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Circularity assessment of industrial heat exchanger and water treatment systems integration

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ABSTRACT

Water recycling and reusing strategies in industries have been promoted to reduce freshwater consumption. In addition, Heat Pipe Heat Exchanger technology has been employed successfully, resulting in the reduction of natural gas consumption and mitigating greenhouse gas emissions. It is important to assess the true benefits of the application of these Circular Economy strategies. Therefore, this work assesses the integration of a Heat Pipe Condenser Economiser (HPCE) and a water treatment system in a ceramic industry. Additionally, rooftop rainwater harvesting is integrated into the industry. The CE assessment methodologies and selected indicators measure the efficiency of the transition from a linear to a circular economy and identify strategies for optimisation. However, the interactions between human and natural systems related to the abstraction of resources and release of outflows are not considered. This is important to understand potential disruptions when implementing circular actions. Therefore, the assessment focuses on circular principles such as resource traceability and value created by implemented actions, and through resource flow and circular action indicators, the intrinsic circularity of system integration is quantified. The assessment showed the integration of both systems and the rooftop rainwater harvesting increased the Circular Water Flow and the Water Withdrawal Reduction up to 33.73 % and 22.88 %, respectively. Moreover, it demonstrates that the HPCE integration increased the Recovered Energy Contribution up to 19.98 %. This indicates the system's integrations increased circular performance over the baseline scenario. Additionally, the assessment enabled a scenario analysis which aided in identifying further strategies to improve the circular actions, such as reducing freshwater withdrawal.

1. Introduction

An increase in global water and energy demands is expected in the coming years due to overall growth in global consumption. However, the requirements and ability to meet these increases are likely to be hindered due to the ever-increasing reliance on (inter)dependencies between water, energy, and climate change [1]. The global water demand is estimated to increase from 3,500 km^3 per year in 2000 to approximately 5,500 km^3 per year in 2050 [2], much due to overall population growth, urbanisation, migration and industrialisation – creating an ever-increasing need for freshwater resources [3]. The industrial sector is responsible for 12 % of global water withdrawals, which is projected to increase by 400 % in 2050, and result in severe consequences for the environment and ecosystems both locally and globally [2]. Energy is another resource highly employed by the industrial sector, with 9,566 TWh of energy employed globally in 2019 [4] being a significant contributor to greenhouse gas emissions [5], and consequently climate change. Therefore, the European Union has identified climate and energy strategies with a focus on energy efficiency, decarbonisation and the development of renewable energy sources as a target to achieve carbon neutrality [6].

As pressures mount on the world to transition to a Circular Economy

Abbreviations: CE, Circular Economy; CWF,CWO, Circular Water Outflow; CWI, Circular Water Inflow; HPCE, Heat Pipe Condenser Economiser; HPHE, Heat Pipe Heat Exchanger; NF, Nanofiltration; NRE, non-Renewable Energy; OWC, Onsite Water Circularity; REC, Recovered Energy Contribution; SDGs, Sustainable Development Goals; UF, Ultrafiltration; WUI, Waste Utilisation Index; WWR, Water Withdrawal Reduction; WWTP, Wastewater Treatment Plant.

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(CE) and valorise all forms of resources by recovering, repurposing, recycling, upcycling, reusing, and others, innovative technologies will help pave the way. In order to demonstrate the decoupling of imprudent resource consumption from economic growth and development, the CE approach has been promoted to achieve resource efficiency, reduce waste production and improve environmental, economic and social sustainability [7]. A CE action can be defined as an action that produces a circular intervention in a linear process or system to endorse circular principles. Circular principles are broadly accepted as those suggested by the Ellen MacArthur Foundation – "Design out waste externalities", "Keep resources in use" and "Regenerate natural capital"[8]. Moreover, CE principles have been employed to tackle the over-consumption of resources, contributing to the Sustainable Development Goals (SDGs). When focusing on industrial economics, the CE was conceptualised as a strategy for waste prevention, regional job creation, resource efficiency, and dematerialisation of the industrial economy. Also, it emphasised the utilisation instead of ownership of goods as the most relevant sustainable business model for a loop economy, allowing industries to profit without externalising costs and risks associated with waste. The contemporary understanding of the Circular Economy and its practical applications to economic systems and industrial processes has evolved to incorporate different features and contributions from a variety of concepts that share the idea of closed loops [9].

The United Nations developed the SDGs initiative which has set a goal for water, namely through Goal No. 6 – "Ensure availability and sustainable management of water and sanitation for all". Thus, water recycling and reuse have been taken as one of the most important methods to achieve the goal. Due to the growth of freshwater scarcity and environmental protection concerns, water recycling and reuse as well as other resource recovery have been promoted in industries. Over the last decade, data have revealed that water recycling and reuse practices have improved exponentially [10]. Nanofiltration method is employed in a variety of water and wastewater from different industrial applications for the selective removal of ions and organic compounds [11], and water purification [12]. Moreover, two-stage ultrafiltration and nanofiltration have been investigated for recycling resources and water from different types of water and wastewater [13,14].

Regarding energy, SDGs have set a target for energy research and technology. The integration of waste heat recovery systems in industrial processes has been important as one of the major areas of research to decrease fuel consumption, mitigate harmful emissions and improve production efficiency. Industrial waste heat is the energy that is generated from industrial processes which is not harnessed in any practical way and is wasted or released into the environment. Waste Heat Recovery systems, also known as Heat Pipe Heat Exchangers (HPHE), are introduced in a system to promote optimum waste heat recovery efficiency [15], and are associated with nearly every industry, mostly in energy generation and heat exchange in general [16]. Furthermore, the HPHE technology can mitigate greenhouse gas emissions in industries which are highly dependent on natural gas consumption like ceramic industries [17].

Some industries generate gases (e.g. flue) that if released into the atmosphere contain a considerable amount of vapor form. If the gas temperature could be reduced below the dew point, the water vapor would begin to condense and sensible heat (convection), as well as latent heat (condensation) of the gas, could be recovered. Also, water in the form of condensate could be used repeatedly in the plant after its treatment [18]. This combination of resource recovery and use is being investigated due to their CE principles and benefits.

The CE strategies on water and energy endorsed by the industrial sector have gained momentum. By adopting CE principles, resource depletion and waste generation can be significantly reduced as materials are kept within the system for as long as possible. To transit towards a more circular and sustainable economic paradigm, it is imperative to assess the circularity potential within a specific industrial estate [19]. Assessing the CE principles is important for the analysis of their true impact. It provides a way to understand how well different industries are integrating circular strategies into their processes, essentially demonstrating how industries are adapting to a more sustainable approach. Assessment methodologies measure the efficiency of the transition from a linear to a circular economy and identify strategies to improve [20]. Measuring circularity requires selecting and validating CE indicators to assess the progress of identified CE actions in a specific system and sector [21].

However, circularity assessment must also characterise and measure the impact of resource abstraction and outflow release on the origin and destination, respectively. Characterising linear and circular resource flows enables an understanding of potential disruptions when implementing circular actions to reduce resource depletion or close resource loops within the industries and their interactions with the natural environment.

Therefore, this work adapted a circularity assessment framework developed for water systems by Nika et al. [22] as the framework incorporates resource flow characterisation and the measurement of the circular action performance. Additionally, the purpose of this work is to transfer this complete framework to the industrial sector. The adapted framework is hereby, applied for the assessment of a ceramic industry which integrated two systems in the production process intending to increase circularity by reducing freshwater and natural gas consumption.

2. Methodology

2.1. Circularity framework

The framework considered has been adapted from Nika et al. [22] and encompasses five steps (Fig. 1):

1) system development;
2) resource flows;
3) circular actions;
4) circularity measurement;
5) circularity assessment.

The first step regards the goal and scope definition, and the system boundaries under the scope. This definition enables the identification of the processes and resources that flow in and out of the assessment boundaries. The resource flow characterisation classifies the circular and linear flows that are part of the intervention in the industry. The flows can be materials, water, energy, waste or economic. Indicators are selected to differentiate the circular and linear fractions of the inflow and outflow. The circular actions are the strategies that the industrial sector can employ to accomplish CE principles. The identification of circular actions determines what needs to be measured and assessed, thus resulting in a crucial step for the selection of appropriate circularity indicators that translate those circular actions [22]. In the circularity measurement step, data is collected to build the model for the material flow analysis that is used to calculate the indicators. The selected indicators should enable the assessment in the fifth step, where a benchmark and a scenario analysis are done. Benchmarking is performed when the goal of the assessment is to compare the CE actions integration in the industry with an identified and chosen baseline, and scenario analysis is more relevant when conducting optimisation steps of CE actions.

2.2. Case study

The case study under investigation is a ceramic industry located in Modena, Italy, which produces a multitude of different ceramic products. In Fig. 2, the processes of the industry and flows are represented, and they compose the baseline of the assessment. The assessment focuses on water and energy use, and waste heat (exhaust gas) generated

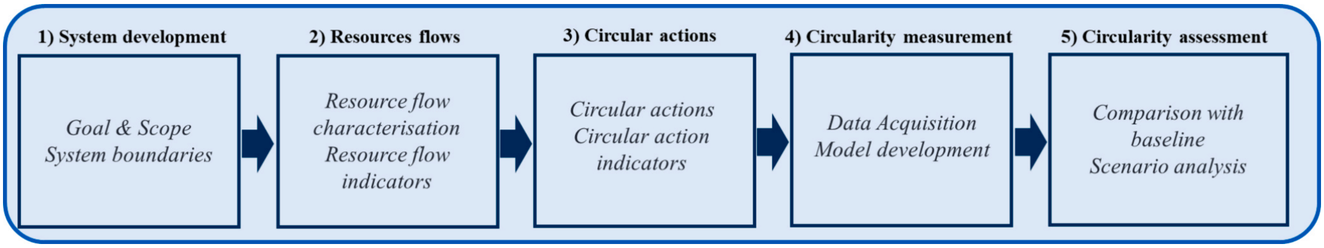

Fig. 1. Methodological framework for measuring and assessing circularity []
adapted from Nika et al. 22.

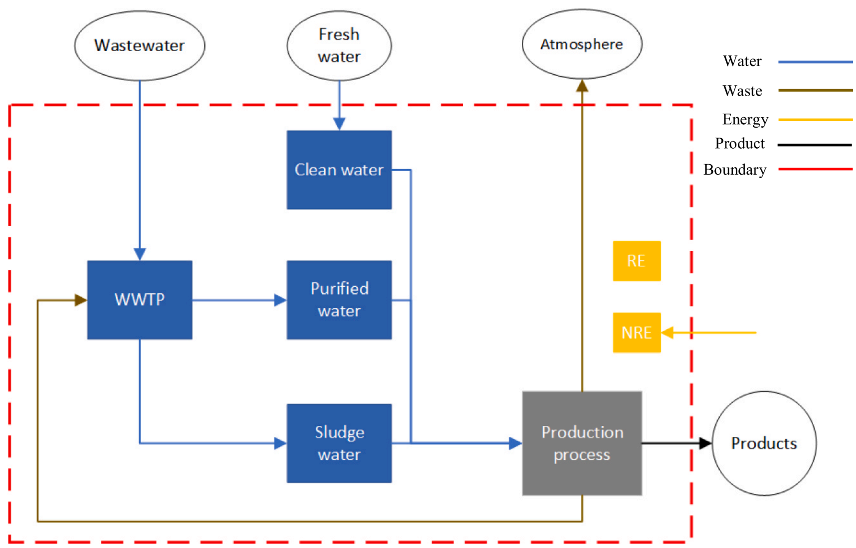

Fig. 2. Processes and flows of the ceramic industry under investigation (baseline). RE: renewable and recovered energy; NRE: non-renewable energy.

from the production process. The products require different volumes of water with varying qualities, which are used depending on the intended production batch and the quality of the final product. Processes in the system which consume the largest quantities of water are a) spray dryer, b) milling, and c) glazing. During milling, water is added to the powder mixture to facilitate the mixing of the ingredients and achieve fine grinding, resulting in a slip. This slip consists of water with varying properties (i.e. cleanest to dirtiest) depending on the colour desired (e.g. Dark ceramics, Grey ceramics and Light ceramics) and the source of water. Water is then removed (>90 %) from the slip with a spray dryer unit and it is lost as water vapour in an exhaust gas that is released through a chimney stack.

Water is sourced from internal and external sources (Fig. 2). The external water sources consist of wastewater and freshwater. Wastewater is obtained from third parties, i.e. industries, and it is treated by the onsite wastewater treatment plant (WWTP). The WWTP also receives wastewater produced by the ceramic industry (internal recirculation) and generates two flows: a purified water flow and a sludge flow which is reused by the industry. The sludge water is used directly in the milling phase when dark-scale ceramics are produced. The purified water can be used as a source for light-coloured ceramic production, however, this is rare and it is usually used for the production of grey-coloured ceramics. Freshwater is stored as clean water for industry use and when grey and light-coloured ceramics are produced. The consumption of fresh, purified and sludge water accounts for 77.6 %, 9.0 % and 13.4 % of the total water consumption of the ceramic industry, respectively. The exhaust gas that is released through a chimney stack to the environment is a mixture of various elements (e.g. organic matter, nitrogen, bicarbonates, ions, etc), including water vapour (40,500 m^3/year) and it is considered to have no value for the industry.

The industry generates electricity through a cogeneration system that uses natural gas (8.03 % of the total energy consumed) and a photovoltaic panels system (0.05 %). Moreover, it employs natural gas (88.61 %) for heating purposes and grid electricity (3.31 %) for the rest of its activities (e.g. lights and heating of boilers, spray dryer).

2.3. System development

Under the scope of the H2020 iWAYs project (grant no. 958274), two systems are integrated with the ceramic industry in order to reduce energy consumption from natural gas and water consumption from freshwater sources. The combination of the systems includes an energy and condensate water recovery system via a Heat Pipe Condenser Economiser (HPCE), and consequent treatment of the recovered condensate via a water treatment system (Fig. 3-a). A projected HPCE system of five units is located downstream of the spray dryer to receive the exhaust gas. The water vapour in the exhaust gas condensates through the operational dynamics of the HPCE system due to temperature difference, i.e. the HPCE is essentially divided into two sections, one where the vapour passes through a series of channels and progressively cools down. In the second section, a coolant liquid flows through the HPCE to cool down the vapour as it flows through different channels. The thermal exchange between the vapour exhaust and the coolant liquid captures thermal energy by heating the coolant liquid which can then be reused to heat boilers or for other purposes. After treating the condensate, it is reused in the industry, for milling or glazing activities. The operational principles of the HPCE system are a maximum capacity of 6.5 MWh for energy recovery and 2.5 m^3/h for condensate water recovery.

The water treatment system treats the recovered condensate from the

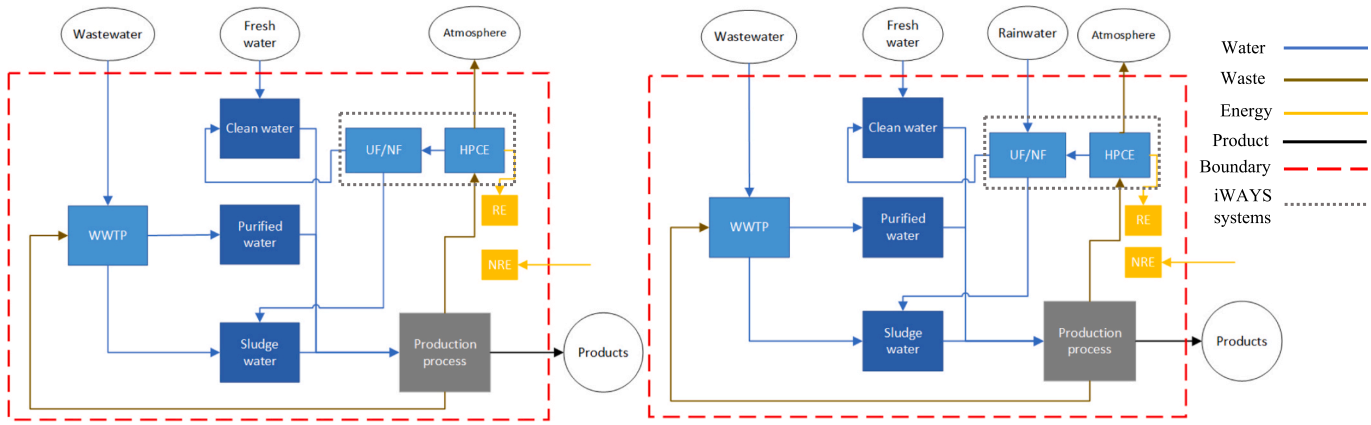

Fig. 3. Processes and flows of the ceramic industry with the HPCE and water treatment systems integration under assessment (Scenario A) (a); and processes and flows of the ceramic industry with the HPCE and water treatment systems and rooftop runoff rainwater harvesting integration under assessment (Scenario B) (b). RE: renewable and recovered energy; NRE: non-renewable energy.

HPCE system. It consists of an ultrafiltration (UF) unit followed by nanofiltration (NF) unit. The UF unit is composed of four vertical hollow fibers and the NF unit is composed of three vertical hollow tubes. The operational characteristics of the water treatment process are shown in Table 1. The operational data was used to calculate the performance impacts of the water treatment process regarding water and energy flows within the assessment boundaries. The water treatment system receives a recoverable condensate rate of 21,900 m^3/year and produces clean water, approx. 7,884 m^3/year – in the best scenario. The clean water is stored in a purified water tank (Fig. 3-a).

In addition to this scenario (Scenario A), a second scenario (scenario B) is proposed and is assessed separately. Scenario B integrates a rooftop rainwater harvesting solution in addition to the system described in Scenario A with the aim of increasing water circularity in the industry (Fig. 3-b). Despite rainwater harvesting adoption remains limited in the industrial sector, its application is becoming more urgent due to the projected water consumption increment. This has led to a growing interest in rainwater harvesting's role in industrial applications, with literature studies suggesting its potential for irrigation and cooling [23]. Therefore, this scenario was integrated into the assessment. The annual precipitation in the industrial area and the rooftop area were used to estimate the potential volumes of harvested rainwater. The harvested rainwater is treated by the water treatment system.

The goal of the assessment is to measure the intrinsic circularity performances of both scenarios (A and B) and compare them with the scenario without integration – baseline (Fig. 2). In addition, scenario analysis is performed to optimise the rainwater harvesting method. Therefore, the scope of the assessment focuses on the impact of the integration on freshwater consumption and natural gas resources which are aimed to be mitigated.

Table 1
Operational and maintenance characteristics and requirements of the UF and NF units.

Process	Efficiency (%)	Max pump flow (m^3/h)	Electricity (kW)	Chemicals
UF	72	7	2.2	Caustic soda (30 % w/w), Citric acid (33 % w/w) Sodium hypochlorite (15 % w/w)
NF	50	5	0.25	Phosphonic acid (10–20 % w/w)

2.4. Resource flows

For the assessment of the integration of the HPCE and water treatment systems, the resource flow characterisation focuses on the water and energy flows within the boundaries of the assessment. To smooth indicator calculation, circular properties must be assigned to water and energy flows in the modelled systems [24]. Regarding the water inflows, the wastewater, freshwater, and rainwater are characterised as inputs to the system. Wastewater is classified as a circular flow, as it results from third parties and is reclaimed [25], while the freshwater is classified as a linear flow because it is sourced from an aquifer and is classified as a virgin source [26]. Harvested rainwater which is renewed by precipitation and the natural water cycle is classified as a circular flow [27]. Regarding the water outflows, water leaving the assessment boundaries is in the form of exhaust gas and in the product. The water in the exhaust gas is classified as a linear outflow because it is lost as a by-product of the industry production process [25]. The water in the products is classified as circular outflow as it is part of the product's characteristics and function.

The industry with the integrated HPCE results in five energy sources. Energy from the HPCE and photovoltaic panel system is classified as circular flows as they are non-virgin and renewable respectively, while energy obtained from cogeneration and natural gas burning is classified as linear flows (from non-renewable material). Regarding energy from the grid, this is classified as both linear and circular flows, as the mix of the energy grid is diversified.

The resource flow indicators are shown in Table 2. For the water flows, the indicators selected are Water Circular Inflow (CWI) and Water

Table 2
Resource flow indicators.

Category	Indicator	Equation	Reference
Water	Water Circular Inflow (as defined by classification approach) (%)	$\frac{\text{Mass Circular Inflow}}{\text{Total Mass of Inflow}}$	[25–27]
	Water Circular Outflow (as defined by classification approach) (%)	$\frac{\text{Mass Circular Outflow}}{\text{Total Mass of Outflow}}$	[25]
	Total Circular Flow (%)	$\frac{\text{Circular Inflow} + \text{Circular Outflow}}{2}$	[26]
Energy	Recovered Energy Contribution (%)	$\frac{\text{Recovered energy from outflow}}{\text{Total Energy Consumption}}$	[27]

Circular Outflow (CWO). The CWI measures the circular fraction that enters the boundaries of the assessment which is defined by the classification approach applied to the wastewater, freshwater and rainwater. Actions like rainwater harvesting or seawater desalination that reduce the freshwater contribution to the overall water demand increase the level of circular water flowing into the industries [25]. The CWO measures the circular water fraction that leaves the boundaries and it is defined by the classification approach applied to the water in the exhaust gas and final product. Actions that reduce the amount of water lost or that treat wastewater and discharge the treated wastewater with equal quality to the watershed can contribute to increasing the circular water outflow of the industries.

ISO 59,020 [27] proposes two indicators for energy. One calculates the percentage of the renewable energy contribution and the second is the percentage of energy recovered or generated from residual, non-renewable and non-recoverable resource outflows. The HPCE recovers waste heat from an outflow of the boundaries which is the exhaust gas, and it is not classified as renewable. However, the use of waste heat allows a decrease in the dependency on natural gas which is a non-renewable energy, thus classified as a linear flow. Therefore, the Recovered Energy Contribution (REC) indicator is used to calculate the fraction of energy recovered from outflows by the industry. As the HPCE and water treatment systems do not impact the renewable energy flow from the photovoltaic panels system, the percentage of renewable energy contribution is not measured.

2.5. Circular action

The strategy of integrating the HPCE and water treatment systems in the industry aims to promote the following CE principles:

- Reducing freshwater withdrawal by recovering resource value through recycling water from the exhaust gas and by harvesting rooftop run-off rainwater;
- Reducing natural gas consumption by recovering resource value through recovering waste heat from the exhaust gas;
- Closing loops by retaining value through the utilisation of outflows.

The circular action indicators selected are shown in Table 3. Each circular action has a group of indicators in order to measure its performance. Moreover, economic indicators were selected as in addition to increasing the intrinsic circularity of the industry, the systems also aim to impose economic savings related to freshwater and natural gas consumption (Table 3).

The performance of the circular action on reducing freshwater withdrawal is measured by the indicators Onsite Water Circularity (OWC) and Water Withdrawal Reduction (WWR). The OWC indicator was selected because it measures the times that water is circulated onsite through recycling and reuse practices before it results in an outflow [25]. If it is higher than one it means water is recycled and reused on site. The WWR indicator measures the percentage of freshwater withdrawal reduction [22]. In addition, the economic savings from reducing freshwater consumption is calculated by the Water Cost Saving indicator.

Regarding the circular action of reducing natural gas dependency by integrating the HPCE, the performance of the action is measured by the calculation of the reduction of CO_2 emissions and economic savings related to the reduction in natural gas consumption.

Through closing the exhaust gas loop by recovering heat and water, the focus is on heat and water vapour loss through the stack chimney and the wastewater produced that goes to the WWTP. The Waste Utilisation Index (WUI) indicates the amount of water vapour in the exhaust gas and the wastewater which is recovered to be used in the industry. To complement this, the Total Cost Saving indicator is used as the sum of Water and Energy Cost-Saving indicators, as the closing loop action allows to potentially reduce costs related to freshwater and energy consumption.

2.6. Circularity measurement

The circularity measurement consists of collecting data in order to build the model that represents the integration of the HPCE and water treatment systems and the rooftop runoff rainwater harvesting in the industry. The model contains the material flow analysis (MFA) required to calculate the resource flow and circular action indicators. Due to confidentiality, the MFA is not presented. Additionally, to calculate the indicators for Scenario B, a rainwater harvesting model was developed based on the rooftop area available for collecting rainwater (63,000 m^2), and historical precipitation data in the region (Modena, Italy) was used – European Climate Assessment & Dataset (https://www.ecad.eu) [28] (Table 4). Based on recorded historical precipitation data, potential

Table 4
The estimated potential collected rooftop runoff rainwater for the ceramic industry.

Month	Average runoff rainwater (m^3)	Max runoff rainwater (m^3)	Min runoff rainwater (m^3)
January	2428	7069	126
February	4296	9778	315
March	3624	8921	176
April	3389	7472	25
May	4052	12,323	1058
June	4229	11,416	441
July	1649	6023	0
August	2265	6728	0
September	3607	8921	491
October	4171	9387	529
November	5045	10,760	1184
December	2227	7459	0
TOTAL	40,981	106,256	4374

Table 3
Circular actions, indicators and equation.

Circular action	Indicator	Equation	Aim
Reducing freshwater withdrawal	Onsite Water Circularity (OWC)	$\frac{\text{Volume of water use} - \text{Total volume of water withdrawal}}{\text{Total volume of water withdrawal}} + 1$	Increase
	Withdrawal Reduction (WWR)	$\frac{WW_{baseline} - WW_{circular\ action}}{WW_{baseline}}$	Up to 100 %
	Water Cost Saving	$\text{Volume of freshwater reduction} \times \text{price of water}$	Increase
Reducing natural gas dependency	CO_2 Emissions Reduction	$\text{Natural gas reduction} \times \text{CO2 emission factor}$	Increase
	Energy Cost Saving	$\text{Natural gas reduction} \times \text{price of natural gas}$	Increase
Closing loops	Waste Utilisation Index (WUI)	$\frac{\text{Amount of utilised waste}}{\text{Amount of utlised waste} + \text{Amount of generated waste}}$	Up to 100 %
	Total Cost Saving	$\text{Water Cost Saving} + \text{Energy Cost Saving}$	Increase

rainwater harvesting volumes were calculated for the past 15 years (Table 4).

The data used for the economic indicators for each circular action are given in Table 5. The costs of the natural gas and freshwater were collected at the beginning of this assessment, and it is worth mentioning that their cost values are subjected to change due to market volatility and inflation. Additionally, chemical costs of the water treatment system were included and the volume of chemicals used was registered during the operational campaign carried out in the iWAYs project. The emission factor of natural gas combustion, 1.9 kg CO_2 eq/m^3, was used [29] to calculate the avoided CO_2 emissions due to replacing natural gas with waste heat.

2.7. Circularity assessment

The circularity assessments were performed through 1) a benchmark assessment evaluating scenarios A and B against the baseline scenario, and 2) a scenario analysis which consists of analysing the effect of rainwater monthly variation and the impact of different rainwater management methods. The rainwater management methods investigated are: 1) treating the harvested rainwater only with the UF unit; and 2) no treatment for harvested rainwater, meaning it is directly used in the production process of the industry.

3. Results and discussion

3.1. Circularity assessment

The circularity assessment consists of quantifying the benchmark and proposed solution through the selected indicators and comparing them with each other. Additionally, a scenario analysis is performed which consist of analysing changes in the rainwater management method.

3.1.1. Benchmark assessments of scenario A and B

Fig. 4-a shows the scores of CWI, CWO, CWF, WWR, REC and WUI indicator calculations, and Fig. 4-b shows the OWC indicator for the baseline and scenarios A and B. The baseline scenario indicates a CWI score of 5.78 % due to the intake of wastewater from third parties meaning the baseline has a large linear water withdrawal flow due to freshwater consumption. Regarding the CWO, the baseline scores a value of 5.00 % which is represented by the amount of water in the manufactured products. This means that a significant volume of water that exits the industry (or assessment boundaries) is classified as a linear flow as it is released and lost through the exhaust gas. The wastewater produced in the production process of the industry is pumped to the WWTP, therefore it is not considered an outflow because the flows are contained within the boundaries of the assessment. The OWC indicator shows that water is reused onsite 1.29 times before it leaves the industry as an outflow.

Scenario A slightly improves the CWI (6.28 %) due to the recovered condensate water from the HPCE system. The CWO increases up to 10.27 % due to the recovery of 21,900 m^3/year of condensate water from the 40 527 m^3/year of vapour water in the exhaust gas by the HPCE system. This contributes to a water withdrawal reduction of 7.97 % from the freshwater source and an increase in the OWC indicator to 1.40.

Scenario B presents a significant increase in water circularity due to the employment of rooftop rainwater harvesting, which increased the CWF and the WWR indicators up to 33.73 % and 22.88 %, respectively. The increase in CWF is credited to the increase in CWI (61.19 %) due to the estimated volume of 40,981 m^3/year of rainwater harvested considering a rooftop area of 63,000 m^2. Additionally, the OWC increased from 1.40 to 1.79, indicating an increment in the number of times water is reused by the industry.

The REC shows that the Baseline has a 0.0 %, scenarios A and B have a 20.01 % and 19.98 % of recovered energy employed. The integration of the HPCE system results in an increment of the circular energy portion by 20 %. The small difference between scenarios A and B is due to the energy consumption of the iWAYS water treatment system. Scenario B recovers more water, therefore the water treatment system requires more energy, increasing the overall energy demand of the industry.

For the Baseline, the WUI is 36.07 % because the industry already reuses wastewater generated from other industries and treats it in its onsite WWTP (or sometimes directly reuses the wastewater with no treatment required). Regarding scenarios A and B, the score is the same (70.62 %) due to the recovery of condensate water from the exhaust gas occurring in both scenarios at the same rate.

Economically, freshwater reduction shows that scenario A results in saving 8,274 € per year due to the water recovery from the exhaust gas compared to the baseline scenario (Fig. 5-a). Furthermore, scenario B demonstrates an increase in the water cost saving by 187 % (23,756 €/year), in relation to the baseline scenario (Fig. 5-a). The assessment indicates a step towards decarbonisation by recovering waste heat from the exhaust gas which results in avoiding 9,875 kg CO_2/year of emissions from natural gas combustion (Fig. 5-b). The circular action of reducing natural gas dependency by integrating the HPCE (scenario A) indicates a fuel cost saving of 4,378,395€ per year (Fig. 5-c). No differences are seen in scenario B because the rainwater harvesting integration does not affect the energy recovered by the HPCE system and natural gas consumption. Economically, the utilisation of the exhaust gas for recovering water and energy contributes to a total saving of 4,386,668 €/year, and the rooftop runoff rainwater harvesting integration contributes to a total saving of 4,402,150 €/year (Fig. 5-c).

The results indicate the HPCE system integration improves more circularity flows related to energy than to water. Additionally, it is the main contributor to the strong performance of the identified circular actions: reducing natural gas dependency and closing loops through decarbonisation. It is also the major contributor to the economic savings.

The lower impact of the HPCE system on the water circular flow and the action reducing freshwater withdrawal is associated with the demand of the industry for freshwater which is almost 12 times higher than the recovered condensate water after the iWAYs water treatment system. However, it is still worth highlighting the slight improvement due to a novel design feature on the HPCE enabling condensate water recovery, as its main functionality is waste heat recovery from exhaust gases.

The water circular flow and the circular action reducing freshwater withdrawal have a significant improvement when rooftop runoff rainwater harvesting is integrated. However, its annual variation is expected to impact the water circularity flows and the circular action performance.

3.1.2. Annual rainwater variation and rainwater management method impacts

Rainwater events are periodic and different each month in the industry region, thus impacting the potential harvesting rate (Table 4). Therefore, the impact of annual rainwater variation is measured. The indicators regarding the water withdrawal reduction (WWR), and the associated value creation of the economic savings generated by reducing freshwater withdrawal are considered for the analysis.

In Fig. 6, the WWR indicator (Fig. 6-a) and the related monetary

Table 5
Prices and cost data for calculation of economic indicators.

Parameter	Price	Unit	Source
Natural gas	7.82	€/kwh	[30]
Freshwater	1.05	€/m^3	Provided
Caustic soda	0.90	€/m^3	Provided
Citric acid	0.80	€/m^3	Provided
Sodium hypochlorite	0.60	€/m^3	Provided
Phosphonic acid	0.07	€/m^3	Provided

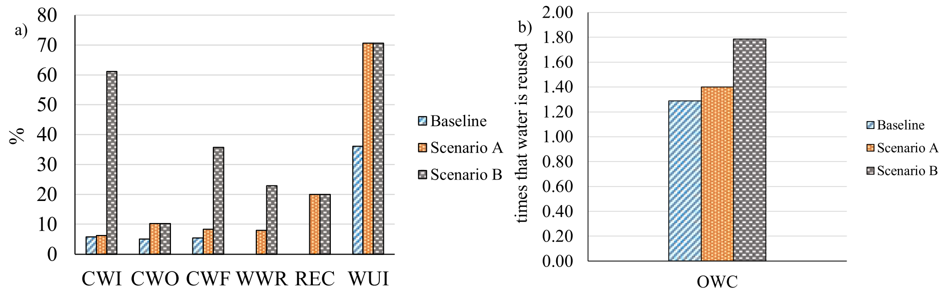

Fig. 4. CWI, CWO, CWF, WWR, REC, WUI (a) and OWC (b) scores for baseline, scenario A and B.

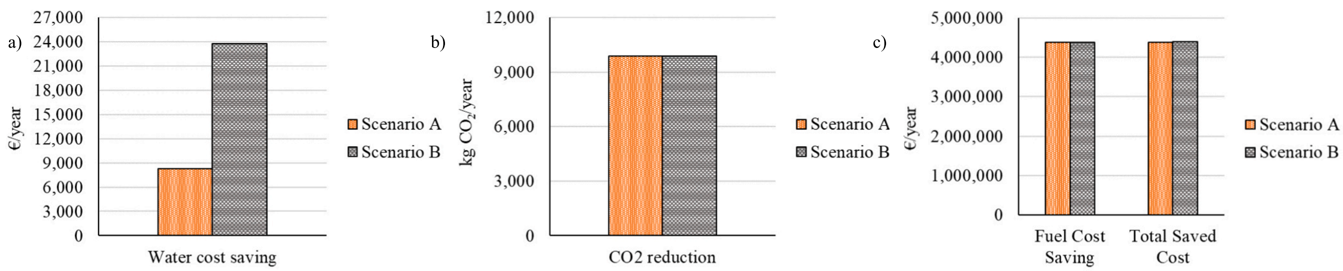

Fig. 5. Water cost saving (a), fuel cost saving (b), total saved cost (b) and CO_2 reduction (c) indicators for scenarios A and B.

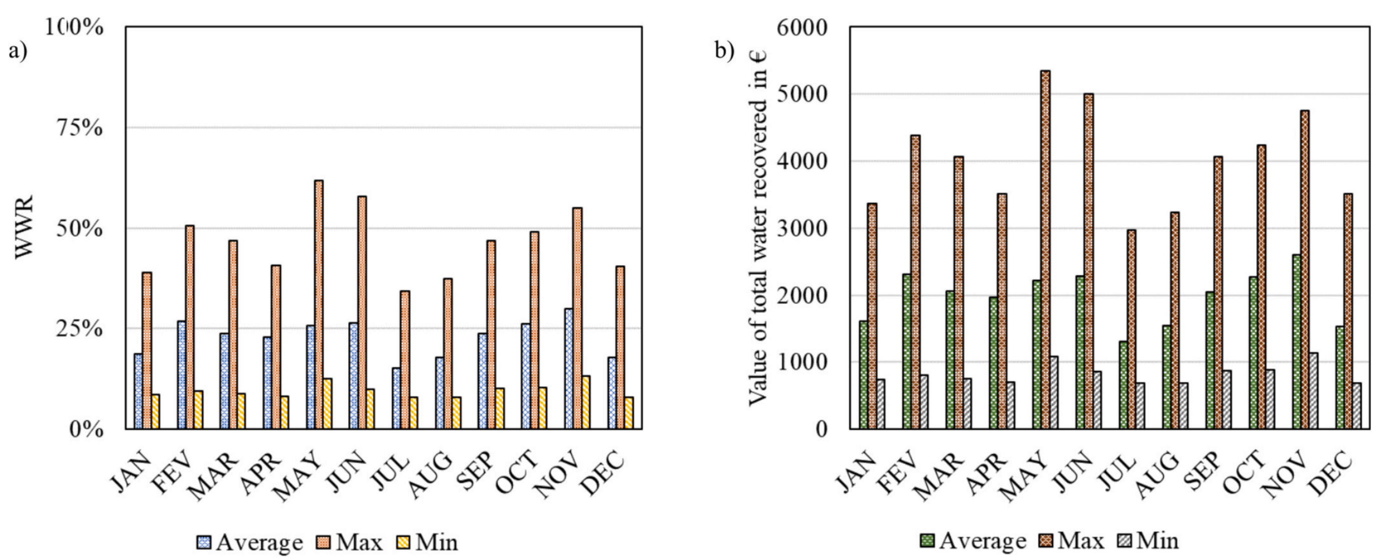

Fig. 6. Average, maximum and minimum for the WWR indicator (a) and the monetary value of the recovered water (condensed and rainwater) (b) during the year.

value of the total water recovered (condensed and rainwater) (Fig. 6-b) for each month are shown. The analysis shows that for February, May, June and November, a WWR score above 50 % is achievable which represents a monetary water saving value of 4,386 €, 5,348 €, 5,005 € and 4,757 €, respectively. On the other hand, the WWR indicator shows the months with lower rainwater harvesting potential are July, August and December. Table 4 indicates that in the past, these three months have recorded no precipitation at all. Therefore, employing rooftop runoff rainwater harvesting shows that large and small freshwater reduction can be observed annually, meaning the benefits of this circular strategy are dependent on uncontrolled and external events.

In fact, an option to increase the WWR indicator, resulting in water savings, would be to stop feeding harvested rainwater to the iWAYs water treatment system, as the UF and NF recovery efficiencies are 72 and 50 %, respectively. The decision to treat harvested rainwater is mainly to remove algae that potentially might grow in the harvesting storage tanks, however, the rainwater composition was analysed and it has a good quality compared with the freshwater (Table SM1). Therefore, two scenarios were studied:

1. treating the harvested rainwater only with the UF unit;
2. absence of UF and NF – direct use of the harvested rainwater in the production process.

Under scenario 1, the WWR average is 39 % (Fig. 7-a) demonstrating a strong improvement when compared to scenario B. Furthermore, the data shows if a rainfall event like the maximum registered in May, June and November occurs, the harvested rainwater and the recovered condensate water can cover all freshwater demand by the industry in those months.

Regarding scenario 2, the WWR indicator increased on average up to 49 % annually. Thus, the potential of covering freshwater requirements

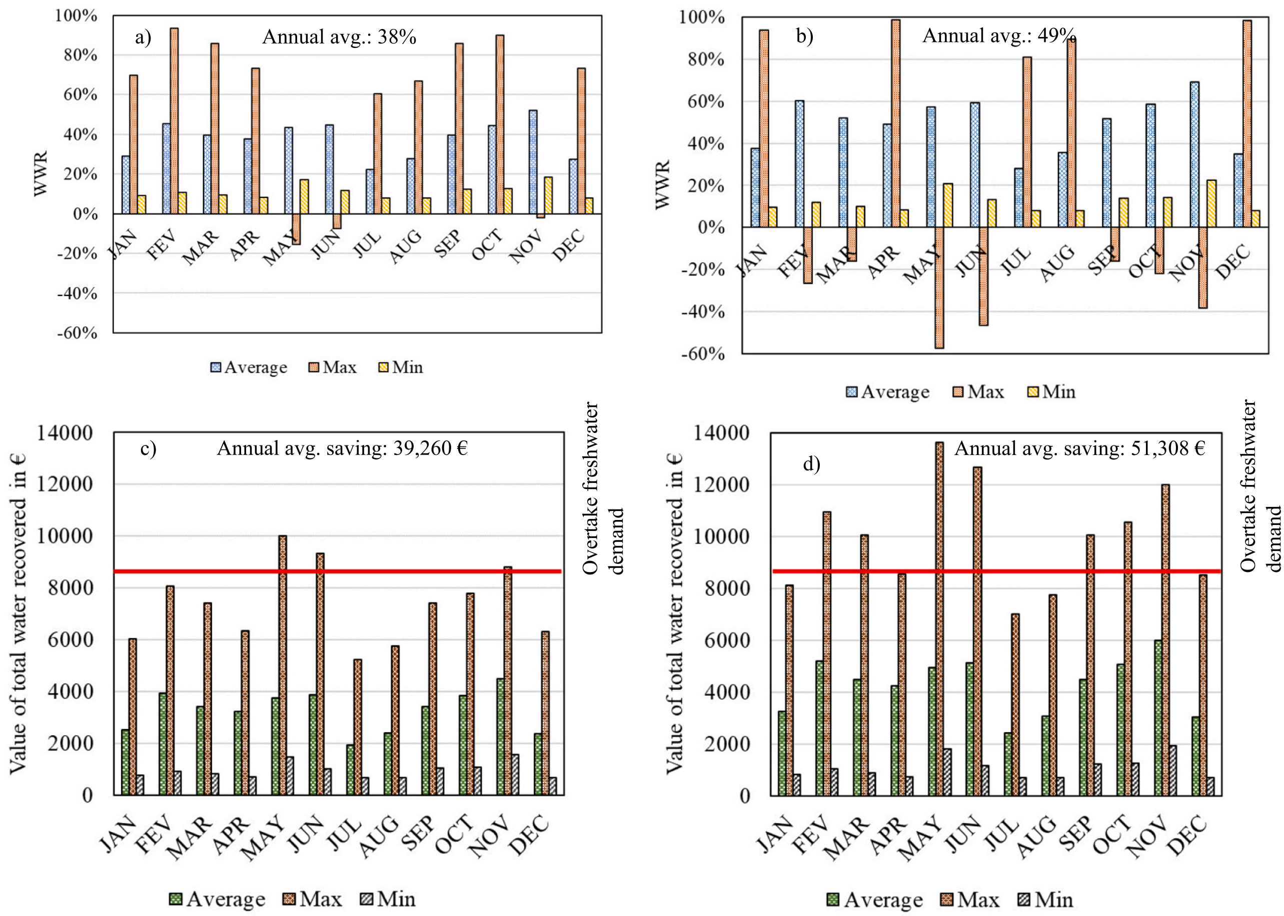

Fig. 7. Average, maximum and minimum for the WWR indicator and the monetary value of the recovered water (condensate water and rainwater) in all the annual months. Scenario 1 (no NF use) (a and c) and scenario 2 (no UF and NF use) (b and d). The red line in figures c and d means when the recovered water overtakes the freshwater demand.

with recovered water is extended to February, March, September, October and November (Fig. 7-b), alongside May and June.

From an economic perspective, scenarios 1 and 2 could lead to savings of on average 39,260 € and 51,308 € in freshwater consumption per year, respectively (Fig. 7-c and d). The excess of recovered water could be stored for further use, reducing the dependency on freshwater. Another option could be selling or sourcing the recovered water to another industry in the vicinity.

4. Conclusion

This study applied a framework for assessing the intrinsic circularity of an integration of two systems in a ceramic industry. The two systems were developed under the scope of the European project iWAYs and they are a Heat Pipe Condenser Economiser system (HPCE) and a water treatment system. The integration was designed to recover waste heat and condensate water from an exhaust gas generated in the production process of the industry with the intention of reducing natural gas and freshwater consumption and closing outflow loops. Additionally, the project proposed the integration of rooftop runoff rainwater harvesting which is further treated in the water treatment system.

The circularity assessment indicates the integration of the HPCE and water treatment system improves the intrinsic circularity of the industry but the recovered waste heat was the main contributor. Additionally, decarbonisation is observed and the recovered waste heat generated significantly higher economic savings than the recovered condensate water. In terms of water circularity, there were slight improvements compared with the baseline. However, by integrating the rooftop runoff rainwater harvesting solution (scenario B), the resource flow and circular action indicator show major increments in water circularity performance. This reflects on the economic value creation which is greater in scenario B, as higher water cost savings are observed.

Additionally, applying different rainwater harvesting management strategies significantly increases the WWR and cost savings. However, algae growth has to be monitored not to negatively affect the circularity level and consequently the production process of the industry. There is potential for the recovered water to meet the freshwater needs of the industry in the months of February, March, May, June, September, October, and November.

As a final thought, the authors of this study strongly believe that this methodology is capable of providing insightful information for this industry. Moreover, it can be flexible and applied to other types of industries (e.g. chemical, steel) as was performed in the iWAYs project. Furthermore, it can provide decision-making on resource management strategies like for water for optimisation of circular actions (e.g. water and costs).

5. Future work

This study assesses the integration of a water system combining Ultrafiltration (UF) and Nanofiltration (NF) processes, which currently exhibit limited water recovery efficiency. A comparative assessment of the water system under investigation against alternatives, such as distillation or reverse osmosis, would help determine if water recovery efficiency can be optimized and identify the benefits and potential hotspots of integrating different systems. In addition, the assessment limits the calculation of indicators as it is based on static data regarding energy and water consumption. From a production perspective, real-time or daily monitoring of circularity performance can offer valuable insights. Moreover, it could allow the development of a decision support system with multi-criteria decision-making in order to employ the best possible decision. Such a dynamic model would incorporate circularity indicators, technical performance metrics (such as product quality), and sustainability indicators (such as greenhouse gas emissions and operational costs), all subject to specific technical, economic and environmental constraints set by the industry to achieve defined goals.

CRediT authorship contribution statement

João Miguel Ribeiro: Writing – original draft, Data curation, Conceptualization. **Daniel Filipe Cristo Dias:** Writing – original draft, Visualization, Conceptualization. **Eliza Nika:** Investigation, Data curation. **Bertrand Delpech:** Formal analysis, Data curation. **Evina Katsou:** Methodology, Data curation, Conceptualization. **Hussam Jouhara:** Writing – original draft, Supervision, Funding acquisition, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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