Life Cycle Assessment of Nickel Powder Production

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Executive Summary

This report investigates the environmental performance of nickel (Ni) powder production, focusing on the comparison between a conventional method using virgin materials and alternative approaches using recycled materials. With rising concerns over global warming, resource scarcity, and the growing emphasis on sustainable development, the industrial sector is under increasing pressure to minimize its environmental impacts, including those of underpinning manufacturing processes, e.g., additive manufacturing (AM). This study specifically assesses the environmental impacts of producing Ni powder, a critical raw material used in AM processes within various industries, including automotive, aerospace, and energy storage, using life cycle assessment (LCA).

The motivation behind this research stems from the growing importance of sustainability in manufacturing processes, particularly in sectors heavily reliant on energy-intensive materials like metals. Ni plays a vital role in these industries due to its desirable physical properties and longevity. Due to the critical status of Ni in the U.S. economy and its application in key technologies, the need for improving the sustainability of its production methods is crucial. In particular, the study focuses on the gas atomization process used in Ni powder production, comparing the environmental impacts of using virgin Ni versus recycled materials in the powder production process.

The LCA methodology employed in this study consists of four stages: defining the study's goal and scope, conducting an inventory analysis, assessing environmental impacts, and interpreting results. Three distinct production scenarios were examined: one using 100% virgin Ni, another incorporating externally recycled Ni (30% of input Ni), and the third using 100% recycled material sourced from internal scrap and local suppliers. All scenarios assumed equivalent outputs of 100 kg of Ni powder. The analysis was conducted using commercial LCA software (*SimaPro 9*) with the IPCC 2013 method for assessing global warming potential (GWP), measured in mass of CO_2 equivalent. Process data was sourced from the *ecoinvent 3* database, subject matter experts, and research literature.

The findings of this study highlight the significant environmental benefits of utilizing recycled materials in Ni powder production. The results clearly show that the use of virgin Ni in the first scenario has the highest environmental impact, with the production phase of virgin Ni contributing to over 96% of GWP. In contrast, the two recycled-material scenarios (Scenarios 2 and 3) demonstrated extreme reductions in GWP, with Scenario 2 achieving a 96.3% reduction and Scenario 3 a remarkable 99.7% reduction compared to Scenario 1. The primary environmental impact drivers in the recycled-material scenarios were transportation, the use of argon gas, and electricity. Scenario 3, which used both green argon and green electricity, showed the lowest GWP, further highlighting the advantages of green materials and green energy.

The study concludes that transitioning from virgin Ni to recycled Ni significantly enhances the sustainability of the powder production process, reducing carbon emissions and promoting a circular economy. These findings emphasize the importance of incorporating recycled materials into manufacturing processes to reduce costs as well as to improve the environmental impacts. The research provides valuable insights for industry stakeholders aiming to optimize production methods, comply with stricter environmental regulations, and contribute to global sustainability goals.

In summary, this report highlights that the incorporation of recycled materials, integrated with energy-efficient practices, presents a path for improving the environmental performance of Ni powder production. These results support the continued exploration of sustainable manufacturing practices, which are crucial in addressing the broader challenges of resource depletion and climate change.

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Motivation

Over the last fifty years, sustainable development has gained significant focus from society, academia, and industry due to issues like global warming, rising public awareness, corporate social responsibility, increasing regulation, and the growing scarcity of resources [1]. Within the industrial sector, it is essential to assess and enhance the sustainability and energy efficiency of manufacturing processes [2,3], as these processes are fundamental to industrial output [4]. Additive manufacturing (AM) is undergoing a transformative phase, driven by its expanding applications across various industries [5]. Innovations are particularly evident in sectors such as food and consumer products, healthcare, automotive, aerospace, architecture, and construction [6,7]. Therefore, it is important to explore and advance the sustainability performance of AM technologies.

The life cycle of products created through AM can be categorized into six stages [8], as presented in Figure 1. Among the various environmental impacts of AM products, a large proportion can be attributed to the feedstock materials, in addition to electrical energy [9–11]. Thus, a thorough assessment of the environmental impacts associated with metal powders is vital for conducting a comprehensive environmental evaluation and identifying strategies for reducing the negative impacts of AM technologies [11]. Metal powders are commonly produced using atomization, electrolysis, chemical precipitation, and powder condensation, with atomization being the most widely used due to its cost-effectiveness and technical maturity [12]. As a result, evaluating materials and energy use and environmental impacts and of powder atomization is critical when performing life cycle assessment (LCA) of AM products and processes. It should be noted that metal powders can either be sourced from virgin or recycled raw materials [13]. This distinction is important as the use of recycled powders offers two primary advantages: enhancing the environmental impacts of AM processes and reducing the cost of raw materials [14]. Therefore, developing and producing metal powders from recycled sources should be prioritized.

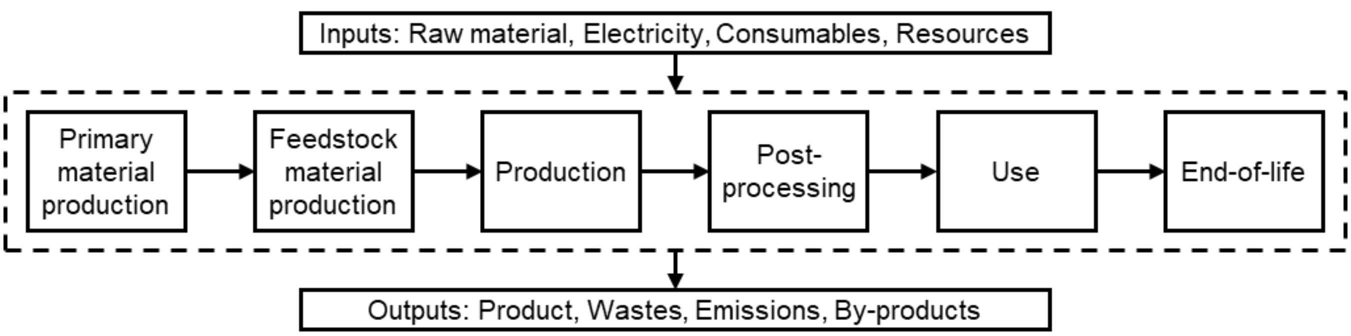

Figure 1. Life cycle stages of an additively manufactured part.

Nickel (Ni) is listed as one of the 50 critical minerals in the United States due to its importance to the nation's economic and security interests [15–18]. It plays a key role in the steel industry as an alloying element [19]. Due to its unique physical and chemical properties, Ni-containing materials can offer superior energy efficiency, longer product life, and lower maintenance requirements compared to alternative materials [20]. As mentioned above, one way to improve the environmental performance of powder production is to use recycled material. Thus, in the report presented herein, the environmental impact (i.e., global warming potential) of Ni powder production using recycled materials are compared to the impacts of conventional powder production.

Methodology

As presented in Figure 2, conducting an LCA study includes four steps: defining the goal and scope of the study, conducting an inventory analysis, conducting an environmental impact assessment, and interpreting results [21]. The goal of this study is to compare the environmental impact (i.e., GWP) of three approaches for producing Ni powder via gas atomization. Material inputs are drawn from virgin and recycled sources. The three approaches are assumed to produce equivalent powders, with the functional unit is defined as 100 kg Ni powder. The scope of the study is cradle-to-gate, considering the impact of transportation, raw materials, and powder production under three selected scenarios.

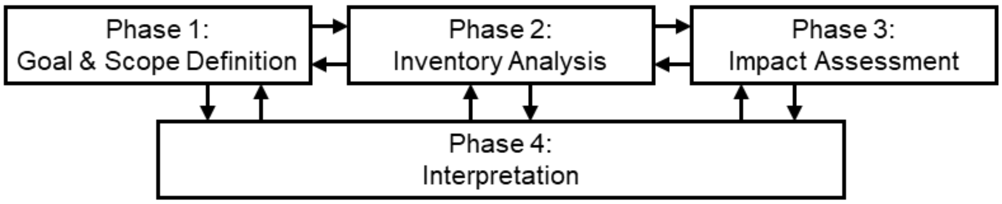

Figure 2. Life cycle assessment framework.

In the first scenario (Scenario 1), virgin Ni is used as the raw material input for powder production. After ore extraction, the raw material is processed to make it ready for powder production. This virgin Ni is then transported to a powder production facility in Cloverdale, CA. Since the atomization yield is assumed as 25%, 400 kg virgin Ni is needed to produce 100 kg powder (functional unit). In Scenario 2, no virgin Ni is used for powder production. Instead, recycled Ni is provided from internal (280 kg) and external (120 kg) sources, considering a 25% process yield to make 100 kg powder. Internally recycled material is generated by the previous powder production cycles at the facility, while externally recycled material is purchased from three suppliers across Canada and the USA. These suppliers, the amount supplied, and their distances from Cloverdale, CA, are summarized in Table 1.

Table 1. Suppliers of the recycled material for production Scenario 2 and Scenario 3.

Origin	Weight (kg)	Percentage	Distance (km)
Sainte Catherine, Quebec, Canada	2,428	10.1%	5,008
Mount Summit, IN, USA	5,601	23.4%	3,892
Houston, TX, USA	15,929	66.5%	3,355

Finally, Scenario 3 uses the same inputs as Scenario 2 to make 100 kg powder. However, Scenario 3 assumes the powder production facility is in Houston, TX. Further, it is assumed that all the suppliers of externally recycled materials are within 100 km of the facility. A summary of the raw material source locations and powder production facility locations is presented in Table 2.

Table 2. Raw material, source location, and powder production location in each scenario.

Scenario	Atomization Process Yield	Raw Material Source			Source Material Location	Powder Production Location
		Internally Recycled	Externally Recycled	Virgin		
1	25%	-	-	400 kg	Eagle Mine, MI	Cloverdale
2	25%	280 kg	120 kg	-	Various (Table 1)	Cloverdale
3	25%	280 kg	120 kg	-	Houston, TX	Houston

It should be noted that Ni powder production has five steps, which starts with feedstock preparation, followed by gas atomization, sieving, lotting, and packaging. Due to their relatively low use of electricity and consumables, this LCA study omits the last three process steps. A summary of the three scenarios is presented in Figure 3.

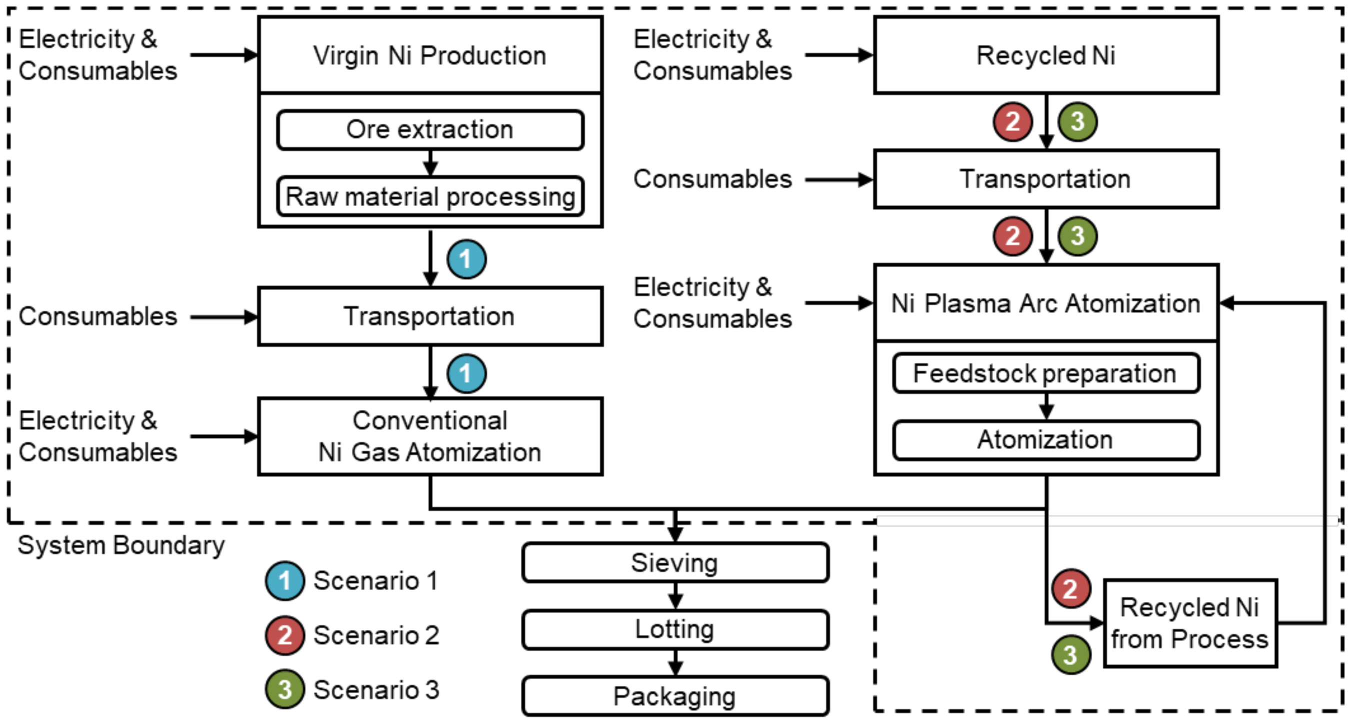

Figure 3. Scenarios for making Ni powder using virgin and recycled raw materials.

Life cycle inventory (LCI) data for processes within the system boundary were captured from research literature and personal communication with practitioners, experts, and vendors in the relative manufacturing domain, as well as using the *ecoinvent 3* database. Detailed materials and energy inputs for the three scenarios are reported in Table 3. SimaPro 9 [22], an commercial LCA software, was used to compile LCI data and conduct the impact assessments.

Table 3. Inventory of material and energy inputs for the three Ni powder production scenarios.

Scenario	Process step	Type	Value (Unit)	Justification
1	Virgin Ni Production	Nickel	400 (kg)	Industry expert
	Transportation (input material)	LTL Truck	3,870 (km)	[24]
	Conventional Gas Atomization	Electricity	0.44 (MJ/kg)	[8,25]
		Argon	4.54 (kg/kg)	Industry expert
		Propane	2.5 (MJ/kg)	[8,25]
2	Recycled Ni (internal)	Nickel	280 (kg)	Industry expert
	Recycled Ni (external)	Nickel	120 (kg)	Industry expert
	Transportation (input material)	LTL Truck	Table 1	Industry expert
	Plasma Arc Atomization	Electricity	181 (kW)	Industry expert
		Argon	4.54 (kg/kg)	Industry expert
		Helium	6.5 (scf/min)	Industry expert
3	Recycled Ni (internal)	Nickel	280 (kg)	Industry expert
	Recycled Ni (external)	Nickel	120 (kg)	Industry expert
	Transportation (input material)	LTL Truck	100 (km)	Industry expert
	Plasma Arc Atomization	Electricity	181 (kW)	Industry expert
		Argon	4.54 (kg/kg)	Industry expert
		Helium	6.5 (scf/min)	Industry expert

Results

To conduct the environmental impact assessment, the TRACI 2.1 method was selected, focusing on its global warming metric. TRACI 2.1 is a multi-indicator method that utilizes ten metrics, i.e., ozone depletion, global warming, smog, acidification, eutrophication, carcinogenics, non-carcinogenics, respiratory effects, ecotoxicity, and fossil fuel depletion. Figure 4 presents the relative GWP of 100 kg Ni powder for the three scenarios. Figure 4a presents the GWP results for each of the scenarios, whereas Figure 4b presents the reduction in GWP for Scenarios 2 and 3 compared to Scenario 1, which are 96.3% and 99.7%, respectively.

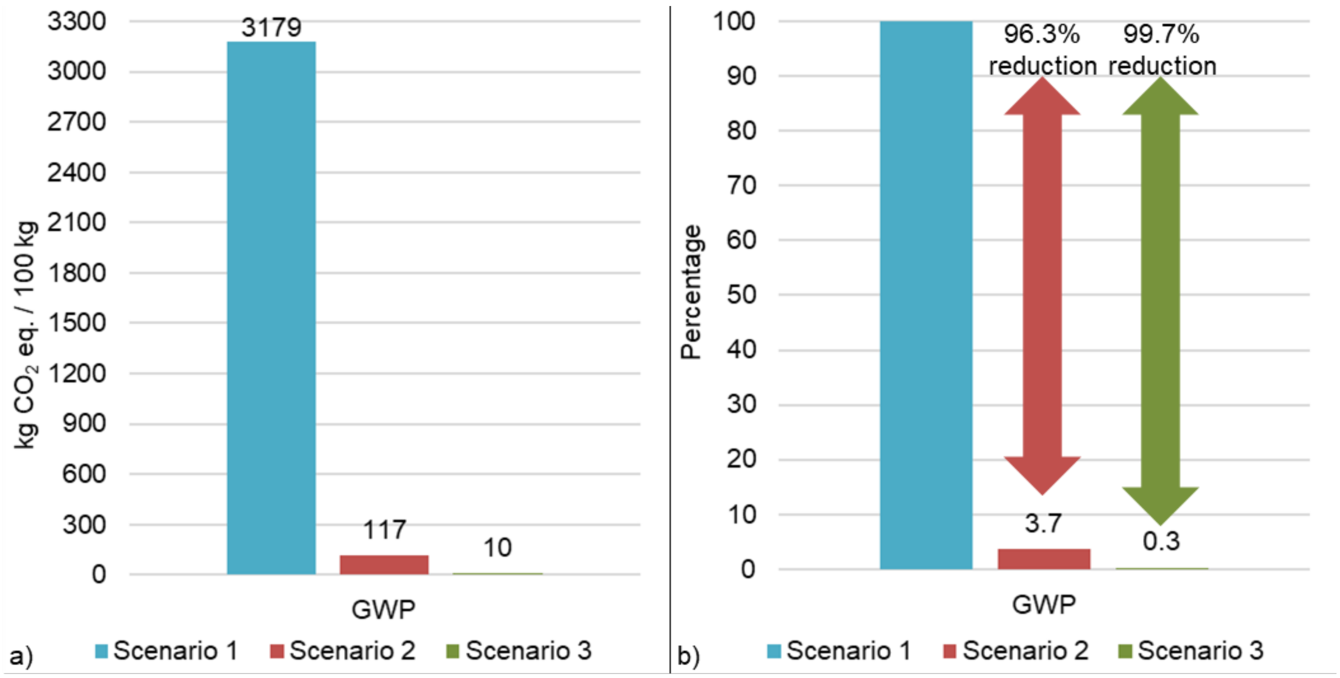

Figure 4. Relative GWP of Ni powder production under the three selected scenarios.

It was found that Scenario 1 has the highest environmental impacts compared to the other scenarios. The main environmental impact driver in this scenario is due to the virgin Ni production, which accounts for 96% of GWP impacts (Figure 5). Scenarios 2 and 3 are significantly lower in GWP than Scenario 1 since they use recycled Ni instead of virgin Ni.

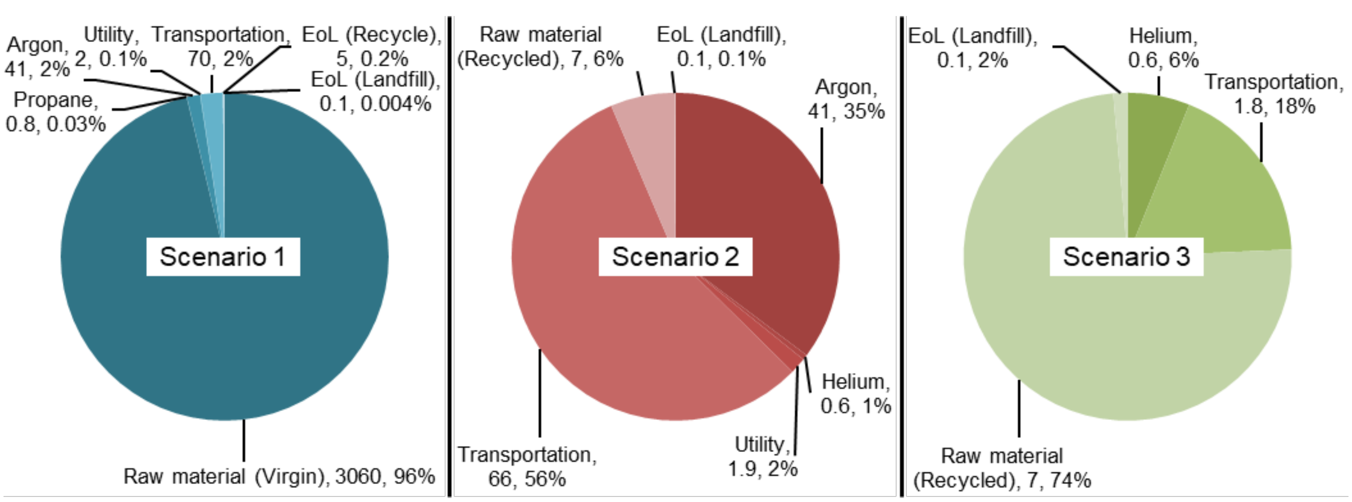

Figure 5. Drivers of GWP for Scenario 1 (left), Scenario 2 (middle), and Scenario 3 (right).

In Scenario 2, the main environmental impact drivers are transportation, argon, and electricity, which account for 56%, 35%, and 2% of GWP impacts, respectively. To improve the environmental performance, Scenario 3 applies green argon and green electricity for the atomization process step. Moreover, the external suppliers of the recycled raw material are selected within a 100 km radius of the powder production facility. Thus, the environmental impacts of transportation in Scenario 3 improve significantly compared to Scenario 2.

Summary and Conclusions

This report investigated the environmental performance of Ni powder production, comparing a conventional gas atomization method using virgin Ni with alternative plasma arc atomization processes utilizing recycled materials. The motivation for this study stems from the growing global emphasis on sustainable manufacturing practices. Ni is an essential material for modern manufacturing, due to its critical importance in various sectors such as automotive, aerospace, and energy. Given the significant environmental impact of traditional production methods, this research investigated the advantages of using recycled materials in Ni powder production, particularly focusing on the gas atomization process.

The life cycle assessment (LCA) methodology is applied herein to evaluate and compare three distinct production scenarios: one using virgin Ni, another incorporating both internally and externally recycled Ni, and a third using entirely recycled materials sourced from local suppliers. These scenarios were assessed for their environmental impact, specifically focusing on global warming potential (GWP). Life cycle inventory (LCI) data was gathered from industry experts, research literature, and the *ecoinvent 3* database to ensure accurate and representative inputs for the analysis.

The findings revealed significant differences in the environmental impacts associated with the three scenarios. The production of Ni powder using virgin materials was identified as the primary environmental impact driver, accounting for 96% of the carbon emissions in the life cycle. In contrast, the two scenarios utilizing recycled materials showed significant reductions in emissions, with Scenarios 2 and 3 (plasma arc atomization) reducing GWP by 96.3% and 99.7%, respectively compared to Scenario 1 (gas atomization). These reductions were attributed to the lower carbon footprint associated with recycling and removing energy-intensive extraction/processing of virgin Ni.

Further analysis of the scenarios highlighted that the key environmental impact drivers in the recycled material scenarios were transportation, electricity, and argon. Scenario 3, which incorporated recycled materials and greener energy sources, demonstrated the most environmental-friendly outcomes. In addition to reducing process carbon emissions, this scenario reduced the GWP of transportation by sourcing external recycled material from nearby suppliers, highlighting the importance of both material sourcing and energy choices in optimizing sustainability performance.

The results of this study highlight the significant environmental advantages of using recycled materials in the production of Ni powder. Recycling Ni reduces the carbon footprint and supports the principles of a circular economy, where waste materials are reintegrated into the production cycle, further contributing to resource conservation. The analysis also emphasizes the importance of improving energy efficiency in the manufacturing process, with the use of renewable energy sources, e.g., green electricity and the optimization of material transport logistics playing crucial roles in reducing overall environmental impacts.

In conclusion, this report supports the continued development of recycling technologies and clean energy practices as key strategies in mitigating climate change, reducing resource depletion, and achieving long-term sustainability in the manufacturing sector. Future research could further explore the economic implications of these findings, including cost savings associated with using recycled materials, to encourage broader adoption of sustainable manufacturing practices across industries. Ultimately, the integration of recycled materials and green materials and energy in Ni powder production is a promising strategy for improving the environmental footprint of the manufacturing process, contributing to both economic and ecological sustainability.

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Disclaimer

Certain commercial software products and consumer products are identified in this paper. These products were used only for demonstration purposes. This use does not imply approval or endorsement by the authors of this paper. Further, the presented analysis relies upon data contained in the software, which cannot be fully reported due to end-user license agreements. It is advisable not to rely solely upon results due to these restrictions.

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