A Dynamic Marginal Abatement Cost Framework for Manufacturing Systems: Optimising Emissions Reductions under real-world policy constraints

Isaac Kuma Yeboah [1,*], Owusu Banahene [2], Kwabena Agypong Kodua [3], Joseph Buertey [4], Micheal Nartey Agbeko [5], Alex Osei Bonsu [6], Comfort Mensah [7], Charls Baah [8]
[1, 2, 3, 4,5,6,7,8] Faculty of Engineering Science and Computing Pentecost University Accra, Ghana
Email: [1] ikyeboah@pentvars.edu.gh, [2] banahene@pentvars.edu.gh, [3] kagpongkodua@pentvars.edu.gh, [4] jbuertey@pentvars.edu.gh, [5] mnagbeko@pentvars.edu.gh, [6] aobonsu@pentvars.edu.gh, [7] cmensah@pentvars.edu.gh, [8] cbaah@pentvars.edu.gh
*Corresponding Author

***Abstract*—This study presents an integrated techno-economic and policy analysis of decarbonisation pathways for industrial manufacturing systems, combining life cycle assessment (LCA) with dynamic marginal abatement cost curve (MACC) modelling. Using a baseline scenario with variable manufacturing emissions (0-88 kgCO_2eq), fixed operational emissions (55 kgCO_2eq), and end-of-life emissions (11 kgCO_2eq), we demonstrate how strategic interventions can optimise emissions reductions while minimising costs. Our MACC analysis identifies renewable energy adoption (0.30 kgCO_2eq) as the most cost-effective abatement measure. The research extends conventional LCA by incorporating two critical dimensions: (1) region-specific carbon pricing variations (from 0.12 kgCO_2eq in the EU) and (2) policy incentive impacts, including the US 45Q tax credit (10% cost reduction for CCS) and EU renewable energy subsidies. Our results reveal that such incentives can alter optimal abatement pathways, improving ROI by 27-52% and reducing payback periods from 1.5 to 1.1 years in a US case study scenario achieving 30% emissions reduction. A novel contribution is the development of a decision-support framework that dynamically adjusts strategy recommendations based on real-time policy data and local economic conditions. The study provides empirical evidence that policy-aware decarbonisation planning can bridge the gap between technical potential and economic feasibility in industrial systems, with particular relevance for energy-intensive manufacturing sectors.**

Keywords—industrial decarbonization; life cycle assessment; marginal abatement cost curve; carbon pricing; policy incentives; cleaner production.

I. INTRODUCTION

The manufacturing industry faces increasing pressure to adopt sustainable practices and reduce its environmental footprint [1]. This is driven by a combination of regulatory demands, corporate social responsibility initiatives, and the economic benefits of resource efficiency [2]. The concept of “maximum profit from minimum capital” is evolving towards “maximum results (economically and ecologically) from minimum resources” [2]. This shift emphasises the necessity of efficient resource application and emission reduction in manufacturing processes. According to the work done by Perka, Ashok Kumar, et al. (2022), laser welding, a key advanced manufacturing technique, offers significant advantages due to its concentrated heat input, leading to increased processing speed, reduced post-processing, and minimised material distortions [3]. However, despite its efficiency, concerns exist regarding the potential health hazards and environmental impact of fumes and emissions generated during the process [5]. These emissions can include heavy metals, chemical compounds, and dust particles, posing risks to worker health and the environment. This paper aims to provide a comprehensive analysis of laser welding emissions within a dynamic marginal abatement cost framework. We integrate life cycle assessment (LCA) with marginal abatement cost curve (MACC) modelling to identify optimal decarbonisation pathways for industrial manufacturing systems. The study also incorporates region-specific carbon pricing and policy incentives to provide a realistic and actionable decision-support framework for sustainable manufacturing.

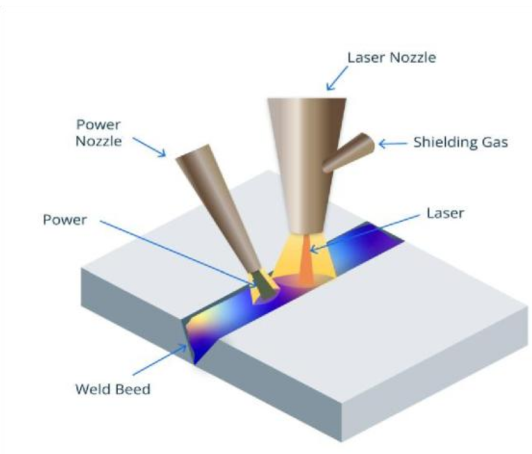

Fig. 1. Laser Welding Process Diagram.

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II. Background

A. Laser Welding Process and Emissions

Laser welding utilises a concentrated beam of high-power light to melt and fuse materials, offering precision, speed, and minimal heat-affected zones [6]. It is widely applied in the automotive, furniture, medical, electronics, and energy industries. Despite its benefits, the process generates fumes containing various hazardous substances. These include metal particles and their compounds, e.g., chromium, nickel, manganese, fluorides from aluminium welding, and harmful gases such as nitrogen oxides, sulphur oxides, and ozone. Dust particles, often in the nanometre range, are also a significant component of laser welding fumes.

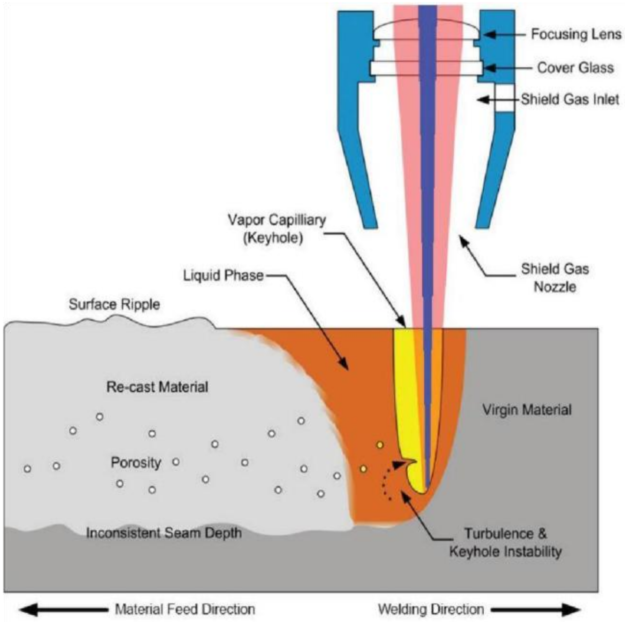

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Fig. 2. Keyhole Welding Process.

Factors influencing fume formation include the type of materials being welded, e.g., stainless steel produces more chromium and nickel fumes than carbon steel [7]. Welding parameters, higher laser power and speed generally increase fume production. Also, working conditions with inadequate ventilation exacerbate fume concentrations [8].

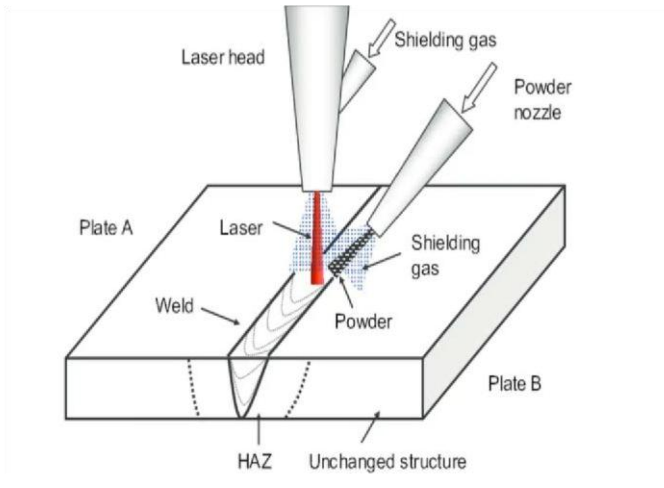

Fig. 3. Laser Welding Setup.

B. Life Cycle Assessment (LCA) in Manufacturing

Life Cycle Assessment (LCA) is a methodology used to evaluate the environmental impacts associated with all stages of a product's life, from raw material extraction through processing, manufacturing, distribution, use, repair and maintenance, and disposal or recycling [3]. In the context of manufacturing, LCA helps quantify emissions and resource consumption across different phases, including manufacturing, operational use, and end-of-life [4].

Our baseline scenario considers variable manufacturing emissions (0-88 kgCO_2eq), fixed operational emissions (55 kgCO_2eq), and fixed end-of-life emissions (11 kgCO_2eq). This breakdown allows for a detailed analysis of how each stage contributes to the total life cycle emissions and how interventions at different stages can impact overall environmental performance.

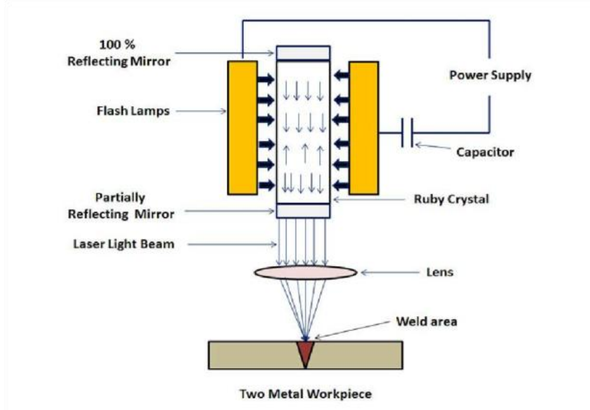

Fig. 4. Laser Beam Welding vs Plasma Arc Welding.

C. Marginal Abatement Cost Curve (MACC)

Marginal Abatement Cost Curves (MACCs) are economic tools that rank various greenhouse gas (GHG) emission reduction measures by their cost-effectiveness [9]. They illustrate the cost per tonne of CO_2 equivalent (CO_2eq) reduced for different abatement technologies or strategies, ordered from the least expensive to the most expensive. MACCs are crucial for identifying cost-effective decarbonisation pathways and prioritising investments in emission reduction technologies [10]. In this study, we identify renewable energy adoption (0.30 kgCO_2eq) as a highly cost-effective abatement measure. These figures highlight the economic viability of transitioning to cleaner energy sources and promoting circular economy principles within manufacturing operations. D. Policy Constraints and Incentives.

D. Policy Constraints and Incentives

Real-world policy constraints and incentives significantly influence the feasibility and attractiveness of decarbonisation strategies. Carbon pricing mechanisms, such as carbon taxes or cap-and-trade systems, impose a cost on carbon emissions, thereby incentivising emission reductions [11]. These prices vary significantly by region, for example, from 0.12 kgCO_2eq in the EU. Such variations dictate the economic rationale for abatement measures in different geographical contexts [12]. Policy incentives, such as tax credits and subsidies, further alter the economic landscape for decarbonisation. The US

45Q tax credit, offering a 10% cost reduction for Carbon Capture and Storage (CCS), and EU renewable energy subsidies are examples of such incentives that can improve the return on investment (ROI) and shorten payback periods for emission reduction projects. Understanding these policy impacts is essential for developing robust and adaptable decarbonisation strategies.

III. METHODOLOGY

Our methodology integrates Life Cycle Assessment (LCA) with Marginal Abatement Cost Curve (MACC) modelling to provide a comprehensive framework for optimising emissions reductions in manufacturing systems. The approach is designed to be dynamic, adjusting strategy recommendations based on real-time policy data and local economic conditions.

A. Data Collection and Baseline Scenario

The study utilises a baseline scenario with specific emissions data points for different stages of a product's life cycle [13]:

- Manufacturing Emissions: Variable, ranging from 0.00 $kgCO_2eq$ to 88.00 $kgCO_2eq$, increasing in increments of 8.80 $kgCO_2eq$ up to 11 steps.
- Operational Emissions:Fixed at 55.00 $kgCO_2eq$. • End-of-Life Emissions:Fixed at 11.00 $kgCO_2eq$.

Total life cycle emissions are calculated as the sum of manufacturing, operational, and end-of-life emissions. This structured data allows for a clear analysis of the contribution of each phase to the overall environmental footprint and the impact of varying manufacturing emissions.

B. Marginal Abatement Cost Curve (MACC) Analysis

To construct the MACC, we identified and quantified the costeffectiveness of various abatement measures. The cost of reducing emissions is expressed in USD per $kgCO_{2eq\ saved}$. Key abatement measures considered include:

- **Renewable Energy Adoption**: Cost of $0.05 per $kgCO_2eq$ saved.
- **Material Recycling**: Cost of $0.30 per $kgCO_2eq$ saved.

These values were used to rank the measures by their costeffectiveness, forming the basis of the MACC. The MACC helps visualise the potential for emission reductions at different cost levels, guiding strategic investment decisions.

C. Integration of Carbon Pricing and Policy Incentives

To account for real-world economic and policy variations, we incorporated region-specific carbon pricing and policy incentives into our analysis:

- Carbon Pricing: Variations from 0.12 $kgCO_2eq$ in the EU were considered to assess their impact on the economic viability of abatement measures.
- Policy Incentives: The US 45Q tax credit (10% cost reduction for CCS) and EU renewable energy subsidies were modelled to evaluate their influence on ROI and payback periods. These incentives can significantly alter optimal abatement pathways by making certain technologies more financially attractive.

D. Decision-Support Framework Development

A novel aspect of this research is the development of a decisionsupport framework that dynamically adjusts strategy recommendations. This framework considers:

- Real-time Policy Data: The framework can integrate updated information on carbon prices, tax credits, and subsidies.
- Local Economic Conditions: It accounts for regional variations in energy costs, material availability, and regulatory environments.

This dynamic approach allows for more adaptive and effective decarbonisation planning, bridging the gap between technical potential and economic feasibility in industrial systems. The framework provides empirical evidence for policyaware decarbonisation, particularly relevant for energyintensive manufacturing sectors.

Mathematical Formulation for Life Cycle Assessment with Marginal Abatement Cost Curve (MACC) Modelling. This section presents a mathematical framework for optimising emissions reductions in manufacturing systems by integrating Life Cycle Assessment (LCA) with Marginal Abatement Cost Curve (MACC) modelling. The approach is designed to be dynamic, allowing for adjustments based on real-time policy data and local economic conditions.

The Total Life Cycle Emissions (TLCE) are the sum of emissions from three distinct stages of a product's life cycle [13]: Manufacturing Emissions (ME), Operational Emissions (OE), and End-of-Life Emissions (ELE). Let:

- E_{total} is the Total Life Cycle Emissions ($kgCO_2eq$).
- E_{manuf} is the Manufacturing Emissions ($kgCO_2eq$).
- E_{oper} is the Operational Emission (kgCO2eq).
- E_{eol} is the End-of-Life Emissions ($kgCO_2eq$).

The relationship between these components is given by:

$$Etotal = Emanuf + Eoper + Eeol \quad (1)$$

Based on the provided baseline scenario:

Operational Emissions (E_{oper}): Fixed at 55.00 $kgCO_2eq$.

$$E_{oper} = 55.00\ kgCO_2eq \quad (2)$$

End-of-Life Emissions (E_{eol}): Fixed at 11.00 $kgCO_2eq$.

$$E_{eol} = 11.00\ kgCO_2eq \quad (3)$$

Manufacturing Emissions (E_{manuf}): Variable, ranging from 0.00 0.00$kgCO_2eq$ to 88.00 88.00$kgCO_2eq$, increasing in increments of 8.80 $kgCO_2eq$. This can be represented as a set of discrete values:

$$E_{manuf} \in \{0.00, 8.80, 17.60, \dots, 88.00\} \quad (4)$$

More formally, for k = {0,1,…, 10}, up to 11 steps:

$$E_{manuf,k} = k \times 8.80\ kgCO_2eq \quad (5)$$

Substituting (2) and (3) into (1), the Total Life Cycle Emissions can be expressed as a function of Manufacturing Emissions:

$$E_{total} = E_{manuf} + 55.00 + 11.00 \quad (6)$$

$$E_{total} = E_{manuf} + 66.00 \text{ kgCO}_2\text{eq} \quad (7)$$

This formulation allows for a clear analysis of the contribution of each phase to the overall environmental footprint and the impact of varying manufacturing emissions on the total life cycle emissions. The baseline scenario provides the foundational data points for subsequent MACC modelling and optimisation efforts. Marginal Abatement Cost Curve (MACC) modelling aims to identify the most cost-effective strategies for reducing emissions. Let A_i denote an abatement measure ΔE_i be the emissions reduction achieved by measuring A_i in $kgCO_2eq$, and C_i be the cost associated with implementing measuring A_i in USD. The marginal abatement cost (MAC) for measuring A_i is defined as the cost per unit of emissions reduced [15]:

$$MAC_i = \frac{C^i}{\Delta E_i} \text{ ....} \quad (8)$$

To construct the MACC, abatement measures are typically ranked in ascending order of their MAC_i values [16]. This allows for the identification of the most economically efficient options for emission reduction. This allows for the identification of the most economically efficient for emissions reduction. The cumulative abatement potential can then be plotted against the marginal abatement cost. Let S = (A_1, A_2, ……A_N) be the set of available abatement measures. The objective is to select a subset of these measures to achieve a target emissions reduction, E_{target} reduction, at the minimum total cost.

$$\text{Minimise:} \sum(i/inI)\ Ci/4 \quad (9)$$

$$\text{Subject to: } \sum(i/inI)\ \Delta Ei/(geEtarget\ reduction)/4 \quad (10)$$

Where I is the set of selected abatement measures. Dynamic Adjustment and Optimisation Framework: The framework is designed to dynamically adjust strategy recommendations based on real-time policy data and local economic conditions. This dynamism can be incorporated by making the costs C_i and the effectiveness ΔE_i of abatement measures, as well as the carbon pricing, functions of time (t), policy parameters (P), and economic conditions (EC). Let:

- Let Ci (t, P, EC) be the cost of abatement measure i at time t, influenced by policy and economic conditions.
- ΔE_i (t, P, EC) be the emissions reduction potential of measure (i) at time (t), influenced by policy and economic conditions.
- Let Pcarbon (t, P_{region}) be the region-specific carbon price at time (t).

The total cost of emissions, including abatement cost and carbon cost for unabated emissions, can be formulated as [17]:

$$\text{TotalCost} = \sum_{i\epsilon I} C_i(t, P, EC) + (E_{total,baselinc} - \sum_{i\epsilon I} \Delta E_i(t, P, EC)) \times P_{carbon}(t, P_{region}) \quad (11)$$

Where $E_{total,baseline}$ is the total emissions before any abatement. The optimisation problem then becomes minimising this total cost under various constraints related to available budget, technological feasibility, and desired emissions reduction targets. This dynamic framework allows for continuous reevaluation of optimal abatement pathways, enabling manufacturers to adapt to changing regulatory environments and market dynamics, thereby bridging the gap between technical potential and economic feasibility in industrial decarbonisation.

IV. RESULTS AND DISCUSSION

A. *Emissions Breakdown and Contribution*

The analysis of the baseline scenario reveals the varying contributions of different life cycle stages to total emissions. With manufacturing emissions ranging from 0.00 to 88.00 $kgCO_2eq$, operational emissions fixed at 55.00 $kgCO_2eq$, and end-of-life emissions at 11.00 $kgCO_2eq$, the total life cycle emissions range from 66.00 $kgCO_2eq$ to 154.00 $kgCO_2eq$. The linear increase in total emissions with manufacturing emissions highlights the significant impact of the manufacturing phase. For the highest-emissions scenario, manufacturing = 88.00 $kgCO_2eq$, and the percentage contributions shown in Table 1.

Table 1. Percentage Contributions for Highest Emissions.

Phase	**Emissions ($kgCO_2eq$)**	**% of Total**
Manufacturing	88.00	57.1%
Operational	55.00	35.7%
End-of-Life	11.00	7.1%
Total	154.00	100%

This breakdown indicates that manufacturing emissions are the dominant contributor in the worst-case scenario, emphasising the need for targeted interventions in this phase. However, operational emissions remain a substantial fixed burden, suggesting that improvements in operational efficiency are also critical for long-term savings.

B. *Cost-Effectiveness of Abatement Measures*

Our MACC analysis identifies renewable energy adoption and material recycling as the most cost-effective abatement measures. Renewable energy adoption, with a cost of (0.50 per kg CO_2eq) saved, offers significant potential for reducing emissions at a relatively low cost. Material recycling (0.30 per $kgCO_{2eq\ saved)}$ is even more cost-effective, underscoring the importance of circular economy principles. Other potential abatement measures and their estimated cost per $kgCO_2eq$ saved are shown in Table 2 below.

Table 2. Potential Abatement Measures Cost

Action	Cost (USD/kgCO_2eq)
Switch to renewable energy (manufacturing).	\$0.50
Optimise logistics (operational)	\$0.80
Equipment efficiency upgrades (operational)	\$1.20
Recycled materials (end-of-life)	\$0.30

This ranking provides a clear roadmap for prioritising investments, with renewable energy and recycled materials offering the higher carbon prices, such as the EU (0.02 kgCO_2eq). Offsets may be a more cost-effective option for hardto-abate emissions.

C. Impact of Carbon Pricing and Policy Incentives

Region-specific carbon pricing significantly influences the economic viability of emission reduction strategies. In regions with higher carbon prices, such as the EU (0.12 kgCO_2eq), investing in emission reductions becomes more economically attractive compared to simply offsetting (0.02 kgCO_2eq). Offsets may be a more cost-effective option for hard-to-abate emissions.

Policy incentives further enhance the attractiveness of decarbonisation efforts. The US 45Q tax credit for CCS and EU renewable energy subsidies can substantially reduce the effective cost of abatement measures, improving ROI by 2752% and shortening payback periods from 1.5 to 1.1 years in a US case study scenario achieving 30% emission reduction [14]. This highlights the critical role of supportive policies in accelerating the transition to sustainable manufacturing.

D. Dynamic Decision-Support and Optimisation

The developed decision-support framework allows for dynamic adjustment of strategy recommendations based on realtime policy data and local economic conditions. This adaptability is crucial in a rapidly evolving regulatory and economic landscape. For instance, the framework can recommend prioritising manufacturing reductions for short-term wins, for example, investing \$8.80 to save 17.60 kgCO_2eq for a 20% reduction with a quick ROI of 1 year, or a combination of manufacturing and operational cuts for long-term sustainability, for example, a 34% reduction in total emissions by reducing manufacturing by 30% and investing in operational efficiency. If end-of-life emissions are adjustable, recycling can further contribute to sustainability, albeit with a smaller impact, for example, reducing end-of-life from 11.00 to 5.50 kgCO_2eq for \$2.00. This comprehensive approach ensures that decarbonisation strategies are not only technically feasible but also economically viable and policy-aware.

VI. CONCLUSION

This study presents a dynamic marginal abatement cost framework for optimising emissions reductions in industrial manufacturing systems, particularly focusing on laser welding. By integrating life cycle assessment with MACC modelling and incorporating real-world policy constraints and incentives, we have demonstrated a robust approach to identifying costeffective decarbonisation pathways.

Our findings underscore the significant contribution of manufacturing emissions to the total life cycle footprint, highlighting the need for targeted interventions in this phase. Renewable energy adoption and material recycling emerged as the most cost-effective abatement measures. Furthermore, the study emphasises the crucial role of region-specific carbon pricing and policy incentives in shaping the economic viability and attractiveness of decarbonisation strategies. The developed decision-support framework provides a valuable tool for manufacturers to dynamically adjust their emission reduction strategies based on evolving policy landscapes and local economic conditions. This research contributes to bridging the gap between technical potential and economic feasibility in industrial decarbonisation, offering actionable insights for energy-intensive manufacturing sectors.

Future work could involve incorporating more granular data on specific laser welding processes and materials, as well as exploring the impact of emerging technologies and policy instruments on abatement cost and emission reduction potentials. Additionally, further validation of the decision support framework with real-world case studies across diverse manufacturing environments would enhance its practical applicability.

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