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Sustainability Assessment and Economic Evaluation of Novel Coating Solutions for Replacing Hard Chromium Coatings

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Abstract

Hard chromium (HC) electroplating is extensively used in engineering applications because of its high hardness and excellent wear and corrosion resistance. However, the process relies on hexavalent chromium (Cr(VI)), a carcinogenic substance subject to increasingly stringent regulatory restrictions under the European REACH framework. The development of technically and environmentally viable alternatives has therefore become a priority for the surface engineering sector. This study evaluates the sustainability and economic performance of two nickel-based nanocomposite coatings reinforced with silicon carbide (Ni–SiC150) and graphene (Ni–Gr) nanoplatelets as potential replacements for conventional hard chromium coatings. A cradle-to-gate life cycle assessment (LCA) and life cycle costing (LCC) analysis were performed with reference to the principles of ISO 14040 and ISO 14044 in respect of goal and scope definition, functional unit, system boundaries, life cycle inventory and impact assessment. A functional unit of 1 m^2 of coated surface with a coating thickness of 10 μm was decided as a measure of comparison, based on the materials and energy used to provide equivalent coating formulations, in terms of geometrical reference. The environmental assessment was conducted using the ReCiPe 2016 methodology and compared the conventional hard chromium process with the two alternative coating systems. Both nanocomposite coatings substantially reduced the environmental burden associated with chromium plating, with global warming potential decreasing by approximately 69%–72% and human carcinogenic toxicity by more than three orders of magnitude, primarily through the elimination of Cr(VI)-related emissions. The alternatives also exhibited lower impact in most midpoint and endpoint categories while maintaining comparable production costs, supporting their economic feasibility. The combined environmental and economic assessment demonstrates that nickel-based nanocomposite coatings constitute promising candidates for the substitution of hard chromium plating and provides quantitative evidence to support the transition towards safer and more sustainable surface engineering technologies.

Keywords: hard chromium replacement; nickel nanocomposite coatings; life cycle assessment (LCA); life cycle costing (LCC); electroplating; Safe and Sustainable by Design (SSbD); REACH

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1. Introduction

Hard chrome (HC) plating, being a premier solution for plating since the 1920s, is linked to numerous benefits: namely, high hardness, a lower coefficient of frictions compared to the base metal, improved wear resistance and higher galling resistance. Combined with its chemical inertness and high corrosion resistance [1], HC is widely considered a competitive and established plating choice because of these properties, remaining an industrial benchmark with widespread applications, including the aerospace, oil, gas, printing and automotive industries [2,3]. Nevertheless, the current plating industry is focused on replacing HC plating techniques, since they have been linked with heavy toxicity-related emissions and health concerns for workers [4]. ECHA has assessed a set of restriction options to maintain a health exposure limit for the chromium plating industry, categorising them into three restriction routes linked to declining levels of exposure permission. As seen also in Figure 1, the stricter the restrictions proposed, the more prominent the companies are: (i) not already complying, (ii) close or relocate, (iii) invest in additional RMMs or (iv) substitute their technique.

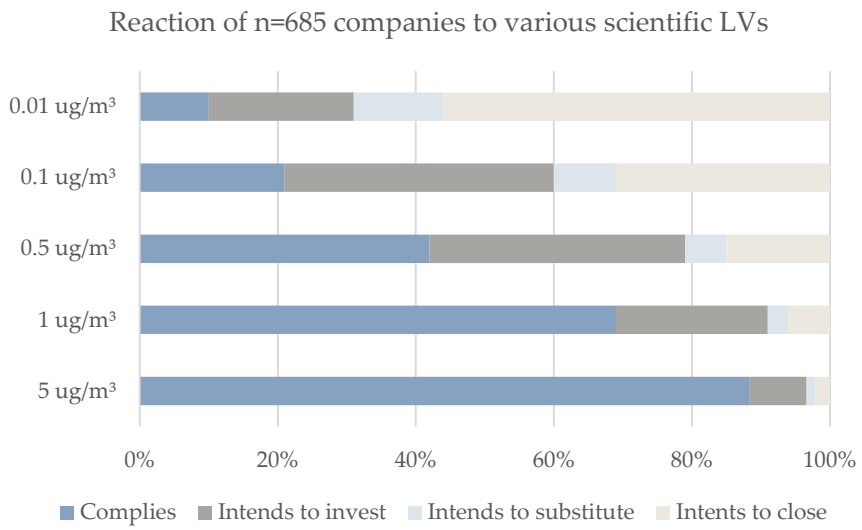

Figure 1. Companies' responses to the restriction proposed by ECHA [4].

Cr(VI) toxicity and REACH restrictions [5] have been documented in a two-decade-long substitution effort (restriction by REACH is documented since 2003 for Chromium (VI) compounds [6]). In order to find a solution for the industrial inconvenience, research is being conducted on substituting chromium plating with novel formulations that comply with current environmental needs [7–10]. In 2008, Krishnan et al. [11] showed the sustainability aspects of comparing hard chrome with thermal sprayed coatings in aircraft landing gears. Key findings include substantial environmental improvement in human health and resource impact indicators. Schopphoven et al. published in 2016 a successful HC alternative based on ultra-high-speed laser material deposition [2], exhibiting advanced wear and corrosion protection. Carneiro et al. developed in 2021 [10] an effective coating alternative (Cr(Al,Si,)N) coating solution for minting applications, whereas Merlo et al. published in 2023 [12] a comparative study on the environmental and techno-economic performance of high-velocity oxy-fuel (HVOF) coating technology compared with hard chromium. The results showed the improved environmental performance of the alternative solution, along with its feasibility.

In the EU, the new coating techniques opt to follow Safe and Sustainable by Design (SSbD) principles. According to the European Commission, the SSbD framework is an innovation guidance approach aiming "to minimise the impact of chemicals, materials

and products on health, climate and the environment during sourcing, production, use and end-of-life" [13]. In terms of support mechanisms, Life Cycle Assessment (LCA) is considered an analysis tool promoting the SSbD principles, especially in the "(re)-design phase of the SSbD framework" [14].

The burden to be overcome is the high applicability of HC plating, whose combination of properties cannot be easily and feasibly replicated: it is extremely hard and corrosion-resistant [15], non-magnetic, and can be applied over any finish, mimicking the base material. It is ideal for heavy-duty industrial applications, where longevity and performance under extreme conditions are crucial [12,16], and can be applied at a wide range of thicknesses [17]. The wide range of properties and applications is the main reason a single alternative cannot be applied to substitute HC [18], regardless of its environmental burden.

Nanoparticle-reinforced nickel coatings have emerged as a promising approach for replacing hard chromium because they can enhance coating performance without relying on Cr(VI)-based electrolytes. Owing to their nanoscale dimensions, incorporated nanoparticles can modify the microstructure of the nickel matrix by promoting grain refinement, reducing coating porosity and defects, and increasing the tortuosity of diffusion pathways for corrosive species. Grain refinement can increase hardness through Hall–Petch strengthening, while well-dispersed nanoparticles can additionally impede dislocation motion and contribute to dispersion strengthening and load transfer within the matrix. The resulting increase in hardness and resistance to plastic deformation can reduce material removal during sliding and thereby improve wear resistance. At the same time, reduced porosity and more tortuous transport pathways can hinder the penetration of aggressive species toward the substrate, contributing to improved corrosion resistance [19]. Documented advantages of NPs reinforcing a coating matrix include high mechanical resistance (for carbon nanotubes), high electrical conductivity and chemical stability (for graphene), and corrosion, abrasion and wear resistances (for oxides, e.g., titanium dioxide) [19]. Li et al. [20] proposed in 2023 a Ni-matrix reinforced with nanoparticle coatings, exhibiting enhanced performance in terms of surface quality, deposition rate, microhardness, wear resistance and toughness. Rao et al. produced Ni-matrix reinforced with SiC nanoparticles to successfully increase the hardness, wear and corrosion resistance of nickel coatings. Yasin et al. showed in 2018 [21] superior corrosion resistance and improved mechanical properties for reinforcing the Ni-matrix with graphene nanomaterials.

The study presented includes the findings of a sustainability assessment and an economic analysis of the solution proposed within the European Research Project MOZART, which aims to find solutions for the replacement of HC plating. The replacement of chrome plating is proposed with novel coating formulations consisting of a nickel matrix reinforced with nanomaterials (NMs). The study investigates two solutions as compared with an HC baseline: (i) Ni-matrix coatings reinforced with SiC150 nanoparticles (NPs) applied on piston rods, and (ii) Ni-matrix with graphene nano-platelets applied on helical gears. After literature review and internal project work, the solutions studied were selected by their potential to address the functional requirements of hard chromium replacement through two complementary nanoparticle reinforcement strategies. Specifically, SiC nanoparticles were selected for their high hardness and their ability to improve the wear resistance and mechanical performance of the nickel matrix, making Ni–SiC particularly relevant for demanding applications such as piston rods. Graphene nanoplatelets were selected for their potential to reduce friction, improve wear behaviour and enhance corrosion resistance—properties of particular interest for components involving repeated mechanical contact, such as helical gears.

The selection is therefore motivated not only by the potential of these coatings to meet application-specific performance requirements, but also by their relevance to the broader

transition towards Cr(VI)-free surface treatments. By evaluating two distinct nanoparticle-reinforced formulations, the study provides quantitative environmental and economic evidence that can inform material selection and future process optimisation.

Although nickel-based nanocomposite coatings have demonstrated promising mechanical and corrosion properties, their environmental and economic implications remain insufficiently quantified, particularly under harmonised life cycle assessment (LCA) and life cycle costing frameworks. The three case studies were assessed via LCA as well as the life cycle costing (LCC) methods. The research output is an analysis with respect to the principles of ISO 14040 [22] and 14044 [23], as aforementioned, providing an in-depth assessment at the midpoint and endpoint levels of the LCA scope and focusing on which are the main contributors to the environmental and economic impact of the system.

2. Materials and Methods

2.1. Study Goal and Scope

The study goal was the detailed evaluation, both in environmental and cost terms, of the novel nickel-based nanocomposite coatings compared with the hard chromium coatings. It does not provide an assessment showcasing functional equivalence, as characteristic such as hardness, durability, wear resistance, corrosion resistance and coefficient of friction are not part of the study scope. The LCA analysis was carried out via software Sphera LCA for Experts Version 10.9.3.0 [24]. To better comprehend the system, the scope of the study consisted of an LCA and LCC assessment of three scenarios: namely, the baseline (hard chromium coatings), scenario 1 (Ni-SiC150 coatings), and scenario 2 (Ni-Gr coatings). The scenarios were compared in a pilot-scale TRL 5 environment, and the system boundaries of each scenario are analysed further below. All coatings were applied on a 1 m^2 (Functional Unit of the system) coating surface with a 10 μm thickness in a cradle-to gate analysis, as shown in Figure 2. In LCA terms, the analysis is under the ReCiPe 2016 v1.1 (H) method to better comprehend the effects of the coatings in a 100-year timeline, both at the midpoint and endpoint level. The analysis does not provide assessment data for the end-of-life of coatings, nor coating lifetime evaluation and maintenance requirements. It is assumed that the coating thickness provides the required functional protection. Thus, the functional unit and 10-μm thickness were used as a means of setting the nominal basis of comparison both in LCA and LCC terms. Not comparing the aforementioned stages of the life cycle studied, is a limitation of the cradle-to-gate analysis. The study also includes the limitation that it does not include a sensitivity and uncertainty analysis, but is instead a deterministic analysis utilising experimental, industrial, and literature-based data as well as database-driven inventory data. It thus does not provide performance differences under all possible production conditions.

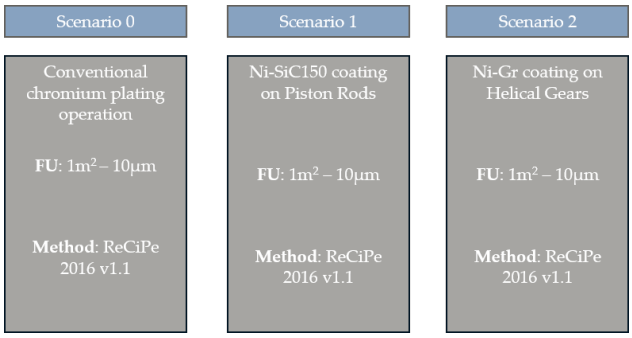

Figure 2. Studied scenarios description.

For scenario 0 (baseline), a hard chromium coating applied on a steel surface, sourced from the Ecoinvent database [17] and scaled as a TRL5 process, was used as the reference of the study to compare all the rest of the scenarios. The system boundaries are shown in Figure 3.

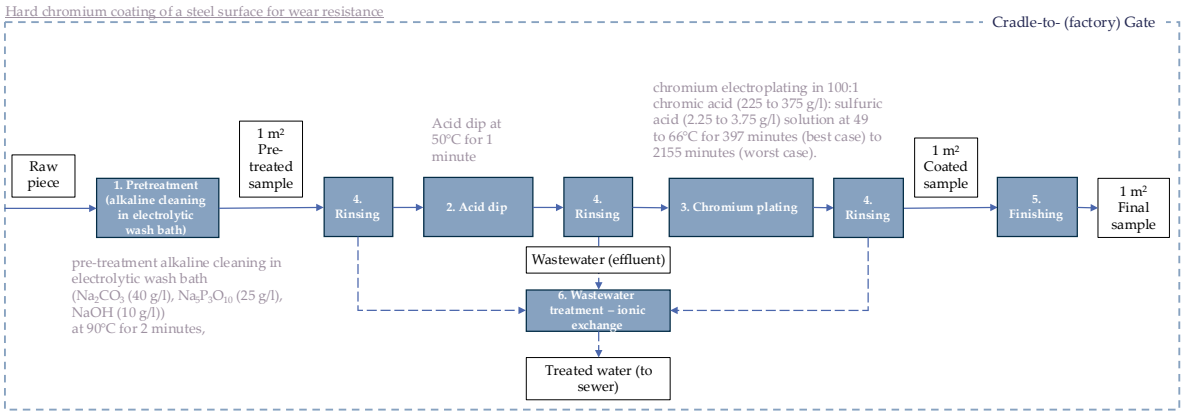

Figure 3. Hard chromium (scenario 0—baseline) system boundaries.

A raw steel piece was pre-treated with alkaline cleaning in an electrolytic wash bath, and after rinsing and acid dipping, it was rinsed again and chromium plated, then rinsed and finished as the final sample. The effluents of the rinsing stages underwent wastewater treatment. The process was analysed as cradle-to-gate, as are all the rest of the scenarios.

Scenario 1 (nickel coating reinforced with SiC150 nanoparticles applied on piston rods) included the production of nanomaterials, as shown in Figure 4. Thus, the production of SiC150 nanoparticles using High Energy Ball Milling (HEBM) by the company MBN Nanomaterialia S.r.l. (Veneto, Italy), followed by pre-functionalisation with liquid ultrasonication and centrifugation, constituted the first two stages before they entered the electrolyte. The electrolyte sample underwent online monitoring activity, which is in line with the plating process. A pre-treated sample entered the electroplating stage with the electrolyte, and the sample post-treatment was the final stage for the coated 1-m^2 sample.

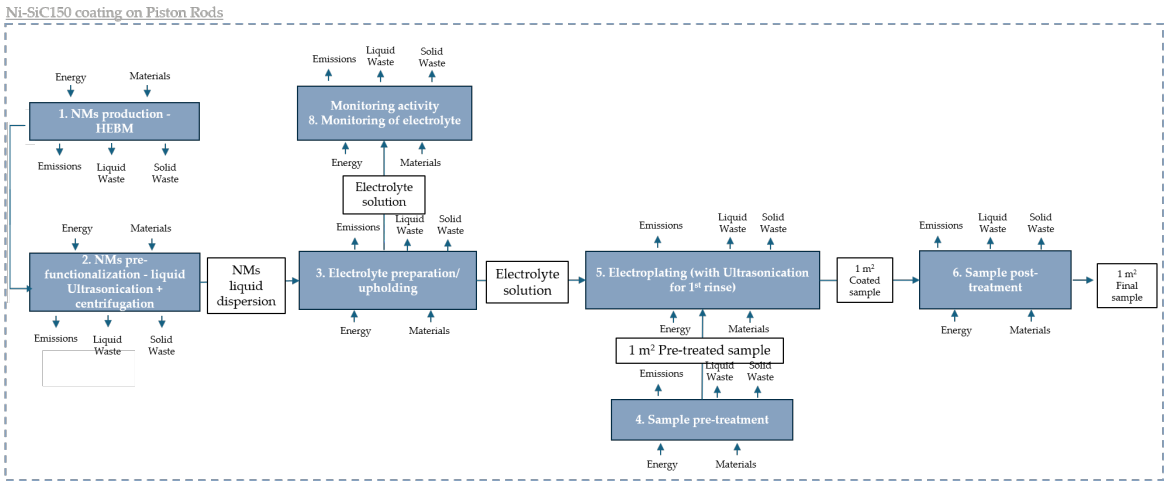

Figure 4. Scenario 1 (Ni-SiC150) coating system boundaries.

Scenario 2, nickel coating reinforced with Gr nano-platelets applied on a helical gear (unit of 1-m^2 surface), is shown in Figure 5. The process is identical in stages as in Figure 4, but in scenario 2, process-ready nano-platelets entered the electrolyte.

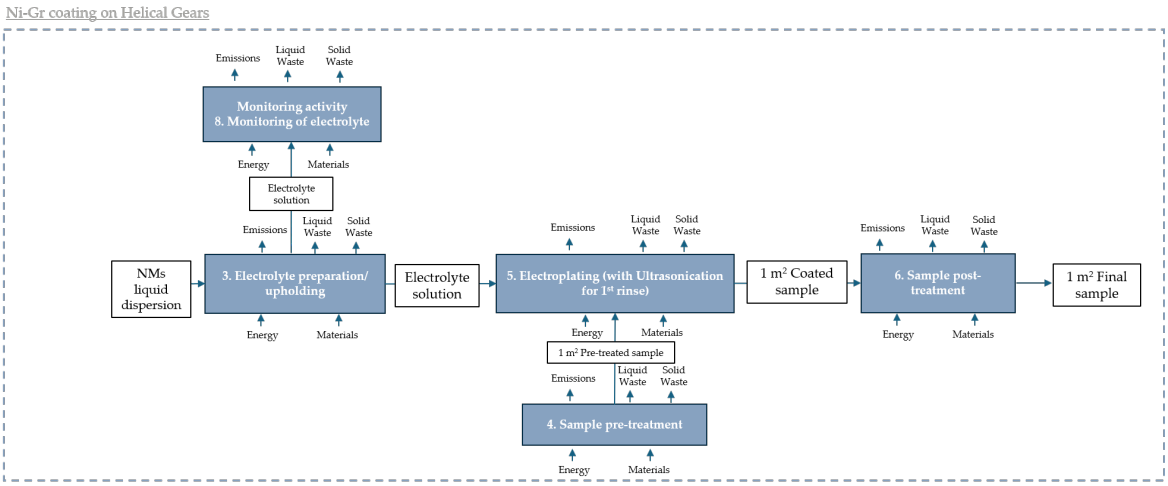

Figure 5. Scenario 2 (Ni-Gr) coating system boundaries.

2.2. Life Cycle Inventory

For the baseline scenario, a conversion was performed to better comprehend how hard chromium would perform compared to the two remaining scenarios on the same scale (pilot). Plating tanks are typically equipped with some type of heat exchanger to be operated at 140 °F (60 °C) and have typical dimensions of 10 m × 4 m × 8 m deep. Mechanical agitators or compressed air supplied through pipes on the tank bottom at 150 fpm of moving air provide uniformity of bath temperature and composition. In each facility, electric heaters are used to raise the temperature of processing liquids to the operating range, and a chilling system is employed to maintain the operating temperature once it is reached [25].

The process flow for hexavalent chromium electroplating (according to the Ecoinvent 3.10 [17]) consists of a surface pretreatment, alkaline cleaning, acid activation and chromium electrodeposition. The pretreatment of the surface for further processing is followed by alkaline cleaning and acid activation to remove surface contaminants and oxide layers. The electrodeposition utilises the chromic acid-based electrolyte (containing sulphuric acid as the catalyst). The final step in the process is the electroplating operation itself. Hexavalent chromium baths are composed of chromic acid, sulphuric acid, and water. Specifically, chromium electroplating is performed in a 100:1 solution of chromic acid (225 to 375 g/L) and sulphuric acid (2.25 to 3.75 g/L) at temperatures from 49 to 66 °C for 397 min (best case) to 2155 min (worst case).

The main source of hexavalent chromium is chromic acid, which is deposited on the metal and is linked to atmospheric emissions. The sulphuric acid, as aforementioned, acts as a catalyst in the chromium deposition and the deposition-linked reactions. The issues arising from the emissions require constant control of the plating bath temperature, plating time, bath composition, and current density. Subsequent hard chrome plating mist is linked to negative health effects, as described further in the Discussion section.

In the framework of this work, the comparison of baseline and the two cases represented within the research had to be on the same technology readiness level and plating conditions. The work developed in the project ends in TRL5 (pilot-scale) conditions, while the Ecoinvent-sourced process refers to an industrial (TRL9) plating process. Different plating conditions—namely, plating tank dimensions, materials and energy consumptions—are applied while proceeding from lab, to pilot, to industrial scale. To better comprehend how the baseline would perform environmentally in the pilot environment conditions of the project, a conversion was applied. The comparison was a twofold methodology via literature review regarding prospective life cycle assessment and conversion between TRL conditions,

as well as via the comparison of typical industrial plating conditions for industrial hard chromium plating and the project-specific plating tank dimensions.

It was assumed that the current density (A/dm^2) and the bath composition (g/L) remained identical to industrial conditions, and the electrolyte composition in the experimental setup mirrored that of the industrial bath. Respectively, the bath volume was proportionally reduced, and the consumption of chemicals (chromic acid, sulfuric acid, and cleaning agents) was linearly scaled down according to the active plating area. Since evaporation and drag-out losses scale with surface area rather than volume, their relative impact on material losses and emissions was higher in the experimental setup. This was corrected during the LCI adjustment by introducing a surface area correction factor (typically between 1.2 and 1.5).

For the experimental setup, the current density and cell voltage (4–6 V) were maintained, resulting in similar specific energy demand (kWh/m^2); however, auxiliary energy for heating, agitation, and cooling was reduced according to the smaller electrolyte volume and the reduced heat capacity of the system. Therefore, the total specific energy consumption was assumed to scale according to the surface area plated while maintaining the same electrochemical efficiency as the industrial system [26].

Furthermore, plate thickness plays a secondary but non-negligible role in defining the overall process' energy requirements and system representativeness. Chromium flakes and electroplating electricity inputs and hexavalent Chromium emissions to air are assumed to be directly proportional to the ratio of the hard chromium-coated layer's thickness to its reference thickness [27], since plating thickness is reliant on the cathode efficiency of the plating solution, the current density and the plating time.

The final inventory for the baseline is shown in Table 1.

Table 1. Baseline inventory.

Flow	Location	Unit	Industrial-Scale Value [28]	Pilot-Scale Value	Conversion Used
Inputs					
Chromium Trioxide, Flakes	GLO	kg	2.71	2.71	$\times(A_{exp}/A_{ind} = 1)$ Area Ratio
Electricity, Medium Voltage	GLO	kWh	498	355.5	$\times f_{aux}$ with $f_{aux} = 0.71$, 0.4–0.8 (range)
Soda Ash, Dense	GLO	kg	0.0103	0.0103	×area ratio (1)
Sodium Phosphate	RER	kg	0.0011	0.0011	×area ratio (1)
Sodium Phosphate	RoW	kg	0.0053	0.0053	×area ratio (1)
Sulphur Dioxide, Liquid	RoW	kg	0.0255	0.0255	×area ratio (1)
Sulphur Dioxide, Liquid	RER	kg	0.0103	0.0103	×area ratio (1)
Sulfuric Acid	RoW	kg	0.0011	0.0011	×area ratio (1)
Sulfuric Acid	RER	kg	0.0001	0.0001	×area ratio (1)
Tap Water	GLO	kg	0.0242	0.0315	$\times f_s$ with $f_s = 1.3$, 1.2–1.5 (range)
Outputs					
Hard Chromium Coat, Electroplating, Steel Substrate, 0.14-mm Thickness	GLO	m^2	1	1	FU fixed (area-normalized)
Chromium VI	GLO	kg	0.0089	0.00064	$\times(f_t = 0.0714)$
Filter Dust from Al Electrolysis	CH	kg	1.82×10^{-5}	1.09×10^{-5}	$\times(f_{aux})$ (electricity-linked)
Filter Dust from Al Electrolysis	RoW	kg	0.378	0.227	$\times(f_{aux})$ (electricity-linked)
Sludge from Steel Rolling	RER	kg	0.0057	0.000408	$\times(f_t)$ (assumed proportional to Cr deposit/drag-out)
Sludge from Steel Rolling	RoW	kg	0.0227	0.00162	$\times(f_t)$
Sludge from Steel Rolling	CA	kg	0.0004	0.0000286	×(f_t)
Wastewater from Black Chrome Coating	CH	m^3	1.1647×10^{-7}	1.51×10^{-7}	$\times(f_s)$ (surface-loss correction)
Wastewater from Black Chrome Coating	RoW	m^3	2.4084×10^{-5}	3.13×10^{-5}	$\times(f_s)$

The two proposed solutions for hard chromium replacement (scenarios 1,2) have comparable inventories based on the system boundaries described in Figures 4 and 5. The inventories are shown in Tables 2 and 3, respectively.

Table 2. Scenario 1—Ni-SiC150 inventory.

Sc.1 Inventory	**Unit**	**Pilot-Scale Value**
Process 1 (Nanomaterials Production/HEBM)		
Inputs		
Silicon	kg	0.7
Graphite	kg	0.3
Inert Gas	m^3	0.71
Electricity	kWh	21
Outputs:		
SiC 150 Powder	kg	1
Process 2 (Liquid Ultrasonication and Centrifugation)		
Inputs:		
SiC 150 Powder	kg	1
Deionized Water	L	10
Electricity	kWh	8
Outputs:		
SiC 150 Liquid Dispersion	L	10
Process 3 (Electrolyte Preparation and Upholding Conditions)		
Inputs:		
SiC 150 Liquid Dispersion	kg	0.0139
Nickel-sulphate Hexahydrate (used for electrolyte preparation)	kg	0.389
Nickel-chloride Hexahydrate (used for electrolyte preparation)	kg	0.0486
Tartaric Acid (used for the electrolyte preparation)	kg	0.0639
Sodium Dodecyl Sulphate (used for electrolyte preparation)	kg	0.00347
Saccharin (used for electrolyte preparation)	kg	0.00278
Concentrated H_2SO_4 (used for pH adjustment)	L	0.00167
NH_3 (used for pH adjustment and upholding conditions)	L	4.7
Reverse Osmosis Water (used for the solution)	L	1.330
Make-up Water (used for upholding conditions)	L	0.167
Electricity	kWh	125.49
Outputs:		
Electrolyte Solution with Nanoparticle Dispersion	L	1.389
Process 4 (Sample Pre-Treatment)		
Inputs		
Acetone (used for degreasing of the sample)	L	0.1
Tape (used for masking)	m^2	0.126
Sulphuric Acid (1.5 M) (used for immersion after anodization)	L	1
Nickel Chloride Hexahydrate (Ni-Woods Electrolyte chemical)	kg	0.0174
Hydrochloric Acid (37%) (Ni-Woods Electrolyte chemical)	kg	1.2
Water (used for rinsing of the sample)	L	25
Copper Sulfate Sentahydrate (Acid Cu electrolyte chemical)	kg	0.0174
Hydrochloric Acid (Acid Cu electrolyte chemical)	L	0.015
Bright Copper ACG-8 (Acid Cu electrolyte chemical)	L	0.2
Reverse Osmosis Water (Acid Cu electrolyte chemical)	L	40
Sodium Hydroxide (1.25 M) (used for anodization)	L	5
Electricity	kWh	19.52
Outputs		
Pre-treated Sample	m^2	1
Liquid Waste (Rinsing with DI water) (to waste)	L	25
Sulphuric Acid (1.5 M)	L	1
Sodium Hydroxide (to waste)	L	5
Acetone (to waste)	L	1

Table 2. *Cont.*

Sc.1 Inventory	Unit	Pilot-Scale Value
Process 5 (Electroplating, with Ultrasonication for First Rinse and Electrolyte Recycling)		
Inputs		
Electrolyte (from Process 3)	L	1.389
Pre-treated Samples (from Process 4)	m^2	1
Water for Replenishment	L	50
Ni-anode Consumption (used as anode for the electroplating process)	kg	0.1
Sulphuric Acid (for pH adjustment)	L	3
Electricity	kWh	48.33
Outputs		
Coated Sample	m^2	1
Spent Plating Bath	L	1.389
Process 6 (Sample post-treatment)		
Inputs		
Coated Sample	m^2	1
Tap Water (used in the Rinsing Tank)	L	5.33
Ultrasonic Bath Energy Consumption	kWh	24
Outputs		
-	-	-
Process 7: Spent Electrolyte (Waste Treatment)		
Inputs		
Spent Bath with 50% Initial Nickel Content	L	1.389
Outputs		
-	-	-
Process 8: Monitoring (In Line with the Plating Process)		
Inputs		
NPs in Electrolyte Solution	-	In-line with the process—no NPs impact attributed
Distilled and Filtrated Water for Online Dilution	L	6.72
Cleaning Solution (96% Ethanol)	kg	0.000695
Electricity	kWh	9.519
Outputs		
Electrolyte Solution to Process 5	L	1.389 (considered in-line with the process)

Table 3. Scenario 2—Ni-Gr inventory.

Sc.2 Inventory	Unit	Pilot-Scale Value
Process 3 (Electrolyte Preparation and Upholding Conditions)		
Inputs:		
Graphene (in dust form)	kg	0.000556
Nickel-Sulphate Hexahydrate (used for electrolyte preparation)	kg	0.389
Nickel-Chloride Hexahydrate (used for electrolyte preparation)	kg	0.0486
Tartaric Acid (used for electrolyte preparation)	kg	0.0625
Sodium Dodecyl Sulphate (used for electrolyte preparation)	kg	0.00111
Saccharin (used for electrolyte preparation)	kg	0.00278
Concentrated H_2SO_4 (used for pH adjustment)	L	0.00167
NH_4OH (used for pH adjustment and upholding conditions)	L	0.00167
Reverse Osmosis Water (used for the solution)	L	0.210
Make-up Water (used for upholding conditions)	L	0.167
Electricity	kWh	125.09
Outputs:		
Electrolyte Solution with Nanoparticle Dispersion	L	1.389

Table 3. *Cont.*

Sc.2 Inventory	Unit	Pilot-Scale Value
Process 4 (Sample Pre-Treatment)		
Inputs		
Acetone (used for degreasing of the sample)	L	1
Tape (used for masking)	L	1
Sulphuric Acid (1.5 M) (used for immersion after anodization)	L	1
Tri-Sodium Citrate ($Na_3O_6H_5O_7.2H_2O$)	kg	0.06
Hydrochloric Acid (37%) (Ni-Woods Electrolyte chemical)	kg	0.0178
Water (used for rinsing of the sample)	L	25
Sodium Hypophosphite ($NaPO_2H_2$) (excluded from the inventory as no available data existed in the literature and quantity was negligible)	kg	0.084
Nickel Sulphate Hexahydrate ($NiSO_4.6H_2O$)	kg	0.096
Ammonium Chloride	g	0.075
Ammonium Hydroxide	L	2.7
Reverse Osmosis Water (Acid Cu electrolyte chemical)	L	40
Sodium Hydroxide (1.25 M) (used for anodization)	L	5
Electricity	kWh	16.03
Outputs		
Pre-treated Samples (to process 5)	m^2	1
Liquid Waste (Rinsing with DI water) (to waste)	L	25
Sulphuric Acid (1.5 M)	L	1
Sodium Hydroxide (to waste)	L	5
Acetone (to waste)	L	1
Process 5 (Electroplating, with Ultrasonication for First Rinse and Electrolyte Recycling)		
Inputs		
Electrolyte (from Process 3)	L	1.389
Pre-treated Samples (from Process 4)	m^2	1
Water for Replenishment	L	50
Sulphuric Acid (for pH adjustment)	L	3
Electricity	L	44.69
Outputs		
Coated Sample	m^2	1
Spent Plating Bath (to waste)	L	1.389
Process 6 (Sample post-treatment)		
Inputs		
Coated Sample	m^2	1
Reverse Osmosis Water (used in the Rinsing Tank)	L	5.3
Electricity	kWh	0.126
Outputs		
-	-	-
Process 7: Spent Electrolyte (Waste Treatment)		
Inputs		
Spent Electrolyte Bath (with 50% initial Nickel concentration)	L	1.389
Outputs		
-	-	-
Process 8: Monitoring (In Line with the Plating Process)		
Inputs		
NPs in Electrolyte Solution	-	In-line with the process—no NPs impact attributed
Distilled and Filtrated Water for Online Dilution	L	6.72
Cleaning Solution (96% Ethanol)	Kg	0.000695
NPs in Electrolyte Solution	kWh	9.519
Outputs		
Electrolyte Solution to Process 5	L	1.389 (considered in-line with the process)

2.3. Life Cycle Costing

An undiscounted cost analysis was conducted to better comprehend the cost share for the three scenarios at the pilot scale. The analysis was twofold; an inventory-wise cost share analysis was performed for the three scenarios to showcase how CAPEX (e.g., equipment acquisition costs) and OPEX categories (e.g., electricity consumption) contributed to the production of the FU. On the other hand, a process-wise cost share analysis for the two solution scenarios was performed to understand which processes (e.g., electrolyte preparation, online monitoring of the electrolyte) were responsible for the highest costs. The analysis excluded labour costs, waste disposal costs, and the replacement of CAPEX equipment (considered to have a service life of 10 years) cost allocation for the production of the FU. The exclusion of the aforementioned costs is a limitation of the study.

For the assessment of all cases, climate change externalities were decided to be part of the analysis, priced at 0.075 € per kg of CO_2 eq. emitted and based on actual values in recent statistical pricing data [29–31]. Including the climate change externalities is not directly linked to the production costs, but it provides a better understanding of how the manufacturing of the three scenarios is substantially affected by their cost.

According to the LCA baseline conversion, the costs for the production of the FU (1 sqm) were calculated as shown Table 4, in which the costs for scenarios 1 and 2 are also included.

Table 4. Baseline costs for the production of 1 sqm.

Cost Category	Cost (€)—Sc.0	Cost (€)—Sc.1	Cost (€)—Sc.2
CAPEX	0.24	0.26	0.32
Materials	5.35	51.18	94.77
Water	1.25×10^{-5}	1.08	2.14
Electricity	35.55	37.70	39.72
Climate Change Externalities	20.69	6.42	5.82
Monitoring	0	0.36	0.36

3. Results

3.1. LCA Comparative Analysis

The total midpoint and endpoint results of the three scenarios are shown in Table 5. It must be noted that the results of LCA and LCC correspond to a productivity of 10,000 sqm per year.

From the midpoint results, a high value for the baseline (Sc.0) was linked with 1720 kg 1,4-DCB equivalents emitted to industrial soil on terrestrial ecotoxicity. Human carcinogenic toxicity was also high (1150 kg 1,4-DCB equivalents emitted to urban air). As discussed in the following sub-chapters, high dichlorobenzene equivalents emissions are linked with hexavalent chromium substances and hexavalent chromium emissions. For Sc.1, terrestrial ecotoxicity indicator was still high, linked to 207 kg of 1,4-DCB equivalents. GWP potential was 85.5 kg CO_2-eq, but 69% lower than baseline GWP impact. For Sc.2, land use was 41% higher than baseline, while mineral resource scarcity was approximately as high as Sc.1. (no more than 5% impact difference between the two scenarios).

The midpoint results are shown graphically in Figure 6, while the endpoint results,—are discussed later.

Table 5. Total midpoint (H) and endpoint (H) results of the three scenarios via ReCiPe 2016 v1.1 method.

Impact Category	Unit	Scenario 0	Scenario 1	Scenario 2
Midpoint (H)				
Fine Particulate Matter Formation	kg PM2.5 eq	5.39×10^{-1}	9.44×10^{-2}	9.78×10^{-2}
Fossil Resource Scarcity	kg oil eq	6.60×10^{1}	3.85×10^{1}	3.51×10^{1}
Freshwater Ecotoxicity	kg 1,4-DCB	1.90×10^{1}	2.00×10^{1}	1.71×10^{0}
Freshwater Eutrophication	kg P eq	1.15×10^{-1}	3.23×10^{-4}	5.18×10^{-4}
Global Warming	kg CO_2 eq	2.76×10^{2}	8.55×10^{1}	7.75×10^{1}
Human Carcinogenic Toxicity	kg 1,4-DCB	1.15×10^{3}	1.52×10^{0}	3.75×10^{-1}
Human Non-carcinogenic Toxicity	kg 1,4-DCB	2.90×10^{2}	3.17×10^{0}	2.89×10^{0}
Ionizing Radiation	kBq Co-60 eq	3.04×10^{1}	5.75×10^{0}	5.02×10^{0}
Land Use	m^2a crop eq	3.89×10^{0}	6.18×10^{0}	5.49×10^{0}
Marine Ecotoxicity	kg 1,4-DCB	2.86×10^{1}	2.12×10^{1}	1.80×10^{1}
Marine Eutrophication	kg N eq	8.43×10^{-3}	3.10×10^{-3}	2.85×10^{-3}
Mineral Resource Scarcity	kg Cu eq	3.98×10^{-1}	1.19×10^{0}	1.25×10^{0}
Ozone Formation, Human Health	kg NO_x eq	6.21×10^{-1}	9.98×10^{-2}	9.31×10^{-2}
Ozone Formation, Terrestrial Ecosystems	kg NO_x eq	6.34×10^{-1}	1.01×10^{-1}	9.41×10^{-2}
Stratospheric Ozone Depletion	kg CFC11 eq	8.69×10^{-5}	3.21×10^{-5}	2.87×10^{-5}
Terrestrial Acidification	kg SO_2 eq	8.94×10^{-1}	3.23×10^{-1}	3.35×10^{-1}
Terrestrial Ecotoxicity	kg 1,4-DCB	1.72×10^{3}	2.07×10^{2}	2.16×10^{2}
Water Consumption	m^3	1.69×10^{0}	1.12×10^{0}	1.03×10^{0}
Endpoint (H)				
Fine Particulate Matter Formation	DALY	3.39×10^{-4}	5.94×10^{-5}	6.15×10^{-5}
Fossil Resource Scarcity	USD2013	1.23×10^{1}	5.05×10^{0}	4.94×10^{0}
Freshwater Ecotoxicity	species.yr	1.32×10^{-8}	1.39×10^{-8}	1.18×10^{-9}
Freshwater Eutrophication	species.yr	7.71×10^{-8}	2.13×10^{-10}	3.44×10^{-10}
Global Warming, Freshwater Ecosystems	species.yr	2.11×10^{-11}	6.54×10^{-12}	5.93×10^{-12}
Global Warming, Human Health	DALY	2.56×10^{-4}	7.94×10^{-5}	7.19×10^{-5}
Global Warming, Terrestrial Ecosystems	species.yr	7.71×10^{-7}	2.39×10^{-7}	2.17×10^{-7}
Human Carcinogenic Toxicity	DALY	3.82×10^{-3}	4.93×10^{-6}	1.13×10^{-6}
Human Non-carcinogenic Toxicity	DALY	6.61×10^{-5}	7.23×10^{-7}	6.59×10^{-7}
Ionizing Radiation	DALY	2.57×10^{-7}	4.89×10^{-8}	4.26×10^{-8}
Land Use	species.yr	3.45×10^{-8}	5.49×10^{-8}	4.87×10^{-8}
Marine Ecotoxicity	species.yr	3.01×10^{-9}	3.56×10^{-10}	1.65×10^{-11}
Marine Eutrophication	species.yr	1.44×10^{-11}	5.12×10^{-12}	4.70×10^{-12}
Mineral Resource Scarcity	USD2013	9.21×10^{-2}	2.76×10^{-1}	2.89×10^{-1}
Ozone Formation, Human Health	DALY	5.66×10^{-7}	9.08×10^{-8}	8.47×10^{-8}
Ozone Formation, Terrestrial Ecosystems	species.yr	8.14×10^{-8}	1.30×10^{-8}	1.21×10^{-8}
Stratospheric Ozone Depletion	DALY	4.61×10^{-8}	1.71×10^{-8}	1.52×10^{-8}
Terrestrial Acidification	species.yr	1.89×10^{-7}	6.84×10^{-8}	7.09×10^{-8}
Terrestrial Ecotoxicity	species.yr	1.96×10^{-8}	2.36×10^{-9}	2.46×10^{-8}
Water Consumption, Aquatic Ecosystems	species.yr	1.02×10^{-12}	7.75×10^{-13}	2.46×10^{-9}
Water Consumption, Human Health	DALY	3.76×10^{-6}	1.46×10^{-6}	7.72×10^{-13}
Water Consumption, Terrestrial Ecosystem	**species.yr**	2.29×10^{-8}	6.77×10^{-9}	1.40×10^{-6}

Figure 6 shows Table 5 midpoint (H) results presented on a logarithmic scale so that all impact categories can be depicted in a single diagram. Overall, the total LCA profile of the baseline was higher than scenarios 1,2 except for three impact indicators: namely, freshwater ecotoxicity, land use and mineral resource scarcity (Figure 7 shows the relative performance of scenarios 1 and 2 as compared with the baseline). Sc.2 was higher in the two latter categories, while Sc.1 was higher in all three categories. It is worth mentioning that the GWP of scenarios 1 and 2 were 69% and 71.9% lower than pilot-scaled Sc.0, respectively. Sc.1,2 were linked to a fossil resource scarcity impact 41.6% and 46.8% lower than Sc.0, while both scenarios were higher than baseline (up to 3.14 times higher) in mineral resource scarcity. As discussed later in subchapter 3.3 "LCA key takeaways", the overall improved environmental profile of scenarios 1 and 2, as compared with baseline, was expected. Impact share analyses presented in the following sub-chapters, along with plating conditions analysis, explain this impact profile with numerical and qualitative data.

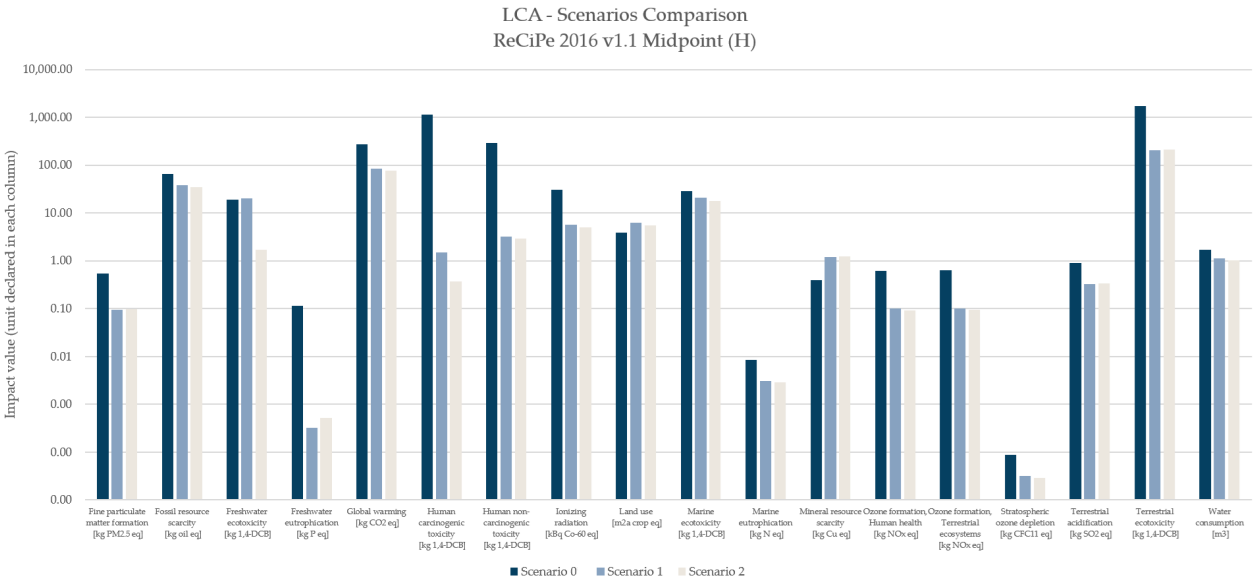

Figure 6. Comparative total LCA midpoint results for the three studied scenarios.

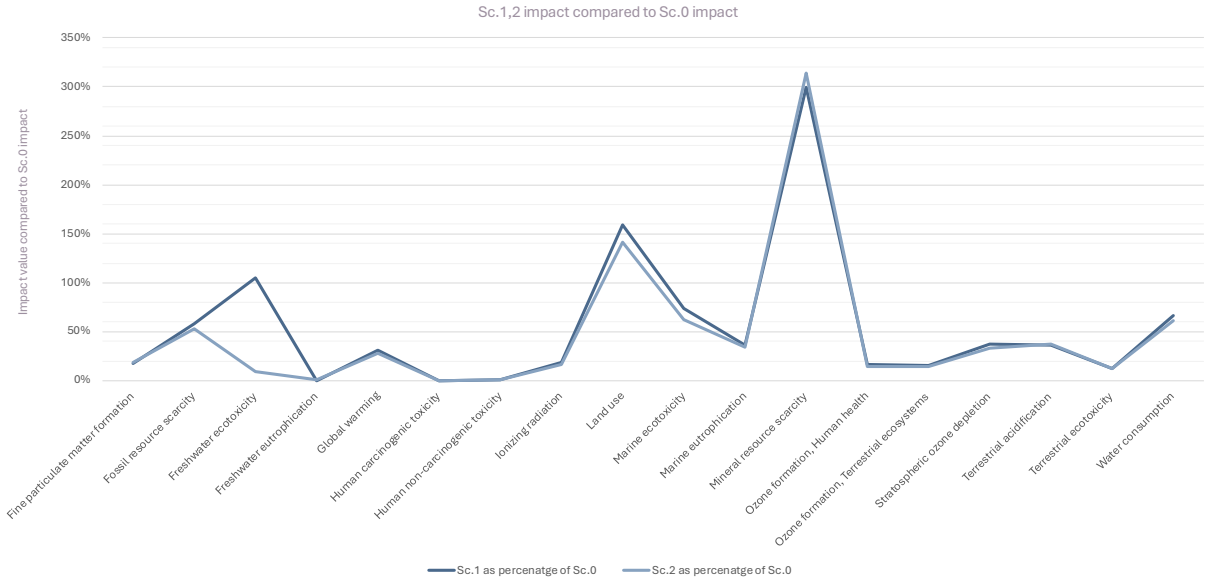

Figure 7. Scenarios 1 and 2 LCA midpoint impact compared to baseline, based on Figure 6.

Scenario 0 had higher cumulative endpoint (H) impact in all three indicators (Figure 8). For baseline, the diagram shows the accumulation of 4.48×10^{-3} disability-adjusted life years in total, the 12.3 USD2013 extra costs involved for future mineral and fossil resource extraction (in total), as well as the cumulative 1.21×10^{-6} species.yr loss over time. For Sc.1, 1.46×10^{-4} disability-adjusted life years in total (reduced drastically by 96.7% compared to baseline DALY impact), 5.32 USD2013 endpoint total impact indicator (57% baseline reduction), and a total 3.99×10^{-7} species.yr loss over time are shown. The latter shows a 67% indicator improved performance compared with Sc.0 ecosystem damage cumulative impact. For Sc.2, there was a relatively equal cumulative endpoint impact profile as in Sc.1, with 1.37×10^{-4} DALYs (6.5% lower than Sc.1), 5.23 USD2013 damage to resource availability (1.8% lower than Sc.1), and 3.60×10^{-7} species.yr (10% lower damage to ecosystems than Sc.1).

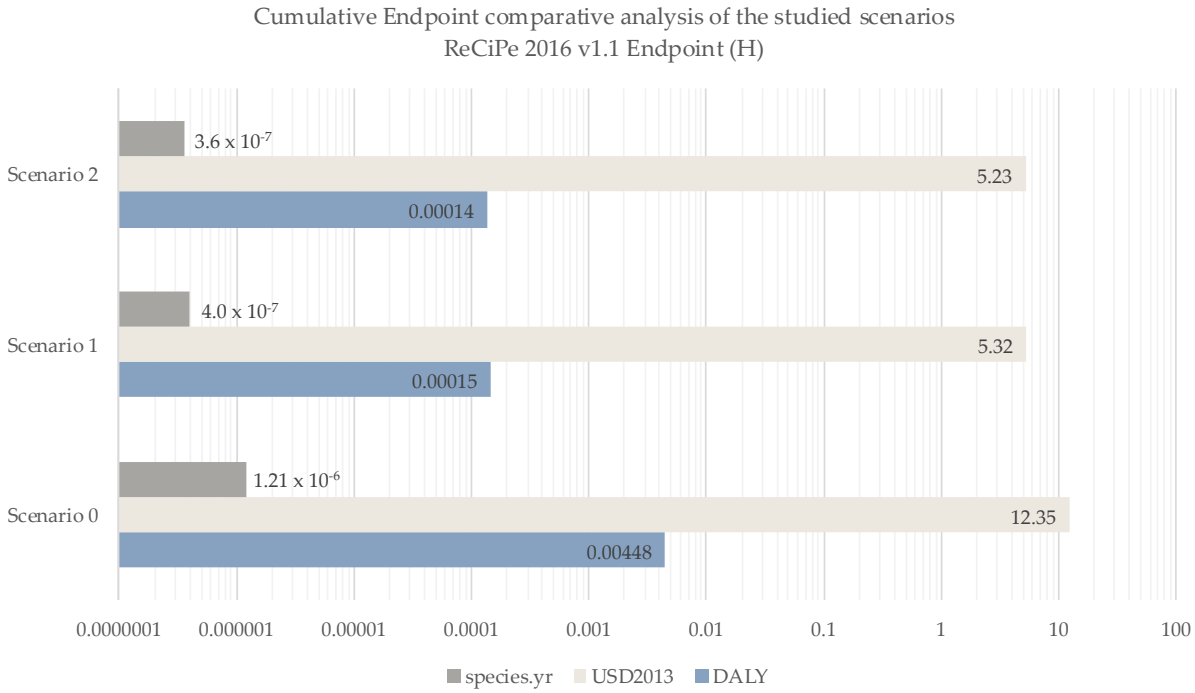

Figure 8. Comparative total LCA endpoint cumulative results for the three studied scenarios, classified in three indicators—species per year loss, USD2013 impact and disability adjusted life years (DALYs).

3.2. LCA Impact Share Analyses

3.2.1. Midpoint (H) Impact Share Analysis

The results were interpreted upon the classification of all flows in 10 impact contribution categories, with minor or major contribution in each impact category: (i) Materials, (ii) Water (iii) Energy, (iv) Electricity, (v) Transport, (vi) Waste Treatment, (vii) Facility Use, (viii) Land Transformation, (ix) Facility Construction, (x) Physical/Mechanical Processes. For Sc.0 (Figure 9), materials, electricity and waste treatment were the major impact contributors. Toxicity categories (cancerous and non-cancerous human toxicity, freshwater, marine and terrestrial ecotoxicity) had high impact values, which, in impact share analysis, are shown to be linked mainly with waste treatment, except for terrestrial ecotoxicity, which is primarily attributed to materials. The main hazardous plating material was chromic acid.

For Sc.1 (Figure 10), the impact share analysis shows that major contributors were materials and electricity, while waste disposal accounted for more than 70% of human toxicity (cancer). Freshwater ecotoxicity, land use and mineral resource scarcity (the categories in which Sc.1 has higher impact than baseline) were linked to different categories of inventory contribution compared to Sc.0 (Figure 9). Sc.0 freshwater ecotoxicity is attributed to waste treatment, while in Sc.1, it is all physical/mechanical processes except waste disposal. Sc.0 land use was linked mainly with land transformation flows, and Sc.1 indicators were impacted by electricity. Finally, Sc.0 mineral resource scarcity was impacted by materials and facility use. On the other hand, the same impact category in Sc.1 was almost entirely linked with materials consumption. Thus, different driving factors increased Sc.1's impact higher than baseline impact (as shown in Figure 7).

As seen in Figure 11, electricity consumption and materials were the major contributors in all impact categories, as in Sc.1. The impact profile is more homogeneous than of Sc.1 (Figure 10), since NMs were provided directly in the electrolyte and not through preparation; thus, two processes were not part of the system boundaries in Sc.2, as seen in Figure 5. The freshwater eutrophication category had more than 95% of its impact linked with physical/mechanical process category.

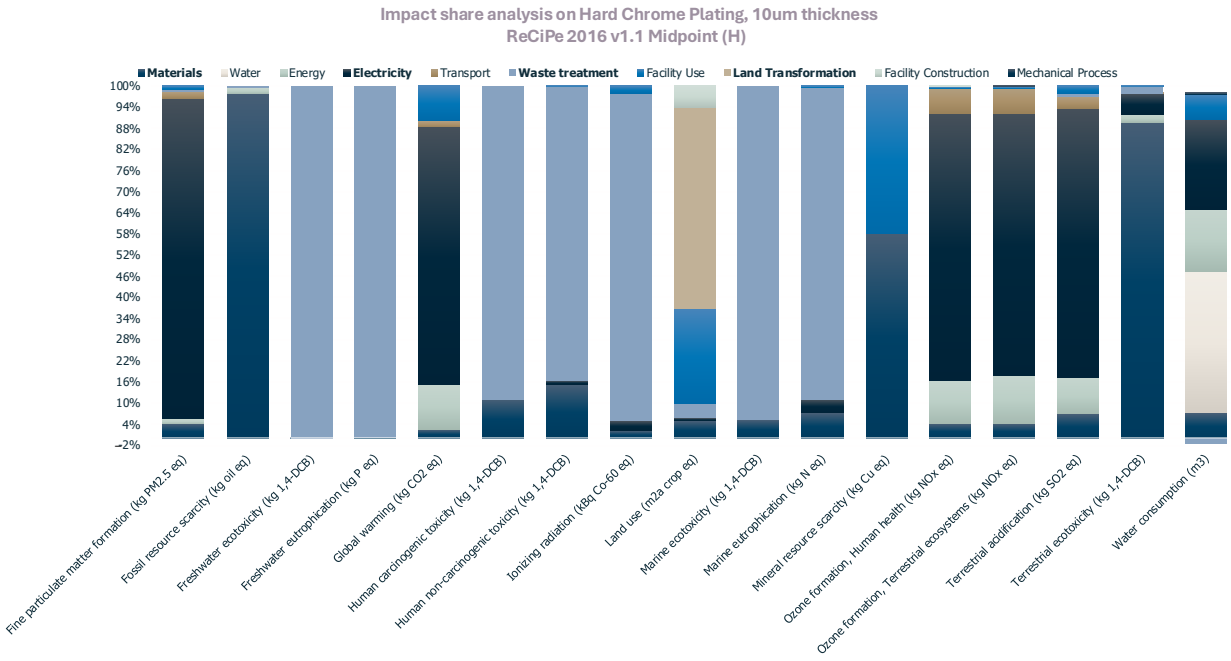

Figure 9. Midpoint inventory-wise impact share analysis on scenario 0.

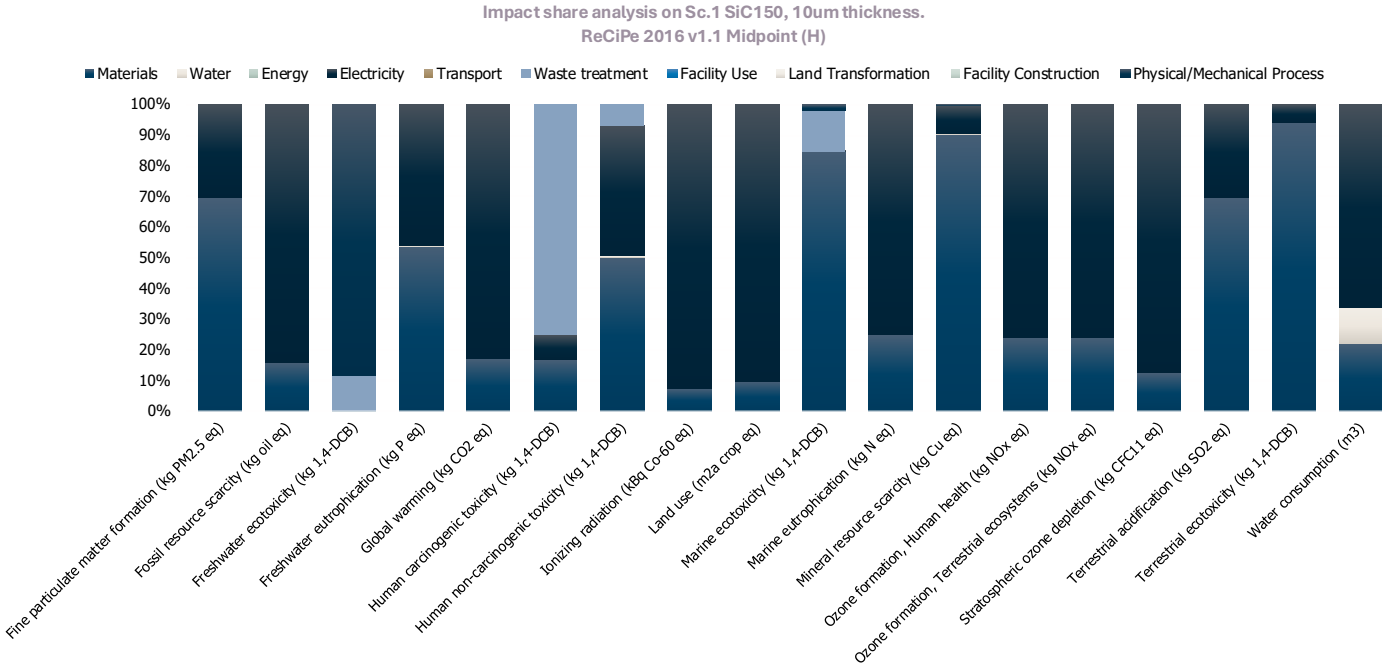

Figure 10. Midpoint inventory-wise impact share analysis on scenario 1.

To better comprehend the impact share of processes as described by Mozart system boundaries (Figures 4 and 5), a process-wise impact share analysis was performed, as shown in Figure 12. It was used to show the contribution of (i) NMs production, (ii) NMs pre-functionalization, (iii) electrolyte preparation, (iv) sample pre-treatment, (v) electroplating, (vi) sample post-treatment, (vii) waste disposal and (viii) online monitoring. The abbreviations of the 18 midpoint impact categories are explained in the abbreviations chart.

For Sc.1, most impact contribution was linked in all impact categories to electrolyte preparation and electroplating. The only two exceptions are freshwater ecotoxicity, linked mainly with sample pre-treatment, and human carcinogenic toxicity, linked with waste disposal. For Sc.2 impact, all categories were most contributed to by electrolyte prepara-

tion except for freshwater eutrophication category, which was linked almost entirely with sample pre-treatment.

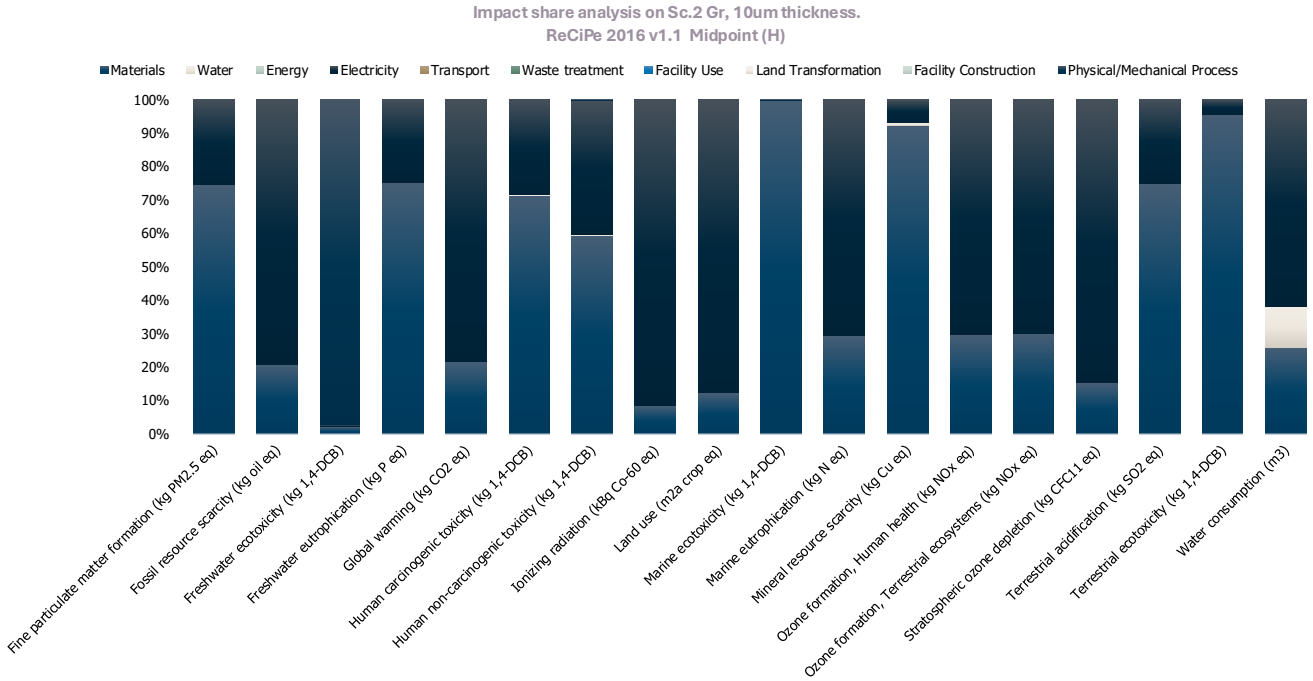

Figure 11. Midpoint inventory-wise impact share analysis on scenario 2.

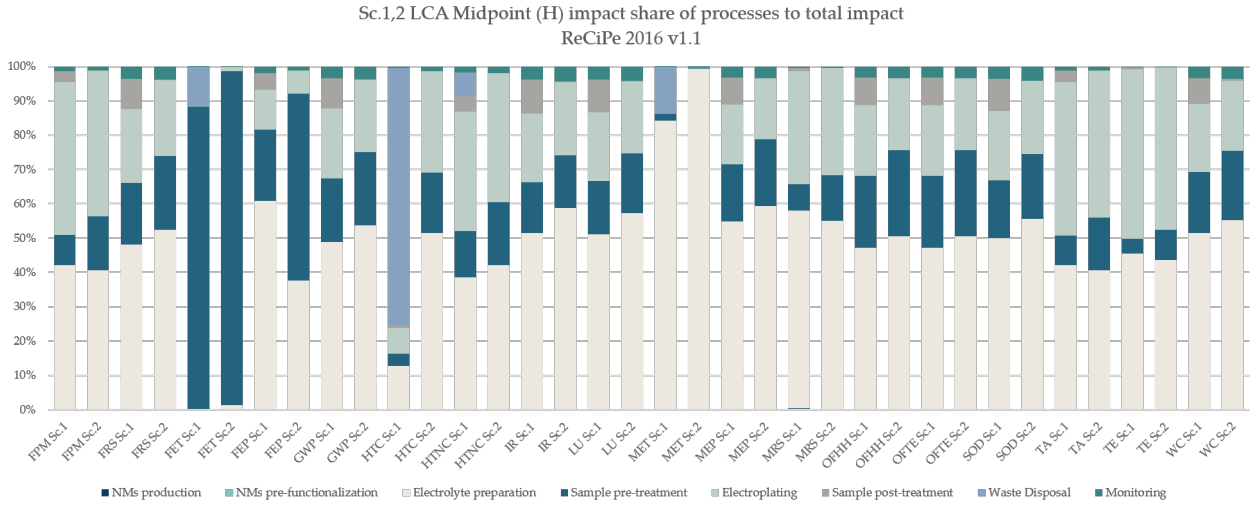

Figure 12. Midpoint process-wise impact share analysis for Sc.1 and Sc.2.

3.2.2. Endpoint (H) Impact Share Analysis

For Mozart scenarios, an endpoint impact share analysis in inventory-wise classification was conducted. Figure 13 shows the materials and electricity major impact contribution in all impact categories for Sc.1, except the human carcinogenic ecotoxicity and marine ecotoxicity, most impacted by waste disposal.

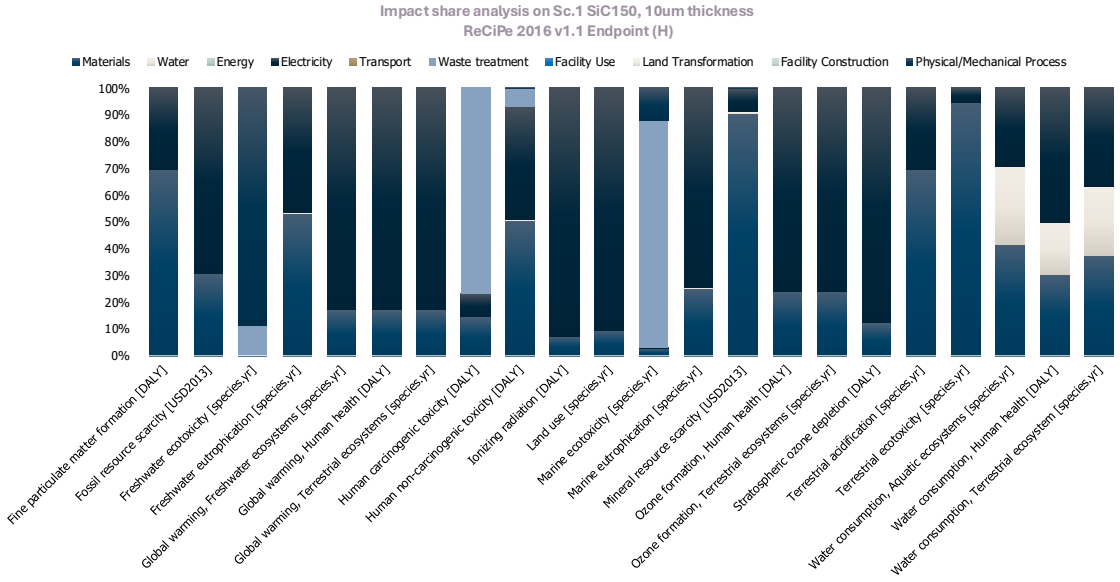

Figure 13. Endpoint inventory-wise impact share analysis on scenario 1.

For Sc.2, Figure 14 shows a direct contribution of materials to terrestrial ecotoxicity and of electricity to ionizing radiation and marine ecotoxicity.

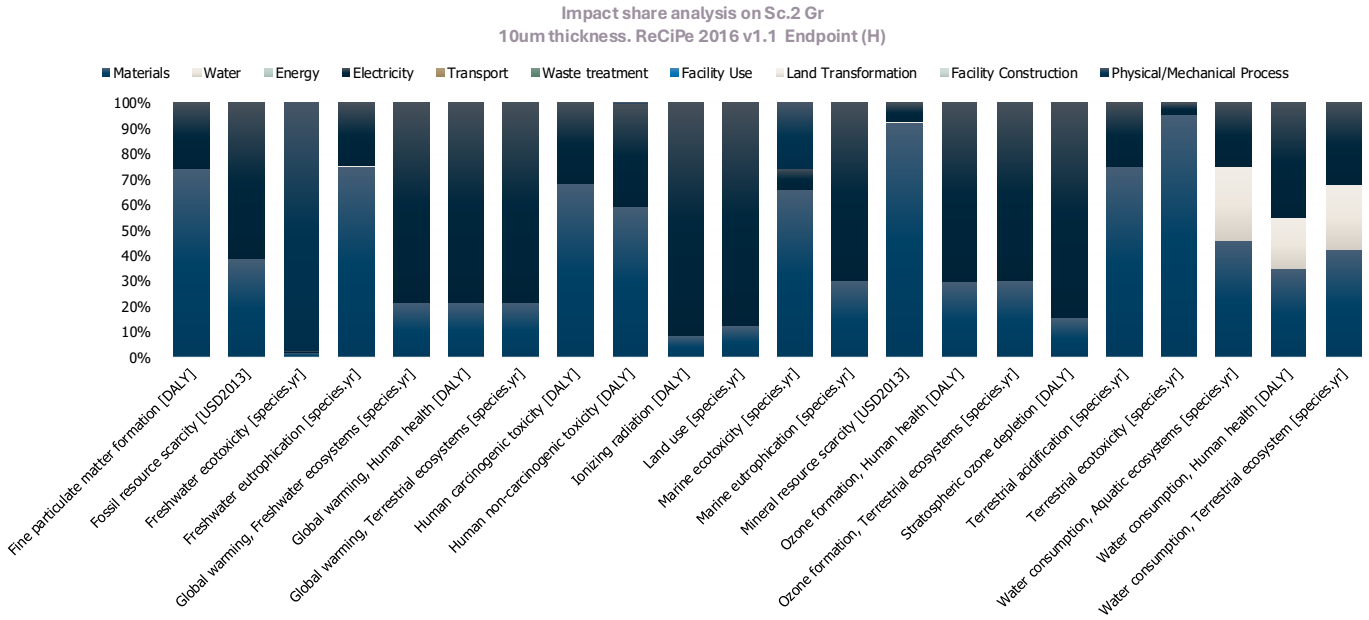

Figure 14. Endpoint inventory-wise impact share analysis on scenario 2.

3.3. LCA Key Takeaways

The pilot-scale comparison of scenarios, as aforementioned, shows Sc.1 and 2 with an improved environmental performance over Sc.0 in most impact categories. Sc.1 and 2 (Figure 12) had a higher impact share linked with electrolyte preparation and electroplating both in land use and mineral resource scarcity, being responsible for heightening the impact values of Sc.1,2, than Sc.0. Sc.1's freshwater ecotoxicity impact was higher than baseline. The result is linked with sample pre-treatment, contributing to 88.24% of the impact share.

Some key points from the study are:

i. Electrolyte preparation, sample pre-treatment and electroplating are the major impact contributors, linked with materials and electricity.

ii. Materials act as the lead impact contributor in 3 out of 18 Sc.0 categories, 7 out of 18 categories in Sc.1, and 8 out of 18 categories in Sc.2.
iii. Electricity, as shown, leads the impact contribution in 5 out of 18 baseline categories in Sc.0, 8 out of 18 categories in Sc.1, and 9 out of 18 categories in Sc.2.

The significance of Sc.0's higher environmental impact than Sc.1 and Sc.2, does not lie only in the nature of nickel. It has been reported that nickel and its compounds are also related to toxicity and health hazards [30–32]. A key aspect of the decreased impact is the chromium mist/aerosols and toxic fumes from HC plating [25], which is reduced in nickel plating through also lower plating bath temperatures. The bath temperature in Mozart solutions was not higher than 56.85 °C, while the baseline operating temperature would reach up to 90 °C. The fine particulate matter emissions in Sc.0 was 0.539 kg PM2.5 eq. for FU plating of 1 sqm 10 um, while for all Mozart scenarios, it was no higher than 0.098 kg PM2.5 eq. (Sc.2).

3.4. LCC Results

The undiscounted costs for the three scenarios studied are shown in Table 6. Scenario 1 was approximately 57% higher than baseline, and scenario 2 was 131% higher than scenario 0. A two-fold cost analysis shows the main costs share for the scenarios (Figures 15 and 16) to better comprehend which part of the inventory contributes most to the costs.

Table 6. Undiscounted total production costs for the three studied scenarios.

Scenario	Production Cost (€/1 m^2)
Baseline	61.8
Scenario 1	97.0
Scenario 2	143.0

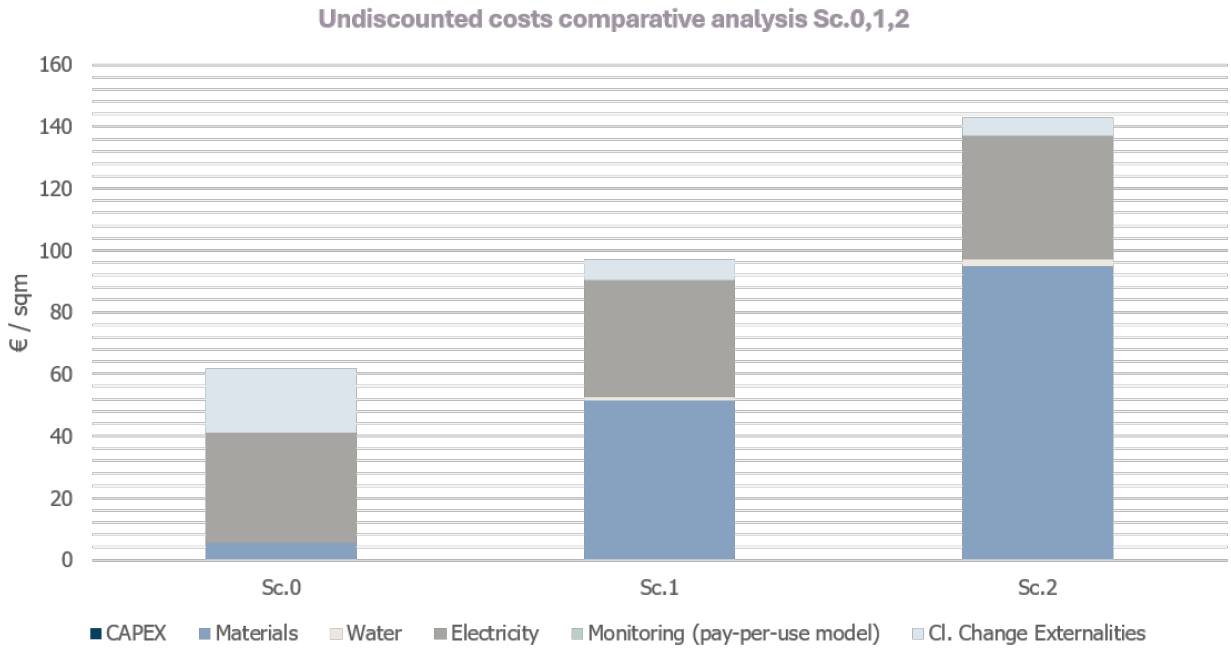

Figure 15. Undiscounted production costs comparative analysis (inventory-wise) for the three studied scenarios.

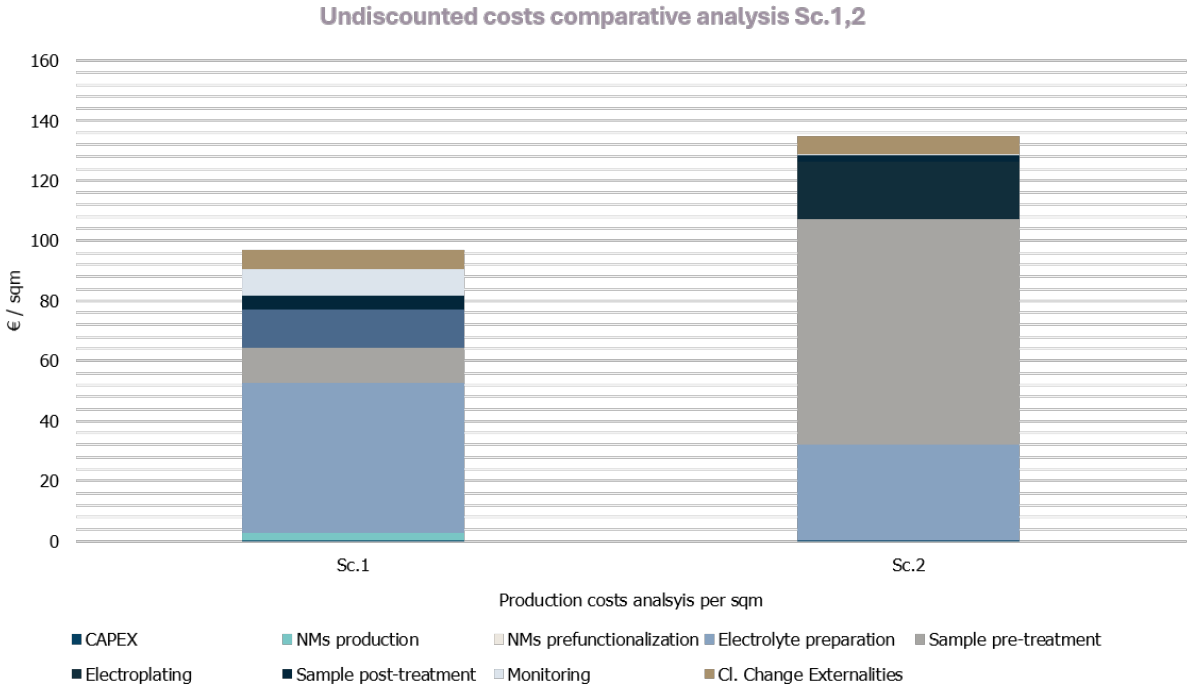

Figure 16. Alternative undiscounted production costs comparative analysis (process-wise) for the three scenarios studied.

For Sc.0 (Figure 15), the highest costs were attributed to electricity and climate change externalities. It must be noted that material cost's share was lower than Sc.1 and Sc.2's material cost share. For Sc.1, the highest costs were attributed to materials (52.8% of production costs) and electricity (38.9% of production costs), while for Sc.2, the highest costs were attributed to materials (66.3% of production costs). In all scenarios, CAPEX cost share was negligible, a fact mainly attributed to the high production volume (10,000 sqm per year) of the pilot considered.

In Figure 16, the highest costs for scenario 1 were attributed to Pr.3—electrolyte preparation (its material and electricity consumption) and climate change externalities. For Sc.2, the highest costs were attributed to Pr.4—sample pre-treatment (its material consumption) and climate change externalities. For both scenarios, sample post-treatment had negligible cost compared to other cost categories.

The results are case-specific, and it is evident that reducing the costs of materials in scenarios 1 and 2 (Figure 15) could essentially lower the gap between the cost of the new formulations and the baseline.

4. Discussion

Some key takeaways from the study include the importance of electricity consumption and material choice. Specifically, all analyses showed that electricity consumption has a driving role (in cases proportional to the environmental or cost impact) in LCA or LCC. Material choice affects the environmental and cost aspects to produce the FU in the same way.

The findings provide a basis for better understanding the requirements, not only from well-established processes (such as HC), but also ready-to-establish solutions, such as the ones presented. The results are case-specific, but they show how a different choice of a heavy metal coating matrix (Ni) reinforced by NPs can alter the whole environmental and cost performance of the coating line.

The ongoing research and discussion for the HC replacement has been discussed in EU strategies since 2019 [32], but its known toxicity and replacement efforts began span-

ning literature years prior to the restriction proposal [11,33–36], even in pre-2000s reports (e.g., [36]). The barrier to be overcome is, as aforementioned, the combination of properties that hard chrome exhibits as an excellent coating solution. The purpose of this work was to support the efforts for finding alternatives that can support the applicability range of HC while analysing the feasibility of the method shown in terms of both environmental and cost. A set of recent publications related to the scope of this plating technique substitution supports all engineering aspects for HC replacement and the monitoring of the plating process [37–41].

Overall, the newly developed formulations exhibited lower environmental impacts than scenario 0 in most impact categories, and key findings for the results (e.g., toxicity indicators, Figure 17) show promising LCA performance results for the solutions.

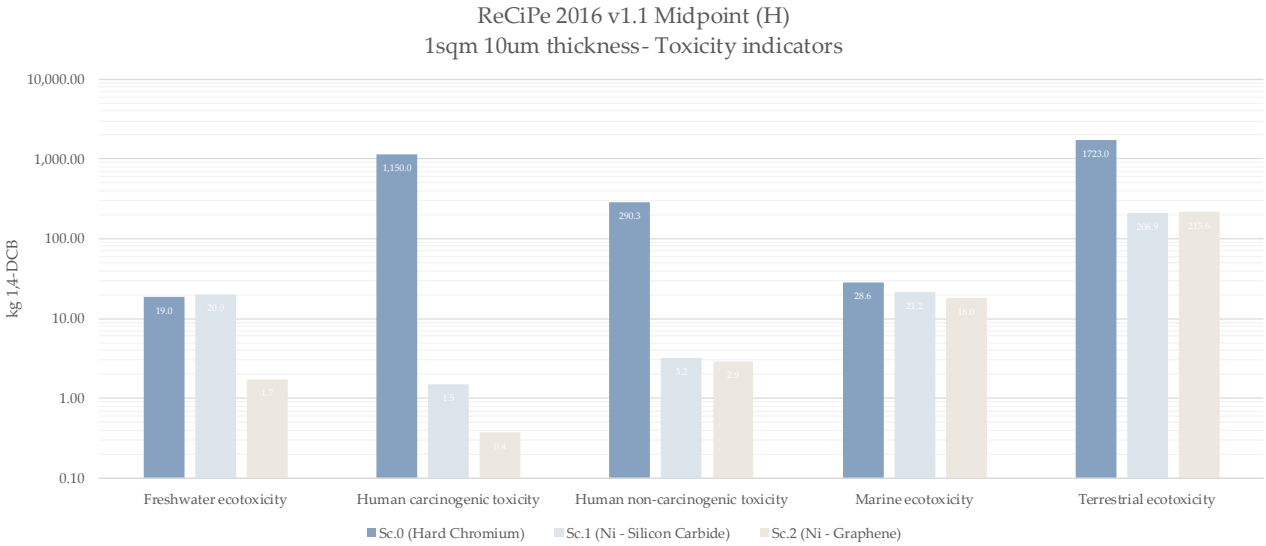

Figure 17. Midpoint toxicity indicators for the studied scenarios.

The feasibility analysis of the study shows how case-dependent the results are and how the selection of electricity and materials can affect the whole cost of the solution. Future work could include more tested cases and industrial-scale applications of the solutions, as well as more performance indicators in cost terms. As aforementioned, the limitation of the study to include certain cost categories could in fact provide a different LCC performance for the solutions. Including further cost categories could be a topic for future research. Future research could also include a cost optimisation for the solutions presented.

Upscaling the solution is expected to lower the cost and can in fact affect these two parameters in the cost share. Independently from the application environment (e.g., small plating line or industrial environments), the solution sets a new alternative that can substitute an established methodology in need of replacement.

Finally, future research could also include an uncertainty and sensitivity analysis for the assessment, as the study only provides a deterministic analysis.

5. Conclusions

This study provides an assessment of the methodology presented in the framework of the MOZART project under environmental and cost terms. The selection of a wide range of environmental impact indicators both at the midpoint and endpoint reinforces the findings of the study. The results are case-specific but show how the methodology results in an improved LCA profile for two real tested applications on piston rods and helical gears. The

cost analysis provides an in-depth evaluation of the applications' inventory cost share and highlights which parts of the process contribute the most to the cost.

In a carbon reduction-driven research perspective, showcasing solutions that can reduce the climate change impact by up to 70% (as shown in the midpoint results) is a step in line not only with the HC replacement but also with the decarbonisation of processes. The set of environmental improvements shown in the study strengthen the solution efficiency and serve as a pathway for future research for advanced alternatives to HC plating.

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Conflicts of Interest: The authors declare no conflicts of interest.

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