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A Study on the Carbon Emission Characteristics of Surface Treatment, Lightweight Metal Processing, and Mold Manufacturing Industries in Taiwan's Metal and Electrical Machinery Sectors

Chia-Chien Cheng*, Huann-Ming Chou **and Chih-Wei Chiang**

Keywords: mold manufacturing industry, lightweight metal processing industry, surface treatment industry, GHGs emissions, smart production,

ABSTRACT

This study examined the greenhouse gas (GHG) emission characteristics of surface treatment, lightweight metal processing, and mold manufacturing industries in Taiwan's metal and electrical machinery manufacturing sectors. Carbon inventory analysis of 22 enterprises revealed that Scope 2 (indirect) emissions accounted for an average of 67.99% of total emissions, while CO_2, CH_4, and HFCs were the main Scope 1 (direct) emissions. Fugitive emissions dominated the lightweight metal processing industry, fixed emissions prevailed in surface treatment, and mold manufacturing had a balanced profile. Notably, per capita carbon emissions in the mold manufacturing industry were 11.07 tonnes CO_2e/person, 4 times higher than in the other two industries, suggesting that Scope 1 and 2 emissions can serve as distinct indicators of the level of process automation or smart production implemented within these industries.

INTRODUCTION

According to a report published by the International Energy Agency (IEA), global energy-related CO_2 emissions experienced a 1.1% increase in 2023, reaching a record high of 37.4 billion tonnes. The report highlights that coal emissions were responsible for more than 65% of this increase.

The IEA also emphasizes that between 2019 and 2023, the growth in global emissions would have been three times higher if not for the sustained deployment of five key clean energy technologies: solar, wind, nuclear, heat pumps, and electric vehicles. However, the report indicates that the current rate of clean energy development is insufficient to fully counterbalance the increase in global energy demand, leading to a continued rise in emissions. This finding underscores the urgent need for accelerated efforts to scale up clean energy technologies and implement effective policies to mitigate GHG emissions and combat climate change (IEA, 2023). The United Nations Climate Change Conference (COP28) has set a global target for 2030, aiming to limit the increase in global average temperature to within 1.5 °C above preindustrial levels (United Nations Climate Change, 2023). In alignment with this international objective, the Taiwanese government has committed to achieving net zero emissions by 2050 and is actively promoting industrial transformation to reduce GHG emissions (Environmental Protection Administration, 2023). The manufacturing industry is a significant contributor to Taiwan's overall GHG emissions, accounting for over 52% of such emissions. Among the various industrial categories, the metal-related industry has the highest emissions, representing 32.3% of the manufacturing sector's emissions (Environmental Protection Administration, 2023). To tackle this challenge, the Industrial Development Bureau of the Ministry of Economic Affairs, Taiwan, developed carbon inventory guidelines specifically for Taiwan's metal product manufacturers (Ministry of Economic Affairs, Industrial Development Bureau, 2023). These guidelines enable enterprises to assess their current carbon emissions through self-evaluation, establishing a foundation for future energy-saving measures, carbon reduction initiatives, and a transition toward green production.

Taiwan's mold manufacturing, lightweight

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***Professor, Department of Mechanical and Energy Engineering, Kun Shan University, Tainan, Taiwan,71070, ROC.*

***Professor, Department of Mechanical and Energy Engineering, Kun Shan University, Tainan, Taiwan,71070, ROC.*

**Ph.D. Candidate, Department of Mechanical and Energy Engineering, Kun Shan University, Tainan, Taiwan,71070, ROC.*

metal processing, and surface treatment industries are crucial components of the metal and electrical machinery manufacturing sector. These closely interconnected industries share similarities in their development trajectories, forming an integrated upstream, midstream, and downstream ecosystem. This study analyzed their greenhouse gas (GHG) emission characteristics to guide targeted energy conservation and carbon reduction measures for enterprises and policymakers. The findings propose strategies to support SMEs in adopting eco-friendly practices while maintaining competitiveness, facilitating a transition towards a low-carbon future and contributing to sustainable development within these industries.

MATERIALS AND METHODS

Analysis of The Current Industries' Development

Enterprises in the surface treatment, lightweight metal processing, and mold manufacturing industries in Taiwan are confronted with common structural challenges, including environmental protection, energy, and manpower (Lin Yuyang,2024; Ministry of Economic Affairs, 2023). Particularly in the context of GHG emission reduction, these three industries frequently involve high-energy-consuming and high-emission processes in their production, which imposes a significant burden on the environment (Huang Chi-Feng and Pan Tze-Chin, 2020). Consequently, when implementing smart and green production initiatives (Shrouf F. et al.,2014), it is crucial to consider the distinct characteristics of each industry to effectively reduce GHG emissions. Moreover, relevant information highlights that in terms of human resource structure, traditional manufacturing processing techniques in these industries rely heavily on manual work and the expertise of experienced workers. As these skilled workers retire, the transfer of knowledge and technology becomes increasingly difficult. Although automated manufacturing and smart production have emerged as prevalent trends, the scarcity of interdisciplinary talent poses a significant obstacle to these industries' pursuit of automation (Chen Tieyuan, 2016).

To address these challenges, it is essential to integrate the information disclosed through a carbon inventory with the establishment of a comprehensive carbon emission management mechanism that covers both upstream and downstream processes. Furthermore, regular disclosure of carbon emission information will enhance the effectiveness of monitoring carbon emission hotspots and enable the formulation of internal corporate carbon emission monitoring strategies (Wen-Hsien Tsai, 2023). By adopting these measures, SMEs in Taiwan can maintain their competitiveness while simultaneously advancing green manufacturing practices (Alexander Leiden a et. al.,2021). This approach will not only contribute to the reduction of GHG emissions but also foster sustainable development within these industries.

Sources and Effects of GHG Emissions

In the mold manufacturing industry, direct energy consumption (e.g., electricity and fossil fuel combustion) and indirect emissions from raw material production and transportation contribute to the industry's carbon emission burden. The use of materials with high carbon footprints, such as certain plastics and metals, further exacerbates this issue. However, adopting induction furnaces for casting processes can lead to a substantial reduction in environmental impacts, with life cycle assessment analysis indicating a potential 57% reduction compared to traditional manufacturing methods. Induction furnaces emit significantly lower CO_2e levels and contribute to energy savings by reducing the energy input required for melting and improving raw material utilization rates (Konstantinos Salonitis, et.al., 2016).

Lightweight metal processing, particularly for aluminum and magnesium, is energy-intensive and generates high emissions. The smelting process contributes to local air pollution through the release of waste gases and dust (Light Metal Age, 2024). However, the aluminum industry has made progress in reducing its environmental impact, with renewable energy accounting for 38.7% of the electricity used in 2021. As a result, the total direct GHG emissions from the aluminum industry decreased by 1% in 2021 compared to 2020, reaching 95.9 million tonnes of CO_2 equivalent. Since 1990, the direct emission intensity of the aluminum industry has decreased by 37.4% (IAI, 2024). To further reduce energy consumption and align with international trends, Taiwan's lightweight metal processing industry should adopt measures to improve energy use efficiency and increase the proportion of renewable energy use.

In the surface treatment industry, electrolysis (plating) and abrasive processes are the primary sources of high energy consumption and chemical usage, leading to a higher carbon footprint and ecological threats. Electrolysis processes require substantial electricity and fossil fuel consumption, with a risk of fugitive emissions during pickling and chemical usage processes (Pernelle Nunez, 2016). Optimizing the design of multilayer coating structures can improve their fatigue strength and service life, indirectly reducing energy consumption and environmental impact during manufacturing and maintenance processes (Jingjing Zhang, et al.,2020).

Research Methods

In the present study, carbon inventory reports from 22 metal enterprises in Taiwan, including four mold manufacturing companies, 12 lightweight metal processing companies, and six surface treatment companies, were collected. The data from these reports were then compiled and analyzed. Each company's carbon inventory report was prepared in accordance with the international ISO14064-1:2018 standard (Environmental Protection Administration, 2023), which provides a systematic approach to quantifying and calculating an enterprise's GHG emissions over a specific period. The scope of the carbon inventory can be divided into Scopes 1, 2, and 3. Scope 1 (direct emissions) refers to GHG emissions generated by combustion or fugitive sources owned or controlled by the enterprise, such as burned fossil fuels and GHGs produced during the manufacturing process. Scope 2 (indirect emissions) refers to GHG emissions resulting from the purchase of energy, such as electricity, steam, and heat. Scope 3 (other indirect emissions) refers to GHG emissions generated by other activities upstream and downstream of the enterprise's value chain, such as employee commuting, product transportation, and waste disposal. The scope of disclosure for the case studies in this research was voluntary, and the reports have not yet been verified by a third-party verification body.

RESULTS AND DISCUSSION

Carbon Inventory Analysis of 22 Metal and Electrical Machinery Manufacturing Enterprises in Taiwan

The data analyzed in this study were obtained from the carbon inventory reports of 22 metal manufacturing enterprises. During the inventory process, the organizational boundaries of all the case companies were defined using the operational control approach, and independent inventory scopes were established for each plant. The research sample consisted of three distinct industry types: mold manufacturing, lightweight metal processing, and surface treatment companies.

Mold manufacturing companies, characterized by high-tech products, customization, and small-volume, high-variety production, accounted for only 18.2% (four companies) of the sample. The low representation of this industry can be attributed to the difficulty of setting up and operating such companies, resulting in a smaller number of establishments. In contrast, lightweight metal processing companies, which require a more general level of technology and produce a high variety of products in large quantities, were the most prevalent, accounting for 54.5% (12 companies). The high number of companies in this sector is due to the ease of starting such companies and the high demand for their products. Surface treatment companies, despite having simpler processes and high product demands, accounted for only 27.3% (six companies) of the sample. This can be explained by the low profit margins per unit product and strict wastewater treatment regulations, which make these companies more challenging to operate.

To protect the privacy of the case companies, the sample companies were referred to as numbers 1–22 and listed according to their industrial attributes, as shown in Table 1.

Table 1. Industry Attributes, Greenhouse Gas Emissions by Category, and Proportion of Total Average Emissions

Company	No. of Employee	Capital (NTD, 10,000)	Scope Category 1	Scope 2 Category 2	Scope 3 Category 4	CO_2e Total (Tonnes)	CO_2e Total (Tonne/person)	Industry Attributes
1	7	3,000	241.886	106.972	36.974	385.832	55.119	Mold manufacturing
2	12	850	0.998	44.114	0.000	45.112	3.759	
3	20	1,000	6.747	117.483	21.135	145.364	7.268	
4	75	26,000	274.417	333.773	72.512	680.701	9.076	
5	8	8,800	3.840	8.534	2.065	14.439	1.805	Lightweight metal processing
6	10	500	8.816	57.736	0.000	66.552	6.655	
7	12	7,000	0.425	9.693	0.000	10.117	0.843	
8	15	1,800	4.934	37.382	0.336	42.652	2.843	
9	20	600	2.975	31.937	5.693	40.605	2.030	
10	30	1,000	1.567	24.555	0.003	26.125	0.871	
11	30	8,500	32.032	46.433	7.474	85.939	2.865	
12	30	500	78.669	106.504	18.195	203.369	6.779	
13	40	1,000	1.162	0.396	0.167	1.725	0.043	
14	90	19,900	11.241	102.386	0.001	113.629	1.263	
15	250	120	67.904	760.478	9.092	837.475	3.350	
16	291	40,000	292.546	524.997	26.790	844.333	2.901	
17	6	9,500	166.591	158.954	30.468	356.013	59.336	Surface treatment
18	25	3	1.462	18.448	0.004	19.913	0.797	
19	25	1,000	60.704	95.535	15.755	171.995	6.880	
20	90	1,680	8.149	174.319	0.003	182.471	2.027	
21	150	10,600	10.115	89.932	0.002	100.048	0.667	
22	200	5,500	35.722	461.819	0.000	497.542	2.488	
Total			1312.901	3312.379	246.668	4871.948		
%			26.95%	67.99%	5.06%	100.00%		

The table also includes the capital amounts of the companies. It can be seen in Table 1 that the number of employees and the capital amount in each industry are roughly proportional. However, there are instances in which companies with higher capital amounts have fewer employees, possibly due to the use of more expensive, high-precision, or automated equipment that requires fewer human workers.

The GHG inventory data of metal and electrical machinery manufacturing enterprises presented in Table 1 reveal significant differences in the number of employees and capital scale among the sample companies in the three major industry categories. The number of employees ranges from 6 to 291 people. However, the overall GHG emission structures of the three types of manufacturers exhibit relatively consistent characteristics. The GHG emissions of each company are primarily concentrated in Scope 2 (indirect emissions), accounting for an average of 67.99%, making it the primary emission source. Scope 1 (direct emissions) and Scope 3 (other indirect emissions) have relatively lower emission levels, with average proportions of 26.95% and 5.06%, respectively.

Notably, the GHG emissions of different enterprises showed a positive correlation with their scale (number of employees and capital amount), as shown in Table 2. This correlation is worth exploring in terms of smart production and green manufacturing transformation. Furthermore, there are differences in the main sources of GHG emissions among companies in each industry attribute, which will be explored simultaneously.

Given the aforementioned findings, this study conducted individual analyses and discussions of the major attributes of the mold manufacturing, lightweight metal processing, and surface treatment industries. By examining each industry characteristic separately, the study aimed to provide insights into the specific attributes and emission sources of each sector, contributing to the development of targeted strategies for reducing GHG emissions and promoting sustainable practices within these industries.

Table 2. Comparison of Capital Intensity and Carbon Emission Intensity across the Three Industries

Industries	No. of Employees	Capital (NTD, 10,000)	Average industrial capital (NTD, 10,000/ company)	Capital per capita (NTD, 10,000/person)	CO_2e Total (tonnes)	Carbon emissions per capita CO_2e (tonnes/person)
Mold manufacturing	114	30,850	7,712.50	270.61	1,257.01	11.03
Lightweight metal processing	826	89,720	7,476.67	108.62	2,286.96	2.77
Surface treatment	496	28,283	4,713.84	57.03	1,327.98	2.68

Table 2 reveals a potential positive correlation between capital intensity and carbon emission intensity. The mold manufacturing industry exhibits the highest per capita capital amount, approximately 2.706 million NTD/person, and its per capita carbon emission intensity ranks first among the three industries. This finding confirms that the mold manufacturing industry is indeed a high-energy-consuming and high-carbon-emitting industry, as mentioned earlier. In contrast, the lightweight metal processing and surface treatment industries have relatively lower capital intensities and correspondingly lower carbon emission intensities.

The aforementioned phenomenon warrants further exploration. Capital-intensive industries often rely on large amounts of mechanical equipment and automated production lines, which may consume more energy during operations, leading to higher carbon emissions. Moreover, the production processes in the mold manufacturing industry, such as high-temperature smelting and precision machining, are inherently associated with higher carbon emissions, and the unit output value is usually higher as well.

In comparison, the surface treatment industry has the lowest per capita capital amount, approximately 0.57 million NTD/person, and the lowest per capita carbon emission intensity. This indicates that although this industry has low capital, it may employ a larger number of workers due to insufficient automation, resulting in lower per capita carbon emissions compared to the mold manufacturing and lightweight metal processing industries.

Therefore, under lower levels of capital investment, the surface treatment industry can achieve energy-saving and emission reduction goals through technological innovation and management optimization. By focusing on these strategies, this industry can reduce its carbon footprint and improve its environmental performance, even with limited capital resources.

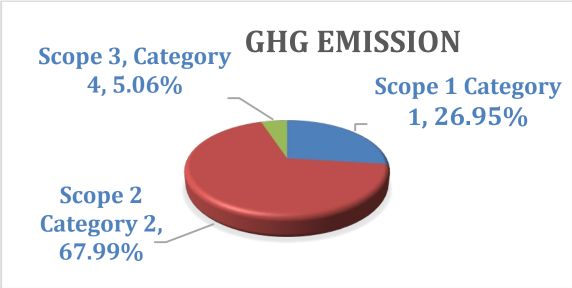

Fig. 1: Total greenhouse gas emissions (carbon dioxide equivalent) from different scopes in 22 enterprise case studies.

Figure 1 reveals that Scope 2 emissions (indirect emissions) are the primary source of carbon emissions for metal and electrical machinery manufacturing enterprises. On average, Scope 2 emissions account for 67.99% of the total emissions generated by these companies.

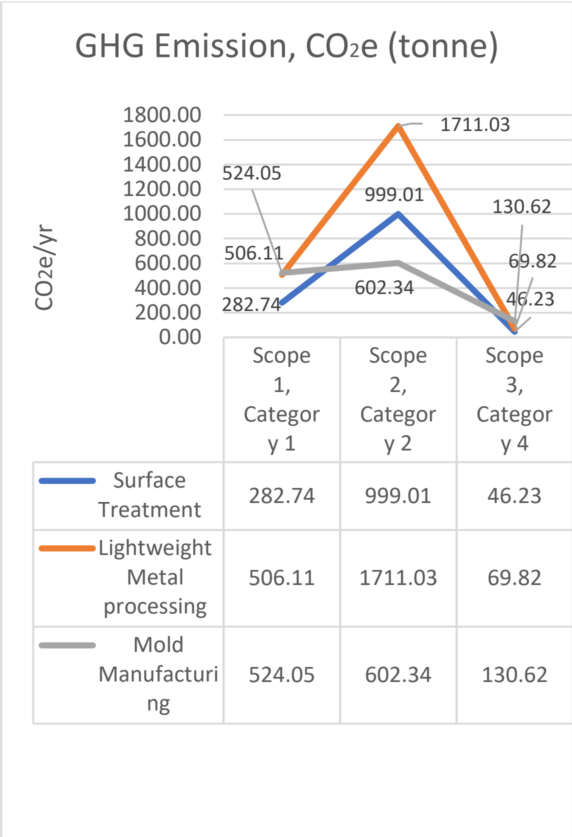

Fig. 2. Comparison of the distribution of total greenhouse gas emissions (carbon dioxide equivalent) from Scopes 1–3 for the surface treatment, lightweight metal processing, and mold manufacturing industries.

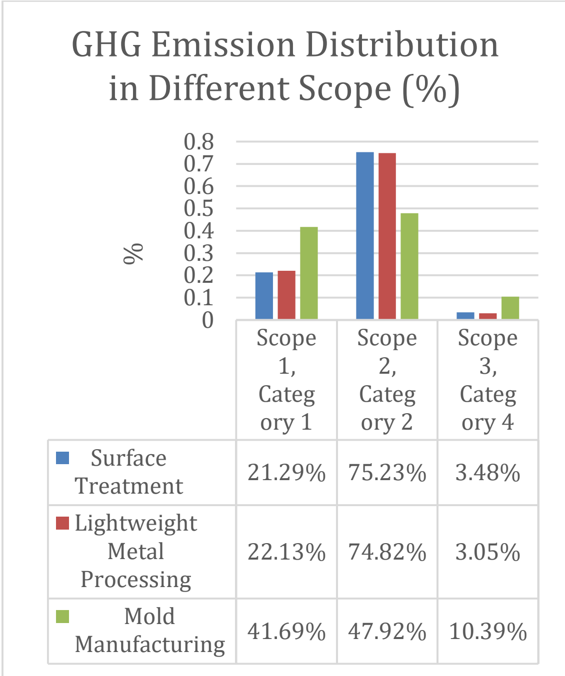

Fig. 3. Proportion of greenhouse gas emissions by scope for the surface treatment, lightweight metal processing, and mold manufacturing industries.

The data presented in Figures 2 and 3 reveal that the GHG emissions in the lightweight metal processing and surface treatment industries are primarily concentrated in Scope 2, which refers to purchased electricity. Scope 2 emissions account for approximately 75% of the total emissions in these industries, which is higher than the overall average of the three industries studied. In contrast, the emissions in the mold manufacturing industry are more evenly distributed, with Scope 1 and 2 emissions each accounting for about 45%, lower than the overall average of the three industries.

The aforementioned findings suggest that for lightweight metal processing and surface treatment companies, formulating and implementing energy-saving and carbon reduction policies aimed at reducing the consumption of purchased electricity will be the most effective way to improve energy efficiency and reduce carbon footprints. However, the structure of Taiwan's electricity supply will have a significant impact on the Scope 2 emissions of these enterprises. Currently, Taiwan's electricity supply relies heavily on thermal power generation. According to Taiwan Power Company data, thermal power generation accounted for 81.8% of the total system generation in 2023, while renewable energy (including hydropower, waste, and biogas power generation) accounted for only 9.9% (Climate Change Administration Ministry of Environment, 2024). Consequently, while industries are actively adopting electricity-saving measures, the government can play a crucial role in reducing the carbon emission intensity per unit of electricity consumption from the source. By formulating relevant policies to increase the proportion of green electricity supply for metal and electrical machinery manufacturing enterprises, the government can help maximize the overall GHG emission reduction benefits. Furthermore, accelerating the development of clean energy and increasing the proportion of renewable energy sources such as nuclear, solar, and wind power in the overall power supply structure is necessary to reduce the production carbon footprints of related industries and achieve environmentally sustainable development.

Analysis of GHG Emission Characteristics in the Industrial Chain

Regarding the composition of emission sources, all the three industry categories studied exhibit stationary emissions, mobile emissions, and fugitive emissions, albeit in varying proportions. Table 4 illustrates these differences.

Table 3. Greenhouse gas emissions from stationary, mobile, and fugitive emission sources in the metal and electrical machinery manufacturing industry (carbon dioxide equivalent)

Companies	No. of Employees	Capital (NTD, 10K)	Scope1 Stationary	Scope1 Mobile	Scope1 Fugitive	CO_2e Total (Tonnes)	CO_{2e} Total (Tonne)/person	Industry Attribute
1	7	3,000	85.658	48.871	107.356	241.886	34.555	Mold Manufacturing
2	12	850	0	0	0.007	0.008	0.001	
3	20	1,000	0	0.729	6.017	6.747	0.337	
4	75	26,000	209.341	58.905	6.169	274.417	3.659	
5	8	8,800	0	1.948	1.891	3.840	0.480	Lightweight metal processing
6	10	500	0	3.434	5.381	8.816	0.882	
7	12	7,000	0	0	0.425	0.425	0.035	
8	15	1,800	1.223	0	3.711	4.934	0.329	
9	20	600	0	1.178	1.796	2.975	0.149	
10	30	1,000	0	0.015	1.551	1.567	0.052	
11	30	8,500	28.057	0.006	3.968	32.032	1.068	
12	30	500	35.884	30.160	12.625	78.669	2.622	
13	40	1,000	0	0.609	0.552	1.162	0.029	
14	90	19,900	0	0.005	11.236	11.241	0.125	
15	250	120	0.087	32.823	34.993	67.904	0.272	
16	291	40,000	68.147	35.221	189.177	292.546	1.005	
17	6	9,500	83.879	26.973	55.738	166.591	27.765	Surface treatment
18	25	3	0	0.013	1.449	1.462	0.058	
19	25	1,000	57.428	0	3.276	60.704	2.428	
20	90	1,680	0	0.010	8.138	8.149	0.091	
21	150	10,600	0	0.005	10.109	10.114	0.067	
22	200	5,500	0	0	35.722	35.722	0.179	
Total			569.709	240.912	501.290	1311.911		
%			43.43%	18.36%	38.21%	100%		

The data from Table 3 show that fugitive emissions are the primary source of emissions in the lightweight metal processing industry, accounting for approximately 55% of the total emissions. In the surface treatment industry, stationary emissions are the main contributors, accounting for about 80%. The mold manufacturing industry has a relatively balanced emission profile, with stationary emissions and fugitive emissions accounting for approximately 45% and 40%, respectively. This reflects the differences in production processes and emission characteristics among the three industries. The lightweight metal processing industry may have higher fugitive emissions due to the larger number of employees, resulting in emissions from septic tanks or office refrigerants. The surface treatment industry consumes a significant amount of energy in processes such as electroplating or baking, leading to higher stationary emissions. The manufacturing processes in the mold industry are relatively dispersed, resulting in similar proportions of various emission types.

Table 4. Types of Greenhouse Gas Emissions (%) and Total Carbon Dioxide Equivalent (Tonne) for the Surface treatment, Lightweight Metal Processing, and Mold Manufacturing Industries.

Industries	CO_2		CH_4		N_2O		HFCs		PFCs	SF6	CO_2e Total (tonnes)	
	%	Carbon Emission CO_2e (Metric Tonne)	%	Carbon Emission CO_2e (Metric Tonne)	%	Carbon Emission CO_2e (Metric Tonne)	%	Carbon Emission CO_2e (Metric Tonne)	%	Carbon Emission CO_2e (Metric Tonne)	%	Carbon Emission CO_2e (Metric Tonne)
Surface Treatment	59.32	167.72	21.99	62.17	0.16	1.69	18.53	52.39	0	0	100	282.743
Mold Manufacturing	76.61	401.46	21.30	111.61	0.33	1.72	1.77	9.26	0	0	100	524.048
Lightweight Metals Processing	46.63	236.00	9.00	45.54	0.44	2.21	43.93	222.35	0	0	100	506.1109

The data presented in Tables 3 and 4 highlight significant differences in the GHG emission structures of the three industries studied. As shown in Table 4, the surface treatment industry exhibits the highest CO2e emissions (59.32%), followed by CH4 (21.99%). The mold manufacturing industry has a high CO2e emission of 76.61%, with lower emissions of other gases. In contrast, the lightweight metal processing industry has similar proportions of CO_2e and HFCs emissions (46.63% and 43.93%, respectively).

It is apparent that the variations in production process characteristics among the industries studied contribute to the differences in their GHG emission structures. For instance, the surface treatment industry has higher CH_4 emissions than the two other industries, which can be directly attributed to the fugitive emissions of the chemicals generated during the electroplating and pickling processes. The mold manufacturing industry primarily relies on fossil fuels for processing and manufacturing, resulting in a large proportion of CO_2e emissions. On the other hand, the lightweight metal processing industry has both fuel combustion and process emissions, leading to a balance between CO_2e and HFCs. These findings underscore the importance of considering industry-specific factors when assessing GHG emission structures and developing targeted strategies for emission reduction.

The comparison of Scope 1 per capita carbon emission intensities of the industries studied provides us with a perspective on the direct emission efficiency levels of different industries. As shown in Table 3, the Scope 1 per capita GHG emission of the mold manufacturing industry is 4.588 CO_2e tonne/person (Scope 1 per capita emission = 523.058 / 114 = 4.588 CO_2e tonne/person), which is significantly higher than the 0.6127 CO_2e tonne/person for lightweight metals and 0.5700 CO_2e tonne/person for surface treatment. The reasons for this difference may be the variation in energy consumption per unit of output value and the degree of automation. The automation level in mold production may be relatively lower, relying more on manual operations, resulting in a higher carbon emission intensity per unit of labor. In contrast, the production processes of lightweight metals and surface treatment may have achieved higher levels of automation, leading to a relatively lower carbon emission intensity per unit of labor.

The level of fugitive emission control in the three industries studied needs to be improved. As shown in Table 3, in most enterprises, fugitive emissions still account for a considerable proportion of emissions. For example, in the 22 lightweight metal processing enterprises studied, the total Scope 1 GHG emission is 292.546 tonnes CO_2e, of which fugitive emissions account for 189.1769 tonnes CO_2e, approximately 64.66%, among the highest fugitive emissions in all the sample enterprises. There may be “fugitive emissions” from industrial production processes, such as material handling and equipment leakage. Therefore, enterprises can adopt equipment upgrades and optimize production parameters through real-time monitoring and feedback control in smart production methods to reduce material and energy waste, which helps to control fugitive emissions from the source. These enterprises’ per capita carbon emissions are 1.005 tonne CO_2e/person, which is also relatively high among all the lightweight metal processing enterprises in the present study. Higher fugitive emissions may also indicate that the enterprise is still in a labor-intensive production mode, with relatively lower levels of automation and intelligence. Specific improvement suggestions can start with using environmentally friendly refrigerants with low global warming potential (GWP) values. These analyses will help lightweight metal processing enterprises formulate targeted fugitive emission control and carbon reduction strategies, maximizing the emission reduction benefits per unit of labor while controlling costs and promoting the low-carbon transformation and development of the industry.

In summary, the mold manufacturing, lightweight metal processing, and surface treatment industries—the three crucial sectors in the material processing industry—exhibit commonalities and distinctions in their GHG emission characteristics, such as emission intensity and structure. When formulating industrial emission reduction policies, policymakers must consider the shared patterns while simultaneously addressing the unique characteristics of each industry to systematically design effective emission reduction pathways. By promoting industrial upgrading and transformation to green manufacturing practices, traditional manufacturing can be elevated to enhance emission reduction levels, ultimately achieving the overall green and low-carbon development of the three industries.

Net Zero Transformation Strategies for the Metal and Electrical Machinery Manufacturing Industry

The data analysis presented above demonstrates that industrial transformation and the extent of smart production and automation can contribute to improved production efficiency and a reduction in the labor required per unit of output, consequently decreasing the per capita carbon emission intensity. However, the relationship between smart production and carbon emissions is not straightforward and exhibits complexities that warrant further investigation. Industry-specific differences exist in various aspects, such as different processes and fuel structures. Companies with a higher proportion of Scope 1 Category 1 carbon emissions tend to have a lower degree of smart production because Scope 1 emissions primarily originate from the combustion of fossil fuels.

In contrast, companies with a higher proportion of Scope 2 Category 2 emissions typically consume more purchased electricity, suggesting that their production processes may be more automated and smarter. By considering the proportion of Scope 1 emissions a "non-smart" indicator and the proportion of Scope 2 emissions a "smart" indicator, we can infer that companies exhibiting the highest degree of "non-smartness," such as Manufacturers 17, 1, and 4, have relatively higher per capita carbon emissions of 59.336, 55.119, and 9.07 CO_2e tonne/person, respectively. In contrast, companies with a higher degree of "smartness," such as Manufacturers 13, 21, and 18, have relatively lower per capita carbon emissions of 0.043, 0.667, and 0.797 CO_2e tonne/person (Table 1), respectively. These findings suggest that when investigating the relationship between smart manufacturing and carbon emissions, it is essential to make comparisons based on industry classifications to account for the inherent differences in production processes and technological adoption among various sectors.

The use of Scope 1 and 2 emission proportions as indicators of "smart manufacturing" requires careful consideration. Traditional manufacturing industries depend heavily on fossil fuels, resulting in a high proportion of Scope 1 emissions. In contrast, industries with a high degree of automation primarily rely on purchased electricity for their production power, leading to higher Scope 2 emissions. While the emission structures of these two scopes can reflect the level of smart production to a certain extent, this approach has limitations. To construct a more rigorous smart manufacturing evaluation system, future research must consider incorporating additional variables, such as the proportion of investment in smart manufacturing technologies and practices.

The energy-saving and emission reduction effects of smart manufacturing may encounter cost pressures during the initial stage of transformation, particularly in recruiting information technology talent and building smart facilities. Adjusting technology and management processes also necessitates a certain amount of time. Some companies in the sample, such as Manufacturer 3, exhibit high Scope 2 emissions (80.8%) but have unsatisfactory per capita carbon emission performance (7.268 CO_2 tonne/person), which may indicate the limited benefits of intelligent manufacturing in the short term. To better evaluate the process of emission reduction benefits, future research must utilize data spanning a longer time period.

Another important consideration is the statistical gaps in Scope 3 emissions. Current domestic and international carbon emission accounting systems are not yet sufficiently well developed for Scope 3 calculations and primarily focus on direct emissions from Scopes 1 and 2. However, as intelligent supply chain management advances, the influence of enterprises may extend upstream and downstream of the value chain, indirectly driving improvements in the overall carbon footprint. For a more comprehensive assessment of the carbon reduction potential of intelligent manufacturing, the availability and accuracy of Scope 3 data must be strengthened.

By comparing the proportions of Scope 1 and 2 emissions and the per capita carbon emission intensity, this study preliminarily found a positive relationship between the level of smart production and carbon emission reduction performance. The level of smart production and per capita carbon emissions exhibited a negative correlation, indicating that higher levels of automation and smart transformation are associated with lower carbon emissions per unit of labor. However, it is important to acknowledge that other factors, such as industry characteristics, also influence per capita carbon emissions. Due to the limitations in sample size and indicator selection, the research inferences drawn from this study require further verification. To improve the reliability of the conclusions, subsequent efforts must focus on expanding the sample size, refining the smart manufacturing evaluation system, concentrating on specific industries, and extending the observation period.

CONCLUSIONS AND SUGGESTIONS

Purchased electricity is the common carbon emission hotspot for the mold manufacturing, lightweight metal processing, and surface treatment industries, accounting for an average of 67.99%. The main GHGs emitted are CO_2, CH_4, and HFCs. Fugitive emissions are the primary source for the lightweight metal processing industry, accounting for 55%, while the surface treatment industry's emissions are mainly from stationary sources, reaching as high as 80%. The mold manufacturing industry has relatively balanced emissions. The correlation between capital intensity and carbon emission intensity is not significant, but the per capita emissions of the mold manufacturing industry are approximately 4 times higher than those of the two other industries. The level of smart production is positively correlated with carbon emission reduction performance. Consequently, metal and electrical machinery manufacturing enterprises can formulate carbon emission reduction strategies based on their respective industry attributes, with a critical focus on reducing per capita emissions in the mold manufacturing industry.

From a policy perspective, vigorously promoting the development of green electricity and increasing the proportion of renewable energy supply for metal and electrical machinery manufacturing enterprises can fundamentally reduce the carbon emission intensity of purchased electricity. For the lightweight metal processing industry, which has more significant fugitive emissions and enterprises still operating in a labor-intensive production mode, it is recommended to simultaneously adopt automated equipment upgrades to reduce per capita carbon emissions and switch to environmentally friendly refrigerants with low GWP values. The surface treatment industry can achieve energy-saving and emission reduction goals by increasing investment in automated production equipment and selecting production and manufacturing equipment with higher International Energy (IE) efficiency levels. In addition to referencing the practices of the above two industries, the mold manufacturing industry can target mobile emission sources, such as by replacing diesel trucks with electric vehicles, to effectively reduce fuel emissions.

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REFERENCES

Alexander Leiden a, Christoph Herrmann a b, Sebastian Thiede a, “Cyber-physical production system approach for energy and resource efficient planning and operation of plating process chains,” Journal of Cleaner Production, Volume 280, Part 2, 125160. (2021)

Chen Tieyuan, “Opportunities and Challenges for Taiwan's Industry from the Perspective of Intelligent Manufacturing Trends,” Technology and Regulatory Information E-Newsletter Issue 123, (2016).

Climate Change Administration Ministry of Environment, “Mandatory Greenhouse Gas Reporting System,” (2024)

Environmental Protection Administration (EPA), Executive Yuan, Taiwan, National Greenhouse Gas Inventory, (2023)

Huang Chi-Feng and Pan Tze-Chin, “Analysis of Energy Use Characteristics and Efficiency Trends in the Metal Product Manufacturing Industry,” Combustion Quarterly, Issue 110, pp.19-30 (2020)

International Aluminium Industry (IAI), Aluminium industry reports decline in greenhouse gas emissions, (2024).

International Energy Agency (IEA), “A new record high, but is there light at the end of the tunnel?” (2023).

Jingjing Zhang, Tingjian Wang, Chuanwei Zhang, Longcheng Yin, Yue Wu, Yang Zhao, Xinxin Ma, Le Gu, and Liqin Wang, “Two-Dimensional Mechanical Behavior Analysis of Multilayered Solids Subjected to Surface Contact Loading Based on a Semi-Analytical Method,” MDPI, (2020).

Konstantinos Salonitis, Mark R. Jolly, Binxu Zeng, Hamid Mehrabi, “Improvements in energy consumption and environmental impact by novel single shot melting process for casting,” Journal

of Cleaner Production, Volume 137, pp. 1532-1542 (2016).
Light Metal Age, "Aluminium Industry Shows Decline in Greenhouse Gas Emissions, "(2024).
Lin Yuyang, "Embracing Productivity 4.0 Towards Future Manufacturing," Industrial Technology and Information Monthly, (2024).
Ministry of Economic Affairs, Industrial Development Bureau, Industrial Energy Conservation and Carbon Reduction, "Metal Product Industry Carbon Footprint Guidelines - Based on International Carbon Tariff Requirements," (2023)
Ministry of Economic Affairs, "White Paper on Small and Medium Enterprises, Small and Medium Enterprise Administration," (2023).
Pernelle Nunez, "Cradle to gate: life cycle impact of primary aluminium production," The International Journal of Life Cycle Assessment Vol.21, p.11, (2016)
Shrouf, F., Ordieres, J., & Miragliotta, G., "Smart factories in Industry 4.0: A review of the concept and of energy management approached in production based on the Internet of Things paradigm." IEEE International Conference on Industrial Engineering and Engineering Management, pp697–701 (2014).
UNCC (United Nations Climate Change), "COP28 Agreement Signals "Beginning of the End" of the Fossil Fuel Era.", (2023).
Wen-Hsien Tsai. "Balancing Profit and Environmental Sustainability with Carbon Emissions Management and Industry 4.0 Technologies." Energies 16, no. 17, p. 6175. (2023)

台灣金屬機電產業中模具、輕金屬及表面處理業之溫室氣體排放特性研究

鄭佳茜 周煥銘 江智偉
崑山科技大學機械與能源研究所

摘 要

本研究探討台灣中小金屬機電產業中的表面處理、輕金屬加工業及模具製造業的溫室氣體排放特性,透過碳盤查分析這三個產業的排放現況,了解不同製程與能源使用下的碳排放強度。研究中分析了 22 家金屬機電中小企業的碳盤查報告數據,涵蓋模具製造業 4 家、輕金屬加工業 12 家和表面處理業 6 家。結果顯示,三類企業的溫室氣體排放主要集中在範疇二(間接能源排放),平均占總排放量的 67.99 %。而在範疇一(直接排放)中,CO_2、CH_4 和 HFCs 是三大產業的主要溫室氣體。排放源結構方面,輕金屬業以逸散排放為主,表面處理業以固定排放為主,模具業則相對均衡,但研究也發現模具業之員工人均排碳量達 11.07 噸 CO_2e/人,約為輕金屬業及表面處理業之 4 倍,為很重要之特性,建議範疇一排放量及範疇二排放量則可視為製程自動化或智慧化程度之一種特性指標。