Advances in Management & Applied Economics, Vol. 15, No. 6, 2025, 119-149
ISSN: 1792-7544 (print version), 1792-7552(online)
https://doi.org/10.47260/amae/1567
Scientific Press International Limited

Carbon Emission Hotspots and Mitigation Strategies in Aluminum Ingot Manufacturing

Cheng-Wen Lee[1] and Ping-Hung Chen[2]

Abstract

This study analyzes the greenhouse gas (GHG) emissions of an aluminum ingot manufacturing plant in southern Taiwan, using complete 2023 inventory data to identify emission structures, hotspots, and feasible reduction strategies. The inventory followed ISO 14064-1:2018 and the Ministry of the Environment's classification guidelines, with emissions calculated using the Intergovernmental Panel on Climate Change (IPCC) Sixth Assessment Report (AR6) global warming potential values. Hotspot analysis identified five major emission sources: procurement of primary aluminum, metallic silicon, and scrap aluminum; combustion of heavy oil in boilers; and purchased electricity. Improvement strategies were proposed for each hotspot, including raw material substitution (e.g., recycled aluminum), fuel switching (e.g., natural gas or biodiesel), energy efficiency measures (e.g., inverters, LED lighting, heat recovery), renewable energy adoption (e.g., solar PV, T-RECs), and supply chain carbon disclosure. A multi-criteria assessment framework—considering controllability, technical maturity, cost, and reduction potential—was used to prioritize actions. The findings demonstrate the dominance of supply-chain-driven emissions in the aluminum industry and underscore the need for supplier cooperation alongside internal efficiency improvements. Although applied to a single factory, the modular framework provides a replicable model for small- and medium-sized enterprises (SMEs) to implement carbon management. Verified by third-party certification (DNV, ISO 14064), the study highlights the value of continuous inventory refinement and future ISO 14067 certification to support Taiwan's net-zero transition.

JEL classification numbers: Q54, Q56, L61, M11.
Keywords: Greenhouse Gas Inventory, Carbon Emission Hotspots, Aluminum Ingot Manufacturing, Mitigation Strategies, ISO 14064.

[1] Department of International Business, College of Business, Chung Yuan Christian University. Taoyuan City, Taiwan.
[2] Ph. D. Program in Business, College of Business, Chung Yuan Christian University. Taoyuan City, Taiwan.

Article Info: *Received:* September 18, 2025. *Revised*: October 1, 2025.
Published online: October 7, 2025.

1. Introduction

With the worsening of global climate change, extreme weather events are occurring with increasing frequency, causing severe impacts on both human society and natural ecosystems. The international community has gradually reached a consensus on the urgent need to reduce greenhouse gas (GHG) emissions through mechanisms such as carbon pricing and border adjustment measures, to achieve a net-zero sustainable environment by 2050.

Enterprises are therefore required to establish comprehensive GHG inventories, identify major emission hotspots, and implement targeted reduction strategies. Without such measures, firms face not only high carbon fees—estimated at approximately NTD 300 per ton of CO_2 in Taiwan and nearly USD 90 per ton in the European Union—but also significant regulatory pressure, restructuring costs, and the responsibility of contributing to a more environmentally sustainable society. In this context, the promotion of GHG inventory and disclosure systems has become a critical starting point for global enterprises to advance sustainable governance.

Table 1: Definition of Categories (Category 1 to Category 6)

Category	Emission Type	Emission Type Description
Direct GHG Emissions	Fixed Sources	Direct emissions from stationary combustion
	Mobile Sources	Direct emissions from mobile combustion
	Process Emissions	Direct emissions from industrial processes
	Fugitive Emissions	Emissions from leakage in systems
	Land Use Change	Emissions from land use and land use change
Energy Indirect Emissions	Purchased Electricity	Emissions from purchased electricity
	Purchased Energy	Emissions from purchased energy (heat, steam, cooling, compressed air, etc.
Transport Related GHS Emissions	Upstream Transport & Delivery	Emissions from the transport of goods and materials during the inventory year
	Downstream Transport & Delivery	Emissions from the transport of products delivered to customers during the inventory year
	Employee Commuting	Emissions from employees traveling to and from work by various means
	Business Travel & Visitor Transport	Emissions from business travel by employees, visitors, and customers
	Business Travel	Emissions from employee business travel via air, sea, rail, etc.
GHG Emissions from Products Used by Organization	Purchased Goods	Emissions from the production of purchased goods and materials relevant to internal operations, including Categories 1, 2, and 3
	Capital Goods	Emissions from the production of purchased capital goods
	Waste Generated in Operations	Emissions from solid and liquid waste generated in operations (e.g., landfilling, incineration, recycling, collection)
	Leased Assets	Emissions from the operation of leased assets not owned by the organization, for which the organization is responsible for Categories 1 & 2 emissions, and for which other entities are responsible for Category 3 emissions.

	Upstream Leased Assets	Emissions from the production of purchased goods, such as consulting, cleaning, software licenses, banking, and packaging
GHG Emissions from Products Using the Organization	Products Used	Emissions from the use of products produced by the organization
	Downstream Leased Assets	Emissions from the operation of all owned and managed assets leased to other entities, where Categories 1 & 2 emissions are reported by the lessee.
	End-of-Life Treatment of Solid Products	Emissions from the end-of-life treatment of products sold by the organization
	Investments	Emissions from investments
Other GHG Emissions	Other	Uncategorized emissions

Aluminum ingot manufacturing is a highly energy-intensive industry, characterized by the combustion of fuels, high-temperature smelting, and the extensive use of carbon-intensive raw materials such as primary aluminum and silicon. These processes generate both direct emissions (e.g., heavy fuel oil combustion) and indirect emissions (e.g., electricity consumption), resulting in substantial overall carbon dioxide emissions. According to the International Aluminum Institute (2021), the raw material and electricity stages account for the majority of the life-cycle carbon footprint of aluminum, with electricity use alone often representing more than 60% of total emissions during primary aluminum production. Similarly, Sáez-Guinoa et al. (2024) demonstrated that energy consumption in the alumina refining stage of the Bayer process significantly increases total environmental impacts, underscoring the importance of energy efficiency improvements.

This study analyzes the 2023 GHG inventory of an aluminum ingot manufacturing plant in southern Taiwan, conducted in accordance with ISO 14064-1:2018, covering six categories of emissions (Categories 1–6) as shown in Table 1. Emissions were converted using the latest Global Warming Potential (GWP) values published in the Intergovernmental Panel on Climate Change (IPCC) Sixth Assessment Report (AR6). The study identifies key emission hotspots, with a focus on high-carbon production equipment, and proposes improvement strategies to support the industry's low-carbon transition. As highlighted by Flannery and Mares (2022), the emissions intensity of aluminum products varies considerably depending on the electricity mix and energy source employed, suggesting that Taiwan's reliance on fossil-based power amplifies its carbon risks under international trade mechanisms.

By addressing these issues, the research aims to strengthen the international competitiveness of Taiwan's aluminum sector, which faces increasing pressure under the EU's Carbon Border Adjustment Mechanism (CBAM), domestic carbon fee policies, and the amended Greenhouse Gas Control Act. Ultimately, this study provides empirical insights into the emission structure of the aluminum manufacturing industry and serves as a practical reference for other small and medium-sized enterprises (SMEs) seeking to implement GHG inventories, manage emission hotspots, and adopt low-carbon technologies.

2. Literature Review

2.1 Characteristics of Greenhouse Gas Emissions from Aluminum Industry

Aluminum ingot manufacturing is a highly energy- and material-intensive industrial activity. Its greenhouse gas (GHG) emissions arise not only from direct processes such as high-temperature melting and casting, but also from many indirect and upstream/downstream sources. Key emission sources include: procurement and transport of raw materials (primary aluminum or recycled scrap, alumina/bauxite, silica, carbon anodes), electricity use (both from purchased grid electricity and/or self-generated power), fuel combustion (especially heavy oils or fossil fuels in furnaces, boilers), molten metal handling (melting, casting, and heat-treatment), product distribution, transport of wastes, and waste treatment.

Based on publicly available data from the International Aluminum Institute (IAI), the life-cycle (cradle-to-gate) emissions intensity of primary aluminum is on the order of ~ 11-12 tons CO_2e per ton of aluminum produced **(≈** 11.5 kg CO_2e per kg**)** for many regions, including contributions from alumina refining (fuel + electricity), electrolysis (smelting) and melting and casting stages, according the report of International Aluminium Institute (2024). By contrast, recycled aluminum (or "secondary" aluminum) can have much lower emission intensities: in several studies, recycled aluminum emits only ~0.6 to ~1.0 kg CO_2e per kg (i.e., ~0.6-1 tons CO_2e per tonne) depending on the quality, source, and treatment of the scrap. This large difference stems from the fact that recycled aluminum production largely eliminates the high-energy electrolysis stage. Peng et al. (2022) find that primary aluminum production in China in 2020 had ~15,947 kg CO_2-eq per ton for GHG emissions, while recycled aluminum was only ~845 kg CO_2-eq per ton, i.e. about 5.3% of the emissions of primary aluminum.

2.1.1 Features of the Emission Structure and Hotspots

1. Upstream Raw Materials & Supply Chain

The emissions embodied in primary alumina refining, produced either domestically or imported, are significant—fuel use for drying/calcination, use of heavy fossil fuels, electricity input, transport of bauxite or alumina over long distances (Hasanbeigi., 2022). For recycled aluminum, supply chain emissions such as scrap collection, transportation (including international shipping of scrap), pretreatment (removal of coatings, impurities) still contribute non-trivially—especially when scrap must be transported long distances. For example, Peng et al. show that ~25.5% of scrap aluminum was imported in the China study, and the ocean shipping accounted for ~36% of transport emissions in the recycled aluminum life cycle (Peng et al., 2022).

2. Dominant Processes: Electrolysis / Smelting

The electrolysis (smelting) stage in primary aluminum dominates energy consumption and GHG emissions. In the China case study, ~80% of GHG emissions in the primary aluminum life cycle originated from electrolysis (Peng et al., 2022). The role of anode consumption (carbon anodes), anode effects (carbon emissions from anode feedstock, decomposition, side reactions), process heat losses, etc., are also important subcomponents. Some emissions are process emissions (e.g., anode oxidation, PFCs, etc.) that extend beyond fuel combustion.

3. Indirect / Energy Emissions (Electricity, Fuel, Heat)

A large share of emissions derives from electricity use, both for direct heating/melting and for electrolysis, and also from boilers or furnaces burning fuel (e.g., heavy oils, natural gas, coal, depending on region). The emissions factor of the electricity mix (grid vs self-generated; share of coal, natural gas, renewable) is critical. Regions with low-carbon grids can greatly reduce cradle-to-gate emissions (Hasanbeigi, 2022). Process inefficiencies (heat losses, sub-optimal furnace insulation, etc.) augment fuel/electricity consumption. Also, fugitive emissions (heat radiation, gas leaks) can be non-negligible, especially in high-temperature equipment.

4. Logistics, Transport, Distribution, Wastes

Transport of raw materials into plants, of scrap to plants, of final ingots/products out to customers, and transport of wastes and by-products are all indirect but important. For recycled aluminum, transport of scrap (especially long-distance import) can add noticeably to emissions. As mentioned, Peng et al. show that import & ocean transport contribute to ~36% of transport stage emissions in their recycled aluminum life cycle case (Peng et al., 2022). Waste treatment/disposal (slag, dross, gas emissions) also contribute throughout the life cycle.

2.1.2 Case of Taiwan

While specific peer-reviewed studies focusing on the full life cycle of aluminum (primary vs recycled) in Taiwan are limited, there are relevant data and national inventories (e.g., Taiwan's GHG Inventory Reports) and energy-sector emissions trends that have implications. Taiwan's GHG Emissions Inventory (excluding LULUCF) shows that in recent years, the *energy sector* is responsible for ~90-91% of all GHG emissions; the IPPU (industrial processes and product use) sector contributes ~7-8%. Although aluminum ingot production is a sub-component of the IPPU/manufacturing sector, its share of total emissions could be non-trivial for aluminum-intensive plants (2050) according to the report of the Climate Change Administration, Ministry of Environment.

As illustrated in Figure 1, the energy sector has consistently been the largest contributor to Taiwan's total greenhouse gas (GHG) emissions over the years. In 2005 and 2022, emissions from the energy sector (excluding LULUCF) accounted for approximately 85.79% and 90.87% of total emissions, respectively. In contrast, the IPPU sector contributed 9.70% and 7.08%, the agricultural sector 1.38% and 1.11%, and the waste sector 3.13% and 0.94% in those same years.

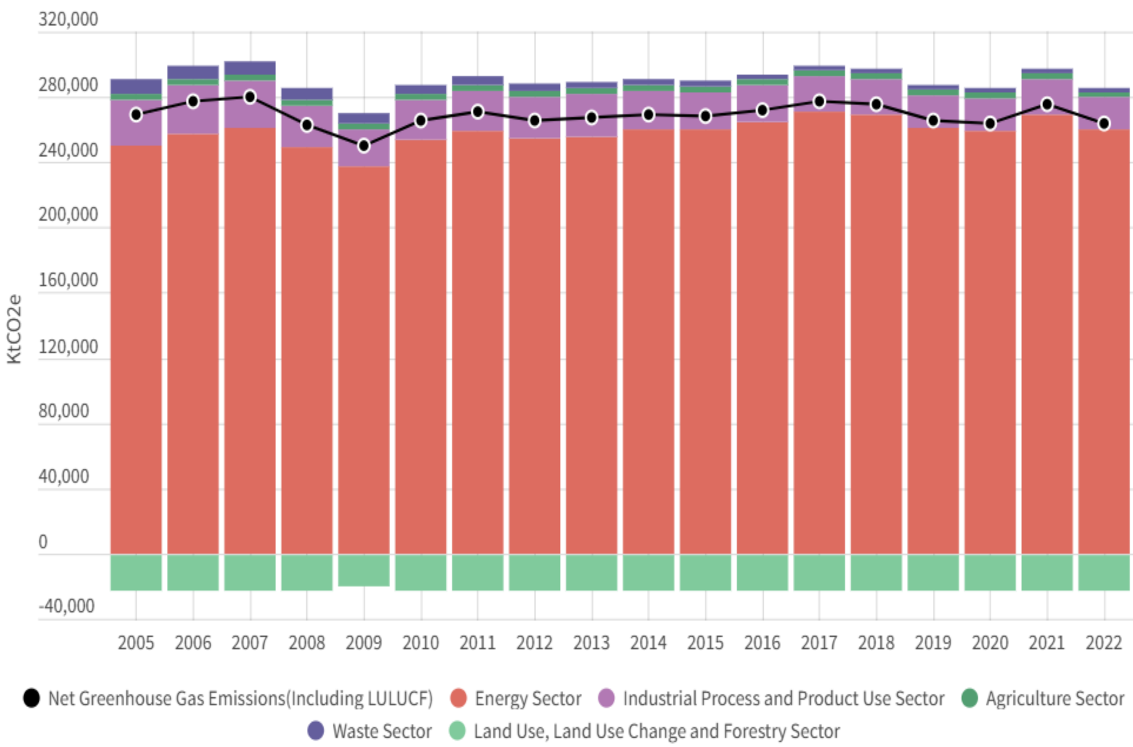

Figure 1: GHG Emissions by Sector in Taiwan

In 2022, Taiwan's total GHG emissions declined by 3.78% compared with 2021. Emissions decreased across all sectors: the energy sector fell by 3.38%, the IPPU sector by 8.58%, the agricultural sector by 3.19%, and the waste sector by 4.76%. Carbon sequestration from the LULUCF sector also decreased slightly, by 0.08%. When compared with the base year 2005, total emissions in 2022 were 1.79% lower. Specifically, emissions from the energy sector increased by 4.03%, while the IPPU sector decreased by 28.37%, the agricultural sector by 21.05%, and the waste sector by 70.36%. Meanwhile, carbon sequestration from the LULUCF sector declined by 2.04%.

2.2 GHG Inventory System and Classification Principles

The establishment of a greenhouse gas (GHG) inventory system forms a critical foundation for enterprises pursuing sustainable transformation and institutionalized carbon management. A standardized inventory process not only identifies the key sources and "hotspots" of emissions but also provides the essential basis for developing reduction strategies, managing policy quotas, setting internal carbon prices, and supporting transparent carbon disclosure (Wiedmann & Minx, 2008; Jang et al., 2018).

At the international level, inventory frameworks are primarily guided by the ISO 14064 standard and the Greenhouse Gas Protocol (GHG Protocol)**.** Among them, ISO 14064-1:2018 is the most widely adopted enterprise-level standard. Its core purpose is to provide organizations with a verifiable and transparent mechanism for reporting carbon emissions (Dai et al., 2021). The standard emphasizes transparency, consistency, completeness, and comparability in emission reporting and classifies emissions into three scopes:

Scope 1: Direct emissions from owned or controlled sources.
Scope 2: Indirect emissions from the consumption of purchased energy.
Scope 3: All other indirect emissions resulting from value chain activities (Green et al., 2012).

In addition to this three-scope framework, some inventory guidelines adopt a more detailed category-based classification to enable refined reporting and comparison. For instance, the "*Technical Guidelines for* Greenhouse *Gas Emissions Inventories"* issued by Taiwan's Environmental Protection Administration (EPA) classify emissions into six categories:

Category 1: Direct emissions from fuel combustion, including stationary, mobile, process, and fugitive sources.
Category 2: Indirect emissions from purchased energy, such as electricity or steam.
Category 3: Indirect emissions from transportation activities, including raw material, product, waste, employee commuting, business travel, and visitor transport.
Category 4: Upstream indirect emissions, such as those from purchased raw materials, energy-related activities, waste disposal, leased assets, fixed assets, and services.
Category 5: Emissions from product use, including downstream processing, leasing, franchising, consumer use, and end-of-life treatment.
Category 6: Other indirect emissions not covered in Categories 3–5, such as those from subsidiary operations (Wiedmann, 2009; Guo et al., 2020).

The aluminum ingot factory inventory report referenced in this study was compiled in accordance with ISO 14064-1:2018 and the technical guidelines of the Ministry of the Environment's Department of Climate Change (MOE). Emission calculations were based on the Global Warming Potential (GWP) values from the IPCC Sixth

Assessment Report (AR6), which provides updated and more accurate conversion factors for methane, nitrous oxide, and other non-CO_2 gases (IPCC, 2021). To ensure accuracy and credibility, third-party verification was conducted by DNV, a Norwegian verification body.

The true value of an inventory and verification system lies not only in data disclosure but also in the establishment of an internal "carbon logic" and an interdepartmental carbon data integration mechanism**.** Through regular inventories, enterprises can progressively accumulate activity data, emission factors, and management costs, enabling performance monitoring and strategic planning for high-emission activities (Downie & Stubbs, 2012; Lee, 2018). In essence, the inventory and verification system constitutes the carbon management infrastructure, serving as the first step toward energy conservation, carbon reduction, and the achievement of net-zero targets.

2.3 Theory of Carbon Emission Hot Spot Analysis and Improvement Strategies

Carbon emission hotspot analysis within the GHG inventory is an essential tool for identifying the contribution of various activities to total GHG emissions and for determining priority areas for intervention. By pinpointing emission hotspots, enterprises can avoid the misallocation of resources under the "average theory" and instead concentrate limited resources on the most impactful targets, thereby improving both carbon reduction effectiveness and management efficiency (Downie & Stubbs, 2012; Lee, 2018).

The definition of a hotspot is not based on a single criterion but rather a combination of factors, including: (1) a high percentage of total GHG emissions, (2) a rapid growth trend in recent years, and (3) a strong correlation with enterprise revenue, costs, or resource input, and (4) clear management responsibilities and accountability (Wiedmann, 2009; Guo et al., 2020).

Thus, hotspots may span across different scopes of emissions, such as upstream raw materials, energy consumption in production processes, or transportation-related emissions (Mattila & Niemi, 2025; Jang et al., 2018). The design of improvement strategies should be grounded in hotspot analysis, taking into account the controllability of activities, available technological solutions, relevant policy and regulatory frameworks, and the enterprise's financial capacity. The literature commonly classifies improvement strategies into five broad categories:

1) Source substitution: raw material replacement or cleaner fuel choices.
2) Energy efficiency improvement: upgrading equipment and facilities.
3) Process optimization: streamlining production processes to reduce waste.
4) Information and monitoring systems: digital data tracking and emission monitoring.
5) Low-carbon behavior guidance: employee training, incentives, and cultural change (Tan et al., 2015; Song et al., 2017).

For instance, in the manufacturing sector, high-emission hotspots may be addressed through fuel switching (e.g., replacing heavy oil with natural gas**),** raw material substitution (e.g., purchasing recycled aluminum), facility upgrades (e.g., modernizing combustion systems), or process monitoring (e.g., minimizing heat loss). Improvement strategies should directly correspond to the carbon emission structure:

1) Category 1 emissions (fuel combustion), low-carbon fuel replacement, and combustion efficiency improvements can reduce CO_2 emissions.
2) Category 2 emissions (purchased electricity), enterprises may adopt renewable energy sources or implement inverter-based equipment to enhance efficiency.
3) Category 3 emissions (transportation), emissions can be reduced by shortening distances or adopting electric vehicles.
4) Category 4 emissions (raw material procurement), supply chain collaboration, and raw material carbon footprint disclosure are crucial.

A structured strategy–emission source matrix enables enterprises to clearly understand focus areas, assign responsibilities, and avoid mismatches between strategies and actual hotspots. Moreover, advanced decision-support tools such as Multi-Criteria Decision Making (MCDM) and Life Cycle Assessment (LCA) can be employed to rank strategies and forecast their impacts. These approaches allow enterprises to evaluate multiple dimensions—including feasibility, cost, effectiveness, and risks—thereby enhancing systematic decision-making (Cinelli et al., 2015; Hertwich & Wood, 2018). While this study does not apply a specific mathematical model, the logical framework of hotspot-based prioritization is integrated into the improvement proposals to ensure both systematic rigor and practical feasibility.

In conclusion, GHG hotspot analysis and improvement strategies should not be regarded as one-off exercises but as continuous processes within an enterprise's carbon management system. Only through systematic hotspot identification, rigorous evaluation mechanisms, and practice-oriented strategy frameworks can enterprises progress from inventory reporting to tangible low-carbon actions, thereby advancing toward the ultimate goal of carbon-neutral management (Legg, 2021; Daddi et al., 2022).

2.4 Carbon Management Challenges and Transformation Practices for SMEs

Compared to large enterprises with more comprehensive resource allocation, technical expertise, and institutional support, small and medium-sized enterprises (SMEs) often face significant limitations beyond their control when promoting carbon management. In Taiwan, SMEs account for more than 97% of enterprises and play a critical role in global supply chains. However, a wide gap exists in terms of GHG inventory disclosure, internal carbon management capacity, and access to financial resources for low-carbon transformation (IEA, 2021; MOEA, 2022).

2.4.1 Information Collection and Data Management Gaps

The first major challenge faced by SMEs in developing greenhouse gas (GHG) inventories lies in the collection and organization of emissions-related data. Carbon accounting requires consolidating information from diverse and often fragmented sources, including fuel purchase receipts, electricity consumption records, logistics and transportation contracts, and raw material specifications. This fragmentation not only increases the complexity of data management but also raises risks of inconsistencies, missing values, and double counting, making it difficult for SMEs to establish a reliable baseline for emissions measurement. Without integrated digital systems, SMEs must rely on manual processing, which is both time-consuming and error-prone. Furthermore, many SMEs lack trained personnel with adequate knowledge of inventory principles, emission factors, and classification logic, often resulting in misreporting or misclassification of emissions (Lee, 2018; Guo et al., 2020).

2.4.2 From Reporting to Decision-Making

Even when SMEs complete inventories, they often fall into the dilemma of "data without decisions." Many enterprises can submit reports but cannot interpret their implications: they struggle to identify emission hotspots, prioritize improvement targets, or allocate resources effectively within limited budgets. The absence of dedicated carbon management departments or structured systems frequently reduces inventories to formalistic exercises, hindering their ability to inform strategic action (Downie & Stubbs, 2012; Wiedmann & Minx, 2008).

2.4.3 External Regulatory and Market Pressures

SMEs also face mounting external pressures. Global supply chains increasingly demand product-level carbon footprint disclosure, reinforced by regulatory mechanisms such as the Carbon Border Adjustment Mechanism (CBAM). Lacking in-house expertise, SMEs often depend on costly consulting services or third-party certification, adding financial strain to already limited budgets. Although government subsidies exist, they rarely address the diverse and sector-specific needs of SMEs, thereby creating a gap between regulatory systems and practical implementation (Hertwich & Wood, 2018; Daddi et al., 2022).

2.4.4 Emerging Transformation Practices

To overcome these barriers, academics and policymakers advocate for SME-oriented low-carbon governance models. Key recommendations include:

1) Simplified inventory tools and modularized data systems tailored to SMEs' limited resources.
2) Tiered promotional frameworks to progressively build capabilities according to enterprise size and readiness (Tan et al., 2015).
3) Cluster management approaches, grouping SMEs by industry type or emission profile and providing sector-specific templates and improvement guidelines.

This avoids the inefficiency of one-size-fits-all policies and enhances implementation effectiveness (Jang et al., 2018). A notable local initiative is the Carbon Inventory Counseling Program promoted by the Industrial Development Bureau of Taiwan's Ministry of Economic Affairs (MOEA), which offers online calculation platforms, inventory templates, and subsidies for third-party verification, thereby lowering entry barriers in 2022.

2.4.5 Case Study Implications

In the case of the aluminum ingot factory examined in this study, although the enterprise operates on a relatively larger scale and has prior inventory experience, it still exhibits the typical SME challenges: insufficient manpower, limited data system integration, and constrained resources for emission reduction investment. By using this sector as a focal point, this study develops a strategic improvement framework that not only addresses the complexity of aluminum ingot operations but also provides a scalable model for broader SME application. The findings are expected to serve as a reference for both policy development and self-management practices among SMEs seeking to enhance their carbon management capacity.

3. Methodology

3.1 Research Design

The logic of this study is grounded in the GHG inventory framework of ISO 14064-1:2018, supplemented by the Category classification system announced by Taiwan's Ministry of Environmental Protection (MEP) for emission source categorization. This combined approach ensures transparency, comparability, and scientific rigor in line with international and domestic best practices (Wiedmann & Minx, 2008; Dai et al., 2021).

First, the research team defined the scope of the GHG inventory in collaboration with an aluminum ingot factory located in southern Taiwan. Comprehensive data for the year 2023 were collected, covering fuel usage, electricity consumption, raw material procurement lists, logistics records, refrigerant replenishment, and waste disposal activities. These datasets were systematically reviewed, verified, and compiled into preliminary inventory records. Following the practice of enterprise-level inventories in previous studies (Jang et al., 2018; Lee, 2018), the data were categorized into Categories 1 to 4 according to their activity attributes, forming the foundation for the subsequent carbon emission structure analysis.

Second, the study conducted the classification and quantification of carbon emissions within the GHG inventory. Emissions were calculated based on standard formulas consistent with ISO 14064-1:2018 and MEP guidelines. Following the calculations, hotspot analysis was performed to identify priority emission sources. In line with existing research (Mattila & Niemi, 2025; Guo et al., 2020), the identification criteria for hotspots were items that either (a) accounted for more than 10% of total emissions, or (b) represented the largest emission share within a given category. Once the hotspots were determined, the research team examined their characteristics, including controllability within the plant, potential for technological improvement, and dependence on external supply chains (Downie & Stubbs, 2012). Third, during the strategy development stage, the research team compiled a portfolio of feasible carbon reduction strategies based on domestic and international literature, industry reports, and practical operational experiences. Similar to frameworks proposed in sustainability strategy research (Tan et al., 2015; Song et al., 2017), the strategies were categorized and tailored to the identified hotspots. Draft low-carbon proposals included, for example:

1) Raw material procurement: substituting primary aluminum with recycled aluminum (Hertwich & Wood, 2018).
2) Refrigerant emissions: adopting low-GWP refrigerants and strengthening leakage detection.
3) Production processes: deploying high-efficiency, automated equipment and optimizing energy use (Daddi et al., 2022).
4) Energy systems: upgrading to energy-saving technologies and restructuring production methods.

Finally, to support practical implementation, the study established a strategy ranking framework. This framework evaluated strategies according to four key criteria: controllability, technical maturity, cost considerations, and carbon reduction potential. Similar approaches using Multi-Criteria Decision-Making (MCDM) and Life Cycle Assessment (LCA) have been demonstrated in prior studies to help enterprises systematically prioritize sustainability strategies (Cinelli et al., 2015; Hertwich & Wood, 2018).

3.2 Research Process

As illustrated in Figure 2, the research process is logically coherent, systematic, and practicable, providing not only actionable recommendations for the aluminum ingot industry but also a replicable framework for SMEs in other manufacturing sectors to advance low-carbon transition and greenhouse gas management.

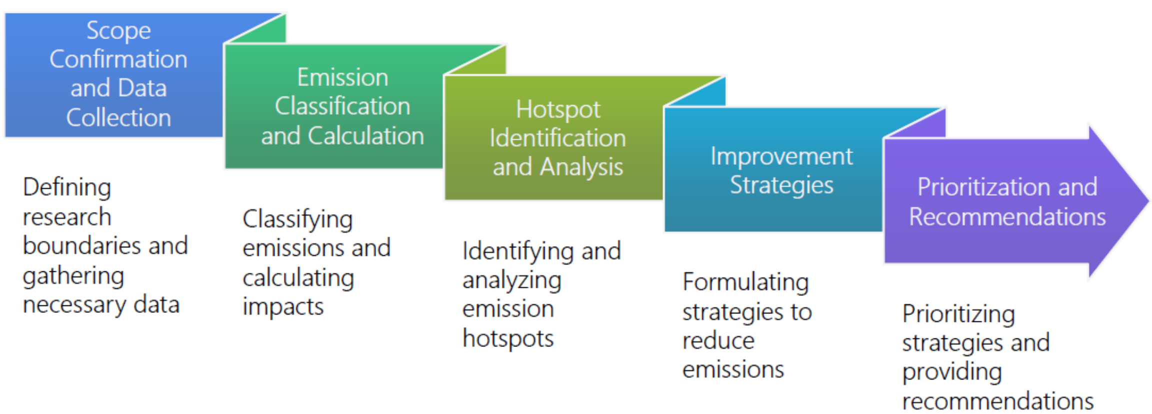

Figure 2: The Chart of Research Process

3.3 Scope Confirmation and Data Collection of GHG Inventory Study

The primary data for this study were obtained from the 2023 GHG inventory report of an aluminum ingot factory in southern Taiwan, prepared in accordance with ISO 14064-1:2018. The report was developed with the assistance of a third-party consultant appointed by the researcher, while inventory planning and data review followed DNV certification standards. Verified by the company's responsible departments, the report encompassed the major processes and indirect activities of the factory's three sub-plants, including raw material procurement, fuel consumption, electricity use, refrigerant replenishment, transportation, and waste disposal (see Figure 3). In cases where report boundaries are modified, the company is required to revise and reissue the inventory in accordance with its Greenhouse Gas Inventory Management Procedures.

The data for this study were primarily derived from the plant's administrative and on-site production record systems, including detailed records of fuel and energy consumption, electricity bills, raw material inflows and outflows, transportation fuel invoices and third-party logistics contracts, refrigerant usage logs, equipment maintenance records, and calorific values provided by CNOOC. All activity data for the year 2023 were systematically converted and quantitatively calculated using the carbon emission coefficient database (version 6.0.4) released by Taiwan's Ministry of Environmental Protection, in conjunction with the Global Warming Potential (GWP) indices published in the IPCC Sixth Assessment Report (AR6).

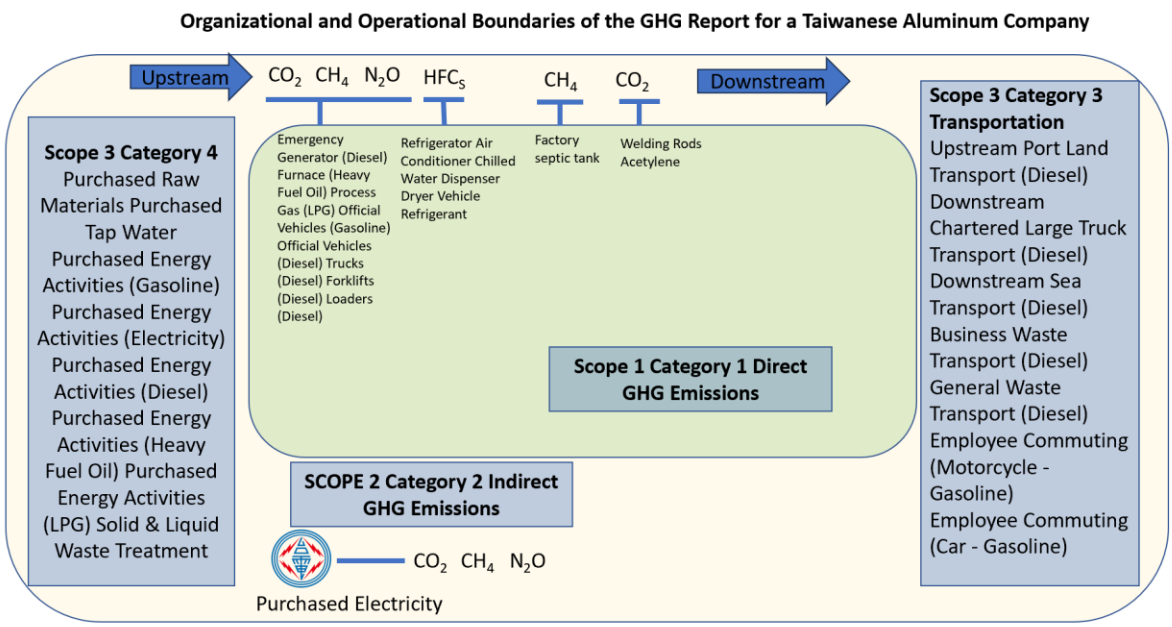

Figure 3: Report Boundary Diagram

3.4 Emissions Classification and Calculation

3.4.1 Classification of Carbon Emissions from GHG Inventories

To ensure analytical consistency, this study classified all carbon emission activities of an aluminum ingot factory in southern Taiwan into four major categories, in accordance with the Technical *Guidelines for Greenhouse Gas Inventory* issued by the Ministry of the Environment of the Executive Yuan (formerly the Environmental Protection Administration):

Category 1: Direct emissions: fixed and mobile fuel combustion, manufacturing processes, and fugitive refrigerants.

Category 2: Indirect energy emissions: use of purchased electricity.

Category 3: Transportation-related indirect emissions: transportation of raw materials, waste, finished products, and personnel.

Category 4: Indirect emissions from raw materials: including raw aluminum and silicon metals (Legg, 2021; Jang et al., 2018).

During the categorization process, the research team cross-verified each recorded emission activity with the original invoices to confirm both classification and calculation logic. For items requiring clarification, in-plant interviews and data comparisons were conducted to ensure the accuracy, consistency, and practical feasibility of the categorization results (Lee, 2018; Guo et al., 2020). As this case represented the factory's first complete GHG inventory, certain activities lacked historical data; thus, conservative estimation methods were applied where necessary (Table 2).

Table 2: Identification of Marginal Emission Sources for GHG Reporting

No.	Category	Source Name	Bio-energy	Emission Type	Scope	Generated GHG
1	1	Process: a. Acetylene, b. Welding Rods, c. LPG	No	Direct	I	CO_2, N_2O, CH_4
2	1	Stationary Source: a. Emergency Generator (Diesel), B. Furnace (Heavy Fuel Oil)	No	Direct	I	CO_2, N_2O, CH_4
3	1	Mobile Source: a. Official Vehicle (Gasoline), b. Official Vehicle (Diesel) & Truck (Diesel), c. Forklift (Diesel), d. Loader (Diesel)	No	Direct	I	CO_2, N_2O, CH_4
4	1	Fugitive Source: Fire Extinguisher (ABC Type)	No	Direct	I	--
5	1	Fugitive Source: a. Refrigerator, b. Air Conditioner, c. Chilled Water Dispenser, d. Dryer, e. Vehicle Refrigerant	No	Direct	I	HFCs
6	1	Fugitive Source: Septic Tank	No	Direct	I	CH_4
7	2	Electricity: Taipower	No	Indirect	II	CO_2, N_2O, CH_4
8	3	Upstream/Downstream Transport: Upstream Port Land Transport (Diesel), Downstream Chartered Lange Truck Transport (Diesel), Downstream Sea Transport (Diesel)	No	Indirect	III	CO_2
9	3	Employee Commuting: Employee Motorcycle Commute, Employee Car Commute	No	Indirect	III	CO_2
10	3	Waste Transport: General Waste Transport (Diesel), Business Waste Transport (Diesel)	No	Indirect	III	CO_2
11	4	Purchased Raw Materials: a. Water Fee, b. Scrap Aluminum, C. Pure Aluminum Ingot, d. Silicon	No	Indirect	III	CO_2
12	4	Purchased Energy Activities: Electricity, Gasoline, Diesel for Vehicles, Diesel for Forklifts, Diesel for Loaders, Diesel for Generators, Heavy Fuel Oil, LPG	No	Indirect	III	CO_2
13	4	Solid & Liquid Waste Treatment	No	Indirect	III	CO_2

For inventory operations, the exclusion threshold for individual sources was set at 0.5%, with the cumulative total of excluded sources not exceeding 5% of overall emissions. If this threshold were surpassed, excluded items would need to be reincorporated into the calculation. Such threshold settings are consistent with recommendations from international GHG inventory practices (Wiedmann & Minx, 2008; Downie & Stubbs, 2012). For instance, the company explained that ALS-777 rust preventive oil was excluded because its specifications indicated no CO_2 content. Overall, the data provided by the aluminum ingot factory was largely complete, except for certain information on logistics, transportation, and upstream suppliers. While further efforts are needed to improve data acquisition for completeness and continuity, the available dataset was sufficient to support hotspot analysis and to provide a reliable basis for the recommendations for improvement presented in this study (Daddi et al., 2022; Hertwich & Wood, 2018).

3.4.2 GHG Inventory Carbon Calculation

The principle of applying emission factors in the plant is to prioritize direct measurements or mass balance calculations**.** If these are not available, nationally published emission factors should be used, followed by regional or external factors**.** In the absence of such data, the internationally recognized emission factors shall be adopted. The formulas for calculating greenhouse gas emissions from different sources and offsets based on the standard IPCC/ISO are as follows:

$$\text{GHG Emissions } (CO_2e) = \text{Activity Data} \times \text{Emission Factor} \times \text{Global Warming Potential (GWP)}$$

1. Direct GHG Emissions (Category 1) Calculation Basis

$\text{Emissions}_i = \text{Annual Diesel Fuel Usage} \times \text{Emission Factor}_i \times \text{GWP}_i$

$i = CO_2, CH_4, N_2O$

Emissionsi = Annual Gasoline Consumption × Emission Factori × GWPi

Emissionsi = Annual Diesel Fuel Consumption (mobile) × Emission Factori × GWPi

Emissionsi = Annual Heavy Oil Consumption (kg) × Emission Factori × GWPi

CH4 Emissions = Population × BOD per capita × Emission Factor (CH4) × GWPCH4

Emissions = Quantity of Substance Used or Refilled (kg) × Emission Factor (leakage or release) × GWP

Accordingly, refrigerant fugitive emissions are calculated using the refrigerant fugitive rate, which serves as the emission factor (see Table 3).

Emissions = Refrigerant Charge × Fugitive Rate × GWP

Table 3: Refrigerant Fugitive Emission Factors (IPCC Guidelines)

IPCC Name	Emission Factors(%)
Domestic Refrigeration	$0.1 \le x \le 0.5$
Stand-alone Commercial Applications	$1 \le x \le 15$
Medium & Large Commercial Refrigeration	$10 \le x \le 35$
Transport Refrigeration	$15 \le x \le 50$
Industrial Refrigeration, including Food Processing and Cold Storage	$7 \le x \le 25$
Chillers	$2 \le x \le 15$
Residential and Commercial A/C including Heat Pumps	$1 \le x \le 10$
Mobile A/C	$10 \le x \le 20$

Note: According to IPCC Guidelines, the lower bound of the emission factor range should be applied for developed countries, while the upper bound should be applied for developing countries.

2. Indirect GHG Emissions (Category 2) Calculation Basis

The calculation of CO_2 emissions from electricity consumption is conducted as follows:

$$CO_2 \text{ Emissions} = \text{Annual Electricity Consumption} \times \text{Electricity Emission Factor}$$

Annual electricity consumption refers to the total amount of electricity used during the reporting year, measured in kilowatt-hours (kWh), with one kilowatt-hour equivalent to one unit of electricity usage. According to the Ministry of Economic Affairs (Department of Energy), the electricity emission factor for FY111 is 0.495 kg CO_2e per kWh. The electricity consumption data, covering both self-consumed electricity and total electricity usage, are obtained from Taipower electricity bills.

3. Significant Indirect GHG Emissions (Categories 3~4) Calculation Basis

1) <u>Category 3: Transportation</u>

a) Upstream and Downstream Transportation of Raw Materials and Products CO_2 emissions from the transportation of raw materials and products are calculated as:

$$CO_2 \text{ Emissions} = \text{Transportation Emission Factor} \times \text{Extended ton-kilometers}$$

Extended ton-kilometers are defined as product weight (tons) × distance traveled (km). Distances are determined using Google Maps for single-trip routes. Emission factors are sourced from the Product Carbon Footprint Database of the Ministry of the Environment: 0.131 kg CO_2e/ton-km for diesel trucks and 0.0198 kg CO_2e/ton-km for international marine transport.

Upstream raw materials are transported from Kaohsiung Port to the company by diesel trucks, with emissions calculated based on the tonnage per trip and single-trip distances. Downstream products are delivered either domestically by diesel trucks to distributors or, in the case of exports, transported by truck to Kaohsiung

Port, with emissions estimated according to the distance traveled and the tonnage carried. For overseas shipments, downstream products are transported from Kaohsiung Port to international destinations by marine vessels, with emissions calculated using route distance, cargo tonnage, and the applicable marine transport emission factors. Responsibility for upstream marine transport lies with the seller.

b) Waste Transportation

Emissions from waste transportation are calculated as waste weight (tons) × distance (km) × emission factor. According to the Carbon Footprint Database, the factor for diesel waste trucks is 0.131 kg CO_2e/ton-km (noting a coefficient of 1.31 kg CO_2e/ton in some cases). Distances are derived from company waste transport data.

c) Employee Commuting

Employee commuting emissions are estimated as:

$$CO_2 \text{ Emissions} = \text{Emission Factor} \times \text{Person-kilometers}$$

Emission factors are categorized by transport mode (car, motorcycle, high-speed rail) based on the Carbon Footprint Database. Distances are measured as the actual commute between home and workplace, multiplied by the number of annual working days. In 2023, calculations were based on 22 employees.

2) <u>Category 4</u>

a) Water Use

CO_2 emissions from water use are calculated as monthly water consumption × Taiwan tap water carbon footprint factor. According to the Ministry of the Environment (Taiwan Water Company, 2020), the factor is 0.233 kg CO_2e/m^3, with 1 degree equivalent to 1 m^3. Data are taken from monthly water bills.

b) Purchased Raw Materials

Since scrap aluminum, pure aluminum, and metallic silicon account for 95% of annual procurement, they are included in calculations:

$$CO_2 \text{ Emissions} = \text{Purchase Volume(kg)} \times \text{Raw Material Emission Factor}$$

Emission factors are from the Ministry of the Environment's Carbon Footprint Database: scrap aluminum 0.14 kg CO_2e/kg, pure aluminum 9.85 kg CO_2e/kg, and metallic silicon 5 kg CO_2e/kg (Jang et al., 2020).

c) Electricity Consumption

Emissions from electricity use are calculated as annual consumption (from Taipower bills) × indirect carbon footprint emission factor. The 2021 value is 9.73E-2 kg CO_2e/kWh (Ministry of the Environment database).

d) Fuel Use

Fuel-related emissions are estimated from monthly purchases of diesel, gasoline, heavy oil, and LPG. Emission factors are from the Ministry of the Environment, Carbon Footprint Database (2021).

- Diesel: 0.673 kg CO_2e/L
- Gasoline: 0.604 kg CO_2e/L
- Heavy oil: 0.764 kg CO_2e/L
- LPG: 0.453 kg CO_2e/L, equivalent to 0.824 kg CO_2e/kg (1 kg = 1.818 L)

e) Waste Disposal

Emissions are calculated as waste weight × disposal emission factor. According to the Ministry of the Environment's Carbon Footprint Network, factors include: general waste incineration 3.27E+2 kg CO_2e/ton, landfill 7.07 kg CO_2e/ton, and ash/waste materialization 123 kg CO_2e/ton (Tainan and Southern Taiwan facilities).

3.5 Hotspot Identification and Analysis

3.5.1 Hotspot Determination Criteria and Filtering Logic

In order to effectively allocate resources and propose specific, feasible actions, this study employs carbon emission hotspot analysis as an advanced tool for processing categorized data. In this context, a *hotspot* is defined as any emission activity that either demonstrates significant magnitude in terms of absolute emissions or relative share, or exhibits high controllability and potential for improvement from a management perspective.

To operationalize this definition, the study evaluates carbon emissions based on importance, relative intensity, and management feasibility**,** and applies three principles for hotspot determination. An emission source is identified as a hotspot if it meets any two of the following criteria:

a) Carbon emissions exceed 10% of total organizational emissions.
b) The emission source ranks within the top 25% of items in its category.
c) The source is highly controllable, with practical and resource-feasible conditions for improvement.

The rationale for these criteria is consistent with the "materiality principle" outlined in ISO 14064-1:2018 and further informed by recognized practices in greenhouse gas management, including the GHG Protocol (2011) and CDP (2022) recommendations for supply chain carbon inventories. These guidelines collectively provide the foundation for identifying emission hotspots and establishing prioritized targets for mitigation in this study.

3.5.2 Analysis of Hotspot in the GHG Inventory

In Indirect Emission Category 4, the organization's use of purchased raw materials contributes significantly to greenhouse gas (GHG) emissions. Specifically, waste aluminum accounts for 3,665.8845 metric tons CO_2e, representing 10.01% of total emissions. Pure aluminum contributes 10,587.5976 metric tons CO_2e, or 28.90% of the total, while metallic silicon accounts for 8,810.5950 metric tons CO_2e, equivalent to 24.05% of overall emissions.

In Direct Emission Category 1, GHG emissions from the combustion of heavy oil in stationary furnaces amount to 8,645.2744 metric tons CO_2e, representing 23.60% of the total. In Indirect Emission Category 2, emissions from purchased electricity and other energy sources total 1,059.8940 metric tons CO_2e per year, accounting for 2.89% of overall emissions.

Applying the established hotspot determination principles and screening logic, the following were identified as emission hotspots: Category 4 (waste aluminum, pure aluminum, and metallic silicon raw materials), Category 1 (heavy oil use in stationary furnaces), and Category 2 (indirect emissions from electricity and energy use). These categories, therefore, represent prioritized targets for improvement in subsequent analyses.

3.6 Improvement Strategies

Aiming at the identified hotspot projects, this study develops a GHG inventory carbon emission hotspot analysis framework to formulate feasible improvement strategies. The strategies proposed include energy substitution, such as fuel switching and the procurement of renewable energy certificates; enhancement of equipment efficiency, for instance through air pressure system replacement or heat recovery and utilization; substitution and adjustment of raw materials, including the use of recycled aluminum or low-carbon primary aluminum; optimization of transportation and logistics by measures such as car pooling, dispatching, or the introduction of rail transportation; and refinement of management systems through strengthened maintenance regimes and the integration of emission monitoring technologies.

The prioritization of these strategies is guided by a multi-criteria comparative assessment (Table 4). The key considerations include the degree of controllability within the enterprise, the technical feasibility of implementation, the estimated potential for carbon reduction (with a benchmark of at least 10% annual reductions), the appropriateness of cost and payback conditions, and the expected implementation timeframe across short-, medium-, and long-term horizons. These indicators were analyzed qualitatively and comparatively according to the specific conditions of the case factory, and the results are consolidated as the foundation for ranking and prioritizing recommendations. In this way, the analysis provides structured guidance to promote improvement actions for each identified hotspot.

Table 4: The Prioritization of Hotspot Improvement Strategies

Improvement Category	Scrap Aluminum Procurement	Pure Aluminum Procurement	Silicon Metal Procurement	Furnace Heavy Fuel Oil Usage	Indirect Emissions from Electricity
Energy Substitution Strategy	5	5	5	1	2
Equipment Efficiency Improvement	2	2	2	3	1
Raw Material Substitution & Adjustment	1	1	1	2	5
Transportation & Logistics Optimization	4	4	4	4	4
Management System Enhancement	3	3	3	5	3

The overall logic of hotspot determination and the associated strategy-filtering framework constructed in this study is modular in design. While demonstrated through the case of an aluminum ingot factory, the methodology also possesses transferability across different factories and can be extended to small- and medium-sized manufacturing enterprises to support carbon reduction decision-making. As such, it can serve as a preliminary decision-support tool for practical implementation. The methodological foundation relies on comprehensive GHG inventory data compiled for the year 2023 and adheres to the classification framework of ISO 14064-1:2018 as well as the announcements of Taiwan's Ministry of the Environment, ensuring both international recognition and local applicability.

Nevertheless, certain limitations must be acknowledged. From a data perspective, this inventory represents the first complete application of the framework to the case factory, and some activity data—such as outsourced logistics distances, third-party transportation emission intensities, and the carbon footprint of certain raw materials—were estimated rather than directly measured. Although conservative assumptions were adopted, uncertainties remain in the precise ranking and quantitative analysis.

Furthermore, the inventory is limited to a single year, preventing longitudinal trend comparisons or before-and-after evaluations, thereby constraining the robustness of the findings. From a methodological perspective, hotspot determination and strategy ranking were conducted using qualitative and semi-quantitative assessments, without applying formal multi-criteria decision-making techniques such as AHP or TOPSIS. While this choice enhances the comprehensibility and practical applicability for SMEs, it reduces the statistical rigor and persuasiveness of the analysis. Additionally, most of the proposed improvement strategies are derived from literature and industry experience rather than tested field implementation, and thus, their estimated benefits remain indicative. Their ultimate effectiveness will depend on future enterprise-level initiatives, financial considerations, workforce training, and supplier cooperation.

Overall, the research methodology developed in this chapter not only addresses the carbon emission management needs of the case aluminum ingot factory but also provides a replicable and adaptable reference model for small and medium-sized manufacturing industries. Its structured yet flexible framework offers both practical relevance and potential for broader promotion across diverse industrial contexts.

4. Emission Structure Analysis

4.1 Distribution and Proportions of Carbon Emissions by Industry Type

According to the greenhouse gas (GHG) inventory conducted for the aluminum ingot factories in 2023, total emissions amounted to 36,637.57 metric tons of CO_2e, encompassing all four major categories (Category 1 to Category 4). The overall emission profile indicates that the plant's GHG emissions are primarily driven by indirect sources, with the raw material stage (Category 4) accounting for the largest share. This outcome underscores the aluminum industry's dependence on carbon-intensive raw materials and highlights the significant emission pressures embedded within the supply chain.

A breakdown of emissions by category shows the following results. Category 1 (direct emissions) totaled 9,072.56 metric tons CO_2e, representing 24.7% of overall emissions, primarily from fuel combustion and fugitive process emissions. Category 2 (indirect emissions from purchased electricity) accounted for 1,059.89 metric tons CO_2e or 2.9%, reflecting electricity consumption. Category 3 (other indirect emissions from transportation) amounted to 924.47 metric tons CO_2e, or 2.5%, covering third-party logistics for raw materials and product shipments. By far the largest share came from Category 4 (indirect emissions from purchased goods and services), which reached 25,581.16 metric tons CO_2e, equivalent to 69.9% of the total. This confirms that the carbon footprints of primary aluminum and auxiliary material inputs exert the greatest influence on the plant's overall emissions.

In summary, the emission structure of the plant is characterized by a concentration of raw-material-driven, supply-chain-related, indirect emissions**.** This finding suggests that future mitigation strategies should prioritize supply chain engagement, substitution with lower-carbon raw materials, and optimization of the energy structure to achieve meaningful reductions.

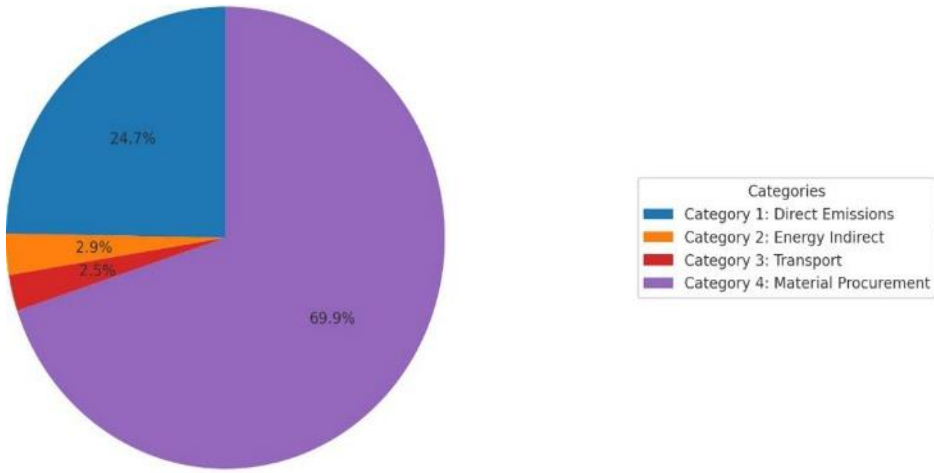

Figure 4: Proportion of Carbon Emissions by Category

Figure 4 presents the distribution of greenhouse gas (GHG) emissions by category for the aluminum ingot plant in 2023. Emissions are divided into four categories. Category 1 (direct emissions), including fuel combustion and fugitive process emissions, accounted for 24.7% of the total. Category 2 (indirect energy emissions), primarily from purchased electricity, represented 2.9%. Category 3 (transportation-related indirect emissions), derived from outsourced logistics and product distribution, contributed 2.5%. By far the largest share was from Category 4 (raw material procurement-related emissions), which amounted to 69.9%, making it the dominant hotspot of the plant's carbon footprint.

The predominance of Category 4 highlights the aluminum industry's reliance on carbon-intensive raw materials such as primary aluminum, metallic silicon, and scrap aluminum. In 2023, most of the primary aluminum used by the plant was imported, with an emission factor of approximately 9.85 kg CO_2e/kg, resulting in a significant impact on overall emissions. While Category 1 emissions are more directly controllable within the plant, they still accounted for more than one-quarter of total emissions. These arise mainly from diesel fuel combustion in boilers, liquefied petroleum gas (LPG) consumption, and refrigerant fugitive emissions. The plant's melting and casting systems rely on traditional combustion-based heating, which contributes heavily to stationary source emissions, with additional contributions from internal transport vehicles.

Category 2 emissions stem from electricity consumption. Although Taiwan's grid emission factor is relatively lower than that of fossil fuels, electricity use remains substantial given the high demand of melting furnaces and compressed air systems. At the time of the inventory, renewable energy had not yet been adopted, though the plant later considered integrating solar power and other clean energy options.

Category 3 emissions include upstream and downstream logistics, covering inbound raw materials and outbound products. These emissions are largely estimated due to variability in transport distances and shipment volumes. Although their share of total emissions is relatively small, improving data precision and enhancing logistics management could present additional opportunities for emission reduction in the future. Overall, the emission structure is "raw-material driven and primarily indirect", indicating that effective carbon reduction strategies must prioritize supply chain management, procurement practices, and energy structure optimization.

4.2 Determination and Explanation of Hotspot Sources

Based on the hotspot determination logic outlined, this study applied the criteria of "total emissions exceeding 10% of overall emissions" and "ranking among the top emission sources within the same category" to identify carbon emission hotspots. Through a category-by-category comparison of Categories 1 to 4, five major hotspot sources were identified: procurement of primary aluminum, procurement of metallic silicon, combustion of heavy oil in boilers (Category 1), purchased electricity (Category 2), and procurement of scrap aluminum (Category 4).

Among these, primary aluminum procurement emerged as the single largest source of emissions, with annual emissions of 10,587.60 metric tons CO_2e, accounting for 38.89% of total emissions. The second-largest source was metallic silicon procurement, which generated 8,810.60 metric tons CO_2e annually, representing 24.04% of total emissions. Heavy oil consumption in boilers contributed 8,645.27 metric tons CO_2e, or 23.59% of the total, while scrap aluminum procurement accounted for 3,665.88 metric tons CO_2e, or 10.00% of the total. By contrast, purchased electricity generated 1,059.89 metric tons CO_2e, representing a smaller but still significant share of 2.89% of total emissions.

4.3 Recommendations for Improvement Strategies

4.3.1 Improvement Direction of Primary Aluminum Procurement Hotspot

Primary aluminum procurement represents the single largest source of carbon emissions, with annual emissions exceeding 10,587.60 metric tons of CO_2e, or 38.89% of total emissions. Given that primary aluminum procurement is the most critical emission hotspot, two strategic directions are proposed: raw material substitution and supply chain cooperation.

From the perspective of raw material substitution, increasing the proportion of recycled and scrap aluminum is the most direct approach to carbon reduction. According to the International Aluminum Association (IAI), recycled and scrap aluminum can reduce carbon intensity by more than 90% compared with primary aluminum, while remaining compatible with most aluminum ingot manufacturing requirements. Nevertheless, challenges such as quality, stability, and price volatility must be considered. To address these limitations, a phased introduction strategy is recommended—beginning with applications in mid-range products or non-critical components, and progressively expanding to broader product lines as stability and supply conditions improve.

From the perspective of supply chain cooperation, it is essential to establish a carbon footprint verification system for upstream suppliers and to incorporate verified emission performance into procurement evaluation indices. By requiring suppliers to disclose carbon emission data and fostering a carbon-transparent supply chain, the organization can progressively increase the proportion of low-carbon primary aluminum in its sourcing portfolio. Such measures, reinforced through contractual agreements and supplier collaboration platforms, not only enhance emission reduction but also align with emerging international requirements such as carbon border adjustment mechanisms (CBAMs) and green procurement standards.

4.3.2 Improvement Direction of Silicon-Metal Procurement Hotspot

The annual emissions associated with silicon-metal procurement exceed 8,810.60 metric tons of CO_2e, representing 24.04% of total emissions. Given the magnitude of this source, two major strategic directions are recommended: raw material substitution and supply chain cooperation**.**

With respect to raw material substitution, opportunities lie in reducing the reliance on high-carbon silicon metal and exploring potential alternatives or process modifications that can partially substitute its use. Such measures should be evaluated in terms of technical feasibility, product performance, and economic cost. A phased introduction strategy is advised, whereby substitution efforts initially target mid-range products or non-critical applications, with gradual expansion to broader product categories once quality assurance and supply stability can be secured.

In parallel, strengthening supply chain cooperation is crucial. This involves engaging with upstream suppliers to disclose carbon emission data, encouraging the adoption of low-carbon production technologies, and integrating emission performance into procurement criteria. Establishing transparent supplier evaluation mechanisms not only promotes emission reductions at the source but also enhances alignment with emerging international standards for sustainable materials management.

4.3.3 Improvement Direction of Heavy Oil Consumption in Boilers

The annual emissions from heavy oil consumption in boilers exceed 8,645.27 metric tons of CO_2e, representing 23.59% of total emissions. To address this significant source, two parallel approaches are recommended: fuel substitution and efficiency enhancement.

From a fuel substitution perspective, the feasibility of transitioning boilers from heavy oil to lower-carbon alternatives such as natural gas, liquefied petroleum gas (LPG), or biomass-based fuels (e.g., liquefied natural gas, LPG, or biodiesel) should be carefully evaluated. In addition, the adoption of electric heating auxiliary modules or infrared heating technology could help reduce dependence on fossil fuels and thereby lower the associated emission factors.

From an equipment efficiency perspective, it is advisable to introduce a boiler exhaust heat recovery system to capture and reuse waste heat for preheating feedwater or producing domestic hot water. Furthermore, installing intelligent temperature control systems and combustion air ratio control devices can enhance combustion stability, minimize excess air, and reduce heat loss. Although these measures typically require relatively high upfront investment, a portion of the costs can be offset over time through the associated energy savings and operational efficiency gains.

4.3.4 Improvement Direction of Aluminum Waste Purchasing Hotspot

The annual emissions from aluminum scrap procurement amount to 3,665.88 metric tons of CO_2e, representing 10.00% of the plant's total emissions. To improve the reliability of this calculation, it is essential to obtain more accurate and verifiable carbon emission coefficients. These data should ideally be provided by upstream supply chain manufacturers or sourced from internationally recognized databases such as the International Carbon Emission Coefficient (ICE). Establishing such a foundation will enhance the precision of the GHG inventory and improve comparability with international reporting standards.

In terms of improvement strategies, two directions are recommended. First, supply chain manufacturers should be encouraged or required to disclose product-level carbon footprint data through standardized reporting mechanisms. This can be achieved by incorporating carbon footprint verification into procurement contracts and supplier evaluation systems. Over time, this would help establish a carbon-transparent supply chain and encourage suppliers to adopt lower-carbon production practices. Second, companies should consider engaging with third-party verification systems or certification bodies to ensure the credibility of supplier-reported data. This could involve leveraging international certification platforms, product category rules (PCRs), or recognized life cycle assessment (LCA) databases to cross-check emission coefficients.

By integrating these measures, the organization can not only improve the accuracy of its carbon footprint accounting but also strengthen its position in meeting the requirements of international green procurement frameworks and carbon border adjustment mechanisms. Ultimately, accurate and transparent emission data for aluminum scrap procurement will contribute to more robust hotspot analysis and more effective carbon reduction strategies.

4.3.5 Improvement Direction of Electricity Use and Energy Saving Strategies

The annual emissions from purchased electricity amount to 1,059.89 metric tons of CO_2e, accounting for 2.89% of total emissions. To address Category 2 emissions, two strategic pathways are recommended: energy efficiency improvement and energy structure transformation.

In the short term, energy-saving measures should be prioritized. These include the installation of inverters, the replacement of conventional lighting with LED systems, and the targeted diagnosis and replacement of high-energy-consuming equipment. Such measures can yield immediate reductions in electricity demand and mitigate dependence on grid-based emission factors. In the medium term, structural adjustments should be pursued through the deployment of solar photovoltaic systems or by collaborating with renewable energy providers to procure Taiwan Renewable Energy Certificates (T-RECs), thereby reducing the share of grid electricity in the overall energy mix.

To strengthen management capacity, it is further recommended to establish an electricity consumption monitoring system that enables regular tracking of consumption by area and equipment. This system would support the implementation of target-based management and foster an internal energy-saving incentive mechanism, thereby embedding continuous improvement within organizational operations.

4.4 Consolidated Ranking and Promotion Suggestions

Based on the five identified hotspots and their corresponding improvement directions, a preliminary ranking of strategies was developed by assessing carbon reduction potential, controllability, cost-effectiveness, and feasible implementation timeframe. The suggested priorities are as follows. First, the replacement of boiler heavy oil systems with high-efficiency, low-carbon fuel equipment should be undertaken, as this represents a short-term measure with technical stability and relatively low investment costs. Second, the installation of inverter-based power-saving devices and the retrofitting of lighting with energy-efficient systems offer a low-cost, high-benefit intervention that can be rapidly implemented. Third, the pilot introduction of recycled aluminum, coupled with the establishment of a carbon disclosure–based procurement system, is recommended for the medium term, given its high emission-reduction potential. Fourth, green power procurement and solar photovoltaic system construction should be pursued in the medium to long term, as part of broader strategic planning for energy structure transformation. Finally, the study of silicon reduction and substitution options is advised as a medium- to long-term strategy with important strategic implications for material decarbonization.

The improvement strategies proposed in this chapter emphasize a balance between practical operational measures and strategic, longer-term planning. They can be flexibly adjusted according to the enterprise's budgetary resources, workforce capacity, and technical readiness. In practice, it is recommended to begin with highly controllable, low-investment projects to deliver immediate results and build internal momentum, while gradually transitioning toward capital-intensive strategic projects that establish a stable and sustainable carbon management trajectory.

5. Conclusion

5.1 Discussion

This study focuses on an aluminum ingot manufacturing plant in southern Taiwan and utilizes its complete greenhouse gas (GHG) inventory data for 2023 to systematically analyze carbon emission structures across Categories 1 to 4. Based on this analysis, major emission hotspots were identified, corresponding improvement strategies were developed, and prioritized action proposals were formulated. The methodology draws on the ISO 14064-1:2018 standard and the Inventory and Classification Guidelines of the Ministry of the Environment, Executive Yuan, supplemented by domestic and international literature as well as practical carbon reduction experience. In doing so, the study constructs a carbon management framework for small- and medium-sized manufacturing enterprises that is both replicable and operationally feasible.

The key findings can be summarized as follows. First, the carbon emission profile of the case plant is dominated by Category 4 (raw material procurement), which accounts for 69.83% of total emissions, followed by Category 1 (direct emissions) at 24.76%. This demonstrates that the plant's carbon footprint arises primarily from upstream raw material inputs and in-factory fuel use. Second, through detailed inventory and hotspot analysis, five major sources of emissions were identified: procurement of primary aluminum, procurement of metallic silicon, combustion of heavy oil in boilers, procurement of scrap aluminum, and purchased electricity. These hotspots span both direct and indirect sources, covering raw materials, energy, equipment, and manufacturing processes. Third, targeted carbon reduction strategies were developed for each hotspot, including raw material substitution, fuel switching, energy efficiency improvement, supply chain carbon disclosure, and carbon emission management. These strategies were evaluated against criteria such as controllability, technological maturity, cost-effectiveness, and carbon reduction potential, resulting in five prioritized recommendations for improvement. Finally, the study establishes a logical and modular analytical framework that integrates hotspot determination, strategy formulation, and prioritization for promotion. This framework accounts for the resource constraints and operational realities of small and medium-sized enterprises, and offers strong potential for broader application and dissemination.

5.2 Practical Implications

For enterprises, it is recommended to conduct regular carbon emission hotspot reviews in accordance with the analytical framework developed in this study. Priority should be given to highly controllable and low-investment projects, such as refrigerant replacement and the retirement of energy-inefficient equipment, as these measures can deliver immediate results while fostering an internal culture of carbon management. Over time, such practices can enhance organizational maturity in sustainability governance and provide a foundation for more strategic, long-term emission reduction initiatives.

For policymakers, particular attention should be directed toward the needs of SMEs. It is recommended that relevant authorities develop and disseminate industry-specific hotspot identification and improvement strategy modules, providing benchmarks and reference values tailored to different sectors. Furthermore, policy support could include capacity-building programs to assist enterprises in establishing robust GHG inventory systems and implementing improvement measures. Financial incentives, such as subsidies or preferential funding mechanisms, would further encourage SMEs to adopt low-carbon technologies and strengthen their role in national and international carbon reduction efforts.

5.3 Future Research

Although this study focuses on a single aluminum ingot factory as a case example, the proposed research framework and analytical logic are broadly applicable. They are expected to provide a concrete reference for SMEs in implementing carbon management, advancing sustainable practices, and responding to the challenges of the net-zero transition. The hotspot ranking and improvement recommendations presented in this study are derived from a logical analysis of current inventory data. However, in practice, differences in internal systems, data recording habits, and equipment conditions across enterprises necessitate the continuous collection of operational feedback and improvement outcomes. Such iterative adjustments enable timely revisions to assumptions and strategic planning, thereby enhancing the stability, operational flexibility, and decision-making precision of carbon management systems, and ultimately facilitating their institutionalization and continuous refinement.

The calculation methods and data verification applied in this study's greenhouse gas inventory have been independently validated by a third-party verifier (DNV) and awarded ISO 14064 certification, which underscores the reliability and accuracy of the inventory results. To further strengthen the credibility of future carbon management initiatives, the company plans to extend its efforts by conducting product-level carbon footprint assessments and obtaining ISO 14067 certification. These steps will provide an additional foundation for the ongoing advancement of systematic and credible carbon management practices.

References

[1] Cinelli, G., Tositti, L., Capaccioni, B., Brattich, E., & Mostacci, D. (2015). Soil gas radon assessment and development of a radon risk map in Bolsena, Central Italy. Environmental Geochemistry and Health, 37(2), 305-319.

[2] Daddi, T., Todaro, N. M., Marrucci, L., & Iraldo, F. (2022). Determinants and relevance of internalisation of environmental management systems. Journal of Cleaner Production, 374, 134064.

[3] Dai, H., Saccardo, S., Han, M. A., Roh, L., Raja, N., Vangala, S., Modi, H., Pandya, S., Slloyan, M. & Croymans, D. M. (2021). Behavioural nudges increase COVID-19 vaccinations. Nature, 597(7876), 404-409.

[4] Downie, J., & Stubbs, W. (2012). Corporate carbon strategies and greenhouse gas emission assessments: the implications of scope 3 emission factor selection. Business Strategy and the Environment, 21(6), 412-422.

[5] Flannery, B. P., & Mares, J. W. (2022). The greenhouse gas index for products in 39 industrial sectors. Working paper. Washington, DC: Resources for the Future.

[6] Green Jr, K. W., Zelbst, P. J., Meacham, J., & Bhadauria, V. S. (2012). Green supply chain management practices: Impact on performance. Supply Chain Management: An International Journal, 17(3), 290-305.

[7] Guo, X., Wu, L., & Lord, D. (2020). Generalized criteria for evaluating hotspot identification methods. Accident Analysis & Prevention, 145, 105684.

[8] Hasanbeigi, A. (2022). Steel Climate Impact. An International Benchmarking of Energy and CO2 Intensities. Global Efficiency Intelligence.

[9] Hertwich, E. G., & Wood, R. (2018). The growing importance of scope 3 greenhouse gas emissions from industry. Environmental Research Letters, 13(10), 104013.

[10] Jang, H. M., Yoo, S., Choi, Y. K., Park, S., & Kan, E. (2018). Adsorption isotherm, kinetic modeling and mechanism of tetracycline on Pinus taeda-derived activated biochar. Bioresource Technology, 259, 24-31.

[11] Jang, K. J., Heo, T. Y., & Jeong, S. H. (2020). Classification option for Korean traditional paper based on type of raw materials, using near-infrared spectroscopy and multivariate statistical methods. BioResources, 15(4), 9045-58.

[12] Lee, J. (2018). Methodological applications of membership categorization analysis for social class research. Applied Linguistics, 39(4), 532-554.

[13] Legg, S. (2021). IPCC, 2021: Climate change 2021-the physical science basis. Interaction, 49(4), 44-45.

[14] Mattila, T. J., & Niemi, J. (2025). Targeting phosphorus loss with carbon farming practices? Results from an on-farm study. BioRxiv, 2025-09.

[15] Peng, S., Ping, J., Li, T., Wang, F., Zhang, H., & Liu, C. (2022). Environmental benefits of remanufacturing mechanical products: a harmonized meta-analysis of comparative life cycle assessment studies. Journal of Environmental Management, 306, 114479.

[16] Sáez-Guinoa, J., García-Franco, E., Llera-Sastresa, E., & Romeo, L. M. (2024). The effects of energy consumption of alumina production in the environmental impacts using life cycle assessment. The International Journal of Life Cycle Assessment, 29(3), 380-393.
[17] Song, C., Wu, L., Xie, Y., He, J., Chen, X., Wang, T., Lin, Y., Jin, T., Wang, A. Liu, Y., Dai, Q. & Mao, H. (2017). Air pollution in China: Status and spatiotemporal variations. Environmental Pollution, 227, 334-347.
[18] Tan, X., Liu, Y., Zeng, G., Wang, X., Hu, X., Gu, Y., & Yang, Z. (2015). Application of biochar for the removal of pollutants from aqueous solutions. Chemosphere, 125, 70-85.
[19] Wiedmann, T. (2009). A review of recent multi-region input–output models used for consumption-based emission and resource accounting. Ecological economics, 69(2), 211-222.
[20] Wiedmann, T., & Minx, J. (2008). A definition of 'carbon footprint'. Ecological Economics Research Trends, 1, 1-11.