EXECUTIVE SUMMARY

ECOWAMA – short for ECO-efficient management of WAter in the MAnufacturing industry – is a research and development project co-funded by the European Union's Seventh Framework Programme. The ECOWAMA team consists of eleven international partners from both science and industry. During the project lifetime, the partners developed a new eco-efficient closed cycle management model for the treatment of effluents from the metal and plastic surface processing industry. Due to the extremely high level of prices for metals at the global market, the ECOWAMA system creates both strong economic benefits and positive environmental impacts.

The ECOWAMA approach consists of interlinking wastewater treatment with recovery of highly pure water, highly valuable metals and energy. The environmental friendly system includes electrocoagulation, electrooxidation and electrowinning technologies. In addition to that, hydrogen produced during the electrically driven processes serves feeding fuel cells to generate electricity, which again may reduce the energy demand of the whole process. Pre- and post-treatment remove oils, greases and conductivity. Through a novel electrowinning process, heavy metals are separated from the wastewater stream and directly obtained with high purity.

The complete removal of hypophosphite from electroless nickel wastewater – depicting the main challenge for the ECOWAMA project - could successfully be confirmed within the short-term as well as within the long-term trials. Furthermore the trials on electrocoagulation showed good performance in terms of phosphorous removal. The recovery of nickel by electrowinning resulted in nickel purities of more than 99.9%. Only negligible impurities of copper and zinc were found in the deposited metallic nickel.

The hydrogen gas produced during electrooxidation and electrocoagulation was collected, cleaned and upgraded having sufficient quality to serve as feed to a fuel cell to be converted into electrical energy. The ECOWAMA team successfully operated the desalination unit in the process at Saxonia Galvanik GmbH which is demonstration site for the pilot plant. The demonstration phase showed that the DS unit manages to achieve the goals of concentrating the wastewater by 15 times, producing on both concentrated wastewater with a valuable level of nickel concentration and clean reusable water.

Overall, the ECOWAMA system constitutes a flexible and modular design that allows using the individual units for further STM applications.

The research leading to results in this project receives funding from the European Union's Seventh Framework Programme for research, technological development and demonstration under GA n° [308432].

SUMMARY DESCRIPTION OF THE PROJECT CONTEXT AND THE MAIN OBJECTIVES

The ECOWAMA Project delivers a new eco-efficient closed cycle management model for the treatment of effluents of the metal and plastic surface processing industry (STM). Such STM waste water is extensively contaminated with oils and greases, organic components (e.g. complexing agents), a salt fraction and especially with heavy metals (e.g. nickel, copper, zinc and others). Annually, European metal finishing and coating operations produce over 300,000 tonnes of hazardous waste and consume over 100 million cubic meters of water for both cleaning of surfaces and as basis for galvanic solutions (electrolytic baths).

As a consequence of amongst others EU legislation (IPPC Directive and the Water Framework Directive which require increasing levels of stringent discharge compliance levels and therefore more stringent treatment levels), water cost and discharge cost are increasing. Additionally costs for raw materials, especially metals, and for energy consumption are rising. Hence STM enterprises are highly interested in efficient, cost-effective and sustainable treatment of their effluents. Picking up this negative tendency, the project's main objective envisages a chemical free closed loop process with up to zero emissions.

ECOWAMA's approach combines wastewater treatment with recovery of highly pure water, highly valuable metals and energy. Therefore an environmental friendly, effective and innovative system will be developed including electrocoagulation, electrooxidation and electrowinning technologies. Additionally hydrogen produced during electrocoagulation/electrooxidation processes will serve as feed for fuel cells to generate electricity which reduces the energy demand of the whole process. Pre- and post-treatment will be carried out to remove oils/greases and conductivity. The heavy metals will be separated from the wastewater stream and directly obtained with high purity by a novel electrowinning process.

The outcome of this is a valuable raw material that can be easily sold or reused for STM operations. Due to the extremely high level of prices for metals on the global market, ECOWAMA's participants and post-project clients will have strong economic benefits in addition to the positive environmental impacts of the process.

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Figure 1: ECOWAMA and the Circular Economy

The ECOWAMA consortium consists of eleven partners with complementary expertise located in four different EU28 states. This expertise is from research communities and industries. It contains necessary capabilities in the enabling technologies, technological and environmental validation and the subsequent exploitation and dissemination, ensuring at all stages that sustainability (economic and environmental) is scientifically verified.

Fraunhofer-Gesellschaft zur Förderung der angewandten Forschung e.V (Fraunhofer)
German non-profit organisation. The executing institute – Fraunhofer Institute for Interfacial Engineering and Biotechnology IGB - delivers expertise and background IP to the project in the area of water treatment technologies and electrochemical processing (e.g. electrooxidation cells, electrolysis, and electrolytic precipitation). They are also leading the ECOWAMA collaborative project management.

Acondicionamiento Tarrasense Associacion (LEITAT)
Spanish non-profit organisation. Contributing to the ECOWAMA project with their know-how in alternative emerging treatment processes for gas and water, including electrocoagulation in industrial applications. Furthermore working on Life Cycle Assessment and Environmental Technology verification.

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E.R.S. – Steuerungstechnik – GmbH & Co. KG (ERS)

German SME contributing to ECOWAMA with innovative solutions for industrial control and automation application, including advanced sensing and signal processing technologies.

HyGear B.V. (HYG)

Dutch company, experts in industrial gas management, including knowledge on hydrogen quality analysis as well as hydrogen upgrading and purification technologies and fuel cell technology

Hidroquimia Tractaments I Quimica Industrial SLU (Hidro)

Spanish SME with competences in water treatment plant design, mechanical construction and compound integration.

Association pour la recherché et le development des methods et processus industriels – ARMINES (Armines)

French private non-profit research and technological organisation contributing with expertise in processing of gases and water recovery. Furthermore possessing strong analysis know-how on gas and metal characterisation.

Knowledge Innovation Market S. L. (KIM)

Spanish knowledge transfer company offering technology based innovation services. Contributing to ECOWAMA with IP right consulting, patent search, market evaluation and dissemination of project results.

Eilenburger Elektrolyse- und Umwelttechnik GmbH (EUT)

German SME with expertise and experience of more than 25 years in galvanic operations, environmental technologies and chemistry focused on sustainable electrochemical metal recovery. ECOWAMA system integrator and technical lead.

Saxonia Galvanik GmbH (SAX)

German company and demonstration site for the ECOWAMA Pilot Plant. They contribute with know-how in STM operations, but also with experience in utilising environmentally friendly technologies to treat wastewater and convert residuals into valuable products.

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AQON Water Solutions GmbH (AQON)

German SME contributing to ECOWAMA with the pre-treatment unit for removal of oils/greases from STM effluents. AQON has wide spread contacts in the market for water treatment and water treatment equipment.

TMW SA (TMW) – France

French cleantech business with focus on innovation in water technology. Contributing with expertise in the field of planning, design, construction, and maintenance of desalination plants, including the knowledge and experience in recovery of ultra-pure water from sea water and industrial effluents.

By fulfilling the technical objectives in the project, ECOWAMA will enhance the acceptance and the wider use of electrochemical and -physical wastewater treatment in Europe's industrial sector as an ecologically friendly alternative to standard processes.

The ECOWAMA pilot plant achieves:

- 100% hypophosphite reduction [electrooxidation]
- >90% nickel recovery [electrowinning]
- Energy efficient generation of pure water ready for reuse > 85% [MHD process]
- Promising hydrogen generation, collection, upgrading & processing
- 70% reduction of disposal costs

As already mentioned, the ECOWAMA pilot plant is located at the facilities of Saxonia Galvanik GmbH in Halsbrücke near Dresden (Germany). If you are interested in visiting the pilot plant, please get in contact with the Project Coordinator and the Technical Manager of the ECOWAMA project whose contact details are provided below.

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MAIN SCIENTIFIC & TECHNOLOGICAL RESULTS/FOREGROUNDS

The focus in ECOWAMA project was the proper treatment of electroless nickel wastewater occurring in the STM (surface treatment of metals and plastics). Currently there is no energy and cost effective technology (process) commercially available. Therefore the concept represented in the figure below was developed

Overall concept of S&T development in ECOWAMA

The following simplified flow sheet is showing the final ECOWAMA overall concept:

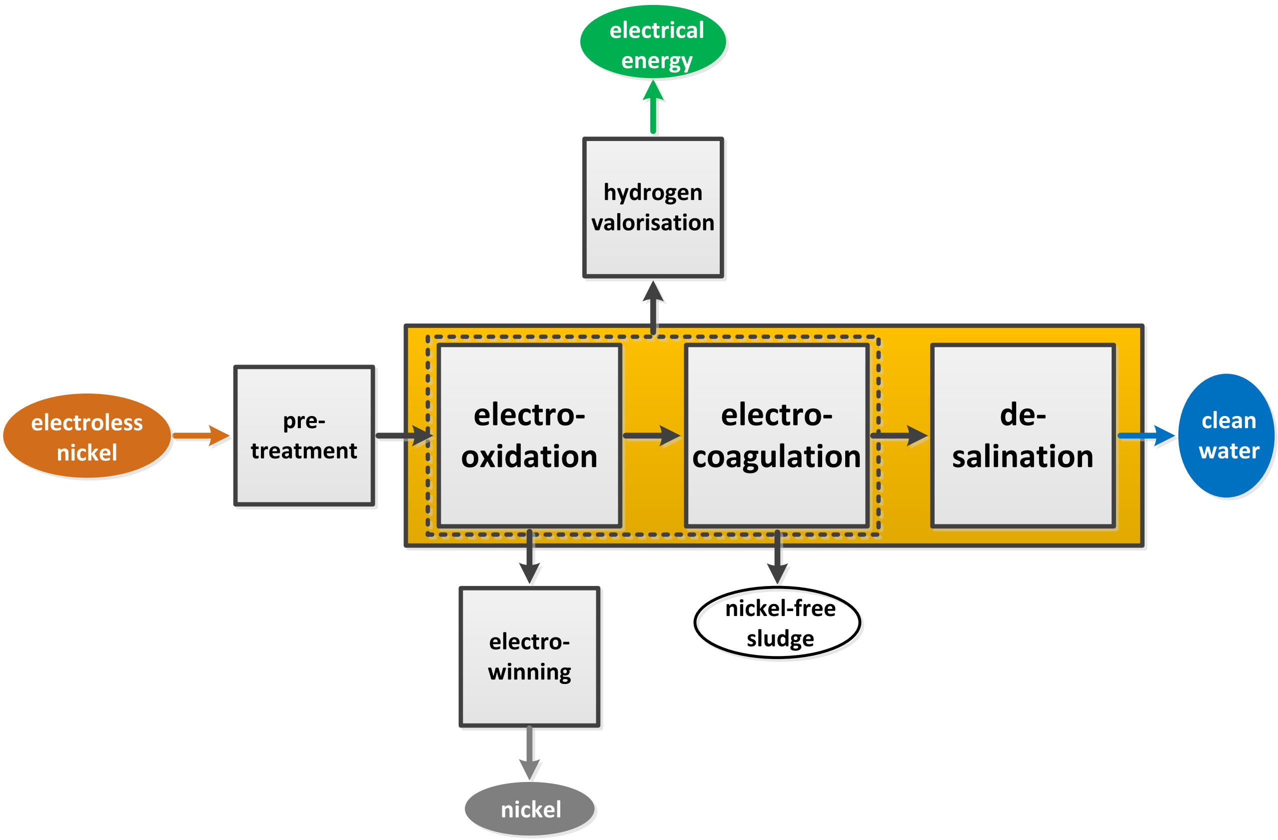

Figure 2: Overall concept of ECOWAMA project

The wastewater (electroless nickel, coloured in orange) is the input to the ECOWAMA system. As valuable outputs we gain nickel, purified clean water, electrical energy and a phosphorous containing nickel-free sludge. The yellow box contains the main (core) process steps regarding the purification of the wastewater. These are electrooxidation, electrocoagulation and desalination (evaporation). The hydrogen valorisation and the electrowinning are the process steps to directly recover valuable materials (nickel) and energy.

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Pre-treatment

For the removal of fats and oils from the coating industry effluent, a new design of a coalescence reactor was considered. Due to the high content of water in the effluent (more than 87 vol.%) and possible short-circuiting which aside causing material damages as well for the deterioration in the removal of oil and fat, an insulation of the used electrodes was necessary. Use of alternative current (AC) was chosen due to the successful experience so far in the AC application for liquids separation.

It exploits strong di-electrophoretic forces and benefits from a simple geometry. Stainless steel electrodes were coated with an insulation layer - PVC-U material of a thickness of 3.6 mm. The electrodes are positioned in a concentric form, thus the reactor is enabling a non-uniform electric field, which makes it suitable to higher voltage supply (necessary in the destabilisation of stable emulsions). As found out from simulation analyses, the content of the treated process water itself has an influence on the electric field. The higher the fat content in the tested process water, the higher is the electric field gradient - which makes the treatment benefiting substantially from di-electrophoresis.

Due to structural material design and electric properties (namely dielectric strength), the highest electric field which can be applied is 20 kV. The operational volume is of 1.5 litre and its construction enables both batch and continuous operation. The control was replaced by supervising the resonance frequency, which gives a hint on the separation behaviour. In this way, this operation parameter enable the automation of the current electrocoalescence reactor.

As already mentioned, the electrocoalescence reactor is operated by alternative current (6 - 10 kV) taking advantage of resonance frequency (45 - 100 kHz). Modulating the resonance frequency in order to have a constant electric field and the lowest energy load possible is reflecting the functionality of electrocoalescence.

The high concentration of mineral salts can cause electrode fouling. However, by operating with AC, this effect is reduced significantly.

The PEF equipment has proven to be appropriate to coalesce oil and fat droplets (up to several hundred nm) in emulsions. It has an efficient energy consumption, exactly enough to destabilise the mixed fat/oil and water phases and separate them into different phases. This energy is identified by the electrocoalescer operation in terms of resonance frequency and adjusted constantly through the electric field strength appropriately applied.

Secondly if an electric field is applied, there is no overheating of the treated flow, neither measurable physical and chemical changes (pH, temperature). The change is measured in the consistency, water cut vol. % (separated water from the initial mixed phase) and turbidity.

Sometimes it happens that voltage rises instead of sinks at the beginning of the experiment. This may be caused by the fact that resonance frequency is not reached exactly. Lowering the frequency is no obligatory requirement, since voltage (read at the oscilloscope) will decrease

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with the time. However, one should change the frequency, if voltage is increasing too strongly or in case the sinus starts to be displayed under an irregular shape.
Modulating the resonance frequency in order to have a constant electric field, is leading to the lowest possible energy supply. This fact implies an efficient energy consumption.
To generate a splitting of emulsions or oil in water formations, a variety of steps are necessary. The first step is the coalescence step where an electric field is applied leading to a number of physical phenomena. The oil drops or liquid fat drops including embedded particles, molecules e.g. proteins come together and build larger agglomerates that float due to their lower density compared to water.
In the second step the floating oil can be removed using a separator. A gravity separator has been developed which is especially designed for the metal working industry and meets all regulations and standards that are required.

Wastewater treatment and metal recovery: Electrooxidation, Electrocoagulation, Electrowinning

The main objective of the ECOWAMA project is the closed cycle management model for the treatment of effluents of the metal and plastic surface processing industry. Such wastewater is contaminated with oils and greases, organic compounds, salts and especially with metals. The wastewater chosen for the ECOWAMA project is spent electroless nickel bath and related rinse water from Saxonia Galvanik GmbH. This effluent has a specific organic loading which does not allow disposal in the internal Saxonia wastewater system. Consequently, this wastewater needs be externally disposed. The electroless nickel wastewater also has a high concentration of metal, which can be reused in the plating process.
In a first step the mixing and dosing unit, installed during the ECOWAMA project, is mixing the wastewater and rinse water from the spent electroless nickel bath and is delivered to the anolyte electrode chamber of the electrooxidation unit. Subsequent the effluent is directly fed to the electrocoagulation unit. In the oxidation unit, the majority of the organic content, especially the hypophosphite, is oxidised to the non-disruptive forms so that an external disposal is no longer necessary. The electrooxidation is also working with a special cation exchange membrane, so that the nickel ions are accumulating within the catholyte chamber of the unit.
In the next step an electrocoagulation unit (ECo) follows. This unit contains a so called sacrificial iron anode which dissolves during the process. The dissolved iron is able to precipitate organic compounds oxidised before. The working pH is < 6 so that no precipitation takes place in the ECo unit. Subsequently the wastewater is no longer determined for a cost intensive external waste disposal.
The electrooxidation unit and the electrocoagulation unit were running with a cation exchange membrane. Thus hydrogen produced on the cathodic side could be collected easier and feed

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the connected fuel cell from the HyGear unit. The produced hydrogen is available in enough quantity to operate this fuel cell.

The electrowinning unit works with concentrated nickel wastewater from TMW's evaporation unit. The dissolved Nickel ions were reduced to a solid aggregate state with high purity. This purified metal can be sold or reused. The deposited Nickel was analysed to have a purity of > 99%.

Hydrogen processing

HyGear being responsible for the development and assembly of the Secondary Power Generator showed during testing at the site of partner Saxonia that it is possible to successfully withdraw low pressure hydrogen rich gas from both the electrooxidation and electrocoagulation units assembled by partner EUT for metal containing wastewater treatment. The gas was successfully upgraded to hydrogen quality suitable to be fed to a PEM fuel cell stack, especially selected for this project with partners Leitat and MINES Paris Tech. The fuel cell stack was shown to produce energy up to 1.5 kW_e (maximum value defined under the inlet conditions).

The Secondary Power Generator was designed following the NPD process developed by NASA for new product delivery. Using this strategy the demands for the prototype were set early in the project as low energy and utilities consumption and high hydrogen upgrading yield at high purity. During the different NPD phases several technologies, such as liquid droplet removal, oxygen removal and hydrogen upgrading were evaluated technically in the lab. Based on technology readiness solutions were implemented. During the project close collaboration with partners to define the integration specifications was held.

Upgrading of the hydrogen gas (removal of carbon dioxide and nitrogen) was performed using novel developed PSA technology for low energy consumption and high yield and high purity hydrogen upgrading. The hydrogen yield was over 95% at purity 2.5 with low energy consumption whereas common PSA technology only has < 70% yield. Other impurities from the wastewater treatment, such as hydrogen sulphide and ammonia were removed by adsorption. Oxygen from the electrooxidation process was removed by reaction in a specially arranged low temperature, low pressure drop deoxidation reactor.

The project showed the PSA and FC technology are mature technologies that are suitable for hydrogen upgrading at low cost and energy production from H_2-containing low pressure gases obtained from wastewater treatment. Due to the chosen solution it was shown that hydrogen upgrading could be performed at over 95% yield and that the electrical yield of the system was over 50% of the input. As the major electrical consumption of the prototype was attributed to the control system it is expected that this will significantly improve for larger upgrading plants. Also H_2-containing low pressure gases from other sources can be upgraded in a similar cost effective, highly efficient way.

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Post-treatment

During the ECOWAMA project, TMW has upgraded and improved its technology MHD (Multistage Humidification – Dehumidification) to integrate the overall process chain and contribute to the challenging objectives defined by the consortium.

The functional requirements assigned to the MHD technology in the ECOWAMA system were:

- To produce pure water (conductivity < 20 µS/cm) ready to reuse in the STM process out of salty mineralised wastewater.
- To produce a concentrated nickel solution ([Ni] >15 g/L) to feed the electrowinning process out of diluted wastewater ([Ni] = 1g/L) which concentration is initially too low to make the electrolysis process technically and economically efficient.

Achievements:

The desalination unit succeed to prove during the demonstration phase its ability to recycle wastewater into an easily reusable pure water (conductivity < 20µS/cm) and bring the diluted nickel rinsing wastewater to an interesting nickel concentration level.

Table 1: Monitored parameter during demonstration phase (stream: nickel rinsing wastewater)

Parameter (Average over the demonstration phase period)	Unit	Raw wastewater	Distillate	Concentrate
Conductivity	µs/cm	4 500	18	35 000
Nickel	mg/L	1000	< 0,1	15 500

Furthermore, to fit industrial needs, important developments were realised focusing on:

- *Energy efficiency optimisation*

A new plastic heat exchanger has successfully been designed and produced, permitting the improvement of the desalination unit condenser efficiency thanks to the use of innovative plastic with high thermal transversal conductivity and a wider heat exchange surface.

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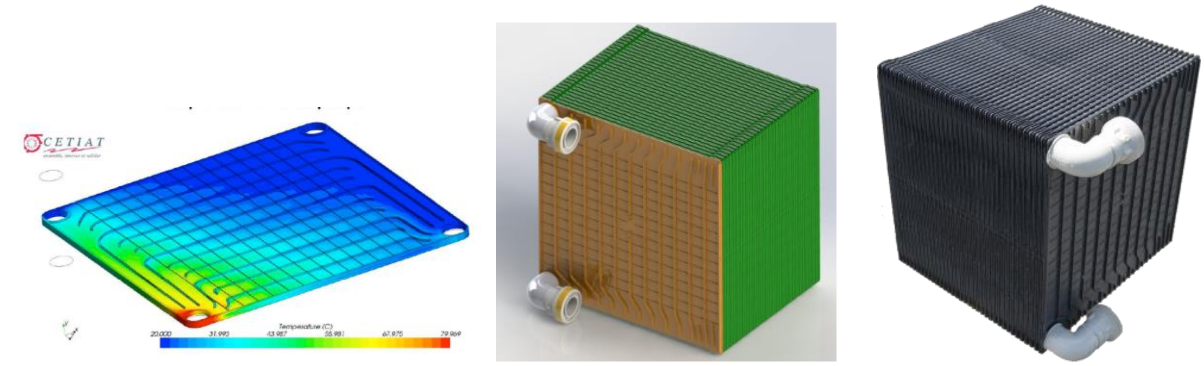

Figure 3: Heat transfer simulation / New plastic heat exchanger (CAO view and real picture)

- Modularity (capacity to be scalable to every wastewater flow rate), compactness, and cost efficiency.

A new evaporation unit has been developed ensuring a larger production capacity per MHD unit, based on an innovative modular design composed of blocks fully produced in EPP. This result in a very flexible approach with the possibility to realise different versions of the evaporation unit from 3 to 6 stages depending on project target (cost versus capacity optimisation or energy optimisation).

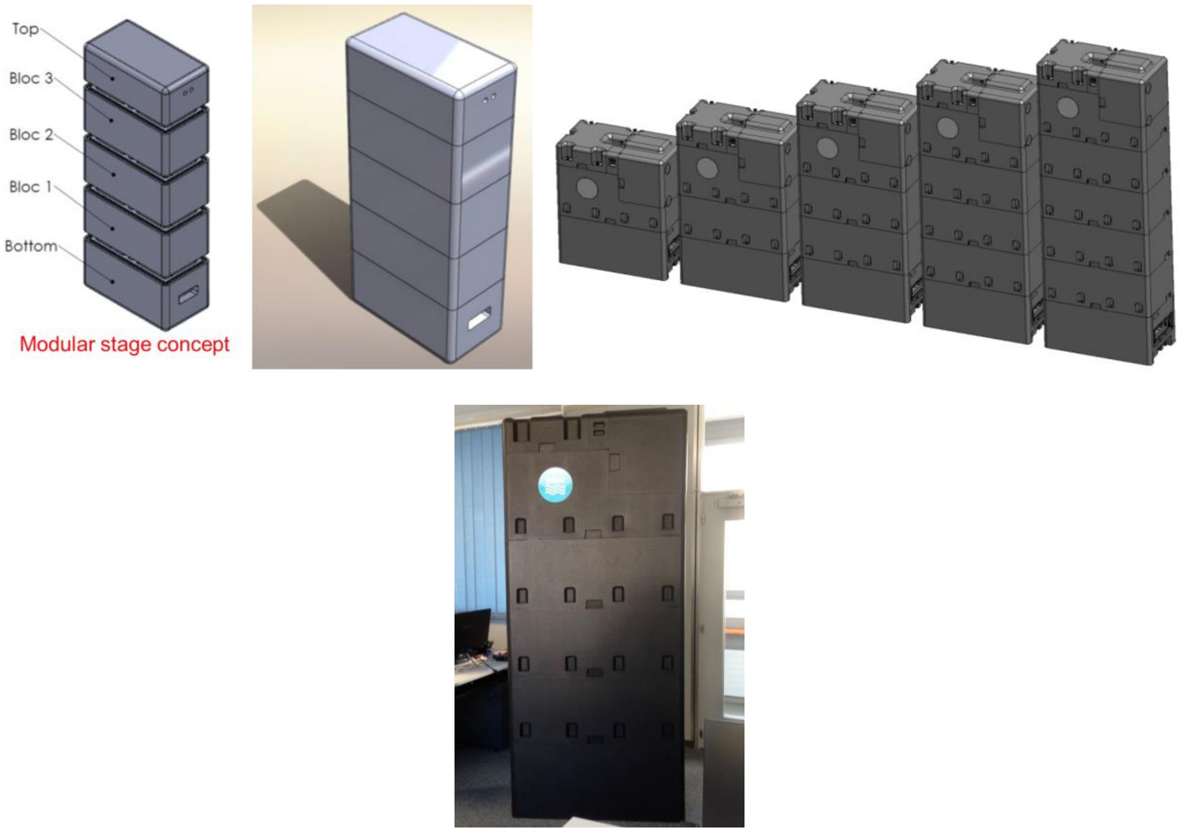

Figure 4: MHD new evaporation unit / CAO views

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- *Output water quality optimisation*

The technology scale up created the necessity to develop a new droplet separator, this component placed between evaporator & condenser chambers allows clean humid air to pass from the evaporator to the condenser, without droplets of polluted water ensuring optimal distillate purity.

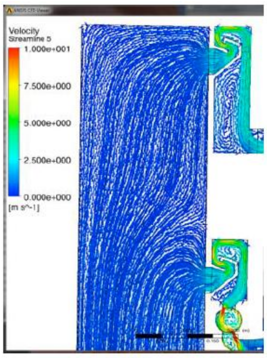

Figure 5: CFD simulation to evaluate the air flow and optimise the droplet separator geometry

- *Operation and maintenance time optimisation (development of a fully automated control system with remote control)*

Around the evaporation unit a global control system to provide a safe and autonomous equipment adapted to STM streams was engineered. This is easy to implement in the ECOWAMA process chain and ready to use in any industrial environment.

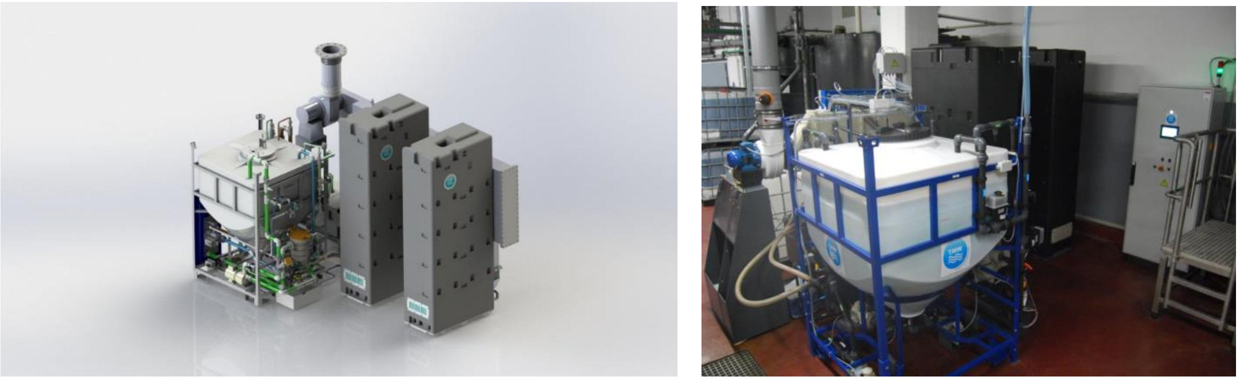

Figure 6: The 2 MHD evaporation units and its control system implemented in the ECOWAMA pilot plant

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Life Cycle Assessment (LCA)

The main objective of the LCA is to perform the environmental analysis of ECOWAMA system, considering their environmental impacts as well as benefits reached by the system: metal recovery, wastewater treatment, electricity production, re-use of extracted pure water, metals and organic compounds. The environmental analysis has another goal, which is to examine every stage of the whole life cycle of ECOWAMA system in order to identify the hotspots of the treatment proposed. This enables identifying possible improvements of the treatment. Moreover, the environmental impacts and benefits of ECOWAMA system have been analysed and compared with the current technology applied in Saxonia Galvanik.

The environmental analysis of ECOWAMA system has been performed based on the Life Cycle Assessment (LCA) methodology. The LCA methodology applied in this project is based on the ISO framework for LCA: ISO 140401 and ISO 140442, as well the recommendations of the International Life Cycle Data System (ILCD) Handbook. Calculations have been done using the SIMAPRO software and taking as a basis the Ecoinvent 3.1 database for general processes, and the ILCD impact assessment method. The ILCD method was released by the European Commission, Joint Research Centre in 2012 and it supports the correct use of the characterisation factors for impact assessment as recommended in the ILCD guidance.
As determined in the ISO standards, this LCA study has been performed according to four phases: goal and scope definition, inventory analysis, impact assessment and interpretation.

1. Goal and scope definition

In this first stage, the general context (system boundaries, functional unit and limitations and assumptions of the study) and the main aims of the study were defined. The environmental analysis done has taken into account all the impacts generated from obtaining raw materials for the pilot plant construction until obtaining a volume of water treated. As it can be seen in Figure 7, it have been considered the construction stage, the operation stage and the maintenance stage of the six units involved in ECOWAMA system. The end-of-life stage has been considered out of scope of the study. In the analysis it have been taken into account, for each unit: all the different components and equipment (tanks, electrodes, piping, etc.) which have been needed to construct each unit; the energy and chemicals consumption involved in the operation stage; and the chemicals needed, replacements, or water consumptions during the maintenance stage. The transports of raw materials and the transport of each unit from the technology provider (project partners) to the assembly location (Saxonia Galvanik), have also been taken into account.

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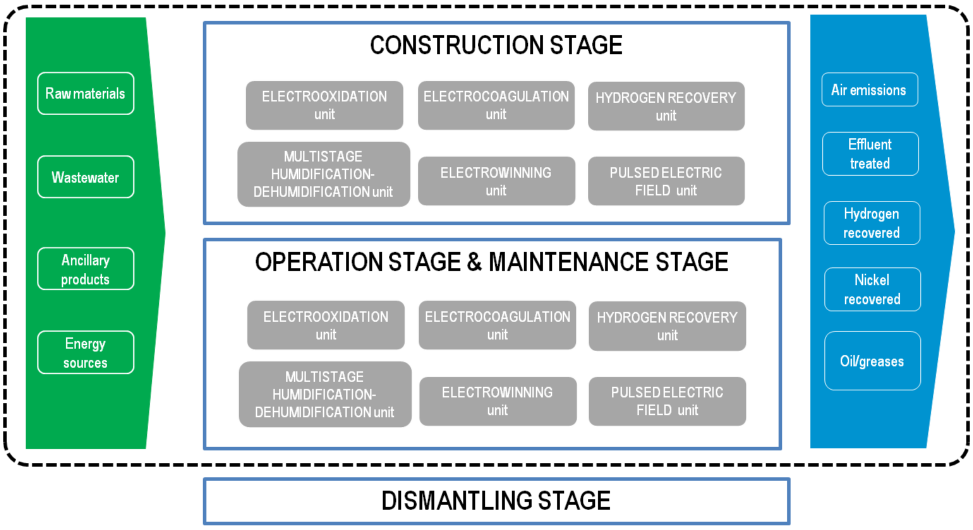

Figure 7. System boundaries of the system under study

Three types of wastewater (WW) have been treated by ECOWAMA pilot plant. Each type of WW has been treated by a combination of units. WW1 (Acidic-Ni-electroless bath and Acidic-Ni-electroless rinsing water) has been treated by the electrooxidation (EO) and electrocoagulation (ECo) process while recovering the hydrogen produced by each sub-treatment (EO and ECo) and obtaining energy. WW2 (mixture of rinsing water from electrolytic Ni-bath) has been treated by the Multistage Humidification - Dehumidification (MHD) technology and electrowinning (EW) technology. And finally, the WW3 (wastewater from the metal and plastic surface processing industry containing oil and grease) has been treated by the pulsed electric field (PEF) unit. Therefore, the operation of ECOWAMA pilot plant has been divided in three lines according to the effluent treated (Figure 8).

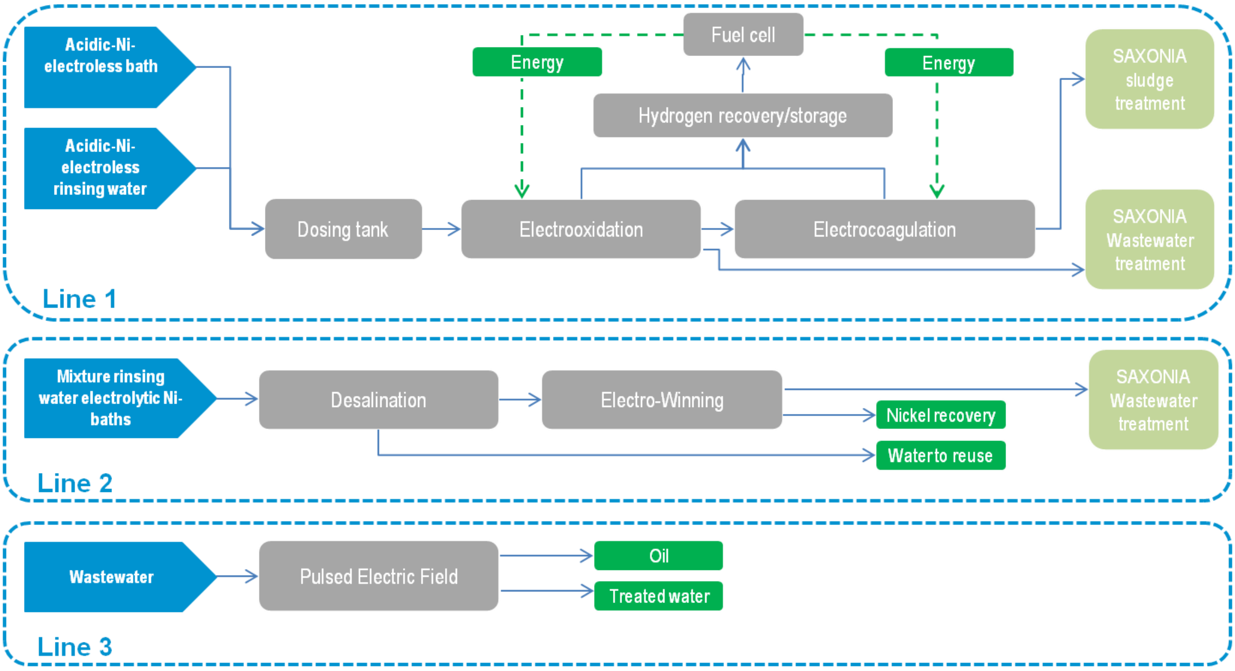

Figure 8. ECOWAMA System definition (operation)

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Functional unit: the functional unit is a quantified definition of the functionality of the studied process and it is used as a reference unit for all the input and output flows of the system. In this study, three functional units has been selected, based on the type and the quantity of wastewater treated by the pilot plant:

- F.U.1: "To treat 125 l/h of wastewater (90% Acidic-Ni-electroless rinsing water and 10% Acidic-Ni-bath) from the metal and plastic surface processing industry by ECOWAMA system" while recovering hydrogen.
- F.U.2: "To treat 150 l/h of wastewater (mixture of rinsing water from electrolytic Ni-baths) from the metal and plastic surface processing industry by ECOWAMA system" while recovering nickel and water to be reused.
- F.U.3:_"To treat 170 l/h of wastewater from the metal and plastic surface processing industry by ECOWAMA system" while recovering oil and grease.

Impact assessment method: as it has been explained before, the base methodology chosen for impact assessment is the ILCD 2011 midpoint method. The ILCD 2011 midpoint method includes 16 midpoint environmental impact categories. For this analysis, the most relevant impact categories for the system studied has been selected. These impact categories are the following: Climate Change, Ozone Depletion, Photochemical Ozone Formation, Acidification, Terrestrial Eutrophication, Freshwater Eutrophication, Marine eutrophication, Water resource depletion, and Mineral, fossil & renewable resource depletion.

2. Inventory Analysis

All the data related to the construction stage, operation stage and maintenance stage of each unit, have been provided by project partners. Also life cycle inventory data (LCID) about the operation and maintenance stages of the current technology applied in Saxonia Galvanik have been requested. Data gathered are not included in this Report due to confidentiality issues.

3. Impact Assessment

The environmental impact assessment of ECOWAMA system has been analysed considering a life span of 20 years. The main results are presented in the following sections. The results are expressed per each line, considering each functional unit defined and each life cycle stage analysed (construction, operation and maintenance).

→ Potential environmental impact of treating WW1 (F.U.1) - Line 1:

The most environmental impact contributor unit in the Line 1, for all the impact categories studied except for the mineral, fossil & renewable resource depletion, has been the electrooxidation (EO), with environmental impact contributions that range from 31% to nearly 62% (Figure 9). The second unit with the highest environmental impact contributions has been the electrocoagulation (EC), with environmental impact contributions from 26% to 68%. The hydrogen recovery (HR) unit installed in Line 1 has had low environmental impact

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contributions, ranging from nearly 1% (mineral, fossil and renewable resource depletion impact category) to 8% (ozone depletion impact category). The benefits of producing energy through the HR are represented with the negative values. These benefits have contributions up to 7%, lower or similarly than the environmental impact contributions of hydrogen recovery unit. Therefore, the balance between benefits of producing energy through hydrogen recovery unit and impacts is negative, or nearly to 0.

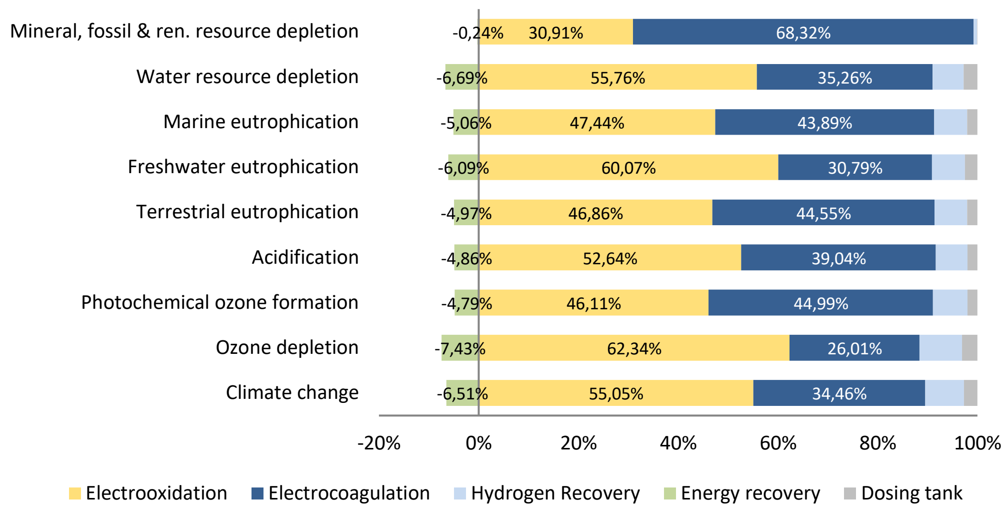

Figure 9. Potential environmental impact contributions of Line1

The main impact generated for the EO has been because of the operation stage, concretely, due to the electricity consumption necessary to run up the process. Maintenance stage has had a relevant environmental impact contribution for the mineral, fossil and renewable resource depletion impact category. The construction stage has had negligible values. The environmental profile of EC unit has revealed that the main environmental impact contributions come from the maintenance stage (due to the steel consumed for replacing the anodes, a maintenance task which is performed every 96 hours). This stage has had contributions ranging from 54% to 85% depending on the impact category analysed. The operation stage has had the highest environmental impact contributions in ozone depletion (68%) and freshwater eutrophication (54%) impact categories. The construction stage has had also negligible values.

→ Potential environmental impact of treating WW2 (F.U.2) - Line 2

The Line 2 includes the Multistage Humidification-Dehumidification (MHD) unit and the electrowinning (EW) unit. The environmental impacts have been represented in positive bars in the Figure 10. Moreover, there have been avoided impacts (or environmental benefits) due to the nickel recovery and water recovery produced during the treatment, represented as negative bars.

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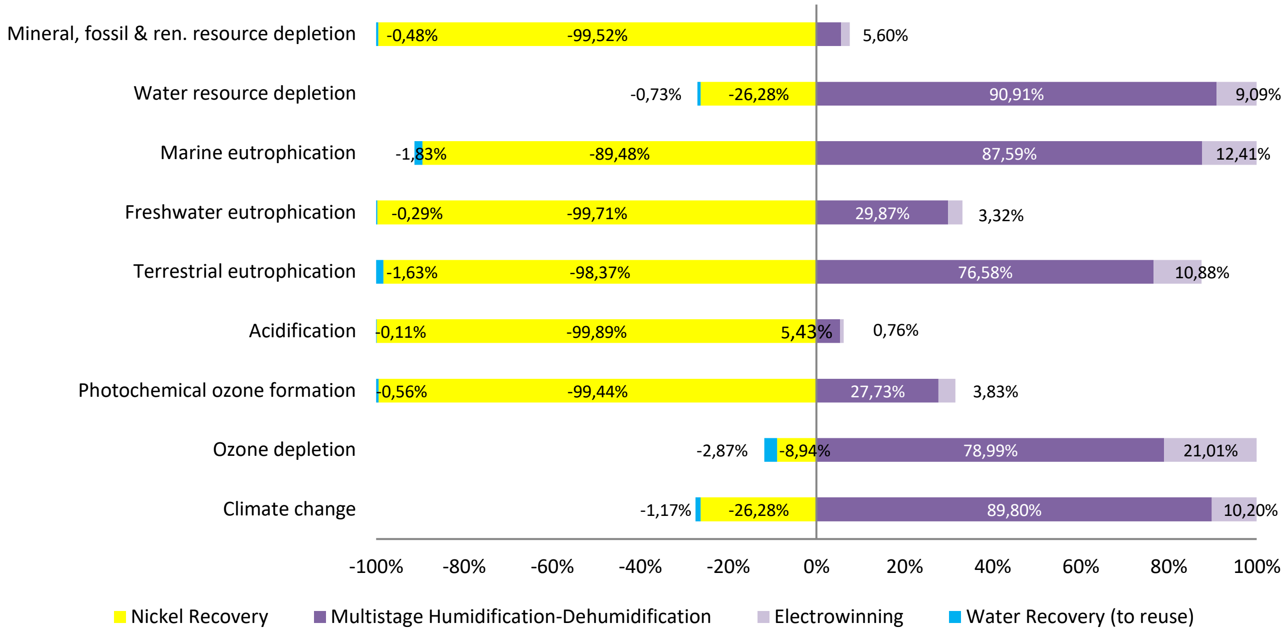

Figure 10. Potential environmental impact contribution of Line 2

In 5 out of 9 impact categories (mineral, fossil & renewable resource depletion; freshwater eutrophication; terrestrial eutrophication; acidification; photochemical ozone formation), the avoided impacts have been higher than the environmental impacts associated to MHD and electrowinning units. The environmental benefits of recovering nickel have been produced due to the avoided impact of obtain the raw nickel material.

On the other hand, there are 4 out of 9 impact categories (water resource depletion; marine eutrophication; ozone depletion; climate change) where the environmental impact generated has been greater than the avoided. In this case, the main environmental impact contributions are related to MHD technology. The environmental profile of MHD unit indicates that the main environmental impact contributions are related to the operation stage (due to electricity consumption once again), following for the maintenance stage. The construction stage has had negligible environmental impact contributions for all the impact categories analysed.

→ Potential environmental impact of treating WW3 (F.U.3) - Line 3

Line 3, formed by the Pulsed electric field (PEF) unit, has low environmental impact contributions, because PEF unit has low environmental contributions, linked to a low energy consumption and few quantities of chemicals used during their operation and maintenance stage. On the other hand, the oil and grease recovery in Line 3 contributes with high avoided impacts, because of the energy recovered and used as a resource in the ECOWAMA pilot plant. Accordingly, it is shown that Line 3 has greater environmental savings than environmental impacts, and has a good environmentally friendly profile for all the impact categories analysed.

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→ Environmental impact comparison between ECOWAMA system and current technology

Taking a look on the comparison of ECOWAMA's Line 1 environmental impact, with the environmental impact of step 2 of current technology applied in Saxonia Galvanik (which performs the same function) it can be seen that Line 1 has lower environmental impact contributions in 6 out of 9 impact categories: ozone depletion, photochemical ozone formation, acidification, terrestrial eutrophication, freshwater eutrophication and marine eutrophication (Figure 11, left figure). The environmental benefits of applying ECOWAMA system by treating WW1 (F.U.1), for the impact categories mentioned before, are in the range of a discreet 7% to a remarkable 66%, depending on the impact category selected. Thus, for the majority of the impact categories studied and for treating WW1, ECOWAMA system has a better environmental profile than the current technology.

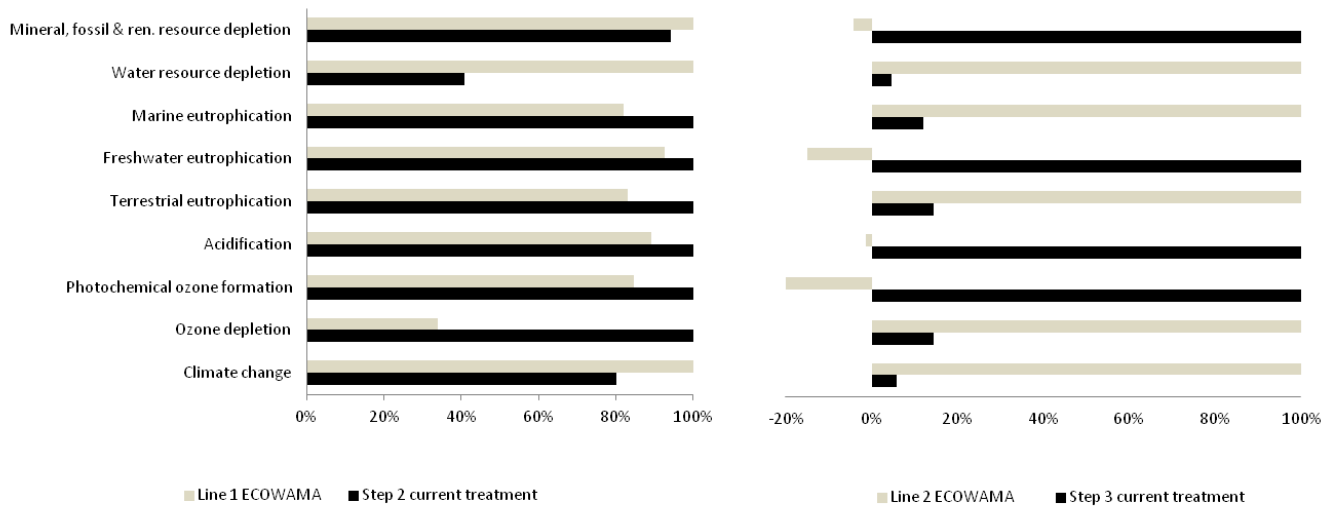

Figure 11. Potential environmental impact contribution of Line 1 and Line 2 of ECOWAMA system compared with the step 2 and step 3 (respectively) of the current treatment performed in Saxonia Galvanik

Figure 11 (right figure) also compares the environmental impact contributions of the operation and maintenance stages of ECOWAMA's Line 2, with the environmental impact contributions of the operation and maintenance stages of the step 3 of the current technology applied in Saxonia Galvanik. In this occasion, it can be observed that current treatment has the lowest environmental impact contributions in 5 out of 9 impact categories: climate change; ozone depletion; terrestrial eutrophication; marine eutrophication; and water resource depletion. In particular, step 3 of the current treatment contributes with important environmental savings, ranging from 86% to 95%. Therefore, for the majority of the impact categories studied and for treating WW2, the current treatment applied in Saxonia Galvanik has a better environmental profile than ECOWAMA system. It is worth mentioning that Line 2 of ECOWAMA system can

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diminish the environmental impact contributions more than one 100% in 4 out of 9 impact categories: photochemical ozone formation; acidification; freshwater eutrophication; and mineral, fossil and renewable resource depletion.

4. Interpretation

In the final step of the LCA, interpretation and critical revision of the results has been done in order to verify its reliability. By interpreting the results obtained in this study, it can be concluded the following:

- Undoubtedly, the incorporation of a hydrogen recovery cell in the Line 1 is a good option in terms of sustainability, but the system needs to be optimised to achieve a better efficiency in energy recovery terms.
- Line 2 has a good environmental profile because in general, environmental savings (or benefits) are greater than environmental impact contributions. Also, Line 2 allows the recovery of nickel, a chemical element that in pure form, can be found only in tiny amounts in the earth's crust. Despite all of this, the Line 2 operation stage could be also optimised in energy consumption terms.

- Line 3 has also a good environmentally profile because for all the impact categories analysed, environmental savings are greater than environmental impact contributions, and allows the recovery of oil and greases from wastewater to produce energy.

- Finally, the comparison of ECOWAMA system with the current treatment applied in Saxonia Galvanik demonstrates a better environmental profile for the case of Line 1, in six out of nine impact categories. And a better environmental profile for the case of Line 2 in four out of nine impact categories. Even though these results are not the most desirables, it is worth mentioning that current treatment applied in Saxonia Galvanik is an industrial scaling treatment, and ECOWAMA system is a pilot plant scale treatment. And this divergence of scales, make difficult the comparison between both systems.

On the other hand, considering potential for innovation and the environmental benefits of technology developed in ECOWAMA, a first analysis has been performed in order to study if ECOWAMA system could be suited for the EU Pilot Programme on Environmental Technology Verification (ETV).

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POTENTIAL IMPACT, INCLUDING THE SOCIO-ECONOMIC IMPACT AND THE WIDER SOCIETAL IMPLICATIONS OF THE PROJECT

By fulfilling the technical objectives in the project, ECOWAMA enhances the acceptance and the wider use of electrochemical and -physical wastewater treatment in Europe's industrial sector as an ecologically friendly alternative to standard processes.

ECOWAMA project intends to contribute to the solution of larger society challenges like:

- Closing the loops in water consumption (85% reduction of water consumption in the envisaged STM operation)
- Increasing the energy efficiency of processes in order to preserve natural resources (5-10% reduction of energy consumption by use of hydrogen from electrically driven processes)
- Avoiding the use of hazardous chemicals to protect the environment (by use of electrically driven technologies)
- Recovering of valuable materials, thus increasing resource efficiency and decreasing the exploitation of primary resources (reuse of nickel and water at high product quality)

ECOWAMA technology expects to strengthen Europe's position in the global market of surface treatment of metals and plastics through focusing on environmentally friendly wastewater treatment. Furthermore, it helps to improve the economic viability of industrial sectors involved in the surface treatment of metals and plastics. Amongst other activities, the ECOWAMA industry workshop in March 2015 started the close contact to first interested customers from the STM sector.

Flexible and modular design of ECOWAMA system will allow the use of individual units for further STM applications (e.g. electrooxidation). Especially for the electrooxidation unit there are already some interested industrial contacts keen on testing parts of the pilot plant.
Furthermore new contacts within academia (e.g. TU Bergakademie Freiberg, Germany) are established in order to evaluate follow-up projects also in terms of scientific advancements.

ECOWAMA project has positive socio-economic impacts related to the recovery and reuse of metals, pure water and hydrogen, and the abatement of organic compounds.

- First of all, the ECOWAMA system allows the recovery of nickel contained in wastewater from STM industry in high percentages. This recovery is especially important because the extraction of raw nickel, causes important environmental and social impacts related to the: blasting operations and processing, the use of chemicals and sulfidic tailing. Moreover, nickel is a chemical element that in pure form, can be found only in tiny amounts in the earth's crust, thus, the reuse of nickel instead of the extraction of a valuable raw material is preferable. It has been

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demonstrated in the framework of ECOWAMA project, that by recovering nickel from the wastewater from STM industry, it can be achieved great environmental savings.

- Secondly, ECOWAMA system also recovers hydrogen, as a by-product of the system, and oil and greases contained in wastewater. This substances have been reused as an energy source, to supply electricity to the own system. In this sense, ECOWAMA system promotes the use of by-products or wastes as alternative and renewable energy sources and therefore, is committed to CO_2 emissions savings.

- Thirdly, ECOWAMA system allows the reuse of water and thus, the avoided impacts related to use new water. This is very interesting for those areas in which water is a scarce resource, as for example the Mediterranean areas and other areas that suffer dry episodes.

In conclusion, ECOWAMA system is in line with environmental concerns such as: the raw materials overconsumption and raw materials scarcity; the waste and wastewater reduction; the energy supply by using alternative energy; and the transition to a circular economy model. Obviously, all these aspects have great impacts and repercussions on local communities, economy and wider society.

ECOWAMA treatment and recovery approach is new for the manufacturing industrial processes, avoiding the further depletion of the available water resources and reducing the emission of pollutants. It leads to a reduced industrial fresh water demand: the freshwater demand of the manufacturing industry is more than 20% of total freshwater demand in Europe. Industrial use of water amounts to 24.6 bn m^3 per year in the EU and varies greatly between countries and industries. The environmental drivers of increasing costs of wastewater treatment to meet environmental standards create a powerful economic driving force to rationalise water use.

Secondary power generator - commercialisation

The project has shown that it is feasible to produce electrical energy from H_2-containing low pressure gases obtained from wastewater treatment to lower the carbon footprint of the WWTP's used. Although at the pilot scale demonstrated the electrical consumption played a critical role in the power efficiency of the Secondary Power Generator it is expected that this will significantly improve for larger upgrading plants.
The technology developed has boosted HyGear's PSA development strategy and will be implemented in HyGear's proprietary PSA technology. It is expected that the technology will be used in HyGear's Hy.REC systems that will recycle pure hydrogen from waste streams. Such systems will lower the overall gas consumption of industrial processes, and as such will reduce the overall feedstock and power use of industry. Main implementation of this technology

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is foreseen in glass and metal treatment industry in which hydrogen is currently used for creating a reducing atmosphere. In current industry this hydrogen is vented and not re-used. With the technology demonstrated in ECOWAMA hydrogen can be reclaimed with high efficiencies. HyGear has started a NPD-process to analyse the economic potential of hydrogen recovery in these markets.
During the workshop organised at the Technical University Bergakademie Freiberg the project was presented to different stake holders. Positive feedback was received.

PEF - commercialisation

With the new PEF technology, it is possible to separate oils and fats from process and wastewater streams to reuse the purified water. This process works without addition of chemical agents and heat in a very short time. The commercialisation of the PEF technology for the separation and filtration process of oil, fat and particles will be focused in the metal working and automobile industry, the galvanic industry, in metal working fluid systems (cooling lubricants) and in the degreasing and cleaning wash processes in the surface treatment industry.

MHD - commercialisation

Since 2012, and because of the efficiency of MHD technology, TMW has been successful in selling many ECOSTILL equipment's (commercial name) in various industrial fields (metal surface treatment, landfill leachate, textile industry, leather skin manufacturing) having wastewater stream from 0.5 m^3/day to 5 m^3/day.
Used as an evapo-concentration solution, the MHD technology help industrial customers to strongly reduce their waste waters (up to 95%) and recover high purity water, which may be reused in the manufacturing process, so making ECOSTILL a key element to be in line with a "ZLD" policy (Zero Liquid discharge). "ZLD" providing insurance to be compliant to current and future regulations making discharge levels more stringent.
Its plastic design, the internal energy recovery process, its very easy maintenance are the main reasons of ECOSTILL success on the market. Added to these technical arguments, the customer users of ECOSTILL take benefits of a very quick pay back and/or cost reduction, because of the competitiveness of the solution.
The improvement done and validated during ECOWAMA program has generated new market opportunity for TMW especially concerning larger wastewater stream, two installation based on the ECOWAMA design had been sold in 2016 (8 m^3/day and 18 m^3/day).

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Electrooxidation, electrocoagulation, electrowinning - commercialisation

The core technologies installed, electrooxidation, electrocoagulation and electrowinning are running at Saxonia Galvanik with the effluent electroless nickel wastewater. This approach as consisting of a combination of technologies for wastewater treatment of STM enterprise is a promising new idea tackling first interested industrial customers, which have already visited the ECOWAMA pilot plant.

Especially through electrooxidation it is possible to avoid the expensive external disposal including cost for the nickel containing wastewater. By this essential treatment step, the electroless nickel wastewater can be treated in the internal wastewater system, which will lead to lower disposal costs.

Communication of results

The communication of results is essential for an important impact from a social and economic point of view. The ECOWAMA partners during the 4 years of execution of the project disseminated the results through different tools:

- Website (http://www.ecowama.eu/)
- Newsletters and press releases
- Policy brief
- Workshops
- Publications
- Two ECOWAMA's videos
- Advertising materials (posters, brochures, flyers, etc).

The targets of stakeholders to which disseminate the achievements of the project, belong to different fields and branches from science, industry, public and politics.

In detail, any individuals, groups of people, institutions or firms that may have a significant interest in the success of ECOWAMA project can be defined as stakeholders. ECOWAMA partner KIM has performed an analysis of potential stakeholders in order improve targeted dissemination and communication activities. The basic steps to perform the analysis were the following:

- Identification of groups with specific interest in ECOWAMA project.
- Investigation of their role, their different interests, their powers and the possibility of their participation in the project.
- Interpretation of findings and integration of the information in the ECOWAMA PUDF, so as to ensure that:
    - Communication resources are allocated according to the needs of the target-groups
    - The promotion of stakeholder participation is foreseen at management and coordination level

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Through this analysis, stakeholders can be classified in the following categories:

- Policy-makers (includes governmental bodies, such as ministries and national agencies, local/regional authorities, etc.)
- Business support organisation (includes chambers of commerce, local/regional development agencies, etc.)
- Academic/research institute (includes universities, colleges, research units etc.)
- Non-Governmental Associations (includes industry, companies).

After the identification of relevant stakeholder facilitated the distribution of newsletters and allowed a targeted invitation of stakeholders to project relevant events.

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PROJECT WEBSITE

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