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IWAYS - Recycling of Heat, Water and Material Across Multiple Sectors: Ceramic, Chemical and Steel Industry

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Abstract. In the framework of the iWAYS project, a synergy between energy and water reclamation and exploitation is addressed by means of the development and the installation of a wide array of technologies in three different industrial sectors: ceramic tile manufacturing, aluminium fluoride production and steel tubes manufacturer. The aim of the project is the creation of customized and integrated systems to achieve a substantial reduction in the thermal waste and in the freshwater consumption; this is the principal challenge the iWAYS project is solving by developing a set of technologies capable of recovering water and energy from challenging exhaust streams for productive use in the industrial processes. iWAYS systems will then treat steam condensate to meet the water quality requirements of each industrial process, while the recovered heat will be used to reduce primary energy consumption. iWAYS will recover additional materials from flue gas such as valuable acids or particulates, improving the production's raw material efficiency and reducing detrimental emissions to the environment. The iWAYS technology will provide a reduction in the freshwater consumption greater that the 30% in each industrial case; with regards to the energy recovery, iWAYS will recover 6 GWh/y in the ceramic sector, more than 5 GWh/y in the chemical scenario and approximately 1 GWh/y in the steel sector. The iWAYS solution will have a payback lower than 5 years.

1 Introduction

Around three quarters of the energy consumption in the EU comes from non-renewable resources, such as oil, gas and coal, and are used for the generation of electricity and heat, the powering of transport, and as materials in certain industrial processes leading to air pollution and carbon emission[1]. Therefore, the EU is looking for a clean, sustainable, decarbonised and competitive energy systems [2]. Indeed, the European Parliament endorsed the net-zero greenhouse gases emissions objective and, in January 2020, sets out a European Green Deal for tackling climate and environmental related challenges [3]. There is the objective of transforming the EU into a prosperous society, with a modern, resource efficient and competitive economy where there are no net emissions of greenhouses gases in 2050 [3].

In this context, energy efficiency is one of the pillars of the EU Energy Union strategy and it has been proposed as a highly effective pathway to improve the economic competitiveness and sustainability of the European economy, to reduce emissions and energy dependency [1]. Indeed, energy efficiency can help to strengthen energy security in short and long terms since it reduces the dependency on the imports of fossil fuels.

This ambitious strategy that aims at no net emissions of greenhouse gases in 2050 calls for the mobilisation of every sector, i.e. residential, tertiary, transport and industry.

Thus, as reported in the Green Deal document, there is a pressing necessity to rethink policies for clean energy supply across the economy, industry, production and consumption, large-scale infrastructure, transport, food and agriculture, construction, taxation and social benefits. The challenge of a sustainable economy is complex and interlinked and it requires the contribution of all the sectors[4]. Another important challenge is related to the water efficiency activities. Today, there is a greater unpredictability of the availability of fresh water due to the climate change; however, the demand for water continues to grow worldwide. In Europe, approximately, 81% of the freshwater is used for agricultural, potable, and industrial purposes and only less than 3% of urban wastewater is reused [5]. This clearly illustrates the importance of improving water efficiency and water reuse solutions across a variety of sectors as one aspect of tackling water scarcity and droughts measures. Within this context, the industrial sector, which is the one of the largest consumers of resources in EU, can play a predominant role. In this regard, improvement in energy efficiency for the technologies already available and the development of green energy systems capable of replacing the fossil fuels can be identified as possible solutions for a cleaner energy sector distinguished by lower emission [6].

In EU28, it is estimated that 70% of the total energy use in the industrial sector is for thermal processes and up to a third of this energy is wasted to the environment [7]. Thus, the valorisation of waste heat by means of the application of Waste Heat Recovery Systems (WHRS) in the industrial context has recently attracted considerable interest due to the constant increase in fuel prices and the regulations and policies introduced to improve energy efficiency in industry. Recovering the heat that it is not put to any practical use and is vented to the environment provides valuable energy sources and reduces the overall energy consumption of the process [8].

The industrial waste heat potential in the EU is 304.13 TWh/year, which is 16.7% of the industrial consumption for process heat and which represents 9.5% of the total industrial energy consumption [9]. The main contributors are the steel and iron industry (168 TWh), followed by the mineral and paper sectors, respectively 73 TWh and 20 TWh; the food industry and the chemical industry are wasting around 10 TWh each [9].

In ETEKINA project [10], [11] the waste heat recovery is addressed in three energy intensive industrial sectors (aluminium, steel and ceramic) reaching a recovery efficiency greater than the 40% of the thermal energy contained in the exhaust by means of a heat pipe based heat exchanger (HPHE) technology.

iWAYS project proposes an evolution of ETEKINA since it aims at recovering not only energy, but also water and materials. The recovery and reutilization of substantial amount of heat through steam condensation by means of an heat pipe condensing economizer (HPCE) result in significant reduction of thermal energy required by the process lines. Similarly, water efficiency is greatly improved, as water vapour is condensed, treated and reused as process water. Thus, iWAYS addressed another important pillar of the EU strategy for a resource efficient economy since the water usage in industry accounts for about the 40% of the total water abstraction, and more only the 60% of industrial wastewater receives treatment before being disposed to the environment [12].

The main objective of the iWAYS project is the recovery of condensed water by pushing on near-zero discharge processes with recovery of materials and resources. This is the unique value of the iWAYS technology: combining the waste heat and water recovery in a unique system.

Numerous technology for improving the performance of industrial processes in terms of energy consumption and water efficiency already exist and comprehensive reviews have been proposed in [8], [13].

With regards the energy efficiency, different strategies and methods for the waste heat recovery, such as regenerative and recuperative burners, economisers, waste heat boilers, air pre-heaters, recuperators, regenerators, plate heat exchangers, heat pipe systems, heat recovery steam generator and thermodynamic cycles were presented in [8]. Wolley and Luob [14] presented a framework to provide manufacturers with a methodology in assessing waste heat source potential and the appropriate heat recovery technology as well as the economic benefit that the technology can bring. Three different unconventional technologies to convert the waste heat into power such as the air turbine cycles which referred as air bottoming cycle, carbon-dioxide based power cycle and Kalina bottoming cycle are presented in an extensive review in [15].

Within the context of water reuse technology, there are different solutions that can be adopted based on the chemical physical properties of the wasted water to be purified [16]. Physical-chemical systems (coagulation-flocculation, sand filters…), membrane technologies (ultrafiltration, reverse osmosis, membrane bioreactor…), disinfection systems (ultraviolet radiation, chlorine dioxide…) are dome of the numerous reclamation technology; each system has its own characteristics and it is usually necessary to use a combination of two or more technologies to achieve the required water quality levels. The selection of the reclamation technology must take into account several premises such as the quality and the quantity of the water to be reclaimed, the final quality required for the specific use, the economic cost, and the environmental impact.
In iWAYS, a unique solution will be developed for recovering a set of technologies capable of recovering water and energy from exhaust gases for productive use in the industrial processes. The iWAYS system is comprised of three main technologies: exhaust and material condensation, water treatment and decision support system based on realtime monitoring system. The iWAYS integrated and modular system is tested in three different sectors: ceramic, chemical and steel.

2 Industrial Cases Description

In this section the three industrial processes of the energy intensive industries where the iWAYS technology will be installed are described.

2.1. Ceramic industry

The first case is focused on a ceramic tile manufacturing plant. The tile production starts by selecting the raw materials (mainly clays, feldspar, sands); these materials are mixed and then milled in continuous mills with a mixture of water. Part of the water contained in the resulting suspension (slip) is then removed by spray drying to obtain a product with the required moisture (at 5-7% moisture content) for process stage. Forming takes then place, by mechanically compressing the paste in the die. After forming, the tile body is dried to reduce the moisture content (0.2-0.5 %) to appropriately levels for the firing. Before firing, nonetheless, decoration is carried out. Once tiles are decorated, they can be fired. Firing is one of the most important tile manufacturing process stages as most tile characteristics depend on it. These include mechanical strength, dimensional stability, chemical resistance, cleanability, fire resistance, etc. To realize an unglazed dry pressed tiles the temperature in the kilns is about 1250°C.
Energy sources used in the ceramic process are natural gas and electricity. Firing is responsible for 53% of thermal consumption, followed by spray drying (35%) and drying (10%). Water is also an important raw material for the tile manufacturing process [17]. The overall fresh-water consumption of a medium size tile manufacturing facility amounts to approximately 75,000 m3/y and covers many uses in the ceramics process, such as washing and slip preparation. Ultimately, all water streams are conveyed to slip preparation and thus the water is discharged by means of the drying process of the final ceramic material. Thus, adding the initial raw material moisture to the freshwater consumption around 80,000 m^3/y of humidity are released to the atmosphere through the spray dryer flue stack.

2.2. Chemical industry: aluminum fluoride production

The second industrial demonstrator is a company that produces aluminum fluoride for primary aluminum smelters and special applications. The chemical and petrochemical industries are among the largest energy consumers [18]
In the production process of the company involved in the iWAYS project, there are two different stages where the steam from natural gas fired boiler are used for heating.
In the first stage, the fluorosilic acid, which is the raw material, is heated with recycled heat in a graphite heat exchanger.
In the second step pure water is preheated up to 70 °C to wash centrifuges and reactors.
The drum dryers are a continuous process and the process steps that needs heat are batch wise, thus an accumulator tank is employed. Currently, only wash water is heated with the existing non-condensing heat pipe heat exchanger.

The exhaust gases enter the scrubber system where the gases are washed and condensed with clean water. The bleeding of this scrubber water runs to the water purification plant, where lime and sodium sulphide are added in the acidic water. This slurry of calcareous water is filtered in the filter press and becomes calcium fluoride which is sold to the construction industry. There are emissions to air in form of gaseous fluorine compounds and dust.
The process gas from drum dryers and calcining furnaces contains gaseous fluorine (HF) and aluminum fluoride dust which are treated in the gas purification scrubber. Washing takes place with circulating water where clean water is added.

2.3. Steel tubes manufacturer

The third process is the steel plant for the production of tubes of various sizes. The energy consumed by the iron and steel industry accounts for 10–15 % of the globe's energy expenditure, and its CO2 emissions account for about 7 % of all anthropogenic CO2 emissions [17]. Additionally, it significantly impacts the climate since steel manufacturing generates 1.9 tonnes of carbon dioxide every ton, which substantially leads to global warming [19]. As for the water consumption, Gao et al [20] reported that the amount of water consumed in the steelmaking process determined by means of the water value analysis is about 129 m^3/t of final steel products. The most water-demanding processes in the chain of steelmaking processes are rolling (about 44 m^3/t), coking (32 m^3/t), ironmaking (20 m^3/t), and casting (13 m^3/t).
The industrial process in which iWAYS system will be installed is an integrated production that comprises steel manufacturing, hot extrusion and cold rolling of the tubes. The production is energy intensive and there are different waste streams that are disposed to the atmosphere. The first wastewater stream comes from the alkaline degreasing bath while the second from the acidic bath. These wastewater stream contains high mineral load composed by potassium and material residues; thus, to reclaim the water and to recover the metals, the wastewater must be evaporated.

3 IWAYS Technologies

The iWAYS project integrates the state of the art water and heat technologies to develop a unique and novel system that is not currently used in the industrial sectors. The waste recovery starts with the condensation of the humidity in the exhaust streams by means of an heat pipe condensing economizer; new materials and design is required for this kind of application to be employed in real environment with aggressive streams.
The water treatment unit treats the condensed humidity and other possible wasted streams to reclaim them in the process. The water technology is composed by treatment units that are generally used for other streams, such as membrane distillation and photocatalytic-nanofiltration. The iWAYS technology is equipped with a monitoring system for detecting critical events of the process.
Figure 1 shows the overall concept of the iWAYS technology; as it can be noticed, the humid exhaust gases of industrial processes are cooled down within the heat pipe condensing economizer. The recovered heat is exploited within the industrial process; the water stream generated by the exhaust condensation is purified in a water treatment system and recycled back to the process.
The concept of iWAYS is applicable not only to ceramics, chemicals and steel sectors, but also to minerals, cement, paper or food industries. Each of these systems reveal a high degree of modularity.

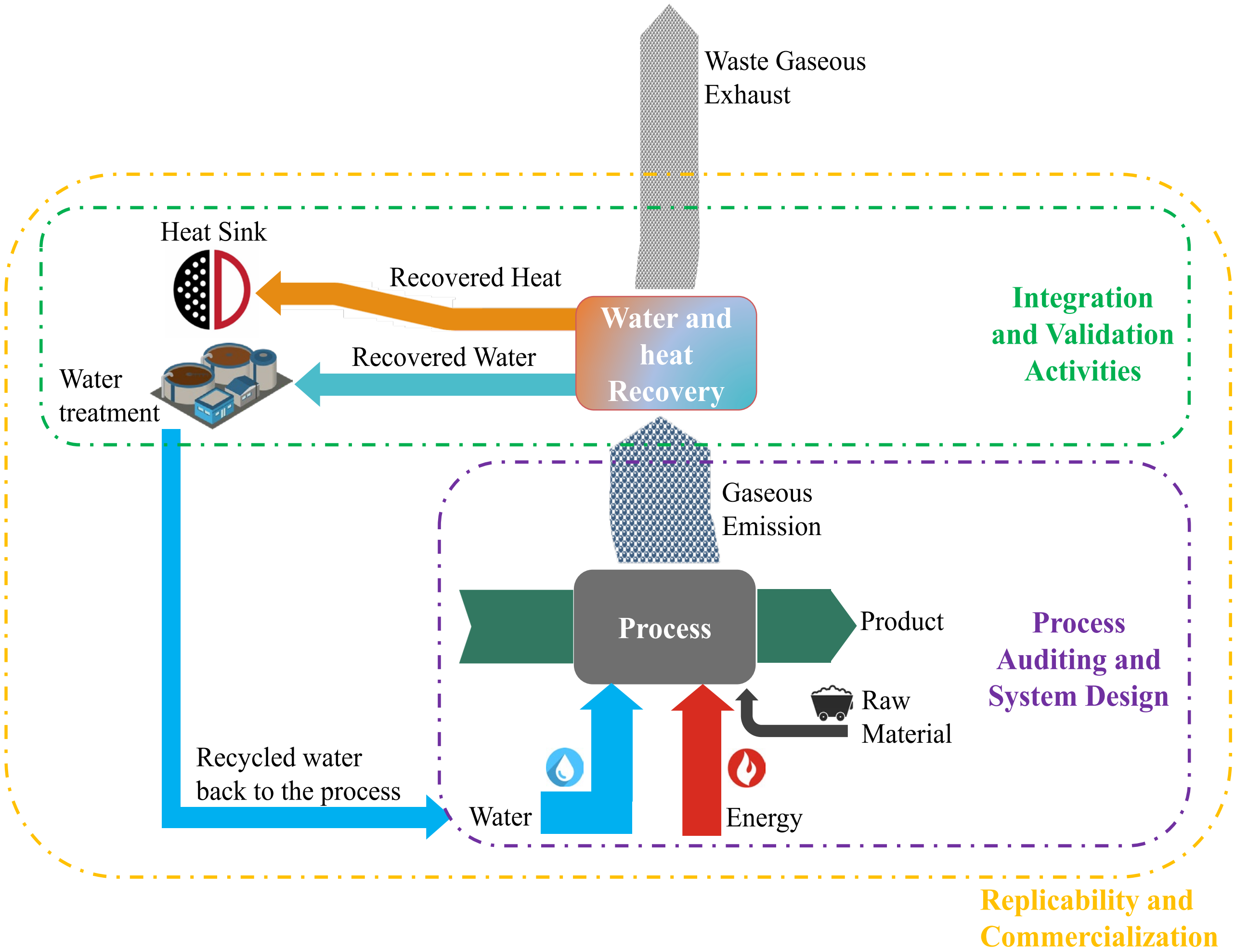

Figure 1 – Visual scheme of the iWAYS solution

3.1. Heat pipe condensing economizer

The heat pipe condenser economiser is based on heat pipe technology. Heat pipes are passive heat transfer devices characterized by a simple configuration, as can be seen from Figure 1. The heat pipe system is a sealed pipe that contains a working fluid; the functioning of this device is based on the vaporization-condensation cycle of the working fluid. The "Evaporator" section of the heat pipe, see Figure 1, is heated by the heat source. The working fluid starts to boil, and it changes phase into saturated vapour. The vapour starts flowing towards the upper part of the heat pipe, called "Condenser"; in this section, the saturated vapour condensates releasing the latent heat to the heat sink, i.e. cold stream. Thus, the liquid flows back by precipitation from the Condenser to the Evaporator section. The heat pipe-based heat exchanger (HPHE) is a unit composed by multiple heat pipes. It is a simple and robust technology in which each pipe can be considered a heat exchanger. For this reason, the HPHE is a redundant system than can operate in an efficient way even in the case of failure of a single pipe. HPHEs offer multiple advantages. The isothermal surface, high thermal conductivity and the independence of each heat pipe in the system, make the heat pipe heat exchanger (HPHE) technology a good candidate for most of the corrosive, high fouling and high temperature exhaust applications. Indeed, heat pipes offers a homogeneous temperature on the external surface. Thus, hot-spots and cold-spots are eliminated enabling perfect control of the temperatures of the hot and cold streams.

In literature there are many examples that investigated the application of HPHEs in industrial processes. Tian et al. [21] analysed an effective way to recover the waste energy from the hot gas in a printing industry located in China. The HPHE operated three months in a continuous way and a saving of the 15% of natural gas was achieved without any blockage of the unit.

A heat pipe-based heat exchanger to recover heat from a bakery oven has been studied in [22]. The effectiveness of the designed heat pipe heat exchanger was 65% and it was able to recover between 20kW and 35kW. Ma et al. [23]. investigated experimentally a heat pipe heat exchanger for waste heat recovery in the steel industry. The HPHE recovers the heat from a wastewater stream to a clean water flow.

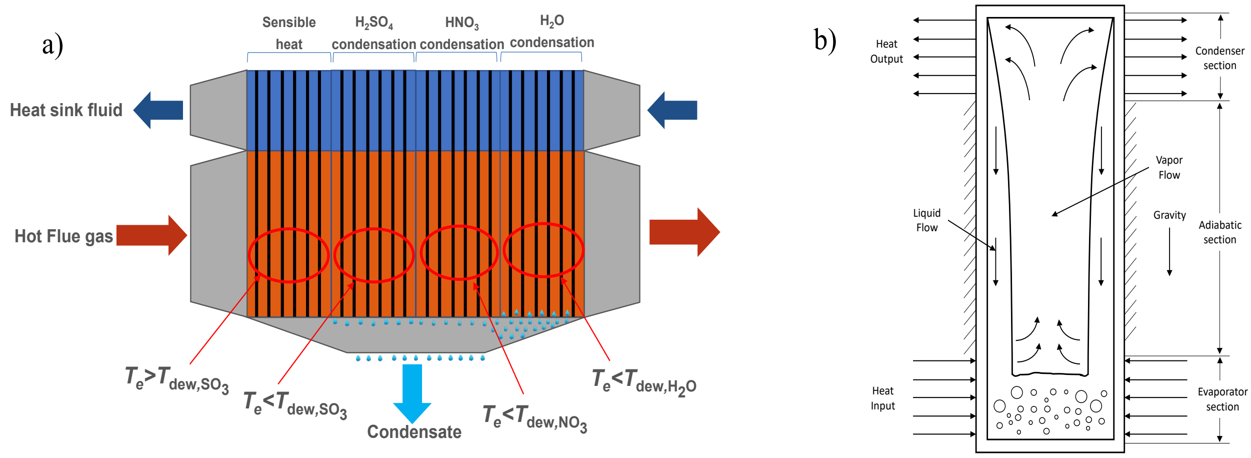

Figure 2 – Heat pipe condensing economizer concept (a) and schematic of an heat pipe (b)

Heat pipe-based heat exchangers have been applied to the ceramic sectors [24] [25] . In [24] a HPHE was installed to recover waste heat from a ceramic kiln and the performance of the system was investigated experimentally, theoretically, and numerically. The HPHE installed in the plant managed to recover up to 876 MWh per year. Venturelli et al [25] investigated numerically under transient conditions the performance of an heat pipe based heat exchanger for the waste heat recovery of the exhaust gases of a ceramic furnace. In [11] [10] the HPHE technology has been installed and validated in three industrial sectors: aluminum, steel and ceramic within the Etekina project. In iWAYS, the gaseous stream will be cooled down below the dewpoints of different compounds in order to recover heat and the condensates; this is something that has not been done before in industries.
A remaining challenge that iWAYS need to address is fouling and corrosion. The fouling will be mitigated by the design of an appropriate geometry system

3.2. Water treatment system

In literature there are different technologies that were applied for treating wastewater to reclaim it as clean water inside the industrial process. A comprehensive review of the technologies for the wastewater treatment in food industry is presented in [26]. The study presents the advantages and drawbacks of different treatment methods such as anaerobic-aerobic methodologies, reverse osmosis, micro/ultra/nano filtration, chemical and electro-oxidation, electrochemical systems. The reverse osmosis technique has been applied in [27] to clean the wastewater of 11 diary plants for reusing it to lower the effluent volume. A scale-up was proposed: a plant of 540 m^2 RO membrane area permits the recovery of 95% of 100 m^3 per day wastewater.
A review of the photocatalytic nanohybrid membranes for highly efficient wastewater treatment was carried out in [28]; Bahadur et al [29] investigated a novel pilot scale photocatalytic treatment of textile and dyeing industry wastewater to enable zero liquid discharged. iWAYS project aims at recovering wastewater from different industrial processes, first of all the condensed water from flue gases. The condensed water from these streams contains organic matter, metals and acidic gas that are difficult to treat with conventional system. The main objective of iWAYS is guiding industry towards a near zero discharge processes. The water treatment system will be designed based on the specific characteristic of the end users. Different technologies will be used. re-treatment by sand and hollow fiber ultrafiltration will eliminate particulate generating particulate fouling. Reverse osmosis operation within the context of this project aims at an exceptionally high water recovery (95%)

generating a high quality, low electrical conductivity (around 150-200 micro-S/cm) stream that can be recirculated directly back to the process.
The iWAYS solution will be equipped with a photocatalytic nanofiltration reactor (PNFR) for the elimination of metals and pollutants where needed. The system includes advanced photocatalytic monoliths and porous polymeric fibers- TiO2 based photocatalysts for the removal of metals and organic matter from the wastewater.
The challenge of the proposed treatment process will be designed and configured specifically for each use case (ceramics, metallurgy, chemistry). In addition, each unit will be scalable to cover all the flow ranges to be treated.
The potential of these technologies will be addressed to prioritize environmental and economic advantages, reaches a high-quality effluent such as to allow the reuse in the production cycle of the industry and to minimize the production of waste.

3.3 Decision support system based on real time monitoring system

The iWAYS project will develop a flexible process monitoring, control and optimization dashboard supporting an end-to-end process of data collection, harmonization, processing and visualization for evidence-based decision making. The data acquired by the monitoring system will be used to predict the behaviour of the iWAYS system enabling the suggestion of optimal strategies to reuse/recycle water. The platform that will be built will enhance to monitor, manage and maintain connected machines and devices in real time and anywhere and to automate the collection and analysis of data, facilitating a greater understanding of each of the processes, together and separately.
These benefits help the industry to boost its operational effectiveness, i.e. increase productivity, improve plant efficiency, uptime and asset quality, reduce operational risks, overall costs and changeover times.

4 Expected Impact and Conclusions

The iWAYS project will enable to achieve a substantial reduction in waste resources in terms of energy and water. In the ceramic industry, iWAYS aims at recovering substantial amount of the water discharged through the spray dryer, i.e. 500 l/h, and the water that is treated by the actual water treatment plant but it can not be used for noble processes (1500 l/h). Thus, 2000 l/h of water recovery can be reached. The HPCE is designed to recover 1.3 MW of thermal power from the spraydryer exhaust, determining an energy recovery of 6 GWh per year.
With regards to the chemical industry, two stages unit HPCE is designed to recover 600 kW of thermal power; the annual estimation is to recover approximately 5 GWh of thermal energy. The iWAYS water treatment system will treat the condensate obtained by means of the HPCE and the water that is recycled and to anymore discharged into the sea; thus, 10 m^3/h of water can be recovered and reused.
In the steel industry, an innovative concept of a radiative HPCE will be installed to recover the heat and to condense the vapour generated by the hot rod cooling. The unit is designed to recover 80 kW and the water recovery will be approximately 450 l/h.
The expected payback of the proposed solution is lower than 5 years for the three demo cases.
Once the benefits of the proposed technology will be demonstrated in terms of energy and water savings, the iWAYS project will open the door to the replicability of the solution in other facilities or similar processes, enabling the industrial processes towards a near zero discharged sector.

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