Ref. Ares(2022)8283100 - 30/11/2022

Deliverable D7.4
Report on the circularity of PureNano technologies

Lead Beneficiary	AXIA
Delivery Date	30 11 2022
Dissemination Level	PU
Version	1.0

This project has received funding from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 821431

Report on the circularity of PureNano technologies

Deliverable D7.4

Document Information

Deliverable name	**Report on the circularity of PureNano technologies**
Deliverable No.	D7.4
Dissemination Level[1]	PU
Work Package	7
Task	7.1
Contributing beneficiary(ies)	Gaser, Captive S, NTUA, ISQ, CNano
Due date of deliverable	30.11.2022
Actual submission date	
Lead beneficiary	AXIA Innovation

Author	**Cristina Onorato, Dr. Ioanna Deligkiozi**	
Version number	1	
Date	30.11.2022	
Reviewed by	PoliMi	
Comments		
Status	✓	Submitted
		Accepted
Action requested		To be revised

Document history

Version	Date	Beneficiary	Author
0.1	16/08/2022	AXIA	Cristina Onorato
0.2	25/11/2022	AXIA	Cristina Onorato
1.0	30/11/2022	PoliMi	Luca Magagnin, Peny Eleni

[1] PU = PUBLIC
PP = Restricted to other programme participants (including the Commission Services)
RE = Restricted to a group specified by the consortium (including the Commission Services)
CO = Confidential, only for mbers of the consortium (including the Commission Services)

Table of Contents

List of Tables

List of Figures

Abbreviations and acronyms

Acronym	Definition
MNPs	Magnetic Nanoparticles
WM	Waste Minimization
CE	Circular Economy
CBM	Circular Business model
SCC	Self-compacting concrete

Publishable Executive Summary

Interest in recycling and the concept of Circular Economy (CE) from government, society, academia, and industry has grown constantly in the last few years. The transition towards a circular economy model is challenging since it requires a change in the economy and production assets; what is considered a waste in the linear economy becomes a resource in the circular approach.

Initially, the circular economy approach was applied exclusively to technical processes, where efficient resource use was examined to reduce their environmental impact. Recently, it has been recognized that to facilitate the transition, not only technology needs to change, but even the entire business strategy and value chain must be adapted, eventually with the help of a new business model.

On this background, the importance of the PureNano concept is even clearer. The plating industry produces every day a huge amount of hazardous waste that is transported to specific treatment plants, where mainly chemical or electrochemical processes are applied, producing a big amount of sludge. The switch from a linear system to a circular system, where the plating bath is not considered a waste, but a resource, can be performed through the PureNano technology. In PureNano, the spent baths are regenerated by using Magnetic nanoparticles (MNPs) that capture the contaminants present in the spent bath. Proposing a transition to a circular perspective, PureNano technology can reduce both the cost and the environmental impact of the process.

The concept of circularity behind the PureNano project and a detailed analysis of recyclability are the main topics covered in D7.4. This deliverable is divided into two parts. The first part provides an overview of the circular economy concept and its application to the plating industry and a clear picture of the current waste management practices. Since the plating bath is usually disposed of with no further treatment, the importance of the PureNano technology for bath regeneration, and the circularity associated with the project are highlighted. It is well known that the wastes generated within the plating industry are mainly wastewater, sludge and spent baths. These wastes can be treated after they are generated, or their production can be prevented by applying the so-called “Waste Minimization Techniques (WM)”. An analysis of the pilot-scale technologies within

the PureNano project is included. To support this action a questionnaire was distributed to the owners of the pilot plants installed during the project (Gaser and Creative Nano) to understand which WM techniques are currently applied in their business and which can be applied in the future to reach higher TRL. Once these techniques are applied, the next step is the regeneration of the plating bath using MNPs, which after being used to capture the metals from the spent bath are reused for other applications or regenerated. The spent MNPs can indeed be used for water treatment, in the cement industry, or can be regenerated. The three regeneration routes have been analyzed considering the possibility to include the regeneration processes in the existing plating plants.

The second part of the deliverable provides an overview of the most used Circular Business Models (CBMs) found in the literature and a clear analysis of their application to the pilot user cases. The pilots' owners have then assessed the CBM selected for their specific business through a questionnaire.

1 Introduction

1.1 Introduction to the circular economy

Based on the Ellen MacArthur foundation definition, the Circular Economy is "a systems solution framework that tackles global challenges like climate change, biodiversity loss, waste, and pollution"[2].

From a linear economy point of view, natural resources are extracted, transformed into capital and consumer goods, and eventually disposed of in landfills or disposal facilities. From a circular perspective, the emphasis is on designing long-lasting goods, easy to repair and reuse, that after recycling are as good as the virgin ones.

The transition to a circular economy is one of the key aspects of the ambitious goals of the European Union (EU) of becoming the first "*climate neutral*" continent by 2050, to make a "*cleaner and more competitive*" Europe. A successful shift to a circular economy could help meet the Sustainable Development Goals, the Paris Climate Agreement targets, and the ambitions of the European Green Deal and reach carbon neutrality in Europe by 2050[3].

In the last few years, the consumption of natural resources and waste generation quickly increased. This phenomenon has economic, social, and environmental consequences. From an economic point of view, the use of natural resources causes an increase in prices due to higher competitiveness. Looking for the social implications, source depletion creates problems for the manufacturer's supply chain. From an environmental point of view, resource depletion and the continuous disposal of waste without their valorization (*e.g.,* regeneration or reuse) create biodiversity problems and irreversibly damage the environment.

Considering the entire EU economic activity, waste generation accounts for up to 2.5 billion tons or 5 tons per capita a year, meaning that each citizen produces (on

---

[2] https://ellenmacarthurfoundation.org/topics/circular-economy-introduction/overview

[3] ETC/WMGE Report 2/2021: Business Models in a Circular Economy

average) around half a ton of municipal waste each year[4]. The human footprint already exceeds the earth's biocapacity by more than 50% and soon we will also reach the limits of global freshwater use [5]. As a consequence, there is a growing need to recirculate materials and products and eliminate waste, as promoted by different drivers, namely the European Commission regulations, public acceptance, and new sustainable market trends and greener solutions. Moreover, boosted by the new policy regulations, more companies responsibly apply changes in their business and become a driving force to promote circular economy strategies in real-life paradigms such as reuse and recycling.

The definition of the circular economy implies the improvement of current economic models, the introduction of new strategies that are sustainable over time, including the elimination of waste and pollution, and the creation of value from the reuse of products and materials. These approaches aim to drastically constrain the extraction of superfluous raw materials and the production of waste [6].

In Europe, to achieve this shift to a circular economy, it is necessary to take several actions such as reducing resource use, adopting and upscaling the lengthening of the useful life of products, reusing and sharing products, repairing and remanufacturing[2]. Nonetheless, as already highlighted, this change doesn't involve only the technological aspects, but also the business models built around them.

One of the main foci of the circular economy perspective is to be restorative and regenerative by design, making sure that products and materials are maintained at their highest value throughout the entire value chain. The concept of a circular economy comes from the observation of the natural system made up of life cycles, and nothing is wasted. As shown in *Figure 1*, we can have two different cycles: biological and technological. The technical cycle includes what does not biodegrade and includes actions such as recycling, remanufacturing share, and

---

[4] Circular economy action plan (europa.eu)

[5] http://kgk.uni-obuda.hu/sites/default/files/EY-brochure-cas-are-you-ready-for-the-circular-economy.pdf

[6] Circular Economy – Sustainability Guide

repair within the value chain. On the other hand, the biological cycle includes what biodegrades and regenerates (*e.g.,* valuable products like cotton and wood). In a world of increasing demand and resource consumption, a linear model of extraction and disposal of materials is no longer sustainable. Resources are becoming increasingly difficult to extract due to higher costs and effects on biodiversity. Consequently, it is crucial to generate a new way of thinking and create new business models, taking into account a circular flow approach of energy and materials by closing the loop in the value chain.

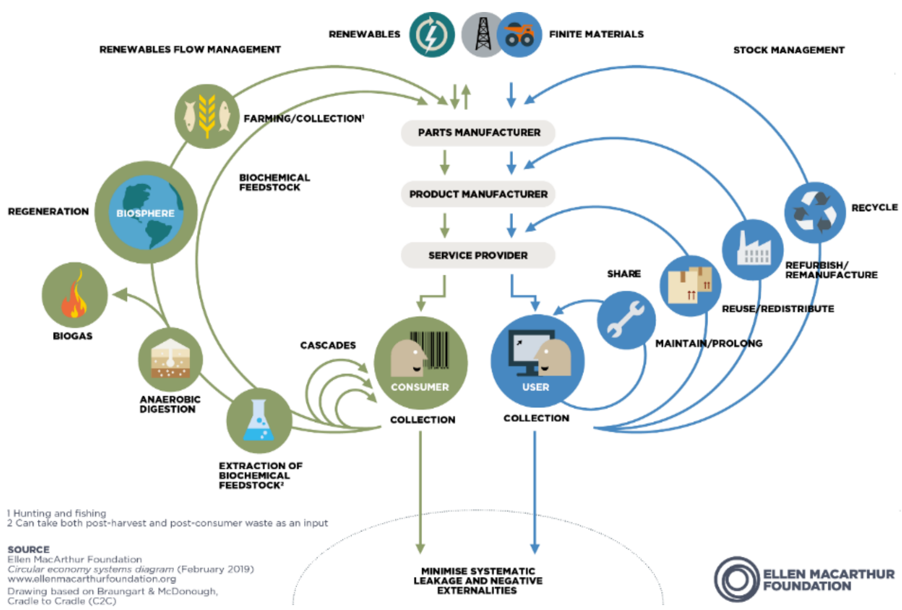

Figure 1. *Circular Economy Model, Ellen MacArthur Foundation (2012)* [2]

In the economic model, as we know it by far, raw materials are exploited. After, products are manufactured, provided to the consumer, and then, disposed of at the end of their life. The application of circular economy models into organizations requires a re-design of the product value chain to maximize value, the utilization of its parts, and the development of new technologies for reusing energy and potential by-products. This change requires a total alteration in the way of thinking and should be supported by policy and educational institutions through incentives and the diffusion of behavioural practices for goods reuse and recycling.

Apart from the benefits in the reduction of environmental pollution (greenhouse gas emissions, particulate pollution, toxicity, biodiversity loss, etc.), the advantages of this holistic change will affect the economy in terms of job creation, expanding the opportunities within industries with the inclusion of innovative technologies, and the reduction of the request for raw materials from the supply chain.

In addition to this, the shift to a circular way of production and consumption also requires fundamental changes in the way products and services are conceived. New types of relationships between producers, retailers, consumers, and service providers need to be built. The concept of ownership needs to be revised since performance, good service, and easy availability become more important than ownership.

The final goal of the implementation of the circular economy within the value chain is to have less waste and more value through material savings and using the sustainable value chain and production processes.

1.2 Benefits of the circular transition

1.2.1 Economic Benefits

One of the main benefits of the circular economy is the reduction of overall costs. Cost reduction characterizes not only the providers' point of view (reduction of products and processing costs) but also the users who benefit from reduced delivery costs and the end-of-life of the product. Moreover, in the circular perspective, there is also greater attention to energy and equipment efficiency, which is translated into the reduction of other relevant operating costs.

The application of reuse, recycling, and remanufacturing strategies also decreases the business risk related to the supply of raw materials and all the business risks related to their shortage. In this perspective, new relationships with customers are built as service and partnership are built.

Other economic advantages come from the possibility to sell or give new life to secondary steams that constituted just a waste in the linear perspective.

1.2.2 Environmental Benefits

From the environmental perspective, the CE concept allows for reducing the environmental impact of the manufacturing processes, improving resource efficiency, and reducing the waste disposed into the environment. The reuse concept also improves the sustainability of the supply chain, thanks to the reduction of raw material extraction.

1.2.3 Social benefits

Taking into account the social benefits, it can be highlighted that they improve reputation and brand value. A sustainable product is a distinctive element for a company that increases the interest of customers, who are often willing to pay more to have a green product. At the same time, a sustainable product rises awareness in people who are not conscious of the problems related to a linear economy and start to question themselves. Probably, they start then to take care of the environmental issues. The research towards sustainable products contribute to job creation (dedicated scientific personnel), and the upgrade of related faculties at the university.

To sum up, Table 1 identifies the benefits pointed out previously.

Table 1. *Economic, Environmental and Social Benefits of Circular Economy*

Economic Benefits	Environmental Benefits	Social Benefits
Reduction of overall costs	Reduction of Environmental Impact	Enhancement of reputation and brand value
Reduction of Business risks	Improvement of resource efficiency	Enhancement of people's awareness towards sustainability
Revenue from Secondary streams	Improvement of Supply Chain Sustainability	Development of innovative skills and job creation

2 Metal surface finishing industry and its role in the circular economy transition

Electroplating is the process in which a thin layer of a specific metal is applied to an object (either a metal or a plastic) by electrodeposition. The aim of this process is to improve the properties of the object by conferring properties such as greater resistance to wear, greater hardness, corrosion resistance and enhanced appearance. The most common metals used for coating are copper, zinc, nickel, chromium, tin, and cadmium.

In the electroplating process, the object to be plated is suspended (e.g., through a barrel) in an electrolytic solution. During the electrolytic process, the object to be plated is the cathode (negative electrode), whereas the anode (positive electrode) is usually a plate of metal to be deposited. A low voltage current is applied to the system, inducing the metallic ion's migration to the cathode where they are deposited.

On the other hand, electroless plating is a non-electrolytic process that uses chemical oxidation and reduction reactions to produce a metal deposit on the object.

The role of the surface finishing industry is crucial in the transition toward a sustainable circular economy. Being one of the largest users of hazardous chemicals, the need to find new routes for sustainable growth is of paramount importance. Every year, a total amount of 300.000 tons of hazardous waste is produced that is needed to be transported to a waste treatment site[7]. Besides that, electroplating industries generate a huge amount of wastewater and sludge which contain a significant amount of heavy metal with strong biological toxicity.

[7] Reis, M. Teresa A. and Ismael, M. Rosinda C.. "Electroplating wastes" Physical Sciences Reviews, vol. 3, no. 6, 2018, pp. 20180024. https://doi.org/10.1515/psr-2018-0024

Effluents from the surface finishing and plating industries must be properly treated before being released, causing environmental damage [8,9].

The circular economy approach has not been applied yet in the whole electroplating process design, where it is a common practice to dispose of the spent bath and the sludge produced by the process. Many studies related to the recovery of metals from wastewater are present in the literature, but research related to the treatment of spent baths and sludge is still ongoing. A huge step forward in terms of technological development and business model development is required to start the transition towards a circular economy in this sector.

The first important contribution to these aspects is provided by the technology developed in PureNano. The PureNano project aims to offer innovative purification technology to treat the spent bath on-site, avoiding waste transportation and disposal (Figure 2). The treatment is performed employing Magnetic Nanoparticles (MNPs) that are reused or recycled after being used.

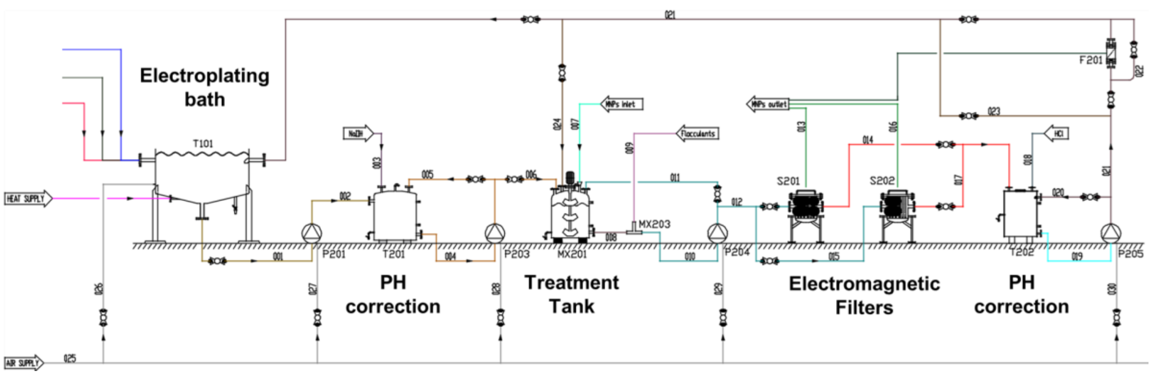

Figure 2. *Scheme of purification of electroplating spent baths with MNPs*

The purification of the plating bath and, consequently, its increased lifetime are the main objectives of the project. The LCA analysis showed that the developed

[8] Rajoria S, Vashishtha M, Sangal VK. Treatment of electroplating industry wastewater: a review on the various techniques. Environ Sci Pollut Res Int. 2022 Jan 27. doi: 10.1007/s11356-022-18643-y. Epub ahead of print. PMID: 35084684.

[9] Wu, Nan, Xue Zhang, Xuemin Zhang, Yanjuan Li, Xiaosan Song, and Sanfan Wang. 2021. "Electrochemical Processes for the Treatment of Hazardous Wastes Exemplified by Electroplating Sludge Leaching Solutions" Water 13, no. 11: 1576. https://doi.org/10.3390/w13111576

process may improve the environmental impact of the plating processes. Moreover, the use of MNPs aggregates for bath purification as well as the design of the purification system, foresee a decrease in the use of hazardous chemicals for the purification of the plating baths minimizing thus health and safety risks. Additionally, the materials taken into consideration for MNPs functionalization include biopolymers such as cellulose, lignin and starch which are often by-products of industrial processes (such as the paper industry). Such activities contribute even further to the principles of circular economy and sustainability. Finally, three different routes for the reuse and disposal of used MNPs (regeneration of MNPs, water treatment, and integration in concrete) are under investigation, which constitutes a promising contribution to the circular economy principles. These procedures will be further investigated in the next paragraphs.

3 Identification of the current End of life management chain for wastes in the electroplating industry

3.1 Characterization of wastes

Waste from the electroplating industry is effluents that are discarded and not used in other processes because their purity, concentration, or composition makes them uneconomical or unsuitable for further use or recycling.

Table 2 shows the main wastes generated from the electroplating industry. The waste can be classified according to its concentration (Figure 3). Waste streams generated from finishing processes can be classified into four categories: wastewater, spent solvents, spent process solutions, and sludges.

Wastewater is a diluted waste stream that comes from the leaning, removing and spilling processes of equipment. The composition of these streams is the same as that of the relevant process solutions and solvents. The concentration of contaminants depends on several aspects such as the shape of the plated piece. It has been estimated that it contains the 10-12% of the metal plating bath solution[10].

Concentrated spent cleaning or plating process solutions are produced with a frequency which depends on the nature of the process. The sludges that accumulate at the bottom of tanks are made up of components of the soil, scale, and insoluble process solution.

---

[10] "Disposal of electroplating wastes – a review of current practices and recommendations for future management", A. Bingham, Department of Heathl, Nea Zealand, 2010

Table 2. Major process waste generated in the electroplating industry [11]

Waste category	Waste Description	Process Origin
Spent solvent	Spent alkaline cleaning solution	Aqueous Cleaning
	Spent Acid cleaning solution	Acid Pickling
Spent solution	Spent plating solution	Electroplating
Treatment residue	Degrease sludge	Solvent Recycling
	Solvent recycling still bottoms	Solvent Recycling
	Filter sludge	Electroplating
	Wastewater treatment sludge	Waste treatment
	Ion exchange resin reagent	Demineralization of process water

A big portion of the wastewater comes from the rinsing steps, followed by leakages, spillage, cleaning and dumping process solutions. Generally, a plant can generate 80 to 200 m^3 of wastewater per day, which contains heavy metals, cyanide, etc. together with solvents and cleaners[11].

Figure 3. Classification of the waste

All bath process solutions must be dumped after reaching the end of their useful life due to the high concentration of some contaminants. As already mentioned,

[11] B. RAMESH BABU, S. UDAYA BHANU & K. SEENI MEERA (2009) Waste Minimization in Electroplating Industries: A Review, Journal of Environmental Science and Health, Part C, 27:3, 155-177

these effluents contain a high concentration of metals and other hazardous compounds which are difficult to handle.

3.2 State of the art of waste treatment in the plating industry

Regarding wastewater treatment, several methodologies can be applied for the recovery of metal ions such as electrowinning, ion exchange, reverse osmosis, and electrodialysis. Industries are looking for better treatment methods that can handle the electroplating effluent without producing secondary effluents. Electrochemical processes do not require any chemicals and allow efficient treatment of the effluents, efficiently[10].

To treat the spent baths and sludge from the finishing industry, the most common practice is the disposal after chemical treatment and neutralization of the acid content. Usually, industries implement on-site waste treatment facilities for pretreatment and recovery. In other cases, they encapsulate the sludge for off-site treatment and disposal.

Concerning smaller companies which are unwilling or unable to treat the waste of this nature, the untreated waste is collected through road tankers and sent to landfill. However, this practice is undesirable for several reasons. First, it could have consequences on the efficiency of biological processes that are necessary to degrade harmful wastes into harmless materials. Secondly, contaminants could interact with other chemicals and produce dangerous compounds[12].

Policy regulations are in place for wastewater treatment to reduce the risk of toxic substances that affect humans and the environment. Table 3 lists the maximum contaminated level (MCL) standards for heavy metals and associated toxicities.

[12] Sonal Rajoria, Manish Vashishtha, Vikas K. Sangal, Review on the treatment of electroplating industry wastewater by electrochemical methods, Materials Today: Proceedings, Volume 47, Part 7, 2021, Pages 1472-1479,

Table 3. The MCL standards for the most hazardous heavy metals and their toxicities[13]

Parameter	Toxicities	Maximum value	Maximum effluent discharge standards (mg/L) (WHO)
As	Diarrhoea, cancer, skin lesion	0.1	0.05
Cd	Fragile bones, diarrhoea	0.1	0.005
Cr	Skin irritation, blood disorders	0.1	NA
Cu	Difficulty breathing, nausea	0.5	1.0
Pb	Kidney failure, thyroid dysfunction, insomnia, fatigue	0.2	0.05
Hg	Affect the circularity system and neutral system	0.01	NA
Ni	Dermatitis, chronic asthma, nausea	0.5	NA
Zn	Depression, neurological signs, lethargy	2	NA

In this context, appropriate steps must be taken to ensure that waste is handled in the most environmentally friendly way, also preserving the economic aspects.

To comply with the specific effluents standard, industries are now obliged to treat their waste before discharge, and this is neither a cost-effective nor an environmentally friendly solution. In fact, waste treatment requires the use of chemicals that are expensive and need to be disposed of after their use.

Regarding the treatment of the plating bath, several technologies have been analyzed, although all of these technologies are applied after the waste is produced ("end of pipe" treatment).

Electrodialysis has been used to treat nickel and copper baths. Effluents containing 10-5000 mg/L Ni have been treated. At the end of the treatment, a concentrated solution of 22 g/L Ni was obtained that could be used as a reinforcement for the plating bath. The dilute solution was of sufficient quality to be used in the final rising steps. Relevant studies on this topic claimed 20% of the

[13] USEPA United States Environmental Protection Agency, WHO World Health Organization

chemical savings for the nickel bath and 90% of the reduction in effluent volume sent to wastewater treatment[14]. Electrodialysis has been also used for the treatment of copper baths, showing that with one-stage treatment, it was possible to extract 99.7% of copper from the solution[15]. Ion Exchange has been also examined as a possible technique to remove heavy metals from electroplating baths. However, the environmental and economic benefits of the various treatment methods under inspection depend on legislative aspects, and several costs, namely costs of baths regeneration and wastewater treatment, new equipment/implementation, and changes/renewal on the existing technology. Therefore, further research is still ongoing to find out the best solution for the bath treatment.

The alternative to the “end of pipe” waste treatment is the waste minimization technique. Frequently, industries have treated the waste after its production and before discharging it into the environment. The alternative solution aims to reduce waste production during the manufacturing process itself.

The first step toward a more sustainable process is to apply a best-practice solution that consists of reducing the waste produced (waste minimization). This could be obtained mainly by i) modifying the processes and the equipment used, ii) changing the technology, iii) substituting the materials and reforming the products. All these principles can be applied by changing the way of thinking and analyzing the process from a circular economy perspective. Before considering methods to recover metals from wastewater, metal finishers should examine processes and operations to find opportunities to reduce the generation of waste at the source. Once best practices are applied, the other step is to find a solution to treat and regenerate the waste produced.

---

[14] Reis, M. Teresa A. and Ismael, M. Rosinda C.. "Electroplating wastes" Physical Sciences Reviews, vol. 3, no. 6, 2018, pp. 20180024

[15] Tatiana Scarazzato, Daniella Cardoso Buzzi, Andréa Moura Bernardes, Denise Crocce Romano Espinosa, Treatment of wastewaters from cyanide-free plating process by electrodialysis, Journal of Cleaner Production, Volume 91, 2015, Pages 241-250.

In the next section, the waste minimization procedure will be analysed and applied to the Electroplating processes and the PureNano user cases. Afterwards, the circular business models and the specific characteristics will be also described and applied to the PureNano pilot lines.

4 Waste minimization and circularity on Pure Nano's Technologies

4.1 Waste minimization approach

Waste minimization is a methodology which deals with the waste problem during the manufacturing process itself. It comprises the application of a systematic approach to reduce the generation of waste at the source, reduce the raw materials used in the process and optimize the recycling and re-use of the waste. Seven heuristic rules have been reported in the literature to minimize the waste produced:[16]:

a) Eliminate waste material at their source wherever possible.
b) Modification of single equipment items.
c) Recycle waste material within the process or, if possible, use off-site recycling.
d) When byproducts are created through a reversible chemical reaction, they should be recycled for as long as possible.
e) Use the utility with the lowest practical temperature for all heating duties.
f) Minimize the number of main equipment items in the process, especially those that handle toxic materials and the total number of pipes.
g) Use a continuous process instead of batch operation to reduce the source of pollution.

These rules can be applied in each waste minimization program and can be widely applied in the electroplating sector. Thus, in this area, the main waste minimization approaches are as follows.

Resource reduction approach: This can be mainly realized through process and equipment modification, process control optimization, technology change, and material substitution.

---

[16] Babu BR, Bhanu SU, Meera KS. Waste minimization in electroplating industries: a review. J Environ Sci Health C Environ Carcinog Ecotoxicol Rev. 2009 Jul;27(3):155-77

Reduction of drag-out: In the electroplating process, drag-out refers to the solution that remains on products, barrels, and other equipment used to move the product through the various process baths. This solution will contaminate the next tank if the equipment is not rinsed before. Generally, an electroplating operation is intolerant of contamination of the drag-out from a previous process. For this reason, the washing step is of fundamental importance. Rinse water is usually the main waste stream from electroplating facilities, and it is environmentally and economically desirable to minimize it. Some expedients allow the minimization of the drag-out solutions, such as i) increasing dripping time to 10-20 seconds before rinsing ii) placing a recovery tank before the rinse tank iii) Introduce drip trays between tanks, iv) Improving drainage system to reduce spillages on floor v) reduce the withdrawal speed allowing a sufficient drainage time vi) lowering the bath concentration, vii) use of surfactant, etc.[17] All these measures must be appropriately adopted so that the plating quality and the whole process operation are not affected.

Reduction of waste: Improved housekeeping, change in process characteristics (*e.g.,* technology, products, input material, recycling process chemicals, and raw materials), recovery of by-products/waste, and reduction of input to the process are some of the techniques that can be applied for this purpose.

Some of the waste minimization techniques can be applied in the pilot lines developed in the PureNano project. Gaser and Creative Nano are indeed the two companies that implemented the new technology in their business. To have a global picture of how waste management is carried out in the two companies, a questionnaire has been distributed. In the next sub-section, the application of waste minimization by PureNano end-users will be analyzed in detail.

4.2 PureNano Value Chain

In this deliverable, we focus on specific electroplating treatments analyzed in the PureNano project. PureNano aims to develop an innovative technology to treat

---

[17] Babu BR, Bhanu SU, Meera KS. Waste minimization in electroplating industries: a review. J Environ Sci Health C Environ Carcinog Ecotoxicol Rev. 2009 Jul;27(3):155-77

spent electroplating baths (produced in Ni, Cu, and Zn plating processes) and electroless Nickel spent plating baths. The two processes are carried out in different facilities. Gaser has installed 4 electroless lines in its facility, while Creative Nano operates mainly electroplating of Ni-P, Cu and Zn coatings for corrosion resistance and decoration applications.

To map the type of business carried out in each pilot line, the wastes produced and the best practices applied to reduce the residues production, AXIA distributed a questionnaire to collect important information, *i.e.,* type of waste that is generated, waste techniques used and current best practices to reduce the waste. The analysis of the main answers is shown below.

4.2.1 Waste Minimization procedure applied in the Gaser user case

Gaser Ossido Duro SRL is an Italian company that isspecializes in the surface treatment of metals, using chemical solutions and electrochemistry. The company is dealing with electroplating processes and, therefore, with the production of wastes that can be classified as wastewater, spent solutions, and sludges. Figure 4 and Figure 5 show the Gaser plating and purification lines.

Figure 4. Gaser Plating Line *Figure 5. Gaser Purification Line*

Table 4 shows the main answer to some general questions asked in the questionnaires.

Table 4. General answers about waste treatment at Gaser's facility

Could you characterize the waste produced within your activity?	Wastewater, sludges, and waste solutions containing light and heavy metals, acids, salts, and surfactants.
Does your company treat the waste in-house or send it to a waste treatment facility?	Some wastes are treated in-house, while others are treated in a waste treatment facility.
What are the current best practices to reduce waste or treat waste within your process?	Precipitation, flocculation, and filtration of pollutants (wet processes).
Are you aware of any regulatory framework that can be applied to waste management?	We are certified ISO 14001.

Methodologies for wastewater treatment are applied mainly to wastewater produced within the process. Although some new techniques are currently being tested on a laboratory scale, the plating bath is not yet treated because of the high concentration of pollutants. Table 5 provides some general answers on the WM approach.

Table 5. General answers to the WM approach

Do you know the waste minimization practice?	Some practices are currently applied, such as water management, evaporation, and distillation. We are active in waste minimization research.
Do you think the WM approach can be applied to your business?	Yes, if correctly and deeply evaluated on process effect.
Which waste minimization approach should be feasible for your business?	• Process modification. • Process solution management.
Which procedures do you apply, or could you apply for the drag-out reduction?	• Slowing down the withdrawal time, reducing the speed of parts removal. • Place a recovery tank before the rinse tank.
How could you modify the process to minimize waste?	• Modifying Equipment, plating bath parameters and condition. • Changing process technology.
Which procedure do you follow, or could you follow, for the management of the process solutions?	• Filtration of the solutions. • Recycling of process bath after concentration and filtration.

To minimize waste production, Gaser improved the pilot by modifying the equipment, the plating bath parameters, and the condition. Modification of such parameters contributes to optimizing bath conditions and reduces contaminant production. This will extend the lifetime of the bath. Gaser has also evaluated the possibility to change the process technology, such as using a different washing/cleaning procedure, recycling the solvent used, and cleaning frequency, etc.

In general, all these WM techniques appear to increase process efficiency and have economic benefits for the company. The reduction of waste production reduces indeed the waste treatment costs and maintenance costs showing that acting a priori instead of at the end of the pipe has a great advantage for the company. Waste management costs are estimated to be reduced by 65% using the PureNano purification system. The raw material used was also decreased by 15% in the nickel-plating formulation.

The company foresees the implementation of other WM approaches to the production line, so this approach together with the PureNano technology will ensure a sustainable process. It is estimated that PureNano technology together with WM approaches can eliminate more than 150 t/yr of nickel waste currently disposed of. Taking into account the actual price of the raw material, this will correspond to a savings of 15-20% on the overall costs correlated with the nickel plating bath.

4.2.2 Waste Minimization procedure applied in the Creative Nano user case

Creative Nano is a research-intensive and commercialization company providing technological solutions in the field of materials nanoscience and nanotechnology. The company was originally founded in 2013 and got its current form after a merging in 2018. It is a pilot/small batch production provider, based in the Municipality of Metamorfosi. The core team of CNano includes several highly qualified and dynamic MSc and Ph.D. level scientists and engineers who have a long experience in their respective research fields. CNano has considerable expertise in several fields, specifically surface treatment, electroplating, development, and validation of advanced materials and nanomaterials, as well as their environmental impact assessment. Moreover, this company is providing technological services, scientific advice, and support on demand to customers in various fields such as automotive, aerospace, environment, decoration and oil & gas. Within this project, the company is dealing with electroplating processes and, therefore, with the production of wastes that can be classified as wastewater and spent solutions.

Figure 6, *Figure* 7 and *Figure* 8 show the CNano plating lines and PureNano purification system installed in the CNano plating line.

Figure 6. *Medium-scale tanks in CNano`s facilities*

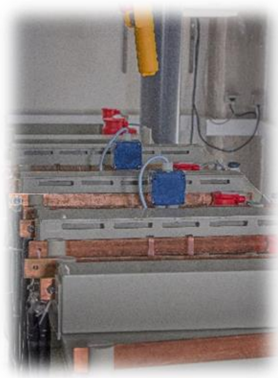

***Figure** 7. Cnano`s electroplating pilot line*

Figure 8. *CNano purification line*

Table 6 shows some general answers about waste treatment in the CNano facility.

Table 6. *General answers about the waste treatment at the CNano facility*

Could you characterize the waste produced within your activity?	Wastewater, Spent solution.
Does your company treat the waste in-house or send it to a waste treatment facility?	Wastes are collected by an external contractor to be treated.
What are the current best practices to reduce waste or treat waste within your process?	There is an ongoing process under development, that will reduce the environmental impact of the electroplating process, through an U/S-assisted electroplating cell. In addition, PureNano technology is being developed and the optimization process is underway at our premises.
Are you aware of any regulatory framework that can be applied to waste management?	Yes, CNano conforms to Greek industrial regulations. Specifically, follows regulation 92108/1045/F.15/2020, which categorizes the environmental impact of industrial activities and gives the main directions for waste management.

The company is aware of waste minimization practices and is active in waste minimization research. General practices have already been applied, and others will be applied later to reach a higher TRL level. Table 7 provides some answers regarding the WM approach.

Table 7. General answers about the WM approach

Which waste minimization approach should be feasible for your business?	• Reduction of Drag-out. • Process modification. • Process solution management.
Which procedures do you apply, or could you apply for the drag-out reduction?	• Place a recovery tank before the rinse tank.
How could you modify the process, to minimize waste?	• Modifying Equipment, plating bath parameters and condition. • Changing the process technology.
Which procedure do you follow, or could you follow for the management of the process solutions?	• Recycling of rinse water (after filtration).

In general, the application of the WM techniques reduces the cost of waste collection and these together with the new electroplating method, will reduce the environmental impact of the process. This approach will reduce the solid wastes (SiC or TiO_2 particles) and the nickel ions in the wastewater. Moreover, there is a simultaneous enhancement of the product's properties so there will be a positive impact also in the final products.

5 Circular Business Models and circular goals

Circular economy aims to meet the needs of society compatibly with the limited availability of resources. The core of the circular economy is represented by the "circular goals" which are recycling, reuse, repair, and shared use. The application of these concepts requires the modification of the production lines, and the waste minimization approach is one of the steps toward technological change. As mentioned above, the transition to the circular economy includes technological, economic, and social changes.

Economic changes can be achieved through an appropriate plan which includes the adoption of an *ad-hoc* circular business model (CBM). A CBM is a means of implementing one or more circular goals in an economically feasible way. Identification of the correct business circular model to be used is the key to achieving circular goals.

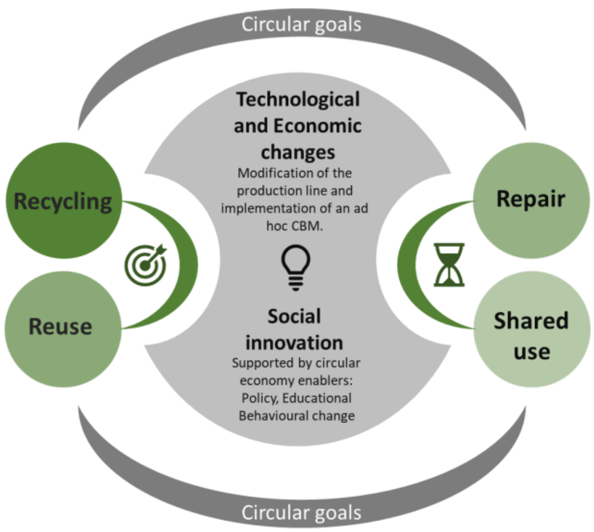

Figure 9. *Circular Business Model and Circular Goals*

Social innovation instead is defined as a process that considers emerging needs that adopt new solutions to meet social goals. The transition is also supported by collaborations and strategies across society by governments, companies, and citizens alike. These collaborations and strategies are named circular economy enablers. Key enablers are Policy and Educational and Behavioral change (Figure 9).

Circular models of production and the business models that include them represent the key activities that could lead to a more resource-efficient and sustainable economic transition. There are several definitions in the literature of a circular business model and several papers attempt a classification based on the functionality. However, the common aspect is that a CBM aims in reducing natural resources and in reusing them.

Different business models can be applied to different parts of the value chain. Therefore, it is important to identify the correct one for each actor contributing to the development of the process.

Effective circular economy policies can encourage the adoption and diffusion of appropriate business models. The most effective policy tools that can be applied to accelerate circular actions are i) legislative measures, ii) support for research and innovation, and iii) economic incentives.

Legislative measures such as the EU Eco-design Directive, or regulations restricting the use of hazardous substances, etc, are already in place and support the transition. At the same time, financial incentives to companies and research and innovation institutes (*e.g.,* Horizon 2020 and Horizon Europe) help businesses and researchers to innovate and develop new strategies to achieve the transition, overcoming the initial costs.

Technological, economic, and social aspects constitute a synergetic action towards the transition. Consumers and companies must take specific actions and work together to return or deposit goods in the right way. Similarly, repairing products, purchasing something used or remanufactured, or renting rather than purchasing items, are all value strategies that demand appropriate behavior and choices from all the actors.

5.1 Circular models typologies

The literature on the circular business model has grown rapidly and continuously in the last few years. There are several approaches to classify them, but for the analysis, the classification adopted by Accenture and reported by OECD is considered[19]. In this approach, circular activities are categorized from a business-centric perspective. The five types of circular business models addressed in this report are: (i) circular supply models, (ii) resource recovery models, (iii) product life extension models, (iv) sharing models, and (v) product service system models. Below, a detailed description of each model is provided. The following paragraphs will focus on the application of the appropriate business model methodology to the PureNano value chain.

5.1.1 Circular supply models

The concept of this model is to replace traditional material inputs derived from virgin resources with biobased, renewable, or recovered materials, which reduces the demand for virgin resources and substitutes them to some extent. This circular model can be applied in the first part of the value chain or product life cycle, and it is based on the cradle-to-cradle concept, where the materials that constitute the product are not disposed of but become inputs in the manufacture of new products.

From a business point of view, the application of the circular supply model has two positive aspects. On the one hand, with the replacement of traditional inputs with recycled ones, a company can claim green products, attracting environmentally conscious consumers who are willing to pay more to have a smaller environmental footprint. The second aspect is related to the reduction of the supply chain risk. In many countries, there are stringent environmental rules for the use of certain polluting inputs in the production process and the use of alternatives helps reduce the risk. This model influences the product design phase, the choice of materials, the production phase, the customer target, and the distribution channels.

---

[19] OECD (2019), Business Models for the Circular Economy: Opportunities and Challenges for Policy, OECD Publishing, Paris, https://doi.org/10.1787/g2g9dd62-en

5.1.2 Resource recovery models

This model consists of recycling waste into secondary raw materials. In the resource recovery model, it is possible to identify three main activities undertaken by different actors which are: i) collection of wastes from local government, ii) sorting of the wastes and separation into the constituent materials in public or private facilities; iii) secondary production where waste materials generate new finished raw materials in private facilities.

This business model gives value to the materials contained in the waste streams. A company can decide to sell the waste at a small price to another one that will give a second life to it or implement a new facility in the existing one. The first case is also called industrial symbiosis. In both cases, the cost of the valorization process should be lower than the market price of the finished material. This model can be applied if there is a market for secondary raw materials and if the required waste is produced in large volumes.

5.1.3 Product life extension models

It consists of extending the use period of existing products and reducing the rate of resource extraction and waste generation. Product life extension models aim at extending the life of products. This is desirable from a circular economy perspective because products, and the materials embedded in them, remain in the economy for longer, reducing the extraction of new resources. To achieve this target, there are three mechanisms involved. First, manufacturers can extend the service life of their products by designing them in a way that increases durability. Second, reuse and repair activities, and their associated business models, ensure that products attain their intended service life (rather than being prematurely discarded). Third, remanufacturing extends the useful life of products, obtaining an entirely new useful life.

5.1.4 Sharing models

Sharing models involve a temporary rather than a permanent transfer of product ownership. Sharing models have two sub-types: co-ownership and co-access. The co-ownership variant of sharing models involves the lending of physical goods.

The co-access allows for the contemporary use of the goods, and it is easy to achieve.

5.1.5 Product service system models (PSS)

In this business model, instead of selling their product, the owner keeps owning it but makes it available to one or more users through a lease contract or a rental fee. In these models, services rather than products are marketed.

The approach followed in this deliverable divides product service system models into three main variants: product-oriented, user-oriented, and result-oriented PSS models. Each of these is briefly discussed below.

5.1.5.1 Product-oriented product service system models

Product-oriented PSS models are focused mostly on the product. Manufacturing firms that adopt this business model continue to produce and sell products conventionally but include additional after-sales service in the value proposition. For instance, services may take the form of maintenance contracts and repair offerings.

5.1.5.2 User-oriented product service system models

User-oriented (or access-oriented as they are sometimes called) PSS models focus both on products and services. Customers pay for temporary access to a particular product, typically through a short- or long-term lease agreement, while the service provider retains full ownership of the product. These models provide access to the services associated with a particular good without the ownership of the good itself. It means that consumers only pay for a product when they need it.

Adopting user-oriented PSS models can create various opportunities for companies. By retaining ownership of products and the components and materials embedded in them, manufacturers can potentially mitigate a range of supply chain risks (for example, access to and price volatility of material inputs). This business model is likely to be used in situations where the security of the virgin raw materials is uncertain or when is more convenient to provide a service rather than sell the product.

5.1.5.3 Result-oriented product service system models

Instead of marketing manufactured assets or goods traditionally, firms market the services or outcomes provided by these goods. For example, an adopting firm might sell a heating outcome (maintaining a certain temperature level within a building), rather than the underlying heating equipment or energy inputs.

In general, it is important to highlight the main differences between normal business models and circular business models, highlighting the aspects that contribute to their realization.

General business models show how an organization creates, delivers and captures values (Figure 10). In fact, four pillars are characteristics of a business model[3]:

- Value proposition: this constitutes the product or service offered by a company and the target customer. (What value is offered to whom).
- Value delivery: the distribution channels (how is the value provided).
- Value creation: the specific features of the product or service.
- Value capture: the company's cost structure and revenue streams (how does the company generate value).

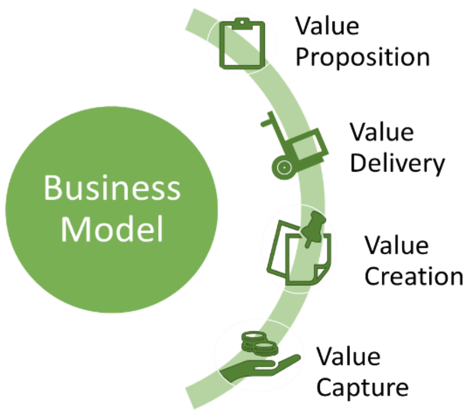

Figure 10. Linear business model

The three dimensions are analyzed based on subcategories:

- Value proposition: (a) Products, (b) Services.
- Value delivery (a) Target customers, (b) Value delivery processes.
- Value creation: (a) Partners and stakeholders, (b)Value creation processes.
- Value capture: (a) Revenues, (b) Costs.

The five CBMs that were previously analyzed will be combined with the different dimensions of the traditional business model providing a general overview reported in Table 8.

Table 8. CBMs design option (adapted from [20])

BM dimension		Circular Supply	Resource Recovery	Product life extension	Sharing	Product service system
Value proposition	Products	•Recycled inputs, fully renewable, recyclable or biodegradable inputs	•Co products based on recycled waste, process residues or by-products •waste as production input	•Long lasting products •Used products or components in as new quality, repaired products, remanufactured products	n.a.	n.a.
	Services	n.a.	n.a	•Upgrading •Take back of used products, deposit systems	•Unlimited and individual access to product (lease), limited and shared access to a product (renting), product maintenance repair and control •Online exchange platform bringing together producers and users of waste	•Collaboration among product users
Value delivery	Target Customers	•Manufacturers	n.a	•Used of industrial equipment, end users buying remarketed products •Green consumers	•waste suppliers and waste users	•Private persons or organization with asset overcapacities
	Value delivery processes	•Replacing virgin materials and linear inputs	•Providing waste ad input to third parties • providing waste as input to internal processes	•taking back used products from distributes and end users offering platforms to sell used products	•Providing products to be used, retaining product ownership, taking back used products, specifying functionality or result but not applied technology (a) •Online matching between waste suppliers and users (b)	•Users share their overcapacities
Value creation	Partners and Stakeholders	n.a.	•Companies producing large volumes of by-products set up a new partnerships (e.g., recycling networks)	•Collaboration with retailers, logistics companies and collection points	•Manufacturers	n.a.
	Value creation processes	•Using waste of third parties as inputs, using own waste as input, recapturing of waste, reusing of waste	•Recovering products and materials at the end of one product lifecycle, reprocessing of materials recycling, upcycling •Making use of underutilised capacities and resources	•Design long lasting products, repairing upgrading rremanufacturing or remarketing of products •recovering products at the end of one product lifecycle, repairing ore remanufacturing own products or products of third parties	•Providing a product, maintaining, repairing and controlling the product, reusing products, using products longer •Identify of gaps between demand and supply of waste	•Matching owners and user of overcapacities
Value capture	Revenues	n.a	•additional revenues for the co products •additional revenues from selling waste •additional revenue potential through green image	•Additional revenue through extended usage	•Leasing fee, rental fee •Transaction fees	•Transaction fees •Renting fees
	Costs	•Reduction of waste disposal costs, reduction of inefficiencies	•Elimination of material leakage and corresponding material costs •Reduction of energy and material costs	•Reduction of material costs, increase of labor and logistics costs	•Product maintenance cost product longevity, reusability and sharing reduces costs, reduction of material costs	n.a.

[20] A review and typology of circular economy business model patterns, Lüdeke-Freund, F., Gold, S., & Bocken, N. (2019).

Generally, the traditional business model highlights the importance of turnover and profit. Sustainable business places greater importance on environmental and social values. A typical example is to refer to a reuse store, categorized within the sharing business model, where the economic value is captured by selling second-hand goods, but it also generates environmental value by reducing the environmental footprint. Therefore, the circular business goals constitute an added value to the general business model concept[3].

The following paragraphs describe the PureNano value chain in detail, giving some insight into the best business model that can be applied.

5.2 Application of the best Circular Business Model to the PureNano value chain

In the framework of the project, AXIA has developed a procedure for the identification and application of the best BCM in the main use cases developed during the project that considers the following steps.

- Literature research about the Circular business models.
- Identification of the main circular business goals, technological and social innovation enablers, and the best fitting CBM for the PureNano use cases.
- Assessment through the questionnaire.

In the next paragraphs, the CBMs related to the two use cases are analyzed.

5.2.1 PureNano use-cases

The PureNano project aims to treat the spent plating bath coming from three different plating processes:

a) Electroless Nickel plating
b) Zn /Cu electroplating
c) Nickel electroplating

The electroless Nickel plating process is carried out at the Gaser facility. Therefore, the in-line bath purification system was installed in Gaser. Gaser purification plants were designed to manage the removal of a by-product of nickel-plating reactions, such as Orthophosphites. This was carried out by using functionalized nanoparticles that are capable of withstanding mildly acidic environments. The separation of nanoparticles from the purified solution is carried out using a combination of a decanter and a filter press. The sludge produced is compact and poor in water, so that can be handled easily and safely. Concerning the CNano`s pilot line, unlike Gaser`s, it is a portable system that can be easily assembled and disassembled and moved to plating shops. However, can treat lower volumes of spent baths, taking into consideration the volume of the baths that CNano uses. However, the volume of the tanks can easily be adapted according to customer needs. In the PureNano project, the portable pilot line was used to treat Ni-P/SiC and Zn/Cu spent baths.

The idea developed in the PureNano project is to use magnetic nanoparticles to remove impurities from the bath to achieve the extension of its life (5-20 regenerations per year). This practice has economic and environmental benefits. From an economic point of view, companies save money from waste treatment. From an environmental point of view, the bath is regenerated and is not disposed of as is common practice. The used MNPs could be disposed of in the classical metallurgical processes to produce alloys. The PureNano project instead proposes to use the spent MNPS used to capture the impurities for three different applications:

a) Regeneration process - The MNPs will be regenerated through an electrolytic process to recover valuable cations (mainly Ni) and reuse the MNPs.
b) Water treatment, in which the MNPs used will be utilized to absorb pollutants from water and then safely dispose of them. It is well known that the presence of natural pollutants and specifically heavy metals (e.g., arsenic, lead, iron, or copper) and metalloids in water is an important environmental and social problem. Phosphates captured and immobilized in the MNPs can be a cheap and easy solution for non-potable water decontamination. The used MNPs form an active phosphate source in a dry powder and can be used for the removal of heavy metals (mainly lead, arsenic, iron, and copper).
c) Integration in concrete formulation to produce composite concrete with improved mechanical properties. Incorporation of MNPs obtained from spent baths, from the removal of different species (Ni^{2+}, Zn^{2+}, Cu^{2+}, lubricant, orthophosphates), into concrete could be a suitable solution/method for their safe disposal and recyclability considering that they are encapsulated into concrete. In addition, MNPs resulted in improving the rheological and mechanical properties of concrete.

In the following paragraphs, the three cases will be analyzed in detail.

5.2.2 CBM for the in-line spent bath purification system

The first case study considered in PureNano is an in-line purification system installed at Gaser to treat the electroless Nickel plating bath.

The main constituents of an Electroless Nickel bath include nickel ions, hypophosphite, buffers, and complexors. The nickel ions, often added to the bath as nickel sulfate, combine with the phosphorous contained in the Hydrophosphite during the plating process to form the nickel deposit. Hydrophosphite, is the reducing agent that catalyzes the chemical reaction of Ni ions. One of the main by-products of the chemical reaction is ortophosphite, and when its concentration increases, the nickel deposition rate decreases and the properties of the deposited layers change. The nickel plating becomes more porous and its appearance less lustrous. At a certain concentration, the bath cannot be used anymore and needs to be chemically treated before being discharged into a wastewater treatment system or sent to a treatment facility and then disposed of. As we have seen in the previous paragraphs, these procedures are not convenient from both the environmental and economical points of view.

The transition from a linear system (where the plating bath was just used and then disposed of) to a circular system (where the spent bath is regenerated for further use) has required the integration of the following circular business goals in the existing business model:

- Design for circularity: The Gaser pilot line has been modified in order to install the regeneration part.
- Reduce the use of resources and increase the resource efficiency of production and distribution processes (recovery and recycling of water and avoiding the transportation of waste due to an *in situ* treatment).
- Increase the useful life of the product, *that is,* of the bath life, thanks to the regeneration procedure.

Collect for reuse. The used MNPs are reused for further application in the water treatment sector.**Error! Reference source not found.** describes how the technology social and business innovator and enablers can support the achievement of the circular business goals.

Table 9. Means to achieve the circular business goals

Technological Innovation	New product lines needed to be designed and adapted to existing ones. This was performed in Gaser, where the new equipment designed by Kampakas, partner of PureNano Technology, has been installed at the facility. New devices such as the magnetic trap had to be designed and produced ad hoc for the project.
Social Innovation	The implementation of this new technology contributes to the development of innovative skills and knowledge within the company, improving overall reputation and value.
Business innovation	From a business point of view, the implementation of such a system in an already-designed facility should result in greater value capture.
Enablers	Politics support innovation by providing funding, imposing waste disposal fees, and supporting research and development.

Since the ownership of the pilot stays with Gaser, the **product-service system** is the best CBM that can be applied to Gaser. In this case, instead of purchasing a good, customers will buy a service that the pilot provides.

Considering the PureNano technology, firstly a **user-oriented business model could be adopted for Gaser**, where customers pay to access the facility (typically through a short-long term lease agreement), while Gaser maintains the ownership of the facility. In this case, a strong involvement of people in the process is needed and the full potential of the pilot will be exploited not only by Gaser but also by private customers willing to implement their ideas.

In the second case, a **result-oriented business model** can be applied. Gaser could indeed offer a service instead of the access in his facility, and take the spent bath, regenerate it, and give it back.

In the third case, a **product-oriented business mode**l can be considered. Gaser could sell modular pilot plans capable of regenerating small plating baths and recovering materials. In addition to normal selling, Gaser could provide after-selling services such as maintenance contracts and repair offerings.

Looking at the last circular goal (g) another business model that can be applied, is **the resource recovery model** in the form of industrial symbiosis. The spent MNPs used in the recycling process can be used in a water treatment plant for the removal of heavy metals from water. The further use of the MNPs is one of the recyclability goals of the PureNano project.

5.2.3 CBM for the portable spent bath purification system

The second case study considered in PureNano is a portable purification system installed at CNano to treat the Electrolytic Nickel and the Zinc and Copper electroplating baths.

Electrolytic composite nickel phosphorus baths are used for a large number of applications such as corrosion and wear resistance, decoration, electric properties etc. Nickel electroplating in general is an electrolytic process in which a nickel metal dissolves at the nickel anode and enters the plating solution as nickel ions. Following that, nickel ions are reduced at the cathode (the part being plated) to form a layer of metallic nickel. The organic addition agents used in decorative nickel plating are in most cases mixtures of more than one compound. These addition agents are used to modify the crystal structure of the nickel as it is deposited, and, depending on the addition agent, they can produce a wide variety of properties. Nickel electroplating solutions are sensitive to many impurities, such as grease, oil, and organic breakdown products from proprietary additives, copper, zinc and iron.

Increased Ni^{2+} ions in the bath are another problem in the plating bath. The cathodic reaction ($Ni^{2+} \rightarrow Ni^{0}$) takes place at lower current densities because of the hydrogen evolution reaction (45-90%, depending on the type of bath) compared to the anodic reaction ($Ni^{0} \rightarrow Ni^{2+}$) that takes place at a 100% current efficiency. This has as a result a gradual increase of Ni ions concentration in the bath. After Ni ions exceed a specific limit (depending on the type of bath), the bath cannot be operated and needs to be removed.

Zinc plating is mainly used for corrosion resistance and decoration while copper plating is used for electronic applications (*e.g.,* PCBs) and decoration as well.

The accumulation of organic additives and decomposition products burdens the bath, and the quality of the coatings is getting lower. Metals such as nickel, cobalt, zinc, and iron will tend to build up in solution rather than being played out with copper. The impurities have effects on the appearance of bright copper deposits. Therefore, the bath needs to be regenerated after the concentration reaches a certain value.

Also, in this case, the transition from a linear system, where the plating bath was just used and then disposed to a circular system where the spent bath is regenerated for further has required the integration of the following circular business goals in the existing business model:

- Design for circularity. CNano pilot line has been modified, including a bypass, to install the regeneration part.
- Reduce resource use and increase the resource efficiency of production and distribution processes (recovery and recycling of water and avoiding the transportation of waste thanks to an in situ treatment). Reduce the material used as a result of the regeneration of the MNPs.
- Increase in product life, *i.e.,* in bath life, due to the regeneration procedure.
- Collect for reuse. The used MNPs are regenerated and reused for further application.

The achievement of the goals needs to be supported by technical, social, and business innovators, as has been reported in **Error! Reference source not found.**.

Since the pilot's ownership stays with CNano, **the product-service system** is the best CBM that can be applied for CNano. In this case, instead of purchasing a good, customers will buy a service that the pilot provides.

Considering the PureNano technology, firstly a **user-oriented business model** could be adopted for CNano, where customers pay to access the facility (typically through a short-long term lease agreement), while CNano maintains the ownership of the facility. Since the developed system is portable, CNano could offer the customer an internal regeneration service. In this case, CNano will go to the customer site, install the unit, regenerate the bath, and take it back. In addition, in this case, the advantage is ownership of the equipment. In this case, a strong involvement of people in the process is needed and the full potential of the pilot will be exploited not only by CNano but also by private customers willing to implement their ideas.

In the second case, a **result-oriented business model** can be applied. CNano could indeed offer a service instead of the access in his facility and take the spent bath, regenerate it, and give it back.

In the third case, a **product-oriented business model** can be considered. CNano could sell modular pilot plans able to regenerate the plating bath and recover materials. In addition to normal sales, CNano could provide after-sales services, such as maintenance contracts and repair offerings.

Looking at the last circular goal (g) another business model that can be applied, is the resource recovery model in the form of industrial symbiosis. The spent MNPs used in the recycling process can be integrated into the concrete formulation to produce composite reinforced concrete. The other route is the regeneration of the MNPs. In this case, the MNPs could be regenerated through the electrolytic process in order to have MNPs and cations. The regeneration could be performed from the MPNs provider (Captive in this case) or in the same area of the CNano facility.

5.2.4 Assessment of the proposed CBM

The last step for CBM development is the assessment from the owners of the PureNano facilities. They were asked to express their opinion on the benefits that the PureNano technology and the business model applied to it could bring to users and producers from an environmental, economic, and technological point of view, using as a reference a work performed by P. Rosa et al.21 As pointed out by the authors, the symbol "U" means that the final users or those who will use the plant will benefit from the specific CBM. Instead, the symbol "P" means that providers or those producing pilot plants will benefit from the selected CBM. Finally, the symbol "-" indicates that the specific benefit is not expected to be reached either by providers or users. The assessment analysis is reported in Table 10.

[21] Paolo Rosa, Claudio Sassanelli, Sergio Terzi, Circular Business Models versus circular benefits: An assessment in the waste from Electrical and Electronic Equipments sector, Journal of Cleaner Production, Volume 231, 2019, Pages 940-952.

Table 10. *Assessment of the CBMs*

	Product-oriented PSS	Use-oriented PSS	Result-oriented PSS	Resource recovery model
Reducing overall costs	U	U	U	U-P
Reducing business risks	U	U	U	U-P
Opening new revenue streams	P	P	P	P
Improving competitive advantage	U	U	U-P	U-P
Compliance with environmental regulations	U	U	U	U-P
Reducing environmental impacts	U	U	U	U-P
Improving resource efficiency	U	U	U	U-P
Improving supply chain sustainability & provisioning	U	U	U	U-P
Reducing supply chain complexity	U	U	U	U-P
Enhancing reputation and brand value	U-P	U-P	U-P	U-P
Reaching new markets & countries	P	P	P	P
Developing innovative skills and knowledge	P	P-U	P	P

Once the best CBMs have been selected, experts have been asked if users or providers take advantage of these benefits.

For all the selected business models, it appears that both providers and users will benefit from the advantages brought by the transition. In general, both U and P take advantage of the benefits related to cost reduction. The possibility of getting revenues from the secondary streams is more provider-related, but in all other cases, the users will also get some benefits.

From the environmental point of view, both the user and the owner will have a reduction in the produced waste. In particular, the whole process for waste treatment and eventual disposal will be treated centrally in one place instead of being managed in different waste treatment facilities. This will reduce the complexity of the value chain and at the same time will improve resource efficiency.

From a social perspective, both providers and users get advantages. The providers will enhance indeed their reputation and will improve the company's skills, but also the user will have the possibility to get in contact with a new way of making business and acquiring new knowledge.

In general, we can conclude that the transition to a circular way of thinking is challenging but it has several positive aspects for both providers and clients from different perspectives.

6 Conclusions

This deliverable is the outcome of the work performed within task 7.1 “Recyclability & Circular economy” of Work Package 7 “Industrial implementation issues”. AXIA Innovation performed a detailed analysis of the concept of circular economy and the role of the finishing industry in creating more sustainable processes by applying the Waste Minimization (WM) approach and the PureNano methodology.

The transition toward a more sustainable process needs the application of new technologies together with the support of new business models and social enablers. A broad literature research has supported the development of a first strategy towards the development of a new perspective that thanks to the support of the main users brought to the identification of the best WM techniques and Circular business models (CBM) for the finishing industry and the representing companies Cnano and Gaser.

The questionnaires that have been distributed provide an overview of the actions that can be taken to improve the existing technology toward more sustainable processes in house.

The implementation of WM practices has shown economic and environmental benefits. At the same time, the application of the selected sustainable circular business models has highlighted that, in most cases, both the provider and the final users get economic, environmental, and social advantages. The user-oriented system model and the result-oriented system model offer to the companies exclusive ownership of the pilots, providing at the same time other exploitation routes. The Resource Recovery Model has been applied to the reuse/regeneration of the MNPs. In this case, the use of a CBM has highlighted the advantages from the environmental and economic points of view and provided new inputs for further investigation.

It is important to highlight that this research should be further developed including financial details to prove the economic benefit coming from the application of the CBMs and considering other user cases, that will implement the WM approach and the PureNano methodology at higher TRL.