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Master of Science in Engineering and Management



Master Thesis

Decision-Making Framework for Emission Reduction Strategies in Aerospace Manufacturing: A Tailored Approach for SMEs and Multinational Companies

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1. Introduction

1.1 Problem Statement and Research Gap

The transition toward low-carbon industrial systems has become a strategic priority for manufacturing sectors worldwide. Within this context, aerospace manufacturing faces a particularly demanding challenge. On one hand, increasing regulatory pressure, sustainability commitments and decarbonization targets require substantial reductions in greenhouse gas emissions. On the other hand, aerospace production systems must continue to satisfy stringent requirements related to quality, safety, reliability and operational performance. As a result, identifying effective decarbonization pathways has become a critical issue for decision-makers operating within the sector.

In recent years, a growing number of emission-reduction solutions have been proposed across different stages of the aerospace value chain. These include process optimization initiatives, energy-efficiency improvements, advanced manufacturing technologies, sustainable materials, digital solutions, advanced energy systems and sustainable aviation fuels. While this increasing availability of alternatives expands the range of opportunities for industrial decarbonization, it also makes the selection process considerably more complex. Each strategy presents specific advantages and limitations, differing in terms of environmental performance, technological maturity, implementation complexity and investment requirements. Furthermore, the suitability of a given solution often depends on the characteristics of the organization implementing it, since differences in resource availability, technological capabilities and strategic priorities can significantly influence both feasibility and attractiveness. Despite the growing body of literature dedicated to aerospace decarbonization and industrial sustainability, existing studies predominantly focus on the technical performance of individual technologies, specific case studies or isolated sustainability initiatives. Although these contributions provide valuable insights into the potential benefits and limitations of particular solutions, they often offer limited support for comparing heterogeneous decarbonization alternatives within a unified decision-making framework. Moreover, relatively little attention has been devoted to understanding how organizational characteristics influence the prioritization of decarbonization strategies, particularly when comparing the perspectives of Small and Medium-sized Enterprises (SMEs) with Multinational Companies (MNCs). This limitation is especially relevant in the

aerospace sector, where organizations operate under significantly different financial, technological and operational conditions.

To address this gap, there is a need for a structured evaluation approach capable of integrating environmental, economic and technological considerations while explicitly accounting for organizational context. Such an approach would enable decision-makers to move beyond the assessment of individual technologies and support a more systematic comparison of alternative decarbonization pathways within aerospace manufacturing.

1.2 Research Objectives and Contribution

In response to the identified research gap, this study aims to develop a structured decision-support framework capable of evaluating and prioritizing alternative decarbonization strategies for aerospace manufacturing. The objective is not to identify a universally optimal solution, but rather to provide a systematic methodology for comparing heterogeneous decarbonization pathways while accounting for the different organizational contexts in which they may be implemented. To achieve this objective, the study addresses the following research questions:

RQ1: *What are the main decarbonization strategies currently available for aerospace manufacturing?*

RQ2: *How can heterogeneous decarbonization strategies be systematically evaluated and compared through a common decision-making framework?*

RQ3: *How do organizational characteristics influence the prioritization of decarbonization strategies within aerospace manufacturing?*

The scope of the research is limited to the manufacturing perspective of the aerospace sector and focuses on the evaluation of representative emission-reduction strategies identified through a structured literature review. The assessment is conducted through a Multi-Criteria Decision-Making (MCDM) framework based on three evaluation dimensions: Environmental Impact (EI), Implementation Cost (IC) and Technological Maturity (TM). Furthermore, the analysis explicitly distinguishes between Small and Medium-sized Enterprises (SMEs) and Multinational Companies (MNCs) in order to capture differences in resource availability, implementation capabilities and strategic priorities.

The main contribution of this research lies in the development of a structured evaluation framework capable of integrating environmental, economic and technological

considerations within a unified decision-making approach. Unlike studies focused on the performance of individual technologies, the proposed methodology enables the comparison of alternative decarbonization pathways while explicitly accounting for organizational context. In addition, the study contributes to the identification of broader decarbonization patterns and strategic directions emerging from the aerospace manufacturing literature, providing both methodological and managerial insights to support sustainability-oriented decision making.

1.3 Thesis Structure

The development of this study is presented as follows. Chapter 2 provides the theoretical background supporting the study, introducing the main concepts related to sustainability, industrial decarbonization and aerospace manufacturing. The chapter also reviews the principal technological domains currently contributing to emission reduction within the aerospace sector. Chapter 3 presents the research methodology adopted for the study. It describes the literature review process, the identification and filtering of relevant scientific contributions, data extraction procedure and the selection of the representative decarbonization strategies included in the analysis. Then, Chapter 4 develops the Multi-Criteria Decision-Making (MCDM) framework proposed in this research. The chapter introduces the evaluation criteria, the weighting methodology and the calculation procedure used to assess and compare alternative decarbonization pathways. Chapter 5 provides a structured analysis of the selected strategies. The identified pathways are grouped into four categories representing the main decarbonization logics emerging from the literature, and each strategy is examined in terms of operating principle, environmental implications, implementation requirements and technological characteristics. Chapter 6 presents the application of the framework and discusses the results. It includes the comparative assessment of the identified strategies, the analysis of differences between SME and MNC perspectives, the sensitivity analysis and the related managerial implications. Finally, Chapter 7 summarizes the main findings of the study, highlights its contributions and discusses the principal limitations and future research directions.

2. Theoretical Background

2.1 Industrial Decarbonization and Sustainability Transition

Industrial decarbonization has emerged as one of the most significant challenges associated with the global sustainability transition. Growing scientific evidence regarding the effects of climate change has progressively increased the urgency of implementing mitigation measures capable of reducing greenhouse gas (GHG) emissions across all economic sectors. In response to this challenge, government, international organizations and private actors have strengthened their commitment to climate action through a variety of regulatory framework, international agreements and long-term sustainability strategies.

One of the most important milestones in this process is represented by the Paris Agreement presented during the 21st Conference of the Parties (COP21). The agreement established a global commitment to hold the increase in average global temperature below 2°C above pre-industrial levels while pursuing efforts to limit warming to 1.5°C. Scientific evidence confirms that exceeding this threshold could significantly increase the severity and frequency of climate catastrophic events such as heatwaves, droughts, extreme water events and disruption to both natural and economic systems. Furthermore, the Agreement emphasizes the necessity of rapid and sustained actions in reducing greenhouse gas emissions, requiring countries to progressively strengthen their climate commitments over time (UNFCCC, 2025).

Achieving these objectives require substantial transformations across the entire global economy. Among all sectors, industry plays a particularly critical role due to its extensive consumption of energy and materials. According to the International Energy Agency (IEA), the industry sector accounts for nearly 40% of global energy demand, highlighting its central responsibility within worldwide decarbonization efforts. This underlines how achieving climate targets is unlikely without an extensive transformation of industrial production systems and manufacturing activities. Within this context, industrial decarbonization can be understood as a broad transformation process aimed at reducing carbon intensity of industrial operations while preserving productivity, competitiveness and economic growth. As emerged in the Net Zero Roadmap proposed by the IEA, the transition is not limited to the adoption of individual technologies, instead, it involves the progressive redesign of industrial systems through technological innovation, process optimization, energy efficiency improvements, electrification, renewable energy integration and the development of emerging low-carbon solutions (IEA, 2023). Even if the transition toward sustainable

industrial systems is already underway, progress remains uneven and insufficient to fully align with long-term climate objectives. According to IEA Global Energy Review, global CO₂ emissions continued to increase during 2024 despite the accelerated deployment of renewable energy technologies and improvements in energy efficiency. This confirms the complexity of the sustainability transition and demonstrates that technological progress alone may not be sufficient without broader structural changes involving industrial process, business models and investment strategies (IEA, 2025).

At the same time, industrial decarbonization is increasingly recognized not only as an environmental necessity but also as a strategic business priority. Rising energy costs, evolving environmental regulations, carbon-pricing mechanisms, investor expectations and supply chain sustainability requirements are progressively reshaping the competitive environment in which firms operate. Consequently, sustainability considerations are becoming increasingly integrated into corporate decision-making processes and long-term strategic planning. This evolution reflects a consistent shift in the perception of sustainability within industrial environments as historically sustainable initiatives were often regarded primarily as compliance requirements. Today, many organizations are evaluating decarbonization as a source of innovation, resilience and competitive advantage (World Economic Forum, 2025).

An important consequence of this transformation is the increasing recognition that economic growth and emission reductions do not necessarily represent conflicting objectives. Recent trends indicate an increasing decoupling between economic development and carbon emissions, suggesting that industrial competitiveness and environmental sustainability can be pursued simultaneously when supported by appropriated strategic decisions. This perspective is particularly relevant for manufacturing industries, where the ability to balance environmental performance, economic feasibility and technological innovation has become a key determinant of long-term success. Industrial decarbonization therefore represents a multidimensional transition extending beyond environmental considerations alone. Understanding the dynamics of this transition is essential for evaluating alternative decarbonization pathways and supporting more informed decision-making processes within increasingly complex industrial environments.

2.2 Decarbonization Challenges in Aerospace Manufacturing

The aerospace industry represents one of the most technologically advanced and strategically significant manufacturing sectors worldwide. Beyond its contribution to global mobility, it plays a fundamental role in promoting international trade, economic development and social connectivity. Despite periodic disruptions caused by economic downturns, geopolitical tensions and global crises, long-term forecasts consistently indicate a sustained growth in air transportation demand. According to the most important players of the industry, global passenger traffic is expected to continue expanding over the coming decades, supported by the continued globalization, sustained international trade and the growth of global middle class. In particular, Airbus forecasts an annual growth rate of approximately 3.6% in passenger traffic, driven by increases in Gross Domestic Product (GDP), trade volumes and population growth. Similarly, Boeing expects an average annual growth rate of 4.2%, highlighting the long-term resilience of the aviation sector despite historical disruptive events. As a consequence of these trends, both Airbus and Boeing forecast a global demand exceeding 43,000 new aircraft between 2025 and 2044, leading to an approximate doubling of the worldwide commercial fleet while simultaneously replacing nearly 80% of the aircraft currently in service (Airbus, 2025; Boeing, 2025).

These projections emphasize a critical challenge for the future of the aerospace sector. Even if fleet expansion is necessary to satisfy mobility demand and support economic development, it also intensifies the urgency of reducing the environmental footprint associated with aviation activities. The International Civil Aviation Organization (ICAO) recognizes that achieving the long-term sustainability of air transport requires substantial reductions in greenhouse gas emissions while preserving the economic and social benefits generated by the industry. Consequently, decarbonization has emerged as a strategic priority across the entire aerospace value chain, extending beyond aircraft operations to encompass manufacturing activities, industrial processes and supply chain management (ICAO, 2025). From a manufacturing perspective, the aerospace sector presents several environmental challenges. The production of aircraft structures, engines and onboard systems requires highly specialized industrial processes characterized by substantial energy consumption, intensive use of raw materials and complex production chains. Unlike many conventional manufacturing industries, this sector must simultaneously satisfy strict requirements in terms of mechanical performance, safety, reliability and certification. These constraints require the adoption of advanced materials and sophisticated technologies, which contribute

significantly to the overall environmental footprint of the sector. The complexity of aerospace manufacturing originates from the need to produce components capable of operating under extreme conditions while maintaining strict performance standards throughout their operational life (GE Aerospace, 2025). In order to meet these requirements, production systems typically involve multiple sequential stages as material preparation, forming operations, machining processes, surface treatments, assembly activities, inspections and testing procedures. Each phase contributes to the overall energy demand and generates environmental impacts through the consumption of electricity, fuels, materials and auxiliary resources. Consequently, reducing the emissions within aerospace manufacturing requires a holistic approach capable of addressing the entire production lifecycle rather than focusing on individual processes.

Among the different sources of environmental impact, material utilization efficiency represents one of the most significant challenges. Aerospace components are commonly produced through subtractive manufacturing in which large quantities of material are removed from billets, forgings or plates, in order to obtain the final geometry. This approach is driven by the need to achieve lightweight structures and optimized designs capable of improving aircraft performance and reducing fuel consumption during flight operations. However, these benefits are often accompanied by considerable material losses during production stages. Watson and Taminger report that buy-to-fly ratios within aerospace application is approximately 10:1, meaning that a very limited fraction of the initial material is kept in the final component, while the major fraction is converted into scrap. This implies that a significant share of energy and resources required for raw material extraction, transportation and processing is invested in material that does not become part of the final product (Watson & Taminger, 2018). The issue becomes even more relevant when considering the scale of production expected over the coming decades. As companies seek to improve operational efficiency through lighter and more complex structures, the challenge of balancing manufacturing sustainability with product performance becomes increasingly difficult.

This phenomenon reflects a broader paradox of aerospace sustainability since many technologies and designs approaches aimed at reducing emission during aircraft operations may require more complex manufacturing processes and greater resource consumption during production. As a result, environmental performance needs a lifecycle perspective which consider emissions and resource consumption across the entire value chain, from raw

material extraction and component manufacturing to product operation and end-of-life management.

Additional challenges arise from the highly regulated nature of aerospace industry. Unlike many other manufacturing sectors, the introduction of raw materials, production technologies and design solutions requires extensive testing, validation and certification procedures before implementation. Safety and reliability remain the priorities throughout the entire product lifecycle, limiting the speed at which innovations can be implemented. Consequently, even solutions with great environmental benefits may require several years before large-scale industrial deployment.

The aerospace sector therefore faces a unique combination of technological complexity, environmental urgency and growing market demand. Numerous decarbonization solutions are currently available or under development, differing considerably in terms of maturity level, implementation requirements, investment intensity and expected environmental benefits. This diversity of alternatives further complicates decision-making processes and increases the importance of structured approaches capable of supporting strategy evaluation and prioritization. Moreover, the feasibility and effectiveness of decarbonization initiatives may vary significantly depending on the characteristics of the organization implementing them. Factors such as financial resources, technological capabilities, organizational flexibility and access to specialized expertise can strongly influence the adoption of sustainability-oriented strategies. For this reason, it is necessary to understand how different types of organizations approach decarbonization in order to identify realistic and effective pathways toward industrial sustainability.

2.3 Organizational Perspectives: SMEs and Multinational Companies

The implementation of decarbonization strategies cannot be analysed independently from the organizational context in which these solutions are adopted. While technological innovation plays a crucial role in reducing industrial emissions, the feasibility, scalability and overall effectiveness of sustainability initiatives are strongly influenced by the resources, capabilities and structural characteristics of the organizations involved. Consequently, the same decarbonization strategy may generate significantly different outcomes depending on the firm's size, operational structure and strategic priorities.

According to the European Commission, Small and Medium-sized Enterprises (SMEs) are organizations employing fewer than 250 people and generating an annual turnover not

exceeding €50 million or a balance-sheet total below €43 million (European Commission, 2026). Despite their smaller size, SMEs represent approximately 99% of businesses worldwide and therefore play a fundamental role in the transition toward more sustainable industrial systems. Collectively, they are estimated to account for between 40% and 50% of global greenhouse gas emissions (OECD, 2025). From a sustainability perspective, SMEs often benefit from relatively flexible organizational structures, shorter decision-making chains and a greater ability to rapidly adapt to changing market conditions. These characteristics facilitate the implementation of targeted environmental improvements, particularly when initiatives require limited investments or incremental modifications to existing production systems. Nevertheless, smaller organizations frequently encounter substantial barriers when pursuing more ambitious decarbonization pathways. Limited financial resources, restricted access to specialized expertise and lower long-term investment capacity can constrain the adoption of advanced technologies and increase the importance of carefully prioritizing available resources and investment opportunities (Cerezo-Narváez et al., 2019).

Conversely, multinational corporations (MNCs) are often better positioned to undertake complex decarbonization initiatives due to their greater access to financial resources, technological capabilities and organizational support structures. Recent evidence suggests that the large-scale deployment of low-carbon technologies is increasingly influenced by factors such as access to capital, infrastructure availability and execution capability, in addition to technological maturity itself (World Economic Forum, 2025). In this context, larger organizations may benefit from advantages that facilitate the implementation of advanced manufacturing technologies, large-scale process transformations and other capital-intensive sustainability investments. Furthermore, MNCs frequently operate through structured innovation processes and specialized technical functions that can support the evaluation, development and deployment of new solutions. However, the scale and complexity of multinational operations also introduce significant managerial challenges. The coordination of multiple production facilities, suppliers and stakeholders distributed across different geographical regions may increase organizational complexity, slow decision-making processes and lengthen implementation timelines.

Beyond differences in resource availability, SMEs and MNCs frequently play distinct roles within aerospace supply chains. SMEs commonly operate as specialized suppliers integrated into broader industrial ecosystems and are often required to comply with increasingly demanding technical, operational and environmental requirements imposed by larger

industrial actors (Cerezo-Narváez et al., 2019). In contrast, multinational companies often play a leading role in technological development and may influence innovation priorities, sustainability objectives and operational practices throughout the supply chain. As a result, larger organizations generally possess a greater capacity not only to implement decarbonization strategies internally but also to promote the diffusion of sustainable practices across wider industrial networks. For these reasons, organizational characteristics represent a critical factor in the evaluation of emission-reduction strategies. Understanding how different industrial contexts influence the feasibility and attractiveness of alternative solutions is essential for developing realistic and actionable decarbonization pathways. At the same time, the growing variety of available decarbonization solutions highlights the need for a systematic assessment of the technological approaches currently proposed within the scientific literature. Consequently, the next chapter presents the methodology adopted to identify, filter and analyse representative decarbonization strategies, providing the analytical basis for the development of the decision-support framework proposed in this study.

3. Research Methodology

This chapter describes the methodological approach adopted for the identification, selection and preliminary characterization of the decarbonization strategies analysed within this study. The research process is defined by a structured literature review methodology aimed at identifying technological solutions and industrial approaches capable of supporting emission reduction within aerospace manufacturing contexts. The methodology progressively evolves through different stages, including literature search, iterative refinement of queries, extraction of qualitative and quantitative information and selection of representative industrial strategies. Particular attention is dedicated not only on the environmental relevance of the identified solutions, but also to their practical applicability, technological characteristics and potential flexibility across different aerospace manufacturing processes. The resulting set of strategies constitutes the analytical basis for the detailed overview developed in Chapter 5 and for the subsequent comparative evaluation performed through the proposed MCDM framework in Chapter 6.

3.1 Scientific Literature Identification and Filtering Process

A structured literature review process was conducted using the Scopus scientific database. The search was performed in June 2025 and considered documents published between 2019 and 2025. To ensure an adequate coverage of emerging technologies, the analysis included journal articles, conference papers, conference reviews and book chapters published in English. The research activity was specifically oriented toward the identification of technological and operational solutions capable of supporting emission reduction within aerospace manufacturing environments. However, the definition of an effective search methodology presented significant complexity due to the multidisciplinary nature of aerospace decarbonization. Moreover, the terminology adopted within the literature often varies considerably depending on the technological field, making the identification of coherent and sufficiently focused scientific contributions particularly challenging.

For these reasons, the literature research activity was developed through an iterative refinement process aimed at progressively improving the thematic coherence, industrial relevance and analytical consistency of the resulting scientific dataset. Rather than relying on a single static query, the search evolved progressively through multiple refinement stages intended to reduce the presence of generic sustainability discussions and increase the

alignment between the retrieved publications and the objective of the study. The overall literature identification, screening and strategy selection process adopted in this study is summarized below:

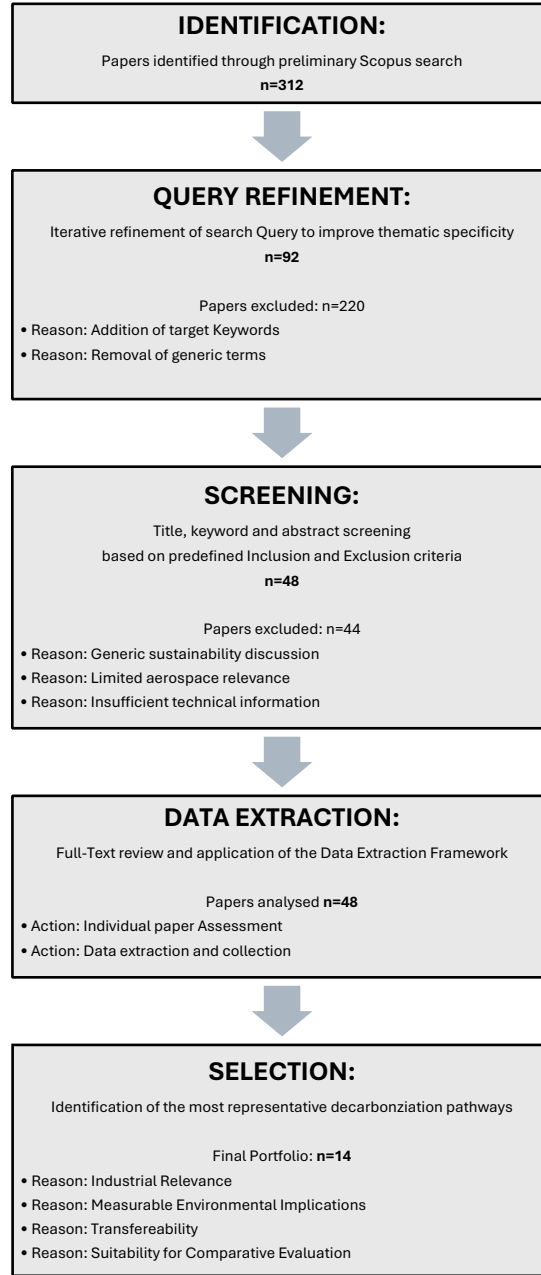


Figure 1 *Research Methodology and Strategy Selection Process*

Initially, a broad exploratory query was defined to capture a wide range of scientific contributions potentially related to industrial decarbonization within aerospace manufacturing contexts. The preliminary search combined keywords associated with sustainability, industrial systems, manufacturing processes, aerospace operations and

decarbonization technologies, generating an initial dataset of more than 300 scientific publications. While this exploratory phase ensured broad coverage of the topic, many retrieved studies were only partially aligned with the objectives of the research, often focusing on generic sustainability issues, non-manufacturing applications or lacking clearly identifiable emission reduction mechanisms.

To improve the relevance of the retrieved papers, the search query was progressively refined through the modification, addition and removal of keywords. This process allowed the gradual reduction of broad results while increasing the specificity of the search toward aerospace manufacturing decarbonization. This activity continued until a dataset characterized by sufficient thematic coherence and a manageable number of records was obtained, enabling subsequent manual screening and detailed assessment. From an operational perspective, a threshold of approximately 100 publications was adopted as a practical criterion to ensure that each contribution could be individually evaluated in the following stages while preserving adequate diversity across the technological approaches identified in the literature.

The final query configuration generated a dataset composed of 92 scientific publications, which constituted the literature base of the study. It is reported below:

```
TITLE-ABS-KEY (("emission reduction" OR "carbon reduction" OR "decarbonization"  
OR "GHG reduction" OR "net zero" OR "carbon neutrality") AND ("manufacturing" OR  
"production process" OR "factory")) AND ("aerospace" OR "aviation" OR "aerospace  
industry" OR "aerospace manufacturing")) AND (LIMIT-TO (SUBJAREA,  
"ENGINEERING" ) ) AND (LIMIT-TO (LANGUAGE, "English"))
```

Following the definition of the final query, the 92 resulting documents were subjected to an individual screening process based on the inclusion and exclusion criteria presented below:

Table 1 *Inclusion/Exclusion Criteria*

<i>Inclusion Criteria</i>	<i>Exclusion Criteria</i>
Focus on decarbonization or emission-reduction strategies	Generic sustainability discussions without specific decarbonization actions
Relevance to manufacturing or industrial systems	Studies unrelated to industrial applications
Potential applicability to aerospace manufacturing, either directly or through transferable industrial principles	Studies whose findings are highly context-specific and not transferable to aerospace manufacturing environments
Availability of sufficient qualitative and/or quantitative information supporting strategy assessment	Insufficient technical detail and data for comparative analysis

Each paper was evaluated through the analysis of titles, keywords and abstracts, while additional sections were consulted whenever the relevance of the contribution could not be clearly determined from the preliminary information. The inclusion criteria were used to identify studies presenting explicit decarbonization strategies, industrial relevance and sufficient technical information to support subsequent comparative analysis. Conversely, the exclusion criteria were applied to remove publications characterized by generic sustainability discussions, limited applicability to manufacturing environments, insufficient implementation detail or lack of clearly identifiable emission-reduction mechanisms. The systematic application of these criteria progressively reduced the initial dataset from 92 to 48 scientific contributions. The resulting set of 48 papers was considered sufficiently aligned with the objectives of the research and therefore provided the foundation for the identification and analysis of the representative decarbonization strategies discussed in the following sections

3.2 Structured Data Extraction and Strategy Characterization

Following the screening process described in the previous section, the 48 selected contributions were subjected to a structured data-extraction phase aimed at systematically categorizing the qualitative and quantitative information associated with each decarbonization strategy. Due to the high heterogeneity which characterizes the retrieved papers in terms of technological focus, industrial application and environmental indicators, the development of a standardized information extraction methodology was necessary to

ensure consistency, standardize the interpretation of the articles and facilitate cross-comparative analysis across different technological pathways.

For this reason, a structured database was progressively developed to collect and organize the main characteristics associated with each contribution. The objective of this phase was not limited to the simple summarization of the studies, but rather to create an organized structure capable of highlighting technological, environmental, economic and industrial aspects relevant to aerospace manufacturing decarbonization routes. Each paper was therefore examined through a combination of qualitative interpretation and quantitative data, allowing the identification of both measurable environmental implications and broader implementation dynamics associated with the proposed strategies. The following template was developed and applied to each article to capture the relevant features of each pathway leading to the production of a standardized dataset capable of supporting subsequent comparison and analysis stages. The information fields included within the extraction framework are summarized in the following table:

Table 2 *Data Extraction Framework*

<i>Information Field</i>	<i>Purpose</i>
LCA Phase	Identify the lifecycle stage primarily affected by the strategy and where the environmental contribution is generated
Strategy Adopted	Define the specific technological or operational solution proposed within the analysed study
Description	Summarize the operating principle, industrial relevance and implementation logic of the strategy
Environmental Impact	Collect qualitative and quantitative evidence regarding the emission-reduction potential of the strategy
Normalized Impact (gCO ₂ /MJ)	Record standardized environmental data when available to facilitate comparison across studies
Cost	Identify economic implications, investment requirements and implementation-related considerations
Normalized Cost (\$/tCO ₂)	Collect comparable economic indicators associated with the implementation
Maturity Level	Assess the technological readiness and industrial development stage of the proposed solution
Target	Evaluate the potential applicability of the strategy for SMEs, MNCs or both organizational contexts

Barriers to Adoption	Identify technical, financial, operational and organizational constraints affecting implementation
Geographic Area of Application	Provide contextual information regarding the industrial or regional environment considered
Authors	Identify the source of the scientific contribution and ensure traceability of the analysed study
Title	Report the title of the article to support the identification of the investigated decarbonization approach
Year	Identify the publication period and contextualize the contribution within the evolution of the field

The extracted information was organized through multiple fields specifically selected to capture different dimensions of the selected sustainable pathways. In particular, the *LCA phase* was introduced to identify the main lifecycle stage affected by the strategy, including material production, manufacturing operations, product use, disposal or transportation activities. This classification allowed a clearer understanding of where the environmental contribution of each strategy is primarily generated. Then the *Strategy Adopted* identifies the specific operational solution proposed within each paper in order to define the industrial intervention associated. The *Description* field was developed to synthesize the logic, technological functioning and industrial relevance of the solution, providing a structured qualitative interpretation. Particular attention was dedicated to the extraction of implementation-related information. The *Environmental Impact* field was used to collect quantitative and qualitative evidence related to the emission reduction potential associated, including reported carbon-footprint data and performance indicators expressed in normalized forms such as gCO₂/MJ, whenever explicitly available within the literature, in order to facilitate direct comparison across the different strategies. Similarly, the *Cost* section was introduced to record implementation-related economic considerations, infrastructure requirements or investment implications related to each alternative. When reported by the authors, normalized economic performance in terms of \$/tCO₂ avoided were also collected to improve comparability.

Additional analytical fields are introduced to improve the industrial interpretability of the dataset. The *Maturity Level* allowed the identification of the technological readiness and industrial development stage associated with each pathway, while the *Target* field highlights their potential applicability within SMEs, multinational companies or both organizational contexts. Furthermore, the *Barriers to Adoption* section was specifically introduced to

identify technical, financial, operational or cultural limitations potentially affecting industrial implementation. Finally, supplementary contextual information including *Geographic Area of Application*, *Authors*, *Title* and *Publication Year* were collected to guarantee traceability, contextual interpretation and analytical consistency throughout the study.

The extracted information was organized through a set of complementary analytical fields designed to capture the technological, environmental, economic and industrial dimensions of each identified pathway. Rather than focusing exclusively on environmental performance, the extraction framework was developed to provide a multidimensional characterization of the analysed strategies, enabling a more comprehensive understanding of their potential contribution to industrial decarbonization. The extraction process is therefore strategy-oriented rather than paper-oriented, as the primary objective was to identify, characterize and compare decarbonization pathways rather than simply summarize individual scientific contributions. Consequently, the structured extraction methodology converts heterogeneous scientific evidence into a coherent analytical basis capable of supporting the identification of recurring patterns, comparative interpretation and subsequent framework development.

3.3 Selection of Representative Industrial Strategies

Following the structured extraction process, a final selection phase was conducted in order to identify the most representative industrial strategies among the 48 scientific contributions included in the final literature dataset. The objective of this stage was not to identify the most cited, recent or technologically advanced studies, but rather to select decarbonization pathways capable of providing meaningful and transferable examples of emission-reduction approaches within aerospace manufacturing environments.

From the extracted dataset, a final portfolio of 14 strategies was selected for subsequent detailed analysis. The selection was not based on citation count, publication year or technological novelty, but on the ability of each strategy to provide a comprehensive and representative example of a decarbonization pathway. Particular preference was given to contributions characterized by detailed technological descriptions, clearly identifiable implementation mechanisms, measurable environmental implications and sufficient information to support subsequent comparative evaluation. The selection process also considered the transferability of the proposed solutions beyond their original application context. The aim was not simply to identify successful individual case studies, but rather to select strategies representative of broader decarbonization principles while preserving their

potential for adaptation across different aerospace manufacturing environments and organizational contexts. In addition, the final portfolio was intentionally designed to preserve diversity in terms of technological domain, implementation requirements, technological maturity and environmental contribution. This diversity was considered essential to capture the multidimensional nature of industrial decarbonization and to avoid focusing exclusively on a single pattern of solutions. Consequently, the selected strategies range from sustainable fuels and hydrogen systems to digital optimization, process-efficiency improvements and advanced material solutions, reflecting the variety of pathways currently available for supporting emission reduction within aerospace manufacturing. The selected portfolio was considered sufficiently broad to capture the main decarbonization logics emerging from the literature while maintaining a level of detail compatible with the subsequent comparative assessment.

This approach converted a heterogeneous body of scientific evidence into a coherent portfolio of representative industrial pathways, providing the analytical basis for the strategic categorization presented in Chapter 5 and the subsequent comparative evaluation developed through the Multi-Criteria Decision-Making framework.

4 Multi-Criteria Decision-Making Framework Development

The previous chapter described the methodology adopted to identify, screen and characterize decarbonization strategies relevant to aerospace manufacturing. However, the identification of potential solutions alone is not sufficient to support decision-making, as the selected strategies differ significantly in terms of environmental performance, implementation requirements and technological readiness. To address this challenge, this chapter develops a Multi-Criteria Decision-Making (MCDM) framework designed to evaluate decarbonization strategies from multiple perspectives simultaneously. The objective is to provide a transparent and replicable assessment methodology capable of translating heterogeneous evidence into a common analytical structure suitable for comparative analysis.

The proposed framework is based on three evaluation criteria: Environmental Impact (EI), Implementation Cost (IC) and Technological Maturity (TM). These dimensions were selected to capture the main environmental, economic and technological factors influencing the adoption of decarbonization strategies within aerospace manufacturing. Since organizational characteristics may substantially affect strategic priorities, the framework also incorporates two alternative weighting configurations representing SMEs and MNCs. The development of the framework follows three main steps. First, the evaluation criteria and their associated scoring scales are defined. Second, criterion weights are assigned to reflect the different priorities associated with the two organizational profiles. Finally, a weighted aggregation procedure is established to combine the individual criterion scores into a single Performance Indicator (PI), which will subsequently be used to compare and rank the identified strategies. The framework defined in this chapter provides the methodological basis for the qualitative assessment presented in Chapter 5 and the quantitative comparative analysis discussed in Chapter 6.

4.1 Definition of Evaluation Criteria

The objective of the proposed framework is to compare heterogeneous decarbonization strategies through a common evaluation structure capable of capturing the main factors influencing their industrial adoption. Since the identified strategies differ significantly in terms of technological characteristics, application domains, implementation requirements and expected outcomes, it is necessary to define a limited set of criteria that can be applied consistently across all alternatives. Based on the evidence emerging from the literature

review and the objectives of this study, three evaluation criteria have been selected: Environmental Impact (EI), Implementation Cost (IC) and Technological Maturity (TM). Together, these dimensions represent the key elements that influence the selection of decarbonization initiatives related to aerospace manufacturing. Environmental Impact reflects the expected contribution of a strategy to emission reduction and sustainability objectives. Implementation Cost captures the economic effort required for adoption, including investment requirements and implementation complexity. Technological Maturity assesses the readiness of a solution for industrial deployment and the risks associated with its implementation. The selection of these criteria is intended to balance different and often conflicting aspects of decarbonization options, defining the necessary trade-offs when selecting the most appropriate solution while integrating environmental performance, economic constraints and technological feasibility.

To ensure consistency across the analysis, each criterion is evaluated through a predefined scoring scale ranging from 0 to 5. The scales have been specifically developed to provide a structured and transparent assessment process while maintaining sufficient flexibility to accommodate the wide variety of technologies examined in this study.

Environmental Impact (EI) represents the primary criterion of the proposed framework, as the ultimate objective of all the strategies analysed in this study is to contribute to decarbonization. Regardless of the technological approach adopted, each strategy aims to reduce the environmental footprint of aerospace manufacturing systems by lowering greenhouse gas emissions, improving resource utilization or supporting the transition towards more sustainable industrial practices. For this reason, environmental performance constitutes the fundamental dimension against which all alternatives must be evaluated.

The criterion assesses the magnitude of the environmental benefits associated with each strategy. In particular, it considers the potential contribution to emission reduction together with broader sustainability improvements that may affect different stages of the aerospace value chain. Depending on the specific characteristics of the strategy, these benefits derive from direct emission reductions, lower energy consumption, improved resource efficiency, waste minimization or lifecycle performance improvements.

The assessment is based on the evidence reported in the analysed studies. Whenever quantitative environmental results are available, they provide the primary basis for the evaluation. However, since the literature reports environmental performance using different indicators and levels of detail, a qualitative assessment is also required to ensure comparability across heterogeneous strategies. For this reason, the scoring scale combines

quantitative reference ranges with qualitative descriptions of the expected environmental contribution associated with each score. Higher scores correspond to greater decarbonization potential and a stronger contribution to long-term sustainability objectives. The adopted scoring scale is presented in the following table:

Table 3 *Environmental Impact (EI) Scoring Scale*

<i>Score</i>	<i>Description</i>
0	The strategy does not generate measurable improvements in environmental performance or its contribution to decarbonization is negligible
1	Environmental benefits remain limited and confined to specific activities or localized improvements. Although positive effects may be observed, their contribution to overall decarbonization remains marginal (<5% emission reduction).
2	The strategy generates a measurable improvement in environmental performance, producing clear sustainability benefits while maintaining a relatively limited influence on the overall environmental footprint of the system (5–15% emission reduction).
3	Environmental improvements become substantial and contribute meaningfully to reducing the environmental burden of industrial activities. The strategy addresses relevant sustainability challenges and generates benefits that are visible across one or more stages of the value chain (15–30% emission reduction).
4	The strategy achieves a high level of environmental performance, delivering substantial emission reductions and creating significant sustainability gains. Its effects extend beyond incremental improvements and can noticeably improve the environmental profile of industrial systems (30–60% emission reduction).
5	The environmental contribution is transformative, enabling an extensive shift in the carbon footprint of processes, products or industrial systems. The strategy addresses major sources of emissions and supports long-term decarbonization objectives on a large scale (>60% emission reduction).

Implementation Cost (IC) evaluates the economic effort required to adopt and integrate a given decarbonization strategy within an industrial environment. Although environmental performance represents the primary objective of decarbonization initiatives, the practical feasibility of their implementation is strongly influenced by the resources required for its deployment. For this reason, cost constitutes a critical decision variable, particularly when comparing strategies characterized by different technological complexity and implementation requirements. The criterion extends beyond direct investment costs and considers the overall effort associated with adoption. In addition to capital expenditures (CAPEX) and operational expenditures (OPEX), the evaluation accounts for infrastructure requirements, integration complexity, implementation effort, required technical expertise and organizational changes.

The assessment therefore reflects not only the absolute level of investment required, but also the accessibility of the strategy from an industrial implementation perspective. Strategies requiring limited resources and minor organizational changes receive higher scores, while solutions involving substantial investments, dedicated infrastructures or significant implementation challenges receive lower scores. The adopted scoring scale is presented below:

Table 4 *Implementation Cost (IC) Scoring Scale*

<i>Score</i>	<i>Description</i>
0	Implementation is currently impractical due to prohibitive economic requirements, infrastructure needs or implementation complexity. The strategy is not realistically accessible under normal industrial conditions.
1	Adoption requires substantial investments, dedicated infrastructures and extensive organizational adaptation. The financial and operational burden is significant, making implementation feasible only under highly favourable conditions.
2	The strategy entails considerable resource requirements, often involving specialized equipment, new infrastructures or complex integration activities. As a result, adoption is generally limited to large organizations.

3	Implementation requires a moderate commitment of financial and organizational resources. While additional investments and process adjustments are necessary, the strategy remains accessible to industrial actors with adequate capabilities.
4	The strategy can be integrated with relatively limited investments and manageable modifications to existing operations. Resource requirements remain moderate and do not represent a major barrier to adoption.
5	Adoption can be achieved through existing infrastructures, capabilities or operational practices, requiring only limited additional resources. Economic and organizational barriers are minimal, facilitating broad implementation.

The last criteria identified is Technological Maturity. It assesses the readiness level of each strategy for industrial implementation based on the concept of Technology Readiness Level (TRL), which is widely used to define the development stage of a technology ranging from early research to full-scale industrial deployment. The TRL framework was originally developed by NASA and classifies technologies along a scale from 1 to 9, where lower levels correspond to basic research and conceptual validation, while higher levels indicate technologies that have been fully tested in operational environments (Manning C. G., 2023). In the context of this study, maturity is particularly relevant because it reflects the level of uncertainty, implementation risk and time required for adoption. Highly mature technologies can be implemented in the short term with limited risk, while less mature technologies may require further development, testing and validation before being integrated into industrial processes. To ensure consistency with the overall evaluation framework, the traditional TRL scale has been adapted into a simplified 0-5 scoring range. This reclassification maintains the conceptual meaning of technological maturity while facilitating comparison with the other criteria and supporting the aggregation process within the MCDM framework. The resulting scale groups the original TRL levels into broader categories, preserving the distinction between early-stage, developing and mature technologies, while improving the readability and applicability of the evaluation.

Table 5 *Technological Maturity (TM) Scoring Scale*

<i>Score</i>	<i>Description</i>
0	The strategy remains purely conceptual, with no experimental validation or practical demonstration reported (TRL 1).
1	The proposal is at an early research stage and is supported primarily by theoretical studies or proof-of-principle investigations (TRL 2–3).
2	Initial experimental validation has been achieved under controlled laboratory conditions, but industrial applicability remains largely unproven (TRL 4).
3	The technology has progressed beyond laboratory testing and has been demonstrated in a relevant environment through pilot-scale or prototype applications (TRL 5–6).
4	Industrial feasibility has been validated and the strategy has undergone initial deployment in operational environments, although widespread adoption is still limited (TRL 7–8).
5	The strategy represents a commercially established solution that has been successfully deployed and validated under real operating conditions (TRL 9).

The three criteria described above constitute the evaluation dimensions adopted throughout the study. To improve transparency and traceability, each strategy analysed in Chapter 5 is associated with an Evaluation Criteria Summary reporting the scores assigned to EI, IC and TM together with a concise justification based on the evidence extracted from the corresponding study. This approach establishes a direct link between the qualitative analysis of the literature and the quantitative values subsequently employed within the decision matrix.

The resulting scores provide the basis for the weighting, normalization and aggregation phases described in the following sections. By combining predefined scoring scales with explicit justifications, the framework provides a transparent and replicable basis for evaluating heterogeneous decarbonization strategies and translating qualitative evidence into comparable decision-making inputs.

4.2 Weighting System

While the evaluation criteria define the dimensions through which decarbonization strategies are assessed, their relative importance may vary according to the characteristics, resources and strategic priorities of the organization adopting them. Companies differ significantly in terms of financial capacity, technological capabilities, organizational structure and risk tolerance. As a result, the same decarbonization strategy may be perceived differently depending on the context in which the decision is made. To account for these differences, this study introduces two distinct weighting configurations representing Small and Medium Enterprises (SMEs) and Multinational Companies (MNCs). The weighting scheme adopted in this study is based on the literature available on sustainability adoption barriers, organizational capabilities and green technology implementation. However, the specific numerical weights do not originate directly from previous studies, as no universally accepted weighting structure was identified in the literature. Instead, the final values represent an author methodological assumption developed to translate the organizational priorities and constraints highlighted by previous research into the two representative profiles. The objective is not to identify an exact representation of organizational preferences, but rather to capture the structural characteristics that typically distinguish SMEs and MNCs and evaluate how they influence the prioritization of decarbonization strategies.

Previous studies consistently highlight that SMEs face greater barriers in the adoption of sustainable technologies due to limited financial resources, restricted access to capital, reduced technical expertise and lower organizational capabilities. Financial constraints are frequently identified as one of the most significant obstacles, particularly because high upfront investments and uncertain returns may discourage the implementation of innovative solutions. At the same time, SMEs often possess limited internal research and development capabilities and fewer specialized resources able to manage complex technological transitions, increasing their exposure to implementation risks and technological uncertainty (Baharom, 2025). Environmental Impact remains an important consideration, but its relative importance is balanced against the economic and technological constraints that typically influence SME decision process.

Conversely, MNCs generally operate within a different context characterized by greater financial capacity, broader access to technical expertise, established R&D infrastructures and stronger innovation capabilities. These conditions enable the adoption of more capital-intensive and technologically advanced solutions, even when associated with longer implementation horizons or higher uncertainty. Furthermore, large organizations are more

exposed to long-term sustainability commitments, environmental regulations and corporate decarbonization targets. As a result, Environmental Impact assumes a more prominent role in the decision-making process, while Implementation Cost and Technological Maturity become comparatively less restrictive factors. Based on these considerations, different weights were assigned to Environmental Impact (EI), Implementation Cost (IC) and Technological Maturity (TM) in order to reflect the distinct priorities associated with the two organizational profiles. The resulting weighting scheme is presented below:

Table 6 *Weighting Scheme for SMEs and MNCs*

<i>Criterion</i>	SME Weight	MNC Weight
Environmental Impact (EI)	0.3	0.5
Implementation Cost (IC)	0.4	0.3
Technological Maturity (TM)	0.3	0.2

The proposed weighting configurations should therefore be intended as representative scenarios able to represent the different constraints and strategic priorities typically associated with SMEs and MNCs. This configuration ensures the alignment between environmental performance and organizational capabilities, enabling a tailored assessment of decarbonization strategies. Given the author-defined nature of the weighting scheme, the robustness of these assumptions will be further investigated through a sensitivity analysis presented in Chapter 6.

4.3 Aggregation Method

Once the evaluation criteria and the corresponding weights have been defined, it is possible to aggregate the individual scores of each strategy in order to obtain the overall Performance Indicator (PI). In this study, a weighted linear aggregation method has been adopted, as it provides a transparent approach to combine multiple evaluation criteria into a single comprehensive score. Moreover, it preserves the direct contribution of each criterion to the final result, facilitating the interpretation and comparison of alternative strategies under

different weighting scenarios. This allows each strategy to be evaluated considering its performance across different dimensions and their relative importance.

Before performing the aggregation, the original scores assigned to Environmental Impact (EI), Implementation Cost (IC) and Technological Maturity (TM) are normalized. Although all criteria are evaluated using the same 0-5 scoring scale, normalization is applied to transform the scores into standardized values ranging from 0 to 1. This step improves the interpretability of the results and ensures consistency with common MCDM practice. The normalization is performed according to the following formulation:

$$x' = \frac{x - \min}{\max - \min} = \frac{x - 0}{5 - 0}$$

where x represents the original score assigned to a given criterion (EI, IC and TM) and x' is the corresponding normalized value. This conversion preserves the relative differences between strategies, while expressing their performance on a common scale in which higher values indicate better performance.

The normalized scores are then used to compute the overall Performance Indicator (PI) of each strategy through a weighted aggregation process. PI is calculated as follows:

$$PI = w_{EI} * EI' + w_{IC} * IC' + w_{TM} * TM'$$

Where w_{EI} , w_{IC} and w_{TM} represent the weights assigned to each criterion and EI' , IC' and TM' correspond to the normalized scores. In order to account for the structural differences between SMEs and MNCs, the PI is calculated using the two distinct weighting schemes defined in the previous section. As a result, each strategy is associated with two different performance indicators computed as:

$$PI_{SME} = 0.3 * EI' + 0.4 * IC' + 0.3 * TM'$$

$$PI_{MNC} = 0.5 * EI' + 0.3 * IC' + 0.2 * TM'$$

This approach enables a direct comparison of strategies across the two main firm typologies and highlights how the same strategy may lead to different outcomes depending on

organizational priorities, resource availability and risk tolerance of the firm considered. Consequently, the framework does not seek to identify a universally optimal decarbonization strategy. Instead, it evaluates how the relative attractiveness of alternative solutions changes under different organizational priorities, providing a more context-sensitive interpretation of the decision-making process. In this way, the most suitable strategies emerge as a function of firm-specific characteristics and the strategic objectives associated with each organizational profile.

5. Overview of the Identified Strategies

The result of the literature review reveals a wide variety of decarbonization strategies applicable to the aerospace manufacturing sector. Each analysed paper proposes a specific approach that differs significantly in terms of technological effort, environmental impact, upfront costs, maturity level, implementation requirements and system boundaries. In order to ensure a consistent interpretation of such heterogeneous solutions, a categorization process has been carried out based on the main decarbonization logics emerging from the literature.

In these energy-intensive systems, decarbonization can be achieved through multiple and often complementary pathways, as it is possible to intervene at different levels of the value chain. For this reason, aerospace manufacturing is interpreted in this study according to a value-chain perspective rather than being restricted to individual production processes. In addition to technologies directly affecting manufacturing operations, the analysis also considers strategies capable of influencing the environmental performance of the industrial systems, energy carriers, feedstocks and supporting infrastructures upon which aerospace manufacturing activities depend. This broader perspective reflects the increasing integration between production systems, energy supply chains and lifecycle-oriented sustainability approaches that characterize contemporary aerospace decarbonization efforts. For example, some approaches intervene directly on manufacturing processes and the related material flows, improving the efficiency with which energy and materials are utilized, recovered or reused. Other solutions optimize existing processes through digital tools, simulation models, artificial intelligence and automated scheduling systems, aiming to reduce the overall carbon footprint without necessarily requiring high capital investments. There is also increasing interest in sustainable aviation fuels, hydrogen-based production pathways and alternative energy infrastructures capable of supporting the transition toward low-carbon aerospace systems. Finally, another important group of strategies focuses on the design and material selection stage, where substantial improvements can be achieved through lightweight structures, hybrid materials and advanced joining solutions. For this reason, the strategies are grouped into the following four categories: *Clean Energy Systems, Hydrogen and Sustainable Fuels*; *Digital Intelligence, AI and Data-Driven Decarbonization*; *Manufacturing Process Optimization and Energy Efficiency*; *Sustainable Materials and Advanced Product Design*. Each category represents a specific decarbonization logic and reflects a distinct way of addressing the environmental challenge. The strategy identification

and selection process described in Chapter 3 resulted in a final set of 14 representative decarbonization alternatives. The categorization discussed above provides an organizational structure through which these strategies can be interpreted according to their dominant decarbonization logic. The following table summarizes the 14 decarbonization strategies selected for this study, together with their corresponding references and identification codes, which are used to facilitate their discussion and evaluation throughout the study.

Table 7 *Overview of identified Decarbonization Strategies*

<i>Category</i>	<i>Strategy adopted</i>	<i>Reference</i>	<i>ID</i>
<i>Clean Energy Systems, Hydrogen and Sustainable Fuels</i>	PtL-Based SAF Production Pathways with Alternative Aromatic Supply	Kim J.; Kim S.; Park S.; Lee I., 2025	A1
	SAF Production from Lignocellulosic Biomass	Shrirame B.S.; Maity S.K., 2025	A2
	Nuclear assisted Hydrogen production for Sustainable aviation fuel	Constantin A., 2024	A3
<i>Digital Intelligence, AI and Data-Driven Decarbonization</i>	Numerical Model for Improving Thermal Management in PEM Fuel Cells	M., Seddiq, Mehdi; M., Alnajideen, Mohammad; R., Navaratne, Rukshan, 2025	B1
	AI-driven PEMWEs optimization	Alipour Bonab S.; Waite T.; Song W.; Flynn D.; Yazdani-Asrami M., 2024	B2
	Energy-flexible scheduling of machining processes	Haddad Y.; De Bonneval E.G.; Afy-Shararah M.; Carter J.; Artingstall J.; Salonitis K., 2024	B3
	Meta-Heuristic Scheduling for Low-Carbon Manufacturing	Wang H.; Zhu J.; Huang X.; Ma H.; Chen Y.; Zhou Y.; Chen J.; Hu Z., 2022	B4
<i>Manufacturing Process Optimization and Energy Efficiency</i>	Chemical utilization of slag waste heat through chemical reactions	Duan W.; Dong X.; Gao L.; Wang Z.; Li B., 2025	C1
	Selective Laser Melting for Turbine Blades Manufacturing	Torres-Carrillo S.; Siller H.R.; Vila C.; López C.; Rodríguez C.A., 2019	C2
	Fixed-Point Modelling for Material and Energy Optimization in Forging Production	He F.; Ma X.; Shen K.; Wang C., 2020	C3

<i>Sustainable Materials and Advanced Product Design</i>	Design-Driven Carbon Footprint Reduction of Composite Materials	Dalpadulo E.; Russo M.; Gherardini F.; Leali F., 2024	D1
	LPBF–HEA Integration for Hydrogen Turbines components	Harithsa S.N.; Anand Kumar S.; Velu R.; Nagesha B.K., 2023	D2
	Permanent magnet Rotor Design for EPU	Von Lindenfels J.; Ihne T.; Franke J.; Kuhl A., 2022	D3
	Direct Titanium–PET Bonding via Heating and Pressurization	K., Kondoh, Katsuyoshi; N., Nishimura, Nodoka; K., Shitara, Kazuki; S., Kariya, Shota; K., Chen, Ke; J., Umeda, Junko, 2025	D4

It is important to clarify that this categorization does not represent isolated domains, as their boundaries are partially overlapping due to the strong complementarity and interconnection that characterize manufacturing systems. However, this organizational approach is necessary to identify the dominant decarbonization mechanisms, provide representative examples that can be translated into strategic actions and support the subsequent comparative assessment carried out in this study.

The purpose of this section is therefore to present the four main pillars identified through the literature analysis and provide a structured qualitative overview of the associated strategies. For each category, representative examples are discussed in order to illustrate how specific approaches can contribute to emission reduction within aerospace manufacturing environments. Although these strategies are often derived from specific case studies or particular industrial domains, their underlying principles are not limited to the original application context and may be transferred to different stages of the aerospace value chain depending on technological capabilities and operational constraints. In this sense, this section not only describes individual solutions but also demonstrates how different decarbonization mechanisms can be implemented in real industrial systems, bridging the gap between theoretical concepts and practical applications.

To support the comparative analysis, each strategy is presented following the common structure derived from the Data Extraction Framework introduced in Chapter 3. The discussion therefore considers the operating principle, application scope, environmental implications, implementation costs, technological maturity, adoption barriers and relevance for different organizational contexts. This standardized approach facilitates the comparison

of heterogeneous decarbonization pathways and ensures consistency throughout the analysis.

In addition, each strategy concludes with the Evaluation Criteria Summary, which provides the justification for the scores assigned to the three evaluation criteria adopted in this study: Environmental Impact (EI), Implementation Cost (IC) and Technological Maturity (TM). These summaries synthesize the main evidence extracted from the literature and establish a transparent link between the qualitative discussion of each strategy and the comparative assessment framework developed in Chapter 6.

5.1 Clean Energy Systems, Hydrogen and Sustainable Fuels

The first category includes all the strategies that approach decarbonization primarily through the transformation of the energy base supporting aerospace systems. In these energy intensive sectors, long-term emission reductions cannot be achieved only by optimizing existing operations, but it is also necessary to introduce alternative energy carriers capable of replacing or complementing conventional fossil fuels. This is particularly relevant in the aerospace field, where the emission reduction challenge is further amplified by the structural dependence on fuels with high volumetric energy density, required to sustain long service life and operational performance, as well as by the technical difficulty of fully electrifying flight operations. In this scenario, clean energy systems, hydrogen and Sustainable Aviation Fuels (SAF) emerge as key pillars of future aerospace decarbonization pathways.

These solutions play a strategic role, as they act directly at the root of the emission problem by altering the carbon intensity of energy inputs. This results in a very high emission mitigation potential. From a sustainable manufacturing perspective, these strategies address the environmental impact associated with the production and supply of energy carriers and industrial feedstocks required throughout aerospace value chains. Their relevance therefore extends beyond aircraft operation, encompassing the industrial processes involved in the generation, conversion and distribution of low-carbon fuels and hydrogen, as well as the broader transformation of energy systems supporting manufacturing activities. However, their main drawbacks lie in the high capital investments required, technological uncertainty and long implementation horizons.

In particular, SAF represents one of the most promising solutions due to its high applicability and scalability. It is a synthetic fuel that can be produced from a variety of renewable feedstocks such as waste oils, agricultural residues or biomass and it is designed to be fully

compatible with existing aircraft engines and infrastructure without requiring modifications. Depending on the specific production pathway, SAF can reduce lifecycle CO₂ emissions by up to 80% compared to conventional kerosene. The relevance of SAF is already reflected in industrial practice, as leading aerospace companies are actively investing in its development and large-scale adoption. For instance, GE Aerospace jet engines are already capable of operating with approved SAF blends, with ongoing efforts aimed at enabling the use of 100% unblended SAF. At the same time, GE is advancing hydrogen combustion technologies and hybrid-electric propulsion systems, following a broader strategy that integrates SAF within a wider portfolio of low-carbon energy solutions (General Electric, 2026). Similarly, Airbus is playing a crucial role in accelerating SAF adoption across its operations. All major Airbus commercial aircraft assembly sites are already implementing SAF, with a progressively increasing share across activities such as delivery flights, internal logistics and business travel. The company aims to reach at least 30% SAF usage in its global fuel mix by 2030, while also supporting the development of the SAF ecosystem through partnerships and investments (Airbus, 2026).

These industrial initiatives demonstrate that the transition towards SAF is already a concrete and viable pathway. However, its large-scale adoption is still constrained by several challenges, including the high production cost compared to traditional fuels (up to 2.8 times higher according to the European Union Aviation Safety Agency), the limited availability of sustainable feedstocks and the need for supportive regulatory frameworks.

These strategies are typically linked to system-level transformations rather than local process adjustments. Their successful implementation often depends on the availability of renewable electricity, clean hydrogen infrastructures, carbon capture systems, large-scale integration capabilities and supportive regulatory frameworks. For this reason, it is important to highlight that their feasibility is not determined only by firm-level technical choices but also depends on several complementary conditions such as energy system development, policy support, market incentives and the maturity of these technologies. Each strategy represents a different trade-off in terms of efficiency, scalability, infrastructure dependence and technological maturity. Some of them appear particularly promising from an environmental perspective but may be limited by low maturity levels and high upfront costs. For this reason, this category must be interpreted as a long-term transition enabler, supporting a progressive shift beyond conventional fossil energy dependence. At present, the adoption of these strategies ranges from commercially deployed solutions, such as SAF utilization, to emerging technologies that are still being validated through pilot projects and demonstration

initiatives. The following section presents a set of representative strategies belonging to this category, illustrating how different approaches can be applied to transform energy systems and support the decarbonization of aerospace manufacturing.

5.1.1 PtL-Based SAF Production Pathways with Alternative Aromatic Supply – A1

Sustainable Aviation Fuel (SAF) is widely recognized as one of the most promising solutions for reducing greenhouse gas emissions in the aviation sector. Its relevance is enhanced by the limitations currently affecting alternative decarbonization pathways, including the low energy density of batteries, the high energy requirements of aircraft and the limited availability of mature alternatives to conventional gas-turbine propulsion systems.

Among the available production routes, Power-to-Liquid (PtL) pathways have attracted significant interest due to their ability to convert renewable electricity, captured carbon dioxide and green hydrogen into synthetic hydrocarbons. In a typical PtL process, renewable electricity is used to produce hydrogen through water electrolysis. The hydrogen subsequently reacts with captured carbon dioxide to generate syngas, which is converted into liquid fuels through Fischer-Tropsch (FT) synthesis. One of the main challenges associated with this route is the low aromatic content naturally produced during FT synthesis. Since aromatics are required to meet ASTM D7566 specifications regarding fuel density, combustion stability and compatibility with aircraft fuel systems, additional aromatic supply strategies must be implemented. From a sustainable manufacturing perspective, the aerospace sector is increasingly extending its decarbonization efforts beyond the boundaries of production facilities, adopting a broader value-chain approach that considers the environmental impact generated across the entire aerospace ecosystem. Within this context, Sustainable Aviation Fuel represents one of the most relevant decarbonization pathways due to its potential to significantly reduce lifecycle emissions while remaining fully compatible with existing aircraft, engines and fuel infrastructures.

In their study, Kim et al. investigate three alternative PtL configurations that differ in the way aromatic compounds are supplied and integrated within the production process, analysing the resulting trade-offs between environmental performance, economic viability and technological complexity. The analysed PtL pathways demonstrate a substantial potential for emission reduction. Compared with conventional aviation fuels, PtL SAF can reduce lifecycle greenhouse gas emissions by up to 90%, while requiring significantly lower land and water consumption than biomass-based alternatives.

From an energy-efficiency perspective, the first configuration achieves the highest performance, reaching an efficiency of 54.8% and producing 8,388 kg/h of SAF. This result is obtained through an optimized utilization of syngas and the external procurement of aromatic compounds. The second configuration introduces an internal aromatic synthesis unit, eliminating reliance on external suppliers but reducing energy efficiency to 47% due to additional syngas consumption and by-product generation. The third configuration further integrates an electrolysis unit to reduce hydrogen demand. Although this approach lowers energy efficiency to 38.8% due to the higher electricity consumption, it substantially decreases hydrogen requirements and improves the overall economic performance of the process.

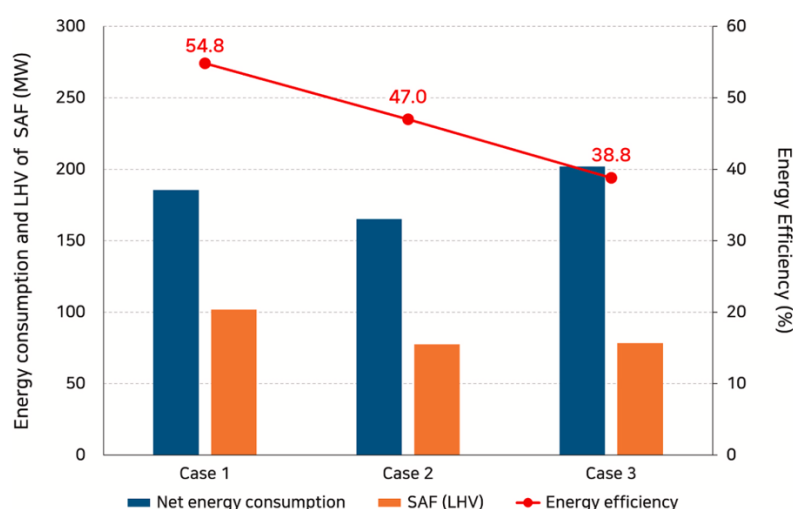


Figure 2 Energy consumption, LHV of SAF and energy efficiency
 Reproduced from *Electrolysis-Assisted CO₂ reduction and aromatic supply method for sustainable aviation fuel Production: Cost optimization and Future cost scenarios*, by Kim J. et al., 2025

The economic performance of the three configurations is strongly influenced by the balance of hydrogen consumption, aromatic supply and process integration. The first configuration benefits from a relatively simple process layout and moderate capital requirements but remains dependent on externally sourced aromatics and significant hydrogen consumption. The second configuration requires additional investment for the syn-to-aroma reactor and associated equipment, resulting in the highest capital expenditure among the analysed alternatives. The third configuration introduces electrolysis-assisted carbon monoxide production, allowing a reduction in hydrogen demand and a downsizing of several process units. As a consequence, it achieves the lowest levelized fuel cost and the lowest capital

investment requirement, estimated at approximately 238 M\$. Despite these improvements, all configurations remain characterized by high capital intensity and significant infrastructure requirements.

The proposed pathways are based on several technologies that are individually well established, including water electrolysis, reverse water gas shift reactors and Fischer-Tropsch synthesis. However, the integration of internal aromatic production and electrolysis-assisted carbon monoxide generation remains relatively novel and has not yet achieved a complete industrial deployment. Consequently, while the underlying technological components are generally mature, the integrated systems analysed by Kim et al. still face scale-up challenges and require further industrial validation before large-scale commercialization

The main barriers limiting the adoption of PtL SAF pathways are associated with their high capital requirements, substantial electricity demand and dependence on green hydrogen availability. In addition, internal aromatic production introduces efficiency losses and additional process complexity, while emerging electrolysis-based configurations still require further technological development. The economic viability of these systems therefore remains strongly dependent on future reductions in renewable electricity and electrolysis costs. These substantial infrastructure requirements, high investment costs and technological complexity associated with PtL SAF production, make this strategy primarily suitable for large multinational companies with significant financial resources and long-term decarbonization objectives. The scale of investment and technological capabilities required make direct adoption by SMEs highly unlikely, except through participation in larger supply-chain initiatives or collaborative projects (Kim et al., 2025).

Table 8 *AI Evaluation Criteria Summary*

Criterion	Score	Justification
EI	5	PtL-based SAF can reduce lifecycle greenhouse gas emissions by up to 90% compared with conventional aviation fuels. All analysed configurations contribute significantly to emission reduction, while the first pathway achieves the highest energy efficiency (54.8%).

IC	1	The strategy requires large-scale PtL infrastructure, electrolyzers, RWGS reactors, Fischer-Tropsch units and significant capital investment. Even the most cost-effective configuration requires approximately 238 M\$ of capital expenditure.
TM	2	Although several individual technologies are mature, the integrated pathways involving internal aromatic production and electrolysis-assisted carbon monoxide generation have not yet reached widespread industrial deployment and require further scale-up and validation.

5.1.2 SAF Production from Lignocellulosic Biomass – A2

The production of SAF from renewable biomass-derived feedstocks is increasingly recognized as an important pathway for reducing lifecycle emissions associated with aviation activities. In this context, the development of efficient biomass-to-fuel conversion routes contributes to the broader sustainability objectives pursued across the aerospace sector.

Lignocellulosic biomass has emerged as a promising feedstock for Sustainable Aviation Fuel (SAF) production due to its abundance, relatively low cost and renewable nature. However, biomass-derived molecules are typically characterized by short carbon chains, which are not suitable for aviation fuel applications and therefore require upgrading processes capable of generating hydrocarbons within the SAF carbon range.

To address this limitation, Shrirame et al. propose a two-step catalytic pathway based on hydroxyalkylation-alkylation (HAA) and hydrodeoxygenation (HDO). In the first stage, furfural derived from lignocellulosic biomass reacts with 2-methylfuran to form a higher-carbon intermediate. This intermediate is subsequently upgraded through hydrodeoxygenation, which removes oxygen and produces paraffinic hydrocarbons compatible with aviation fuel requirements. The authors demonstrate that catalyst composition and operating conditions strongly influence process performance. Under optimal conditions, a catalyst containing 10 wt.% NiO and 10 wt.% WO₃ calcined at 1023 K achieved approximately 80% oxygenate conversion, whereas only 2% conversion was observed at 923 K, highlighting the importance of catalyst preparation in determining hydrodeoxygenation activity. The resulting product distribution was dominated by C13 and C14 branched alkanes, which accounted respectively for 33.9% and 36.2% of the total

hydrocarbons produced. These compounds fall within the C8–C16 molecular range typically required for sustainable aviation fuels (Liu et al., 2017), demonstrating the capability of the proposed pathway to selectively generate molecules suitable for jet fuel applications.

The environmental relevance of this strategy lies in its ability to convert renewable lignocellulosic biomass into hydrocarbons suitable for aviation fuel applications. By replacing fossil-derived feedstocks with renewable carbon sources, the proposed pathway contributes to the production of lower-carbon aviation fuels and supports the decarbonization objectives of the aerospace sector. In addition, the use of biomass-derived intermediates promotes a more efficient use of renewable resources and reduces dependence on conventional production routes. From an implementation perspective, the availability and relatively low cost of lignocellulosic biomass represent an important advantage. Nevertheless, the process requires multiple conversion stages, dedicated catalyst preparation and hydrogen-assisted hydrodeoxygenation. The optimized catalyst formulation involves mesoporous NiW-ZrO₂ materials calcined at temperatures up to 1023 K, while the upgrading stage relies on hydrogen consumption and controlled operating conditions. Although no economic assessment is provided by the authors, these characteristics suggest moderate-to-high implementation requirements compared with more mature fuel production pathways.

The strategy benefits from the large availability and relatively low cost of lignocellulosic biomass. However, industrial implementation requires multiple conversion stages, dedicated catalyst preparation and hydrogen-assisted hydrodeoxygenation. The optimized catalyst formulation involves mesoporous NiW-ZrO₂ materials calcined at temperatures up to 1023 K, while the upgrading stage relies on hydrogen consumption and controlled operating conditions which increases the technological complexity and suggests moderate-to-high implementation costs compared with more mature fuel production pathways.

The study shows promising results under laboratory conditions, achieving significant oxygenate conversion with the optimized catalyst formulation. However, it focuses on catalyst development and reaction performance, with no evidence of pilot-scale or industrial-scale deployment. Therefore, despite the encouraging experimental results, the technology remains at an early stage of industrial maturity. This represents one of the major limitations since additional research is needed to evaluate long-term operational performance and economic feasibility at industrial scale. Other barriers are associated with hydrogen availability, catalyst stability, process scale-up and the integration with existing fuel production systems. The technological complexity of the process and the infrastructure required for large-scale production, makes this strategy more suitable for large multinational

companies and industrial consortia operating within the energy, chemical and aerospace sectors. SMEs may contribute to specific segments of the supply chain but are unlikely to independently implement the complete production route. (Shrirame et al., 2025).

Table 9 *A2 Evaluation Criteria Summary*

Criterion	Score	Justification
EI	4	The optimized pathway achieves approximately 80% oxygenate conversion, demonstrating an effective transformation of biomass-derived intermediates into fuel-range products and supporting the exploitation of renewable carbon resources.
IC	2	Although lignocellulosic biomass is widely available and relatively inexpensive, the process requires multiple conversion stages, dedicated catalyst preparation, hydrogen-assisted hydrodeoxygenation and controlled operating conditions which increase technological complexity and suggest moderate-to-high implementation requirements.
TM	2	The technology is at an early stage of development, with no evidence of pilot-scale or commercial deployment.

5.1.3 Nuclear Assisted Hydrogen Production for Sustainable Aviation Fuel – A3

Hydrogen is a key enabler of industrial decarbonization due to its potential to support the production of low-carbon synthetic fuels for sectors where direct electrification remains technically challenging, including flight operations, maritime transport and heavy industry. In this context, Constantin explores the role of nuclear energy as a low-carbon source of electricity and process heat for large-scale hydrogen production, highlighting its potential contribution to future sustainable fuel supply chains. Hydrogen can be used as a feedstock for the synthesis of hydrogen-based aviation fuels, providing a viable pathway for reducing lifecycle greenhouse gas emissions associated with air transport. The proposed approach relies on the integration of nuclear power plants with advanced hydrogen production technologies, particularly High-Temperature Steam Electrolysis (HTSE). Unlike conventional electrolysis, HTSE operates at temperatures between 750°C and 950°C and combines electrical and thermal energy to split water into hydrogen and oxygen (Revankar, 2019). The availability of high-temperature heat from nuclear reactors significantly reduces

the electrical energy required by the process, thereby improving overall efficiency and minimizing conversion losses. Advanced reactor technologies can provide outlet temperatures ranging from approximately 500°C to 1000°C, enabling the direct utilization of thermal energy for hydrogen generation rather than converting heat into electricity first. Several characteristics make nuclear-assisted hydrogen production particularly attractive from a sustainability perspective. A single 1000 MW nuclear reactor can produce more than 150000 tonnes of hydrogen annually (U.S. Department of Energy, 2022), while operating at capacity factors exceeding 90%, which is considerably higher than the typical 20–40% associated with renewable energy sources. The technology also benefits from a very low carbon footprint, with nuclear-based HTSE generating approximately 0.43 kg CO₂ per kg H₂ compared with 10.6 kg CO₂ per kg H₂ for steam methane reforming and around 2–2.3 kg CO₂ per kg H₂ for solar-based alkaline electrolysis (Yadav et al., 2020). In addition, nuclear systems require significantly less land than renewable alternatives, while offshore wind installations potentially require up to 1,400 times more surface area to produce an equivalent amount of hydrogen. These characteristics highlight the ability of nuclear energy to provide a reliable and scalable source of low-carbon hydrogen capable of supporting future SAF production pathways.

Despite its considerable potential, several challenges still limit the large-scale deployment of nuclear-assisted hydrogen production. The implementation of this strategy is associated with very high investment requirements as it involves not only the construction and operation of nuclear power facilities, but also the development of dedicated hydrogen production plants, storage systems, transportation infrastructure and integration technologies capable of coupling nuclear reactors with advanced hydrogen generation processes. The need for specialized equipment, extensive safety measures and long project development timelines further increases implementation costs, making the economic feasibility of this approach more suitable for large-scale projects supported by substantial financial resources and supportive policy frameworks.

In addition, although nuclear power generation itself represents a commercially mature technology, the specific application of nuclear energy for large-scale hydrogen production remains at an earlier stage of development. Technologies such as High-Temperature Steam Electrolysis (HTSE) and thermochemical water-splitting cycles have demonstrated promising performance and efficiency improvements, but several technical, operational and regulatory challenges still need to be addressed before full commercial deployment can be achieved. As a result, current implementation efforts are primarily concentrated in pilot tests

and demonstration initiatives aimed at validating the technical feasibility and economic competitiveness of nuclear hydrogen production systems.

Consequently, the adoption of this strategy will depend on continued technological progress, long-term investments, supportive regulatory frameworks and public acceptance of nuclear energy. (Constantin A., 2024)

Table 10 *A3 Evaluation Criteria Summary*

Criterion	Score	Justification
EI	5	Enables large-scale production of low-carbon hydrogen with emissions of only 0.43 kg CO ₂ /kg H ₂ , compared with 10.6 kg CO ₂ /kg H ₂ for conventional Steam Methane Reforming, supporting significant emission reductions in SAF production.
IC	1	Requires significant investments in nuclear infrastructure, hydrogen production facilities, storage systems and transport networks, resulting in very high implementation costs and long development timelines.
TM	2	While nuclear power is commercially mature, key hydrogen production technologies such as HTSE and thermochemical cycles are still largely limited to pilot and demonstration projects.

5.2 Digital Intelligence, AI and Data-driven Decarbonization

The second category groups the strategies that contribute to decarbonization through the use of digital technologies, advanced data processing and intelligent decision-support systems. This approach focuses on improving the way industrial systems are monitored, controlled, predicted and managed, thus increasing the overall efficiency of production systems. This aspect is particularly relevant in contemporary manufacturing, which is characterized by the continuous generation of data related to machine parameters, energy demand, process conditions, scheduling constraints, maintenance activities and production flows. Within aerospace manufacturing, these data streams are generated across highly complex and tightly integrated production environments, where even small inefficiencies can translate into significant material waste, energy consumption and operational costs. As a result, the ability to effectively exploit production data has become a key component of sustainable

manufacturing initiatives. This growing data availability represents a valuable resource for environmental improvement. However, raw data do not automatically translate into sustainability benefits. It is therefore necessary to interpret and convert them into actionable operational knowledge through the implementation of digital intelligence, simulation models and AI-based approaches. By improving process visibility, prediction accuracy and decision quality, these technologies can support more efficient resource utilization and reduce avoidable environmental impacts without necessarily requiring major modifications to existing manufacturing infrastructure.

A key advantage of these strategies lies in the fact that they do not require radical modifications of existing production systems, as they improve performance by enhancing decision quality through more effective use of information. For this reason, these solutions are generally more flexible, require relatively lower investments and offer faster implementation compared to more infrastructure-intensive approaches. At the same time, their effectiveness strongly depends on the quality and availability of data, the robustness of the implemented algorithms, and their integration with real production systems. In this sense, the main barriers to adoption are less related to physical infrastructure and more associated with digital maturity, data governance and the ability to design and implement tailored digital solutions.

Another key characteristic of this category is its transversality, as these approaches are not limited to specific domains but can be adapted across different industrial contexts to improve efficiency, support predictive capabilities and reduce operational uncertainty. The common element of these strategies lies in their ability to support decarbonization through more intelligent system behaviour, better anticipation of process conditions and more responsive decision-making, while remaining compatible with existing infrastructures. This aspect is particularly relevant in highly competitive sectors such as aerospace, where radical process substitution may be difficult, slow or economically demanding. In such contexts, digital and data-driven approaches represent a practical and scalable pathway for achieving environmental improvements without disrupting established production systems.

The following strategies are therefore grouped within this category because they all exemplify how data, modelling and intelligent computational tools can become active levers for supporting decarbonization in aerospace manufacturing.

5.2.1 Numerical Model for Improving Thermal Management in PEM Fuel Cells – B1

Proton Exchange Membrane Fuel Cells (PEMFCs) is a promising energy conversion technology for future aerospace propulsion systems capable of supporting decarbonization objectives. These systems convert the chemical energy stored in hydrogen into electricity through an electrochemical process that produces only water and heat as by-products during operation. Hydrogen is split into protons and electrons at the anode; the protons migrate through the membrane while the electrons travel through an external circuit, generating electrical current. Individual PEMFC cells typically produce between 0.5 and 0.8 V and are therefore assembled into stacks to achieve the power levels required for practical aerospace applications.

PEMFCs are attracting increasing attention within the aerospace sector due to their high power density, compact design, scalability and environmentally friendly operation. However, several technical and economic barriers still limit their widespread adoption. High production costs, mainly associated with platinum-based catalysts, together with durability issues related to membrane degradation and water management, remain significant challenges. These limitations become even more critical in aerospace environments, where fuel cells are exposed to reduced atmospheric pressure, limited oxygen availability and significant temperature fluctuations that can strongly affect performance and reliability.

To address these challenges, Seddiq et al. developed a validated numerical model aimed at investigating the transient thermal behaviour of PEM fuel cells subjected to thermal shock cycles. The study focuses on understanding how sudden temperature variations influence fuel cell performance by simulating thermal shocks in which bipolar plate temperatures are reduced from 50°C to 10°C, reproducing operating conditions representative of extreme aerospace environments. The simulations revealed three main effects associated with thermal shock events. First, current density decreased from 9,263 A/m² to 7,709 A/m², corresponding to an approximate 15% reduction in power generation capability, with recovery times exceeding four seconds before stable operating conditions were restored. Second, oxygen concentration within the cathode catalyst layer decreased significantly, particularly near cell edges where gas diffusion was naturally more limited. The study reports reductions exceeding 20% in minimum oxygen concentration, leading to lower electrochemical reaction rates and temporary efficiency losses. Third, membrane water content exhibited substantial transient variations, decreasing during the cooling phase and subsequently exceeding steady-state values during recovery. These phenomena collectively affected cell performance by altering reactant transport, membrane conductivity and

electrochemical reaction kinetics. One of the most interesting findings concerns the post-recovery behaviour observed after thermal shocks. Once the temperature returned to nominal operating conditions, the fuel cell did not simply recover its initial performance level but temporarily exceeded the original steady-state performance. According to the authors, this behaviour is associated with the redistribution of oxygen, hydrogen and water within the cell during the recovery phase. This result highlights the intrinsic resilience of PEMFC systems and demonstrates their ability to rapidly re-establish favourable operating conditions when appropriate thermal management strategies are implemented.

The relevance of this strategy lies in supporting the development of more reliable and durable hydrogen-based energy systems. By improving the understanding of thermal and water management mechanisms, the proposed model contributes to the optimization of fuel cell performance under variable operating conditions. Such improvements can support longer operational lifetimes, reduce performance degradation and facilitate the future deployment of hydrogen-based propulsion technologies within the aerospace sector.

Despite these potential benefits, several barriers still limit large-scale implementation. The use of platinum-based catalysts and advanced system components increases production costs compared with conventional energy systems, while the integration of PEMFC technologies into existing aircraft architectures requires modifications to power distribution systems, safety procedures and maintenance protocols. Nevertheless, since the strategy is based on a numerical modelling approach rather than on the immediate deployment of new hardware, implementation costs remain moderate and are primarily associated with simulation activities, engineering studies and future system integration efforts. As a result, the approach can be adopted by both large organizations and medium-sized companies involved in fuel cell research and development, although full-scale industrial implementation would require more substantial investments. Although the proposed model relies on several simplifying assumptions, including idealized thermal boundary conditions, a single-cell configuration and limited representation of real flight conditions, it provides valuable insights into the transient behaviour of PEM fuel cells. The results emphasize the importance of thermal and water management for improving stability, durability and operational reliability, while offering a useful foundation for future research aimed at supporting the integration of hydrogen-based propulsion systems within the aerospace sector (Seddiq et al., 2025).

Table 11 *B1 Evaluation Criteria Summary*

Criterion	Score	Justification
EI	4	Improves the efficiency, stability and durability of PEM fuel cells under transient operating conditions. By supporting the development of more reliable hydrogen-based propulsion systems, it can facilitate the future adoption of low-emission aerospace technologies.
IC	3	The numerical model relies on simulation and computational analyses, requiring limited resources during the research and development phase. Nevertheless, the future deployment of PEM fuel cell systems involves advanced materials, platinum-based catalysts and integration requirements that increase overall implementation costs, resulting in a moderate cost profile.
TM	1	The proposed approach remains at an early research stage and is currently limited to numerical simulations. Further experimental validation and large-scale testing are required before practical aerospace implementation.

5.2.2 AI-driven PEMWEs optimization – B2

Proton Exchange Membrane Water Electrolyzers (PEMWEs) are currently considered one of the most mature technologies for large-scale green hydrogen production from renewable electricity sources. Their high efficiency, rapid dynamic response, operational flexibility and scalability make them particularly suitable for coupling with intermittent renewable energy systems such as wind power. As hydrogen is increasingly recognized as a promising energy carrier for future aerospace applications, improving the efficiency and reliability of PEMWEs has become a critical research objective. Hydrogen has attracted considerable attention also in the aerospace context due to its high specific energy and potential to support long-range operations with lower environmental impacts than conventional fossil fuels. However, the adoption of hydrogen technologies remains constrained by the costs associated with hydrogen production, storage and transportation. Consequently, improving the performance and durability of PEMWEs is essential for supporting future hydrogen-based aerospace systems.

Despite their advantages, PEMWE performance gradually deteriorates over time due to degradation mechanisms affecting catalysts, membranes and other operating components. Even if the main degradation factors have been identified, the complex interactions between

operating conditions, material properties and electrochemical processes make it difficult to accurately predict cell performance and lifetime. This uncertainty increases the need for extensive testing activities, which result in significant time and resource usage during system development. To address this challenge, Bonab et al. defined an artificial intelligence-based predictive framework capable of estimating PEMWE cell potential under different operating conditions. The study evaluates five machine learning techniques, namely Cascade Forward Neural Network (CFNN), Support Vector Machine (SVM), Decision Tree (DT), Extra Tree (ET) and Extreme Gradient Boosting (XGBoost), with the objective of identifying the most effective approach for PEMWE performance prediction. The model was trained using experimental and simulation data collected under different operating conditions, including variations in temperature, current density and anodic catalyst materials. The cell potential was selected as the target parameter, and the dataset was divided into training and testing subsets using an 80%-20% split.

Among the investigated techniques, the Cascade Forward Neural Network demonstrated the best overall performance. The optimal configuration consisted of five hidden layers with twenty neurons per layer and a Tansig-Purelin activation function. The model achieved an accuracy of 99.998% and a relative error below 0.65%, while maintaining absolute deviations lower than 10 mV between predicted and measured cell potential values, demonstrating an almost perfect correspondence with experimental observations. Another significant advantage concerns computational efficiency. Predictions can be generated within only a few milliseconds, making the framework suitable not only for design optimization but also for real-time monitoring and operational support applications. By rapidly evaluating PEMWE performance under different conditions, the model can significantly reduce the need for repeated experimental campaigns while maintaining high predictive reliability.

The relevance of this strategy lies in its ability to accelerate the development of green hydrogen production technologies through digital intelligence tools. By replacing part of the experimental testing activities with highly accurate predictions, the model can reduce development time, resource consumption and design iterations. Furthermore, a better understanding of performance degradation mechanisms can support more efficient operation and maintenance strategies, contributing to the long-term reliability of hydrogen production systems. Since green hydrogen is expected to play a key role in future aerospace decarbonization pathways, improvements in PEMWE performance can support the transition toward lower-emission aviation technologies. From an implementation

perspective, the proposed strategy presents a moderate cost profile. The development and deployment of the CFNN model primarily require computational resources, software infrastructure and access to operational datasets. However, its practical application remains linked to PEMWE technologies, whose deployment still relies on advanced materials, specialized components and integration efforts. As a result, while the AI framework itself involves relatively limited implementation costs, its industrial application remains associated with the moderate investment requirements typical of hydrogen production systems. Despite these advantages, some limitations remain. The predictive capability of the model strongly depends on the quality and representativeness of the available data. Moreover, the framework was developed using specific operating conditions and catalyst configurations, requiring further validation before broader industrial application.

Overall, the CFNN model developed by Bonab et al. represents a significant example of how artificial intelligence can support sustainable manufacturing through data-driven optimization. Although the proposed framework is specifically applied to PEMWE technologies and hydrogen production systems, the underlying approach is highly transferable and can be adapted to a wide range of industrial processes characterized by complex operating conditions and large amounts of data. Its combination of exceptional predictive accuracy, computational efficiency and real-time applicability demonstrates the potential of AI-based tools to reduce experimental efforts, accelerate design optimization and support more efficient resource utilization. Consequently, this study highlights not only the benefits of AI for hydrogen-related applications, but also its broader role as an enabling technology for improving productivity, reducing development costs and supporting sustainability objectives across advanced manufacturing systems (Bonab et al., 2024).

Table 12 B2 Evaluation Criteria Summary

Criterion	Score	Justification
EI	4	The CFNN model supports the optimization of PEMWE systems by improving performance prediction, reducing development inefficiencies and facilitating the advancement of green hydrogen production technologies. By enabling more efficient and reliable hydrogen generation, it can indirectly support aerospace decarbonization efforts.

IC	3	Requires computational resources and operational datasets, while its rapid and highly accurate predictions can reduce testing requirements and development costs. However, industrial deployment remains associated with the advanced materials and integration efforts required by PEMWE technologies, resulting in a moderate overall cost profile.
TM	1	Still at an early research stage despite its excellent predictive performance. Further validation, industrial testing and large-scale implementation are required before widespread adoption within aerospace applications can be achieved.

5.2.3 Energy-flexible scheduling of machining processes – B3

The aerospace sector is one of the most energy-intensive manufacturing industries due to the complexity of its products and the large number of processing stages required throughout production. As production volumes continue to increase, energy consumption and the associated carbon emissions are expected to remain significant challenges for manufacturers. In this context, the concept of energy flexibility is a valuable approach for reducing emissions without requiring disruptive technological changes. Energy flexibility refers to the capability of adapting energy consumption according to external factors such as electricity price fluctuations, renewable energy availability and grid carbon intensity. Rather than relying on new equipment or major infrastructure investments, this approach seeks to optimize existing production processes by scheduling energy-intensive operations during periods characterized by a cleaner electricity mix, thereby reducing the environmental impact of manufacturing activities.

To explore this concept, Haddad et al. proposed a simulation-based decision support framework that integrates real-time carbon intensity information into production scheduling. The framework was developed in collaboration with GKN Aerospace and validated within a real aerospace manufacturing facility in the United Kingdom producing aluminium structural components aircraft programs. The case study involved a large-scale production facility with approximately 1,300 employees and more than 800 active stock-keeping units, providing a realistic industrial context for evaluating the effectiveness of the proposed strategy.

The framework combines detailed manufacturing process data with information obtained through a Carbon Intensity Application Programming Interface (CI-API), which continuously provides updates on the carbon intensity of the electricity grid. By associating

each manufacturing activity with the corresponding carbon intensity of the time period in which it is scheduled, the model can estimate the environmental impact of different production plans. Subsequently, a discrete-event simulation environment evaluates alternative scheduling configurations while respecting operational constraints such as machine availability, process sequencing and production deadlines. The objective is to identify production schedules capable of minimizing carbon emissions without compromising manufacturing performance. Unlike traditional scheduling approaches, which primarily focus on productivity and delivery targets, the proposed framework introduces carbon intensity as an additional decision variable, allowing sustainability considerations to be incorporated directly into production planning activities.

The results demonstrate the practical benefits of this approach. The optimized schedules achieved a reduction of approximately 7% in CO₂ emissions while simultaneously reducing manufacturing lead time by around 12%. These improvements were obtained without introducing new production technologies or modifying existing equipment, highlighting the significant potential of operational decision-making as a decarbonization lever. This finding is particularly relevant because sustainability initiatives are often associated with productivity losses or additional operational constraints. In contrast, the study demonstrates that environmental and operational objectives can be pursued simultaneously through more effective planning strategies. The framework represents an example of how digital technologies and real-time data can support emission reduction initiatives through the optimization of existing processes. By aligning energy-intensive operations with periods of lower-carbon electricity availability, manufacturers can reduce their environmental footprint while maintaining production performance. Furthermore, the approach contributes to more efficient resource allocation and promotes a greater integration between manufacturing operations and energy management practices.

One of the main strengths of this solution refers to its low implementation cost. Since the strategy relies primarily on existing production data, simulation tools and scheduling adjustments, no significant capital investments or infrastructure modifications are required. This characteristic makes the approach particularly attractive for both large organizations and smaller manufacturers seeking cost-effective decarbonization solutions. In addition, the framework can potentially be integrated into existing Manufacturing Execution Systems (MES) and Enterprise Resource Planning (ERP) platforms, facilitating adoption within current digital environments. Despite these advantages, some limitations remain. The effectiveness of the framework depends on the availability and quality of energy

consumption data, as well as on the accuracy of carbon intensity forecasts. Moreover, the potential benefits are strongly influenced by the degree of scheduling flexibility available within the production system. Manufacturing environments characterized by highly constrained production sequences or strict delivery requirements may offer fewer opportunities for rescheduling activities according to grid carbon intensity variations.

Haddad et al. demonstrated that meaningful emission reductions can be achieved through data-driven production planning rather than through major technological transformations. The successful industrial validation within an aerospace manufacturing environment, combined with measurable environmental and operational improvements, highlights the potential of energy-flexible scheduling as a practical and scalable strategy for supporting sustainable manufacturing. More broadly, the study illustrates how digital decision-support tools can transform energy from a passive operating cost into an active planning variable, enabling organizations to pursue sustainability objectives while simultaneously improving operational performance (Haddad et al., 2024).

Table 13 *B3 Evaluation Criteria Summary*

Criterion	Score	Justification
EI	2	A demonstrated reduction of approximately 7% in CO ₂ emissions was achieved by scheduling energy-intensive operations during periods of lower grid carbon intensity, providing measurable environmental benefits without requiring modifications to existing production technologies.
IC	5	The framework relies on existing production data, simulation tools and scheduling adjustments, avoiding new equipment or infrastructure investments. Emission reductions are achieved through operational decision-making, resulting in very low implementation costs.
TM	4	Validated within a real aerospace manufacturing environment and demonstrated measurable operational and environmental benefits. Its successful industrial application indicates a high level of maturity, although widespread adoption is still limited.

5.2.4 Meta-Heuristic Scheduling for Low-Carbon Manufacturing – B4

Forging processes play a crucial role within the aerospace industry due to their ability to produce high-strength components characterized by excellent mechanical properties and structural reliability. However, forging operations are also among the most energy-intensive manufacturing activities because they involve repeated heating cycles, high-temperature forming operations and complex production sequences. As aerospace manufacturers continue to increase production volumes while pursuing decarbonization targets, improving the efficiency of forging operations has become an important research area within sustainable manufacturing. Traditionally, production scheduling has focused on objectives such as minimizing completion time, improving equipment utilization and meeting delivery deadlines. However, growing environmental concerns have progressively expanded the role of scheduling systems beyond operational efficiency. According to Wang et al., modern manufacturing systems increasingly require scheduling approaches capable of simultaneously considering economic, operational and environmental objectives, including energy consumption and carbon emissions. As a result, production scheduling is evolving from a purely operational tool into a strategic mechanism for supporting sustainable manufacturing practices.

Wang et al. analysed the application of advanced scheduling techniques for forging production systems, with particular attention to multi-objective optimization approaches. The study highlights that modern forging environments are characterized by numerous constraints related to machine availability, process routing, processing times, resource allocation and product quality requirements. These factors create highly complex optimization problems that are difficult to solve using conventional planning methods.

To address these challenges, the authors review three main categories of scheduling approaches: exact algorithms, heuristic methods and meta-heuristic algorithms. While exact methods can identify optimal solutions, their computational complexity rapidly increases when applied to large-scale industrial systems. Heuristic approaches provide faster solutions but may become trapped in local optima. Consequently, the literature increasingly focuses on meta-heuristic techniques, which combine computational efficiency with the ability to explore a broader range of feasible solutions. Among these approaches, genetic algorithms emerge as one of the most widely adopted solutions for forging production scheduling. Inspired by the principles of biological evolution, genetic algorithms generate multiple alternative scheduling configurations and iteratively improve them through selection, crossover and mutation operations. This search mechanism allows the algorithm to identify

near-optimal production schedules while simultaneously considering multiple and often conflicting objectives.

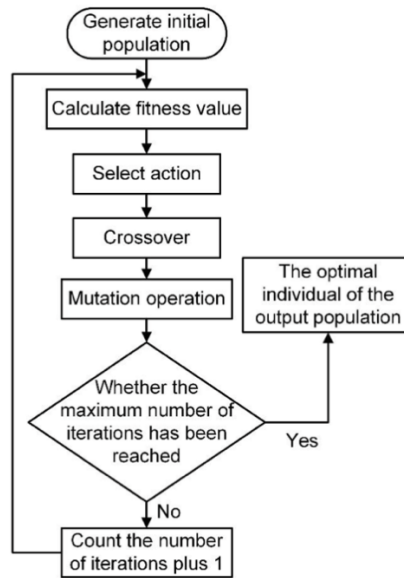


Figure 3 Flowchart of genetic algorithm

Reproduced from Key Technology and Application of production scheduling for heating forming of forgings: A review, Wang et al., 2022

From a sustainability perspective, the relevance of this approach lies in its ability to optimize production activities while reducing energy-intensive inefficiencies. By minimizing idle times, improving machine utilization, balancing workloads and reducing unnecessary reheating operations, optimized schedules can decrease overall energy demand and the associated environmental impact of forging processes. Unlike decarbonization strategies based on new equipment or alternative energy systems, this approach focuses on improving the way existing resources are managed, enabling sustainability improvements without fundamentally altering production technologies.

An additional contribution highlighted by Wang et al. concerns the integration of scheduling systems within broader intelligent manufacturing architectures. The study emphasizes that advanced scheduling tools can be connected with Computer-Aided Process Planning (CAPP), Manufacturing Execution Systems (MES), process control platforms and quality inspection systems, enabling a more coordinated and data-driven management of manufacturing operations. This integration supports real-time decision-making and creates the foundation for future smart manufacturing environments capable of simultaneously optimizing productivity, quality and sustainability performance. The implementation of

meta-heuristic scheduling systems requires a moderate level of investment. Although no major equipment modifications are necessary, successful deployment depends on the availability of accurate production data, digital infrastructure, algorithm customization and specialized expertise. Furthermore, integrating scheduling tools with existing manufacturing information systems may require additional development efforts, particularly in facilities characterized by complex production flows. The technological maturity of the approach is relatively high since genetic algorithms and other meta-heuristic optimization methods have been extensively investigated in the literature and successfully applied across numerous industrial scheduling problems. Their effectiveness in handling large-scale and multi-objective optimization tasks makes them particularly suitable for modern aerospace manufacturing environments, where operational complexity continues to increase.

Overall, the study by Wang et al. demonstrates how production scheduling can contribute to sustainable manufacturing beyond its traditional operational role. By incorporating energy consumption and environmental performance into scheduling decisions, meta-heuristic optimization approaches enable manufacturers to improve resource utilization, reduce production inefficiencies and support emission reduction objectives. More broadly, the work highlights the growing importance of data-driven decision-making and intelligent planning systems as practical tools for balancing productivity, competitiveness and sustainability within advanced manufacturing environments (Wang et al., 2022).

Table 14 *B4 Evaluation Criteria Summary*

Criterion	Score	Justification
EI	3	Meta-heuristic scheduling enables the simultaneous optimization of energy consumption, resource utilization and production efficiency. By reducing operational inefficiencies, idle times and unnecessary energy-intensive activities, it can contribute to meaningful emission reductions in forging manufacturing environments.
IC	3	Implementation requires production data integration, digital infrastructure, algorithm customization and specialized expertise. While no major equipment investments are necessary, the deployment effort results in a moderate overall cost profile.
TM	4	Genetic and meta-heuristic scheduling algorithms are well-established optimization techniques supported by a broad body of literature and numerous industrial applications.

5.3 Manufacturing Process Optimization and Energy Efficiency

The third category addresses the environmental issue by acting directly on the internal efficiency of manufacturing processes. A considerable share of industrial emissions does not originate exclusively from the nature of the final product or its energy source, but also from the way production processes are structured, how resources are converted and how losses occur across the system. In aerospace manufacturing, where most processes are energy-intensive, a significant portion of environmental impact is linked to avoidable inefficiencies such as energy dissipation, process interruptions and poorly coordinated production flows. For this reason, improving the efficiency of manufacturing systems represents a key lever for emission reduction, as it enables a more effective use of energy and materials without necessarily altering the final product or its functional performance.

Rather than focusing on the substitution of energy sources or the redesign of product architecture, this category includes strategies that aim to enhance environmental performance by acting on the operational core of manufacturing systems. This can be achieved through the recovery of waste energy, the reduction of thermal losses, the optimization of material usage and a deeper understanding of the interactions between process variables and resource consumption. However, it is important to highlight that the strategies within this category do not follow a single implementation logic but rather span a spectrum ranging from advanced technological solutions to analytical and process-oriented optimization approaches. Some strategies involve complex and capital-intensive innovations that can significantly modify existing production configurations, such as the integration of new heat recovery systems or advanced manufacturing technologies. Others rely on modelling, process analysis and decision-support tools to improve process visibility, identify inefficiencies and support optimization initiatives without requiring major physical modifications to existing production systems.

Despite these differences, all the strategies share a common objective: improving the efficiency with which energy and materials are utilized within manufacturing processes, while enhancing the understanding of resource flows and loss mechanisms across the production system, thereby reducing emissions associated with avoidable losses and suboptimal process configurations. Within the aerospace context, this approach is particularly relevant due to the high complexity, cost and performance requirements that characterize manufacturing processes such as forging, casting, machining and advanced material processing. In such environments, even marginal improvements in efficiency can generate significant environmental and economic benefits.

The following strategies are therefore presented as representative examples of this category, illustrating how different technological, analytical and data-driven approaches can be applied to improve process efficiency, optimize resource utilization and support the decarbonization of aerospace manufacturing systems.

5.3.1 Chemical utilization of Slag Waste heat through Chemical Reactions – C1

The iron and steel industry is among the most energy-intensive industrial sectors and is responsible for approximately 7–9% of global greenhouse gas emissions (Alex et al., 2025). At the same time, aerospace manufacturing relies heavily on upstream metallurgical processes for the production of structural steels, forged components, titanium alloys and nickel-based superalloys used in aircraft structures and propulsion systems. Consequently, improving the sustainability of these upstream activities can directly contribute to reducing the lifecycle emissions associated with aerospace manufacturing. One of the major inefficiencies of metallurgical production is associated with the generation of blast furnace slag, a by-product that retains a considerable amount of thermal energy after steelmaking operations. Despite the significant recovery potential of this resource, the utilization efficiency of high-quality slag waste heat remains limited to approximately 35%, meaning that a large fraction of this energy is still dissipated during conventional cooling processes. This represents both an environmental burden and a missed opportunity for improving industrial resource efficiency.

To address this issue, Duan et al. review several technologies capable of converting slag waste heat into valuable chemical products through thermochemical reactions. Unlike conventional recovery methods, which primarily generate steam or electricity, chemical recovery pathways transform thermal energy into chemical energy stored within useful products. This approach facilitates energy storage, transportation and reuse while simultaneously reducing waste heat losses. Among the different alternatives investigated, two pathways emerge as particularly promising: mineral carbonation and syngas generation. Mineral carbonation exploits the high concentration of reactive oxides naturally present in steel slag to capture carbon dioxide and convert it into stable carbonate compounds. The residual thermal energy contained within the slag provides the activation energy required for the carbonation reactions, reducing the need for additional external energy inputs. According to the results reported by Duan et al., this process can capture approximately 55.19 kg of CO₂ per tonne of steel slag, achieving a carbon capture efficiency of 92.73%. The resulting

carbonates provide permanent carbon sequestration while simultaneously supporting an industrial by-product that would otherwise represent a waste stream. These results demonstrate the considerable environmental potential of coupling waste heat recovery with carbon capture technologies.

A second promising pathway involves the production of syngas, which is a gaseous mixture mainly composed of hydrogen and carbon monoxide that can be used as a feedstock for chemical and energy-related applications. In this approach, slag waste heat is used to drive highly endothermic gasification reactions that would otherwise require substantial external energy inputs. The reviewed studies investigate several gasification pathways, including coal–steam, coal–CO₂ and biomass gasification, operating under temperature ranges between 673 K and 1773 K depending on the specific process configuration. The reported waste heat-to-chemical energy conversion efficiencies range between 60% and 88%, highlighting the significant potential of slag waste heat as an alternative energy source for thermochemical conversion processes. Among the various syngas-generation pathways reviewed by Duan et al., biomass pyrolysis and gasification emerge as the most promising example of waste heat valorization. Biomass is considered a carbon-neutral feedstock and therefore offers additional environmental benefits compared to conventional fossil-based gasification routes. The reviewed studies show that complete biomass pyrolysis can be achieved at a slag-to-biomass ratio of 0.8 and a temperature of 973 K, demonstrating the ability of blast furnace slag waste heat to effectively sustain thermochemical conversion processes. Furthermore, bio-oil conversion efficiencies of 97.84% were reported at 1073 K when the slag contained 3% Ni (Yu et al., 2017), highlighting the potential for producing valuable secondary products from biomass-derived streams. Particularly significant results were obtained in a two-stage system combining biomass pyrolysis and bio-oil reforming, where the utilization of 71.23 kg of biomass and 1 tonne of blast furnace slag generated approximately 78.48 kg of reforming syngas and 10.50 kg of pyrolysis syngas, while achieving an overall energy efficiency of 0.88 (Yao et al., 2023).

From a sustainable manufacturing perspective, both mineral carbonation and syngas generation embody the principles of circular resource utilization. Rather than treating slag as a waste product, these approaches transform it into a source of valuable energy and chemical resources, reducing both energy losses and environmental impacts. This concept is particularly relevant for aerospace manufacturing because the sector depends on highly energy-intensive metallurgical supply chains for the production of advanced materials and

components. Consequently, improving the sustainability of these upstream processes actively reduce the lifecycle emissions associated with aerospace manufacturing. Despite their considerable environmental potential, both technologies still face important implementation challenges. The effectiveness of the processes is strongly influenced by slag composition, operating conditions and system integration requirements. Furthermore, the available evidence remains limited to laboratory-scale and pilot-scale studies, while large-scale industrial deployment is relatively limited. The implementation of these technologies would require dedicated reactors, advanced slag handling systems and substantial modifications to existing metallurgical facilities. Consequently, capital investment requirements remain very high and adoption is currently feasible primarily for large industrial plants characterized by substantial production volumes. The chemical utilization of slag waste heat represents a promising pathway for improving resource efficiency and reducing industrial emissions. By simultaneously recovering waste heat, enabling carbon capture and generating valuable chemical feedstocks, these technologies support the transition toward more circular and climate-neutral manufacturing systems. Although further industrial validation is still required, the high carbon capture efficiencies and waste heat conversion performances reported in the literature suggest considerable long-term potential for supporting the decarbonization of metallurgical supply chains (Duan et al., 2025).

Table 15 *CI Evaluation Criteria Summary*

Criterion	Score	Justification
EI	5	Mineral carbonation can capture approximately 55.19 kg CO ₂ per tonne of slag with a 92.73% carbon capture efficiency, while syngas generation achieves waste-to-energy conversion efficiencies ranging from 60% to 88%, suggesting very high decarbonization potential.
IC	1	Implementation requires dedicated reactors, advanced slag handling systems and extensive integration with existing metallurgical facilities, resulting in very high capital investment requirements.
TM	2	Although technically validated through numerous laboratory and pilot-scale studies, large-scale industrial deployment remains limited and further development is required before widespread commercialization.

5.3.2 Selective Laser Melting for Turbine Blade Manufacturing – C2

The aerospace industry is characterized by extremely demanding requirements in terms of performance, safety and resource efficiency. In this context, weight reduction represents one of the most important design objectives, as lighter aircraft require less fuel consumption and consequently generate lower emissions throughout their operational life. According to the literature reviewed by Torres-Carrillo et al., aircraft weight is mainly distributed among functional components (72%), payload (19%) and fuel (9%), highlighting the significant influence that component design and manufacturing have on the overall environmental performance of aerospace systems. In addition, raw materials account for approximately 61% of aircraft production costs, while handling and production supplies represent an additional 12% each, emphasizing the importance of manufacturing strategies capable of improving material utilization and reducing waste.

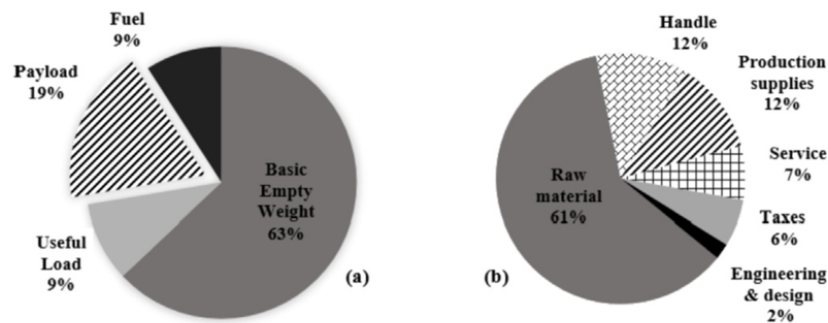


Figure 4 Aircraft distribution of weight used (a) and cost production (b)
Reproduced from Environmental analysis of selective laser melting in the manufacturing of aeronautical turbine blades, Torres-Carrillo et al., 2019

To address these challenges, additive manufacturing (AM) has emerged as a promising alternative to conventional manufacturing processes due to its versatility, productivity and potential for cost reduction (Read et al., 2015). Unlike traditional subtractive methods, where material is removed from a larger workpiece to obtain the final geometry, additive manufacturing builds components layer by layer directly from a digital model. This approach enables the production of highly complex geometries while significantly reducing material waste and simplifying manufacturing routes.

AM is often regarded as a “clean” manufacturing technology because it uses only the material required for the final component, thereby minimizing scrap generation (Bourhis et al., 2014). Moreover, many additive manufacturing processes do not require coolants,

lubricants or other environmentally hazardous substances commonly employed in conventional machining operations to extend tool life (Gebler et al., 2014). These characteristics contribute to lower resource consumption and reduced environmental impacts throughout the production process.

The environmental benefits of additive manufacturing have also been highlighted by several studies. Paris et al. (2016) reported that additive-manufactured components may require only 33–50% of the energy consumption associated with subtractive manufacturing routes. Similarly, Serres et al. (2011) demonstrated that the adoption of Direct Laser Additive Manufacturing (DLAM) for an aerospace structural component enabled reductions of up to 70% in manufacturing energy demand and CO₂ emissions compared with conventional machining of monolithic titanium alloys.

Among the different additive manufacturing technologies available, Selective Laser Melting (SLM) is one of the most relevant for aerospace applications. The process uses a high-power laser to selectively melt thin layers of metallic powder following to a predefined digital design. Successive layers are deposited and fused until the complete component is manufactured. Typical layer thicknesses range between 25 and 50 µm, allowing the production of highly detailed and geometrically complex parts with excellent dimensional accuracy. Such characteristics make SLM particularly suitable for aerospace components where lightweight design, material efficiency and high performance are critical requirements.

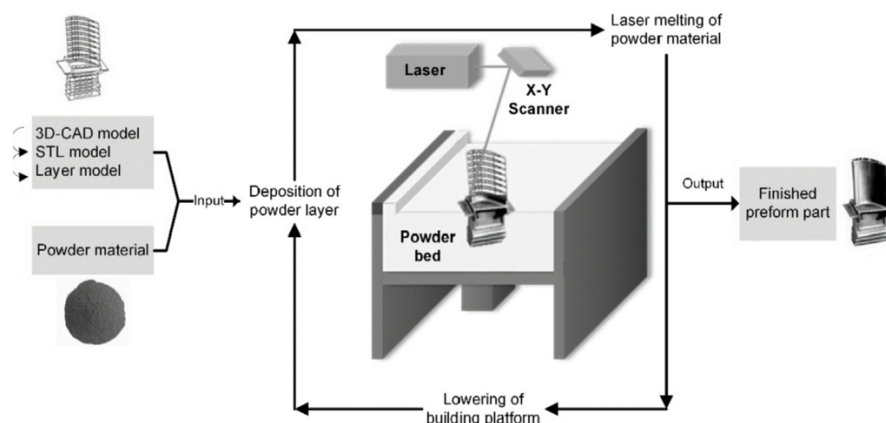


Figure 5 Selective Laser Melting process

Reproduced from *Environmental analysis of selective laser melting in the manufacturing of*

The growing interest in SLM derives from its ability to reduce material waste, simplify supply chains and enable the production of near-net-shape components. Furthermore, the technology allows the integration of multiple subcomponents into a single structure, reducing assembly operations and potentially improving overall product performance. These advantages are particularly relevant in aerospace manufacturing, where conventional production routes often involve multiple processing stages, extensive machining operations and high material losses.

To evaluate the sustainability benefits of this technology, Torres-Carrillo et al. conducted a life cycle assessment comparing the production of 600 turbine blades manufactured through a conventional route consisting of investment casting and precision machining with an alternative route based on Selective Laser Melting.

The results indicate that the conventional manufacturing route generated approximately 7325.28 kg CO₂, while the SLM-based process produced 7027.20 kg CO₂, corresponding to an overall reduction of approximately 4%.

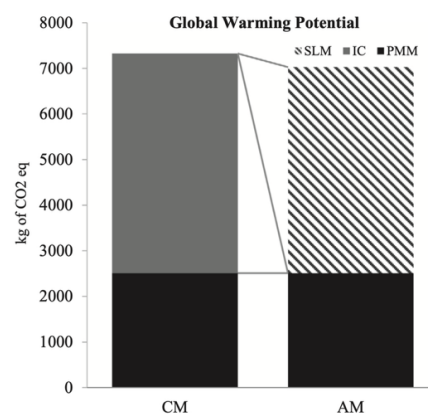


Figure 6 Comparison of carbon footprint
 Reproduced from *Environmental analysis of selective laser melting in the manufacturing of aeronautical turbine blades*, Torres-Carrillo et al., 2019

From an energy perspective, the conventional process consumed approximately 10,853.34 kWh, whereas the SLM alternative required 10,181.57 kWh, resulting in an energy reduction of about 6%. Although these improvements may appear moderate, they demonstrate the capability of additive manufacturing to reduce environmental impacts while maintaining the required performance and quality standards for aerospace components.

The environmental benefits of SLM extend beyond the results observed in the specific turbine blade case study. The literature reviewed by Torres-Carrillo et al. highlights that the

sustainability performance of additive manufacturing strongly depends on the geometry of the component, the amount of material waste avoided and the manufacturing route being replaced. Components characterized by complex geometries, high buy-to-fly ratios and extensive machining requirements can achieve significantly greater environmental benefits than those observed in the turbine blade case study.

Despite its advantages, SLM still presents important implementation challenges. The technology requires specialized equipment, controlled manufacturing environments, high-quality metal powders and qualified personnel, resulting in substantial initial investment costs. In addition, production rates remain relatively limited compared with some conventional mass-production processes, making economic feasibility highly dependent on production volume and component complexity. Certification requirements and quality standards also remain critical considerations within the aerospace industry. Nevertheless, the technology has already reached a significant level of industrial adoption and is currently employed for the production of several aerospace components. Its capability to combine lightweight design, material efficiency and process simplification makes SLM one of the most promising additive manufacturing technologies for supporting the transition toward more sustainable aerospace production systems. By reducing material waste, consolidating manufacturing operations and enabling more efficient component designs, SLM demonstrates how advanced manufacturing technologies can simultaneously improve environmental performance, resource efficiency and manufacturing sustainability. (Torres-Carrillo et al., 2019).

Table 16 *C2 Evaluation Criteria Summary*

Criterion	Score	Justification
EI	4	SLM reduces material waste and improves resource efficiency. While the analysed turbine blade case study reports reductions of approximately 4% in CO ₂ emissions and 6% in energy consumption, the environmental benefits of AM vary considerably across applications. Other aerospace studies show energy requirements as low as 33–50% of those associated with conventional manufacturing and reductions of up to 70% in manufacturing energy demand and CO ₂ emissions.
IC	2	The technology requires specialized equipment, high-quality metal powders and qualified personnel, resulting in substantial upfront investment costs despite potential long-term savings associated with material efficiency and process consolidation.

AM is already employed in aerospace manufacturing for selected high-value components and benefits from a well-established technological and industrial ecosystem. However, certification requirements, process qualification procedures and economic constraints still limit broader adoption across all production contexts.

5.3.3 Fixed-Point Modelling for Material and Energy Optimization in Forging Production – C3

Forging is one of the most widely adopted manufacturing processes in the aerospace industry due to its ability to produce components with excellent mechanical properties, high structural integrity and superior fatigue resistance. Critical aerospace parts such as turbine disks, shafts, landing gear components and structural elements are commonly manufactured through forging processes. However, forging operations are also characterized by high energy consumption and significant material losses, making them an important target for decarbonization initiatives.

The environmental relevance of forging derives from the large amount of thermal and mechanical energy required throughout the production cycle. According to He et al., the forging production process can be divided into four main stages: blanking, heating, forging and heat treatment (Ünver et al., 2019). Among these, heating operations account for the largest share of total energy consumption. In particular, pre-forging heating represents approximately 20–25% of overall energy demand, heat treatment heating accounts for 30–35%, while the forging operation itself contributes approximately 25–30%. Auxiliary activities represent the remaining 10–15% of total energy consumption. These values highlight the significant opportunity for improving resource utilization and reducing energy losses throughout the process.

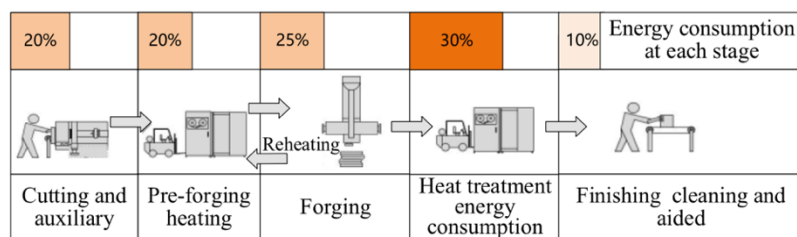


Figure 7 Forging core process and energy consumption

Reproduced from *Study on Material and Energy Flow in Steel Forging Production Process*, by F. He et al., 2020

To address this challenge, Fei He et al. developed an integrated framework based on Material Flow Analysis (MFA) and Energy Flow Analysis (EFA) capable of mapping the movement of materials and energy across the entire forging production system. Rather than focusing on the introduction of new manufacturing technologies, the proposed approach aims to identify inefficiencies hidden within existing processes by tracking the flow of raw materials, auxiliary resources, waste streams and energy carriers throughout each production stage. The framework is based on a fixed-point modelling approach in which the manufacturing system is decomposed into a series of production units, each representing a specific processing stage such as blanking, heating, forging or heat treatment. Every production unit is treated as an independent observation point where incoming and outgoing flows can be systematically measured and evaluated. Within each unit, material flows are tracked according to mass conservation principles by quantifying raw materials, intermediate products, finished components, recycled materials and waste streams. This allows the identification of material losses occurring throughout the production chain and highlights opportunities for improving resource utilization. In parallel, energy flows are monitored by accounting for energy supplied to the process, useful energy transferred to the product, recoverable heat and energy dissipated through exhaust gases, radiation and other losses.

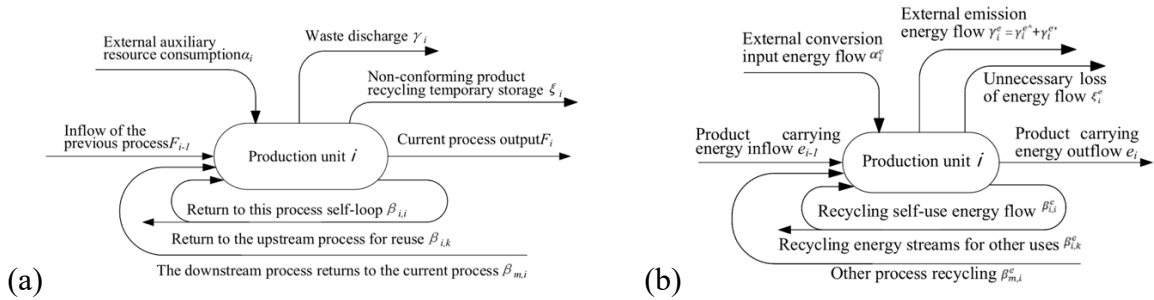


Figure 8 Material Flow Diagram (a) and Energy Flow Diagram (b)
Reproduced from *Study on Material and Energy Flow in Steel Forging Production Process*, by F. He et al., 2020

By combining material and energy flow analysis, it is possible to notice the strong interdependence between resource utilization and energy consumption within forging operations. Forged components act as carriers of thermal energy throughout the production

process, meaning that any material discarded as scrap also removes a corresponding amount of embedded energy already invested in heating, processing and handling operations. Consequently, improving material utilization not only reduces raw material consumption but also prevents avoidable energy losses. This integrated perspective enables the simultaneous evaluation of resource efficiency and energy performance, allowing companies to identify optimization opportunities that may remain hidden when analysing material and energy flows separately. The study further reveals that a substantial share of energy losses originates from high-temperature exhaust streams, oxidation scale formation, residual smoke emissions and heat dissipation to the surrounding environment. The framework therefore provides a structured methodology for identifying improvement opportunities such as waste heat recovery, enhanced furnace insulation, reduction of discharge temperatures and optimization of process sequencing. Rather than prescribing a specific technological solution, the model supports informed decision-making by revealing where the largest inefficiencies occur and where corrective actions can generate the greatest environmental and operational benefits. From a sustainability perspective, this approach is particularly relevant because forged components are extensively used in critical aerospace applications and often require multiple thermal treatments and energy-intensive processing stages. The ability to systematically monitor resource consumption and identify avoidable losses can therefore support more sustainable production practices without requiring major modifications to existing manufacturing equipment. Although the study focuses on forging operations, the proposed methodology is not process-specific. The same material and energy flow analysis principles can be extended to a wide range of aerospace manufacturing processes, including machining, casting, additive manufacturing, heat treatment and assembly operations. This makes the framework a versatile decision-support tool capable of supporting optimization activities across different production environments.

The implementation cost of the framework remains relatively limited, as it primarily relies on process monitoring, production data collection and modelling activities rather than expensive technological upgrades. However, its effectiveness depends on the availability of accurate production data and on the capability of organizations to continuously monitor and update material and energy information. The environmental benefits achievable through the framework are closely linked to the optimization opportunities identified and to the characteristics of the manufacturing process under analysis. By systematically revealing the main sources of material and energy losses, the model supports the development of targeted improvement actions capable of enhancing both operational and environmental

performance. The framework proposed by Fei He et al. demonstrates how a better understanding of material and energy interactions can support energy conservation and more efficient resource utilization in forging operations. More broadly, the study provides a structured and transferable methodology for prioritizing improvement actions and supporting sustainability-oriented decision making across energy-intensive aerospace production systems. Although direct emission reductions are not quantified, the framework establishes a foundation for data-driven resource optimization that can be replicated across multiple manufacturing processes and industrial contexts (Fei He et al., 2020).

Table 17 *C3 Evaluation Criteria Summary*

Criterion	Score	Justification
EI	4	The framework enables the identification of material losses, energy inefficiencies and waste recovery opportunities across manufacturing operations. The magnitude of the environmental benefits depends on the characteristics of the process under analysis and the optimization measures implemented. By improving resource utilization and reducing avoidable energy consumption, the methodology can support significant sustainability improvements.
IC	2	Implementation mainly relies on process monitoring, data collection and modelling activities rather than major equipment upgrades. As the framework can be integrated within existing production systems, adoption costs remain limited.
TM	4	Material and energy flow analysis methodologies are well-established industrial engineering tools and can be applied using existing production data and monitoring systems.

5.4 Sustainable Materials and Advanced Product Design

This last category includes strategies that contribute to emission reduction through innovative materials, lightweight design and advanced product development. A substantial portion of the environmental impact of aerospace components is determined upstream, during the stage in which products are conceived, materials are selected and technical requirements are translated into design choices. These early decisions strongly influence the sustainability of subsequent manufacturing activities, affecting material consumption, process complexity, production waste, energy requirements and end-of-life management

options. Consequently, product design and material selection represent critical elements of sustainable manufacturing, as they shape many of the environmental impacts generated throughout the production lifecycle.

In the aerospace sector, this aspect is particularly relevant because product weight, durability and structural integrity strongly influence both the manufacturing phase and the use phase. Even relatively small improvements in component design, material selection and structural efficiency can generate significant environmental benefits during operation through lower fuel consumption, improved system performance and enhanced compatibility with emerging low-carbon propulsion technologies. However, these solutions often involve trade-offs between different lifecycle stages. Innovative designs and high-performance materials may reduce operational emissions, but require energy-intensive production processes, complex qualification procedures or specific end-of-life treatments. Therefore, their environmental contribution depends on the balance between manufacturing burdens, functional performance and long-term sustainability benefits. In several cases, their impact is not limited to direct emission reductions but also derives from their ability to enable the adoption of emerging low-carbon technologies and next-generation aerospace systems.

Despite these constraints, design-driven strategies represent one of the most impactful levers for decarbonization, as their effects extend over the entire lifecycle of the product. Their benefits emerge progressively through weight reduction, improved durability, design simplification, reduced maintenance requirements and enhanced compatibility with low-carbon propulsion systems. In this sense, their effectiveness is maximized when sustainability considerations are integrated during the early design phase, where the main product characteristics are still flexible and can be optimized without major constraints.

The strategies identified within this category cover different dimensions of design-driven decarbonization, including innovative materials, lightweight structures, novel joining mechanisms, modular product architectures and material solutions capable of supporting future aerospace systems.

5.4.1 Design-Driven Carbon Footprint Reduction of Composite Materials – D1

Composite materials represent a valuable sustainable opportunity within the aerospace industry due to their ability to combine low weight with high mechanical performance. Their high strength-to-weight and stiffness-to-weight ratios, together with excellent corrosion resistance and thermal stability, make them particularly suitable for aerospace structures and

components subjected to extreme operating conditions. As a result, composite materials are extensively employed in aircraft fuselage sections, wing structures, engine components and interior elements, contributing to weight reduction and improved operational efficiency. From an environmental perspective, lightweight design represents one of their most significant advantages. Previous studies have reported that each 10% reduction in aircraft mass can lead to approximately 5% lower fuel consumption (Czerwinski, 2021), while even small weight reductions can generate substantial savings throughout the operational life of the aircraft.

Despite these benefits, composite materials present important sustainability challenges as their production often involves energy-intensive manufacturing processes, advanced raw materials and complex end-of-life management practices. Furthermore, recycling remains a critical issue for many composite applications, as material recovery is frequently limited and a considerable proportion of composite waste is still disposed of through landfilling. For this reason, the environmental performance of composite materials cannot be assessed solely for their contribution to weight reduction during the use phase but must be evaluated across the entire product lifecycle.

To address this challenge, Dalpadulo et al. propose a design-driven approach in which environmental considerations are integrated directly into the development phase of composite components. The underlying principle is that many of the environmental impacts associated with composite materials are determined during the design phase, where decisions regarding material selection, component architecture, manufacturing processes and end-of-life strategies are made. By incorporating sustainability criteria from the earliest stages of product definition, it becomes possible to reduce lifecycle impacts before production activities begin.

Particular attention is given by the author to the growing adoption of bio-composites, which incorporate natural fibres such as hemp, wood, rice husk, coir and basalt as reinforcement materials. Although these alternatives generally exhibit lower mechanical performance than conventional carbon-fibre composites, they offer advantages in terms of recyclability, lower environmental impact and reduced dependence on resource-intensive feedstocks. For this reason, bio-composites are increasingly considered for non-structural aerospace applications such as interior panels, storage compartments and cabin components. A central aspect of the strategy proposed by Dalpadulo et al. is the integration of digital technologies to support sustainability-oriented design decisions. Tools such as Computer-Aided Engineering (CAE), Product Lifecycle Management (PLM) systems and Life Cycle Assessment (LCA)

methodologies allow designers to evaluate environmental impacts alongside technical and economic requirements. In addition, digital technologies including Internet of Things (IoT), blockchain and virtual or augmented reality can improve lifecycle data collection, information traceability, design validation and maintenance planning. These tools further contribute to reducing uncertainty during product development while limiting material waste and the need for extensive physical prototyping.

From an aerospace manufacturing perspective, this approach is particularly relevant because design decisions strongly influence both operational and manufacturing emissions. The selection of materials, production routes and component geometries directly affects material consumption, process efficiency, maintenance requirements and recyclability. As a result, environmental improvements achieved during the design phase can generate benefits throughout the entire lifecycle of aerospace products. The implementation cost of this strategy remains moderate, as it primarily relies on design methodologies, digital tools and lifecycle assessment practices rather than major investments in manufacturing equipment. However, its successful adoption requires the availability of reliable data and specialized engineering expertise capable of integrating sustainability considerations into product development activities. The environmental benefits achievable through this approach are strongly influenced by the characteristics of the component and the decisions taken during its development, including material selection, manufacturing routes, component geometry and end-of-life strategies. Since these factors largely determine resource consumption, waste generation and emissions throughout the product lifecycle, sustainability-oriented design can become a powerful lever for improving environmental performance across multiple stages, from raw material sourcing and manufacturing to product use and disposal.

Overall, the design-driven approach proposed by Dalpadulo et al. demonstrates how sustainability can be embedded directly within the development of composite materials rather than being considered only after production has been completed. By combining lightweight design, sustainable material selection, digital decision-support tools and lifecycle thinking, the methodology provides a structured pathway for reducing the carbon footprint of composite components and supporting a more environmentally responsible adoption of these materials in aerospace applications (Dalpadulo et al., 2024).

Table 18 D1 Evaluation Criteria Summary

Criterion	Score	Justification
EI	3	Sustainability-oriented design decisions influence material selection, manufacturing routes, recyclability and lifecycle emissions, providing opportunities for environmental improvements across multiple stages of the product lifecycle.
IC	3	Adoption primarily requires digital design tools, lifecycle assessment practices and specialized engineering expertise, resulting in moderate implementation costs without major manufacturing investments.
TM	3	The approach combines established methodologies such as CAD/CAE, PLM and LCA with emerging solutions including bio-composites and advanced digital design technologies, resulting in an intermediate level of maturity.

5.4.2 LPBF–HEA Integration for Hydrogen Turbines components – D2

Hydrogen is increasingly considered one of the most interesting pathways for decarbonizing the aerospace sector. However, its adoption introduces significant engineering challenges due to critical combustion characteristics and the extreme operating conditions generated within gas turbines. In particular, the laminar burning rate of hydrogen is reported to be between three and seven times higher than that of conventional fuels at the same flame temperature, resulting in higher thermal loads, increased oxidation rates and more severe material degradation mechanisms. These elements are particularly critical for turbine components already operating under severe thermo-mechanical loads. Modern high-pressure turbine stages are typically exposed to inlet temperatures ranging between 1300 °C and 1600 °C, while the high steam content of hydrogen combustion products further accelerates oxidation, corrosion and creep phenomena. Consequently, the successful implementation of hydrogen-fuelled propulsion systems requires the development of new materials capable of maintaining mechanical integrity and durability under these demanding operating conditions.

To address these challenges, Harithsa et al. propose the integration of Laser Powder Bed Fusion (LPBF) and High Entropy Alloys (HEAs) as a promising manufacturing pathway for future hydrogen turbine components. HEAs are advanced metallic materials composed of multiple principal alloying elements. Unlike conventional alloys, they exhibit a unique combination of tensile strength, fracture toughness, corrosion resistance and ductility,

making them particularly attractive for extreme-temperature aerospace applications. However, traditional manufacturing routes for HEAs often involve multiple casting operations, rolling processes, homogenization treatments and heat treatments, resulting in considerable manufacturing complexity.

In this context, LPBF provides a highly compatible manufacturing solution. As an additive manufacturing technology, LPBF fabricates components layer-by-layer directly from metal powder feedstock, enabling near-net-shape production, reduced material waste and significantly greater design flexibility compared with conventional manufacturing routes. The process also facilitates the production of complex geometries, internal cooling channels and lightweight lattice structures, which are particularly valuable for aerospace turbine applications. Furthermore, LPBF simplifies the fabrication of HEAs by bypassing several conventional processing steps and enabling the direct production of geometrically complex components.

The synergy between LPBF and HEAs is further supported by experimental evidence reported in the literature. For an LPBF-manufactured CrMnFeCoNi high entropy alloy, the yield strength increased from 729.6 MPa to 752.6 MPa after hydrogen charging, demonstrating excellent resistance to hydrogen-related degradation mechanisms and highlighting the suitability of these materials for hydrogen operating environments (Kim et al., 2020). Additional studies reviewed by the authors also indicate that advanced HEA families, including refractory and eutectic high entropy alloys, exhibit excellent oxidation resistance, thermal stability and high-temperature mechanical performance, with some eutectic HEAs capable of operating at temperatures up to 700 °C while maintaining lower density than conventional nickel-based superalloys.

Rather than reducing emissions through manufacturing efficiency alone, LPBF–HEA integration supports the development of high-quality turbine components capable of enabling hydrogen-fuelled propulsion systems, which represent one of the most promising long-term decarbonization pathways for aviation. At the same time, the additive manufacturing process contributes to improved material utilization and reduced production waste compared with traditional manufacturing routes. Despite its potential, the strategy remains characterized by significant implementation challenges. LPBF systems require substantial capital investments, specialized process knowledge and extensive post-processing operations. In addition, the certification of additively manufactured aerospace components remains a demanding process due to the stringent quality and reliability requirements of the aerospace sector. The development and qualification of HEAs for

industrial aerospace applications also remains an active research area as the technology still require additional industrial validation.

The integration of LPBF and HEAs represents a promising technological pathway for supporting the transition toward hydrogen-powered aviation. By combining the manufacturing flexibility of additive manufacturing with the exceptional high-temperature properties of advanced alloys, this strategy addresses one of the key material challenges associated with next generation aerospace propulsion systems (Harithsa et al., 2023).

Table 19 D2 Evaluation Criteria Summary

Criterion	Score	Justification
EI	5	Supports the development of turbine components capable of operating under the extreme conditions generated by hydrogen combustion, thereby enabling the adoption of hydrogen-powered propulsion systems, one of the most promising long-term decarbonization pathways for aviation.
IC	2	Adoption requires high-cost LPBF equipment, specialized process expertise, advanced alloy development and extensive qualification activities, resulting in substantial upfront investments.
TM	3	LPBF is already established in aerospace manufacturing, while the application of High Entropy Alloys for hydrogen-fuelled turbine components remains under active development and industrial validation.

5.4.3 Permanent Magnet Rotor Design for EPUs – D3

Electric propulsion is one of the most promising pathways for reducing aerospace emissions. However, the large-scale adoption of Electric Propulsion Units (EPUs) remains constrained by the need to simultaneously achieve high power density, low weight, compact dimensions and high efficiency. Current electric propulsion systems generally remain below the power-density levels required for future regional and long-range aircraft, making the development of more advanced motor architectures a critical research priority. To address this challenge, Von Lindenfels et al. propose a permanent magnet rotor design based on a Halbach array configuration specifically developed for aerospace Electric Propulsion Units. Permanent magnet machines are particularly attractive for aviation applications due to their high

efficiency, reliability and favourable gravimetric and volumetric power densities. Among the various configurations available, Halbach arrays offer additional advantages by concentrating magnetic flux where it is most effective while reducing magnetic losses, enabling higher torque density and more efficient utilization of magnetic material. These characteristics make Halbach-based rotor designs particularly suitable for lightweight aerospace propulsion systems, where weight reduction and energy efficiency are key design objectives.

The need for such solutions becomes even more evident when considering the performance requirements of future electric aircraft. Studies reviewed by the authors indicate that regional electric aircraft carrying more than one hundred passengers may require propulsion systems exceeding 16 kW/kg, while long-range applications could require power densities above 25 kW/kg (Luongo et al., 2009). In contrast, currently available electric propulsion units generally remain below 10 kW/kg (Hoelzen et al., 2018), thus highlighting the significant technological gap that still separates current solutions from future aviation requirements.

The proposed rotor adopts a modular architecture composed of multiple pole segments mounted on a common support structure. Each segment incorporates permanent magnets arranged according to the Halbach principle, maximizing magnetic flux density while improving the utilization of magnetic material. The modular concept simplifies manufacturing and assembly through the repetition of standardized components and also facilitates maintenance activities by enabling the replacement of individual modules rather than the entire rotor assembly. In addition, the design integrates dedicated cooling channels intended to improve thermal management and operational reliability under extreme operating conditions.

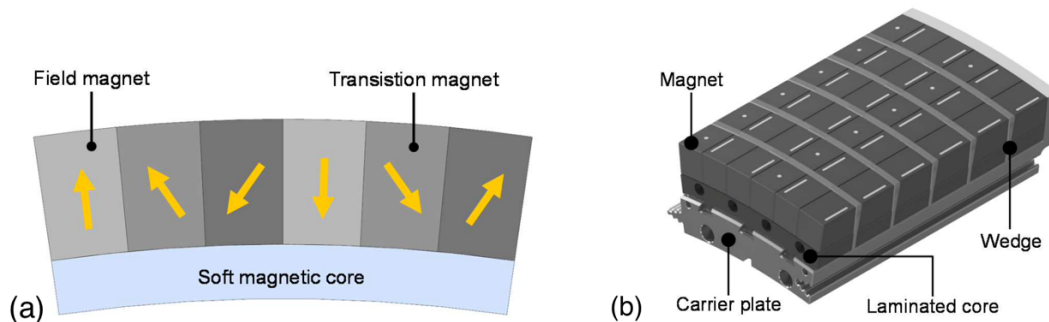


Figure 9 Single Halbach Segment (a) and Structure of Pole Parts (b)
Reproduced from *Electric Propulsion Units in aviation - approach for a mechanical permanent magnet rotor design and the related manufacturing concept*, Von Lindenfels et al., 2022

A further contribution of the study concerns the magnetization process. Conventional manufacturing approaches typically magnetize individual magnets before assembly, creating handling difficulties and safety concerns due to strong magnetic forces. The authors therefore propose alternative magnetization strategies in which larger subassemblies, or even the complete rotor, are magnetized after assembly. This approach reduces handling complexity, improves manufacturing safety and may contribute to lower defect rates during production.

The environmental contribution of this strategy derives primarily from its role in enabling more efficient electric propulsion systems. By improving magnetic flux utilization, reducing rotor mass and supporting higher power densities, the proposed design contributes to overcoming some of the major technological barriers currently limiting the adoption of electric aircraft. In addition, the modular architecture promotes manufacturing efficiency through the use of standardized and interchangeable components, simplifying assembly, maintenance and replacement operations. This approach can reduce material waste, facilitate repair and refurbishment activities and improve resource utilization throughout the product lifecycle. The same modular design principles could be extended to other aerospace systems and components, supporting more flexible manufacturing processes, easier maintenance operations and a reduction in lifecycle resource consumption.

Despite its potential, several challenges still limit industrial implementation. The design relies on high-performance permanent magnets, advanced manufacturing capabilities and extensive engineering development activities. Furthermore, certification requirements remain particularly demanding within the aerospace sector, especially for innovative propulsion architectures where reliability and safety are critical. The dependence on specialized magnetic materials and the early stage of development of electric aviation technologies further contribute to the limited maturity of the concept. As a result, the strategy is currently more suitable for large aerospace manufacturers and research-intensive organizations capable of supporting the substantial development and qualification efforts required.

The permanent magnet rotor design proposed by Von Lindenfels et al. represents a promising enabling technology for future electric propulsion systems. By combining a Halbach array configuration with a modular and lightweight architecture, the concept seeks to improve power density, manufacturing efficiency and maintainability, supporting the long-term transition toward more sustainable aviation propulsion technologies. (Von Lindenfels et al., 2022).

Table 20 D3 Evaluation Criteria Summary

Criterion	Score	Justification
EI	4	The proposed rotor design supports the development of high-performance electric propulsion systems, contributing to the broader adoption of electric aviation. Improvements in power density, weight reduction and manufacturing modularity can enhance both operational efficiency and resource utilization.
IC	3	Implementation requires advanced permanent magnets, specialized manufacturing processes and extensive engineering development activities. However, in the long-term the modular architecture may partially offset costs by simplifying production, assembly and maintenance operations.
TM	1	The concept remains at an early development stage and still requires further validation, industrial qualification and aerospace certification before large-scale deployment can be achieved.

5.4.4 Direct Titanium–PET Bonding via Heating and Pressurization – D4

The increasing adoption of lightweight multi-material structures is a promising lever for reducing emissions in the aerospace industry. By combining materials with complementary properties, manufacturers can optimize structural performance while minimizing component weight, thus reducing fuel consumption during aircraft operation. However, the integration of dissimilar materials still is a significant challenge, as conventional joining methods often rely on mechanical fasteners or adhesives that introduce additional weight, increase manufacturing complexity and may negatively affect recyclability.

Titanium and polymer-based materials are widely used in aerospace applications due to their optimal mechanical properties. Titanium provides excellent strength, corrosion resistance and thermal stability, while polymer-based materials offer significant weight savings. Traditionally, these materials are joined using bolts, rivets or adhesive bonding techniques. Although effective, mechanical fastening increases structural weight and may generate stress concentrations, whereas adhesive bonding often requires extensive surface preparation, long curing times and the use of potentially hazardous chemical substances. These limitations made necessary the development of alternative joining technologies capable of directly bonding dissimilar materials while maintaining structural integrity and lightweight performance. To address this challenge, Kondoh et al. propose a direct bonding process between titanium (Ti) and polyethylene terephthalate (PET) based on a simple heating and

pressurization approach. Unlike conventional joining techniques, the proposed method does not require adhesives, mechanical fasteners or expensive laser-based systems. The process consists of heating the Ti–PET assembly while applying a small compressive load, allowing the formation of a direct bond at the interface. Experimental investigations identified an optimal bonding temperature range between 200 and 300 °C, with effective bonding achieved using a holding time of only one minute under a relatively small applied load. A key finding of the study concerns the role of bubble formation at the bonding interface. During heating, partial thermal degradation of PET generates gaseous compounds that form bubbles between the two materials. As these bubbles expand, they create localized pressure that promotes intimate contact between the softened PET and the titanium surface. The authors demonstrated that bonding strength increases with the fraction of bubbles present at the interface up to a critical threshold, after which excessive bubble formation begins to act as a defect and reduces joint performance. The results therefore highlight the importance of carefully controlling temperature, pressure and surface conditions to optimize the bonding process.

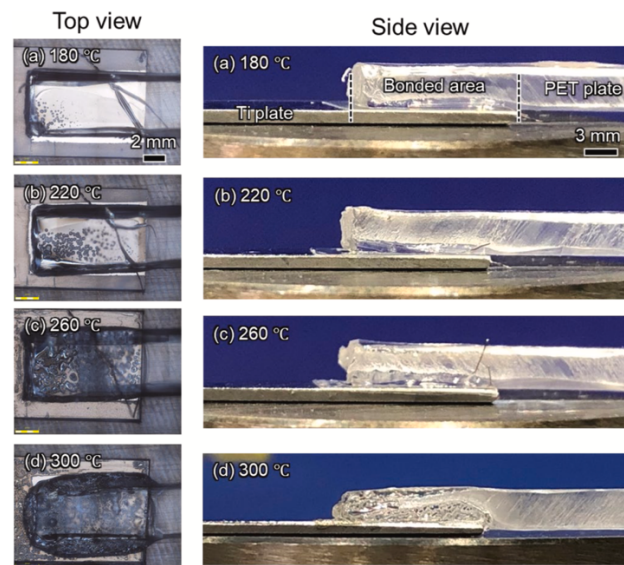


Figure 10 Bonding condition of PET sheet at different temperatures

Reproduced from *Direct bonding mechanism of titanium and PET resin via heating and pressurization: Influence of bubble dynamics on bonding strength*, Kondoh K. et al., 2025

Further analyses revealed that the bonding mechanism is not purely mechanical. X-ray photoelectron spectroscopy showed the formation of Ti–C chemical bonds at the interface, confirming that direct chemical interactions occur between titanium and the polymer during processing. The combination of localized pressure generated by bubble expansion and the

formation of chemical bonds contributes to the development of a strong and stable joint without requiring additional joining materials.

The environmental benefits of this approach derive primarily from its ability to facilitate lightweight multi-material designs while simplifying joining operations. Eliminating adhesives and reducing the use of mechanical fasteners can decrease material consumption, simplify manufacturing routes and improve recyclability at the end of life. Furthermore, the process relies on relatively simple equipment and short processing times, reducing manufacturing complexity compared with several alternative joining technologies. The resulting weight savings achievable through multi-material structures can also contribute to lower fuel consumption and lifecycle emissions during aircraft operation. The implementation barriers of the strategy remain relatively moderate as it does not require sophisticated joining equipment or major modifications to existing manufacturing systems. Nevertheless, further development and validation are required before large-scale aerospace adoption can be achieved. In particular, long-term durability, structural reliability and certification requirements remain critical aspects that must be addressed before the technology can be deployed in safety-critical aerospace applications.

Overall, the direct titanium–PET bonding approach proposed by Kondoh et al. demonstrates how innovative joining technologies can support the development of lightweight multi-material structures while simplifying manufacturing processes. By eliminating auxiliary joining materials and enabling more efficient structural designs, the strategy provides a promising pathway for improving both environmental and operational performance in future aerospace manufacturing systems (Kondoh K. et al., 2025).

Table 21 *D4 Evaluation Criteria Summary*

Criterion	Score	Justification
EI	4	The strategy enables lightweight titanium–polymer structures while eliminating adhesives and reducing the need for mechanical fasteners. By lowering component weight, simplifying joining operations and reducing auxiliary material consumption, it offers tangible opportunities to improve resource efficiency and decrease lifecycle environmental impacts.
IC	3	The bonding process relies on relatively simple heating and pressurization equipment, requiring limited additional investments compared with conventional joining technologies.
TM	1	Although the bonding mechanism has been experimentally demonstrated, further validation, durability assessment and aerospace certification are required before industrial implementation.

5.5 Insights and Strategic Implications

Overall, the analysed categories highlight the multifaceted nature of decarbonization within aerospace manufacturing, demonstrating how emission reduction can be pursued through multiple and complementary pathways. The reviewed strategies differ substantially in terms of environmental benefits, implementation requirements, technological readiness and industrial applicability, reflecting the complexity of sustainability transitions in aerospace systems. While some approaches focus on transforming energy systems and industrial feedstocks, others aim to improve process efficiency, enhance decision-making capabilities through digital technologies or reduce environmental impacts through product and material innovation.

Despite their differences, all strategies contribute to a common objective: reducing the environmental footprint of aerospace manufacturing while maintaining the high standards of performance, reliability and quality required by the sector. However, the qualitative assessment also reveals that there's no single strategy that simultaneously maximizes environmental impact, economic feasibility and technological maturity. As a result, each solution involves specific trade-offs that must be carefully considered according to the priorities, capabilities and constraints of the adopting organization.

Building upon these results, the following chapter applies the Multi-Criteria Decision-Making framework to compare the identified strategies and analyse their relative

performance under the SME and MNC decision-making scenarios. This enables a systematic investigation of how different organizational priorities influence the ranking of decarbonization alternatives and supports the identification of the most suitable strategies for different industrial contexts.

6 Multi-Criteria Decision-Making Application and Results Analysis

This chapter presents the results obtained from the application of the Multi-Criteria Decision-Making (MCDM) framework to the portfolio of representative decarbonization strategies identified through the literature review process. Building upon the methodology developed in Chapter 4, the analysis moves from framework design to practical application, enabling a structured comparison of alternative decarbonization pathways under different organizational contexts. The chapter starts with the presentation of the evaluation data and the calculation procedure adopted to determine the overall Performance Indicator (PI) for each strategy. Using the scores assigned to Environmental Impact (EI), Implementation Cost (IC) and Technological Maturity (TM), together with the weighting schemes developed for SMEs and MNCs, the framework generates a comparative ranking of the identified strategies.

Subsequently, the results are analysed from multiple perspectives. First, the performance of the strategies is examined across the four decarbonization categories identified in Chapter 5. The analysis then explores the differences emerging between SME and MNC configurations, highlighting how variations in organizational priorities influence the competitiveness of the alternative pathways. Finally, a sensitivity analysis is conducted to assess the robustness of the framework under alternative weighting scenarios and to verify the stability of the ranking results. The chapter concludes by discussing the broader managerial implications of the findings and by evaluating the potential of the proposed framework as a decision-support tool for industrial decarbonization within aerospace manufacturing environments.

6.1 Data Presentation and Calculation Process

This section presents the scores of the MCDM model, providing a structured overview of how the decarbonization strategies have been assessed and compared. The following sequence of tables shows the different stages of the evaluation process, from the initial scoring to the final computation of the Performance Indicators.

The first step of the analysis consists in assigning the initial scores to each strategy based on the three evaluation criteria: Environmental Impact (EI), Implementation Cost (IC) and Technological Maturity (TM). These values represent the first level of assessment derived directly from the literature and constitute the starting point of the evaluation.

Table 22 *Raw Evaluation Matrix*

<i>Strategy adopted</i>	ID	EI	IC	TM
PtL-Based SAF Production Pathways with Alternative Aromatic Supply	A1	5	1	2
SAF Production from Lignocellulosic Biomass	A2	4	2	2
Nuclear assisted Hydrogen production for Sustainable aviation fuel	A3	5	1	2
Numerical Model for Improving Thermal Management in PEM Fuel Cells	B1	4	3	1
AI-driven PEMWEs optimization	B2	4	3	1
Energy-flexible scheduling of machining processes	B3	2	5	4
Meta-Heuristic Scheduling for Low-Carbon Manufacturing	B4	3	3	4
Chemical utilization of slag waste heat through chemical reactions	C1	5	1	2
Selective Laser Melting for Turbine Blades Manufacturing	C2	4	2	4
Fixed-Point Modelling for Material and Energy Optimization in Forging Production	C3	3	4	4
Design-Driven Carbon Footprint Reduction of Composite Materials	D1	3	3	3
LPBF–HEA Integration for Hydrogen Turbines components	D2	5	2	3
Permanent magnet Rotor Design for EPU	D3	4	3	1
Direct Titanium–PET Bonding via Heating and Pressurization	D4	3	4	2

In order to ensure comparability across criteria and improve the interpretability of the results, the original scores are transformed into normalized values. This step allows all criteria to be expressed on a common scale, facilitating the subsequent aggregation process.

Table 23 *Normalized Evaluation Matrix*

<i>Strategy adopted</i>	ID	EI'	IC'	TM'
PtL-Based SAF Production Pathways with Alternative Aromatic Supply	A1	1,00	0,20	0,40
SAF Production from Lignocellulosic Biomass	A2	0,80	0,40	0,40
Nuclear assisted Hydrogen production for Sustainable aviation fuel	A3	1,00	0,20	0,40
Numerical Model for Improving Thermal Management in PEM Fuel Cells	B1	0,80	0,60	0,20
AI-driven PEMWEs optimization	B2	0,80	0,60	0,20
Energy-flexible scheduling of machining processes	B3	0,40	1,00	0,80
Meta-Heuristic Scheduling for Low-Carbon Manufacturing	B4	0,60	0,60	0,80
Chemical utilization of slag waste heat through chemical reactions	C1	1,00	0,20	0,40
Selective Laser Melting for Turbine Blades Manufacturing	C2	0,80	0,40	0,80
Fixed-Point Modelling for Material and Energy Optimization in Forging Production	C3	0,60	0,80	0,80
Design-Driven Carbon Footprint Reduction of Composite Materials	D1	0,60	0,60	0,60
LPBF–HEA Integration for Hydrogen Turbines components	D2	1,00	0,40	0,60
Permanent magnet Rotor Design for EPU	D3	0,80	0,60	0,20
Direct Titanium–PET Bonding via Heating and Pressurization	D4	0,60	0,80	0,40

Finally, the normalized scores are aggregated using the weighting schemes defined in the previous chapter, leading to the computation of the Performance Indicators for both SMEs and MNCs. These indicators represent the overall performance of each strategy under the two different decision-making contexts.

Table 24 *Performance Indicators*

<i>Strategy adopted</i>	ID	PI_{SME}	PI_{MNC}
PtL-Based SAF Production Pathways with Alternative Aromatic Supply	A1	0,50	0,64
SAF Production from Lignocellulosic Biomass	A2	0,52	0,60
Nuclear assisted Hydrogen production for Sustainable aviation fuel	A3	0,50	0,64
Numerical Model for Improving Thermal Management in PEM Fuel Cells	B1	0,54	0,62
AI-driven PEMWEs optimization	B2	0,54	0,62
Energy-flexible scheduling of machining processes	B3	0,76	0,66
Meta-Heuristic Scheduling for Low-Carbon Manufacturing	B4	0,66	0,64
Chemical utilization of slag waste heat through chemical reactions	C1	0,50	0,64
Selective Laser Melting for Turbine Blades Manufacturing	C2	0,64	0,68
Fixed-Point Modelling for Material and Energy Optimization in Forging Production	C3	0,74	0,70
Design-Driven Carbon Footprint Reduction of Composite Materials	D1	0,60	0,60
LPBF–HEA Integration for Hydrogen Turbines components	D2	0,64	0,74
Permanent magnet Rotor Design for EPU	D3	0,54	0,62
Direct Titanium–PET Bonding via Heating and Pressurization	D4	0,62	0,62

The tables presented above constitute the basis for the subsequent analysis, allowing a clear comparison of the performance of the evaluated strategies.

6.2 Results Overview

The results summarized in Table 8 show how the different evaluation priorities influence the ranking of the strategies. A first observation concerns the overall distribution of performance values, since the calculated PI scores range from approximately 0.50 to 0.76 in the SME configuration and from 0.60 to 0.74 in the MNC configuration. This relatively narrow range indicates that most strategies achieve a moderate level of overall performance. It is also

particularly relevant that higher performance values are observed in the MNC configuration with respect to SMEs, where the scores tend to be slightly lower and more constrained. This suggests that the evaluated strategies may be more aligned with the characteristics and capabilities of larger organizations, which are typically better positioned to support more complex and impactful initiatives.

Focusing on the SME perspective, the ranking is dominated by strategies with a balanced combination of cost efficiency and technological maturity. In particular, *Energy-flexible scheduling of machining processes* (B3) emerges as the best-performance strategy, reaching the highest score with a $PI_{SME} = 0.76$. It is closely followed by *Fixed-Point Modelling for Material and Energy Optimization in Forging Production* (C3) ($PI_{SME} = 0.74$), confirming the strong potential of process optimization solutions for small firms. A second group of strategies occupies the upper-middle part of the ranking, including *Selective Laser Melting for Turbine Blades Manufacturing* (C2) and *LPBF–HEA Integration for Hydrogen Turbines components* (D2), both achieving a $PI_{SME} = 0.64$. These solutions, although more technologically advanced, maintain a sufficient level of maturity that mitigate the implementation cost barrier. At the lower end of the SME ranking, strategies associated with advanced fuel production and large-scale energy transformation are found, such as *PtL-Based SAF Production Pathways* (A1), *Nuclear assisted Hydrogen production* (A3) and *Chemical utilization of slag waste heat* (C1), all recording the lowest scores ($PI_{SME} = 0.50$). Despite their high environmental impact, their elevated cost and limited technological maturity significantly reduce their suitability for SMEs.

Table 25 *SMEs Ranking of Decarbonization Strategies*

<i>Strategy adopted</i>	ID	PI_{SME}	Rank
Energy-flexible scheduling of machining processes	B3	0,76	1 st
Fixed-Point Modelling for Material and Energy Optimization in Forging Production	C3	0,74	2 nd
Meta-Heuristic Scheduling for Low-Carbon Manufacturing	B4	0,66	3 rd
LPBF–HEA Integration for Hydrogen Turbines components	D2	0,64	4 th
Selective Laser Melting for Turbine Blades Manufacturing	C2	0,64	5 th

Direct Titanium–PET Bonding via Heating and Pressurization	D4	0,62	6 th
Design-Driven Carbon Footprint Reduction of Composite Materials	D1	0,60	7 th
Numerical Model for Improving Thermal Management in PEM Fuel Cells	B1	0,54	8 th
AI-driven PEMWEs optimization	B2	0,54	9 th
Permanent magnet Rotor Design for EPU	D3	0,54	10 th
SAF Production from Lignocellulosic Biomass	A2	0,52	11 th
PtL-Based SAF Production Pathways with Alternative Aromatic Supply	A1	0,50	12 th
Nuclear assisted Hydrogen production for Sustainable aviation fuel	A3	0,50	13 th
Chemical utilization of slag waste heat through chemical reactions	C1	0,50	14 th

Moving to the MNC results, the ranking shows a partially different structure. The highest performing strategy becomes *LPBF–HEA Integration for Hydrogen Turbines components* (D2) with a $PI_{MNC} = 0.74$ followed by *Fixed-Point Modelling* (C3) ($PI_{MNC} = 0.70$) and *Selective Laser Melting* (C2) ($PI_{MNC} = 0.68$). The best-performing for SMEs, which is *Energy-flexible scheduling* (B3), slightly decrease in the MNC ranking, while maintaining a $PI_{MNC} = 0.66$. A relevant variation can be observed instead for strategies characterized by high emission reduction potential such as *PtL-Based SAF Production* (A1) and *Chemical utilization of slag waste heat* (C1) which show a considerable improvement in their relative positioning reaching a $PI_{MNC} = 0.64$. This further confirms that MNCs are more capable of supporting capital-intensive and less mature technologies when these offer significant environmental benefits.

Table 26 *MNCs Ranking of Decarbonization Strategies*

<i>Strategy adopted</i>	ID	PI_{MNC}	Rank
LPBF–HEA Integration for Hydrogen Turbines components	D2	0,74	1 st
Fixed-Point Modelling for Material and Energy Optimization in Forging Production	C3	0,70	2 nd
Selective Laser Melting for Turbine Blades Manufacturing	C2	0,68	3 rd
Energy-flexible scheduling of machining processes	B3	0,66	4 th
PtL-Based SAF Production Pathways with Alternative Aromatic Supply	A1	0,64	5 th
Nuclear assisted Hydrogen production for Sustainable aviation fuel	A3	0,64	6 th
Chemical utilization of slag waste heat through chemical reactions	C1	0,64	7 th
Meta-Heuristic Scheduling for Low-Carbon Manufacturing	B4	0,64	8 th
Numerical Model for Improving Thermal Management in PEM Fuel Cells	B1	0,62	9 th
AI-driven PEMWEs optimization	B2	0,62	10 th
Permanent magnet Rotor Design for EPU	D3	0,62	11 th
Direct Titanium–PET Bonding via Heating and Pressurization	D4	0,62	12 th
SAF Production from Lignocellulosic Biomass	A2	0,60	13 th
Design-Driven Carbon Footprint Reduction of Composite Materials	D1	0,60	14 th

From a categorial perspective, a preliminary observation can be made. Strategies belonging to the Manufacturing Process Optimization and Energy Efficiency category systematically occupy the top positions in the SME ranking, due to their alignment with cost and feasibility constraints. A similar trend can be observed for strategies related to Digital Intelligence and Data-Driven Decarbonization, which also achieve competitive performance when do not require significant investments or complex technological systems. As a result, they are particularly suitable for SMEs, as they enable improvements through the optimization of existing processes and resources. In contrast, strategies related to Clean Energy Systems, Sustainable Fuels and Advanced Product Design tend to perform better for MNCs because

the environmental impact plays a more dominant role with respect to maturity and implementation cost.

Overall, the result highlights the presence of a clear differentiation in the ranking structure between SMEs and MNCs, driven by the different weighting of the evaluation criteria, which reflects strength and limitations of the two categories. While SMEs tend to prefer strategies that are immediately implementable and economically sustainable, MNCs show a greater openness toward high-impact, disruptive and long-term solutions. Although this section focuses on presenting the results and identifying the main differences in ranking, a more structured interpretation of these trends is developed in the following sections.

6.3 Structural Analysis of Decarbonization Strategies across Categories

While the PIs provide a synesthetic measure of the overall effectiveness of the evaluated strategies, it is interesting to analyse the results from a broader perspective. By aggregating the strategies according to the four previously defined categories, it is possible to identify recurring characteristics and common performance dynamics shared by strategies belonging to the same technological pathway and how they systematically influence Environmental Impact, Implementation Cost and Technological Maturity. This perspective allows the identification of different decarbonization logics and reveals how certain categories are naturally more aligned with the constraints, priorities and implementation capabilities of SMEs or MNCs

In the following section, each category is analysed in detail through a combined interpretation of quantitative results and qualitative consideration, with the aim of explaining the structural mechanisms that lead different groups of strategies to exhibit specific performance profiles within the proposed framework.

6.3.1 Clean Energy Systems: Driving Transformative Industrial Transition

The strategies associated with clean energy systems, hydrogen technologies and sustainable fuels exhibit one of the most distinctive performance profiles within the proposed framework. This is characterized by a strong polarization across the three evaluated criteria, combining very high environmental benefits with significant implementation barriers. This behaviour clearly emerges from the values reported in Table 7, where these strategies consistently achieve the highest Environmental Impact scores while simultaneously recording some of the lowest performances in terms of Implementation Cost and

Technological Maturity. From an environmental perspective, these solutions represent the most transformative approaches among the evaluated alternatives. Unlike process-oriented interventions which mainly act through efficiency improvements and optimization of the existing operations, clean-energy pathways directly target the energy source itself, replacing conventional fossil-based systems with low-carbon alternatives, therefore reaching the maximum EI values.

However, the elevated emission reduction potential is systematically associated with lower feasibility. These solutions generally present low normalized Implementation Cost scores, typically between 0.2 and 0.4, reflecting the substantial investments required for infrastructure adaptation, energy system integration and technological deployment. In parallel, Technological Maturity values remain around 0.4, indicating that many of these solutions are still undergoing development, pilot testing or early industrial adoption. Consequently, their implementation often involves elevated uncertainty, long investment horizons and the need for advanced technical capabilities. This imbalance between impact and feasibility strongly influences the aggregated results. In the SME configuration, where cost and maturity receive greater weight within the MCDM framework, these strategies consistently occupy the lower part of the ranking with PI values around 0.50. This result should not be interpreted as an indication of low technological relevance, but rather as evidence of the mismatch between structural requirements and the operational constraints typically faced by these companies. Smaller firms generally operate under more limited financial capacity, lower risk tolerance and shorter investment cycles, making the adoption of large-scale energy transition technologies considerably more difficult.

A partially different behaviour emerges in the MNC configuration. The greater importance assigned to Environmental Impact allows these strategies to improve their relative positioning, with PI values increasing up to 0.64. This shift highlights how larger organizations are structurally better aligned to support complex decarbonization initiatives, particularly when they are associated with long-term sustainability objectives. MNCs usually possess greater access to capital, more advanced technological infrastructures and stronger integration with research and innovation ecosystems, enabling them to manage higher implementation risks and longer payback periods. Another relevant aspect emerging from this category concerns the strategic nature of the transition itself. The implementation of these kinds of solutions require the coordinated effort of multiple actors such as energy suppliers, logistics networks, regulatory frameworks and industrial infrastructures. As a result, their deployment is strongly influenced not only by internal company capabilities, but

also by the external ecosystem conditions. This further contributes to explain why these pathways appear more compatible with large industrial companies.

From a broader perspective, this category represents a decarbonization route centred on long-term industrial transformation rather than immediate operational application. Its main strength lies in the possibility of achieving deep and systemic emission reductions, particularly in energy-intensive sectors such as aerospace manufacturing. At the same time, the analysis highlights that the effectiveness of these strategies can't be evaluated solely on the basis of environmental performance, since economic accessibility and implementation readiness play a crucial role in determining their actual applicability across different industrial contexts.

6.3.2 Digital Intelligence: Enabling Smarter Decarbonization Pathways

Solutions based on digital intelligence and data-driven optimization show scalable performance profiles associated with the ability to improve resource efficiency through information management, predictive capabilities and intelligent coordination of industrial processes. These approaches support emission reduction objectives by enhancing decision-making, reducing operational inefficiencies and improving the overall responsiveness and adaptability of industrial environments.

The strategies included within this category generally display balanced performances across all three criteria. In particular, Environmental Impact values remain competitive, while Implementation Cost and Technological Maturity maintain relatively stable levels. In most cases, integration barriers are moderate due to the limited infrastructural requirements associated with software integration. At the same time, the implementation process is generally faster compared to capital-intensive strategies, since digital solutions are often integrated into already existing industrial systems with limited operational disruption. The category presents an internal differentiation in terms of technological maturity and environmental potential. Certain solutions are based on already established digital tools capable of generating rapid and accessible improvements, although with medium environmental impact. Other strategies, such as those involving AI or predictive algorithms, still present lower maturity levels but potentially higher long-term benefits in terms of emission reductions. This creates a flexible technological spectrum within the category itself, allowing different types of companies to select digital solutions according to their own resources, priorities and readiness for innovation.

This effect is reflected in the high PI scores achieved by this category in both configurations, even if some distinctions emerge. Smaller firms exploit digital intelligence solutions to improve production coordination, resource allocation and energy management without facing the substantial investments typically associated with large-scale industrial transformation. The particularly high ranking achieved within the SME configuration can also be associated with the lower initial level of digitalization that characterizes most of SMEs. In this context, even relatively accessible digital interventions may generate proportionally significant improvements, enhancing organizational efficiency and production responsiveness. This tendency is particularly evident in the case of *Energy-flexible scheduling of machining processes* (B3) and *Meta-Heuristic Scheduling for Low-Carbon Manufacturing* (B4) which achieve the highest PI values, respectively 0.76 and 0.66, due to the strong balance between implementation feasibility and technological maturity. Beyond environmental performance, digitalization also supports the broader industrial development of SMEs. The integration of data-driven systems improves coordination capabilities, interaction with more advanced supply-chain networks and support smaller firms in operating within increasingly interconnected industrial markets. In this sense, digital intelligence contributes not only to emission reduction, but also to the progressive modernization and competitiveness of industrial organizations.

A different but equally relevant dynamic emerges in the MNC configuration. Larger organizations generally operate with more advanced digital infrastructures already integrated within production systems, which partially reduce the relative impact generated by additional digital improvements. Nevertheless, MNCs can exploit these technologies on a significantly larger scale, extending optimization capabilities across multiple facilities and production lines. In these highly complex industrial ecosystems, even relatively small efficiency improvements translate into substantial environmental benefits due to the scale of the operations involved. The greater financial capacity of large companies allows them to invest also in more advanced AI-driven systems that are currently characterized by lower maturity levels. Although these approaches may still present implementation uncertainty, they also show higher environmental potential compared to more mature solutions already available on the market. This makes MNCs better positioned to support the development and industrial integration of next-generation digital technologies, accelerating the evolution of smart factories and autonomous decarbonization systems. This explains the results obtained by these strategies also within MNC setting, with PI values ranging between 0.62 and 0.66.

Another key-factor which contributes to the relevance of this category lies in its role as enabler of industrial transition. Digital technologies do not operate as isolated decarbonization solutions but rather enhance the effectiveness of other strategies. Real-time monitoring systems, predictive algorithms and AI-driven optimization models can improve process controllability, support energy efficiency initiatives and facilitate the integration of more advanced technological solutions. As industrial systems become increasingly interconnected, data-driven solutions progressively become essential tools for coordinating, optimizing and supporting broader industrial decarbonization processes.

Despite these advantages, the environmental benefits generated by digital-intelligence strategies are strongly dependent on the quality, availability and integration of industrial data. Inadequate digital infrastructures, fragmented information systems or excessively low digital maturity may significantly reduce the effectiveness of these approaches. In addition, since emission reductions are mainly achieved through indirect optimization mechanisms, the absolute impact of these strategies may remain lower compared to technologies capable of directly transforming industrial processes.

Overall, digitalization represents not only a technological upgrade, but also a strategic tool for improving industrial adaptability, operational responsiveness and organizational integration. The combination of implementation speed, scalability and flexibility makes digital-intelligence solutions highly adaptable across heterogeneous industrial contexts, supporting progressive transition pathways at different levels of the aerospace manufacturing sector.

6.3.3 Process Optimization: Incremental and Industry-Oriented Solutions

Although operational efficiency and process optimization are generally associated with relatively mature technologies, their actual performance varies significantly depending on the type of industrial process involved and on the intensity of process intervention. This aspect becomes particularly evident when comparing the strategies included within this category, which present different combinations of Environmental Impact, Implementation Cost and Technological Maturity despite sharing a common operational logic.

The results display the presence of a progressive relationship between environmental benefits and implementation complexity. Strategies capable of generating higher emission reductions tend to require more advanced technological solutions, additional infrastructure adaptations and greater integration efforts, which consequently increase implementation

costs and reduce operational readiness. This trend can be clearly observed in the case of *Chemical utilization of slag waste heat through chemical reactions* (C1) which achieves the highest EI score within the category, reflecting significant decarbonization potential associated with waste heat recovery. However, the same strategy records low values for both cost efficiency and technological maturity due to the complexity of integrating chemical recovery systems into industrial environments. A substantially different configuration emerges for *Fixed-Point Modelling for Material and Energy Optimization in Forging Production* (C3). In this case, the strategy is based on optimization methodologies applied to already established production processes, facilitating their implementation. The absence of major infrastructural requirements and the reliance on existing systems contribute to the high maturity and feasibility observed in the corresponding scores. However, the environmental contribution remains comparatively lower, as the strategy mainly acts through incremental efficiency rather than radical process transformation. Between these two extremes, *Selective Laser Melting for Turbine Blades Manufacturing* (C2) exhibits a more balanced profile. It combines relatively high environmental benefits with a significantly more advanced maturity level compared to the previous case, while still maintaining considerable implementation costs associated with AM technologies, specialized equipment and process integration requirements. This positioning confirms how this category does not follow a uniform performance pattern, but rather includes strategies characterized by different balances between impact, feasibility and readiness.

Such variability partially explains the high PI scores achieved by this category for both configurations. Even if certain strategies involve relevant investments or advanced technological capabilities, their implementation generally remains connected to the optimization and enhancement of already existing industrial systems, which considerably reduces implementation barriers compared to fully transformative pathways. This allows companies to pursue progressive emission reductions while maintaining operational continuity and greater control over implementation risks. At the same time, the broader diversity of approaches included within this category increases its adaptability across different industrial contexts. The coexistence of strategies characterized by different trade-offs between EI, IC and TM performance allow both SMEs and MNCs to identify solutions that are more aligned with their respective operational requirements, financial capabilities and strategic priorities. Despite these advantages, the environmental contribution of process optimization and energy efficiency strategies, although significant, generally remains lower than that associated with disruptive transition routes such as clean-energy systems, which radically modify the existing manufacturing processes. The effectiveness of process

optimization is linked to incremental improvements in efficiency rather than to structural changes of the industrial systems. As a consequence, smaller firms can benefit from the accessibility and gradual implementation of these alternatives. Larger organizations can instead exploit the same approaches across more complex and energy-intensive production systems, where operational improvements may generate absolute emission reductions even when percentage variations appear relatively limited.

Taken together, the results indicate that energy efficiency and process optimization strategies represent one of the most immediately applicable decarbonization pathways within aerospace manufacturing. Their strong alignment with feasibility, scalability and implementation readiness makes them highly adaptable across different industrial contexts and the most versatile group within the framework. However, even if these approaches are highly effective in supporting progressive emission reductions in medium or short-term horizons, they may not be sufficient on their own to achieve deep long-term decarbonization targets.

6.3.4 Sustainable Materials and Design: Shaping Long-Term Lifecycle Strategies

Strategies related to sustainable materials and advanced product design exhibit a decarbonization logic strongly oriented toward long-term industrial transformation. Their environmental contribution is primarily generated through modifications in material selection, structural configuration and lifecycle characteristics of aerospace components. By acting directly on the physical properties and functional design of products it is possible to obtain significant emission reductions across multiple stages of the industrial life of the products, ranging from raw-material extraction to manufacturing activities, maintenance requirements and end-of-life management.

This lifecycle-oriented perspective allows to achieve high environmental performance (EI values ranging from 0.6 to 1) which are counterbalanced by relatively low Technological Maturity levels (TM from 0.2 to 0.6). Such distribution reflects the experimental nature that characterizes these advanced materials and innovative design-oriented solutions. In many cases, their implementation requires substantial engineering development, redesign activities, validation procedures and adaptation of production lines before the full industrialization. As a results, these approaches are frequently associated with longer development horizons, higher implementation uncertainty and more complex industrial integration processes compared to other solutions. The coexistence of relatively high

environmental performances and moderate maturity levels highlights the strategic nature of this category. Rather than representing immediately deployable solutions, many sustainable material and design strategies can be interpreted as long-term industrial investments whose environmental benefits may become fully visible only after extended development and operational integration phases. This tendency can also be observed within the strategies. For example, *LPBF-HEA Integration for Hydrogen Turbines Components* (D2) reaches the highest PI value within the MNC configuration ($PI_{MNC} = 0.74$), combining strong environmental potential with significantly higher technological complexity and implementation requirements.

However, the delayed nature of the environmental benefits generated is the main concern related to this category. Unlike other decarbonization logics able to realize immediate efficiency gains during manufacturing operations, sustainable material and design solutions often create cumulative environmental advantages that become progressively more significant over time. Lightweight structures, advanced composite materials and innovative component architectures may reduce fuel consumption, improve energy efficiency, extend component durability and decrease maintenance requirements throughout the operational life of aerospace systems. Consequently, their environmental value emerges during different phases of the product lifecycle, rather than just during production activities. From an organizational perspective, the implementation of these strategies is strongly influenced by engineering capabilities, R&D availability and integration within broader industrial ecosystems. For this reason, SMEs may encounter greater difficulties in supporting extensive redesign activities, qualification procedures and advanced material development programs due to financial and technical constraints. Nevertheless, smaller firms can still take part in these transition pathways through specialized manufacturing activities and collaborative industrial partnerships. MNCs are generally better positioned to absorb long development cycles and support large-scale innovation programs, particularly when long-term sustainability objectives justify implementation risks and delayed economic returns.

Despite their significant potential, the environmental impact associated with sustainable materials and advanced design solutions is often more difficult to assess in the short-term. Their effectiveness depends on lifecycle assumptions, operational conditions and industrial integration. All these factors contribute to introduce additional uncertainties into the performance evaluation. Furthermore, qualification requirements, certification constraints and supply-chain dependencies may considerably slow industrial adoption within highly regulated manufacturing sectors such as aerospace.

Finally, this category represents a sustained industrial transition proposal characterized by high innovation potential and lifecycle-oriented environmental benefits. Although their implementation often requires substantial technological integration and extended development horizons, these approaches may support deep and systemic sustainability improvements capable of shaping the future evolution of aerospace manufacturing systems.

6.3.5 Cross-Category Discussion

The analysis conducted across the four categories shows how industrial decarbonization can't be interpreted as a single or uniform transition pathway. Each category operates through different technological mechanisms and defines specific balances between Environmental Impact, Implementation Cost and Technological Maturity. The evaluated strategies do not simply differ in terms of technological content but also in the way environmental improvements are generated and integrated within the industrial systems.

It is possible to identify two main decarbonization trajectories characterized by different temporal horizons and operational logics. Categories such as clean-energy systems, sustainable materials and innovative design are mainly associated with long-term industrial transformation. Their implementation often requires substantial infrastructure adaptation, long development cycles and significant technological evolution before environmental benefits can be fully realized. These paths are generally characterized with higher implementation complexity, lower maturity levels and greater uncertainty, but also by potentially higher environmental impact. On the other side, process optimization and digital intelligence strategies are more associated with short and medium-term operational improvements. These approaches mainly act through efficiency enhancement and intelligent coordination of already existing systems. For this reason, their environmental contribution is generally more progressive and incremental, but at the same time they present higher implementation readiness, faster integration processes and lower operational disruption. This allows companies to obtain measurable environmental improvements within shorter implementation horizons while maintaining greater operational continuity.

The coexistence of these two different routes suggests that there isn't a universally optimal solution which is sufficient on its own. The strategies characterized by high transformative potential often require significant operational improvements to support industrial integration, while highly feasible and mature solutions may not independently achieve deep long-term emission reductions. For this reason, the effectiveness of industrial

decarbonization depends on the ability to combine different technologies pathways capable of generating complementary contributions across multiple dimensions of industrial sustainability. Decarbonization should not be interpreted as a competition between alternative solutions, but rather as a multidimensional transition process where different strategies reinforce and support each other. Consequently, the transition toward a more sustainable aerospace manufacturing is strongly dependent on the ability to progressively integrate short-term operational improvements with long-term transformative industrial strategies.

6.4 Comparative Analysis: SME vs MNC

The comparison between SME and MNC configurations demonstrates how different organizational priorities significantly influence the final positioning of the evaluated decarbonization strategies. Even if the same set of alternatives is evaluated within both configurations, the adoption of different weighting structures produces relevant variations in the Performance Indicators and consequently modifies the ranking structure of several strategies. These differences reflect the distinct operational conditions, investment capabilities and strategic objectives that typically characterize small and medium-sized enterprises compared to large multinational organizations.

The comparative analysis also confirms that the effectiveness of decarbonization strategies can't be evaluated without considering the industrial context in which they are implemented. Certain strategies maintain relatively stable performances across both configurations, suggesting a balanced combination of the three evaluated criteria. Other solutions instead show significant ranking variations depending on the weighting priorities adopted within the framework. In particular, strategies characterized by high environmental potential, but lower implementation readiness generally improve their positioning in the MNC configuration, while more mature and accessible solutions tend to perform better within the SME setting. To understand these variations, the following table summarizes the PI values obtained within the two configurations together and the related performance differences defined as $\Delta PI = PI_{MNC} - PI_{SME}$.

Table 27 *Comparative PI Variation*

<i>Strategy adopted</i>	ID	PI_{SME}	PI_{MNC}	Δ PI
PtL-Based SAF Production Pathways with Alternative Aromatic Supply	A1	0,50	0,64	+0,14
SAF Production from Lignocellulosic Biomass	A2	0,52	0,60	+0,08
Nuclear assisted Hydrogen production for Sustainable aviation fuel	A3	0,50	0,64	+0,14
Numerical Model for Improving Thermal Management in PEM Fuel Cells	B1	0,54	0,62	+0,08
AI-driven PEMWEs optimization	B2	0,54	0,62	+0,08
Energy-flexible scheduling of machining processes	B3	0,76	0,66	-0,10
Meta-Heuristic Scheduling for Low-Carbon Manufacturing	B4	0,66	0,64	-0,02
Chemical utilization of slag waste heat through chemical reactions	C1	0,50	0,64	+0,14
Selective Laser Melting for Turbine Blades Manufacturing	C2	0,64	0,68	+0,04
Fixed-Point Modelling for Material and Energy Optimization in Forging Production	C3	0,74	0,70	-0,04
Design-Driven Carbon Footprint Reduction of Composite Materials	D1	0,60	0,60	0,00
LPBF–HEA Integration for Hydrogen Turbines components	D2	0,64	0,74	+0,10
Permanent magnet Rotor Design for EPU	D3	0,54	0,62	+0,08
Direct Titanium–PET Bonding via Heating and Pressurization	D4	0,62	0,62	0,00

The results obtained reveal the presence of different behavioural patterns among the evaluated strategies. Several solutions exhibit positive Δ PI values, reflecting stronger performances within the MNC configuration. Other strategies maintain higher rankings in the SME setting due to their strong alignment with feasibility, implementation readiness and operational scalability. At the same time, a limited number of strategies preserve stable performances across both profiles, highlighting more balanced technological solutions capable of adapting to different industrial conditions.

These comparative dynamics are further explored in the following sections through the analysis of ranking variations, criterion interactions and the broader industrial implications emerging from the proposed framework. Particular attention is dedicated to understanding

how different organizational conditions influence the competitiveness, applicability and strategic relevance of decarbonization pathways across SME and MNC configurations.

6.4.1 Stable and Divergent Strategies

The comparative results confirm the presence of significantly different behavioural patterns among the evaluated strategies. While certain solutions maintain coherent performances across both configurations, others display substantial ranking variations depending on the weighting structure defined in the framework. These differences are not randomly distributed but strongly connected to the internal balance between Environmental Impact, Implementation Cost and Technological Maturity characterizing each strategy.

A first important observation concerns the limited number of strategies characterized by low ΔPI values. In particular, *Design-Driven Carbon Footprint Reduction of Composite Materials* (D1) and *Direct Titanium–PET Bonding via Heating and Pressurization* (D4) maintain identical PI scores across both configurations. This stability is mainly generated by their balanced criterion distribution. Regarding D1, all normalized criteria maintain intermediate values ($EI' = 0.60$; $IC' = 0.60$; $TM' = 0.60$), producing a highly stable performance profile independent of weighting variations. Similarly, D4 combines moderate environmental yield with acceptable implementation feasibility and maturity ($EI' = 0.60$; $IC' = 0.80$; $TM' = 0.40$), granting the implementation on a wide range of organizations. A similar tendency can be observed for *Meta-Heuristic Scheduling for Low-Carbon Manufacturing* (B4) and *Selective Laser Melting for Turbine Blades Manufacturing* (C2). B4 shows a very limited ΔPI of -0.02, preserving competitive performances in both setups due to the balanced interaction between medium Environmental Impact ($EI' = 0.60$) and high Technological Maturity ($TM' = 0.80$). In contrast, C2 records a positive ΔPI of +0.04, supported by a strong EI value ($EI' = 0.80$). Although it requires greater implementation resources ($IC' = 0.40$), it still provides the same level of readiness observed for B4. These cases demonstrate how balanced technological profiles reduce ranking volatility even when strategic priorities and organizational capabilities change.

The largest positive variations emerge instead for strategies characterized by extremely polarized criterion distributions. *PtL-Based SAF Production Pathways* (A1), *Nuclear Assisted Hydrogen Production for Sustainable Aviation Fuel* (A3) and *Chemical Utilization of Slag Waste Heat through Chemical Reactions* (C1) reflect the highest PI increase within the framework ($\Delta PI = +0.14$). These strategies share an almost identical normalized

structure: maximum Environmental Impact ($EI' = 1.00$) combined with very low Implementation Cost and Technological Maturity values ($IC' = 0.20$; $TM' = 0.40$). Their behaviour clearly demonstrates the strong influence exerted by the weighting structure on highly transformative but less mature technologies. Within the SME configuration, where implementation feasibility and maturity receive greater importance, these strategies remain positioned at the bottom of the ranking with PI values of 0.50. However, when EI becomes more influential within the MNC setting, their strong decarbonization potential significantly improves their overall performance, increasing PI values up to 0.64. The magnitude of this variation confirms that these strategies are highly sensitive to weighting changes because their technological profiles are strongly unbalanced toward environmental performance.

Another relevant case is represented by *LPBF-HEA Integration for Hydrogen Turbines Components* (D2), which records a ΔPI of +0.10 and becomes the highest-ranked strategy within the MNC configuration ($PI_{MNC} = 0.74$). Unlike the previously discussed A1, A3 and C1, D2 combines the maximum Environmental Impact score with more balanced maturity and feasibility conditions ($IC' = 0.40$; $TM' = 0.60$). This partially reduces the implementation penalties observed for clean-energy pathways, while preserving at the same time a strong transformative potential. As a result, D2 achieves high scores for both categories, but particularly benefits from the stronger importance assigned to EI within the MNC setting. An opposite dynamic emerges for strategies primarily associated with operational efficiency and implementation readiness such as *Energy-flexible Scheduling of Machining Processes* (B3). It records the largest negative variation within the framework, decreasing from $PI_{SME} = 0.76$ to $PI_{MNC} = 0.66$. This behaviour is explained by the strategy's criterion distribution, characterized by maximum feasibility and maturity performances ($IC' = 1.00$; $TM' = 0.80$) combined with a relatively limited environmental contribution ($EI' = 0.40$). Consequently, the strategy strongly benefits from weighting structures that prioritize implementation readiness, operational accessibility and rapid integration within existing industrial systems, as observed for SMEs. Instead, even if still competitive, it loses relative importance within the MNC configuration, where Environmental Impact and long-term transformative potential receive greater interest. A similar but less pronounced tendency can also be observed for *Fixed-Point Modelling for Material and Energy Optimization in Forging Production* (C3), whose PI decreases from $PI_{SME} = 0.74$ to $PI_{MNC} = 0.70$. Compared to B3, the reduction is limited because C3 maintains a more balanced criterion structure ($EI' = 0.60$; $IC' = 0.80$; $TM' = 0.80$), allowing the strategy to preserve strong performance even when weighting priorities shift toward environmental impact.

The coexistence of highly stable and strongly divergent strategies shows one of the most important findings emerging from the framework. Ranking variations are not randomly generated but directly reflect the internal criterion balance characterizing each technological pathway. Strategies with highly polarized profiles tend to exhibit stronger sensitivity to weighting changes, whereas more balanced solutions maintain greater ranking stability across different organizational conditions. As a result, the comparative analysis confirms the internal coherence of the proposed MCDM framework and its capability to capture how specific characteristics interact with different decision-making priorities.

6.4.2 Criterion Interaction and Competitiveness Dynamics

The comparative results demonstrate that the competitiveness of decarbonization strategies doesn't depend on the maximization of a single evaluation criterion, but rather on the interaction between Environmental Impact, Implementation Cost and Technological Maturity. Although emission reduction remains the central objective of every evaluated strategy, the analysis shows that the environmental performance alone isn't sufficient to determine the absolute validity and applicability of a decarbonization pathway. In order to become effectively competitive within industrial environments, emission reduction strategies must also remain sustainable from an economic, operational and technological perspective according to the capabilities and constraints of different organizational contexts.

The first major insight concerns the absence of a universally dominant criterion. Strategies characterized by maximum EI do not automatically achieve the highest overall performances. This tendency is particularly evident for solutions such as *PtL-Based SAF Production Pathways (A1)*, *Nuclear Assisted Hydrogen Production for Sustainable Aviation Fuel (A3)* and *Chemical Utilization of Slag Waste Heat through Chemical Reactions (C1)*. Although these strategies achieve the highest normalized EI values ($EI' = 1.00$), their competitiveness is partially reduced by lower performances in terms of Implementation Cost and Technological Maturity. These results demonstrate that strong decarbonization potential alone cannot guarantee industrial applicability when economic accessibility and operational readiness remain limited. At the same time, high feasibility and maturity performances alone do not necessarily guarantee competitive profiles. Strategies with excellent implementation accessibility but limited environmental contribution may preserve strong operational applicability while losing relative competitiveness when broader sustainability objectives become more relevant within the evaluation process. This behaviour is visible in the case of

Energy-flexible Scheduling of Machining Processes (B3), whose very high IC and TM values strongly support its positioning, although the strategy presents a comparatively lower environmental contribution.

The best performing strategies within the framework are therefore those presenting a more balanced criterion structure rather than strategies which maximize a single performance dimension. This tendency clearly emerges in the case of *Fixed-Point Modelling for Material and Energy Optimization in Forging Production* (C3) and *LPBF-HEA Integration for Hydrogen Turbines Components* (D2). Even if these strategies do not simultaneously excel in all the evaluation dimensions, they maintain sufficiently strong performances across multiple criteria, allowing them to preserve competitiveness under both weighting systems. This suggests that balanced technological profiles generate greater adaptability and ranking stability compared to highly polarized solutions. Strategies characterized by strongly unbalanced criterion distributions tend to exhibit larger ΔPI variations because their competitiveness depends on the relative importance assigned to specific evaluation dimensions. Conversely, more balanced strategies generally maintain greater stability since their performances are supported by multiple criteria. This explains why certain strategies preserve competitive positions across both configurations while others experience substantial ranking fluctuations.

The framework highlights that industrial decarbonization competitiveness emerges from the balance between environmental ambition, implementation feasibility and technological readiness rather than from the optimization of a single criterion. Emission reduction remains the core objective of the transition process, but decarbonization strategies can generate concrete industrial benefits only when environmental ambition is accompanied by feasible implementation conditions, technological readiness and sustainable integration within actual industrial systems. The proposed MCDM is able to capture the multidimensional nature of sustainability and emphasizes the importance of evaluating sustainable pathways through context-sensitive perspectives.

6.4.3 Industrial Interpretation

The differences observed between SME and MNC configurations are not limited to numerical ranking variations. They reflect deeper industrial and organizational dynamics which influence the applicability of decarbonization strategies. The framework highlights how different types of companies tend to converge toward distinct transition pathways

according to the structure, investment capacity and strategic priorities. Consequently, the effectiveness of a specific strategy can't be evaluated independently from the industrial environment in which it is implemented.

A first important distinction concerns the different approach adopted toward implementation risk and operational continuity. SMEs generally prioritize solutions characterized by accessibility, technological readiness and limited organizational disruption. Within smaller industrial environments, decarbonization initiatives must remain compatible with constrained financial resources, shorter investment horizons and a lower risk appetite. In many cases, unsuccessful investments or excessively complex industrialization processes may directly affect production continuity and operational stability. For this reason, SMEs tend to favour gradual transition pathways capable of generating measurable environmental improvements while preserving industrial flexibility and limiting exposure to technological uncertainty. This tendency is reflected in the strong performances achieved by process optimization and digital-intelligence strategies within the SME configuration. Solutions based on operational efficiency, intelligent scheduling and data-driven coordination generally require lower infrastructural transformation while maintaining relatively high implementation feasibility. Their competitiveness is therefore associated not only with environmental contribution, but also with the possibility of being integrated into already existing industrial systems. Another relevant aspect refers to the temporal perspective associated to industrial transition. SMEs frequently require shorter implementation horizons and more visible operational returns to justify investments related to sustainability initiatives. Within this context, decarbonization evolves as a process of industrial adaptation rather than radical transformation.

A substantially different industrial logic emerges within the MNC configuration. Larger organizations generally possess broader financial resources, stronger technological infrastructures and more advanced integration with research and innovation ecosystems. This allows them to absorb higher implementation complexity, longer payback periods and greater technological uncertainty without compromising industrial continuity. MNCs preserve competitiveness across a wide range of decarbonization alternatives, including highly transformative technologies characterized by elevated implementation costs and lower maturity levels. This broader strategic flexibility also enables multinational companies to pursue multiple transition trajectories simultaneously, combining short-term operational optimization initiatives with long-term transformative investments. Industrial decarbonization within large organizations therefore tends to evolve through parallel and

interconnected transition processes rather than through isolated technological interventions. Sustainability investments are frequently associated not only with environmental objectives, but also with long-term industrial positioning, technological leadership and future competitiveness. Investments in hydrogen systems, sustainable fuels and advanced materials consequently become part of broader industrial transformation strategies characterized by high levels of innovation and systemic change. Such approaches are supported by the greater ability of multinational companies to face temporary inefficiencies, delayed returns and implementation uncertainty due to their higher risk tolerance and stronger organizational capacity compared to small and medium-sized enterprises.

Another important distinction between the two settings regards the role played within the industrial ecosystems and supply-chain structures. SMEs frequently participate in operations as specialized suppliers integrated within broader production networks, adapting progressively to sustainability requirements imposed by larger industrial actors. MNCs act as coordinators of industrial transition, influencing technological standards, innovation priorities and sustainability objectives across the supply chain. As a consequence, larger organizations own greater capacity not only to adopt decarbonization strategies internally, but also to accelerate the diffusion of sustainable practices throughout broader industrial ecosystems influencing smaller partners.

The framework demonstrates that emission reduction in the aerospace manufacturing can't be interpreted as a standardized or homogeneous transition process. The competitiveness, feasibility and long-term applicability of decarbonization pathways are deeply influenced by organizational resources, operational structures and strategic priorities. Sustainability transition therefore emerges as a multidimensional process which require alignment between technological characteristics, implementation capabilities and the industrial conditions of the organizations involved. In this sense the effectiveness of a strategy depends not only on its emission-reduction potential, but also on its consistency with specific resources, constraints and transition goals characterizing different industrial contexts. SMEs generally benefit more from mature, accessible and operationally flexible solutions capable of generating progressive environmental improvements with limited infrastructural requirements. Conversely, MNCs are better positioned to support highly transformative pathways requiring substantial investments, longer development horizons and greater technological integration.

The analysis confirms that there is no universally optimal strategy or set of solutions independently applicable from the industrial environment considered. The evaluated

pathways should rather be interpreted as complementary technological and operational pillars through which companies can structure tailored decarbonization trajectories according to their specific priorities and capabilities. Some strategies support rapid and accessible operational improvements, while others contribute to long-term industrial transformation through more complex and systemic innovation processes. Consequently, industrial decarbonization should not be interpreted as the selection of a single ideal solution, but rather as the progressive integration of complementary approaches capable of supporting emission reduction across different temporal, operational and strategic dimensions.

6.4.4 Sensitivity Analysis and Framework Robustness

The weighting schemes adopted for SMEs and MNCs reflect assumptions derived from literature evidence and author judgement. For this reason, a sensitivity analysis was conducted to evaluate the robustness of the proposed Multi-Criteria Decision-Making framework. The objective was to assess whether moderate variations in the relative importance assigned to Environmental Impact (EI), Implementation Cost (IC) and Technological Maturity (TM) would significantly alter the ranking of the identified strategies or whether the overall results would remain stable across different scenarios. Rather than testing arbitrary numerical variations, the sensitivity analysis was designed to simulate plausible managerial priorities by increasing the relative importance of one criterion at a time while maintaining the overall sum of weights equal to one. This approach allows the assessment of how ranking results respond to realistic changes in organizational preferences and strategic objectives.

For SMEs, the baseline configuration assigns weights of 0.3, 0.4 and 0.3 to EI, IC and TM respectively. Three alternative scenarios were therefore developed to represent different decision-making orientations. The first scenario increases the importance of environmental performance (EI = 0.4; IC = 0.3; TM = 0.3), representing organizations that prioritize emission reduction objectives. The second scenario emphasizes implementation cost (EI = 0.3; IC = 0.5; TM = 0.2), reflecting a more cost-oriented decision-making approach. Finally, a technology-oriented scenario was considered (EI = 0.3; IC = 0.3; TM = 0.4), representing organizations placing greater importance on technological maturity and implementation risk. The resulting rankings obtained under the baseline and alternative SME weighting configurations are summarized below:

Table 28 *SME Rankings under Alternative Weighting Configurations*

<i>Standard SME configuration EI=0,3 IC=0,4 TM=0,3</i>		<i>Environmental-Oriented SME configuration EI=0,4 IC=0,3 TM=0,3</i>		<i>Cost-Oriented SME configuration EI=0,3 IC=0,5 TM=0,2</i>		<i>Technology-Oriented SME configuration EI=0,3 IC=0,3 TM=0,4</i>	
ID	PI _{SME}	ID	PI _{SME}	ID	PI _{SME}	ID	PI _{SME}
B3	0,76	C3	0,72	B3	0,78	B3	0,74
C3	0,74	B3	0,70	C3	0,74	C3	0,74
B4	0,66	D2	0,70	D4	0,66	B4	0,68
D2	0,64	C2	0,68	B4	0,64	C2	0,68
C2	0,64	B4	0,66	D2	0,62	D2	0,66
D4	0,62	D4	0,60	C2	0,60	D1	0,60
D1	0,60	D1	0,60	D1	0,60	D4	0,58
B1	0,54	A1	0,58	B2	0,58	A1	0,52
B2	0,54	A3	0,58	B1	0,58	A2	0,52
D3	0,54	C1	0,58	D3	0,58	A3	0,52
A2	0,52	A2	0,56	A2	0,52	C1	0,52
A1	0,50	B2	0,56	A1	0,48	B2	0,50
A3	0,50	B1	0,56	A3	0,48	B1	0,50

For multinational companies, the baseline configuration assigns weights of 0.5, 0.3 and 0.2 to EI, IC and TM respectively. Similarly, three alternative scenarios were considered in order to evaluate the stability of the ranking under different strategic priorities. These included a more environmentally focused configuration (EI = 0.6; IC = 0.2; TM = 0.2), a cost-oriented setting (EI = 0.4; IC = 0.4; TM = 0.2) and a technology-oriented configuration (EI = 0.4; IC = 0.3; TM = 0.3). The corresponding results are reported in the following Table:

Table 29 *MNC Rankings under Alternative Weighting Configurations*

Standard MNC configuration EI=0,5 IC=0,3 TM=0,2		Environmental-Oriented MNC configuration EI=0,6 IC=0,2 TM=0,2		Cost-Oriented MNC configuration EI=0,4 IC=0,4 TM=0,2		Technology-Oriented MNC configuration EI=0,4 IC=0,3 TM=0,3	
ID	PI _{MNC}	ID	PI _{MNC}	ID	PI _{MNC}	ID	PI _{MNC}
D2	0,74	D2	0,80	B3	0,72	C3	0,72
C3	0,70	C2	0,72	C3	0,72	B3	0,70
C2	0,68	A1	0,72	D2	0,68	D2	0,70
B3	0,66	A3	0,72	C2	0,64	C2	0,68
A1	0,64	C1	0,72	D4	0,64	B4	0,66
A3	0,64	C3	0,68	B4	0,64	D4	0,60
C1	0,64	A2	0,64	B2	0,60	D1	0,60
B4	0,64	B2	0,64	B1	0,60	A1	0,58
B1	0,62	B1	0,64	D3	0,60	A3	0,58
B2	0,62	B4	0,64	D1	0,60	C1	0,58
D3	0,62	D3	0,64	A1	0,56	A2	0,56
D4	0,62	B3	0,60	A2	0,56	B2	0,56
A2	0,60	D4	0,60	A3	0,56	B1	0,56

The comparison of the rankings obtained under the different weighting configurations highlights a significant degree of consistency across the evaluated scenarios. Although some variations in ranking positions are observed, the highest-performing strategies remain largely unchanged. In the SME analysis, the strategies B3 (*Energy-flexible Scheduling of Machining Processes*) and C3 (*Fixed-Point Modelling for Material and Energy Optimization in Forging Production*) systematically remain among the best-performing alternatives under all weighting configurations. Similarly, D2 (*LPBF-HEA Integration for Hydrogen Turbine Components*), C2 (*Selective Laser Melting for Turbine Blades Manufacturing*) and B4 (*Meta-Heuristic Scheduling for Low-Carbon Manufacturing*) consistently appear within the highest-ranked group of strategies, despite minor changes in their relative ordering.

A similar pattern emerges in the MNC analysis. The strategies D2, C3, C2 and B3 remain among the highest-ranked alternatives across all tested weighting configurations. While the exact ordering varies according to the relative importance assigned to the evaluation criteria, the composition of the leading group remains substantially unchanged. This suggests that the competitiveness of these strategies is not driven by a specific weighting configuration, but rather by balanced performances across multiple evaluation dimensions.

The sensitivity analysis also reveals that most ranking changes occur among intermediate-ranked strategies characterized by relatively similar Performance Indicator values. Consequently, moderate modifications in the weighting structure may produce limited shifts in ranking position without implying substantial differences in overall performance. In contrast, the highest-ranked strategies maintain their relative advantage regardless of the tested scenarios, confirming that their superior performance is not exclusively determined by the initial weighting assumptions. Overall, the results confirm that the proposed framework is not excessively sensitive to moderate changes in the weighting structure. The persistence of the same leading strategies across multiple decision-making scenarios demonstrates that the ranking is driven primarily by the intrinsic characteristics of the evaluated pathways rather than by a specific set of weights. Therefore, the sensitivity analysis strengthens the credibility of the framework and supports the reliability of the conclusions derived from the application of the defined MCDM framework.

6.5 Managerial Implications

The proposed framework may support industrial decision-making not only in the evaluation of decarbonization alternatives, but also in the practical structuring of transition according to different organizational conditions and operational priorities. Within aerospace manufacturing, companies are frequently exposed to a wide range of technological options characterized by different environmental benefits, implementation requirements and development horizons. In this complex scenario, the framework can operate as a strategic screening tool capable of reducing decision-making complexity and supporting the identification of decarbonization pathways that are more aligned with available resources, technological capabilities and long-term industrial objectives. This may help companies to avoid investments in solutions that, despite their strong environmental potential, could not perfectly fit with their structure and capacity. Another key aspect is the ability of this framework of providing a structured classification and integrated overview of heterogeneous decarbonization strategies. By classifying the identified strategies into macro-categories

according to common criteria, the framework highlights the key characteristics, strengths and limitations associated with different technological pathways. At the same time, the comparative SME/MNC configurations make it possible to emphasize how the same strategy may generate different levels of competitiveness depending on the industrial conditions of the organizations involved. In this sense, the framework operates not only as a decision-making support but also as an analytical tool capable of revealing broader organizational and industrial dynamics associated with sustainability transition processes.

Another important managerial implication concerns the possibility of using the framework to support prioritization and implementation sequencing. The results suggest that industrial decarbonization should not be approached through isolated interventions, but rather through progressive transition roadmaps capable of integrating different approaches over time. Companies may initially prioritize mature and rapidly deployable solutions aimed at improving operational efficiency, reducing energy consumption and strengthening coordination, while progressively preparing the industrial conditions required for more transformative investments. In this sense, digital-intelligence and process-optimization strategies may facilitate the early stage of transition by generating measurable improvements with limited operational disruption, whereas advanced energy systems, sustainable fuels and innovative material solutions may support deeper long-term industrial transformation.

The study also reflects the importance of approaching emission reduction issue through a portfolio of strategies rather than the selection of a single preferred technology. Different logics contribute to sustainability objectives through complementary mechanisms involving optimization. Consequently, companies may benefit from combining multiple technological approaches characterized by different implementation horizons, maturity levels and environmental contributions. Such integration allows industrial organizations to balance short-term feasibility with long-term ambition maintaining greater adaptability toward evolving technological and regulatory conditions. Moreover, the flexibility of the proposed framework allows companies to further personalize the evaluation process according to their own strategic priorities. Organizations may adapt the weighting structure of the criteria in order to reflect specific operational objectives, investments capabilities, sustainability targets and industrial constraints, therefore generating tailored portfolios of decarbonization strategies aligned with their specific transition needs. In addition, companies may periodically reassess alternatives by modifying criteria weights, updating strategic priorities and integrating new technological solutions. This adaptive structure allows the framework

to support not only the initial selection of sustainability strategies, but also their continuous monitoring and evolution.

The framework also facilitates the comparison from a managerial standpoint. By translating technological characteristics into structured evaluation criteria, it simplifies the interpretation of sustainability strategies, supporting communication between technical, operational and managerial functions. In this sense, it contributes to transform complex technological alternatives into more accessible strategic decision variables capable of supporting industrial planning. Overall, the proposed framework provides a structured decision-support approach which links environmental objectives with industrial feasibility and organizational capabilities. Rather than identifying universally optimal technologies, it supports the selection of context sensitive transition strategies that can evolve progressively according to operational conditions, technological readiness and long-term industrial priorities. In this sense, industrial decarbonization emerges not as a single technological selection, but as a coordinated evolution process requiring continuous adaptation, prioritization and integration of complementary sustainability solutions.

7 Conclusions

7.1 Main Findings and Research Contribution

This study addressed the challenge of evaluating and prioritizing decarbonization strategies within aerospace manufacturing, a sector increasingly required to reduce its environmental footprint while maintaining the high levels of quality, safety and reliability that characterize its production systems. Although a growing number of emission-reduction solutions have been proposed in recent years, selecting the most appropriate strategy remains a complex decision-making problem due to the diversity of available technologies, the different implementation requirements associated with each solution and the heterogeneity of organizational contexts across the industry. To address this challenge, a structured Multi-Criteria Decision-Making (MCDM) framework was developed to support the comparative assessment of alternative decarbonization pathways. The framework was designed to integrate three complementary evaluation dimensions: Environmental Impact (EI), Implementation Cost (IC) and Technological Maturity (TM). Unlike many existing studies that focus primarily on the technical performance of individual technologies, the proposed approach adopts a broader decision-support perspective aimed at facilitating the selection of decarbonization strategies according to specific organizational conditions.

The analysis began with a structured literature review conducted on the Scopus database, which enabled the identification of fourteen representative decarbonization strategies. These strategies were subsequently organized into four categories reflecting the main decarbonization logics emerging from the literature: Clean Energy Systems, Hydrogen and Sustainable Fuels; Digital Intelligence, AI and Data-Driven Decarbonization; Manufacturing Process Optimization and Energy Efficiency; and Sustainable Materials and Advanced Product Design. This categorization highlighted the multidimensional nature of industrial decarbonization and demonstrated that emission reduction can be pursued through complementary pathways ranging from process optimization and digital technologies to advanced materials, sustainable fuels and hydrogen-based systems. The application of the MCDM framework revealed that organizational context plays a significant role in influencing the attractiveness of alternative decarbonization strategies. The results obtained for SMEs indicate that the highest-ranked solutions are generally associated with process optimization and digital intelligence approaches characterized by relatively low implementation costs, higher technological maturity and easier integration within existing manufacturing environments. In particular, Energy-Flexible Scheduling of Machining

Processes (B3) and Fixed-Point Modelling for Material and Energy Optimization in Forging Production (C3) emerged as the most competitive alternatives under the SME weighting configuration, achieving Performance Indicator values of 0.76 and 0.74 respectively. Conversely, the MNC-oriented evaluation highlighted a stronger preference for strategies characterized by higher environmental impact despite greater implementation complexity and investment requirements. In this context, LPBF–HEA Integration for Hydrogen Turbine Components (D2) achieved the highest-ranking position, followed by other solutions associated with advanced manufacturing technologies and sustainable fuels. These results suggest that larger organizations are generally better positioned to pursue transformative decarbonization pathways requiring substantial financial resources, longer implementation horizons and higher technological uncertainty.

Beyond the ranking results, the study also identified two complementary decarbonization trajectories emerging across the analysed strategies. The first is represented by incremental solutions focused on process optimization, operational efficiency and digitalization, which provide relatively rapid implementation and immediate environmental benefits. The second includes more transformative approaches involving hydrogen systems, sustainable aviation fuels and advanced materials, which offer potentially greater long-term environmental gains but require more significant investments and organizational commitment. The coexistence of these pathways suggests that industrial decarbonization should not be interpreted as the adoption of a single optimal solution, but rather as the progressive combination of complementary strategies aligned with the capabilities and objectives of individual organizations. Overall, the main contribution of this research lies in the development of a structured decision-support framework capable of evaluating heterogeneous decarbonization strategies through a simple assessment methodology while explicitly accounting for organizational differences between SMEs and MNCs. By integrating environmental, economic and technological considerations within a single evaluation structure, the framework provides a practical tool for supporting sustainability-oriented decision making and contributes to a more systematic understanding of decarbonization pathways within aerospace manufacturing.

7.1 Limitations and Future Research Directions

While the proposed framework provides a structured approach for evaluating and prioritizing decarbonization strategies within aerospace manufacturing, some limitations should be

considered when interpreting the results and identifying potential directions for future research.

First, the analysis was conducted on a portfolio of fourteen representative strategies identified through a structured literature review. Although these strategies were selected to capture the main decarbonization logics emerging from the literature and were considered sufficiently representative for comparative assessment, they do not encompass the full range of technologies and solutions currently available or under development. Future studies could expand the literature base and periodically update the portfolio of strategies in order to reflect the continuous evolution of decarbonization technologies, regulatory frameworks and industrial practices.

A second limitation concerns the availability and consistency of information reported in the scientific literature. The analysed studies differ considerably in terms of scope, evaluation metrics and reporting practices. While some contributions provide detailed quantitative evidence regarding environmental performance, costs or technological maturity, others rely primarily on qualitative assessments. However, this challenge represents one of the motivations behind the development of the proposed framework, which was specifically designed to integrate heterogeneous sources of information within a common evaluation structure. Future research could strengthen the quantitative dimension of the assessment by incorporating industrial datasets, lifecycle inventories or company-specific performance indicators, thereby improving the precision of the scoring process. The distinction between SMEs and MNCs also represents a simplification of the diversity that characterizes the aerospace sector. Although the two weighting configurations were developed to capture significant differences in resource availability, implementation capabilities and strategic priorities, individual companies may exhibit specific characteristics that differ from these generalized profiles. Nevertheless, the sensitivity analysis demonstrated that the framework remains relatively robust under alternative weighting scenarios, suggesting that the identified trends are not excessively dependent on a single set of assumptions. Future applications could further increase the level of customization by defining company-specific weighting schemes based on expert judgement, stakeholder involvement or organizational objectives.

Finally, the framework was validated through a literature-based application rather than through direct implementation within industrial organizations. Consequently, future research should focus on applying the methodology to real-world aerospace manufacturing environments in order to evaluate its practical effectiveness as a decision-support tool.

Despite these limitations, the framework establishes a structured foundation for comparing heterogeneous decarbonization pathways and demonstrates how environmental, economic and technological considerations can be integrated into a unified decision-support approach. Future developments may therefore contribute to increasing both the practical applicability and the analytical depth of the framework, supporting more informed sustainability decisions across different aerospace manufacturing contexts.

Bibliography and Sitography

Airbus (2025). Global Market Forecast 2025–2044. <https://www.airbus.com/en/products-services/commercial-aircraft/global-market-forecast>

Airbus (2026). Airbus' commitment to sustainable aviation fuel. <https://www.airbus.com/en/innovation/energy-transition/our-commitment-to-saf>

Alipour Bonab, S., Waite, T., Song, W., Flynn, D., & Yazdani-Asrami, M. (2024). Machine learning-powered performance monitoring of proton exchange membrane water electrolyzers for enhancing green hydrogen production as a sustainable fuel for aviation industry. *Energy Reports.*, 12, 2270–2282. <https://doi.org/10.1016/j.egyr.2024.08.028>

Baharom, Z. (2025). Drivers and Obstacles: A Narrative Review of Green Technology adoption in SMEs. *International Journal of Research and Innovation in Social Science*, 9(11), 6903–6917. <https://doi.org/10.47772/ijriss.2025.91100538>

Boeing (2025). Commercial Market Outlook 2025–2044. <https://www.boeing.com/commercial/market/commercial-market-outlook>

Bourhis, F. L., Kerbrat, O., Dembinski, L., Hascoet, J., & Mognol, P. (2014). Predictive model for environmental assessment in additive manufacturing process. *Procedia CIRP*, 15, 26–31. <https://doi.org/10.1016/j.procir.2014.06.031>

C. A. Luongo et al., “Next Generation More-Electric Aircraft: A Potential Application for HTS Superconductors,” *IEEE Trans. Appl. Supercond.*, vol. 19, no. 3, pp. 1055–1068, 2009, doi: 10.1109/TASC.2009.2019021.

Cerezo-Narváez, A., García-Jurado, D., González-Cruz, M. C., Pastor-Fernández, A., Otero-Mateo, M., & Ballesteros-Pérez, P. (2019). Standardizing innovation management: An opportunity for SMEs in the aerospace industry. *Processes*, 7(5), 282.

Constantin, A. (2024). Nuclear hydrogen projects to support clean energy transition: Updates on international initiatives and IAEA activities. *International Journal of Hydrogen Energy.*, 54, 768–779. <https://doi.org/10.1016/j.ijhydene.2023.09.250>

Czerwinski, F. (2021). Current Trends in Automotive Lightweighting Strategies and Materials. *Materials*, 14(21), 6631. <https://doi.org/10.3390/ma14216631>

Dalpadulo, E., Russo, M., Gherardini, F., & Leali, F. (2024). Towards the Design-Driven Carbon Footprint Reduction of Composite Aerospace and Automotive Components: An Overview. *SAE Technical Paper Series.*, 1. <https://doi.org/10.4271/2024-37-0032>

Duan, W., Dong, X., Gao, L., Wang, Z., & Li, B. (2025). Chemical utilization of slag waste heat for carbon emission reduction in the iron and steel industry. *Journal of Environmental Chemical Engineering* /, 13(4), Article 117224. <https://doi.org/10.1016/j.jece.2025.117224>

European commission (2026). SME definition https://single-market-economy.ec.europa.eu/smes/sme-fundamentals/sme-definition_en

GE Aerospace. (2025). Sustainability Report 2025. <https://www.geaerospace.com/sites/default/files/2025-sustainability-report.pdf>

Gebler, M., Uiterkamp, A. J. S., & Visser, C. (2014). A global sustainability perspective on 3D printing technologies. *Energy Policy*, 74, 158–167. <https://doi.org/10.1016/j.enpol.2014.08.033>

General Electric (2026). Sustainable Aviation Fuel and more. <https://www.geaerospace.com/sustainability/innovation/alternative-fuels>

H.M. Yu, T. Ma, Y.L. Shen, D.Z. Chen, Experimental study on catalytic effect of biomass pyrolysis volatile over nickel catalyst supported by waste iron slag, *Int. J. Energy Res.* 41 (2017) 2063–2073.

Haddad, Y., De Bonneval, E. G., Afy-Shararah, M., Carter, J., Artingstall, J., & Salonitis, K. (2024). Energy flexibility in aerospace manufacturing: The case of low carbon intensity production. *Journal of Manufacturing Systems.*, 74, 812–825. <https://doi.org/10.1016/j.jmsy.2024.05.004>

Harithsa, S. N., Anand Kumar, S., Velu, R., & Nagesha, B. (2023). Laser powder bed fusion technique of hydrogen–fueled gas turbine: Role of advanced materials and its challenges. *Materials Today : Proceedings* /, 90, 11–14. <https://doi.org/10.1016/j.matpr.2023.03.389>

He, F., Ma, X., Shen, K., & Wang, C. (2020). Study on Material and Energy Flow in Steel Forging Production Process. *IEEE Access : Practical Innovations, Open Solutions.*, 8, Article 8930544. <https://doi.org/10.1109/ACCESS.2019.2958630>

Institute of Electrical and Electronics Engineers (IEEE), Von Lindenfels J., Ihne T., Franke J., Kuhl A. (2022). Electric Propulsion Units in aviation - approach for a mechanical permanent magnet rotor design and the related manufacturing concept. 2022 12th International Electric Drives Production Conference (EDPC) /, 15–09. <https://doi.org/10.1109/EDPC56367.2022.10019761>

International Civil Aviation Organization. (2025). ICAO Environmental Report 2025. <https://www.icao.int/environmental-protection/envrep2025>

International Energy Agency. (2023). Net Zero Roadmap: A Global Pathway to Keep the 1.5°C Goal in Reach. <https://www.iea.org/reports/net-zero-roadmap-a-global-pathway-to-keep-the-15-c-goal-in-reach>

International Energy Agency. (2025). Global Energy Review 2025. https://www.iea.org/reports/global-energy-review-2025?utm_source=chatgpt.com

J. Hoelzen et al., “Conceptual Design of Operation Strategies for Hybrid Electric Aircraft,” *Energies*, vol. 11, no. 1, p. 217, 2018, doi: 10.3390/en11010217.

Kim, J., Kim, S., Park, S., & Lee, I. (2025). CO₂ Electrolysis-Assisted CO₂ reduction and aromatic supply method for sustainable aviation fuel Production: Cost optimization and Future cost scenarios. *Energy Conversion and Management : An International Journal*, 341, Article 120063. <https://doi.org/10.1016/j.enconman.2025.120063>

Kondoh, K., Nishimura, N., Shitara, K., Kariya, S., Chen, K., & Umeda, J. (2025). Direct bonding mechanism of titanium and PET resin via heating and pressurization: Influence of bubble dynamics on bonding strength. *Journal of Advanced Joining Processes.*, 11, Article 100301. <https://doi.org/10.1016/j.jajp.2025.100301>

Koreen, M., M. Kuzmanovic and G. Honegger (2025), “OECD Guidance Note on fostering convergence in SME sustainability reporting”, OECD SME and Entrepreneurship Papers, No. 70, OECD Publishing, Paris, <https://doi.org/10.1787/d95a25de-en>.

Lévêque, F. (2021, June). The future of hydrogen. In *Energy, COVID, and Climate Change*, 1st IAEE Online Conference, June 7-9, 2021. International Association for Energy Economics.

Liu, S., Dutta, S., Zheng, W., Gould, N. S., Cheng, Z., Xu, B., Saha, B., & Vlachos, D. G. (2017). Catalytic Hydrodeoxygenation of High Carbon Furylmethanes to Renewable Jet-fuel Ranged Alkanes over a Rhenium-Modified Iridium Catalyst. *ChemSusChem*, 10(16), 3225–3234. <https://doi.org/10.1002/cssc.201700863>

Manning, C. G. (2023, September 27). Technology readiness levels. NASA. <https://www.nasa.gov/directorates/somd/space-communications-navigation-program/technology-readiness-levels/>

Paris, H., Mokhtarian, H., Coatanéa, E., Museau, M., & Ituarte, I. F. (2016). Comparative environmental impacts of additive and subtractive manufacturing technologies. *CIRP Annals*, 65(1), 29–32. <https://doi.org/10.1016/j.cirp.2016.04.036>

Read, N., Wang, W., Essa, K., & Attallah, M. M. (2015). Selective laser melting of AlSi10Mg alloy: Process optimisation and mechanical properties development. *Materials & Design (1980-2015)*, 65, 417–424. <https://doi.org/10.1016/j.matdes.2014.09.044>

Revankar, S. T. (2019). Nuclear hydrogen production. In *Storage and hybridization of nuclear energy*. Academic Press.

Roman, D., Saxena, S., Robu, V., Pecht, M., Flynn, D. (2021). Machine learning pipeline for battery state-of-health estimation (Apr.). *Nat. Mach. Intell.* vol. 3 (5), 447–456. <https://doi.org/10.1038/s42256-021-00312-3>

Seddiq, M., Alnajideen, M., & Navaratne, R. (2025). Thermal Transient Performance of PEM Fuel Cells in Aerospace Applications: A Numerical Study. *Energy & Fuels.*, 39(16), 7876–7889. <https://doi.org/10.1021/acs.energyfuels.4c04834>

Serres, N., Tidu, D., Sankare, S., & Hlawka, F. (2011). Environmental comparison of MESO-CLAD® process and conventional machining implementing life cycle assessment. *Journal of Cleaner Production*, 19(9–10), 1117–1124. <https://doi.org/10.1016/j.jclepro.2010.12.010>

Shrirame, B. S., & Maity, S. K. (2025). Sustainable aviation fuel range branched alkanes via hydrodeoxygenation of furfural-derived trifurylmethane over mesoporous NiW-ZrO₂ composite catalysts. *Biomass and Bioenergy*, 196, Article 107759. <https://doi.org/10.1016/j.biombioe.2025.107759>

T.C. Alex, R. Singla, D.P. Sahoo, K.D. Mehta, S. Kumar, Avenues of resources efficiency enhancement in iron and steel production, *Miner. Eng.* 222 (2025) 109160.

Torres-Carrillo, S., Siller, H. R., Vila, C., López, C., & Rodríguez, C. A. (2019). Environmental analysis of selective laser melting in the manufacturing of aeronautical turbine blades. *Journal of Cleaner Production*, 246, 119068. <https://doi.org/10.1016/j.jclepro.2019.119068>

U.S. Department of Energy. Could Hydrogen Open New Markets for Nuclear? (2022) <https://www.energy.gov/ne/articles/could-hydrogen-open-new-markets-nuclear>

United Nations Framework Convention on Climate Change. (2025). The Paris Agreement. <https://unfccc.int/process-and-meetings/the-paris-agreement>

Ünver, Ü., & Kara, O. (2019). Energy efficiency by determining the production process with the lowest energy consumption in a steel forging facility. *Journal of Cleaner Production*, vol. 215, pp. 1362–1370.

Wang, H., Zhu, J., Huang, X., Ma, H., Chen, Y., Zhou, Y., Chen, J., & Hu, Z. (2022). Key Technology and Application of Production Scheduling for Heating Forming of Forgings: A Review. *Metals.*, 12(11), Article 1790. <https://doi.org/10.3390/met12111790>

Wang, M., Dewil, R., Maniatis, K., Wheeldon, J., Tan, T., Baeyens, J., & Fang, Y. (2019). Biomass-derived aviation fuels: Challenges and perspective. *Progress in Energy and Combustion Science.*, 74, 31–49. <https://doi.org/10.1016/j.pecs.2019.04.004>

Watson, J. K., & Taminger, K. M. B. (2018). A decision-support model for selecting additive manufacturing versus subtractive manufacturing based on energy consumption. *Journal of Cleaner Production*, 176, 1316-1322.

World Economic Forum. (2025). Fostering Effective Energy Transition 2025. <https://www.weforum.org/publications/fostering-effective-energy-transition-2025/>

WORLD NUCLEAR ASSOCIATION. Hydrogen production and uses. 2021. <https://www.world-nuclear.org/information-library/energy-and-the-environment/hydrogen-production-and-uses.aspx>.

X. Yao, Y. Liu, Q.B. Yu, S.H. Wang, Energy consumption of two-stage system of biomass pyrolysis and bio-oil reforming to recover waste heat from granulated BF slag, *Energy* 273 (2023) 127204.

Xia, Q., Xia, Y., Xi, J., Liu, X., Zhang, Y., Guo, Y., & Wang, Y. (2017). Selective One-Pot Production of High-Grade Diesel-Range Alkanes from Furfural and 2-Methylfuran over Pd/NbOPO 4. *ChemSusChem.*, 10(4), 747–753. <https://doi.org/10.1002/cssc.201601522>

Y.-K. Kim, J.-Y. Suh, K.-A. Lee, Effect of gaseous hydrogen embrittlement on the mechanical properties of additively manufactured CrMnFeCoNi high-entropy alloy strengthened by in-situ formed oxide, *Mater. Sci. Eng. A-struct. Mater. Propert. Microstruct. Process.* 796 (2020) 140039, <https://doi.org/10.1016/j.msea.2020.140039>.

Yadav, D., & Banerjee, R. (2020). Net energy and carbon footprint analysis of solar hydrogen production from the high-temperature electrolysis process. *Applied Energy*, 262, 114503. <https://doi.org/10.1016/j.apenergy.2020.114503>