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Comparative Life Cycle Assessment of Industrial Zn and Zn-Al Hot-Dip Galvanizing Processes for Steel Wire Production

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Abstract. Hot-dip galvanizing (HDG) is a widely adopted industrial process for enhancing the corrosion resistance and service life of steel products; however, it is also characterized by high energy and material consumption. In this study, a process-oriented Life Cycle Assessment (LCA) is applied to compare the environmental performance of two industrial steel wire coating routes: conventional hot-dip zinc (Zn) coating and zinc–aluminum (Zn–Al) coating. The analysis is based on primary data collected from an industrial galvanizing line operated by Metallurgica Abruzzese S.p.A. (Italy) and focuses exclusively on the manufacturing stage, using a gate-to-gate approach. The system boundary includes surface preparation, thermo-metallurgical coating treatment—comprising induction annealing, hot-dip galvanizing and, for the Zn–Al route, an additional molten Zn–Al bath—followed by wire cooling and final handling operations.

Results show that the Zn–Al coating route leads to a significantly higher environmental impact at the manufacturing stage, with an approximately 44% higher GWP100 compared to conventional Zn coating. Contribution analysis reveals that this increase is primarily driven by the additional thermo-metallurgical coating step, which entails higher material input and thermal energy consumption, rather than by aluminum content alone. The findings highlight the dominant role of material selection and thermal process management in determining the environmental performance of industrial galvanizing lines.

Introduction

Steel remains the cornerstone of modern industrial manufacturing and an indispensable material for sectors such as automotive, construction, and household appliances due to its high strength and durability [1]. In recent years, the demand for steel has grown rapidly [2]. At the same time, the iron and steel industry ranks among the world's most carbon-intensive industrial sectors, alongside cement production [3]. Despite its widespread use, steel remains highly susceptible to corrosion when exposed to diverse service environments, resulting in socio-economic losses estimated at approximately 3.4% of the global Gross Domestic Product (GDP) [4].

To protect steel and extend its service life, a wide range of anticorrosion technologies has been developed, including electroplating, painting, thermal spraying, surface chemical treatments and physical vapor deposition. These approaches mainly rely on the application of protective surface coatings, such as Zn-based alloys or polymeric systems to shield the steel substrate and improve durability [5–7]. Among these techniques, hot-dip galvanizing (HDG) remains one of the most established and reliable solutions for extending the service life of steel products [8]. By creating a metallurgical bond between the zinc and the steel, HDG provides both a physical barrier and cathodic protection, effectively increasing the lifespan of structures by several decades [9]. Nevertheless, HDG is associated with substantial energy consumption, intensive use of raw materials, and the generation

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of emissions and process residues, including spent pickling acids and metallic wastes, which are raising growing environmental concerns [10,11].

In response, the development of Zn–Al alloy coatings over the recent decades has been driven by the need to improve corrosion resistance and overall coating performance. By combining zind's sacrificial protection with aluminum's superior passivation properties, coatings such as Zn–5%Al (Galfan) and Zn–55%Al (Galvalume) have demonstrated a significantly extended the service life of steel compared to conventional pure zinc coatings, while also allowing a reduction in coating weight [12].

While Zn-Al alloy coatings offer clear technical advantages in terms of corrosion resistance, their environmental burden must be rigorously evaluated through Life Cycle Assessment (LCA). Previous LCA studies on hot-dip galvanizing (HDG) processes have highlighted the significance of energy consumption and primary zinc production as major contributors to environmental impacts. For instance, Arguillarena et al. conducted a comprehensive cradle-to-gate LCA of industrial HDG plants in Spain, showing that steel and zinc production dominate most impact categories, whereas the galvanizing stage mainly influences toxicity-related indicators [13]. In a complementary study, the same authors focused specifically on the carbon footprint of HDG installations, demonstrating that upstream processes—particularly primary zinc and steel production—account for the majority of greenhouse gas emissions, while direct process emissions play a secondary role [14].

This paper presents a comprehensive comparative LCA of industrial steel wire coating routes. Unlike previous studies based on laboratory-scale data, our analysis utilizes primary data collected from an industrial galvanizing line operated by Metallurgica Abruzzese S.p.A. Using a gate-to-gate system boundary approach, we compare the environmental performance of conventional hot-dip zinc (Zn) coating with that of the zinc–aluminum (Zn–Al) route. By focusing on the manufacturing stage—including surface preparation, induction annealing, and thermo-metallurgical treatments—the study aims to identify the key process drivers that determine the environmental footprint of high-performance steel wire production.

The Hot Dip Galvanization Process: The Industrial Line

As introduced earlier, Hot-dip galvanization is a continuous industrial process used to apply a zinc-based metallic coating from corrosion protection of steel wire.

In the investigated industrial line (Metallurgica Abruzzese S.p.A., Italy), the process begins with surface preparation, which includes cleaning and acid pickling, to remove contaminants and oxides from the steel surface. The wire then rinsed and cleaned before undergoing induction annealing to stabilize the microstructure and ensure suitable mechanical properties prior to coating. Subsequently, the steel wire is immersed in a molten zinc bath or, in the case for the Zn–Al route (figure 1), in an additional molten Zn–Al bath (figure 2), where metallurgical bonding between the coating and the steel substrate occurs. After coating, the wire undergoes controlled cooling to stabilize the coating layer, followed by final handling operations such as rewinding and packaging.

The following section details the LCA methodology applied in this study.

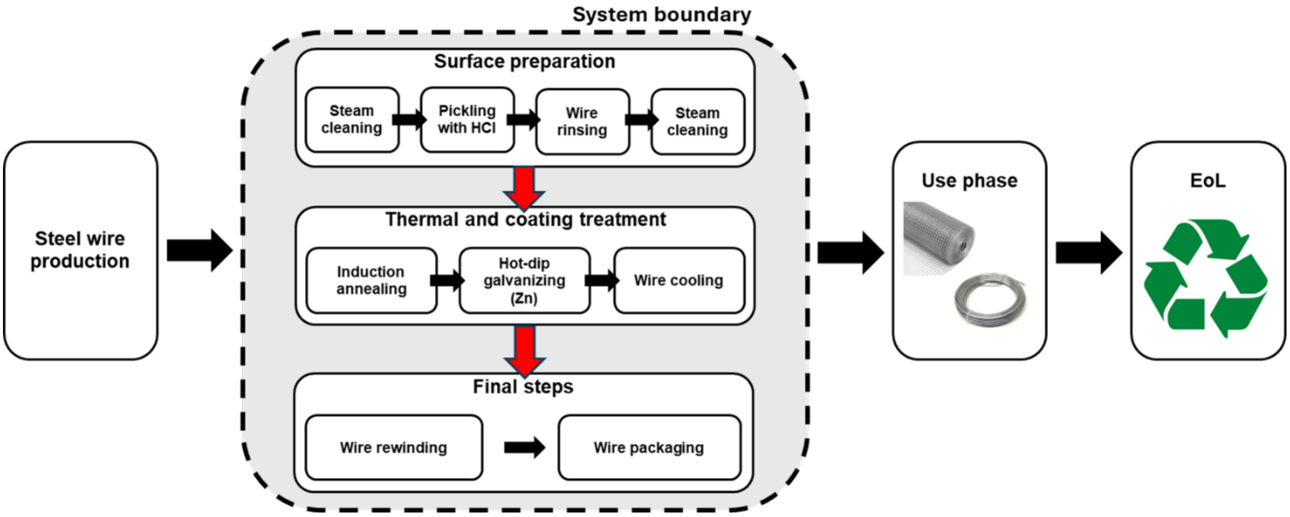


Fig. 1. Process flow and system boundary of the industrial steel wire galvanizing line (Zn only).

Life Cycle Assessment (LCA) Methodology

Life Cycle Assessment (LCA) is a standardized methodology for evaluating the environmental impacts associated with a product, process, or service by systematically accounting for material and energy flows and associated emissions over its life cycle. Defined by the ISO 14040 and 14044 standards, LCA is widely applied in industrial contexts to identify environmental hotspots and to support process optimization and compare technological alternatives. According to these standards, LCA is structured into four main phases: (i) goal and scope definition, (ii) life cycle inventory analysis, (iii) life cycle impact assessment, and (iv) interpretation.

In this study, the LCA focuses on a hot-dip galvanizing process based on a production line operated by Metallurgica Abruzzese S.p.A. Inventory data were collected from on-site measurements and production records to ensure the analysis reflects real-world industrial operating conditions rather than laboratory-scale or simulated scenarios.

Goal and scope definition

The Life Cycle Assessment (LCA) is conducted using a gate-to-gate approach and focuses exclusively on the manufacturing stage of the steel wire galvanizing process. The system boundary includes surface preparation, the thermo-metallurgical coating stage, which includes induction annealing, hot-dip galvanizing and, in the case of Zn–Al coated wire, immersion in an additional molten Zn–Al bath. Wire cooling and final handling operations complete the defined boundary (see Figures 1 and 2).

Upstream processes (e.g., steel wire production), the product use phase, and the end-of-life of the coated product are excluded from the assessment. The functional unit is defined as 1 ton of finished galvanized steel wire, ready for dispatch. Primary data were collected from an industrial galvanizing line operating under representative conditions during the reference year.

Environmental impacts of these two processes were estimated using Impact 2002+ assessment method, with results reported for the Global Warming Potential over a 100-year time horizon (GWP100) and Cumulative Energy Demand (CED).

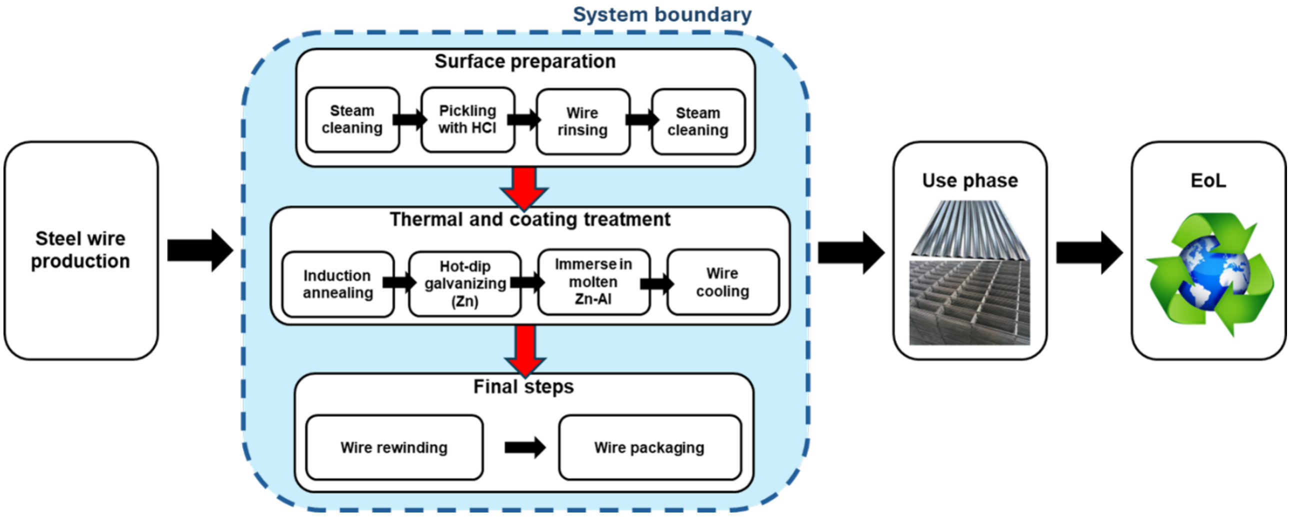


Fig. 2. Process flow and system boundary of the industrial steel wire galvanizing line, including the molten Zn–Al coating stage.

Table 1 Life Cycle Inventory (LCI) of the Zn hot-dip galvanizing process (per 1 t of finished galvanized wire).

Description	Quantity	Unit	Flow type
Output			
Galvanized steel wire	1,000	kg	Product
Material inputs			
Steel wire input to galvanizing	1,000	kg	Material
Metallic coating alloy (Zn)	33.9	kg	Material
Acid solution for pickling	13.25	kg	Material
Sodium hydroxide for emission treatment (E15)	1.75	kg	Material
Lime for wastewater treatment	3.64	kg	Material
Technical water for washing and cooling	500	kg	Material
Inert gas for controlled atmosphere (market supply)	33.73	kg	Material
Nitrogen produced on-site via PSA technology	11.85	kg	Material
Energy inputs			
Electricity consumption (total)	368.5	kWh	Energy
Thermal energy from natural gas	500	kWh	Thermal energy
Transport			
Internal handling (diesel vehicle EURO 5)	0.1667	t·km	Transport
Outputs (emissions and wastes)			
Fine particulate matter (PM < 2.5 µm)	0.005	kg	Direct emission
Sludge from wastewater treatment and solid residues	6.92	kg	Non-hazardous waste
Spent acidic solutions from pickling	3.91	kg	Non-hazardous waste
Metallic dross from galvanizing bath	15.41	kg	Waste for recovery
Minor metallic scrap after galvanizing	0.9	kg	Waste for recovery

Life Cycle Inventory (LCI) analysis

The Life Cycle Inventory (LCI) analysis was carried out by quantifying all relevant material and energy flows associated with the manufacturing stage of the steel wire galvanizing process, in accordance with the system boundary defined in the goal and scope. The inventory includes inputs of raw materials, auxiliary chemicals, energy carriers and utilities, as well as outputs in the form of emissions and solid and liquid wastes generated during the galvanizing operations.

As already mentioned, the industrial system was modelled by focusing exclusively on the galvanizing line, starting from the incoming steel wire and excluding upstream wire drawing operations. The process was represented in SimaPro software as a series of interconnected unit processes representing the main manufacturing steps. For the Zn–Al coating route, the thermo-metallurgical coating stage incorporates an additional molten Zn–Al bath.

Detailed life cycle inventory data for the Zn and Zn–Al hot-dip galvanizing processes are reported in Table 1 and Table 2, respectively.

Table 2. Life Cycle Inventory (LCI) of the Zn–Al hot-dip galvanizing process (per 1 t of finished Zn–Al coated wire).

Flow	Quantity	Unit	Type
Output			
Galvanized steel wire (Zn–Al)	1,000	kg	Product
Material inputs			
Steel wire input to galvanizing	1,000	kg	Material
Metallic coating alloy (Zn)	33.9	kg	Material
Zn coating material	31.59	kg	Material
Al coating material	3.51	kg	Material
Acid solution for pickling (HCl)	13.25	kg	Material
Sodium hydroxide (emission treatment)	1.75	kg	Material
Lime for wastewater treatment	3.64	kg	Material
Technical water for washing and cooling	500	kg	Material
Inert gas (market supply)	33.73	kg	Material
Nitrogen produced on-site (PSA)	11.85	kg	Material
Energy inputs			
Electricity (total)	368.5	kWh	Energy
Thermal energy from natural gas	658	kWh	Thermal energy
Transport			
Internal handling (diesel, EURO 5)	0.1667	t·km	Transport
Outputs (emissions and wastes)			
Fine particulate matter (PM < 2.5 μm)	0.005	kg	Direct emission
Sludge from wastewater treatment	6.92	kg	Non-hazardous waste
Spent pickling solutions	3.91	kg	Non-hazardous waste
Zinc dross from galvanizing bath	15.41	kg	Waste for recovery
Zn–Al dross from coating bath	29.2	kg	Waste for recovery
Minor metallic scrap	0.9	kg	Waste for recovery

Primary data were collected directly from the industrial plant for the reference year and were normalised to the functional unit of 1 t of finished galvanized wire. For both coating routes, the principal material input is the steel wire (1,000 kg). The metallic coating consumption is 33.9 kg of Zn for the conventional galvanizing route (Table 1) and 35.1 kg of alloy for the Zn–Al route, consisting of 31.6 kg of Zn and 3.5 kg of Al (Table 2). Surface preparation requires 13.25 kg of acid solution for pickling, supplemented by auxiliary chemicals such as sodium hydroxide (1.75 kg) for emission treatment and lime (3.64 kg) for wastewater neutralisation. Technical water consumption for washing and cooling operations is approximately 500 kg per ton of product for both configurations.

Energy inputs are dominated by electricity and thermal energy demand. Electricity consumption is comparable for the two routes at 368.5 kWh per ton of galvanized wire, mainly associated with induction heating, line operation and auxiliary equipment. In contrast, the Zn–Al coating route requires more thermal energy from natural gas (658 kWh versus 500 kWh for the conventional Zn route), reflecting the additional energy needed to maintain the molten Zn–Al bath. Controlled atmosphere conditions are ensured using a combination of commercially supplied inert gas (33.7 kg) and on-site nitrogen generated via pressure swing adsorption (PSA) technology (11.9 kg).

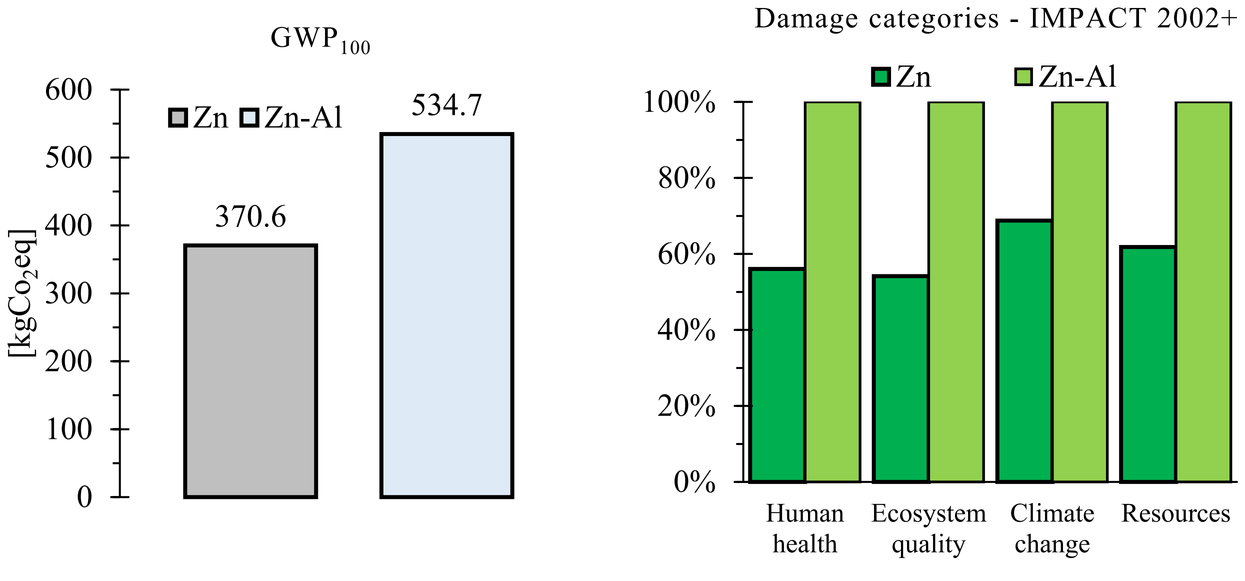
Outputs include direct air emissions and solid and liquid wastes generated during galvanizing. Fine particulate matter emissions (PM < 2.5 μm) were estimated at 0.005 kg per ton of product for both routes. Waste streams mainly consist of sludge from wastewater treatment (6.92 kg), spent pickling solutions (3.91 kg), and metallic residues from the coating baths. In particular, zinc dross from the galvanizing bath amounts to 15.41 kg in both configurations, while the Zn–Al route additionally generates 29.2 kg of Zn–Al dross. Minor metallic scrap (0.9 kg) and all metallic residues are assumed to be sent to recovery. Internal material handling, performed by a diesel-powered EURO 5 vehicle, accounts for 0.1667 t·km per ton of product.

Background data for electricity supply, fuel production, raw material extraction and upstream chemical processes were sourced from the Ecoinvent database (version 3.11), selecting datasets representative of the European and Italian context.

Life Cycle Impact Assessment (LCIA) and results

The Life Cycle Impact Assessment (LCIA) was carried out using the Impact 2002+ method Global Warming Potential over a 100-year time horizon (GWP100) and Cumulative Energy Demand (CED). GWP_{100} and CED are particularly relevant for assessing energy and material intensive surface treatment processes such as hot-dip galvanizing.

Figure 3a compares the GWP100 results for the two coating routes. The production of 1 ton of Zn-coated steel wire results in a GWP of 370.6 kg CO_2 eq. In contrast, the Zn–Al coating route shows a higher impact of 534.7 kg CO_2 eq per ton, corresponding to an increase of approximately 44%. This difference is mainly attributable to the additional molten Zn–Al coating stage, which leads to increased material consumption and higher thermal energy demand.



a) b)

Fig. 3. (a) Comparison of Global Warming Potential over a 100-year time horizon (GWP100) for the Zn and Zn–Al hot-dip galvanizing routes, expressed as kg CO_2 equivalent per ton of finished galvanized wire. (b) Relative contribution of the main IMPACT 2002+ damage categories for the two coating routes, normalised to the Zn–Al process.

Figure 3b illustrates the relative contributions of the four main categories IMPACT 2002+ damage categories—human health, ecosystem quality, climate change, and resources—normalized to the Zn–Al process. The analysis reveals that the Zn-Al alloy coating consistently exhibits a higher environmental footprint than pure Zn across all categories. The most pronounced disparity is observed in Ecosystem Quality category and Human Health, where the Zn-Al route incurs nearly double the impact of pure Zn (approximately 100% vs. 55%). This significant increase can be attributed to the high ecotoxicity and resource-intensive nature of aluminum extraction and its primary production, which introduces higher concentrations of heavy metals and pollutants during upstream mining and refining processes.

Furthermore, the Climate Change and Resources categories show that the Zn-Al coating results in approximately 30% and 38% higher impacts, respectively, compared to the pure Zn route. This increase is likely driven by the higher energy requirements for producing the secondary aluminum alloy and the higher melting point in the galvanizing bath, which together lead to greater greenhouse gas emissions and fossil fuel consumption during the production phase.

Figure 4 provides a qualitative comparison of the environmental impact profiles for the Zn and Zn–Al hot-dip galvanizing processes across all 15 impact categories defined by the Impact 2002+ method. For toxicity-related categories—including carcinogens, non-carcinogens, respiratory inorganics, and both aquatic and terrestrial ecotoxicity—the impacts associated with the pure Zn route range approximately between 40% and 70% of those of the Zn–Al route. A similar trend is observed for ionising radiation and land occupation, where differences between the two processes remain moderate and are largely driven by background system contributions.

Climate change impacts show the pure Zn route reaching about 69–79% of the Zn–Al impact, in line with the higher energy demand associated with the additional thermo-metallurgical coating stage required for the Zn–Al process. Acidification and eutrophication categories follow comparable patterns, with the Zn route generally remaining below 60% of the Zn–Al reference.

More pronounced differences are observed in resource-related categories, particularly non-renewable energy use and mineral extraction, where the pure Zn route accounts for roughly 50–65% of the Zn–Al impact. These results reflect the higher material intensity and energy demand associated with the Zn–Al coating route, rather than process-specific emissions.

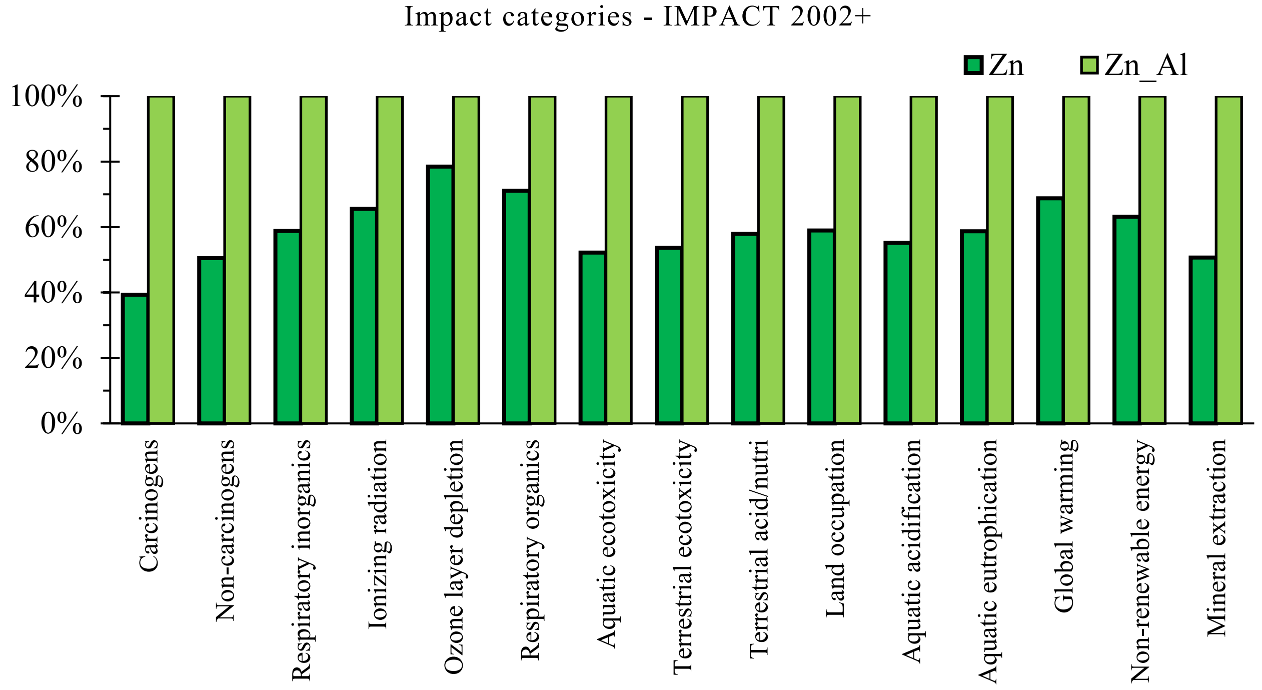


Fig. 4. Environmental impact categories for Zn and Zn–Al hot-dip galvanizing processes, based on the Impact 2002+ method (normalized values).

Figure 5 shows the cumulative energy demand (CED) for the Zn and Zn–Al hot-dip galvanizing processes. Panel (a) compares the total CED for the two coating routes, highlighting a higher primary energy demand for the Zn–Al process as expected. The total CED for the Zn–Al route is 10.4 GJ, which is approximately 40% greater than the 7.4 GJ required for pure Zn (Figure 5a). Panel (b) presents the contribution of different primary energy sources, indicating that non-renewable fossil energy is the dominant component for both routes. Non-renewable, fossil fuels are the dominant energy source for both processes. The significantly higher fossil fuel demand for Zn–Al (approx. 7.6 GJ vs 5.5 GJ) may explain its higher impacts in the Climate Change and Resource Use categories, as shown in Figure 3b. The elevated CED of the Zn–Al coating route is mainly driven by the additional thermo-metallurgical coating stage, which results in greater thermal energy consumption and higher embodied energy of the coating material. Contributions from renewable energy sources remain comparatively low and do not substantially alter the overall energy balance. The observed trends are consistent with the GWP100 results, confirming the strong link between energy demand and climate change impacts in industrial galvanizing.

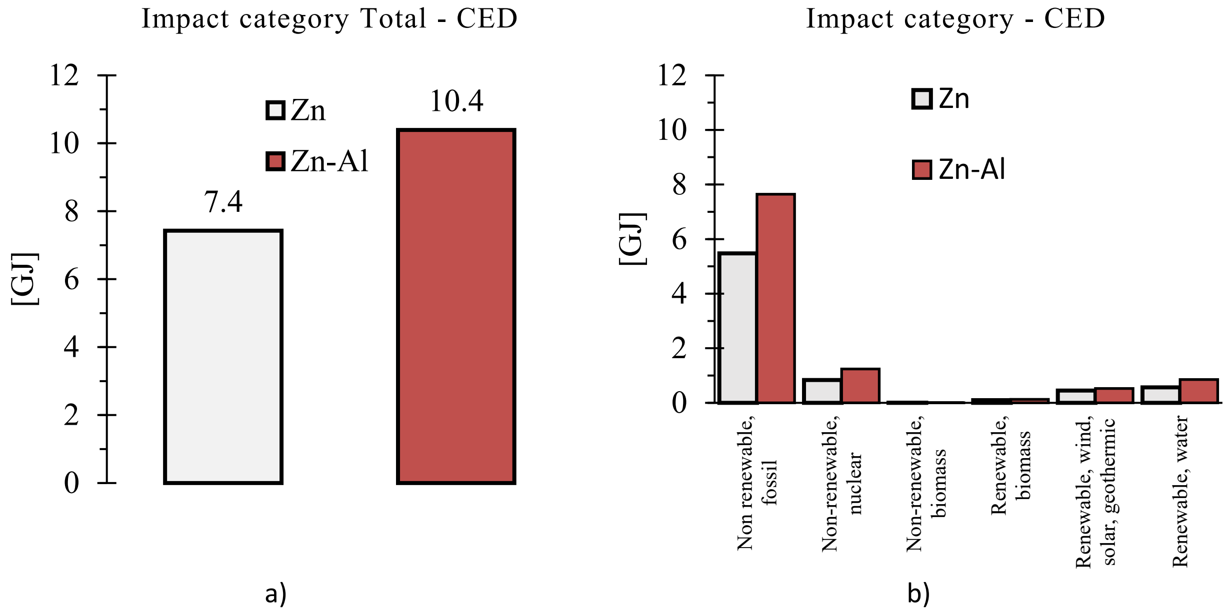


Fig. 5. Cumulative Energy Demand (CED) for Zn and Zn–Al hot-dip galvanizing processes: (a) total CED and (b) contribution by primary energy source.

The Life Cycle Impact Assessment results show that the environmental performance of the hot-dip galvanizing process is mainly driven by the thermo-metallurgical coating stage. For both pure Zn and Zn–Al coating routes, this stage is the dominant contributor to climate change impacts and cumulative energy demand, confirming the energy and material intensive nature of industrial galvanizing operations.

The comparison between the two routes highlights a clear increase in environmental burden for the Zn–Al option at the manufacturing stage. Midpoint characterization indicates that the Zn–Al route reaches the highest relative impact across almost all evaluated categories. In particular, the GWP100 of the Zn–Al route is approximately 44% higher than that of pure Zn. This increase is not solely related to the presence of aluminum, but results from the combined effect of higher coating material input and the addition of a second molten coating bath. This additional step prolongs the process and leads to significantly higher thermal energy consumption, directly affecting both GWP and CED.

The CED results support this interpretation, showing that the Zn–Al route requires 10.4 GJ of primary energy, corresponding to a 40.5% increase compared to the 7.4 GJ required for the Zn route. In both cases, energy demand is dominated by non-renewable fossil sources, accounting for approximately 7.8 GJ for Zn–Al and 5.5 GJ for Zn.

From a process engineering perspective, these results suggest that material selection and thermal energy management play a more critical role than electrical energy use in shaping the overall environmental profile of the galvanizing line. The higher environmental impact associated with the Zn–Al route is mainly attributable to the use of primary aluminium and the energy demand required to maintain the molten bath at elevated temperatures. A potential strategy to reduce the environmental burden would be the partial or total substitution of primary aluminium with secondary (recycled) aluminium, which is known to significantly lower energy consumption and greenhouse gas emissions compared to primary production. In addition, process optimization strategies such as improved thermal insulation of the molten bath, heat recovery systems, and the use of low-carbon electricity mixes could further mitigate the overall impact. From an LCA perspective, these measures would primarily affect the Climate Change and Resource damage categories, potentially narrowing the environmental gap between the Zn–Al and alternative routes.

The results also suggest that the environmental performance of the galvanizing process could be improved through the adoption of on-site renewable electricity generation. The use of self-produced electricity from sources such as photovoltaic systems could reduce the contribution of grid electricity to both climate change and energy-related impacts, particularly for auxiliary operations and electrical equipment.

Although Zn–Al coatings are commonly selected for their improved corrosion resistance and extended service life, this gate-to-gate analysis shows that these functional benefits are accompanied by a higher environmental burden during manufacturing. The Zn–Al route exhibits the highest relative impacts in the Human Health, Ecosystem Quality, Climate Change, and Resources damage categories, whereas the pure Zn route ranges between approximately 55% and 70% in the same categories. While the present study is limited to the manufacturing stage, the results highlight a clear environmental trade-off and identify the thermo-metallurgical coating stage as the primary target for future improvement strategies. A cradle-to-grave assessment would be required to evaluate whether the enhanced durability of Zn–Al coatings can offset the higher impacts observed during production.

Conclusions

A gate-to-gate Life Cycle Assessment (LCA) was conducted to compare Zn and Zn–Al hot-dip galvanizing routes for steel wire, using industrial data from a full-scale production line. The results demonstrate that:

- the Zn–Al coating route is associated with a significantly higher environmental impact at the manufacturing stage, with an increase of approximately 44% in Global Warming Potential (GWP100) compared to conventional Zn coating;
- the higher impacts of the Zn–Al route are mainly driven by increased total material input and higher thermal energy demand linked to the additional molten coating bath, rather than by electrical energy consumption;
- from a process engineering perspective, material selection and thermal management emerge as key levers for reducing the environmental footprint of galvanizing operations;
- while Zn–Al coatings may offer superior corrosion resistance, their adoption involves a clear environmental trade-offs at the manufacturing stage, which should be carefully considered in process and technology selection decisions.

Potential environmental benefits associated with extended product durability and reduced maintenance requirements were not considered in the present analysis. A cradle-to-grave life cycle assessment in future studies could provide further insight into whether the higher manufacturing impacts of Zn–Al coatings are offset advantages during the product use phase.

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