Quantifying Value Chain Emissions: A Case Study at GKN Aerospace

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Abstract: Growing concerns over environmental degradation and global warming have compelled companies worldwide to take an active role in mitigating climate change. To develop effective climate change mitigation strategies, organizations must first assess their value chain emissions. The Greenhouse Gas (GHG) Protocol, developed by the World Resources Institute (WRI) and the World Business Council for Sustainable Development (WBCSD), provides a standardized framework for quantifying such emissions. It categorizes them into three scopes: direct emissions (Scope 1), indirect energy-related emissions (Scope 2), and other indirect value chain emissions (Scope 3). Scope 3 emissions often account for more than 75% of a company's total footprint, and in manufacturing sectors such as aerospace they can exceed 90%, highlighting the need to prioritize Scope 3 in target setting and mitigation actions. This study focuses on quantifying Scope 3 Category 1 emissions, or *Purchased Goods and Services* (PG&S), within the aerospace sector using GKN Aerospace as a case study. These emissions arise from procured raw materials, components, and outsourced processes, many of which are energy-intensive. Two estimation methods were compared across 2022–2023 procurement data: mass-based and spend-based approaches. The results show that the spend-based approach tends to overestimate emissions by approximately a factor of three compared with the mass-based method. For 2023, mass-based accounting estimated Category 1 emissions at 0.012 Mt CO_2eq for the focal site, with titanium and nickel alloys dominating the footprint, while process-level analysis identified forging as the principal emitter. To explore mitigation potential, scenario analyses were developed drawing on prior life cycle assessment (LCA) evidence comparing conventional manufacturing with additive manufacturing (AM). Based on realistic adoption projections, expert input, and internal roadmaps, the study estimates that approximately 22% of relevant production could transition to AM by 2035 at GKN Aerospace, resulting in an ~18% reduction in site-level PG&S emissions relative to a non-AM scenario. This quantification of value chain emissions provides a data-driven decarbonization pathway for the aerospace sector centered on materials, processes, and the deployment of AM technologies.

1. Introduction and Motivation

Human-induced greenhouse gas (GHG) emissions are the primary driver of the rapid warming observed in recent decades (IPCC, 2021). Limiting global warming to below 2 °C with a >67 % probability requires achieving net-zero CO_2 emissions by the early-to-mid 2070s under cost-effective pathways (IPCC, 2022). However, current global climate policies, despite the commitments made under the Paris Agreement, are projected to lead to a median temperature rise of about 2.8 °C above pre-industrial levels by the end of the 21st century (UNEP, 2025). In the near term, the World Meteorological Organization forecasts an 86 % probability that at least one year between 2025 and 2029 will temporarily exceed 1.5 °C above the 1850–1900 baseline (WMO, 2025). Taken together, these findings underscore the growing urgency for more ambitious and accelerated climate-mitigation efforts. Escalating climate risks, combined with heightened regulatory and stakeholder expectations, have intensified the focus on corporate transparency and accountability in emissions reporting. Central to corporate climate-reporting efforts is the GHG Protocol, developed by the World Resources Institute (WRI) and the World Business Council for Sustainable Development (WBCSD). This widely adopted framework categorises emissions into three scopes: Scope 1 (direct), Scope 2 (indirect, energy-related), and Scope 3 (value-chain) (Barrow et al., 2013). Among the three scopes, Scope 3 typically represents the largest share of a company’s carbon footprint (TCFD, 2021). Scope 3 includes fifteen categories, covering everything from upstream purchased materials to downstream product use and end-of-life.

For aerospace OEMs, the most material category depends on product mission profiles: use-phase emissions (Category 11) dominate for commercial aviation (EASA, 2019), whereas in manufacturing-intensive sectors, upstream emissions from purchased goods and services (Category 1) account for the largest share. Category 1 encompasses all upstream (cradle-to-gate) emissions associated with the goods and services a company purchases, including extraction, processing, and transport of raw materials and manufactured components. Recent studies highlight the growing importance of carbon accounting under emerging mandatory disclosure regimes (Amel-Zadeh & Tang, 2025). In the EU, regulatory frameworks such as the Corporate Sustainability Reporting Directive (CSRD) and the European Sustainability Reporting Standards (ESRS) now mandate disclosure of all three scopes, while in the USA, companies registered with the Securities and Exchange Commission (SEC) face comparable reporting requirements. Despite this regulatory momentum, reporting gaps persist. Many firms continue to provide incomplete or inconsistent Scope 3 disclosures, indicating that transparency and accountability, while improving, remain uneven (Traub et al., 2025). These gaps underscore the need for firms to measure and report emissions accurately to guide effective mitigation strategies (Delmas et al., 2025; Traub et al., 2025).

Against this backdrop, the present study focuses on estimating Scope 3 emissions from Category 1 Purchased Goods and Services (PG&S) within the aerospace sector. It compares mass-based and spend-based methodologies to identify the most accurate approach for quantifying the climate impact of PG&S. The study also examines how detailed emissions data can inform corporate sustainability strategies and explores the potential influence of emerging technologies such as Additive Manufacturing (AM) on future emission profiles. For clarity and focus, the investigation is confined to procurement data for civil engine components at GKN Aerospace Engine Systems' Trollhättan facility in Sweden, deliberately excluding defence-related data and other emission categories due to confidentiality and legal constraints. This research poses several critical questions. How do mass-based and spend-based methods compare in assessing the climate impact of PG&S in the aerospace sector? In what ways can companies leverage Scope 3 Category 1 emissions data to enhance their sustainability strategies? And how might the adoption of AM technologies influence future PG&S emissions? Answering these questions will contribute valuable academic insights and practical guidelines for companies striving to achieve robust climate action and long-term sustainability.

The paper is structured as follows. Section 2 provides a review of related work. Section 3 presents the research design and methodology. Section 4 provides results based on the GKN Aerospace case study. Section 5 provides discussion and conclusion and future research directions.

2. Review of Related Work

Multiple methodological approaches have been developed to estimate Scope 3 emissions. Mass-based (activity-based) methods estimate emissions by multiplying physical flows, such as kilograms of purchased material, by emission factors, offering high fidelity when detailed activity data are available (Barrow et al., 2013). Spend-based (economic) approaches apply monetary emission factors to procurement expenses; while highly scalable, they can obscure variations in material carbon intensity and regional production practices (Barrow et al., 2013). Supplier-specific methods collect cradle-to-gate emissions directly from suppliers, providing granular product-level insights but remaining constrained by supplier capacity, data-sharing limitations, and verification requirements (IAEG, 2021). Hybrid methods integrate these data sources by leveraging supplier-specific data where available and supplementing gaps with mass- or spend-based proxies to produce more complete inventories (Stridsland, Stounbjerg & Sanderson, 2023). Life Cycle Assessment (LCA) and hybrid LCA approaches further capture emissions across material extraction, manufacturing, use, and end of life, reducing truncation errors and identifying the most carbon-intensive stages within a product’s life cycle (Kokare, Oliveira & Godina, 2023; Kokare et al., 2024).

These methodological choices are particularly salient in the aerospace sector, where upstream emissions from energy-intensive alloys and processes such as forging and casting commonly dominate Scope 3 footprints. Aerospace supply chains are highly fragmented and multi-tiered, leading many firms to initially default to spend-based estimation for Purchased Goods and Services (Category 1), despite inherent uncertainties (IAEG, 2021). Peer-reviewed studies highlight the potential of more refined approaches: hybrid inventories combining process data and input-output modelling can produce robust procurement emission profiles (Stridsland, Stounbjerg & Sanderson, 2023), while LCA studies of AM components demonstrate that material selection and manufacturing techniques substantially influence life-cycle carbon impacts (Kokare, Oliveira & Godina, 2023; Reis, Kokare, Oliveira & Godina, 2023).

More accurate Scope 3 accounting enables targeted mitigation. Hotspot analyses derived from LCA or hybrid methods can identify high-emitting materials or processes, thereby guiding investments in new technological solutions. AM techniques reduce material waste, improve buy-to-fly ratios, and exhibit lower embodied carbon than conventional subtractive methods (Torres-Carrillo et al., 2020; Gibson et al., 2020). Although implementing AM in aerospace requires qualification, capital investment, and supplier readiness, comparative life-cycle studies frequently demonstrate substantial reductions in Global Warming Potential for AM-produced components (Reis, Kokare, Oliveira & Godina, 2023; Kokare et al., 2024). Data-driven approaches, including the use of large language models applied to financial transaction data, further enhance spend-based inventories by inferring emissions where supplier data are incomplete (Jain et al., 2023).

A pragmatic pathway for aerospace companies is therefore to begin with scalable spend- or mass-based Scope 3 inventories to establish baseline visibility, gradually enrich the inventory with hybrid or supplier-specific data, and apply LCA-informed hotspot analyses to guide mitigation actions such as AM adoption, material substitution, and targeted supplier engagement. This staged approach balances measurement fidelity with operational feasibility and helps ensure that improved accounting translates into tangible emissions reductions.

3. Methodology

This study implements the GHG Protocol for estimating Scope 3 Category 1 emissions at GKN Aerospace. The implementation process involved a structured, multi-step approach, ensuring the accurate quantification of GHG emissions while enabling actionable insights for sustainability improvements.

3.1 Portfolio Analysis

The first step was a portfolio analysis of all PG&S categories within GKN Aerospace's operations to identify emission-intensive procurement areas and define data-collection boundaries. For 2023, the analysis covered three business segments—civil, engines, and defence—with 42 civil engine models representing nearly the full civil portfolio and including components supplied to major OEMs such as GE, PW, RR, and Safran (GKN Aerospace, 2024). Items were mapped by material type, component category, and manufacturing process, providing a detailed view of upstream emission sources. This structured categorisation aligns with prior work underscoring the value of transparent supply-chain segmentation for Scope 3 accounting (Schulman et al., 2021; Grekin, 2023).

3.2 CO_2 Emission Calculation Method

Based on the portfolio analysis, a decision tree was used to select the most suitable method for estimating Scope 3 emissions. The choice considered company strategy, the relative importance of different PG&S categories, and the availability and quality of procurement data. While GKN Aerospace maintains robust records of purchased quantities, Tier 1 suppliers often lacked complete emission data. Consequently, a mass-based method was adopted as the primary approach, using procurement mass (kg) and industry-average emission factors (EFs) for higher accuracy than spend-based estimates, which rely on price-driven financial proxies. A spend-based calculation was also performed for comparison, enabling identification of discrepancies and clarifying trade-offs between physically grounded and value-based estimations.

3.3 Data Collection and Emission Calculations

Data collection focused on assembling the activity data and emission factors needed to estimate CO_2 emissions from PG&S. Internal procurement systems provided 2022–2023 records on both mass (kg) and economic value ($), which were analysed by material to identify procurement trends. Secondary emission factors were sourced from the IAEG Aerospace Scope 3 Category 1 calculation tool, which aggregates data from EIO-LCA, the DoD database, the USEEIO model and Base IMPACT (Carnegie Mellon University, 2017; DENIX, 2017; U.S. EPA, 2020; ADEME, 2018). Using these inputs, emissions were calculated with both mass-based and spend-based methods, matching each procurement item to the most appropriate factor to ensure accurate Scope 3 quantification.

For mass-based emissions estimation, the following formula was applied:

$$\text{Mass based } CO_{2eq} \text{ emissions} = \sum \text{mass of PG\&S (kg)} \times \text{EF} \left(\frac{\text{kg CO2eq}}{\text{kg}}\right) \quad (1)$$

For spend-based emissions estimation, the following formula was applied:

$$\text{Spend based } CO_{2eq} \text{ emissions} = \sum \text{ Value of PG\&S (\$)} \times \text{EF} \left(\frac{\text{kg CO2eq}}{\$}\right) \quad (2)$$

3.4 Interpretation of Results and Improvement Actions

The final stage involved analysing the calculated emissions results to derive actionable insights for procurement and sustainability improvements at GKN Aerospace. The interpretation process focused on assessing emission contributions by material type, procurement category, and manufacturing process. Particular attention was given to high-intensity materials such as titanium and nickel, as well as to forging and casting operations, which together represented the dominant upstream emission sources. Insights from LCAs of AM-based components (Léonard, 2023, 2024) and qualitative findings from expert interviews were used to assess the feasibility and potential benefits of AM integration. Together, these analyses enabled a more comprehensive understanding of current emission hotspots and informed the subsequent scenario modelling of AM adoption within the company.

4. Results

4.1 CO₂ Emissions from Category 1 PG&S

More than 3,000 procurement records for civil aero-engine production were collected for 2022 and 2023 at GKN Aerospace's Trollhättan site. These entries fall under Scope 3 Category 1 and include components produced/sourced from multiple suppliers. The dataset contained key fields for emissions accounting, including Item ID, Item Description, Commodity, Invoice Quantity, Total Spend, Material Type, Net Weight (kg), and Total Weight (kg). A year-on-year comparison showed a 14.04% increase in total procured material mass and a 20.03% rise in overall expenditure, reflecting higher production activity and cost escalation. Material analysis confirmed continued reliance on titanium and nickel alloys, with significant volumes linked to forging, casting, and machining operations. Given their high embodied carbon intensities, these materials represented the dominant contributors to Scope 3 Category 1 emissions, highlighting the need for targeted material- and process-level mitigation strategies within the aerospace supply chain. Procurement by material type is summarised in Table 1.

Table 1 Procurement by Material Type (in Kg)

	2022				**2023**			
Method	Titanium	Nickel	Other Materials	Total (in Kg)	Titanium	Nickel	Other Materials	Total (in Kg)
Casting	80464	13412	0	93876	80976	9281	0	90257
Forging	221442	242161	28	463630	234547	292431	0	526979
Machining	12813	60650	24	73487	22336	52893	20	75249
Other	4233	28125	24754	57112	7255	57155	27786	92196
Total	318951	344348	24806	688105	345115	411761	27806	784681

Procurement items were categorized into three groups to ensure accurate emission estimation and the selection of appropriate emission factors (EFs): (i) assembly and structural components, (ii) manufactured components and materials, and (iii) raw materials. Each group was further classified into metallic and non-metallic categories based on material type and associated production processes. Every unique combination of group, category, material, and production method was assigned a corresponding EF, with the full set of factors listed in Table 2. For each procurement entry, total emissions were calculated by multiplying the item's total weight by its respective EF. Summing the emissions across all items provided the total CO_2 emissions from PG&S for 2022 and 2023.

Table 2 Emission Factors for Mass-based Method

Group	**Category**	**Material**	**Production method**	**Proxy EF**	**Value (kg CO_2eq / kg)**
Assembly and structural components	Metallic assembly and structural components	Nickel	Forging	Ni alloy + Forging	11.9570
		Nickel	Machining	Ni alloy + Machining	11.9268
		Nickel	Unspecified process	Processed Ni alloy	19.1148
		Stainless Steel	Unspecified process	Stainless Steel	0.1846
		Steel	Unspecified process	Steel	1.6953
		Titanium	Unspecified process	Ti	26.6541
Manufactured components and materials	Metallic manufactured components	Aluminium	Machining	Al + Machining	2.4844
		Aluminium	Unspecified process	Processed Al extrusion profile	3.7953
		Nickel	Casting	Ni alloy + Casting	12.5331
		Nickel	Forging	Ni alloy + Forging	11.9570
		Nickel	Machining	Ni alloy + Machining	11.9268
		Nickel	Unspecified process	Processed Ni alloy	19.1148
		Stainless Steel	Unspecified process	Stainless Steel	0.1846
		Steel	Unspecified process	Steel	1.6953
		Titanium	Casting	Ti + Casting	18.1992
		Titanium	Forging	Ti + Forging	17.6231
		Titanium	Machining	Ti + Machining	17.5929
		Titanium	Unspecified process	Ti	26.6541
	Non-metallic manufactured components	Carbon fiber, high strengths	General worldwide production	Carbon fiber (high strengths, long fibers)	42.0800
	Electrical and electronic equipment	Electrical cable	General worldwide production	Electrical cable	0.1568
Raw materials	Metallic raw materials	Aluminium	General, worldwide production	General worldwide production	13.0555
		Nickel	Production of class 1 nickel	Ni - production of class 1 Ni	7.6400
		Steel	Production of steel	Production of steel	1.2900
		Titanium	Unspecified process	Ti	17.6232
		Zinc	Production of zinc concentrate	Zn concentrate	0.4310

In contrast, the spend-based approach relies on a less detailed and more general categorization, reflecting the limited availability of expenditure-based EFs within the aerospace sector. The complete set of EFs utilized in the spend-based methodology is detailed in Table 3.

Table 3 Emission Factors for Spend-based Method

Group	**Category**	**Subcategory**	**Proxy EF**	**Value (kg CO_2eq / kUSD)**
Assembly and structural components	Metallic assembly and structural components	Other basic metals and casting	Other basic metals and casting	791.3108
Manufactured components and materials	Metallic manufactured components	Aircraft engines, engine parts and other propulsion systems, unknown material and mass	Aircraft Engines and Parts	144.2768
		Aluminium-based manufactured products, unknown mass	Al product manufacturing from purchased Al	361.8308
		Steel-based manufactured components, unknown mass	Steel product manufacturing from purchased steel	362.6513
	Non-metallic manufactured components	Composite-based manufactured products, unknown mass	Carbon fiber (high strengths, long fibers)	189.0550
		Glass-based manufactured products, unknown mass	Glass And Glass Products	655.9316
		Non-metal based aircraft engines, engine parts and other propulsion systems, unknown material and mass	Aircraft Engines and Parts	144.2768
	Electrical and electronic equipment	Other electronic equipment	Other electronic component manufacturing	86.9707
Raw materials	Metallic raw materials	Aluminum and aluminum alloys, unknown mass	Secondary smelting and alloying of Al	585.8213
		Iron, steel and ferro-alloys, unknown mass	Iron and steel mills and ferroalloy manufacturing	1.7215
		Metals, unknown material and mass	Al, cuivre, etc.	1359.6554
	Gases and chemicals	Basic inorganic chemicals	Other Basic Inorganic Chemicals	895.4487

Whereas the mass-based approach enables a more precise evaluation grounded in physical attributes, the spend-based approach provides a useful alternative for addressing data gaps despite its lower specificity. Table 4 presents a comparative analysis of emissions estimated using both approaches, highlighting a notable increase in total emissions from 2022 to 2023.

Table 4 Procurement Emission Analysis

Year	Mass-based Emissions Estimation (tCO_2eq)	Growth	Spend-based Emissions Estimation (tCO_2eq)	Growth
2022	10 060	14.7 %	31 968	19.7 %
2023	11 538		38 273	

The spend-based method yielded substantially higher emission estimates; approximately three times those estimated by the mass-based approach. This outcome is consistent with prior research identifying financial proxies as a common source of overestimation, driven by variability in supplier pricing and broader economic valuation effects (Grekin, 2023). The discrepancy highlights a key limitation of the spend-based approach, which bases emissions on monetary value rather than material-specific characteristics. In contrast, the mass-based method enables more granular classification through the use of process-, assembly-, and material-specific emission factors, resulting in more reliable estimates. Based on these findings, all subsequent analyses in this study are grounded in mass-based calculations.

4.1.1 CO_2 Emissions by Material Type

Figure 1 presents a material-wise breakdown of total procured mass and associated CO_2 emissions for 2023. The distribution shows that titanium and nickel dominate both the material inflow and the resulting emission profile. Titanium accounted for 44% of the total material weight yet contributed 54% of total emissions (6,179 tCO_2eq).

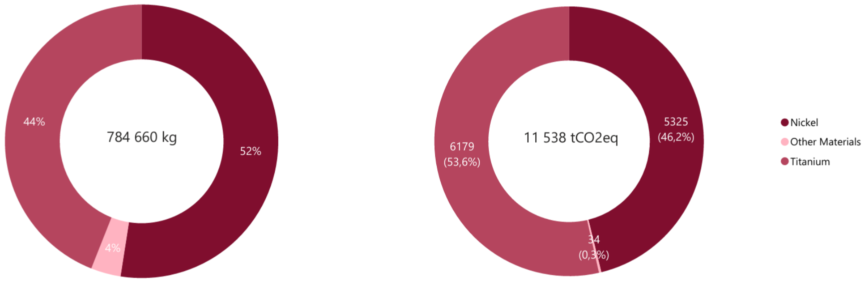

Figure 1Percentage of Weight (a) and CO_2 Emission in tCO_2eq (b) by Material Type in 2023

This disproportionate impact reflects titanium's highly energy-intensive extraction and processing stages, a pattern consistently emphasized in prior aerospace sustainability studies (Holzapfel et al., 2024). Nickel represented the largest share of total material mass at 52% and contributed 46% of emissions, indicating a comparatively lower emission intensity per kilogram. The remaining material categories constituted only 4% of total mass and less than 1% of total emissions. This finding highlights the need for targeted interventions in titanium and nickel procurement and processing, as well as the strategic evaluation of alternative materials and manufacturing technologies capable of reducing the upstream carbon footprint.

4.1.2 CO_2 Emissions by Manufacturing Process

Figure 2 illustrates the distribution of procured material weight and the corresponding CO_2 emissions across casting, forging, and other manufacturing processes for 2022 and 2023.

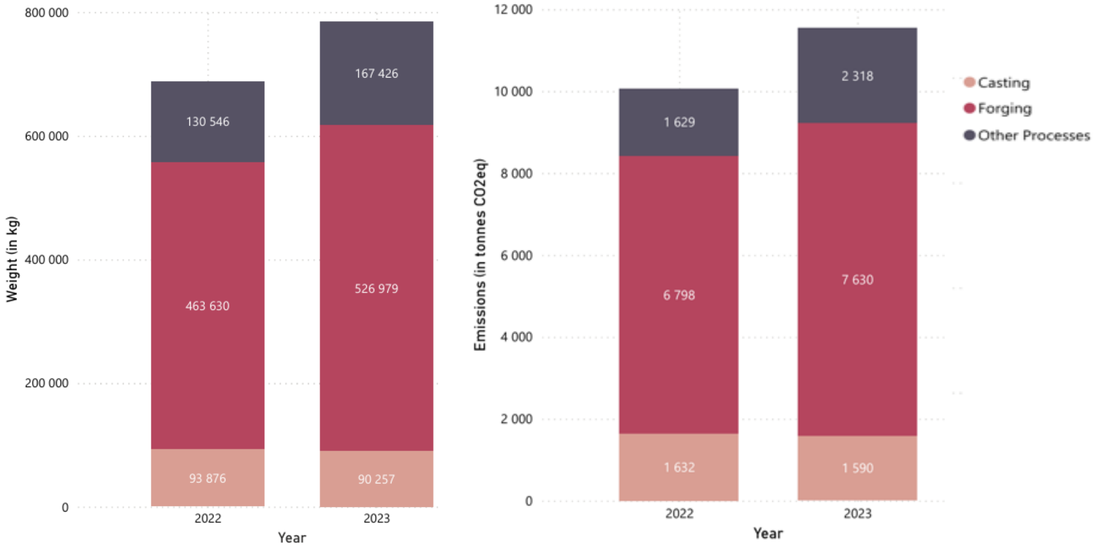

Figure 2 Weight in Kg (a) and CO_2 Emission in tCO_{2eq} (b) by process in 2022 & 2023

Across both years, forging consistently dominated total material weight, accounting for approximately 67%. This reflects the manufacturing profile of aero-engine components, where forged parts constitute a major share of structural and rotating hardware. A similar pattern emerges in the emissions distribution as forging contributed the largest proportion of CO_2 emissions; 67.6% in 2022 and 66.1% in 2023. Casting contributed 16.2% of emissions in 2022 and 13.8% in 2023, proportionally higher than its weight share. This indicates that although cast components are fewer in mass, they still carry a notable carbon intensity, mostly driven by melting, alloying, and mold preparation processes (Zheng, Huang & Zhou, 2018).

This finding reinforces the strategic importance of decarbonizing forged components in aerospace industry through material efficiency, supplier engagement, and manufacturing innovation. It also highlights why emerging technologies such as AM, which can significantly reduce buy-to-fly ratios, represent a promising pathway for lowering Scope 3 Category 1 emissions. This connection is further explored in the next section.

4.2 Impact of AM on emissions from PG&S

4.2.1 Interview Outcomes

The semi-structured interviews offered practical insights into GKN Aerospace's long-term strategy for integrating AM and its potential to reduce upstream emissions. Consistent with earlier research on decarbonizing aerospace supply chains, interviewees highlighted that current production remains dominated by subtractive machining and high-buy-to-fly forging operations, both of which generate substantial material waste (Schulman et al., 2021). Approximately 90% of procured material ultimately becomes scrap or recycled feedstock, with forging identified as the principal contributor. In line with ongoing industry trends, GKN Aerospace intends to gradually replace selected casting and structural forging operations with AM, while acknowledging that rotational components such as turbine shafts and blades will continue to rely on forging due to stringent performance and certification requirements.

A key metric emphasized during the interviews was the buy-to-fly ratio, which currently averages about 10:1 for structural components. AM adoption is expected to reduce this ratio to roughly 3:1 by 2035, reflecting the technology's ability to minimize machining allowances, consolidate geometries, and improve material utilization. Interviewees also discussed long-term procurement developments. Under a business-as-usual scenario, total purchased mass is projected to increase by 76.2% by 2035, reaching approximately 1.38 million kilograms. However, partial replacement of casting and forging with AM is expected to reduce this material demand by 18.7% relative to the baseline. Although the mass of final ("fly") parts is projected to increase by around 76%, associated waste is expected to rise by only 45%, reducing the overall buy-to-fly ratio to an estimated 8.4:1 by 2035 (Thordén, 2024).

Overall, the interviews reinforce AM's strategic role in supporting circular manufacturing by reducing raw material requirements, lowering upstream emissions, and improving material circularity (Huang et al., 2009; Schulman et al., 2021). The qualitative evidence is therefore consistent with, and complementary to the scenario-based emission reduction analysis presented in next section.

4.2.2 Emission Reduction from AM

Cradle-to-gate LCA conducted by GKN Aerospace offer strong quantitative evidence of the emission-reduction potential associated with transitioning from conventional forging to AM. These LCAs focus on upstream impacts; including raw material extraction, production, and manufacturing processes. Downstream processes such as transportation, use-phase impacts, and end-of-life handling were excluded to maintain methodological alignment. For Product A, currently produced in the United States through one-piece forging, replacing traditional manufacturing with Laser Metal Deposition (LMD) using green feedstock and improved buy-to-fly ratios resulted in a 78% reduction in total cradle-to-gate emissions and an 89% reduction in Category 1 emissions (Léonard, 2024). Similarly, for Product B, evaluated across two engine programs (GEnX and LEAP), transitioning to full-LMD production yielded 76% and 79% reductions in Category 1 emissions, respectively. On average, these assessments indicate that substituting forging with AM has the potential to reduce upstream emissions by approximately 81% (Léonard, 2023).

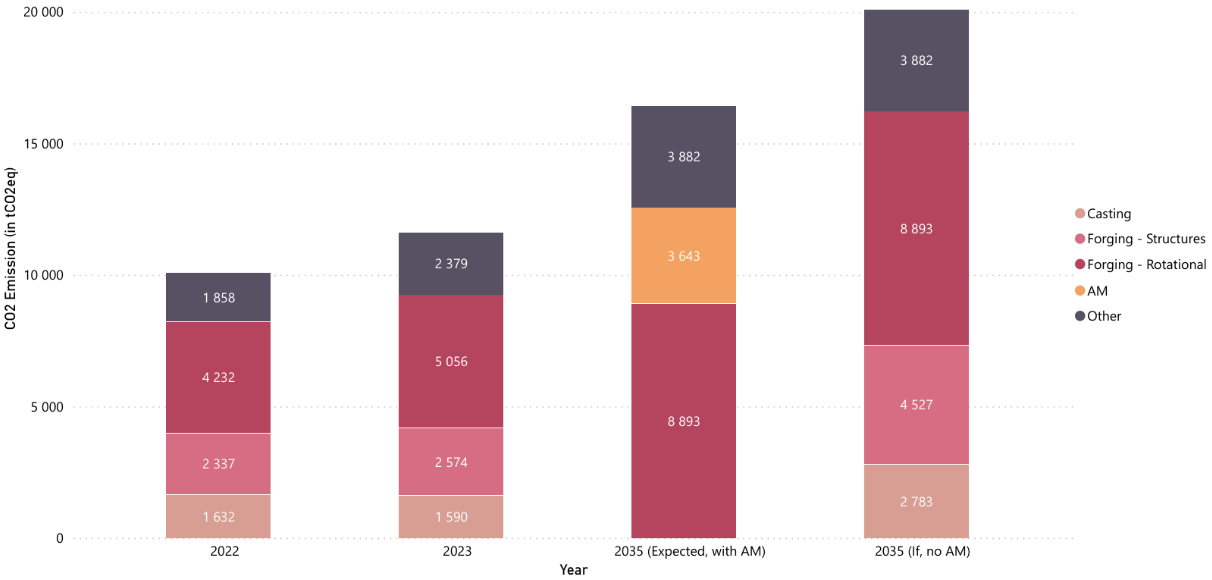

Figure 3 Expected Emission by Process (in tCO_2eq)

However, reductions for components currently manufactured via casting remain more difficult to quantify. The transition from casting to AM processes involves uncertainties related to recycled content and powder production energy, electricity mix, powder atomization efficiency, and achievable buy-to-fly ratios (Kokare, et al., 2023; Sabzi, 2023). These factors introduce variability in final emission outcomes and highlight the need for more component-specific LCAs for cast-to-AM transitions. Under a business-as-usual trajectory, emissions are projected to reach 20,085 tCO_2eq by 2035, driven primarily by the growth of forging and casting operations. In contrast, the AM-enabled scenario reduces projected 2035 emissions to 16,418 tCO_2eq; an 18.26% decrease relative to the no-AM case.

5. Discussion and conclusion

This study shows that the choice of estimation method has a major influence on Scope 3 Category 1 results in aerospace manufacturing. The large gap between mass-based and spend-based estimates reveals a core methodological sensitivity: spend-based calculations, while easy to implement, systematically overestimate emissions because they rely on broad economic proxies. In contrast, the mass-based approach, grounded in physical procurement data and sector-specific emission factors, provides a more reliable basis for internal decision-making and external reporting.

At the material and process level, the analysis confirms that titanium and nickel alloys, together with forging operations, dominate upstream emissions. These hotspots clearly indicate where procurement strategies, supplier engagement and process innovations can deliver the greatest impact. Scenario modelling further suggests that partially replacing structural forging and casting with AM could offset much of the expected growth in production, reducing projected 2035 PG&S emissions by around 18% relative to a no-AM baseline despite a 76% increase in procurement demand.

The findings have several wider implications. For industry, they underline the value of mass-based Scope 3 inventories as a foundation for more granular, supplier-specific accounting and highlight AM as a strategic lever for decarbonizing high buy-to-fly components. For policymakers, they reinforce the need for clearer guidance on supplier disclosures, incentives for circular material flows, and standardized emission factor databases tailored to high-performance alloys and processes. For researchers, gaps in aerospace-specific emission factors, data quality, and AM life-cycle evidence point to the need for more component-level LCAs, multi-site studies and improved real-time emissions data. Overall, improving Category 1 performance emerges not as a narrow manufacturing challenge but as a systemic transition requiring aligned technological, organisational and regulatory change

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