution was modelled based on the information in D4.2, and the iWAYS HPCE thermal and condensate recovery efficiency was modelled according to conversations with the partners in charge of commissioning (Brunel). The HPCE's were individually modelled considering that 100% efficiency in terms of operation corresponds to a combined 600 kWh (split of 300 + 300 kwh) for energy recovery and 934 l/h (split of 545 + 389 l/h) for condensate recovery (Figure 17 – a and b). The efficiency of the HPCE will vary depending on the input temperature of vapour exhaust gas to the HPCE's, which ultimately affects operational dynamics. In this step, the selected efficiency levels of the HPCE's ranged from 0 through 40, 60, 80 and 100%, with the corresponding condensate recovery efficiency, but limited to a maximum 600 kWh (exponential equation in Figure 17, but capped at combined maximum 600 kWh). Even if no thermal energy is recovered, it is still expected that residual condensate recovery will occur (minimum total of 73.3 l/h).

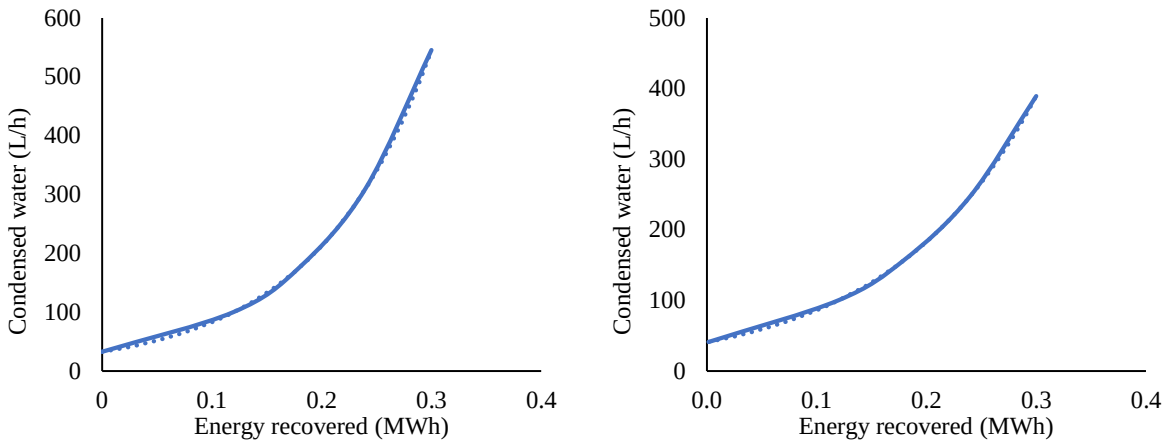

Figure 17 – HPCE efficiency correlation curve (condensed water recovery vs thermal energy recovery) ALU AB.

The iWAYs water treatment system water recovery efficiency was calculated as a total of 93.33%, with the remaining % (6.67%) allocated to the discharge from the treatment to the sea (D4.2).

Economic coverage

Monetary values were acquired and assumptions were made to calculate the economic indicators for (Table 27).

Table 27 – Monetary values and assumptions for economic coverage indicator calculation ALU AB.

Parameter	Value	Unit	Source
Natural Gas	0.085	€ / kWh	Alufluor AB
Emissions Allowances	85.22	€ / ton CO_2	https://www.statista.com/statistics/1322214/carbon-prices-european-union-emission-trading-scheme/
Tap / Freshwater	1.09	€ / m^3	Alufluor AB

3.2.2.4 System testing

The *system testing* step assesses if the selected indicators are sensitive or resilient to changes in the data and consequent system changes. As scenario B considers the integration of both iWAYS processes, i.e. HPCE and water treatment plant, and rainwater harvesting, it is considered the best scenario to perform the system testing step. This exercise consists in

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calculating and testing the indicators with different energy recovery efficiencies of the HPCE – this will vary depending on the operational temperature of exhaust vapour gas to the HPCE and ultimately affect operational dynamics (i.e. thermal energy and condensate recovery). The HPCE's were modelled according to conversations with partners in charge of designing and building the process, varying according to the models shown in Figure 17. The combined thermal energy recovery and condensate recovery are varied in accordance with potential efficiency levels of the HPCE's, which range from 0% through 40, 60, 80 and 100%.

The results of the system testing can be seen in Figure 18 when varying the HPCE's efficiency, and translating in potential energy and condensate recovery (Figure 17). This crucial step allows to identify the sensitivity of the selected indicators that represent the circular actions. Regarding the water nexus, no changes in the indicators were observed because the majority of wastewater already comes from existing activities that already require treatment and are then discharged by the onsite water treatment plant – the iWAYS water treatment plant recovers only a portion of the discharged water to be reused – therefore no changes would be expected to this value. In summary, through a circular lens for the HPCE's technology and rainwater harvesting system, these will not impact significantly the identified circular actions targeting the water nexus, as the main contribution of a renewable source of water is already found in the water discharged by the onsite water treatment plant – this could change if the capacity (i.e. iWAYS water treatment process) of treating and reusing more water in the system increased. This interpretation is confirmed with the water cost saving indicator, where it is possible to observe that no changes occur.

On the other hand, regarding the energy and waste nexus, the REC and EUI varied significantly with changes in the HPCE's performance. Comparing with 100% efficiency scenario (first image – REC = 16%), the REC indicator regarding the different efficiencies reduced by: 23.5% (80% efficiency), 44.3% (60%), 63.9% (40%) and 100% (0%), in comparison to 100% efficiency (Figure 18). Regarding the EUI indicator (EUI = 29%), the decrease in efficiency also resulted in a reduction by: is 32.6% (80%), 56.3% (60%), 72.4% (40%) and 89.4% (0%) compared to 100% efficiency (Figure 18). This is where the main impacts of the iWAYS HPCE's are obtained, and where it can reflect the most on this industry in the current context as demonstrated through the economic indicators regarding the fuel cost saving and consequential CO_2 savings – societal gains. The water indicators are not sensitive to changes in the HPCE's operation, however this has more to do with the current context of how water is recovered, treated and reused, and not the sensitivity of the indicator per se. As water is recovered from the onsite WWTP, the injection of more water, in the form of condensate, will not affect the water indicators. If more water were to be treated and recirculated through the industrial system, then the HPCE's impact would be evident through the indicators, however, with current planning, the recovery of more water in the form of condensate will not impact water circularity as demonstrated by the water indicators.

As demonstrated by the system testing step, it was possible to confirm that the selected indicators were indeed sensitive to operational variations of the HPCE (with focus on the energy side). Water indicators did not vary due to the volume of water that is recovered by varying the HPCE's efficiency, due to the fact the recovered water does not exclusively depend on the condensate recovered by the HPCE's. Further changes in water indicators would be expected if different precipitation events for rainwater harvesting were considered in the system testing step, and consequently feedback to the water nexus economic indicator. Other changes to the water indicators would be expected if more volumes of water were treated and recirculated throughout the industry, therefore highlighting the effects of the HPCE in terms of water recovery. In the current exercise, the HPCE will contribute the most to the industrial system through the energy indicators, as shown in Figure 18 and explained above.

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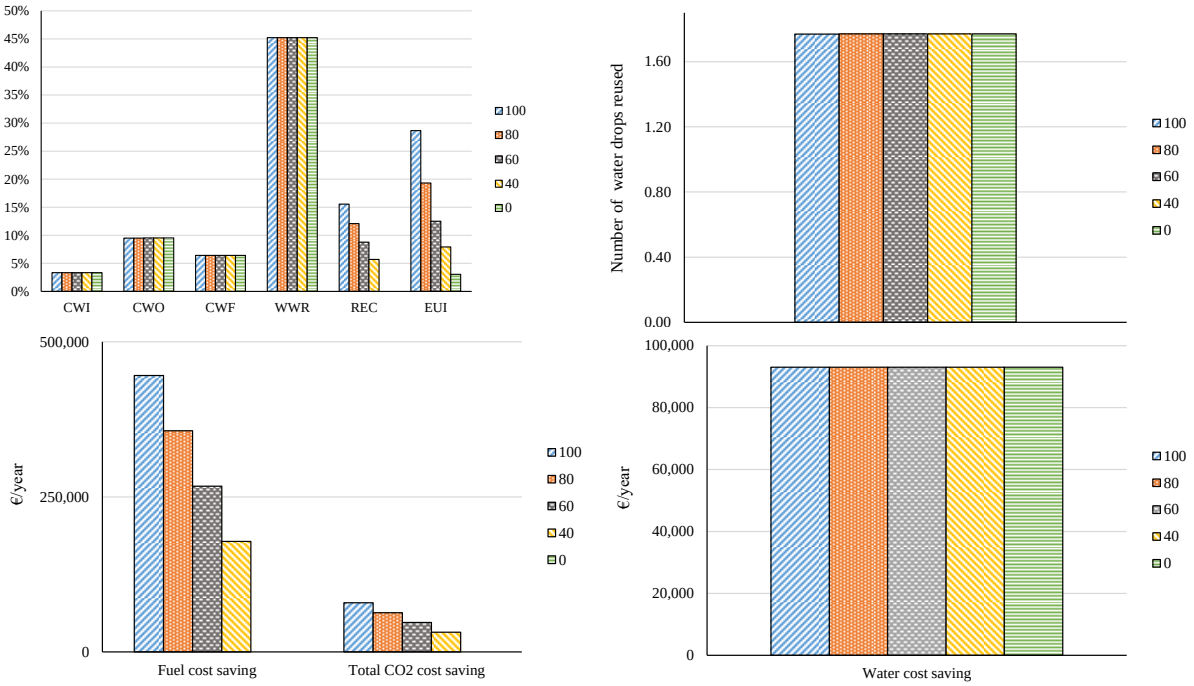

Figure 18 – Results of the system testing by varying the HPCE energy efficiency ALU AB (CWI – Circular Water Inflow; CWO – Circular Water Outflow; CWF – Circular Water Flow; OWC – Onsite Water Circularity; WWR – Water Withdrawal Reduction; REC – Renewable Energy Contributions; EUI – Emissions Utilisation Index). The y-axis of the first image is in % as it indicates the units from indicator calculation.

3.2.2.5 Circularity assessment

The circularity assessment consists in benchmarking scenarios A and B vs current operations (baseline scenario) considering the identified circular actions and indicators. It also consists in performing a dynamic simulation with historical rainfall data and assessing the results in relation to feasibility.

To perform the benchmark assessment, the identified circular actions indicators are assessed and compared with the baseline scenario. In relation to the dynamic assessment, the objective is to understand what changes (if any) occur to the indicators and consequent circular actions concerning freshwater consumption (water circularity) and its impact on economic performance. This includes varying potential monthly rainwater harvesting volumes, however for the ALU AB use case, this was not performed as the following conclusions were reached when performing a preliminary-analysis of the information in D4.1:

- The volume of rainwater harvested (potentially 3 602 m^3 / year) compared to 188 765 m^3 / year of freshwater consumed does not induce substantial changes to the indicators, as it will potentially cover ~2% of total freshwater requirements, and this is without considering that a treatment process would need to be implemented and therefore reduce the amount of rainwater recovered – high quality water required, equivalent to tap water or better;
- The roof area of the industrial park was completely accounted for in the analysis (D4.1), therefore additional rainwater harvesting structures would be required to increase the volume of water harvested, resulting in increased capital expenditure. However, as shown with the NF and UF unit (CON), the volume of clean, freshwater recoverable will

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likely be ~60% (the other ~40% is concentrate) – D4.2, therefore the volume of recoverable water would need to justify the additional structures.

3.2.2.5.1 Circularity measurement and assessment: Baseline vs scenario A vs B (benchmark assessment)

Table 28 shows the circular economy (CE) and economic indicators scores for the baseline, scenario A and B. Each nexus represented in the Table 28 is discussed in detail below.

Table 28 – Circularity assessment results for the baseline and scenario A and B, ALU AB.

Category	Indicator	Unit	Baseline	Scenario A	Scenario B
Water	CWI	%	0.00	0.00	3.33
	CWO	%	5.60	7.03	9.49
	CWF	%	2.80	3.51	6.41
	OWC	Number of drops	1.00	1.76	1.77
	WWR	%	0.00	43.31	45.22
Energy	REC	%	0.19	15.74	15.74
Waste	EUI	%	0.00	28.65	28.65
Economic	Fuel Cost Saving	€/year	-	445 675	445 675
	Total CO_2 Cost Saving	€/year	-	79 112	79 112
	Water Cost Saving	€/year	-	89 114	93 042
	Total Saved Cost	€/year	-	613 900	617 829

CWI – Circular Water Inflow; CWO – Circular Water Outflow; CWF – Circular Water Flow; OWC – Onsite Water Circularity; WWR – Water Withdrawal Reduction; REC – Renewable Energy Contributions; EUI – Emissions Utilisation Index.

3.2.2.5.2 Water nexus

The current baseline liquid input for 2021 was 207 008 m^3/year (a combination of freshwater and H_2SiF_6), resulting in 175 236 m^3/year of treated water discharged to the sea, 20 172 m^3/year of water lost through the chimney stack, and the remaining 11 680 m^3/year left in products and by-products. Assessing the *baseline scenario*'s indicators shows that withdrawal of non-renewable water (freshwater) is 100% and that no water is recovered as it is exhausted as vapour gas and discharged (WWR = 0.0%). By assuming that exhausted vapour gas does not return back to its origin (aquifer or dam), and that only some of the water stays within the products and by-products, hence the CWO score of 5.60%, the resulting CWF score therefore indicates that water use for the current system is 2.80% circular. As CWO is an intermediate step to calculate CWF (Annex), it also needs the contribution from CWI which yielded a value of 0%. Therefore, CWF's scores exclusively from CWO (Annex). This score was obtained due to the loss of water that occurs through the chimney stack to the environment and discharged from the water treatment to the sea, while the remaining volumes of water end up in the products and by-products (circular water until the boundary of the system).

Scenario A consisted in integrating the iWAYS HPCE and water treatment plant to the baseline setup. The maximum recovery rate of condensate by the HPCE is 934 l/h (100% efficiency) corresponding to potentially 8 182 m^3/year of recovered water condensate from potentially 20 172 m^3/year of exhausted vapour gas. The iWAYS water treatment system's total recovery efficiency was calculated as 93.33% (D4.2), with the remaining 6.67% discharged to the sea. However, the observed increase in circularity as mentioned previously, does not depend on the amount of water recovered by the HPCE, but exclusively from the amount of water discharged by the onsite water treatment plant and consequently the amount of water treated by the iWAYs water treatment plant. For this scenario the total amount of water discharged from the onsite water treatment plant was 183 472 m^3/year (increase due to the HPCE recovery), where 87 600 m^3/year was assumed to be treated by the iWAYS water treatment plant (D4.2). This yielded some slight changes to the system in terms of water circularity as

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demonstrated by the increase to the CWF indicator (3.51%), up ~25% over the baseline and attributed to an increase in the CWO indicator (7.03%) as water was retained in the system. CWI still presented a contribution of 0%, as no external source of circular water occurs in this scenario. On the other hand, the WWR indicator increased to 43.31% over the baseline scenario, potentially resulting in a significant decrease in freshwater withdrawal with the inclusion of the iWAYS water treatment plant. This also led to a significant increase in water reuse and recycling, as the OWC score increased by ~76% over the baseline to 1.76 (number of times the drops circulate in the system).

Scenario B consisted in extending scenario A with the rainwater harvesting solution. This scenario assumes that rainwater is treated onsite by the iWAYS WWTP before use. By analysing D2.2, it was possible to assume that on average 3 602 m^3/year of rainwater can potentially be harvested from a rooftop area of 5 360 m^2. This extension reflected in a potential increase in water circularity, with CWF increasing by ~51% to 6.41%, which also reflects in a ~4% increase regarding the WWR indicator over scenario A. The increase in CWF is credited with the increase of the CWO (9.49%) as more volumes of water is maintained in the system (that can be used in other processes) and the increase in CWI from 0% to 3.33% is due to the potential harvested rainwater. The CWF indicator's overall value increases because rainwater harvesting is considered a form of water withdrawal from a circular input (OECD, 2023). Additionally, the OWC increased ever so slightly from 1.76 to 1.77 indicating a slight increase on the reused and recycled water by the industry. The roof area of the industrial park is relatively small, therefore resulting in a small increase in circular water sourcing as the amount of potential rainwater harvested is comparatively low compared to the amount of water sourced (~2%).

3.2.2.5.3 Energy nexus

By introducing the HPCE, thermal energy is captured from wasted heat which can potentially be used to preheat processes in the industrial system (e.g. evaporator). To quantify current (baseline) and potential changes induced by incorporating the HPCE in scenario's A and B, the Renewable Energy Contribution (REC) indicator was selected. The REC informs on the amount of RE sourced and therefore the transitional progress of the system to a more sustainable and carbon neutral reality. By calculating the REC for the three scenarios, it is possible to conclude for the baseline scenario the indicator scored 0.19%, due to a small contribution of renewable thermal energy from an onsite heat exchanger, which is applied to heat water for washing processes. With the integration of the HPCE, the REC increased its value to 15.74% in both scenario's A and B, as rainwater will not impact the results. Scenarios A and B present a positive increase in RE use over the baseline scenario, indicating a very positive step towards decarbonisation.

3.2.2.5.4 Waste nexus

As the assessment does not cover solid waste because the iWAYS solutions will not impact overall production of solid waste, this was not accounted for the modelling exercise of the WWE nexus model. However, as shown in section 3.2.2.3.1, solid waste produced by the facility originates from the onsite water treatment facility, resulting on average 3 177 tons of Calcium Fluoride (CaF) which will not change due to the incorporation of the iWAYS solutions. Therefore, in the current context, waste was considered as exhausted vapour gas lost through the chimney stack and the Emission Utilisation Index (EUI) was selected to represent the % of emissions used or recycled that would otherwise be lost, back into the system. For the baseline scenario, the EUI was calculated as 0% contribution, as the emissions in the form of exhausted vapour gas are completely lost through the chimney. For both scenario A and B, as rainwater will not affect the volume of recovered condensate or thermal heat, both presented a value of 28.65%. This value indicates that out of total waste in the form of gas vapour, not accounting for solid waste, potentially 28.65% of total emissions are recoverable by the HPCE. This also

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translates in a reduced pollution load to the atmosphere and energy recovery, therefore contributing to closing the loops in terms waste.

3.2.2.5.5 Economic coverage

Economic indicators were selected to cover the identified circular actions to indicate the value added by the interventions, therefore they indicate what potential annual economic savings are potentially achieved in regard to water and energy resources, as well as emissions (i.e. monetary CO_2 savings for society). Therefore, economic indicators were selected to demonstrate their economic coverage of the identified circular actions (Table 28 – proposed in D6.1 / D6.2). The circular actions of reducing natural gas consumption and overall CO_2 footprint by integrating the HPCE (scenario A) indicates a potential fuel cost saving and CO_2 cost saving of 445 675 € and 79 112 € per year, respectively for both scenario A and B. Regarding reduction of fresh water withdrawal, upcycling recovered water and, reusing and recycling of recovered water shows that scenario A can potentially contribute by saving 89 114 € per year due to the water recovery and upcycling through the iWAYS water treatment system compared to the baseline scenario (water savings do not necessary depend on the HPCE's contribution). Scenario B results demonstrates that an increase in the water cost saving occurs of ~ 4% (3 928 €/year), in relation to the scenario A, however, this is only possible if water is reused in other processes.

Therefore, through the lens of the identified circular actions, the iWAYS solutions have the potential to promote savings of up to 613 900 €/year for scenario A and 617 829 €/year for scenario B over the baseline scenario, though the former is the more probable. The main contribution to the monetary savings is attributed to the decrease in non-renewable energy requirements and substitution with a renewable form of energy. Water cost savings are also relatively significant, reflected by the WWR indicator and the systems progress to closing the loops.

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3.3 Steel – Tubacex

3.3.1 Process description

As mentioned in section 1.3.3, as part of TTI's production, freshwater is used to cool down the hot parts that exit from the 3 gas ovens (process B – see Grant Agreement (GA)), with no recovery of heat or steam (i.e. condensate). The proposed solution for the Heat Pipe Condenser Economiser (HPCE) – WP2 – will not recover condensed vapour due to the specificities of the location where it will be installed – its prime focus will be on thermal heat recovery and the latent heat of the steam will be used to preheat the liquid that feeds the evaporator equipment in the WWTP from process A (see GA). This will allow to reduce the energy and gas requirements for the degreasing tanks and evaporator equipment. The iWAYS wastewater treatment plant proposes to treat the sludge produced in water circuit 1, which is independent from the activities and solutions proposed by the HPCE for exclusively energy recovery. The objective is to reduce freshwater consumption and sludge disposal through transport with this solution, resulting in economic savings, among others, for the industry as mentioned in D4.2:

i) quality posing challenges for standard treatment processes (receiving the mineral greases and solvent from the above describes industrial processes);
ii) high environmental footprint in its current state having a high energetic cost and GHG emission in its treatment (the wastewater is transported by a third party for incineration);
iii) high economical value (80 euros per m^3 transported).

3.3.2 Circular Economy (CE) framework

3.3.2.1 System development

In the TTI Use-Case, three scenarios were considered: a baseline scenario, and scenario A and B. The goal of the assessment consists in comparing the baseline scenario with the other two proposed scenarios. The scope of the assessment considers the Water-Waste-Energy Nexus of the industrial system, which captures only the industrial processes necessary for the assessment. The inputs to the system, as delimited by the boundary, are freshwater, and energy, i.e. Non-Renewable Energy (NRE). Outputs considered are products and by-products (i.e. sludge from water circuit 1). Exhaust vapour emissions are also shown, but were not considered for the assessment as explained below.

3.3.2.1.1 Baseline scenario

Figure 19 presents a high-level overview of the operations (baseline). The boundary defines the processes (industry and sludge tank) with inputs regarding the water cycle, energy sources and outputs related with exhausted vapour gas emissions, products and by-products. Exhausted vapour gas emissions and products are not accounted for in the assessment – D2.2. Freshwater is sourced for various operations (section 1.3.3), and to some extent onsite recovery, treatment and reuse is already implemented in the baseline of operations (water circuit 3). Detailed information on the characteristics of the water source and exhaust vapour gas emissions can be consulted in D2.2.

Freshwater is used in all sections of the system processes, while a portion of water is reused in water circuit 3.

Energy consumed by the industry is obtained from 2 different sources of non-renewable energy (NRE) (Figure 19):

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- Electricity sourced from the grid;
- Natural gas used for heating (e.g. ovens and evaporator).

No form of renewable energy is currently employed in the industrial system.

Regarding waste and emissions, solid waste such as the by-product (sludge) produced in water circuit 1 was considered, while emissions was not as it will not be covered by the iWAYS interventions.

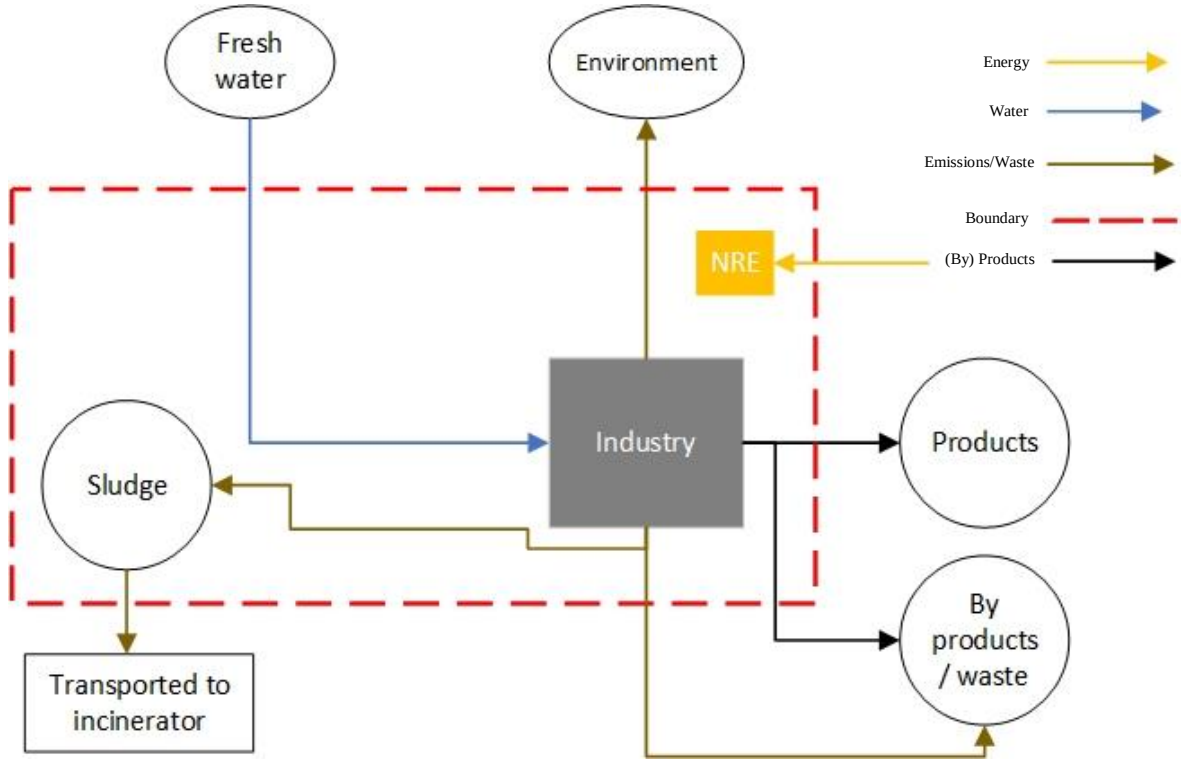

Figure 19 - Baseline: Water cycle of the (water circuit 1) TTI industry and water source and flows; Non-renewable energy sources and flows of TTI; TTI sludge and exhausted gas emissions flows; NRE: Non-renewable energy.

3.3.2.1.2 Scenario A – Energy recovery

Scenario A considers the integration of the proposed iWAYS solution, consisting of one experimental Heat Pipe Condenser Economiser (HPCE) and the iWAYS water treatment process (Figure 20) – within the defined boundary. The objective of the iWAYS solution integration is to increase the internal circularity level of the industry (i.e. energy and water recovery). Scenario A builds on the baseline (see description in section 3.3.2.1.1), and considers the integration of the HPCE (above a gap between the heating and cooling zone in the kiln HH3). No condensate will be recovered, as the HPCE is novel in design and operation, and focuses solely on thermal energy recovery.

A coolant liquid (insulated) flows through the HPCE's and is heated by the vapour as it flows upwards, while never in direct contact with the vapour exhaust. This thermal exchange between the vapour exhaust with the coolant liquid captures thermal energy by heating up the coolant liquid that can then be reused for purposes that require heating (e.g. pre heat the water for evaporator). This exchange can translate in a reduction of sourcing natural gas for heating purposes and consequently a source of renewable energy (RE) – Figure 20.

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The iWAYS water treatment system will treat the sludge produced in water circuit 1 by employing a pre-treatment process based on coagulation-flocculation with dissolved air flotation (DAF), a Membrane Distillation (MD) process and, a Photocatalytic Nano Filtration Reactor (PNFR) in series (D4.2), with the resulting treated water flowed directly back to the industry (Figure 20). The recovery rate of freshwater from sludge was calculated as ~66% (contribution: DAF = 91%; MD = 98%; PNFR = 74%). The resulting volume of sludge will decrease and be cheaper to transport for disposal.

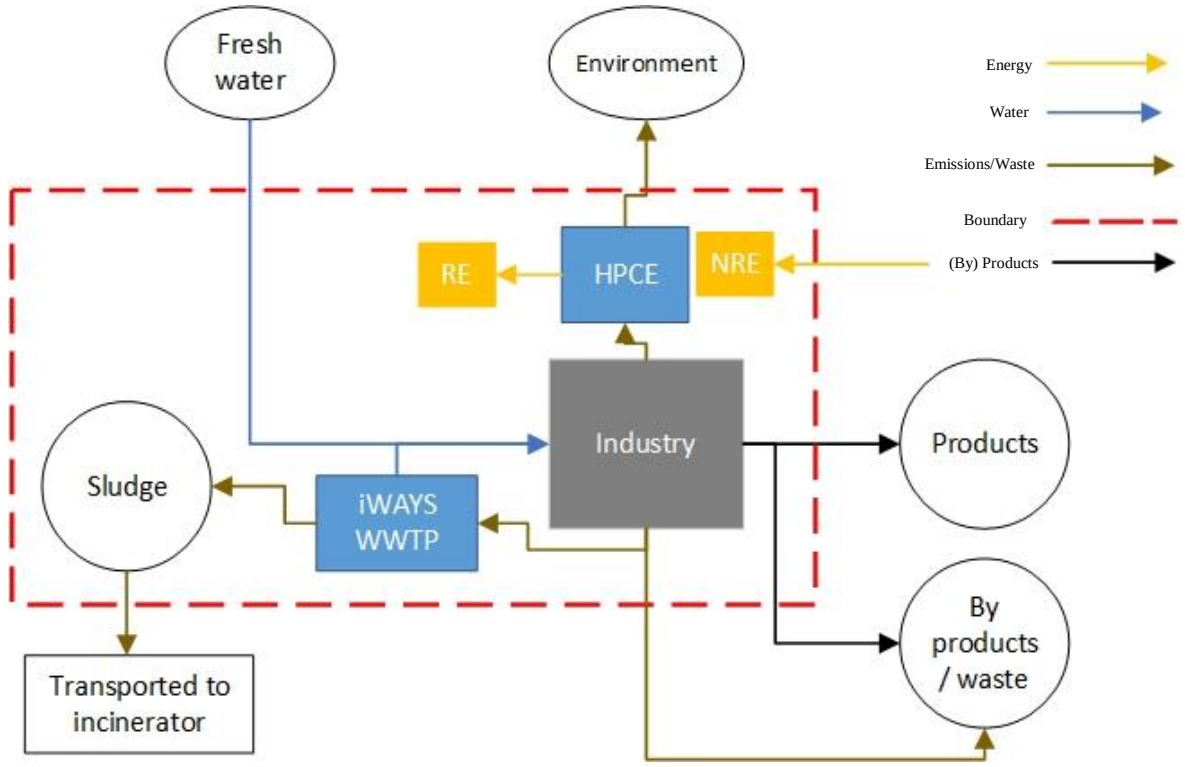

Figure 20 – Scenario A: Water cycle of TTI, and types of water sources and flows of the water treatment system; Renewable and non-renewable energy (HPCE) sources and flows of TTI; TTI waste and exhausted gas emissions flows; NRE: Non-renewable energy; RE: Renewable energy.

3.3.2.1.3 Scenario B – Scenario A + Rainwater harvesting

The third scenario, scenario B builds on scenario A with the integration of a rainwater rooftop harvesting process (Figure 21). The recovered rainwater volume can be used directly in the industrial processes as it presents a good enough quality (D4.1) – probably just requiring chlorine or other chemicals to control algal growth – or can be treated by the iWAYS water system and then stored / used. Annual precipitation in the industrial area and the roof-top area were considered in order to estimate the potential volumes of harvested rainwater (for further details consult D4.1) – including the first flush practise.

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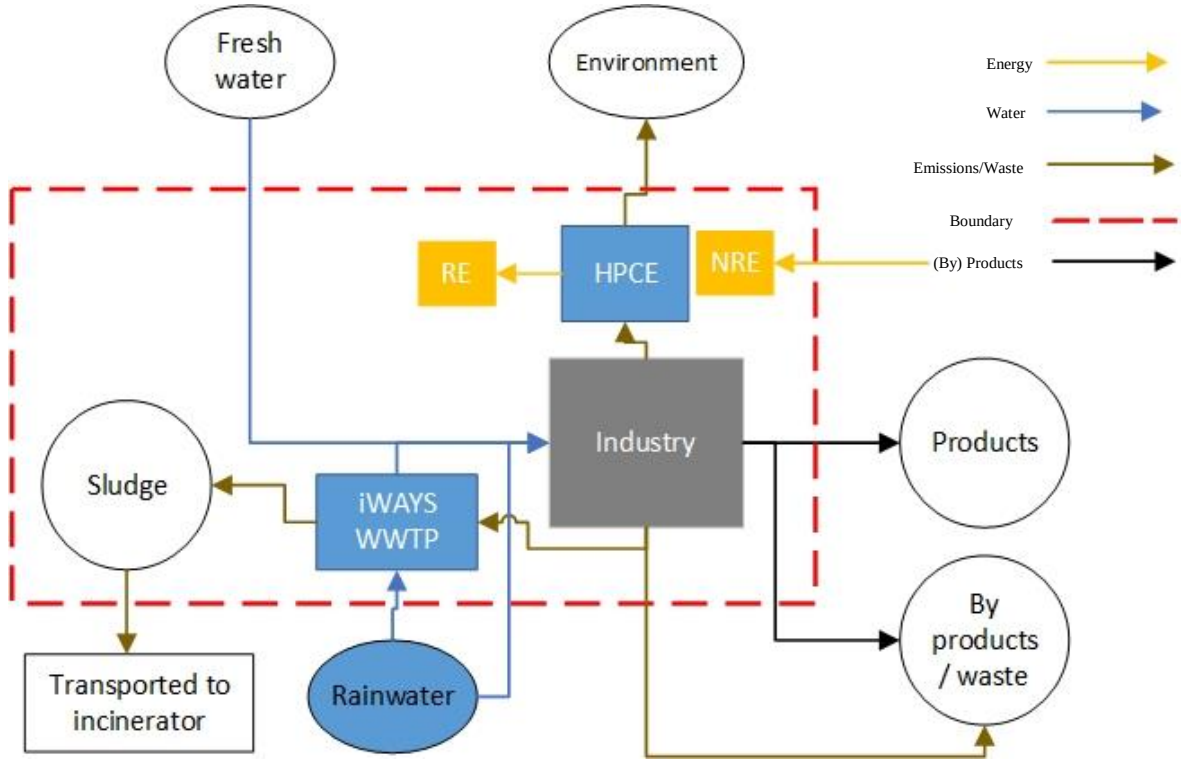

Figure 21 – Scenario B: Water cycle of the TTI, and types of water sources and flows with the water treatment system and rainwater harvesting integration; Renewable and non-renewable energy (HPCE) sources and flows of TTI; TTI sludge and exhausted gas emissions flows; NRE: Non-renewable energy; RE: Renewable energy.

3.3.2.1.4 Identification of the circular actions

The integration of the proposed iWAYS solutions intends to address the following identified circular actions:

- Reduce withdrawal of freshwater from the mainline by recovering water from the produced sludge in water circuit 1 and rooftop run-off;
- Upcycling the recovered water from sludge by treating it in the proposed iWAYS water treatment system;
- Reusing and recycling treated water and rainwater from the sludge tank and rooftop run-off, respectively;
- Reducing natural gas consumption (dependency) for pre-heating by recycling the wasted heat captured by the HPCE from the exhausted vapour gas;
- Reducing overall CO_2 footprint from natural gas consumption.

This resulted in an adaptation of the proposed by Nika et al. (2022) to measure the circularity level relating to 5 circular actions identified in the industrial Use Case within the WWE nexus framework: considering before (scenario - baseline) and after (scenario – A and B) the integration of the iWAYS solutions.

Furthermore, economic indicators were proposed to measure the potential economic performance of each scenario and aligned with the identified circular actions:

- Reducing overall costs associated with water withdrawal, energy and CO_2.

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3.3.2.2 Indicator selection

Table 29 presents the *Indicator selection* process method. The process consisted in exploiting the information gathered during the *System Development* step and to identify the category (Nexus) of the indicators, the purpose of the category, the overall goal of the category, and finally the indicators selected to represent each category. Complementary columns indicate the coverage (i.e. circular action) of the indicators: Reducing of Freshwater Withdrawal (*RFW*), Reducing Natural Gas Dependency (*RNGD*), Upcycling the Recovered Water (*URW*), Reusing and Recycling of Recovered Water, Condensate and Rainwater (*RRRWCR*), and Reducing Overall CO_2 Footprint (*ROCO$_2$F*). Indicators were proposed and selected from a collection of indicators for being the most appropriate for the identified circular actions (coverage).

Table 29 – Indicator selection process TTI: CE – Water, energy and waste CE indicators; and economic indicators.

Nexus	Purpose	Goal	Indicator	Coverage				
				RFW	RNGD	URW	RRRWCR	ROCO$_2$F
Water nexus	Close the loops / reduce environmental impact	Water circularity	Circular Water Inflow (CWI) Circular Water Outflow (CWO) Circular Water Flow (CWF) Onsite Water Circularity (OWC) Water Withdrawal Reduction (WWR)	X		X	X	
Energy nexus	Close the loops / reduce environmental impact / reduce non-renewable energy requirements	Energy circularity / sustainability	Renewable Energy Contribution (REC)		X			X
Waste nexus	Close the loops / reduce environmental impact	Waste circularity	Waste Utilisation Index (WUI)	X		X		
Economic coverage	Added value	Value gained with circular actions	Fuel Cost Saving (FCS) Total CO2 Cost Saving Water Cost Saving Total Saved Cost	X	X	X	X	X

RFW: Reducing Freshwater Withdrawal; RNGD: Reducing Natural Gas Dependency; URW: Upcycling the Recovered Water; RRRWCR: Reusing and Recycling of Recovered Water, Condensate and Rainwater; and ROCO$_2$F: Reducing Overall CO_2 Footprint.

Water nexus: the purpose of the assessment as explained in the system's development step focuses on the Reduction of Freshwater Withdrawal, Upcycling the Recovered Water and, Reusing and Recycling Wastewater, Condensate and Rainwater. Therefore, five (5) indicators were identified and selected to assess and cover three (3) of the identified circular action.

Energy nexus: relates to the heat recovered by the HPCE, resulting in a reduction of emitted emissions and wasted energy, consequently increasing energy circularity. Therefore, two (2) of the identified circular actions are covered by one (1) selected indicator.

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Waste nexus: exclusively regarding sludge water treatment, therefore neglecting vapour loss for the assessment – one (1) indicator was selected to cover two (2) circular actions. As the source of waste is not emissions (e.g. as with the previous two use cases), and rather solid waste in the form of sludge, the indicator employed has a slight change in naming but is calculated in the same manner:

- Waste Utilisation Index (WUI) indicates the amount of water recovered and used from sludge water by the iWAYS water treatment solution.

Economic indicators: after selecting the circular indicators that cover all identified circular actions (Table 29), the economic indicators must therefore inform on the economic benefits of the transition to sustainable renewable energy and water circularity. The total saved costs indicator covers all identified circular actions.

More information on the description of the indicators can be found in section 3.1.2.2 and Annex. The indicators selected to assess the TTI are the same as the indicators selected for CON, and ALU, therefore resulting in a direct form of comparison between all three industries and the proposed interventions.

3.3.2.3 Circularity measurement

3.3.2.3.1 Material Flow Analysis and Data collection – Water, Waste and Energy

With the identification of the circular actions and consequent indicator selection process complete, a Material Flow Analysis (MFA) was performed to identify flows and required data sets. As the CE assessment is performed within the WWE nexus framework, data requirements included TTI's monthly and annual operations regarding water use, waste (solid) production and energy consumption, as well as details relating to the nexus (e.g. source of energy, source of water, etc). The data supplied by TTI partners spanned from 2013 to 2022 (2021 and 2022 not complete). The year 2020 was not excluded from the analysis due to the COVID-19 pandemic, although operations during this year deviated slightly from normal industrial operations, it was included, while 2021 dataset was not complete due to a strike, and 2022's dataset was incomplete. Only datasets 2018, 2019 and 2020 were considered, as data was available for the three (3) nexus during these years

WATER

The Water nexus comprised of measuring linear and circular water flows identified in the system.

Monthly (2018 – 2020) and annual (2018 – 2020) freshwater consumption was supplied by the partners – datasets from 2021 and 2022 were not considered for the analysis as explained above. Table 30 presents monthly average, median, minimum and maximum values of fresh water consumption (2018 – 2020), and Table 31 presents annual average, median, maximum and minimum of freshwater consumption (2018 – 2020).

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Table 30 – Monthly Freshwater Consumption TTI (2018 – 2020).

Monthly Freshwater Consumption (m^3 / month): 2018 – 2020			
Month	Average	Maximum	Minimum
January	6 917	7 423	6 164
February	7 953	10 743	6 279
March	8 903	10 124	6 792
April	6 505	7 535	4 685
May	7 066	8 793	5 005
June	8 666	10 826	6 228
July	12 284	14 820	10 080
August*	-	-	-
September	10 470	17 369	4 601
October	8 582	10 487	6 027
November	3 720	4 367	3 394
December	5 385	9 929	2 428
Monthly	**7 859**	**17 369**	**2 428**

*closed for summer holidays

Table 31 – Annual Freshwater Consumption TTI (2018 – 2020).

Annual Freshwater Consumption (m^3 / year): 2018 – 2020			
Parameter	Average	Maximum	Minimum
Freshwater	**87 694**	**99 322**	**65 475**

For the WWE nexus modelling exercise, and a form to ensure that operations are current, the dataset from 2021 should be considered. However, due to the specificities of the current use case concerning the year 2021, and also 2022, it was decided to use the averages from the 2018 – 2020 (monthly and yearly). 2018 and 2019 datasets presented the highest values that indicate the highest freshwater consumption, with a decrease (~34%) in 2020, therefore the sets can be considered representative of the last years of operation. The percentage of freshwater use in the system on an annual basis (2018 – 2020) is shown in Figure 22. The majority of freshwater from 2018 to 2020 was consumed by the pickling process and pools (~85%).

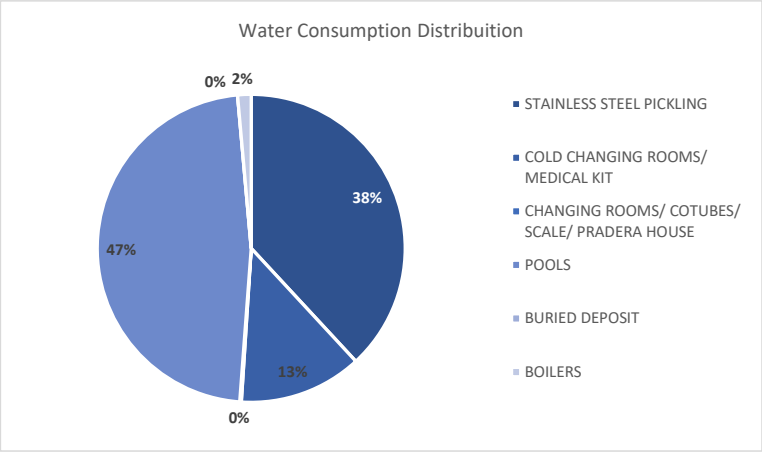

Figure 22 – Freshwater Consumption Distribution TTI (2018 – 2020).

ENERGY / ELECTRICITY

The Energy nexus also consisted in measuring linear and circular energy flows of the system.

Monthly and annual energy / electricity consumption from 2018 – 2020, were supplied by TTI partners (2021 and 2022 were not used for the same reasons as explained above). Energy is

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obtained from two (2) Non-Renewable Energy (NRE) sources, which includes electricity from the grid and Natural Gas to burn to produce thermal energy.
Table 32 presents monthly average, median, minimum and maximum values regarding energy / electricity consumption, and Table 33 presents annual average, median, maximum and minimum of energy / electricity consumption.

Table 32 – Total Monthly Energy / Electricity Consumption TTI (2018 – 2020).

Total Monthly Energy / Electricity Consumption (MWh / month): 2018 – 2020			
Month	Average	Maximum	Minimum
January	5 018	5 141	4 778
February	4 856	5 116	4 704
March	4 384	4 715	3 743
April	3 725	4 339	2 902
May	4 189	4 962	3 004
June	4 144	4 893	3 242
July	6 135	7 066	5 082
August	-	-	
September	3 803	4 665	3 120
October	4 177	4 767	3 297
November	4 236	5 165	3 139
December	3 416	3 534	3 224
Monthly	**4 371**	**7 066**	**2 902**

Table 33 – Total Annual Energy / Electricity Consumption TTI (2018 – 2020).

Total Annual Energy / Electricity Consumption (MWh / year): 2018 - 2020			
Years	Average	Maximum	Minimum
2018 – 2020	**48 084**	**52 353**	**40 544**

For the WWE nexus modelling exercise, and a form to ensure that operations are current, the dataset from 2021 should be considered. However, due to the specificities of the current use case (and datasets) concerning the year 2021, and also 2022, it was decided to use the averages from the 2018 – 2020 (monthly) and 2018 – 2020 (yearly). 2018 and 2019 datasets presented the highest values that indicate the highest energy consumption, with a slight decrease (~22%) in 2020, therefore the sets can be considered representative of the last years of operation. The percentage of energy sourcing of the system on an annual basis (2018 – 2020) is shown Figure 23. The majority of energy sourcing during 2018 to 2020 was from natural gas burning (~70%).

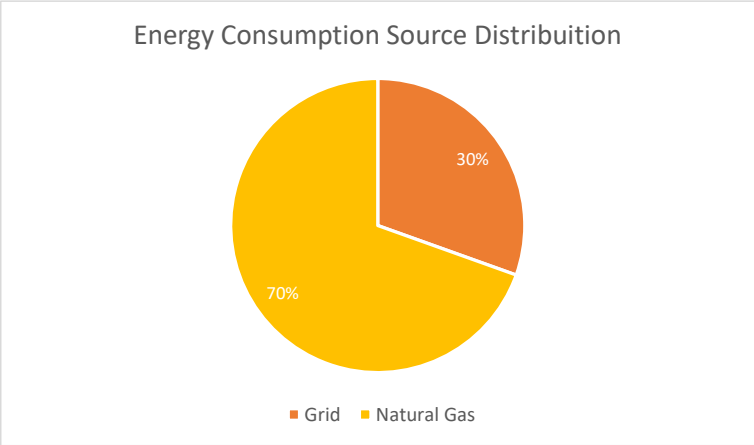

Figure 23 – Energy / Electricity Consumption Source Distribution TTI (2018 – 2020).

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WASTE

The waste nexus also consisted in measuring linear and circular waste flows of the system. As no emissions will be condensed, this was not modelled and characterised for the WWE nexus exercise, however the iWAYS water treatment process will treat the waste stream (sludge) from the water circuit 1, and consequently recover the water to be reused in the system. Therefore, Table 34 and Table 35 present the monthly and annual production rates regarding the sludge production from water circuit 1 for 2018 – 2020. Pollutant concentrations and loads can be found in D2.2.

Table 34 – Total Monthly Sludge Production TTI (2018 – 2020).

Total Monthly Sludge Production (m^3 / month): 2018 – 2020			
Month	Average	Maximum	Minimum
January	85	175	10
February	165	243	85
March	117	196	64
April	59	110	22
May	110	195	39
June	67	91	23
July	102	152	67
August	40	89	8
September	82	138	41
October	109	176	66
November	131	245	61
December	112	242	5
Monthly	**98**	**245**	**5**

Table 35 – Total Annual Sludge Production TTI (2018 – 2020).

Total Annual Sludge Production (m^3 / month): 2018 – 2020			
Years	Average	Maximum	Minimum
2018 – 2020	**1 180**	**1 479**	**909**

Sources of waste from the TTI use-case are displayed in Figure 24. It is possible to observe that the majority of waste produced by the industrial case is in the form of sludge drainage from water circuit 1, the target of the iWAYS waste treatment plant.

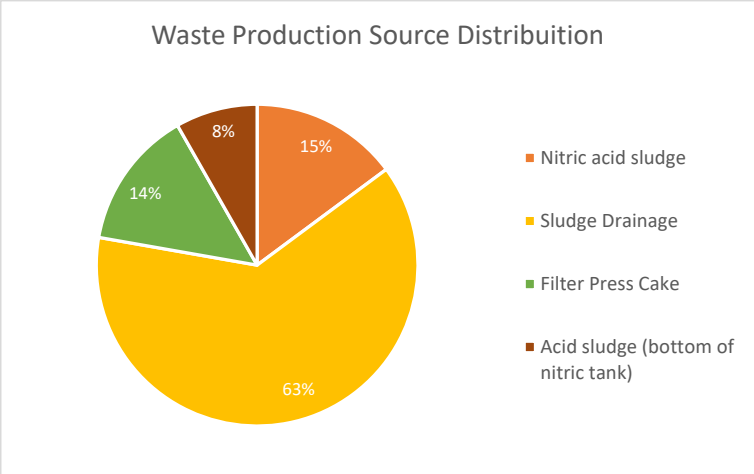

Figure 24 – Waste Production Source Distribution TTI (2018 – 2020).

Models

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The WWE nexus was modelled according to the data supplied by TTI partners (input and output), and a consequent mass balance. No modelling exercise was performed for the HPCE as it will not recover condensate.

Economic coverage

Monetary values were acquired and assumptions were made to calculate the economic indicators for (Table 36).

Table 36 – Monetary values and assumptions for economic coverage indicator calculation TTI.

Parameter	Value	Unit	Source
Natural Gas	0.058	€ / kWh	https://www.statista.com/statistics/1320867/monthly-natural-gas-procurement-prices-spain/
Emissions Allowances	85.22	€ / ton CO_2	https://www.statista.com/statistics/1322214/carbon-prices-european-union-emission-trading-scheme/
Tap / Freshwater	1.60	€ / m^3	https://virtoproperty.com/info/utilities-in-spain-electricity-gas-water-costs#4

3.3.2.4 System testing

The *system testing* step assesses whether the selected indicators are sensitive or resilient to changes in the data and consequent system changes. However, for the TTI use case this was not performed due to the experimental nature of the HPCE. It is an experimental unit with the objective to recover thermal heat and will not recover any condensate. The current novel design will be tested at the TTI use case to observe the efficiency for thermal energy recovery.

3.3.2.5 Circularity assessment

The circularity assessment consists in benchmarking scenarios A and B against current operations (baseline scenario) considering the identified circular actions and indicators. It also consists in performing a dynamic simulation with historical rainfall data and assessing the results regarding potentiality. To perform the benchmark assessment, the identified circular actions indicators are assessed and compared with the baseline scenario. Regarding the dynamic assessment, the objective is to understand what variations (if any) occur to the indicators and consequent circular actions concerning freshwater consumption (water circularity) and its impact on economic performance.

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3.3.2.5.1 Circularity measurement and assessment: Baseline vs scenario A vs B (benchmark assessment)

Table 37 shows the circular economy (CE) and economic indicators scores for the baseline, scenario A and B. Each nexus is discussed in detail below.

Table 37 – Circularity assessment results for the baseline and scenario A and B, TTI.

Category	Indicator	Unit	Baseline	Scenario A	Scenario B
Water	CWI	%	0.00	0.00	64.70
	CWO	%	0.00	0.00	0.00
	CWF	%	0.00	0.00	32.35
	OWC	Number of drops	1.00	1.01	2.86
	WWR	%	-	0.89	65.01
Energy	REC	%	-	1.46	1.46
Waste	WUI	%	-	74.47	74.47
Economic	Fuel Cost Saving	€/year	-	40 646	40 646
	Total CO_2 Cost Saving	€/year	-	10 533	10 533
	Water Cost Saving	€/year	-	1 241	91 112
	Total Saved Cost*	€/year	-	44 100	133 972

CWI – Circular Water Inflow; CWO – Circular Water Outflow; CWF – Circular Water Flow; OWC – Onsite Water Circularity; WWR – Water Withdrawal Reduction; REC – Renewable Energy Contributions; WUI – Waste Utilisation Index. *Accounts for the sludge residue that still needs to be transported for incineration + gains from not transporting the volume recovered (80 €/m3).

3.3.2.5.2 Water nexus

The current average baseline freshwater input for the industry was 87 694 m^3/year, resulting in 1 180 m^3/year of produced sludge which is transported for disposal, and the remaining amount of water is lost in the processes and as vapour through the chimney stacks. Assessing the *baseline scenario*'s indicators shows that withdrawal of non-renewable water (freshwater) is 100% and that no water is recovered as it is exhausted as vapour gas and discharged (WWR = 0.0%) – not accounting for water circuit 1 which already closed the loop, however the indicators do not consider the calculation of internal circular water input to the system, only external sources of the boundary are considered. As produced water vapour volumes are low, this was not quantified in the assessment – preliminary calculations indicate that between 3 and 9 m^3/year of water vapour from HH1 and HH2 are potentially produced (D2.2) – potentially other stacks have higher vapour loss. Assuming that water is not left in the products or by products, this results in a CWF score of 0.00% and implies that current the circular water flow is 0.00% circular. This is due to the CWI and CWO indicators, which contribute to calculate CWF (Annex), both yielding 0.00%. The OWC demonstrates that water has a one-use purpose (OWC = 1.0) and is disposed of, again no accounting for the loop closed in water circuit 3.

Scenario A consisted in integrating the iWAYS HPCE and water treatment plant to the baseline setup. The maximum recovery rate of condensate by the HPCE was considered 0 l/h (100% efficiency) corresponding to 0 m^3/year of recovered water condensate from potentially because the design is novel and the unit experimental. The iWAYS water treatment system's total recovery efficiency was calculated as 66% (D4.2), with the remaining 34% resulting in waste and requiring disposal. For this scenario the total amount of sludge water produced was 1 180 m^3/year, where 66% of the volume is treated, recovered and recycled into the water circuit 1 processes (D4.2). However, this did not yield any changes to the system in terms of water as demonstrated by the CWF indicator (0.00%), as there is no condensate recovery. Observing the CWI and CWO indicators demonstrates a score equal to the baseline scenario (0.00%), which was expected. The reason is that internal circular water input to the system is not accounted for in the indicators calculation, only external sources from the boundary. OWC increased only to by 0.01 (OWC = 1.01) as the integration of the iWAYS water treatment

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recovers 776 m^3/y (relatively low to the total amount of freshwater consumption of 87 694 m^3/year). This can also be seen as the iWAYS water treatment system's total recovery efficiency of around 66% contributes by only increasing the WWR indicator to 0.89% over the baseline scenario, signifying there was a slight decrease in freshwater withdrawal and slight increase in the water reuse (the volume of recovered water is relatively low compared to the amount of freshwater withdrawn).

Scenario B consisted in extending scenario A with the rainwater harvesting solution. This scenario assumes that rainwater can be used directly onsite (requiring only chemical treatment to reduce algal growth) as it potentially presents an equivalent quality compared to the treated and recovered sludge water (D4.1 and D4.2). By analysing D2.2, it was possible to assume that on average 56 111 m^3/year of rainwater can potentially be harvested from a rooftop area of 72 216 m^2. This potential volume of harvested rainwater reflected in a positive increase in water circularity, with CWF increasing to 32.35%, and also WWR increased to 65.01%. The increase in CWF is credited with the increase of the CWI (64.70%) due to the harvested rainwater. The CWF indicator overall value increases because rainwater harvesting is considered a form of water withdrawal from a circular input (OECD, 2023). No contribution was verified from the CWO indicator. The current assessment included the dataset from the Victoria Fonda location (D4.1). If the Bilbao datasets were considered in the assessment, the volume of potential rainwater would be higher (potentially 30 000 m^3/year more), affecting on the water indicators further. However, this exercise preferred to take on a conservative approach for calculating the potential of rainwater harvesting. Additionally, the OWC increased from 1.00 to 2.86 indicating a significant increase on reused water by the industry.

3.3.2.5.3 Energy nexus

By introducing the HPCE, thermal energy is captured from wasted heat which can potentially be used to preheat processes in the industrial system (e.g. evaporator). To quantify current (baseline) and potential changes induced by incorporating the HPCE in scenario's A and B, the Renewable Energy Contribution (REC) indicator was selected. The REC informs on the amount of RE sourced and therefore the transitional progress of the system to a more sustainable and carbon neutral reality. By calculating the REC for the three scenarios, it is possible to conclude for the baseline scenario the indicator scored 0.00%, as no RE is captured. With the integration of the HPCE, the REC can potentially increase its value to 1.46% in both scenario's A and B. Scenarios A and B present a relatively small increase in RE use over the baseline scenario.

3.3.2.5.4 Waste nexus

As mentioned previously, solid waste was the only waste accounted for the modelling exercise of the WWE nexus model, as it is the target of the iWAYs water/sludge treatment plant. Therefore, waste was considered as sludge produced from water circuit 1 and the Waste Utilisation Index (WUI) was considered to quantify the baseline scenario and scenario A and B. the WUI represents the % of emissions used or recycled that would otherwise be lost, back into the system. As no waste is recirculated in the baseline scenario considering water circuit 1 was 0.00%. Regarding scenario A and B, it is possible to observe that both presented the same value of 74.47% exclusively due to the treatment of all the sludge water produced in water circuit 1. This indicates that 74.47% of the water in the total sludge produced from water circuit 1 is recovered, treated and reused in the system (the remaining % is sent for sludge for disposal). This has an offset effect regarding monetary value for transporting sludge for incineration (see section 3.3.2.5.5).

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3.3.2.5.5 Economic coverage

Economic indicators were selected to cover the identified circular actions to indicate the value added by the interventions, therefore they indicate what potential annual economic savings are potentially achieved in regard to water and energy resources, as well as emissions (i.e. monetary CO_2 savings for society). Therefore, economic indicators were selected to demonstrate their economic coverage of the identified circular actions (Table 37 and proposed in D6.1 / D6.2). The circular actions of reducing natural gas consumption and overall CO_2 footprint by integrating the HPCE (scenario A) indicates a potential fuel cost saving and CO_2 cost saving of 40 646 € and 10 533 € per year, respectively for both scenario A and B. Regarding reduction of fresh water withdrawal, upcycling recovered sludge water and, reusing and recycling of recovered water shows that scenario A can potentially contribute by saving 1 241 € per year due to the water recovery and upcycling through the iWAYS water treatment system compared to the baseline scenario (water savings do not depend on the HPCE's contribution). Scenario B on the other hand demonstrates that an increase in the water cost saving by 73 times (91 112 €/year), in relation to scenario A through rainwater harvesting practices.

Therefore, through the lens of the identified circular actions, the iWAYS solutions have the potential to promote savings of up to 44 100 €/year for scenario A and 133 972 €/year for scenario B over the baseline scenario. The main contribution to the monetary savings is attributed to the decrease in non-renewable energy requirements and consequent decarbonisation, and rainwater harvesting in scenario B. The value of transported sludge in the baseline scenario is 94 416 €/year, with the inclusion of the iWAYS solutions this has the potential to decrease to 32 373 €/year, saving up to 62 042 €/year.

3.3.2.5.6 Dynamic assessment – Annual rainwater variation impact

For the water circularity assessment, a potential scenario analysis was performed by considering the historical annual precipitation in the Victoria Fonda region in Spain between the year 1943 and 2021 (D2.2). Considering a potential harvesting rooftop area of 72 216 m^2 – D2.2 – the potential rainwater harvesting volumes were calculated for the historical time period (Table 38). As mentioned before this exercise took on a conservative form by utilising the information from Victoria Fonda weather station and not Bilbao weather station, which presented a potentially higher volume of harvested rainwater (D2.2). The rainwater harvesting potential considers maximum, minimum, average and median rainfall volumes for the industrial location, therefore demonstrating significant differences in potential. Considering the dynamic modelling exercise for rainwater harvesting, indicators regarding Water Withdrawal Reduction (WWR) and the associated economic indicator for total potential water recovery (rainwater) were calculated.

Table 38 - Potential rainwater harvesting volume (1943 - 2021) TTI.

Month	Average (m^3)	Median (m^3)	Max (m^3)	Min (m^3)
January	5 887	5 517	17 563	0
February	5 019	4 362	16 754	260
March	4 921	4 365	14 277	87
April	5 259	4 788	12 580	737
May	4 913	4 369	14 537	0
June	3 767	3 466	12 219	339
July	2 385	1 935	9 814	36
August	2 650	2 116	17 512	108
September	3 553	2 614	21 080	130
October	4 965	4 607	17 216	332
November	6 579	5 860	18 271	0

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December	6 272	5 889	18 292	0
TOTAL	**56 111**	**49 831**	**190 057**	**1 970**

Figure 25 presents:

- The calculation of the WWR indicator considering the potential average, maximum and minimum rainwater harvested and the relating;
- Average, maximum and minimum monetary value of the potential water rainwater recovered;
- The red line indicates the potential average monthly savings.

The dynamic assessment considers that the harvested rainwater does not require treatment as it already presents a good enough quality to be used in the system, other than the addition of chlorine (or other chemical) to eliminate or reduce potential growth of algal biomass. The analysis shows that for all months, except July and August, a WWR score above 50% is potentially achievable (average freshwater coverage with rainwater is around 65%) which represents a potential monetary saving of 91 112 €/year (monthly average savings of 7 600 €). On the other hand, Figure 25 also shows that, the months with potentially lower average harvested rainwater (WWR = 34 and 37%) are July and August, which can be considered the drier months for the region and therefore result in lower water savings per month (~4 000 €) (Table 38). Regarding the maximum volumes that can be harvested, it is possible to see that harvested rainwater can cover all freshwater requirements for the TTI industry in all months (negative values), which can be stored for later use, or sold to other industries in the vicinity, therefore promoting industrial symbiosis.

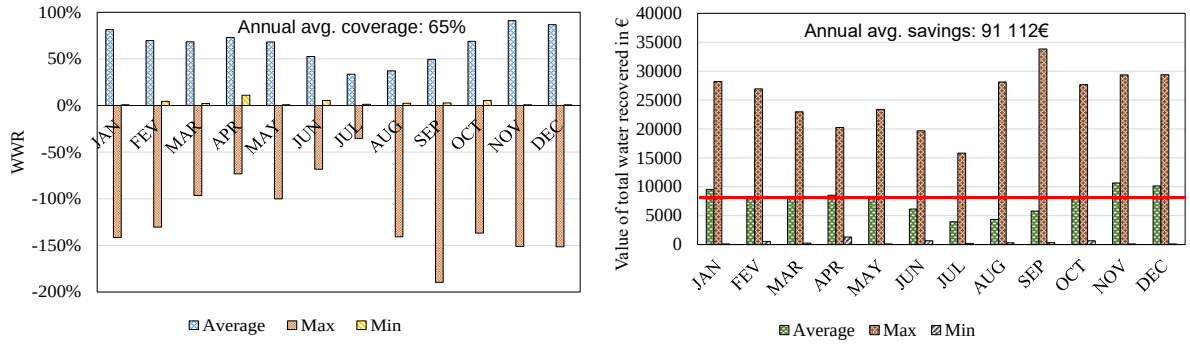

Figure 25 – (a) Average, maximum and minimum for the WWR indicator and (b) the monetary value of the recovered water (condensed and rainwater) monthly, TTI.

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4 Conclusion

Through the circularity measurement under the Nexus umbrella, the integration of the iWAYs solutions (i.e. iWAYS HPCE, iWAYS water treatment and rainwater harvesting) were assessed. Table 39 andTable 40 show the circular and economic indicators of the scenarios A and B of each end-user, respectively.

Table 39 – Scenario A circularity and economic scores of the 3 end-users.

Category	Indicator	Unit	CON	ALU	TTI
Water	CWI	%	0.00	0.00	0.00
	CWO	%	5.57	7.03	0.00
	CWF	%	2.79	3.51	0.00
	OWC	Number of drops	1.31	1.76	1.01
	WWR	%	1.59	43.31	0.89
Energy	REC	%	4.05	15.74	1.46
Waste	EUI	%	10.81	28.65	74.47
Economic	Fuel Cost Saving	€/year	875 678	445 675	40 646
	Total CO_2 Cost Saving	€/year	176 272	79 112	10 533
	Water Cost Saving	€/year	1 655	89 114	1 241
	Total Saved Cost	€/year	1 053 606	613 900	44 100

Table 40 - Scenario B circularity and economic scores of the 3 end-users.

Category	Indicator	Unit	CON	ALU	TTI
Water	CWI	%	33.15	3.33	64.70
	CWO	%	5.57	9.49	0.00
	CWF	%	19.36	6.41	32.35
	OWC	Number of drops	1.70	1.77	2.86
	WWR	%	16.50	45.22	65.01
Energy	REC	%	4.04	15.74	1.46
Waste	EUI	%	10.81	28.65	74.47
Economic	Fuel Cost Saving	€/year	875 678	445 675	40 646
	Total CO_2 Cost Saving	€/year	176 272	79 112	10 533
	Water Cost Saving	€/year	17 137	93 042	91 112
	Total Saved Cost	€/year	1 069 088	617 829	133 972

The iWAYs HPCE integration shows an increase of renewable energy use for all end-users indicating steps towards circularity and sustainability, and consequently decarbonisation. The Renewable Energy Contribution (REC) indicator, calculated for each end-user is different due to the specificities of each use case such as the amount of non-renewable energy consumption (e.g. natural gas), different HPCE capacity, the number of units and overall design. Despite, the HPCE designed for the CON industry having a higher energy recovery capacity (1.3 MWh) compared with the HPCE planned for the ALU AB (600 kWh) and TTI (80 kWh) use-cases, the CON industry has a much higher demand for thermal energy compared with the ALU AB industry, therefore resulting in REC indicator that lower when compared with ALU AB (CON = 4.05% vs ALU AB = 15.74%).

Regarding water circularity, the HPCE does not increase significantly the water circularity for CON and nothing for TTI (experimental) due to the low amount of water recovered compared with the amount of water demand. Only if the rainwater harvesting solutions are integrated does the water circularity potentially present significant increases for the CON and TTI of

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19.36% and 32.35%, respectively. Moreover, rainwater harvesting can potentially promote a significant water withdrawal reduction for both use-cases (CON – 16.50%, TTI – 65.01%), and the dynamic assessment shows that in certain months, harvested rainwater can cover the water demand for CON and TTI. Regarding ALU AB, the new water cycle flow imposed in scenario A immediately increased water circularity, however no significant increase was observed regarding rainwater harvesting.

Regarding the waste nexus, the integration of the HPCE (rainwater harvesting does not affect it) potentially decreases emissions in CON and ALU AB, while sludge waste is reduced in the TTI use-case as volumes of water are recovered and reused, therefore demonstrating an increase in waste utilisation.

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6 Annexes

Circular Water Inflow (CWI):

$$\text{CWI} = 1 - \frac{\text{Volume of water withdrawal from non circular sources}}{\text{Total volume of water withdrawal}}$$

Circular Water Outflow (CWO):

$$\text{CWO} = 1 - \frac{\text{Volume of water discharged} + \text{Volume of water losses}}{\text{Total volume of water outflow (circular and non circular)}}$$

Exhausted gas that is being emitted is considered as a non-circular water flow because it is emitted to the air, therefore this volume of water is lost from the freshwater resources of the area. Another outflow consider is the water discharged into the environment or treatment system outside of the boundaries.

Circular Water Flow (CWF):

$$\text{CWF} = \frac{\text{CWI} + \text{CWO}}{2}$$

Water Withdrawal Reduction (WWR):

$$\text{WWR} = \frac{\text{WW}_0 - \text{WW}_1}{\text{WW}_0}$$

Where, WW_0 is the volume of water that would be withdrawn from freshwater resources if no circularity actions were taken, or the volume of water that is withdrawn from freshwater resources during the first year of system's operation; and WW_1 is the volume of water that is actually withdrawn from freshwater resources in the investigated end-user case.

Onsite Water Circularity (OWC):

$$\text{OWC} = \frac{\text{Volume of water use} - \text{Total volume of water withdrawal}}{\text{Total volume of water withdrawal}} + 1$$

Where the Volume of water is the sum of all water required by all its processes.

Renewable Energy Contribution (REC):

$$\text{REC} = \frac{\text{Renewable energy in kWh used in the system}}{\text{Total energy demand of the system}}$$

Emissions Utilisation Index (EUI):

$$\text{EUI} = \frac{\text{Amount of utilized direct emissions}}{\text{Amount of utlized direct emissions} + \text{Amount of generated direct emissions}}$$

Where the amount of utilized direct emissions is the amount of water recovered from the exhausted gas, and the amount of generated direct emissions is the total amount of water in the exhausted gas.

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Waste Utilisation Index (WUI):

$$\mathrm{WUI} = \frac{\text{Amount of utilized waste}}{\text{Amount of utilized waste} + \text{Amount of generated waste}}$$

Where the amount of utilized waste is the amount of waste used for resource recovery purpose, and the amount of generated waste is the total amount of waste produced.

Fuel Cost Saving (FCS):

$$\mathrm{FCS} = \text{Total energy recovered} \times \text{Price of energy}$$

Total CO_2 cost saving*:

$$\mathrm{CO2\ saving} = \text{Saved CO2} \times \text{Cost of CO2 emissions}$$

Where CO_2 saved is in € / year, the price of natural gas is in ton / year and the emission allowance is in € / ton of CO_2.

Water cost saving:

$$\text{Water cost saving} = \text{Total volume of water recovered} \times \text{Price of water}$$

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