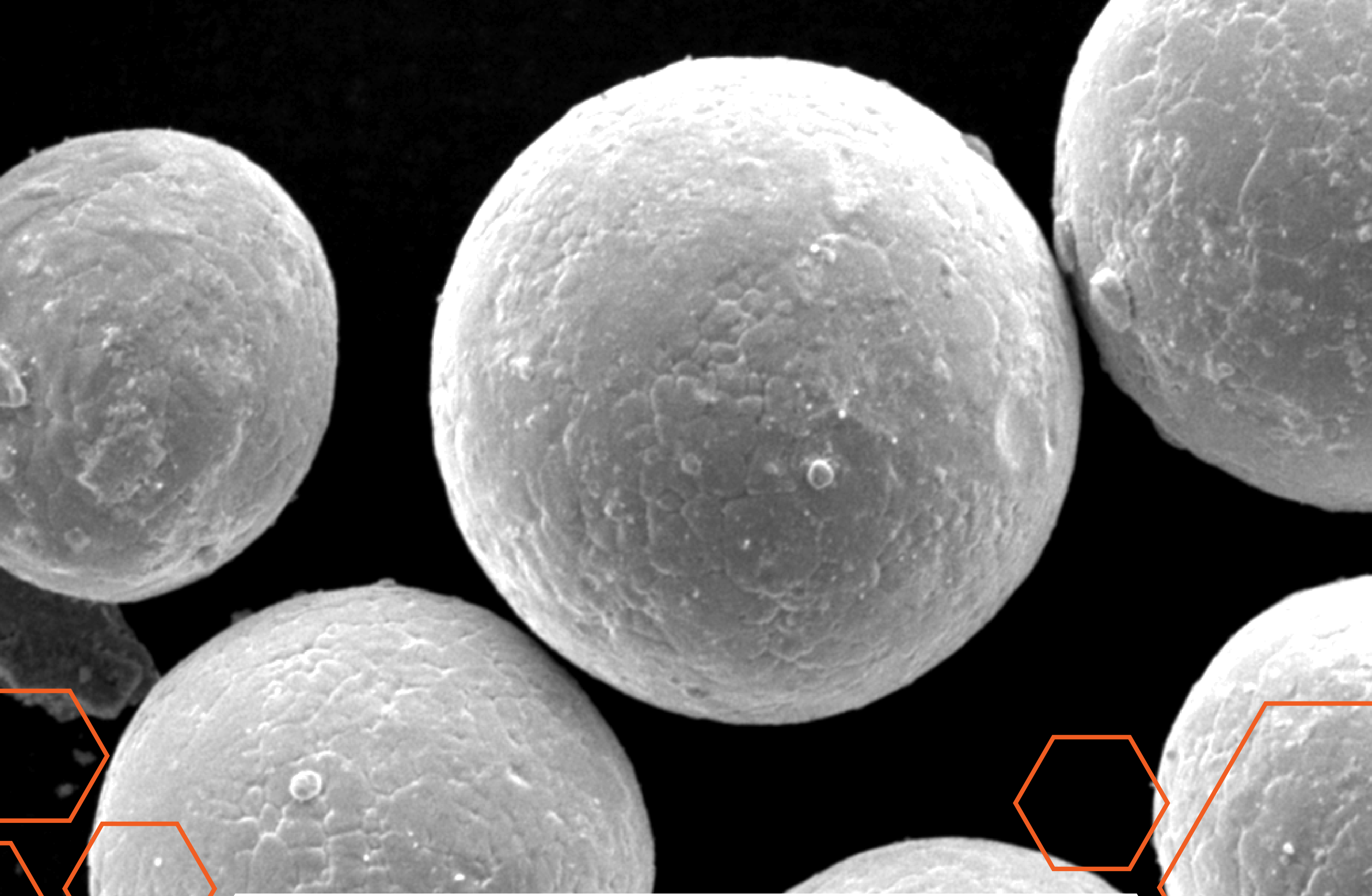

Life Cycle Assessment of **Nickel Powder Production**

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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 assesses the environmental impacts, measured as global warming potential (mass of CO_2 equivalent), 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 performance 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. Scenario 1 uses conventional gas atomization with 100% virgin Ni. Scenario 2 employs Continuum Powders' novel plasma arc atomization technology, utilizing recycled Ni (70% internally/30% externally sourced). Scenario 3 also uses Continuum's plasma arc atomization technology, but sources recycled Ni from internal scrap (70%) and local suppliers (30%), as well as utilizing carbon offsets for energy and argon purchases. All scenarios assume an output of 100 kg of Ni powder for use in additive manufacturing processes. The analysis was conducted using commercial LCA software (SimaPro 10.3) with the TRACI 2.1 v1.09 method for assessing global warming potential (GWP), measured in kg CO_2 eq. Process data was sourced from the *ecoinvent* v3.10 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 Scenario 1 has the highest environmental impact, with the production phase of virgin Ni contributing to 61.9% of GWP. In contrast, the two recycled-material scenarios (Scenario 2 and Scenario 3) demonstrated significant reductions in GWP, with Scenario 2 achieving a 58.8% reduction and Scenario 3 a remarkable 98.7% reduction compared to Scenario 1. The primary environmental impact drivers in the recycled-material scenarios were the use of argon, helium, and electricity. Scenario 3, which used 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 greenhouse gas (GHG) emissions and promoting a circular economy. These findings emphasize the importance of incorporating recycled materials into manufacturing processes to reduce costs while reducing the environmental impacts. The research provides valuable insights for industry stakeholders aiming to optimize production, comply with environmental regulations, and contribute to global sustainability goals.

In summary, this report shows that incorporating recycled materials and energy-efficient practices can reduce environmental impacts of Ni powder production. These results support continued exploration of sustainable manufacturing approaches to help address resource depletion and reduce CO_2 emissions linked to climate change.

Motivation

Industrial sustainability has gained increasing attention over the past several decades due to corporate social responsibility, public awareness, regulations, emissions reduction goals, and the growing scarcity of resources [1]. Within the industrial sector, it is essential to assess and enhance the sustainability, manufacturing and energy efficiency of manufacturing processes [2,3], as these processes are fundamental to industrial efficiency [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 social, economic, environmental, and operational performance of AM technologies.

The life cycle of products created through AM can be categorized into six stages, including primary material extraction, feedstock material production, part production, post processing, use, and end-of-life management [8]. 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 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: reducing 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.

Nickel (Ni) is listed as one of more than 60 critical minerals in the United States due to its importance to the nation's economic and security interests [15]. It plays a key role in the steel industry as an alloying element [16]. 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 [17]. 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, GWP, in kg CO_2 eq.) of Ni powder production using recycled materials is compared to the impacts of conventional powder production

Methodology

As presented in Figure 1, 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 [18]. 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 atomization yield of 25%, with the functional unit defined as 100 kg Ni powder. The yield assumption is based on Continuum's Greyhound M2P Platform-Gen 3 technology. The scope of the study is cradle-to-gate, considering the impact of raw materials, transportation, and powder production under three scenarios.

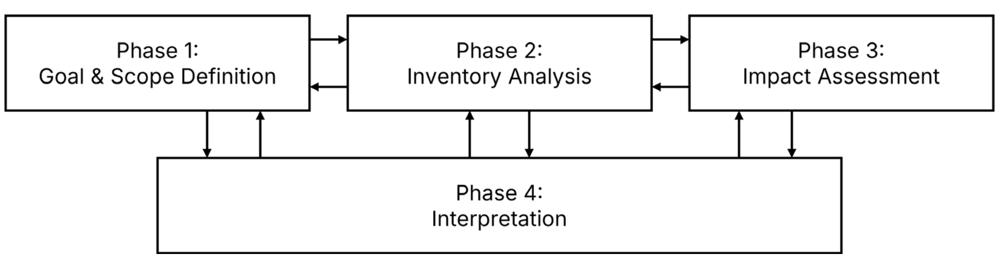

FIGURE 1. LIFE CYCLE ASSESSMENT FRAMEWORK [18]

In Scenario 1, powder production is modeled using conventional gas atomization with virgin Ni as the raw material input. 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%, only one quarter of the input nickel is converted into AM-usable powder within the standard 15–45 µm particle size distribution (PSD). Consequently, 400 kg of virgin nickel is required to produce 100 kg of usable powder, defined as the functional unit. Since conventional gas atomization cannot reuse unatomized Ni, 70% of the unatomized Ni is sent for recycling and the remaining 5% is assumed to be removed and managed as non-recoverable material, through cleanup operations. In Scenario 2, powder production is modeled using Continuum's novel plasma arc atomization technology, which enables the reuse of unatomized nickel. Further, no virgin Ni is used. Instead, 400 kg of recycled Ni is provided from internal (280 kg) and external (120 kg) sources, based on the 25% process yield assumption. Internally recycled material is comprised of unatomized Ni from 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

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 models the Continuum production facility in Houston, TX and uses the same material inputs and plasma arc atomization as Scenario 2 to make 100 kg powder. In addition, 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. Scenario 3 further assumes the use of green argon and green electricity for the atomization process. Both are sourced from renewable electricity, and any remaining associated emissions are offset through purchased offsets; therefore, they are modeled as having zero GHG emissions in this study. The study team relied on Continuum subject matter experts for process data collection, helping ensure the modeled inputs reflect real industrial operating conditions rather than theoretical assumptions.

TABLE 2. RAW MATERIAL, SOURCE LOCATION, AND POWDER PRODUCTION LOCATION FOR 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 Continuum's state-of-the-art powder production facilities are designed to deliver production-grade, reclaimed metal powders with lower environmental impacts than conventional production methods. Operations are supported by renewable electricity sources and incorporate green argon for atomization and powder handling, helping reduce the emissions tied to use of energy and inert gases while maintaining tight process control. Continuum employs its Melt-to-Powder approach and quality framework to produce consistent, spherical, high-flow powder engineered for demanding additive and advanced manufacturing applications—without sacrificing performance, availability, or supply-chain resilience.

Ni powder production has five steps, which start with feedstock preparation, followed by gas atomization, sieving, lotting, and packaging. Due to their relatively low use of electricity and consumables (and identical operations for all scenarios), this LCA study omits the last three process steps. A summary of the three scenarios is presented in Figure 2.

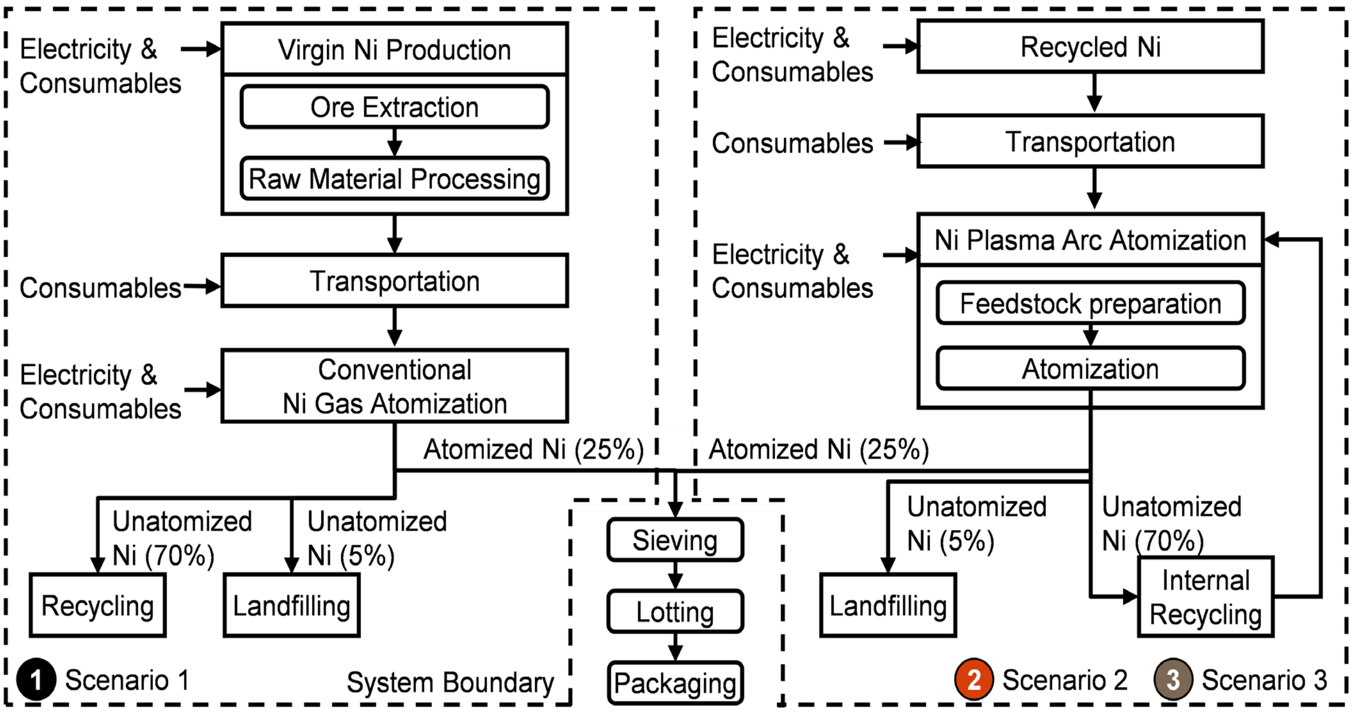

FIGURE 2. SCENARIOS FOR MAKING NI POWDER USING VIRGIN AND RECYCLED RAW MATERIALS

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* 3.10 database. Detailed materials and energy inputs for the three scenarios are reported in Table 3. SimaPro 10.3 [19], a commercial LCA software was used to compile LCI data and conduct the impact assessments. Unatomized Ni handled in cleanup operations at end-of-life (EoL) is modeled using a Ni landfill treatment process from the *ecoinvent* database which is comprised of waste handling and compaction, landfill infrastructure, leachate generation and treatment, and long-term emissions during landfill aftercare.

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)**	[20]
	Conventional Gas Atomization	Electricity	**0.44 (MJ/kg)**	[8,21]
		Argon	**4.54 (kg/kg)**	Industry expert
		Propane	**2.5 (MJ/kg)**	[8,21]
2	**Recycled Ni (internal)**	Nickel	**280 (kg)**	Industry expert
	Recycled Ni (external)	Nickel	**120 (kg)**	
	Transportation (input material)	LTL Truck	**Table 1**	
	Plasma Arc Atomization	Electricity	**2.73 (kWh/kg)**	
		Argon	**4.54 (kg/kg)**	
		Helium	**6.2 (scf/kg)**	
3	**Recycled Ni (internal)**	Nickel	**280 (kg)**	Industry expert
	Recycled Ni (external)	Nickel	**120 (kg)**	
	Transportation (input material)	LTL Truck	**100 (km)**	
	Plasma Arc Atomization	Electricity	**2.73 (kWh/kg)**	
		Argon	**4.54 (kg/kg)**	
		Helium	**6.2 (scf/kg)**	

Results

To conduct the environmental impact assessment, the TRACI 2.1 v1.09 method was used, focusing on its global warming impact category which measures the effect of GHGs in kg CO_2 eq. TRACI 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. TRACI is specifically designed for North American applications and aligns with U.S. environmental and regulatory contexts [22]. Figure 3 presents the GWP of 100 kg Ni powder under each of the three selected production scenarios, as well as the reduction in GWP for Scenario 2 and Scenario 3 relative to Scenario 1 – representing reductions of 58.8% and 98.7% in GWP, respectively.

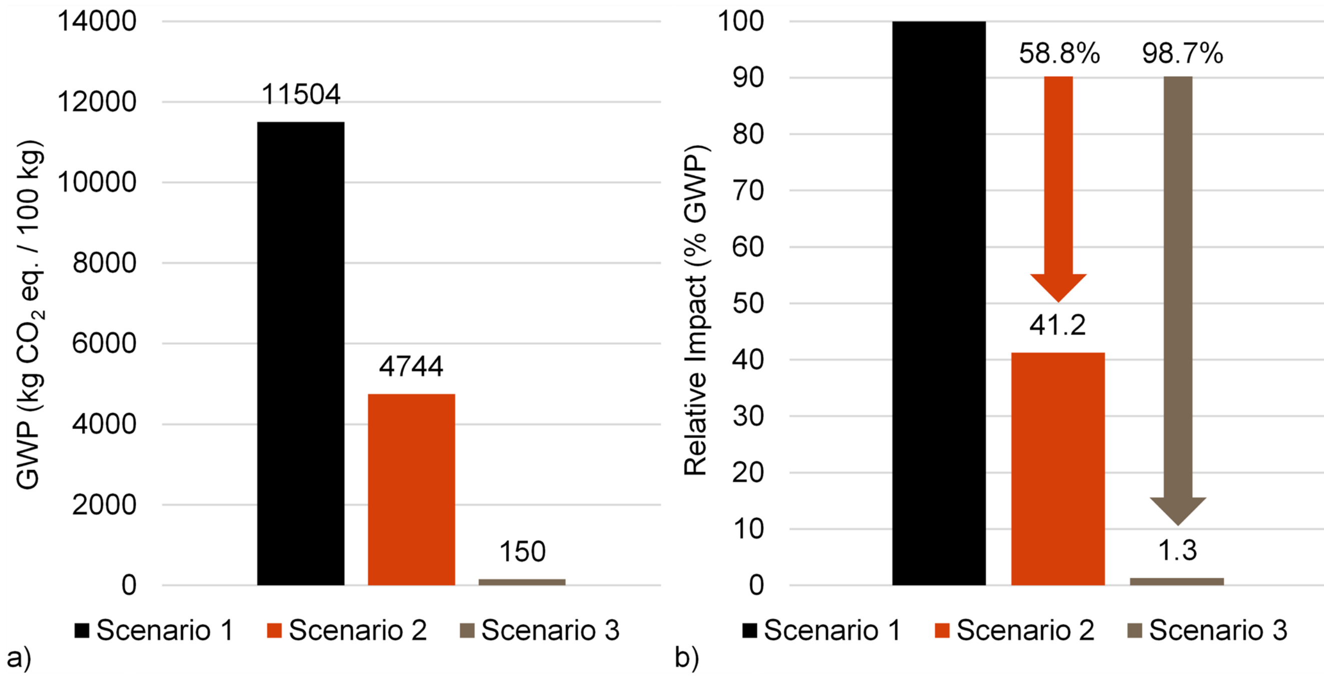

FIGURE 3. IMPACT OF NI POWDER PRODUCTION UNDER THE THREE SELECTED SCENARIOS: A) GWP AND B) RELATIVE REDUCTION IN GWP. SCENARIO 3 MODELS CONTINUUM'S HOUSTON FACILITY PROCESS.

It was found that Scenario 1 has the highest environmental impacts, measured as GWP, compared to the other two scenarios. The main environmental impact drivers in this scenario are due to the virgin Ni production, which accounts for 62% of GWP, and use of argon, which accounts for 36% of GWP (Figure 4). Scenario 2 and Scenario 3 are significantly lower in GWP than Scenario 1 since they use recycled Ni instead of virgin Ni. While electricity consumption is higher in Scenario 2 (419 kg CO_2 eq. vs. 18 kg CO_2 eq. in Scenario 1), this increase is more than offset by the reductions achieved using recycled Ni.

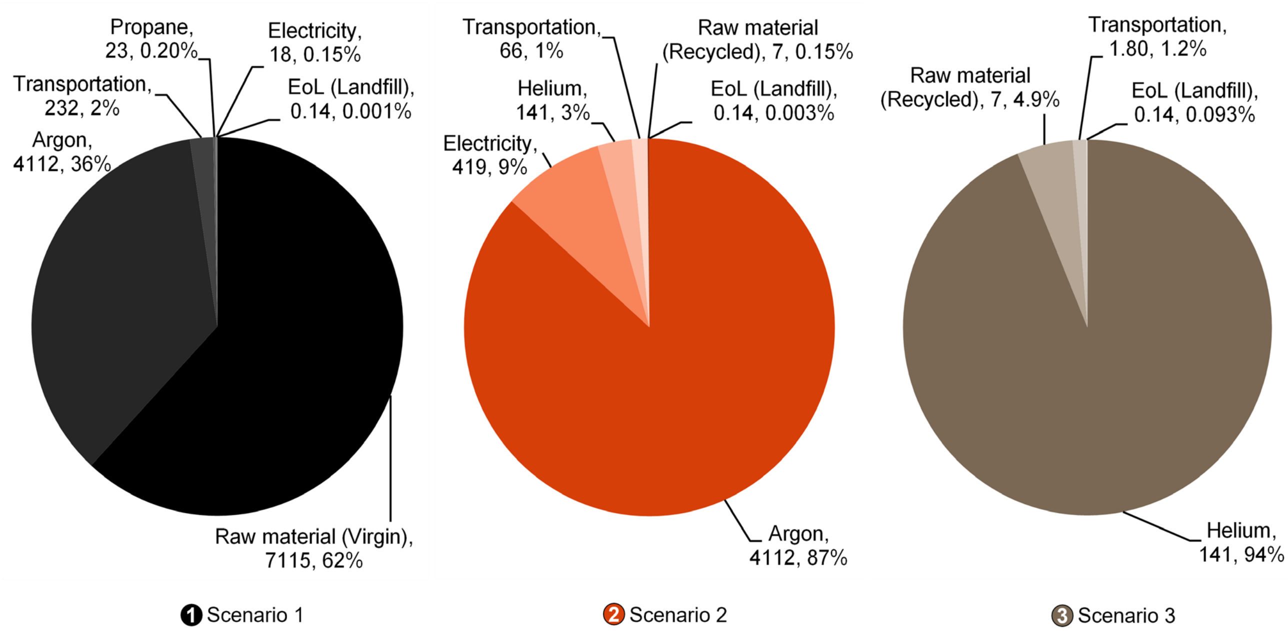

FIGURE 4. DRIVERS OF GWP FOR SCENARIO 1 (LEFT), SCENARIO 2 (MIDDLE), AND SCENARIO 3 (RIGHT). SCENARIO 3 MODELS CONTINUUM'S HOUSTON FACILITY PROCESS.

In Scenario 2, the main environmental impact drivers are argon and electricity, which account for 87% and 9% of GWP impacts, respectively. Producing and liquefying argon is an energy-intensive process that is known to cause significant environmental impacts [23]. 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 (GWP, kg CO_2 eq.) of transportation in Scenario 3 reduce significantly compared to Scenario 2.

Summary and Conclusions

This report investigated the environmental performance of Ni powder production, measured using global warming potential (GWP, kg CO_2 eq.), 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 impacts and raw material resource requirements 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 GWP via TRACI 2.1. Life cycle inventory (LCI) data was gathered from industry experts, research literature, and the *ecoinvent* 3.10 database to ensure accurate and representative input 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 62% of total carbon-equivalent 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 58.8% and 98.7%, 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 argon, electricity, helium, and transportation, respectively. Scenario 3, which incorporated recycled materials and greener energy sources, demonstrated the most environmentally friendly outcomes. In addition to reducing process-related greenhouse gas (GHG) 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 improving 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 and using green materials in manufacturing, with the use of renewable energy sources, green argon, and thoughtful 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 inputs, greener materials, and cleaner energy in metal 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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