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Quantifying Life Cycle Environmental Impact of Emerging Aluminum High-Pressure Die Cast (HPDC) Mega-Castings Replacing Stamped Steel Solutions

Brandie Sebastian[1] and Russ Balzer[2]

[1]*Brandie Sebastian Consulting LLC, USA*
[2]*IISI: World Steel Association, USA*

Abstract

Over the last few years, there has been an uptick in the exploration and implementation of aluminum high-pressure die casting (HPDC) mega-castings as replacements for conventional stamped steel parts in vehicles. This trend is expected to increase with common justifications, including claims of reduced costs and lower environmental impacts associated with the replacement of dozens of individual parts with a single casted piece, along with reduced demands on associated tooling and machinery. However, the data and literature to support these claims are limited and at times contradictory, with some studies showing increased costs and energy demands for mega-casting technologies. This study presents the results of a literature review and a gate-to-gate life cycle inventory (LCI) adapted from conventional HPDC aluminum casting unit processes that may be used to quantify potential life cycle global warming potential (GWP), cumulative energy demand (CED), and other environmental impacts of aluminum mega-castings. A set of cradle-to-gate example calculations is also provided to demonstrate the application of the inventory and significance of the findings, which point to significantly higher GWP and CED for aluminum mega-castings versus stamped steel parts and warrant further study to inform vehicle design decision makers.

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Introduction

The life cycle environmental impacts of vehicles have been studied for decades, with analyses most recently focusing on vehicle lightweighting and electrification to reduce the impacts associated with use phase or vehicle driving cycle. Prior studies [1, 2] have shown that material substitution to reduce vehicle mass and fuel consumption during the use phase can increase the emissions of vehicles, highlighting the importance of a full life cycle perspective for vehicle design decisions and automotive policies. In conventional automotive body shops, most components are manufactured from steel using deep-drawing and forming processes. Only small components, such as suspension struts, are currently made of aluminum castings. Over the last few years, there has been an uptick in the exploration and implementation of aluminum high-pressure die casting (HPDC) mega-castings as replacements for conventional stamped steel parts in vehicles. This trend is expected to increase, with one forecast suggesting mega-castings could account for 15% to 20% of traditional body-in-white (BIW) stampings in 2030 [3].

Justifications for the use of these mega-castings typically include claims of reduced costs and lower environmental impacts associated with the replacement of dozens of individual parts with a single, casted piece, along with reduced demands on associated tooling and machinery [4]. However, the data and literature to justify these claims are limited and at times contradictory. This study aims to summarize the latest research, data, and insights from subject matter experts and present an adapted life cycle inventory (LCI) for aluminum HPDC mega-castings. This LCI is presented along with recommendations to enable the quantification of life cycle greenhouse gas (GHG) emissions and energy demand (total and fossil) associated with the use of new aluminum HPDC mega-casting technologies in place of stamped steel in automotive life cycle assessment (LCA) tools and studies. One potential application of these data is in a future iteration of the WorldAutoSteel/University of California Santa Barbara Automotive Energy and Greenhouse Gas Model (UCSB Model), commissioned by WorldAutoSteel [5], which is a publicly available, cradle-to-grave vehicle LCA model that allows users to evaluate the differences in GHG emissions and energy demand between alternative material vehicle designs of equivalent size, utility, equipment, and powertrain configuration. The UCSB Model methodology has been critically reviewed for conformance with ISO 14044:2006.

Literature Review

Aluminum HPDC Mega-Castings Process vs. Conventional Technologies

Aluminum die casting has been used in automotive applications historically for box-type parts, such as engine blocks and gearboxes, with limited structural casted aluminum parts used mainly as shock towers in sports vehicles and vehicles in the upper mid-range and luxury class segments. The aluminum HPDC process entails receiving primary aluminum alloys, typically as ingots, melting the metal, casting it into the desired shape using high-pressure clamping machines with customized die molds, trimming excess aluminum, inspecting the casted part, and post-processing surface treatment, cutting, cleaning, and final inspection [4, 6]. Scrap generated during the processes downstream of melting is typically collected and returned to the melt furnace. The process overview is shown in Figure 1. Mass flows are calculated based on an example 150-kg mega-casted part (e.g., a single underbody) with forming yields based on data presented herein.

The process of producing a stamped steel part as incorporated into the UCSB Automotive Energy and GHG Model is simpler [5]. Steel slabs from integrated blast furnace and basic oxygen furnace (BF-BOF) and electric arc furnace (EAF) steel mill sources are converted into hot-rolled and hot-dip galvanized steel coils. These coils are stamped into parts creating "prompt scrap", which is modeled in the UCSB Model using a forming yield for the stamping process, scrap collection rate, and recovery rate. Steel scrap is collected and returned to steel mills via long-established material recovery and recycling streams for remelting into new steel products. Stamped steel parts are then assembled into vehicles via handling and welding process steps followed by painting. The steel process overview is shown in Figure 2. In the aluminum HPDC process, scrap is generated at the trimming, inspection, and post-processing stages. These flows are analogous to home scrap in steelmaking, since they are all generated pre-consumer and downstream of material production.

One key difference between aluminum mega-castings and the conventional aluminum HPDC process is the vast increase in scale. Conventional HPDC technology is represented by die casting machines with a locking force of up to 4500 tons, with a general agreement in the literature that mega-castings (also called "giga-castings") are defined by HPDC machines with a locking force of over 5000 tons

FIGURE 1 Process flow diagram for aluminum HPDC mega-casting.

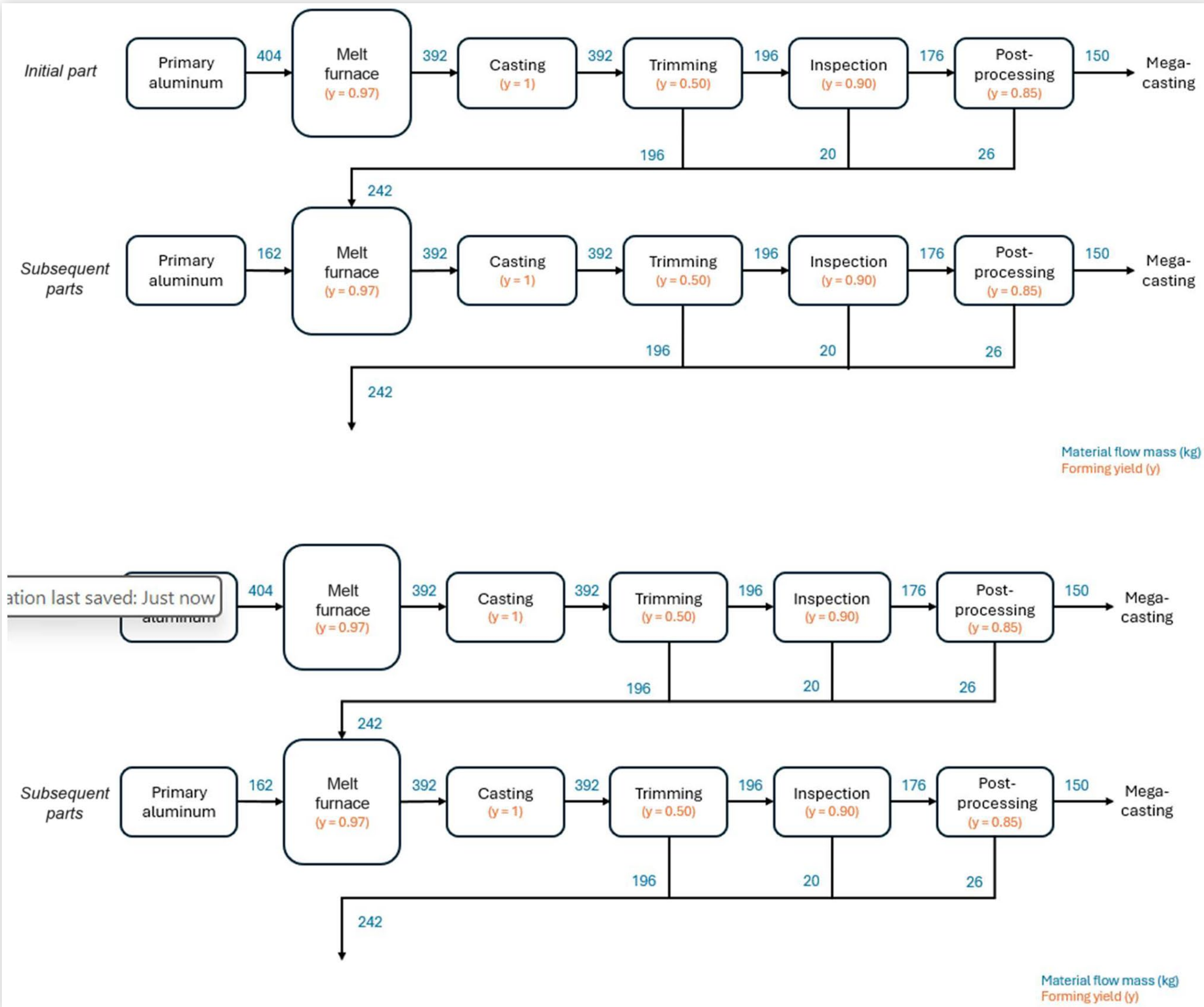
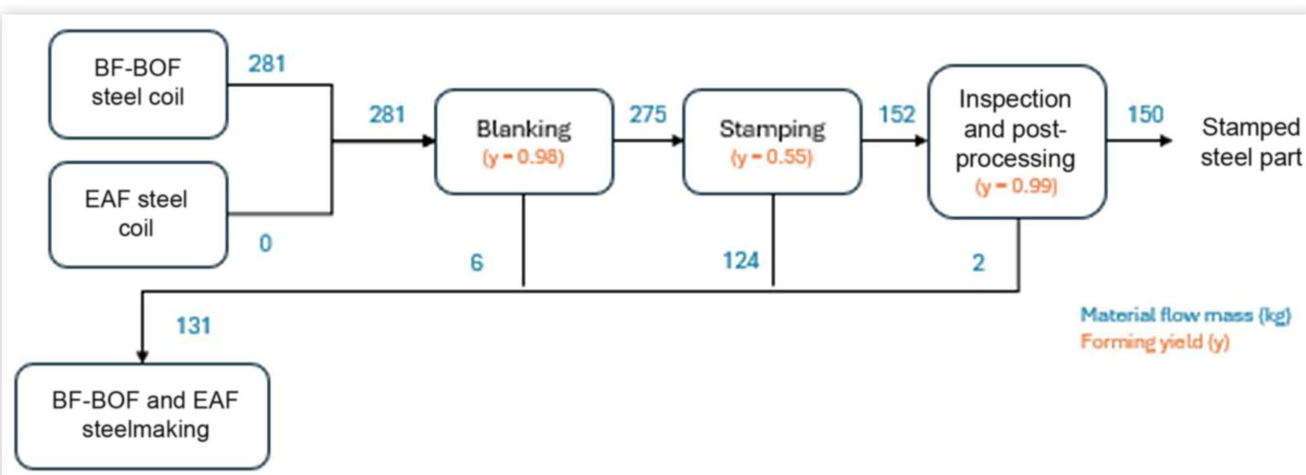


FIGURE 2 Process flow diagram for stamped steel part.



[4, 7]. Die casting machines with a locking force of roughly 6000 tons are necessary for mega-castings of a front or rear part, with estimates of 18,000 tons of locking force needed for casting a complete underbody [4]. The largest existing die casting machine in 2024 was developed by *LK* with a locking force of 16,000 ton [4]; however, new machines with a locking force of over 20,000 tons are in development [8]. Burgraff et al. [4] illustrated how the die casting machine's locking force increases as the casted part size and complexity in die casting/mold making increases while the number of parts decreases.

Cost Estimates

Given the HPDC mega-casting technology is relatively new, there is limited publicly available data on comprehensive cost implications. Literature is conflicting with some publications noting overall cost savings due to the improved efficiency of the casting process, reduced length of the assembly line and fewer welds, and elimination of processes related to the production, shipping, and assembling of replaced parts [9, 10]. On the other hand, studies note the massive capital equipment and space requirements, frequency and machinery demands of tool changes, high scrap rates, and raw material requirements as negative cost factors [4, 11]. Multiple sources indicate that the mega-casting technology will only be financially viable given high production volumes in greenfield (new site) applications when depreciation of existing capital equipment is considered.

S&P Global Mobility reported on a study of costs for steel stamping and joining, aluminum stamping and joining, and aluminum mega-casting in 2023 [3]. The findings are presented in Table 1, which shows that stamped steel is significantly lower in both investment and variable costs compared to aluminum sheet and mega-casting alternatives. It is recommended to revisit these data points for updates periodically as new information becomes available.

Repairability is also a significant cost concern. It will take time for vehicles with mega-casted parts to be driven long enough for data points to emerge; however, some sources note that casted components are unable to be straightened or replaced, so bending or cracking would result in a total loss of the vehicle [4, 8, 12].

Method

The mega-casting process results in casted aluminum structural parts used in vehicles. As the parts may have varying configurations and may be used in vehicles with various engine types, driving conditions, and other regional considerations for use and end-of-life stages, this study has a primarily gate-to-gate system boundary. The study results are expressed as a declared unit (1 kg mega-casted part) and are intended to be used as an input to future automotive LCA studies designed around a functional unit with more complete system boundaries per ISO 14040:2006 and 14044:2006 requirements. The system boundaries are expanded to cradle-to-gate by the inclusion of upstream raw material inputs to demonstrate the significance of the findings.

This study included three phases: (1) literature research, (2) subject matter expert interviews, and (3) synthesis, gate-to-gate LCI development, and recommendations. During the initial phase, searching of available public literature, including journal articles, equipment

TABLE 1 Manufacturing differences for a rear underbody.

		Steel stamping and joining		Aluminum stamping and joining		Aluminum mega-casting	
Category	Subcategory	Min	Max	Min	Max	Min	Max
Production efficiency	Yield	97%		92%		85%	
	Doable jobs per hour	24.4		25.7		27.8	
Investment costs (million USD)	Stamping machine	1.0	1.5	1.4	1.8		
	Stamping tooling	0.7	1.1	1.0	1.3		
	Joining line	0.6	0.8	1.2	1.6		
	HPDC machine					6.0	6.0
	HPDC tooling					1.2	1.5
	Stamping machine	1.0	1.5	1.4	1.8		
Variable costs (USD)	Labor costs	28.3		31	37	11	23
	Indirect costs	47.2		42	52	9	14
	Raw material	75.6		264	377	151	226
Total investment cost (million USD)		2.3	3.4	3.6	4.7	7.2	7.5
Total variable costs (USD)		151		337	466	171	263

Note: Based on producing 100,000 units/year, operating 16 h/day, 22 days/month, for 12 months. The production efficiency yields are inputs to the source study cost model and may not align with the specific or overall process yields used elsewhere in this study.
Source: Data taken from S&P Global Mobility, 2023 [3].

manufacture literature, and other public sources, was conducted using key search terms, such as "alumin(i)um mega-casting" or "alumin(i)um giga-casting" or "high pressure die cast" or "steel stamping auto" or "vehicle assembly" + "life cycle assessment" or "life cycle" or "greenhouse gas" or "energy consumption" or "MJ" or "scrap" or "yield" or "material efficiency" or "cost." Resultant sources were reviewed, and relevant data points were logged and summarized. The literature study and industry knowledge informed the identification of both potential interviewees and interview questions for subject matter experts. Interviews were conducted in March and April 2025 by three experts associated with research institutions in Germany and the USA.

Information gathered during the literature research and expert interview phases was synthesized to develop a gate-to-gate LCI for aluminum HPDC mega-castings. The LCI was applied in a set of example cradle-to-gate calculations to demonstrate the application of the inventory and significance of the findings and to form the basis of recommendations for future work.

Findings

Forming Yield and Scrap Rates

Detailed data on the mega-casting process are currently limited. The approach taken in this study was to estimate forming yields and scrap rates by process steps, conservatively based on literature specific to conventional structural aluminum HPDC processes. The following rates have been included:

1. Melting forming yield (%)
2. Trimming scrap (%)
3. Inspection scrap (%)
4. Post-processing and final inspection scrap (%)

Scrap rates are a measure of the proportion of material input to a process that becomes scrap. The forming yield, on the other hand, represents the material efficiency of a process by quantifying the mass of material lost during processing. For the melting of aluminum ingots, two studies included data points for material loss ranging from 2.0% [13] to 3.2% [6]. The forming yield itself indicates the percent of material input to a process that becomes the output of the process, i.e., 1−[process scrap rate %].

Publications specific to conventional aluminum HPDC technologies [6, 13, 14] indicate that the rate of scrap generation due to trimming post-casting is 45%–50%, with the aluminum scrap returned for remelting. To account for the additional material that becomes scrap, aluminum inputs must be increased by 1.45–1.5 times the final part weight, plus 3% to account for melting loss [6]. After the mega-casting process is optimized, the additional material is circulated within the facility. This is analogous to internal scrap within a steel facility and is not considered secondary material or recycled content.

Two other scrap rates of relevance are post-processing scrap generated during surface treatment and other steps downstream of the casting process, and inspection scrap (also called the rejection rate). In literature references to scrap rates, there is a lack of clarity regarding which specific process is generating the scrap. For example, one study cites a "10% scrap rate" that creates a material input flow within the mega-casting facility, which can reduce the quantity of primary aluminum inputs [4]. Another publication indicates that the scrap rate for mega-castings remains high at "2-digit percentage of rejection rate for components" [7]. Publications specific to conventional aluminum HPDC technologies [6, 13, 14] indicate rates ranging from 5% to 26% for post-processing scrap and 3% to 21% for inspection scrap.

One of the goals of this study is to develop data that can be used in the future versions of the UCSB Model. UCSB Model calculations are based upon the forming yield for material processing. Therefore, scrap rates from the literature were converted to forming yields (forming yield % = 1−scrap rate %). Table 2 lists the forming yield for each process calculated from the literature, along with the selected value for each process step. While the scrap rates associated with conventional HPDC may not be fully representative for mega-casting processes, there is indication that they can be considered conservative. According to subject matter experts interviewed as part of this

TABLE 2 Recommended forming yields for mega-casting process steps.

Process step	Tharumarajah (2009)	Zeng et al. (2014)	Liu et al. (2021)	Selected value
Melting	—	98.0%	96.8%	96.8% (Liu study closer to mega-casting process)
Trimming	55.0%	50.5%	45.0%	50% (average value, indications of increase in scrap rate with larger castings)
Inspection	97%	79%	93%	90% (average value, indications of increase in scrap rate with larger castings)
Post-processing and final inspection	86.8%	73.9%	93%	85% (average value, indications of increase in scrap rate with larger castings) 4%–5% of the scrap generated during post-processing steps is treated as a waste or externally recycled

research [8, 15] and during a prior study by the University of Siegen [4], scrap rates in die casting are expected to increase with the complexity of the process; they are expected to be higher for large mega-casted components compared to conventional HPDC parts and are anticipated to be higher than scrap rates associated with today's sheet metal processes.

Establishing the Life Cycle Inventory for Aluminum Mega-Castings

In order to quantify cradle-to-gate global warming potential (GWP-100) in kg CO_2eq/kg mega-casting and cumulative energy demand (total and fossil) in MJ/kg mega-casting, a gate-to-gate LCI for the mega-casting process must be established with a consideration of the type and quantity of the aluminum raw material supply. GHG emissions and energy demand of aluminum mega-castings are largely dependent upon the sourcing location of the aluminum ingot supply, scrap rates, energy demands, and electricity grid mix of the mega-casting process. These metrics are included for each unit process building upon the forming yields presented in Table 2. Tooling and maintenance requirements have been excluded from the study scope due to data limitations, though the inclusion of these potentially significant aspects is recommended for future consideration.

Raw Materials—Aluminum Input

Structural aluminum HPDC castings and mega-castings require aluminum alloys that meet specific criteria, including long flow lengths within the die molds, and currently require the use of primary aluminum input. Some HPDC equipment manufacturers and automotive original equipment manufacturers (OEMs) claim that up to half of the aluminum input can be "secondary alloy," which is expected to greatly reduce the life cycle energy demand and GHG emissions of mega-castings [7, 16]. While recycled or secondary aluminum is technically possible, it is not feasible at present due to the precise physical property requirements, along with the supply of clean post-consumer aluminum being highly limited [15]. Specific aluminum alloys are used for mega-castings that have physical properties suitable for the die casting process and allow the material to be used without heat treatment. The use of heat treatment improves physical properties and enables thinner castings; however, it is not feasible for mega-castings due to their size and shape complexity [4, 8, 17]. While thicknesses of 0.7 mm are typical for sheet metal parts, mega-castings have a minimum thickness of 2–3 mm, calling into question the capability of mass reduction for vehicle designs that utilize mega-castings [4, 11, 12]. Literature indicates that aluminum alloys used in mega-castings contain a silicon content of 6%–7%, along with smaller amounts of magnesium for strength, manganese to minimize die soldering, and also vanadium, copper, and low levels of iron (under 0.25%) [4, 9].

Aluminum HPDC mega-castings are currently produced only in select geographies, including the USA, Europe, and China. The International Aluminum Institute published primary aluminum production data for 2019, accounting for the geographic specificity of the production supply chain, including data for China, Europe, and a global average [18]. The Aluminum Association published primary aluminum production data for the North American region, with the latest available representing production in 2016 [19]. These data points are summarized in Table 3. This study presents LCIs for mega-castings produced in the USA and China.

HPDC Melting, Casting, and Post-Processing

The HPDC mega-casting process is characterized by three main process steps:

1. Melting—melting of the aluminum ingots, dross removal, degassing, and pollutant treatment
2. Casting—holding, pouring, solidifying, unloading, cooling, trimming, and inspection and
3. Post-processing—surface treatment, cutting, cleaning, and final inspection

TABLE 3 Primary aluminum GWP and CED.

Region	CED, total (MJ/kg)	CED, fossil (MJ/kg)	GWP-100 (kg CO_2eq/kg)	Source
China	183	171	20.3	IAI, 2022 (GWP) [17] R&D GREET 2, 2025 (CED) [20]
Europe	104	53	7.4	IAI, 2022 (GWP) R&D GREET 2, 2025 (CED)
USA	123	74	7.9	R&D GREET 2, 2025
North America	136	NR	8.5	Aluminum Association, 2022 [18]
Global average	NR	NR	16.8	IAI, 2022

NR = not reported.

LCI inputs and outputs for each unit process step were adapted from the study of Liu et al. 2021 [6] conducted by Zhejiang University, the University of Tokyo, and the University of Cambridge, which presents detailed LCI data along with GWP and cumulative energy demand (CED) results for the conventional aluminum HPDC process using a nearly 4500-ton die casting machine to produce structural automotive parts. In the study of Liu et al. 2021, LCI was derived from a field investigation of 13 companies, including four HPDC factories, two aluminum melting and holding furnace manufacturers, two die cast machine manufacturers, two die makers, one heat treatment equipment manufacturer, one vacuum equipment manufacturer, and one semisolid feedstock equipment manufacturer during an unspecified time period. Conventional aluminum HPDC processes also include heat treatment with solution annealing, quenching, and pollutant treatment [6]; however, as described previously, specific aluminum alloys are used in mega-castings that avoid the need for heat treatment. Therefore, the heat treatment process has been excluded from the recommended inventory. Unit process energy inputs and CO_2 emissions were assumed to scale linearly, and the melting yield and scrap rates from Table 2 were used to calculate the aluminum inputs required by each process step. Table 4 presents the unit process for each mega-casting step. Each unit process step shows the required amount of aluminum input, energy consumption by type, and CO_2 emissions per output of the unit process.

The primary contributor to energy demand and GWP for the gate-to-gate mega-casting process is electricity consumption, which can vary significantly by region. When applying the LCI, it is recommended that the location of the HPDC mega-casting process be specified and linked to geographically representative electricity grid factors. Table 5 shows two examples of gate-to-gate results for HPDC mega-casting processes located in China and the USA using national average grid mixes and natural gas GWP and CED from R&D GREET 1, 2025 [20]. The total impacts account for the yield of each process and subsequent process steps. Table 6 shows the cradle-to-gate results by pairing the gate-to-gate results from Table 5 with raw material supply impacts from Table 3.

Significance of Findings

The magnitude of impact can be considered significant when it was benchmarked against a stamped steel part of the same weight, 150 kg for example. As discussed herein, literature indicates that there may be no mass savings for comparable vehicle designs using HPDC mega-casted parts versus conventional stamped steel parts. Using data from the UCSB Model for steel

TABLE 4 Mega-casting unit processes.

Process step	Flow name	Inventory value	Units	CED, total (MJ/kg)	CED, fossil (MJ/kg)	GWP-100 (kg CO_2eq/kg)
Melting	Input—Al ingots	1.03	kg			
	Electricity	0.0594	MJ/kg	*	*	*
	Natural gas**	3.15	MJ/kg	3.43	3.43	0.031
	CO_2 emissions	0.175	kg/kg			0.175
	Output—molten Al	1.0	kg			
Casting and trimming	Input—molten Al	1.99	kg			
	Electricity	1.91	MJ/kg	*	*	*
	Natural gas**	0.434	MJ/kg	0.47	0.47	0.0043
	CO_2 emissions	0.0241	kg/kg			0.024
	Output—casted Al semiproduct	1.0	kg			
Inspection	Input—casted Al semiproduct	1.12	kg			
	Output—accepted casted Al	1.0	kg			
Post-processing and final inspection	Input—casted Al	1.18	kg			
	Electricity	1.71	MJ/kg	*	*	*
	Output—finished Al casting	1.0	kg			
Total aluminum demand		2.72	kg			
Recirculated aluminum scrap		1.63	kg			

Notes: Aluminum input and output mass flows are based on the material yields in Table 2.
Source: The energy and CO_2 emissions inventory values for each unit process were sourced from Liu et al. 2021 [6].
* Region-specific; the quantity in MJ should be multiplied by CED and GWP factors for the region of electricity consumption, such as those included in the R&D GREET 1, 2025 [20].
** CED and GWP factors were sourced from R&D GREET 1, 2025 [20].

TABLE 5 Mega-casting gate-to-gate process example results.

Process step	Flow name	China (average grid) CED, tot. (MJ/kg)	China (average grid) CED, fos. (MJ/kg)	China (average grid) GWP-100 (kg CO_2eq/kg)	USA (average grid) CED, tot. (MJ/kg)	USA (average grid) CED, fos. (MJ/kg)	USA (average grid) GWP-100 (kg CO_2eq/kg)
Melting	Electricity	0.145	0.118	0.0115	0.118	0.0908	0.00655
	Natural gas	3.43	3.43	0.0313	3.43	3.43	0.0313
	CO_2 emissions	—	—	0.175	—	—	0.175
	Total—melting unit process	3.57	3.54	0.218	3.55	3.52	0.213
Casting and inspection	Electricity	4.65	3.79	0.371	3.80	2.92	0.211
	Natural gas	0.472	0.472	0.00431	0.472	0.472	0.00431
	CO_2 emissions	—	—	0.024	—	—	0.024
	Total—casting unit process	5.13	4.26	0.399	4.27	3.39	0.239
Post-processing and final inspection	Electricity	4.16	3.39	0.331	3.39	2.61	0.188
	Total—finishing unit process	4.16	3.39	0.331	3.39	2.61	0.188
Total process impact accounting for forming yields		21.1	18.9	1.49	19.0	16.8	1.10

Note: Total process impact values are the sum of each process step multiplied by the material demand for each process and subsequent processes as shown in Table 4. For example, the melting process contribution to the total is melting total × 1.99 × 1.12 × 1.18.

TABLE 6 Mega-casting cradle-to-gate process example results.

Process step	China (average grid) CED, tot. (MJ/kg)	China (average grid) CED, fos. (MJ/kg)	China (average grid) GWP-100 (kg CO_2eq/kg)	USA (average grid) CED, tot. (MJ/kg)	USA (average grid) CED, fos. (MJ/kg)	USA (average grid) GWP-100 (kg CO_2eq/kg)
Material impact	199	186	22.1	134	81.2	8.6
Process impact	21.1	18.9	1.5	19.0	16.8	1.1
Total	220	205	23.5	153	98.0	9.7

Note: Material impact values were sourced from Table 3, and process impacts were from Table 5.

production as shown in Table 7, which is derived from the World Steel Association 2024 data release, for a global average stamped steel part conservatively assuming all BF-BOF steel production, along with data from GREET 2025 [20] for stamping (0.842 mmBTU electricity/ton steel), a mega-casted aluminum part could be approximately 100%–380% higher in GWP and 150%–260% higher in total energy consumption than an average stamped steel solution, as shown in Table 8.

TABLE 7 Steel production GWP and CED assumptions.

	CED, tot. (MJ/kg)	CED, fos. (MJ/kg)	GWP-100 (kg CO_2eq/kg)	Source
Steel, BF-BOF slab	23.7	22.9	2.13	UCSB Model v5.1 [5]
Steel HDG	8.89	7.78	0.460	UCSB Model v5.1
Steel HRC	3.13	2.90	0.160	UCSB Model v5.1
Share of HRC		25%		UCSB Model v5.1
Steel sheet input total	31.2	29.4	2.5	Calculated

These findings are specific to mass-equivalent substitutions, which may not reflect optimized vehicle designs and are based on current scrap rates, raw material supply chains, and electricity grid mixes. They directionally show that a significant increase in production impacts paired with limited or no use phase savings may result in substantive life cycle impacts if the aluminum mega-casting technology uptake expands, indicating further study is needed. End-of-life considerations, such as recovery and recycling rates, should also be considered when a sufficient number of vehicles using mega-castings reach their effective end of life.

Conclusions and Recommendations

This article summarizes research findings on the topic of life cycle energy demand and GWP for aluminum HPDC mega-castings. The use of mega-casting technology is relatively new, so limited data are available to fully assess the technology. Until primary data for the mega-casting process can be collected and analyzed, the adapted

TABLE 8 Stamped steel part GWP and CED results.

	China (average grid)			USA (average grid)		
Process step	CED, tot. (MJ/kg)	CED, fos. (MJ/kg)	GWP-100 (kg CO_2eq/kg)	CED, tot. (MJ/kg)	CED, fos. (MJ/kg)	GWP-100 (kg CO_2eq/kg)
Material impact	59.0	55.7	4.8	59.0	55.7	4.8
Process impact	2.38	1.94	0.19	1.95	1.50	0.11
Total	61.4	57.7	5.0	60.9	57.2	4.87

inventory presented herein may be used for assessing potential environmental impacts and making informed decisions regarding adoption of the technology.

The research presented herein indicates directional learnings that mega-castings may not compare favorably to conventional sheet steel-intensive vehicle designs on the basis of cradle-to-gate GWP, energy demand, and, potentially, cost. During the production phase, mega-casted parts require 100% primary aluminum input to meet strict physical property requirements and have high energy demands and low forming yields for the melting and casting process. Furthermore, the resulting parts have not clearly demonstrated mass reduction in vehicle designs compared to steel-intensive designs, thereby negating the use phase benefits of vehicle lightweighting. This implies that the learnings may extend throughout the vehicle life cycle. While aluminum scrap generated during the mega-casting process steps is typically returned as an input to the melting process on-site, it must be remelted and cast again, subjecting it to the energy demands of those process steps.

The results of this study rely on publicly available data and an LCI adapted from conventional HPDC processes. The unit process inventory was assumed to scale linearly and was paired with conservative scrap rates. Primary data on the HPDC mega-casting process should be collected in the future as the use of mega-castings increases. If energy demands or scrap rates increase as HPDC processes are scaled, the associated GWP, energy demands, and costs will be higher than those estimated herein. Conversely, if energy demands or scrap rates decrease as the process is scaled, the associated impacts will be lower than the findings of this study. It is recommended that future LCAs applying these data conduct sensitivity analyses on both process energy demands and scrap rates.

Another recommendation for future LCAs of the potential GWP and energy demand of mega-castings is to also assess the impacts of die manufacturing and tooling. Mega-casting dies require large cranes for replacement and must be replaced after 100,000–150,000 uses compared to 6 million or more uses for a conventional sheet steel stamping die. Capital equipment considerations are also important when evaluating the costs of the two technologies, with indications that mega-casting technologies have higher costs to install and maintain than conventional steel stamping technologies and may only be cost competitive in greenfield applications. Repairability is also noted in the literature and by subject matter experts as a significant concern from the full vehicle life cycle cost perspective, with early indications that vehicles with mega-casted parts may be less repairable and totaled at a higher rate than steel-intensive vehicles.

These findings may collectively be relevant for vehicle manufacturers, especially those with corporate GHG reduction targets inclusive of scopes 1–3, who may be assessing the expanded use of the HPDC mega-casting process. The study results may also be relevant to external stakeholders, like policymakers who are establishing automotive environmental policies. The potential environmental impacts of the mega-casting process should be considered alongside capital and operational costs, raw material supply, and other factors for a holistic decision-making process that includes potential trade-offs. The data presented in this paper should be incorporated into a comparative LCA study that conforms with ISO 14040 and 14044 requirements to assess of the cradle-to-grave life cycle potential environmental impacts of the competing technologies for the development of comparative claims and informed decision making.

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Declaration of AI-Assisted Technologies

The authors declare that no generative AI technologies were used in the preparation and writing of this article. In doing so, the authors take full responsibility for the authenticity and scientific integrity of this article.

Contact Information

Russ Balzer, corresponding author
Technical Director, WorldAutoSteel
russbalzer@worldautosteel.org

Nomenclature/Definitions/ Abbreviations

BF-BOF - blast furnace and basic oxygen furnace
CED - cumulative energy demand
EAF - electric arc furnace
GWP - global warming potential
HPDC - high-pressure die casting
LCA - life cycle assessment
LCI - life cycle inventory

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