A comparative entropy analysis in aviation and supply chains for decarbonization

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Abstract

Purpose – In an era of increasing globalization, given their significant energy consumption, concerns regarding energy efficiency and management have come to the fore for the aviation and supply chains (SCs) sectors. The purpose of this study is to present an approach to assessing environmental sustainability based on decarbonization for all chains, particularly the aviation, maritime, and shipping sectors. An entropy-based approach that can be used effectively in defining the decarbonization responsibility of aviation and SCs, especially in line with the global 2050 targets defined in international strategies, is targeted.

Design/methodology/approach – This study primarily focuses on aviation and transportation, evaluating their energy and environmental impacts, providing a new perspective to support carbon removal strategies. An entropy-based analytical approach is applied to evaluate energy performance, while a newly developed decarbonisation index (DCI) is used to comparatively examine the environmental impacts of aviation and other vehicles.

Findings – In aviation, the exergy efficiency of conventional fuels is 25.55% on average, compared to 67.2% for electric alternatives. Fossil fuel-powered vehicles and ships have an average exergy efficiency of 31.01%, while electric alternatives are significantly more efficient at 62.12%. The exergy destruction potential is 74.45% for fossil fuel-powered units and 37.88% for electric ones. The average fossil fuel-based transportation Environmental Performance Index is 0.69, approximately two times higher than for electric alternatives. In high-power aviation, the DCI has the lowest value at 0.21 after road vehicles. This shows that improvements are needed for all vehicles including the high-power electric alternative.

Originality/value – The highlight of this study is that it provides a new criterion in decision-making processes with the DCI defined to improve the decarbonisation perspective. In the comparison, it is seen that especially in aviation, the choice of electric engines has the lowest impact on decarbonisation for high powers.

Keywords Supply chains, Aviation, Entropy management, Sustainability, Decarbonization

Paper type Research paper

Nomenclature

$\dot{m}$ = Mass flow rate;
$\dot{Q}$ = Net heat work;
$\dot{W}$ = Net work;
$\dot{E}$ = Energy flow rate;
$\dot{E}x$ = Exergy flow rate;
$\dot{E}x, dest$ = Exergy flow rate;
ψ = Flow exergy;
$\dot{S}_{gen}$ = Entropy generation;
EPI = Environment potential index;
η_{Carnot} = Carnot efficiency;
$S_{gen,c}$ = Entropy generation for Carnot;
SI = Sustainable Index;
h = Enthalpy;
s = Entropy;
T_0 = Surrounding temperature;
η_{Ex} = Exergy efficiency;
IP = Improvement rate;
$\dot{Q}_k$ = Heat transfer; and
θ = Energy efficiency rate.

Sub index

in = Input;
out = Output;
dest = Destruction;
kin = Kinetic;
ph = Physical;
ch = Chemical;
pot = Potential; and
0 = Surrounding.

1. Introduction

The evolution of modern trade has been characterised by a concerted effort to maintain competitive advantage in the face of

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intensifying global market competition. Environmental concerns have emerged as a pivotal factor in the transformation of supply chains (SCs), encompassing aviation, maritime, road and rail transportation sectors (Savi *et al.*, 2025; Soonhong *et al.*, 2019; Keskin *et al.*, 2025a). The increasingly dynamic and complex structure of the global business environment has had a significant impact on both air and maritime transportation. The mounting pressure to incorporate environmental concerns at each stage of SCs, including the aviation sector, has given rise to the concept of green supply chain management (Thoo *et al.*, 2015; Koç and Erden, 2021). This emerging paradigm has two main pillars: efficiency and environment. In this context, the efficiency of the basic operations of aviation and maritime, such as all mode of transportation, distribution, handling, packaging and storage, and the environmentally sensitive management of waste generated throughout the SC processes have become pivotal. In this context, decision makers have been effective in the development of sustainable and environmentally friendly product transfer, the development of environmentally sensitive suppliers (Oluwafunmilayo *et al.*, 2024). This process, which is now commonly referred to as supply logistics, has been precipitated by the advent of rapid SCs, such as air transportation, and the pursuit of solutions that mitigate environmental degradation in SC processes. Furthermore, strategic choices based on fuel efficiency have been demonstrated to reduce SC costs with operational reliability and to promote environmental sustainability, depending on the operational processes in question. However, significant inefficiencies and environmental pollution develop along with environmental impacts in current engine technologies (Ekici *et al.*, 2020). For example, the impact of engine inefficiencies in aviation applications gives important results in this context (Sohret *et al.*, 2016; Degirmenci *et al.*, 2023). The environmental negativities that arise in all these processes and advances in technology have also led to an increased focus on the development of novel engine technologies (Milewska and Milewski, 2022; Chao *et al.*, 2023). Specifically, studies show that the reinjection technique applied during missed approach manoeuvres in standard A320 aircraft can result in fuel savings ranging from 55% to 90%, highlighting the operational and environmental significance of such innovations (Carmona *et al.*, 2024). Improving fuel efficiency in current technologies can strengthen the resilience of SC operations in air transportation by reducing their vulnerability to rising fuel costs (Ekici *et al.*, 2021). Concurrently, this enhancement will streamline compliance with mounting regulatory imperatives concerning fossil fuel emissions. However, achieving energy efficiency necessitates a multifaceted approach. Although engine capacities of transport vehicles and vessels vary depending on the mode of transportation, the existence of a universal method for evaluating their performance facilitates a more holistic assessment. The entropy approach was used to conduct a comparative analysis of air, sea and other vehicles or vessels based on exergy destruction (Bhaskaran Anangapal, 2014; Sogut, 2021, 2024). These vehicles and vessels were examined in relation to current fossil fuels and alternative electric engine preferences. In the present study, environmental impacts were evaluated using the Environmental Performance Index (EPI) and the Decarbonisation Index (DCI), according to data from all three sectors and defined engine power ranges. This process yielded two fundamental issues that guided the construction of the study's logical framework, as delineated by its objectives:

- The development of a criterion for corporate sustainability and decarbonisation targets in aviation and other sectors is the central question of this study.
- In considering aviation and other sector chains, which parametric evaluations in terms of energy and environmental efficiency should be given priority?

Based on these basic research areas, distance- and payload-based energy and environmental performance assessments were carried out for all reference vehicles, especially aviation vehicles, produced with the corporate model developed by evaluating literature examples and current processes. Then, based on the outputs obtained from environmental performance energy and exergy analyses, the dimensions of irreversibility were evaluated in comparison with the literature in terms of entropy production and exergy destruction. Based on the findings obtained from these assessments, comparative results were developed in terms of environmental impact assessment, EPI and Sustainability Index (SI) based analyses were performed and the results were examined comparatively. Then, the analysis outputs of the vehicles were comparatively evaluated using the strategic target DCI. Thus, our study pioneers the integration of a DCI adapted to aviation, maritime and land transportation modes, enabling comparative assessment of carbon reduction potential across these sectors.

2. Aviation's role in global supply chain optimisation

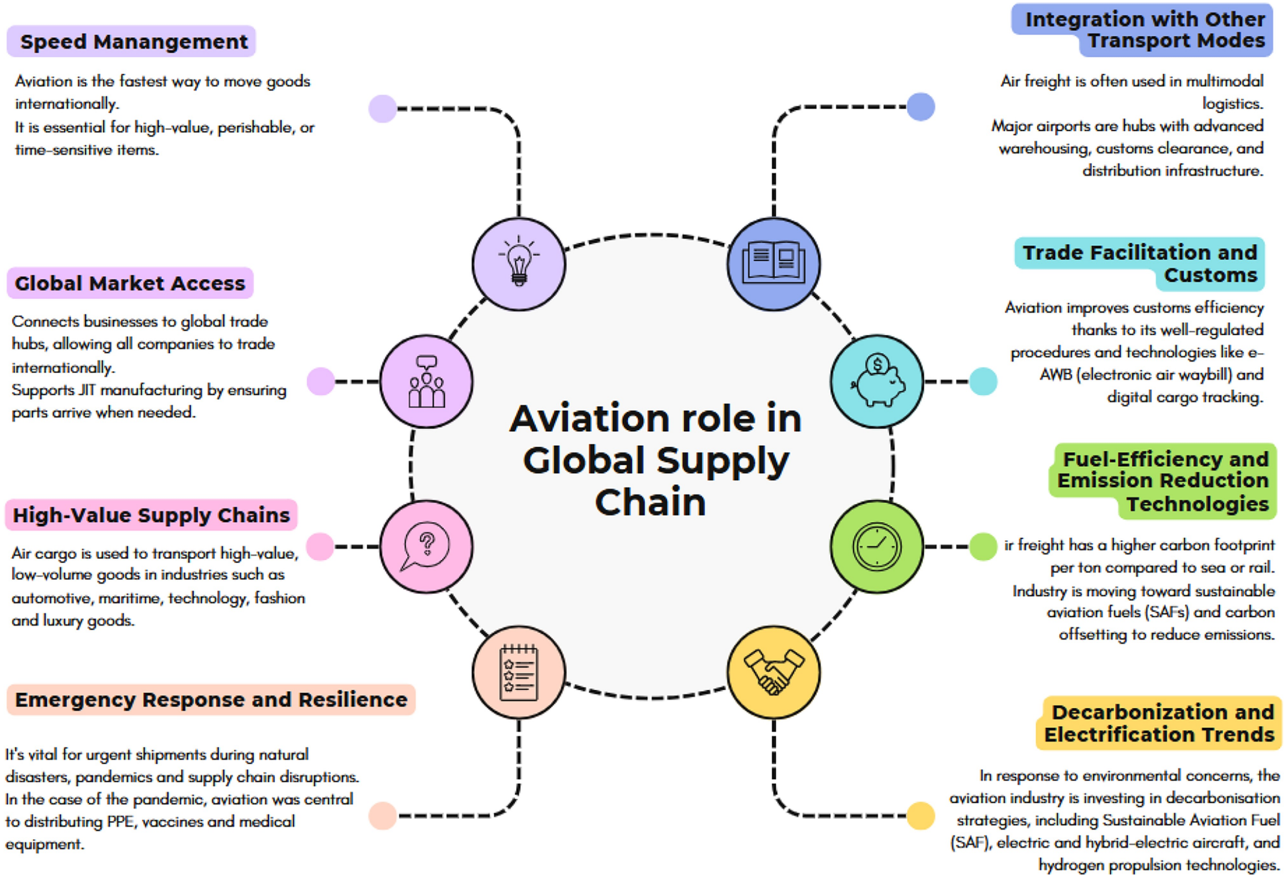
In recent years, the aviation sector has focused on technology-based efficiency as a key player in the problematic areas of global trade. Especially in the interconnected processes of SCs, the speed changes that vehicles have (Torralba-Carnerero *et al.*, 2024) have developed as a technological criterion. Indeed, the criteria brought by technology renewal in aircraft production and maintenance processes have supported environmental sustainability. Indeed, engine technologies developed in aviation not only support energy and environmental efficiency as well as managing customer demand in sectoral competition, but also can affect environmental sustainability, especially in the SC, by up to 15% (Ahlström *et al.*, 2023). This can become a widespread practice that increases the efficiency of the supply process and creates opportunities and can be managed. Today, ensuring the continuity of technological management models of aircraft and using information technologies such as machine learning and predictive maintenance in decision-making processes have supported the development of effective control strategies to improve the environmental manageability of aviation (Feliciani Merizio *et al.*, 2025). This has also provided areas where efficiency can be optimised through energy-efficient management. Artificial intelligence-supported predictive maintenance management, especially developed for aircraft with technical maintenance problems, has also provided cost-effectiveness gains. Within this structure, it has become an important facilitator in decision-making processes such as developing the ecosystem and improving sustainability in important stakeholders of SCs such as aviation, maritime transportation and land logistics. Today, aviation and other chain vehicles support such mobility in line with environmental sustainability. In addition, advanced communication and joint problem-solving in stakeholder management can be seen within this framework. These approaches are also an important component of rapid decision-making in solving problems such as technology-related or efficiency. For example, integrated sensor data from aircraft components can support predictive maintenance programmes (Basri *et al.*, 2017), increasing aircraft engine efficiency and supporting environmental sustainability. In addition, these structures can produce tools that will facilitate secure and transparent transactions such as blockchain in terms of global trade, while significantly reducing the risk of fraud. Artificial intelligence-supported Internet of things devices placed in aircraft systems will support proactive maintenance actions by providing traceability and continuous performance monitoring throughout the value chain. In aviation, other chain vehicles, especially aeroplanes, can be developed to support environmental efficiency in line with the sustainability of the portfolio in global services. In addition, multidisciplinary orientations support the manageability of processes from energy efficiency to route management, communication and joint problem-solving. The role of aviation in the global SC has been evaluated in all these processes, and a framework is presented in Figure 1.

2.1 Technology transition for decarbonisation

It is estimated that the aviation sector accounts for approximately 2%–3% of all anthropogenic CO_2 emissions, thereby constituting a substantial contributor to the global carbon footprint. This figure is set to rise unless new fuels and technologies are created, as air traffic is predicted to double by 2050 (Walker *et al.*, 2024).

This renders the decarbonisation of aviation a matter of utmost importance, particularly in the context of global climate targets, such as those established within the Paris Agreement (Huang and Zhai, 2021). The aviation sector faces specific decarbonisation challenges due to its dependence on high-energy-density jet fuels and the complexity of large-scale aircraft propulsion systems. The transition to a low-carbon future in aviation is driving significant technological innovation, with electric propulsion systems emerging as an important part of strategies to reduce greenhouse gas emissions. As regulatory pressure and global climate action commitments intensify, the development and integration of electric and hybrid-electric engines have emerged as a promising strategy to reduce emissions, particularly in the context of short-haul and regional aviation. Nevertheless, the ongoing endeavour to achieve electrification, which is propelling transformation across all sectors to attain net zero emissions, persists in multiple domains to decarbonise aviation (Sustainable Aviation, 2020). Electric propulsion systems encompass electric motors that are powered by batteries or fuel cells, with the purpose of propelling the aircraft. These technological advancements are expected to substantially mitigate in-flight emissions of carbon dioxide and nitrogen oxides by obviating the need for combustion-based

Figure 1 The aviation industry's role in the global supply chain



Source: Developed by the authors

propulsion systems. The most sophisticated design paradigms prioritise distributed electric propulsion, which enhances aerodynamic efficiency and facilitates the development of novel airframe architectures. Such innovations are anticipated to yield additional benefits in terms of fuel economy and noise abatement, thereby constituting a critical milestone in the trajectory towards aviation decarbonisation.

2.2 Technology and supply chain for decarbonisation

Logistics dates back to the dawn of human history, but SCs (logistics support systems for businesses) emerged only after Second World War. Various factors led to their development: technology advances, the collapse of the Berlin Wall (White, 2011), a global culture that homogenises consumer habits, economic integrations that remove borders and create large-scale markets and the transformation of business manners under intense global competition pressures. An effective SC system is vital for businesses to survive and compete. It has evolved beyond logistics (Luo, 2007; Keskin *et al.*, 2025b). In today's competitive market, having a well-structured and efficiently managed SC is not just about profitability – it is essential for business survival (Are and Birgit, 2020). SCs involve integrated processes where suppliers, manufacturers, distributors and retailers collaborate.

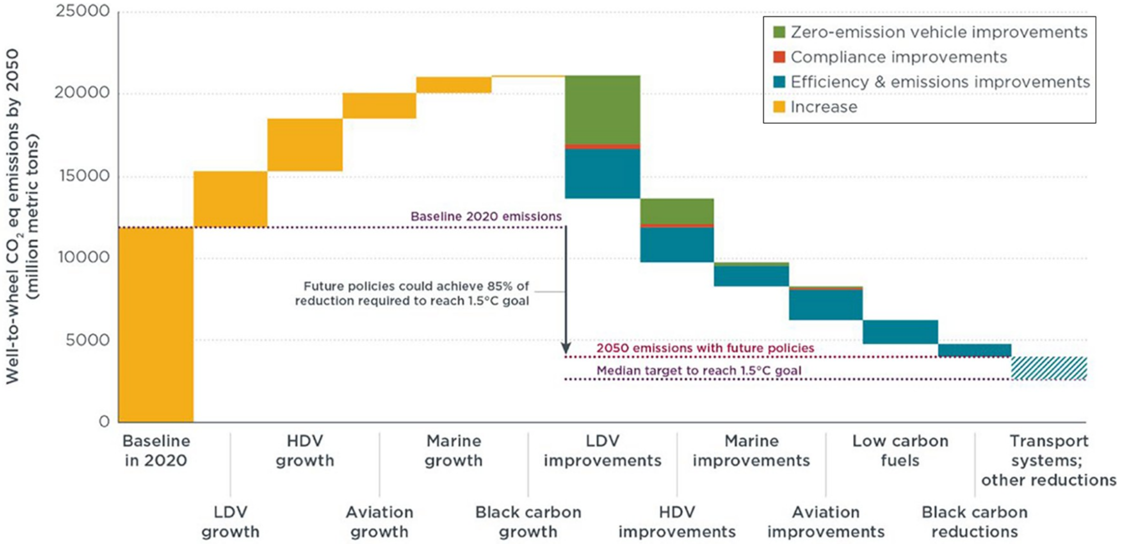
Despite their complexity and global reach, SC operations revolve around three core functions: procurement, production and distribution. Procurement involves sourcing raw materials and semi-finished products. Production involves transforming these materials into finished goods. Distribution focuses on facilitating transactions to ensure products reach consumers. Contemporary SC procedures have had a significant impact on this evolution thanks to high-tech logistics vehicles and other technologies (Kain and Verma, 2018; Omoush, 2022). As SCs have evolved into a complex structure encompassing multiple disciplines, it has become necessary to manage them with professional skills and competence (Jelti *et al.*, 2023). Transportation is a primary cost-determining factor in global logistics, accounting for approximately 90% of total logistics responsibility. The decarbonisation strategy has evolved as a sectoral necessity to limit global warming to 1.5°C, as outlined in the Paris Agreement (Trafton, 2023). Sectoral projections, especially regarding a 50% reduction in emissions by 2050, have been established as a target outcome. As illustrated in Figure 2, this process involves strategic transformations such as improving technological efficiency, electrifying vehicles, decarbonising grids by transitioning away from fossil fuels and promoting the use of low-carbon fuels.

Since the 2010s, the transportation sector has accounted for around 27% of total energy consumption and is projected to reach TWh by the 2040s, driven by an annual growth rate of 1.4% (International Energy Agency, 2021). This sector varies across regions depending on development indicators and economic sustainability factors, particularly in The Organisation for Economic Co-operation and Development countries. Given its dependence on fossil fuels, the sector exhibits markedly intensified energy consumption patterns, especially in economically advanced nations.

As decarbonisation gains prominence, the environmental and economic sustainability of energy has become critical across all sectors. In logistics, the cost and environmental impact of energy are considered fundamental components of sustainability within core SC structures. Today, the manageability of energy expenditures has emerged as a key process in transportation systems relying on land, air and sea vehicles. In decarbonisation efforts, where electrification is being evaluated from multiple perspectives, energy transition and process management are crucial stages. The development of energy efficiency measures in the sector is essential for ensuring cost-effectiveness and environmental responsibility in the flow of goods and services. Although alternative fuel options are not always the most cost-effective solution, they play a significant role in decarbonisation strategies. However, before transitioning directly to full electrification, the sector is expected to explore and advance alternative technologies as part of its adaptation process. Before switching to full electrification, the sector is expected to explore and advance alternative technologies. Sectoral studies use various approaches, including mathematical modelling, statistical analyses and life cycle assessments. The standard methodology often relies on emission factors published by the intergovernmental panel on climate change (IPCC) (IPCC, 2018). However, studies on carbon emissions in transportation involve both macro-level evaluations and micro-scale analyses. These assessments are integral to sustainability evaluations within SCs. For instance, aviation and maritime account for an estimated 3% of total emissions, while road transportation is subject to detailed local and international analyses. These evaluations align with global environmental frameworks, shaping sector-wide and corporate carbon management strategies (UNFCC, 2008: EC, 2008). As carbon management evolves, structural assessments of fossil fuel consumption continue to drive decarbonisation initiatives. For instance, the Carbon Disclosure Project (CDP) (CDP-2011) demonstrated that the corporate-scale carbon footprint in SCs exceeded initial estimates. While SCs in logistics encompass storage and distribution operations, the transportation segment remains a key area of concern due to its significant contributions to global emissions (Munich Re, 2011). Transportation is a key indicator of global trade expansion, so reducing its reliance on fossil fuels is vital for reducing global emissions and advancing environmental sustainability. The transportation sector therefore needs to develop institutional frameworks for decarbonisation and adopt comprehensive energy management strategies (IPCC, 2018; Ceder, 2016). Research emphasises that achieving decarbonisation goals in transportation requires reducing fossil fuel-based energy consumption and improving energy efficiency through the adoption of alternative fuel and technology solutions. Entropy and exergy destruction are primary issues that must be addressed regardless of the transportation mode. The literature has therefore focused on entropy management and decarbonisation strategies for each mode of transportation.

To achieve sustainable (green) transportation, it is essential to examine pollutants that harm the environment, implement zero waste and zero emission strategies and enhance the efficiency of entropy management in a way that minimises exergy destruction and maximises negentropy. In maritime transportation networks, which are interconnected with all other transportation modes, the increase in the rate of decentralisation leads to a rise in vulnerability, highlighting the

Figure 2 CO$_2$-equivalent emissions in 2050 and their mitigation potential, categorised by major transport sectors



Source: Kodjak, 2021

importance of entropy management in the context of the green transition (Wen *et al.*, 2022).

Although studies have developed a Sustainable Supply Chain Framework, it has not reached global acceptance. Consequently, different practices are emerging in the green transition, creating gaps in logistics responsibilities (Durmaz *et al.*, 2021). Carbon dioxide emissions have been identified as the most significant determinant criterion in studies to determine the key performance indicators for low-efficiency third-party logistics providers (Wang *et al.*, 2023). Technological innovations significantly contribute to reducing energy consumption and enhancing operational efficiency (Xiao *et al.*, 2022). A study revealed that companies predominantly invest in low-carbon logistics, neglecting low-carbon manufacturing processes and products. This is considered a significant challenge for decarbonisation efforts (Wanke *et al.*, 2021). SC emissions are approximately 5.5 times higher than direct emissions (Zhang *et al.*, 2022). Green and digital corridors are critical for IMO's 2050 greenhouse gas reduction targets (Song *et al.*, 2023). These include zero-emission vehicles, fuels and cargo owners using them. Optimising fuel efficiency in green logistics operations can enhance SC resilience. This can be done by solving vehicle routeing problems, using multi-criteria decision-making methods and adopting green practices in storage and packaging. These approaches can mitigate the environmental impacts of logistics operations (Coşkun *et al.*, 2022). Recent studies have increasingly applied second-law thermodynamic metrics, such as exergy analysis and entropy generation, to the evaluation of aviation systems. For instance, Aygun *et al.* (2024) conducted a comprehensive analysis of a turbofan engine under various design conditions, assessing entropy generation, exergy efficiency and sustainability indicators. Their findings highlight the importance of thermodynamic evaluation in optimising aircraft propulsion systems and reducing environmental impacts. Building upon this approach, the present study introduces the DCI as an additional metric to facilitate comparative assessment of aviation, maritime and ground transportation modes. While extensive studies exist on thermodynamic evaluations of individual transportation systems, comparative assessments across aviation, maritime and ground transport modes using entropy-based and sustainability metrics remain scarce. This study aims to address this gap by introducing the DCI as a unified comparative metric.

3. Methodological framework

This research presents an exploratory approach to assess how fuel efficiency and decarbonisation can increase the resilience and sustainability of aviation and other SC operations. It aims to develop a model based on a strategic framework to advance sustainability in aviation. From an analytical perspective, it provides a method to optimise fuel efficiency at different stages of SC operations, reducing logistics costs and achieving a more sustainable and competitive position in the global market.

This study develops a framework for decision makers to evaluate energy and environmental sustainability in direct aviation and other SCs. It also examines the most effective approach for integrating corporate sustainability and decarbonisation strategies, especially with conventional fuel versus electric engine preferences for the aviation sector.

The study consists of two sections that include both practical and theoretical analyses to address fundamental questions. The first section evaluates the performances of direct aviation and all logistics operations based on energy and exergy analyses. In the second part, an index-based assessment is proposed for the practical application of decarbonisation regardless of scale.

In recent times, carbon management has evolved into a sectoral and institutional framework. This supports sustainability alongside the approach of the circular economy. It enhances corporate sustainability and input utilisation in management tools. It also improves efficiency in all operational processes. At the same time, it facilitates the reduction or prevention of emissions and compliance costs. It enables the development of new strategic models or policies that foster effective competition (Tang and Luo, 2014, p. 84).

Companies are becoming more aware of their global responsibilities, with sectoral SCs highlighting the need for transport management tools to minimise carbon emissions (Ahi and Searcy, 2013). This involves all stakeholders in the SC participating in carbon reduction activities. Approaches to carbon strategies developed in response to global competition emphasise sustainability, with a model focusing on suppliers and customers (Dahlmann and Röhrich, 2019). This approach triggers new mechanisms for circular markets formed around carbon management. Technological change is crucial in the fight against global climate change, with green and zero-carbon technologies replacing fossil fuel technologies (Corbett and Klassen, 2006). Technological change is necessary for competitive SCs, manageability and sustainability (Vachon and Klassen, 2006).

Structures that consider environmental needs for all stakeholders have promoted sustainability. This is also an economic method for social structures, supporting value-based approaches (Paulraj *et al.*, 2017). Since the Paris Agreement, this structure has become an effective pressure tool for all parties, transforming environmentally friendly approaches into a strategic advantage for all stakeholders (Blome *et al.*, 2017; Sharfman *et al.*, 2009). The consumer society has turned environmental sustainability into a value in the short- and medium-term expectations. This can be seen as a change in management tools for the labour market, supporting the development of an effective carbon management culture for stakeholders (Sarkis *et al.*, 2010). As pressures grow, environmental consciousness evolves in terms of value culture in life processes, and the process responsibility of all stakeholders is perceived as a moral motivation (Montiel, 2008). This motivation has developed sustainability as a powerful force for the labour market, driven by stakeholders' and SC preferences for a value-based approach. Thus, carbon management has gained importance as a means of benefit and a valuable resource for stakeholders and processes within the SC (Blanco *et al.*, 2016). Carbon management shapes itself as a quality management tool for all structural cycles. As shown in Figure 3, this structure has a system flow focused on four key pillars.

A holistic approach in engineering integrates various disciplines and perspectives, simplifies problems and resolves complex issues. This approach integrates and interacts with systems, considering how solutions affect and are affected by social, environmental and economic factors. Using systems thinking, sustainable engineering practices and human-centred design, engineers can develop solutions that meet technical requirements and ensure long-term resilience, providing benefits to society. This requires an approach to decision management that ensures solutions are functional, ethical, efficient and sustainable. As seen in Figure 4, the holistic approach supports decision-making processes in terms of the holistic effects of thermodynamic systems (Close *et al.*, 2024).

The laws of thermodynamics provide a fundamental framework for developing engineering solutions. The first and second laws of thermodynamics form the core principles that govern energy behaviour within physical systems. The first law, often referred to as the law of conservation of energy, asserts that energy cannot be created or destroyed, but only converted from one form to another. This law reinforces the principle that the total energy in an isolated system remains constant. In practical terms, it means the amount of energy entering and exiting a system must balance the change in the system's internal energy. This principle is crucial for understanding and designing systems where energy transformations are central to their operation. For instance, in a heat engine, thermal energy is converted into mechanical work, yet the total energy remains unchanged in line with the first law. The second law of thermodynamics introduces the concept of entropy, a measure of disorder or randomness within a system. According to this law, in any natural thermodynamic process, the total entropy of the system and its surroundings will always increase over time.

This indicates that energy transformations are inherently inefficient, as some energy is inevitably lost as heat, leading to an increase in entropy. Furthermore, the second law emphasises the spontaneous direction of processes, suggesting that systems naturally evolve towards higher levels of disorder and equilibrium. This thermodynamic perspective plays a crucial role in the design and optimisation of energy systems, helping improve efficiency and deepen our understanding of natural processes. The analysis of processes dependent on fossil fuels is examined through the lens of mass flow dynamics, as explored under steady-state and equilibrium conditions by Cengel and Boles (2014) and Moran *et al.* (2011).

This approach focuses on the flow of energy through various processes and cycles across systems. By applying an energy balance to identified energy users, valuable insights can be gained into the environmental impacts of energy consumption in transportation systems:

$$\dot{Q} - \dot{W} + \sum \dot{E}_{in} - \sum \dot{E}_{out} = 0 \tag{1}$$

where $\dot{Q}$ and $\dot{W}$ are the net heat and network produced from boundaries of the system input and output, respectively. This structure is directly related to the quantitative values resulting from the defined mass flows. For dead state conditions where energy systems exist, the real extent of possible irreversibility is related to exergy analyses. For such systems and their components, the exergy balance as a function of the dead state temperature for each user behaviour is as follows:

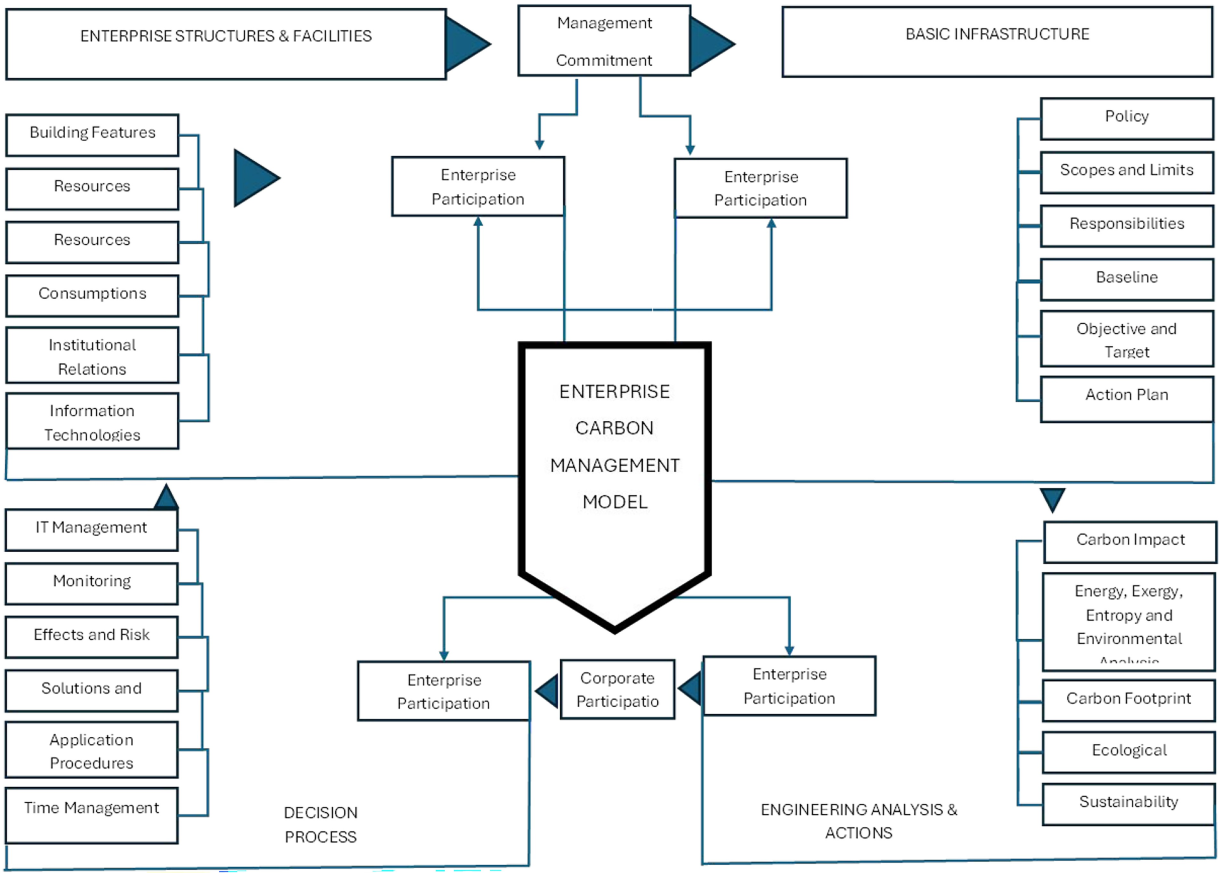
$$\sum \left(1 - \frac{T_0}{T_k}\right)\dot{Q}_k - \dot{W} + \sum \dot{E}x_{in} - \sum \dot{E}x_{out} - \dot{E}x_{dest} = 0 \tag{2}$$

$\dot{Q}_k$ refers to the heat transfer rate of passing from boundaries of the system, Ex states to the exergy flow of the system passing from boundaries and $\dot{E}x_{dest}$ refers to the exergy destruction of the flow related to seeing the limits of the irreversibility. Flow-induced exergy flow for the system where there is a physical process (ψ):

$$\psi = (h - h_0) - T_0(s - s_0) \tag{3}$$

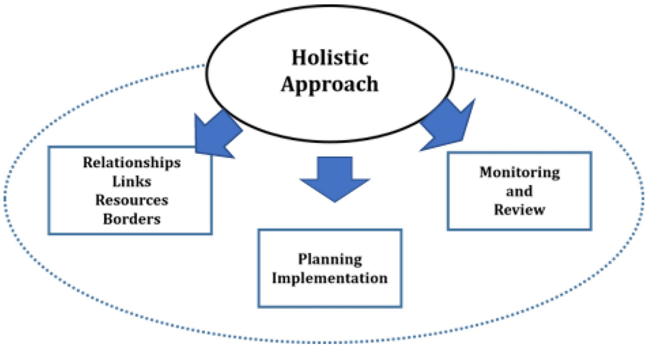
where ψ is the flow exergy (kJ/kg), h is the enthalpy (kJ/kg) of the flow, T_0 is the surrounding temperature (K or °C) and s refers to the entropy (kJ/kg/K). Exergy flow is directly based on the enthalpy (h) and the entropy (s) potentials at the surrounding temperature (Cornelissen, 1997). The degree of irreversibility of the system, which refers to the environmental influence in processes, depends directly on the amount of entropy produced. The Gouy–Stodola theorem states that the

Figure 3 Carbon management model for institutional structures



Source: Sogut *et al.*, 2019

Figure 4 Holistic approach for engineering



Source: Torres, 2014

environmental influence for entropy production is directly due to the irreversibility in the system and depends on the exergy destruction (Moran *et al.*, 2011; Dincer and Rosen, 2012):

$$\dot{E}x_{dest} = T_0\dot{S}_{gen} \tag{4}$$

where $\dot{E}x_{dest}$ refers to exergy destruction (kW), and $\dot{S}_{gen}$ is the entropy generation (kW/K) of the process. All structures consume energy, and their environmental performance is a function of their efficiency.

In exergy analysis, the performance of systems depends directly on the effect of the work produced. In fact, the exergy efficiency of a system is defined by the standard exergy efficiency, which is developed based on the data obtained at the inlet and outlet conditions of the flow process. In this context, exergy efficiency is used (Moran *et al.*, 2011):

$$\eta_{\mathrm{Ex}} = \frac{\dot{E}x_{out}}{\dot{E}x_{in}} = 1 - \frac{\dot{E}x_{dest}}{\dot{E}x_{in}} \tag{5}$$

where η_{Ex} is the exergy efficiency, $\sum \dot{E}x_{in}$ is the total exergy input (kW) and $\sum \dot{E}x_{out}$ is the total exergy output(kW). All processes are subject to an assessment in terms of their operational issues and potential for improvement. An important indicator for reducing environmental impact is the potential for improvement in entropy production. Improvement potential (IP) for these processes (Van Gool, 1997):

$$\dot{IP} = (1-\eta_{Ex})\left(\sum \dot{E}x_{in} - \sum \dot{E}x_{out}\right) \tag{6}$$

In combustion technologies, operational processes directly impact energy efficiency and management. Associated with flow parameters, energy processes in these systems are linked to engine efficiency and environmental sustainability. Environmental impacts are often linked to entropy production. The potential environmental impacts of entropy-generated entropy are shaped by irreversibility.

In exergy-driven processes, environmental impact potential is also dependent on operational efficiency. Entropy production influences this potential, along with pollution and operational parameters. This effect should be considered continuous in engines operating in a cycle. Sectoral assessments often consider pollution from fossil fuels, dependent on CO_2 emission factors developed by the IPCC. From a thermodynamic perspective, the use of fossil fuels is generally due to irreversibility. Therefore, the potential environmental impact is a form of pollution resulting from heat emitted in thermal processes.

However, in terms of emission releases, fossil fuels represent a holistic threat, with their impact being influenced by the multiplier effect of total consumption. As noted by Sogut (2021), for thermal processes, pollution is also a function of the entropy production, and the potential effects of this pollution reflect the potential of the irreversibility that occurs. In this study, an entropy-based structure is proposed alongside the EPI and the SI, which are presented as boundary conditions (Sogut, 2021). Both criteria highlight an area where the possible entropy production between the actual and expected process reversals will be evaluated. EPI is:

$$EPI = \left(\frac{\sum S_{gen}}{\sum \dot{E}x_{in}}\right) * T_0 \tag{7}$$

EPI is a measure of performance that ranges from zero to a maximum value. The environmental impact is positive if it is close to zero, but this proximity depends on the reversibility of the process. The SI value is a boundary condition for the system being analysed. Therefore, the value of EPI directly reflects the potential for pollution. All real processes are inefficient because they are irreversible. The potential for irreversibility, depending on operational parameters, also affects pollution. This pollution can be represented as an environmental impact in terms of CO_2 emissions (Yale Center for Environmental Law and Policy, 2024). However, considering the improvement effects in all processes, it also suggests the development of a goal for engineering studies. This boundary condition shows a change dependent on possible improvement goals. It can be related to the entropy produced under reversibility conditions in the equation developed by Van Gool (1997). Accordingly:

$$IP = (\eta_{Carnot} - \eta_{II}).(\dot{E}x_{in} - \dot{E}x_{out}) \tag{8}$$

The potential impacts for process improvements should be seen as an organisational goal for reducing irreversibility. The developed metric indices provide a manageable area for evaluation. Particularly, in fossil fuel-based processes, the assessment and management of operational effects can be viewed as a new perspective. For these structures, the SI value serves as a threshold for potential reversibility and can be considered as a criterion for the optimisation of operational parameters. In this case, Thermodynamic Sustainability Index (SI):

$$SI = \left(\frac{\sum S_{gen,c}}{\sum \dot{E}x_{in}}\right) * T_0 \tag{9}$$

The surrounding temperature in the conditions of the systems varies for all processes of the process and thermophysical properties may also change depending on the structural properties of the system. However, in this study, for the calculation of EPI and SI, fixed reference environmental conditions were used to ensure consistency and comparability across scenarios: a surrounding temperature of 22°C (295.15 K) and an ambient pressure of 1 atm. These reference values were applied uniformly throughout the entire flight process. In thermal processes, energy-related irreversibility is the primary cause of environmental pollution within the processes. Specifically, exergy destruction, which appears in exergy analyses, represents the extent of these irreversibility, while the defined entropy production indicates the potential for pollution created from the system to the environment. Of course, this potential is also an effect of the possible load difference in a reversible state. This structure points to an efficiency potential that should be considered in corporate energy management. Improvement goals should be set with this potential in mind. As stated by Sogut (2021), this potential, developed as the energy efficiency ratio (EER), is directly related to the two key indices mentioned above in relation to the environment. Accordingly:

$$\theta = \frac{\sum (EPI - SI).IP}{\sum Ex_{in}} \tag{10}$$

EER, which is a usable parametric value in the energy management process for corporate sustainability, offers an applicable structure in this respect. It can be presented as a tool, especially in monitoring environmental sustainability and evaluating it as a criterion.

The manageability of decarbonisation for corporate models is a strategy that has found its direction through electrification. In particular, the potential reversibility limits of fossil fuel-based resources should also be considered as a boundary for environmental manageability. In this context, the DCI developed by Sogut provides a manageable tool for businesses' potential strategies. Specifically, the DCI, which creates a boundary condition based on reversibility for actual processes, can also be used as a model that supports the development of potential opportunities. DCI developed for this purpose:

$$DCI = \frac{\sum E_{irev} - \sum E_{rev}}{\sum E_{irrev}} \tag{11}$$

Here, E_{irrev} represents the total energy consumption in actual processes, while E_{rev} denotes the energy demand required by the system or process under reversible conditions. In analyses, it is crucial to consider both the actual consumption under real-world conditions and the energy demand under reversible conditions, particularly for electric vehicles or processes. In processes where multiple fuels are consumed, each consumption factor must be considered in reversible processes or systems. The DCI is a dimensionless index ranging between 0 and 1, where lower values indicate higher decarbonisation potential (i.e. lower entropy generation compared to the reference case), and higher values indicate lower decarbonisation performance. Of course, real conditions consume high energy due to their irreversibility. This value directly means that the system demand moves away from zero and takes a value depending on the entropy. In this context, the DCI values are evaluated directly with their potential to approach zero.

4. Results and discussion

This study aims to develop an institutional perspective on decarbonisation strategies in transportation and to provide a framework. Initially, the study focused on sectoral scales, such as km and tonne-km metrics, and developed thermodynamic analyses based on energy consumption data. According to the obtained data, environmental indicators for aviation and other vehicles were calculated, together with environmental pollution levels, and the developed DCI was comparatively evaluated with electric vehicles. In particular, the potential of aircraft and vehicles for sea and land transport were examined (Schäfer and Waitz, 2014; IEA, 2023a; IEA, 2023b; UNCTAD, 2024; DOE, 2023; FAO, 2023, IEA, 2023c), according to defined threshold values, using the consumption data presented in Table 1. In the analyses, losses from vehicle usage, viscous and aerodynamic effects, irreversibility due to ageing and lifespan effects, as well as potential problem points in engines were neglected.

For the analyses performed, unit consumption data for these vehicles was taken as a reference, along with defined kJ/km and kJ/ton-km values. Both parametric values were then evaluated under adiabatic efficiency conditions of 0.85 and 0.95. In particular, direct consumption data were developed for electric motors, in addition to battery capacity, and an analytical model was produced. The reference speed values used in the analyses

Table 1 Consumption and power values of vehicles in transportation based on parameters

Transport	Parameters	Power (kW)	References
Aviation (Jet A1)	Min	230	Air Partner (2025)
	Max	38000	
Road (diesel trucks/trylers)	Min	246	Kuleshov (2005)
	Max	391	
Railway (diesel)	Min	2000	AIP Conf. Proc. (2020)
	Max	7000	
Ships (diesel)	Min	7400	IACS (2022) Sustainable Ships (2022)
	Max	80080	
Road vehicles (electric)	Min	160	EV Database; Wired (2024)
	Max	370	
Trawlers (electric) (10 knot)	Min	148	Oh *et al*. (2023)
	Max	198	
Trucks (electric)	Min	250	Goering and Rahimi-Eichi (2022), WEVJ 10(2), 22
	Max	600	
Aviation (electric)	Min	657	Mukhopadhaya and Graver (2022); CASA (2017)
	Max	2515	

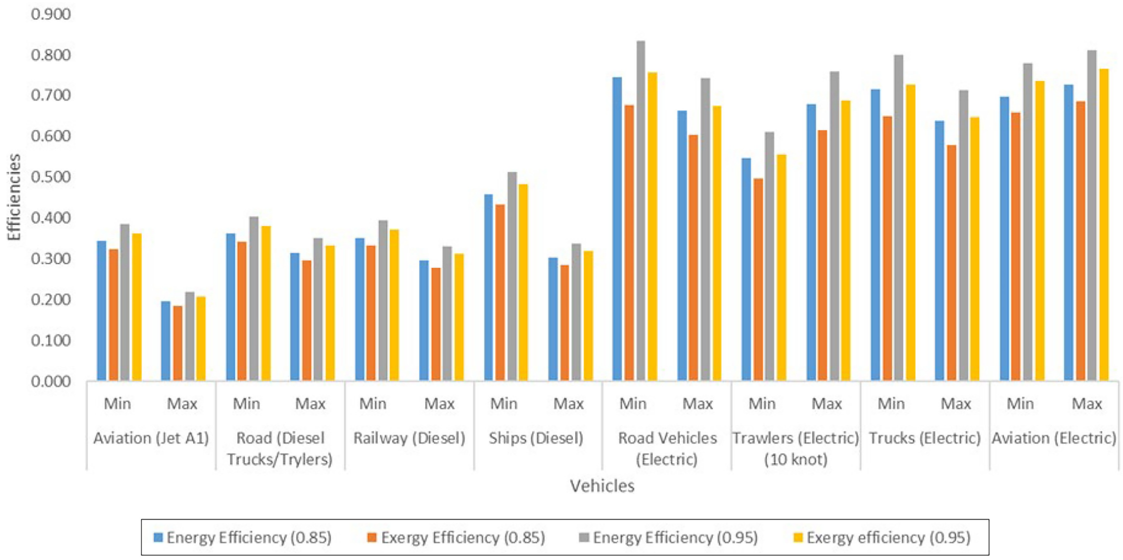
Source(s): Derived by authors

Table 2 Reference data for evaluation of the vehicles

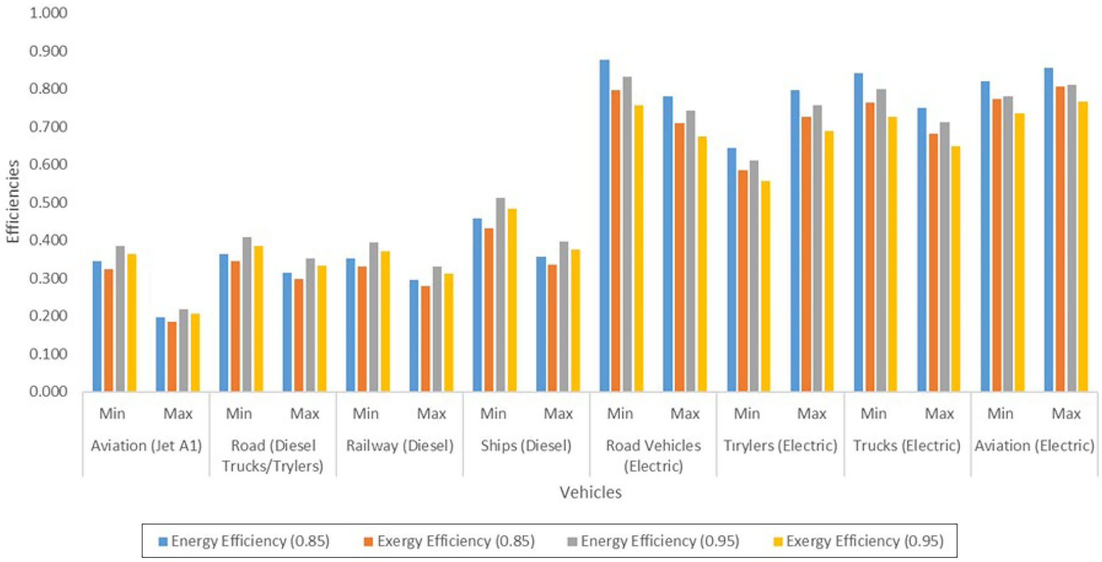
	Fossil fuels					Electricity			
Vehicles	SFC (kg/s)	Average unit cons. (kJ/km)	Average unit cons. (kJ/ton-km)	Tonnage capacity (tonne)	Vehicles	SFC (Wh/km	Average unit cons. (kJ/s)	Average unit cons. (kJ/ton-km)	Tonnage capacity (tonne)
Aviation (Jet A1)					*Road vehicles (electric)*				
Min	0.0132	2462.26	3788.09	0.6	Min	150	0	540	1
Max	3.825	73.06	0.609	120	Max	170	13.06	122.4	5
Road (diesel trucks/trylers)					*Trawlers Electric) (10 knot)*				
Min	192	33.1	3.31	10	Min	147.65	4.247	265.77	2
Max	226	63335	3166.75	20	Max	168.7	3.915	60.73	10
Railway (diesel)					*Trucks (electric)*				
Min	202	289.48	144.75	2000	Min	1.19	84.85	856.8	5
Max	240	1204002	301	4000	Max	1.42	113.5	511.2	10
Ships (diesel)					*Aviation (electric)*				
Min	155	2218051	221.81	10000	Min	942.3	215.68	6784.56	0.5
Max	235	36357503	58.07	230000	Max	3491.6	872.46	1256.98	10

Source(s): Derived by authors

Figure 5 Thermodynamics efficiencies of vehicles



(a) Efficiencies for per km



(b) Efficiencies for per ton-km

Source: Developed by the authors

were 60 km/h for fossil fuel vehicles, 12 knots for ships running on fossil fuels and 10 knots for electric fishing boats. For aircraft, 167.5 m/s reference for 38000 kW was accepted. Based on these data, energy and exergy analyses were performed using the parametric values defined in Table 2, and the results were compared directly with those in the literature.

Nowadays, particularly electric vehicles have been evaluated mainly based on land preferences, and their consumption behaviours have been assessed in comparative evaluations accordingly. Based on these data, the study examines the energy and exergy efficiencies for each vehicle according to the first and second laws of thermodynamics [based on equations (1)–(3) and (5)], with the results provided separately for both reference metrics in Figure 5.

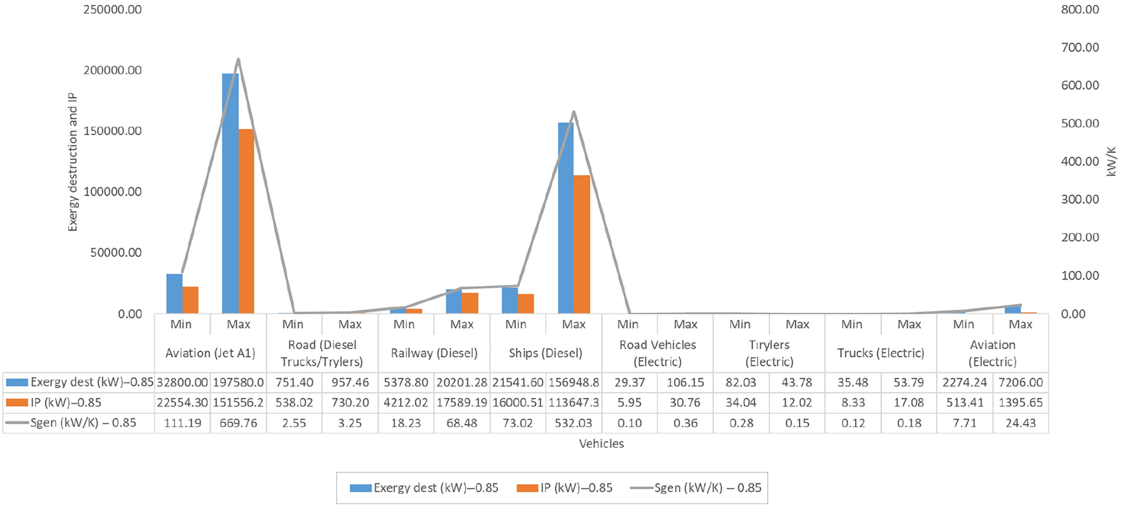
The concept of exergy refers to the maximum obtainable output for power-generating processes. Accordingly, exergy efficiency was analysed based on the environmental conditions where the vehicles operate, also known as dead state conditions. The study assumes a reference ambient temperature of 22°C and a pressure of 1 atm. The exergy factor related to engine efficiency was taken as 1.06 for fossil fuels.

The evaluation of fuel-based vehicles in transportation was conducted based on two reference conditions. In this context, the average energy and exergy efficiency for fuel-based vehicles were found to be 32.9% and 31%, respectively.

For electric vehicles, under conditions where the adiabatic efficiency is assumed to be 0.85, the average energy and exergy efficiency were determined to be 67.7% and 62.12%, respectively. In particular, when the efficiency is assumed to be 0.95, the efficiency metric for electric vehicles was observed to vary between 75.6% and 69.43%. When considering ton-km metrics, the average energy efficiency for fuel-based vehicles was found to be 33.6%, while the average exergy efficiency was 31.67%. For electric vehicles, the average energy efficiency was 79.6%, and the average exergy efficiency was 73.09%. When km and ton-km metrics are taken into account, the impact in terms of efficiency distribution corresponds to a ratio of 5.29%. These data particularly highlight the significant potential of exergy destruction in fuel-based systems. In this context, exergy parameters were examined based on both criteria with equations (4) and (6), and the distributions are presented in Figure 6.

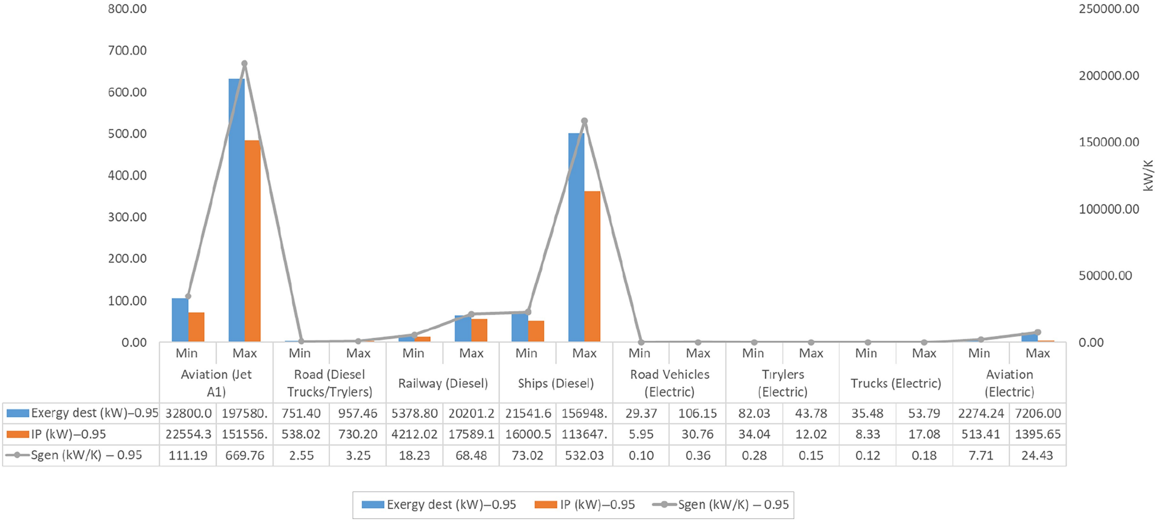
Considering fossil fuel consumption, the consumption-related exergy destruction of the aviation sector shows a potential of 17.9% higher than the general average, while it indicates 8.89% less exergy destruction in electric vehicles. Although these conditions are values for the limits defined together with instantaneous evaluations, they offer a parametric evaluation in terms of fuel preferences in energy management. For fossil-fuelled vehicles, the average exergy destruction represents a potential of 68.93% in total consumption, whereas

Figure 6 Exergetic parameters for per km



	Aviation (Jet A1)		Road (Diesel Trucks/Trylers)		Railway (Diesel)		Ships (Diesel)		Road Vehicles (Electric)		Tırylers (Electric)		Trucks (Electric)		Aviation (Electric)	
	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max
Exergy dest (kW)–0.85	32800.00	197580.0	751.40	957.46	5378.80	20201.28	21541.60	156948.8	29.37	106.15	82.03	43.78	35.48	53.79	2274.24	7206.00
IP (kW)–0.85	22554.30	151556.2	538.02	730.20	4212.02	17589.19	16000.51	113647.3	5.95	30.76	34.04	12.02	8.33	17.08	513.41	1395.65
Sgen (kW/K) – 0.85	111.19	669.76	2.55	3.25	18.23	68.48	73.02	532.03	0.10	0.36	0.28	0.15	0.12	0.18	7.71	24.43

(a) Exergetic parameters for case 0.85



	Aviation (Jet A1)		Road (Diesel Trucks/Trylers)		Railway (Diesel)		Ships (Diesel)		Road Vehicles (Electric)		Tırylers (Electric)		Trucks (Electric)		Aviation (Electric)	
	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max
Exergy dest (kW)–0.95	32800.0	197580.	751.40	957.46	5378.80	20201.2	21541.6	156948.	29.37	106.15	82.03	43.78	35.48	53.79	2274.24	7206.00
IP (kW)–0.95	22554.3	151556.	538.02	730.20	4212.02	17589.1	16000.5	113647.	5.95	30.76	34.04	12.02	8.33	17.08	513.41	1395.65
Sgen (kW/K) – 0.95	111.19	669.76	2.55	3.25	18.23	68.48	73.02	532.03	0.10	0.36	0.28	0.15	0.12	0.18	7.71	24.43

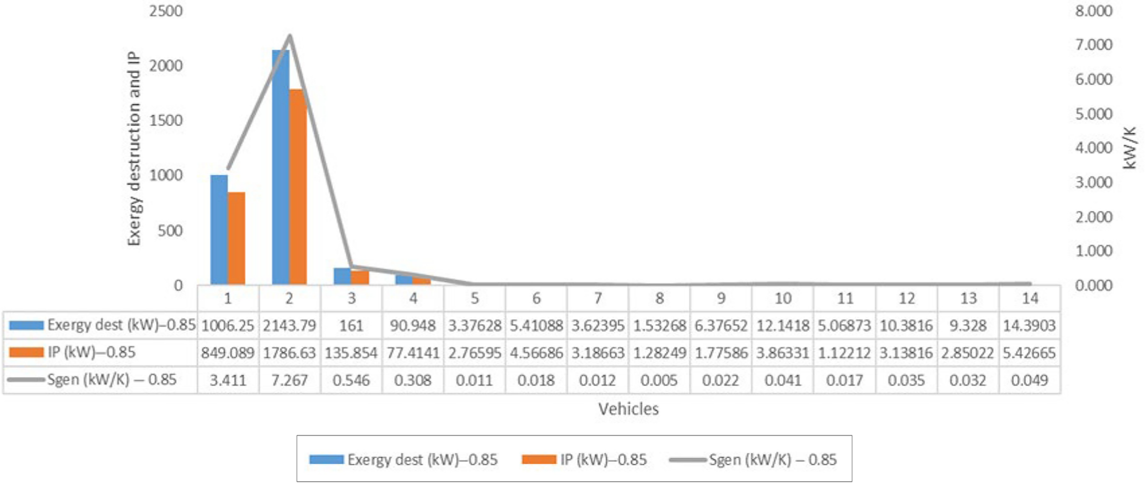
(b) Exergetic parameters for case 0.95

Source: Developed by the authors

this rate was found to be 37.88% for electric vehicles. This value drops to 31.29% for the value of 0.95. According to this data, the exergy destruction for the choice of electric technology in aviation was found to be 24.9%. Within this potential, the improvement potential (IP) ratio relative to exergy destruction was 7.45% for fossil-fuelled vehicles, while the average value for electric vehicles was found to be 35.19%. However, this potential is particularly important for aviation. In contrast, for aerospace technologies in particular, the IP ratio ranges from 33.67% at 0.85 to 6.14% at 0.95 performance. Regarding these exergy destruction values, entropy generation in fossil fuels was found to be 1155.18 kW/K, while for the electric structure this ratio was found to be only 1.60 kW/K. While this evaluation is 0.95, it shows a 3.97% reduction in the total fossil fuel consumption, while for the electric structure this value was found to be 23.1%. These analyses were also examined within the km-ton framework, and the distributions are presented in Figure 7.

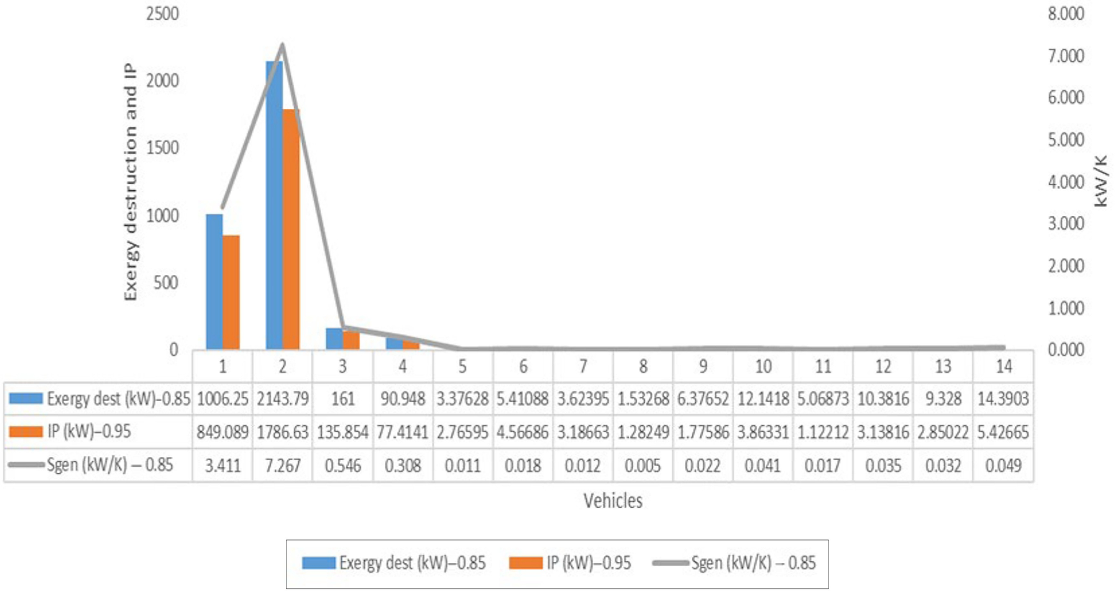
The average exergy destruction associated with load was found to be 79.90% for fossil fuel-consuming vehicles, while this rate was 23.68% for electric vehicles with an efficiency of 0.85. In this context, the irreversibility potential (IP) rate relative to total exergy destruction was calculated as 60.74% for fossil-fuelled vehicles, while the IP rate for electric vehicles was defined as 23.68%. In all these values, the rate of improvement of aviation over fossil fuels in transportation due to reduced exergy destruction is also minimal.

Figure 7 Exergetic parameters for per ton-km



	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Exergy dest (kW)–0.85	1006.25	2143.79	161	90.948	3.37628	5.41088	3.62395	1.53268	6.37652	12.1418	5.06873	10.3816	9.328	14.3903
IP (kW)–0.85	849.089	1786.63	135.854	77.4141	2.76595	4.56686	3.18663	1.28249	1.77586	3.86331	1.12212	3.13816	2.85022	5.42665
Sgen (kW/K) – 0.85	3.411	7.267	0.546	0.308	0.011	0.018	0.012	0.005	0.022	0.041	0.017	0.035	0.032	0.049

(a) Exergetic parameters for case 0.85



	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Exergy dest (kW)-0.85	1006.25	2143.79	161	90.948	3.37628	5.41088	3.62395	1.53268	6.37652	12.1418	5.06873	10.3816	9.328	14.3903
IP (kW)–0.95	849.089	1786.63	135.854	77.4141	2.76595	4.56686	3.18663	1.28249	1.77586	3.86331	1.12212	3.13816	2.85022	5.42665
Sgen (kW/K) – 0.85	3.411	7.267	0.546	0.308	0.011	0.018	0.012	0.005	0.022	0.041	0.017	0.035	0.032	0.049

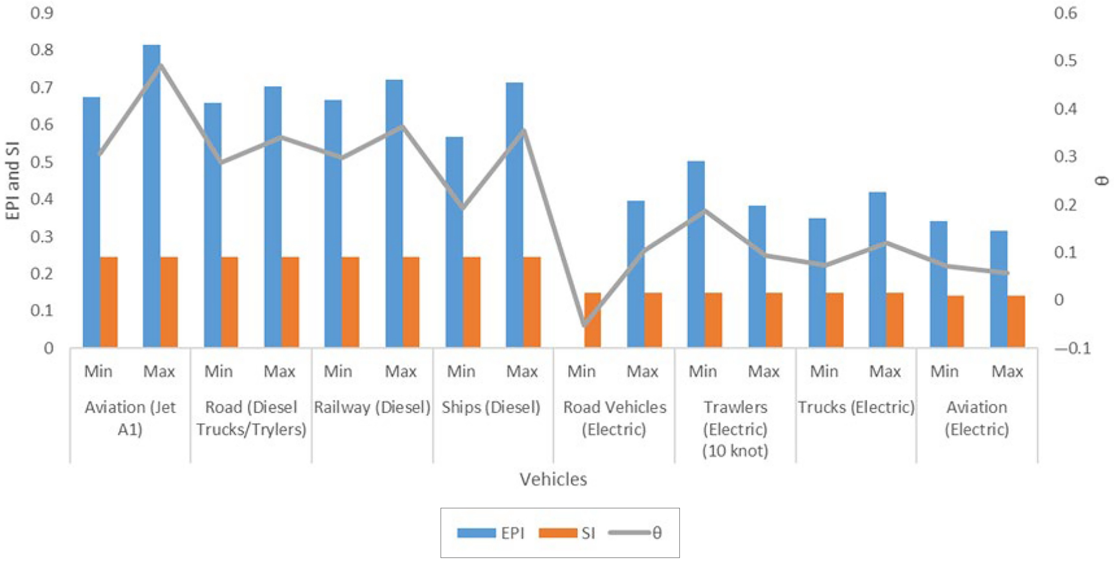
(b) Exergetic parameters for case 0.95

Source: Developed by the authors

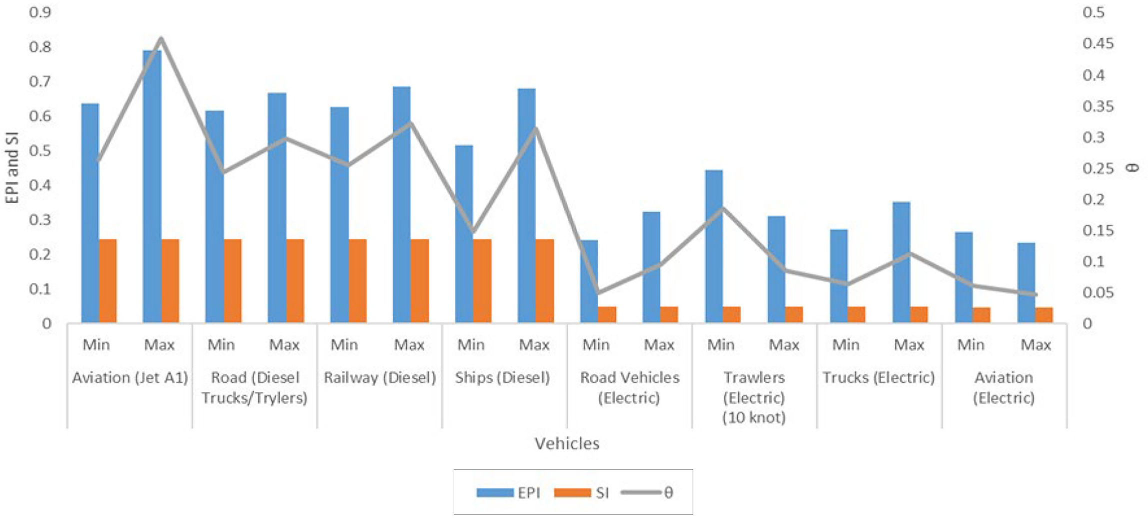
This indicates that the entropy-induced environmental impact of aviation will yield analogous results. Indeed, the ambient temperature was hypothesised to be 25°C for the purposes of analysis. In this instance, the lower temperatures of the aeroplanes at varying altitudes during flight processes will increase exergy efficiency, whilst concomitantly reducing exergy destruction and the associated entropy production. In the analysis, the effect of combining tonnage with km consumption distribution shows a proportional effect for electricity and fossil fuels, while the pollution effect of aviation, especially large-capacity aircraft, is seen to significantly affect environmental pollution. It is seen that this process corresponds to 352.83 vehicles in terms of land vehicles. In this respect, the effect of emission management in aviation can be seen as an important parameter. In this context, the environmental impact assessment was examined and possible environmental impacts were evaluated for both criteria. The environmental impact of consumption was evaluated using the developed EPI and SI values. The performance impact for both cases was assessed by using equations (7)–(9), and the distributions are presented in Figure 8.

In the study, for fuel-based vehicles, the average EPI value was found to be 0.69 based on the entropy production potential in irreversible processes. However, for aviation preference, this value indicates an average potential of 0.74. For the SI, which defines reversibility, the value was found to be 0.25. Meanwhile, the EER related to total potential was calculated as 32.93%.

Figure 8 Environmental impact and energy efficiency rate per km



(a) Environmental impact and energy efficiency rate for case 0.85



(b) Environmental impact and energy efficiency rate for case 0.95

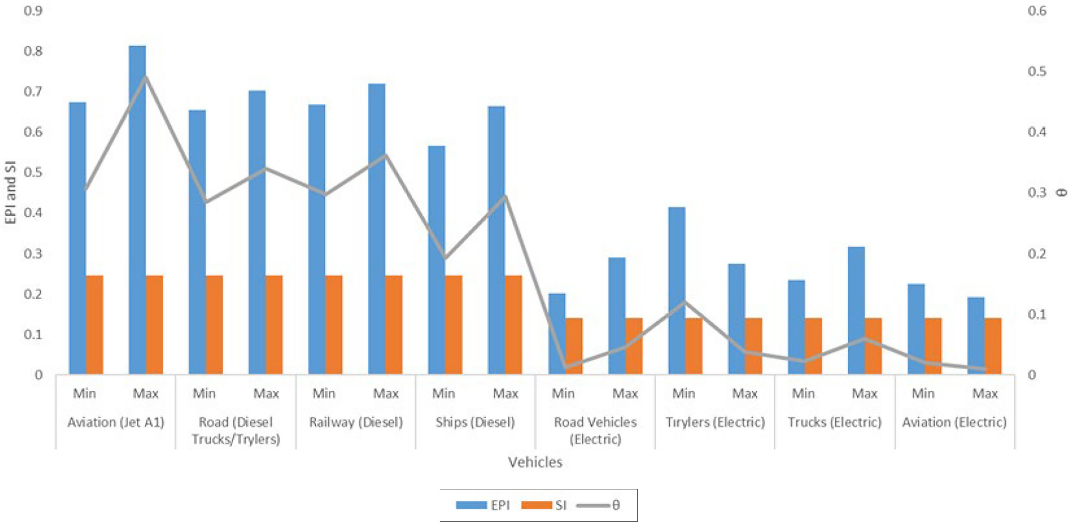
Source: Developed by the authors

For electric vehicles operating under adiabatic conditions of less than 0.38, the EPI value was found to be 0.38, indicating average potential. In contrast, aviation's preference for electricity indicates a potential value of 0.33. In contrast, the average SI value for such vehicles was found to be 0.14.

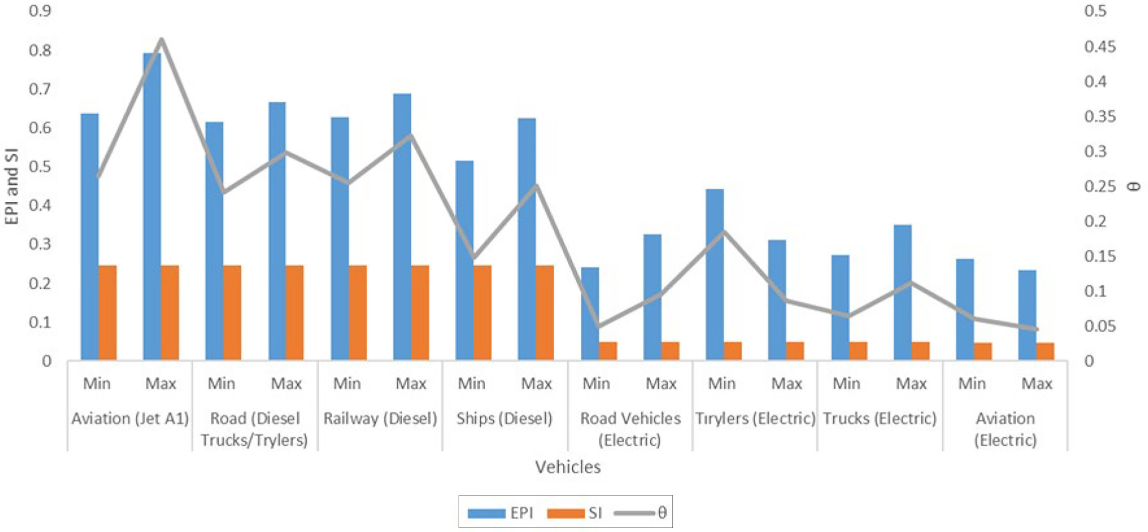
According to these data, the EER for electric vehicles under 0.85 adiabatic conditions was calculated as 9.62%. In this distribution, for 0.95 adiabatic conditions, the EPI value was found to be 0.31, while the SI value was determined to be 0.05. On the other hand, it shows a potential value of 0.36, which is particularly relevant for cases involving a preference for fossil fuels in aviation. In contrast, the EER value indicates a potential of 0.087 for aviation with an electric preference. These analyses were evaluated separately for km-ton metrics, and the distributions are demonstrated in Figure 9.

In the study, for environmental performance analyzes of vehicles based on the ton-km scale, the average EPI for fuel-based vehicles was found to be 0.68, while the average SI was 0.25. According to aviation data, the EPI value for this parameter is 0.75 on average, whereas for the choice of electric motor, this ratio is 0.21. On the other hand, the EER for these potentials was calculated as 32.14%. For electric vehicles under 0.85 adiabatic conditions, the average EPI value was found to be 0.27, and the SI value was 0.14. According to these data, the θ value was determined to be 4%. Under 0.95 adiabatic conditions for electric vehicles, the EPI value remained similar at 0.31, while the SI value was 0.05. As a result, the EER value was found to be 8.75%. Based on these results, DCI performances used equation (11) were evaluated for sectoral assessments, and the distributions are presented in Figure 10.

Figure 9 Environmental impact and energy efficiency rate per ton-km



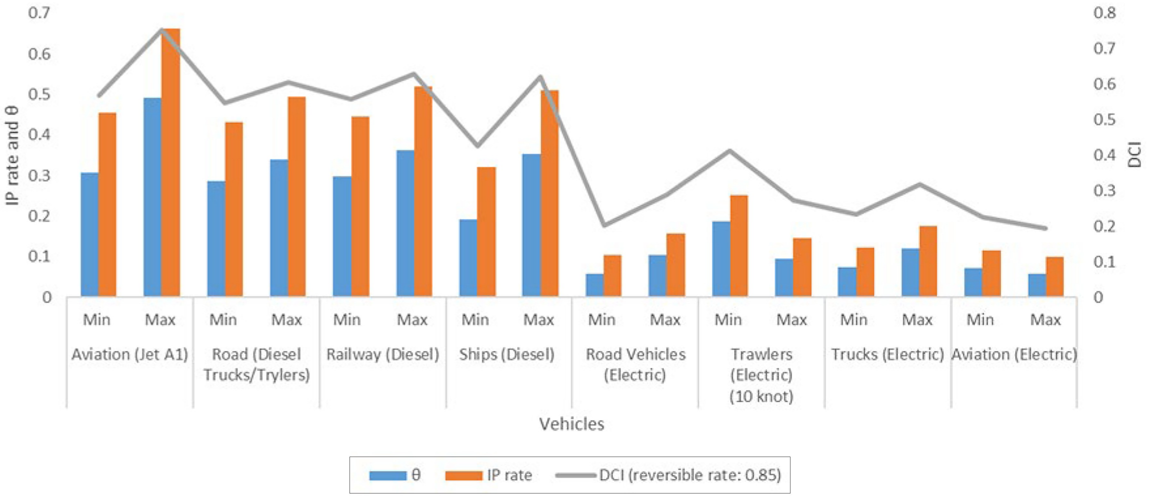
(a) Environmental impact and energy efficiency rate for case 0.85



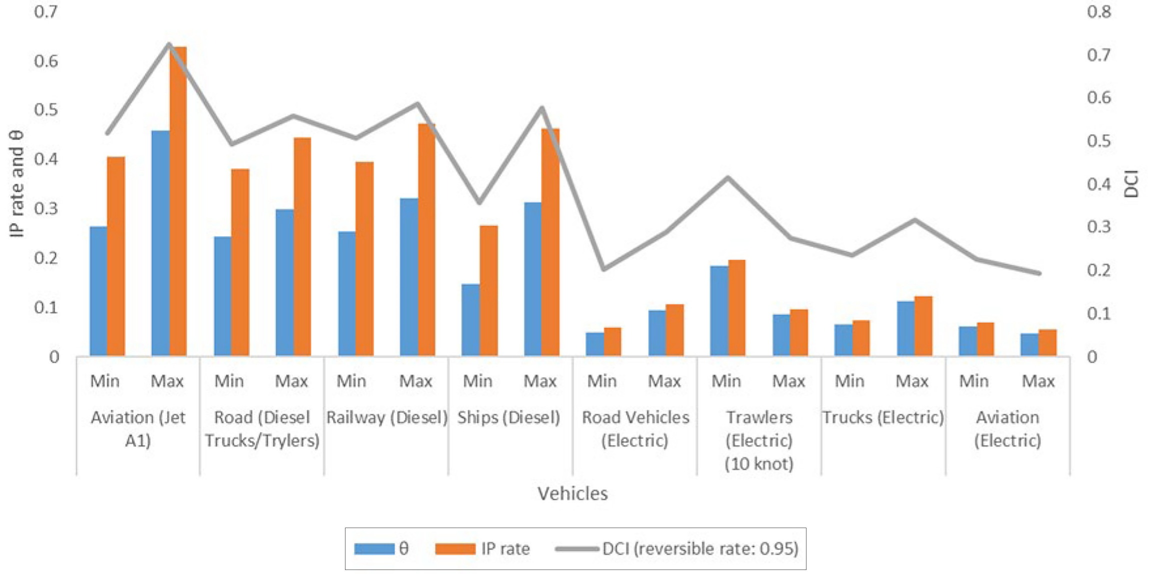
(b) Environmental impact and energy efficiency rate for case 0.95

Source: Developed by the authors

Figure 10 DCI impact per km



(a) DCI impact for 0.85



(b) DCI impact for 0.95

Source: Developed by the authors

In the study, an impact assessment was conducted for the vehicles examined in the decarbonisation process. Based on the km scale, the average DCI for fuel-based vehicles was found to be 0.58. In the case of the aviation sector, the average was found to be 0.66. This value represents the decarbonisation ratio required according to the irreversibility scale. For electric vehicles, this potential was determined to be 0.14 and the aviation rate was found as 0.07. Notably, under 0.85 adiabatic conditions for electric vehicles, a decarbonisation ratio also emerged.

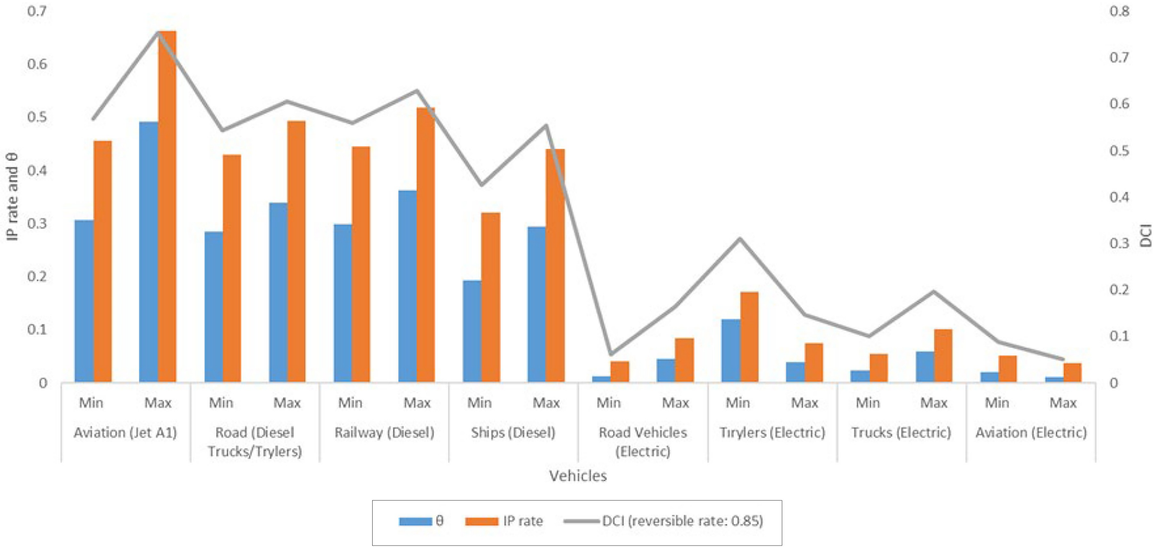
The corresponding decarbonisation ratio for 0.95 adiabatic conditions was found to be 0.25. This result particularly highlights the need to improve efficiency in electric vehicles as well, especially in terms of consumption. In the study, DCI distributions were also examined on the ton-km scale, and the distributions are presented in Figure 11.

In the analysis, it was seen that the lowest DCI potential among electric vehicles, especially for the value of 0.95, is valid for aviation vehicles and gives effective results. Indeed, the decarbonisation values of fossil fuel-consuming vehicles are not sustainable and contain very high values. In this context, strategic solutions that include high-efficiency potentials together with alternative fuel data should be developed for these engines.

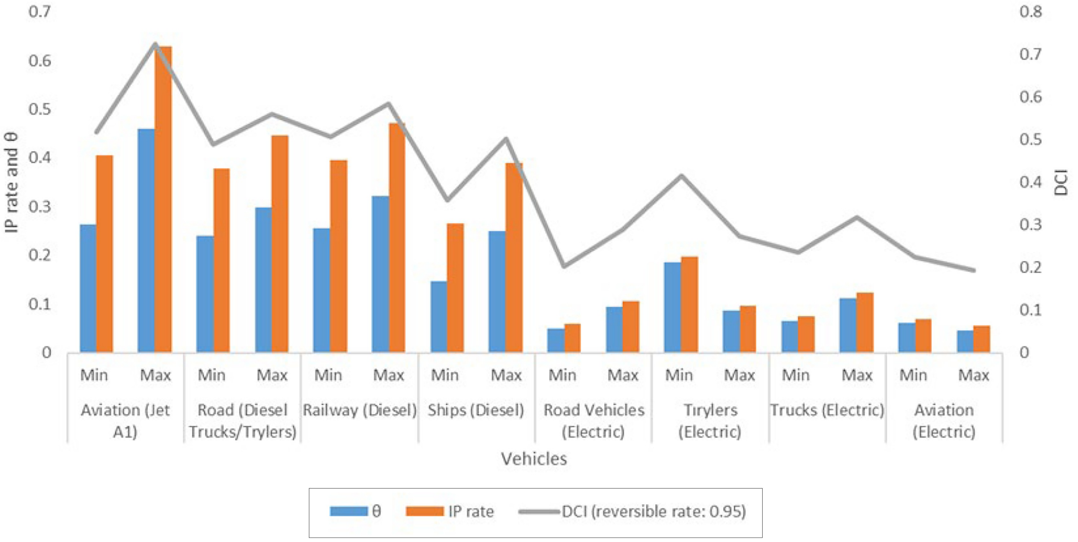
5. Conclusion

This study presents a comparative analysis of aviation and other transportation potentials based on logistic chains,

Figure 11 DCI impact per ton-km



(a) DCI impact for 0.85



(b) DCI impact for 0.95

Source: Developed by the authors

taking into account the boundary conditions. In particular, the study evaluates the performance of aviation in relation to other sectoral choices depending on energy resource preference and comparative decarbonisation potentials are evaluated.

In this context, an approach that assesses energy and environmental sustainability is presented to contribute to the development of decarbonisation strategies in aviation transportation. In particular, considering the decarbonisation processes of transport vehicles supporting the energy transition, the following conclusions have been reached:

- Aviation applications have yielded more efficient results compared to other chain structures in both fossil fuel and electric system preferences.
- While the average energy efficiency in fuel-based vehicles is 32.1% and in electric vehicles it is 62.12%, in aviation these values are 25.51% and 67.2%, respectively.
- Analysis of exergy destruction showed that fossil-fuelled vehicles experience a potential exergy loss of 67.9%, whereas electric vehicles reduce this value to 37.8%.
- The average EPI value for fossil-fuelled vehicles was found to be 0.69, while electric vehicles had an EPI distribution of 0.38. The SI value for fossil-fuelled vehicles was 0.25. Conversely, for electric vehicles under 0.95 adiabatic conditions, the EPI value was 0.31, and the average SI value was 0.05. On the other hand, the EPI value for the aviation sector was found to be 0.72 to 0.25.

- The developed DCI serves as an evaluation framework, with an average DCI of 0.69 for fossil-fuelled vehicles and 0.27 for electric vehicles under 0.85. But, in aviation vehicles these values were found to be 0.66 and 0.21, respectively.
- This finding indicates that the environmental performance of electric vehicles can also be improved. Moreover, under 0.95 adiabatic conditions, the SI value could decrease to 0.66. Under these conditions, the EER for electric vehicles indicates a potential of 9.2%.

The findings of this study provide a framework for the transition to electrification of the transportation sector, with the aviation chain being revealed as an indispensable feature, particularly within the context of the SC. Disregarding the financial implications, it is evident that aviation will emerge as a more efficient and expeditious option for addressing sectoral energy consumption. However, in the course of these transformation processes, the transition to decarbonisation, primarily for aviation and maritime transportation, is seen to have significant efficiency potential for decarbonisation when the defined EER value is taken into account.

This study contributes to the literature by addressing the identified gap in comparative thermodynamic assessment across transport modes and proposes the development of sectoral roadmaps and technology management-focused strategies for the aviation sector. Moreover, the study can be presented in a framework that includes thermo-economic analyses along with entropy cost effects. The study can also provide a different perspective with time series analyses outlining the decarbonisation roadmap for transportation. In future work, the DCI can be extended to account for altitude-dependent conditions in aircraft operations. This would involve calculating entropy generation and exergy destruction at different flight phases. Such an approach would enable the assessment of the DCI as a dynamic metric across the entire flight profile, providing deeper insights into the thermodynamic performance and decarbonisation potential of aircraft systems under realistic operational conditions.

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