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Innovative solutions relating to the net-zero strategies of high-tech companies and manufacturing supply chains: An analysis of the off-highway sector

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Abstract

This thesis examines how net-zero strategies can be translated into operational supply chain actions in the off-highway manufacturing sector. Although corporate climate commitments have increased significantly, their practical implementation remains challenging in industrial contexts characterised by complex products, long life cycles, limited production volumes and fragmented global supplier networks.

The off-highway sector provides a relevant setting for this investigation. Production relies heavily on carbon-intensive materials and upstream industrial processes, resulting in a large share of emissions being concentrated in Scope 3 categories, outside the direct control of original equipment manufacturers (OEMs). Therefore, addressing decarbonisation in this context cannot rely solely on improving internal efficiency, but requires engagement with suppliers and closer coordination along the whole supply chain.

The research adopts a qualitative approach, combining academic literature, institutional and industry reports, and an in-depth case study of Tier1 Bosch Mobility. International frameworks are used as reference points to analyse how net-zero objectives are structured, implemented and monitored. Particular attention is given to the role of materials, production processes, logistics, digital traceability and governance mechanisms in shaping Scope 3 reduction pathways.

The thesis outlines a roadmap to 2030 across three successive timeframes: short-term (2026–2028), medium-term (2028–2030) and long-term (post-2030) horizons. Rather than assuming rapid transformation, it reflects the technical, economic and organisational constraints that shape the off-highway sector and therefore proposes a gradual sequencing of priorities. Indeed, the analysis suggests that progress in this context is unlikely to stem from single breakthrough technologies. Instead, meaningful emission reductions appear to depend on how firms combine material innovation, supplier engagement and governance mechanisms over time.

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1. Introduction

This thesis, entitled “Innovative solutions relating to the net-zero strategies of high-tech companies and manufacturing supply chains”, focuses its analysis on the off-highway sector, as it represents an industrial context in which advanced engineering requirements, low production volumes and highly customized products translate into a strong concentration of emissions along the upstream supply chain.

In this sector, the predominance of material-intensive components and complex manufacturing processes shifts the decarbonization challenge beyond direct operations, making Scope 3 emissions a central strategic issue rather than a marginal extension of corporate climate action. For this reason, the off-highway industry provides a suitable setting to investigate how net-zero strategies must be interpreted and implemented in supply chains characterized by limited direct control and high structural complexity.

1.1 The off-highway sector and its supply chain: context, characteristics and complexity

In the off-highway sector, the design and production of industrial systems are shaped by logics that differ fundamentally from those of traditional automotive manufacturing. These differences arise from the nature of the applications served, the required performance standards, the high degree of product customisation and the structural complexity of the underlying supply chains. Unlike more standardised manufacturing environments, off-highway value chains are characterised by heterogeneous actors, varying production scales and fragmented technological capabilities, which increase coordination requirements and governance challenges (Koberg & Longoni, 2019; Zils et al., 2023).

Compared with the on-road automotive context, typically operating under relatively stable and tightly regulated usage conditions, off-highway machines function in highly variable and often demanding professional environments. These machines are deployed in sectors where operational continuity, durability and reliability are essential, frequently in the absence of controlled environmental conditions. Applications include agriculture — with tractors, combine harvesters and precision farming equipment — construction and earthmoving, intralogistics and material handling, as well as specialised domains such as forestry, mining and high-criticality industrial vehicles, including airport ground support equipment, firefighting vehicles and specialised lifting platforms (Shekarian et al., 2023).

The diversity of these application contexts renders the off-highway sector inherently interdisciplinary. Each machine results from the integration of heterogeneous engineering competences, spanning heavy mechanical systems, hydraulic power technologies, advanced mechatronics, embedded control systems and digital solutions supporting performance optimisation, operational monitoring and predictive maintenance. The increasing incorporation of Industry 4.0 and digital supply chain technologies further reinforces this technological convergence, while simultaneously adding layers of organisational and informational complexity (Ma et al., 2024; Shen et al., 2026; Zaoui et al., 2026). This convergence of technological domains contributes to the sector's structural complexity and underlines its strategic importance within modern industrial economies.

The combination of stringent robustness requirements, strong product customisation and the integration of complex subsystems leads at the same time to high material intensity and production processes associated with substantial embedded energy. Off-highway equipment relies extensively on carbon-intensive materials such as steel and aluminium, whose upstream production processes remain among the most emission-intensive segments of heavy industry (Arens et al., 2021; Material Economics, 2019; IEA, 2022). As a consequence, a significant share of the overall carbon footprint of off-highway machines is generated in upstream supply chain stages and falls predominantly within Scope 3 emissions, as defined by the GHG Protocol (GHG Protocol, 2011; Borchardt et al., 2025).

This structural configuration has direct implications for decarbonisation strategies. Emission reduction efforts cannot be confined to improvements in direct operations (Scope 1) or purchased energy (Scope 2), but must address the embedded emissions associated with materials, components and upstream production processes. In the off-highway context, supply chain decarbonisation therefore becomes a central strategic challenge, closely intertwined with procurement decisions, product design choices and long-term supplier relationships (Zhang et al., 2022; Both & Wilhelm, 2025).

Table 1. Structural characteristics of the off-highway sector

Characteristic	Description	Implications for decarbonisation
High material intensity	Extensive use of steel and aluminium	High embedded emissions
Product customisation	Large number of configurations	Limited standardisation of low-carbon solutions
Long product life cycles	Machines often operate 10–20 years	Lifecycle emissions become critical
Complex supply chains	Multi-tier global supplier networks	Scope 3 emissions dominate

1.1.1 Severe operating conditions and design implications

As noted above, machines used in off-highway applications are required to deliver high performance in environments characterised by significant variability and, frequently, harsh physical conditions. During outdoor operation, they are continuously exposed to dust, mud, sand, humidity and, in some cases, saline water. These environmental stressors necessitate the use of dedicated sealing systems, protective surface treatments and corrosion-resistant materials, increasing both material complexity and manufacturing requirements (IEA, 2022; Shekarian et al., 2023). In addition, intense vibrations and mechanical shocks — typical, for example, of mining operations, excavation sites or heavy construction activities — demand structures and components capable of withstanding sustained mechanical stress without premature degradation. Such operating conditions directly affect system architecture, component sizing and material selection.

Extreme conditions also include substantial thermal fluctuations. Very high or very low temperatures may alter the viscosity of hydraulic fluids, influence the mechanical performance of structural materials and affect the reliability of sensors and electronic control units. Moreover, operating cycles in off-highway machinery are generally longer and more load-intensive than in conventional on-road automotive applications. They are often characterised by sustained high loads and repeated power peaks occurring hundreds or even thousands of times within a single working day. These features impose stringent durability and fatigue resistance requirements at both component and system level.

The design implications of these operating conditions are significant. From a managerial and supply chain perspective, they frequently lead to systematic oversizing of critical components, the adoption of high-strength alloys and the use of materials whose production processes are energy-intensive and carbon-intensive. In sectors where steel and aluminium remain dominant structural inputs, this has direct consequences for embedded emissions upstream in the value chain (Arens et al., 2021; Material Economics, 2019; IEA, 2022). As a result, a substantial share of the emissions associated with off-highway equipment is concentrated within Scope 3, particularly in categories related to purchased goods and services (GHG Protocol, 2011; Borchardt et al., 2025; World Economic Forum & Boston Consulting Group, 2021).

To meet operational reliability requirements, off-highway machine components are typically engineered with safety factors above those commonly observed in traditional automotive manufacturing. This approach ensures resistance to repeated mechanical stress, fatigue and accelerated wear, but also increases material use and embedded energy per unit of output. Materials are selected for specific mechanical, thermal and metallurgical properties, with priority given to durability and long-term stability under demanding application conditions. Overall system optimisation therefore depends on careful coordination among mechanical subsystems, hydraulic systems, powertrains and electronic control architectures, in order to avoid functional trade-offs that could compromise reliability or safety.

Within this framework, diagnostics and control software assume a central role. Digital monitoring systems, predictive maintenance solutions and advanced control architectures contribute to maintaining operational continuity and reducing the probability of unexpected failures (Ma et al., 2024; Shen et al., 2026; Zaoui et al., 2026). In sectors such as construction and agriculture, where equipment downtime can generate substantial economic losses, the capacity to anticipate anomalies and minimise unplanned interruptions becomes a strategic design objective rather than a secondary feature.

The level of robustness required in the off-highway sector is generally higher than in traditional automotive manufacturing. This is compounded by particularly long expected service lives — often exceeding ten years and, in many cases, extending to twenty — combined with intensive duty cycles that impose demanding quality and durability standards (Shekarian et al., 2023). The combination of long lifetimes, high structural requirements and material intensity reinforces the structural relevance of upstream emissions within the total carbon footprint of off-highway systems (Arens et al., 2021; Borchardt et al., 2025).

1.1.2 Multi-level structure of the off-highway supply chain

Within this context, the off-highway supply chain is characterised by a historically complex and highly articulated structure, in which the different production tiers are closely interconnected. This complexity stems not only from the technological nature of the products, but also from the geographical fragmentation of suppliers and the need to coordinate diverse competences across the entire production cycle (Koberg & Longoni, 2019; Gereffi, 2018). In global value chains characterised by high asset specificity and differentiated technological capabilities, coordination mechanisms and governance structures play a decisive role in shaping performance outcomes.

Analysing the value chain through a tiered structure — including OEMs, Tier-1, Tier-2 and Tier-3 suppliers, as well as material producers — makes it possible to identify more clearly where critical capabilities are concentrated and where the most significant environmental impacts arise. Research on supply chain sustainability highlights how environmental burdens are often distributed unevenly across tiers, with upstream actors — particularly material producers and specialised component suppliers — accounting for a disproportionate share of embedded emissions (GHG Protocol, 2011; Borchardt et al., 2025; World Economic Forum & Boston Consulting Group, 2021).

This multi-level perspective, further examined in the following sections, helps clarify which actors play a decisive role in determining the final performance of off-highway machines and which segments account for the largest share of the sector's carbon footprint. In complex industrial supply chains, such as those characterising heavy vehicle and equipment manufacturing, sustainability outcomes depend not only on the focal firm but on the orchestration, capacity exercised across tiers (Shekarian et al., 2023; Shen et al., 2026). Understanding the distribution of technical capabilities, bargaining power and emission intensity across supply chain levels is therefore a prerequisite for designing credible Scope 3 decarbonisation strategies.

The multi-tier structure of the off-highway supply chain is summarised in Figure 1, highlighting the main actors involved and their relative position within the value chain.

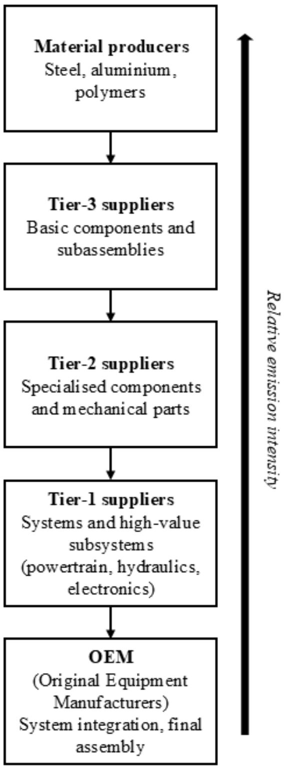


Figure 1. Multi-tier structure of the off-highway supply chain

1.1.1.1 OEM (Original Equipment Manufacturers)

OEMs sit at the apex of the off-highway value chain and play a central role in defining the technical, functional and performance characteristics of the final machines. Their activities range from the design and engineering of the entire product to the definition of the overall technical architecture, encompassing mechanical components, electronic systems, hydraulic subsystems and control software (Shekarian et al., 2023). In heavy equipment industries, OEMs typically assume responsibility for systems integration and architectural coordination across heterogeneous technological domains.

In addition, OEMs are responsible for integrating the systems supplied by Tier-1 providers, ensuring that all subsystems operate in a coordinated and coherent manner in line with design specifications. This is followed by final assembly and product validation through functional, durability and safety testing. Such integrative responsibilities are characteristic of focal firms in complex global value chains, where governance structures shape coordination intensity and capability distribution (Gereffi, 2018).

Once the machines are placed on the market, OEMs also manage the commercial network and, in most cases, after-sales services and maintenance activities, thereby safeguarding product quality throughout the entire life cycle. The long service life typical of off-highway equipment reinforces the strategic relevance of lifecycle-oriented management and durability considerations (Poschmann et al., 2023).

Taken together, these responsibilities require OEMs to balance multiple and often competing objectives: high operational performance, compliance with safety regulations, energy efficiency, reliability under extreme operating conditions and, increasingly, the integration of sustainability criteria and the reduction of life-cycle emissions (McKinsey & Company, 2021; IEA, 2022). In hard-to-abate industrial sectors, such trade-offs are structural rather than temporary, requiring explicit prioritisation and long-term planning.

From a net-zero perspective, the role of OEMs becomes even more significant. Positioned at the centre of the value chain, they possess concrete levers to influence sustainability choices across the supply base. In particular, OEMs define ESG requirements for suppliers and increasingly request detailed Life Cycle Assessment data on components and materials, in line with the growing emphasis on Scope 3 transparency under international reporting frameworks (GHG Protocol, 2011; Science Based Targets initiative, 2021). Through procurement policies, they can encourage the uptake of lower-carbon solutions by favouring suppliers that invest in recycled materials, low-emission production processes or innovative decarbonisation technologies (World Economic Forum & Boston Consulting Group, 2021).

Nevertheless, this steering capacity should not be equated with direct control over the entire supply chain. OEM influence is largely indirect at more upstream levels, especially with regard to Tier-2 and Tier-3 suppliers. As highlighted in the literature on supply chain sustainability governance, power asymmetries and capability gaps often constrain the effectiveness of unilateral requirements (Bag et al., 2024; Both & Wilhelm, 2025). As a result, reducing Scope 3 emissions cannot rely solely on the imposition of formal requirements, but requires the development of supply chain governance mechanisms based on collaboration, transparency and the gradual alignment of objectives among the actors involved (Koberg & Longoni, 2019; Shen et al., 2026).

In this respect, OEMs not only respond to regulatory and market pressures, but also act as key drivers in shaping the environmental transition of the off-highway sector. Their orchestration capacity — exercised through procurement, design decisions and long-term supplier relationships — becomes central to the credibility and feasibility of sectoral net-zero pathways.

1.1.2.2 Tier-1 suppliers

Tier-1 suppliers constitute the technological core of the off-highway supply chain and, alongside OEMs, play a decisive role in shaping the comprehensive performance of the machines. They are responsible for delivering complex, high value-added systems whose quality and level of innovation directly affect the functionality, efficiency and reliability of the final product (Shekarian et al., 2023). In complex capital goods industries, Tier-1 firms frequently operate as system integrators of subsystems, combining specialised competences with deep engineering expertise.

At this tier of the value chain, many of the key technologies that define the sector are concentrated, including:

- Powertrain systems (latest-generation diesel engines, electrified systems, hybrid solutions and fuel cell applications).
- Mechanical and automatic transmissions, essential for managing power and torque under extreme operating conditions.
- Hydraulic power systems, such as pumps, valves, actuators and cylinders, which represent one of the distinctive features of off-highway machines.
- Electronic control units (ECUs), responsible for managing operating parameters and supervising electronic components.
- ADAS systems and advanced automation solutions, including remote-control or semi-autonomous functionalities.
- Embedded software, energy management platforms and telematics systems, which are crucial for optimising performance and enabling predictive maintenance.

The increasing integration of digital technologies and intelligent manufacturing solutions further reinforces the technological centrality of Tier-1 suppliers within the supply chain architecture (Ma et al., 2024; Zaoui et al., 2026). In this context, technological innovation at Tier-1 level does not only affect performance metrics, but also reshapes data flows, interoperability requirements and lifecycle management practices across the value chain.

Owing to their specialisation and concentration of advanced engineering capabilities, Tier-1 suppliers play a pivotal role in developing the technologies that characterise the off-highway sector. In many cases, they hold patents, proprietary know-how and technological solutions that significantly influence not only machine performance but also energy efficiency and general environmental impact. In global value chain terms, they often occupy strategically significant positions within modular or relational governance structures, shaping innovation trajectories and technological standards (Gereffi, 2018).

From a net-zero perspective, their position within the value chain places Tier-1 suppliers among the actors with the greatest capacity to influence the decarbonisation trajectory of the final product. They can introduce enabling technologies upstream in the supply chain — such as electrified powertrains, high-efficiency hydraulic systems or innovative lightweight and low-carbon materials — thereby substantially altering the emissions profile of the finished machine (Arens et al., 2021; Material Economics, 2019). In parallel, they can act on their own production processes, reducing energy consumption and direct emissions, while contributing to improving life-cycle efficiency and operational performance. Such technological shifts are widely recognised as critical enablers of supply chain decarbonisation in capital-intensive industries (McKinsey & Company, 2021; Zhang et al., 2022).

However, the effectiveness of these contributions depends not only on technological availability, but also on coordination mechanisms with OEMs and upstream suppliers. The diffusion of low-carbon technologies across tiers requires alignment of investment horizons, data transparency and collaborative governance arrangements, particularly when Scope 3 emissions are structurally embedded in purchased goods and services (GHG Protocol, 2011; Koberg & Longoni, 2019; Borchardt et al., 2025).

1.1.2.3 Tier-2 and Tier-3 suppliers

The Tier-2 and Tier-3 levels of the off-highway supply chain comprise a broad and highly heterogeneous set of specialised manufacturers, each contributing in an essential way to the systems subsequently integrated by Tier-1 suppliers. Activities at these tiers span a wide range of operations, from precision mechanical manufacturing — including components such as gears, shafts, bearings and flanges — to electronic production, covering printed circuit boards (PCBs), wiring systems, sensors and other critical elements.

These activities are complemented by material processing through energy-intensive thermal and mechanical treatments, as well as the production of semi-finished goods destined for subsequent stages of the value chain. Owing to the nature of these processes and the overall scale of operations involved, Tier-2 and Tier-3 suppliers play a particularly significant role in the sector’s decarbonisation strategies. They represent the primary source of Scope 3 emissions for Tier-1 suppliers and, by cascade effect, for OEMs, since upstream purchased goods and services typically account for the largest share of corporate carbon footprints in industrial supply chains (GHG Protocol, 2011; Hettler et al., 2024).

A substantial share of the total carbon footprint associated with the production of an off-highway machine originates precisely at these levels, where the use of carbon-intensive materials, complex thermal processes and energy-intensive machinery contributes to elevated emissions. In heavy industry value chains, steel, aluminium and other basic materials remain structurally dominant inputs, and their upstream production processes are among the most emission-intensive segments of the industrial economy (Arens et al., 2021; Material Economics, 2019).

The situation is further complicated by the fact that many of these suppliers are small- and medium-sized enterprises, often focused on highly specialised and niche production capabilities. While such specialisation is crucial for the quality and reliability of the final product, it may also imply more limited economic, technological and organisational resources available for targeted decarbonisation investments. Empirical studies on sustainable supply chains in heavy vehicle and equipment industries highlight that smaller suppliers frequently face structural constraints in adopting advanced environmental practices, particularly in relation to data availability, capital access and technical expertise (Shekarian et al., 2023; Borchardt et al., 2025).

As a result, one of the main bottlenecks in the sector’s net-zero transition emerges at this stage of the supply chain: a segment that is critical from an emissions perspective yet often characterised by fragmented governance structures and limited direct influence from downstream actors. The literature on sustainable supply chain management emphasises that, in multi-tier contexts, emission reduction cannot be achieved solely through contractual requirements but requires relational governance mechanisms, knowledge transfer and capability development across tiers (Koberg & Longoni, 2019; Both & Wilhelm, 2025).

Concurrently, precisely because of their central contribution to upstream emissions, Tier-2 and Tier-3 suppliers represent a potentially powerful leverage point for supply chain decarbonisation. When supported by appropriate measures — such as capacity-building initiatives, improved access to primary emissions data and economic incentive mechanisms — these actors have the potential to contribute substantially to reducing emissions across the supply chain (Hettler et al., 2024).

Further upstream lies the level of material producers, which forms the most upstream layer of the value chain and accounts for the largest absolute share of emissions in material-intensive industries.

1.1.2.4 Materials producers

Material producers form the most upstream layer of the off-highway supply chain and are characterised by production processes with extremely high energy intensity. This level includes, among others, steel mills, aluminium smelters, producers of polymers and advanced composite materials, as well as companies specialised in the manufacture of technical rubber used in numerous mechanical components and sealing systems. The intrinsic nature of the metallurgical and chemical processes involved makes these industries one of the principal sources of emissions across the entire value chain, contributing substantially to the sector's overall carbon footprint (Material Economics, 2019).

Steel production, for instance, is associated with significant direct and indirect emission levels due to the continued predominance of blast furnace–basic oxygen furnace routes in many regions. The impact is even more pronounced in the case of primary aluminium, owing to the high electricity demand of electrolytic smelting processes and the carbon intensity of electricity mixes in several producing countries (Arens et al., 2021; IEA, 2022). These structural characteristics position basic material industries among the most challenging segments in the transition towards net zero, particularly in hard-to-abate sectors dependent on high-temperature processes and fossil-based inputs (Material Economics, 2019; World Economic Forum & Boston Consulting Group, 2021).

In the off-highway sector, the relevance of these upstream emissions is particularly marked. Machines rely extensively on structural steel, specialised cast irons and large metal components, which are essential to ensure robustness, reliability and long service life under severe operating conditions. The high material intensity required to meet durability and safety standards directly links the environmental performance of final equipment to the decarbonisation pathways available in upstream heavy industry (Arens et al., 2021).

The contribution of these upstream processes to the comprehensive environmental impact of the supply chain will be examined in greater detail in the section dedicated to the analysis of emissions along the value chain, where the concentration of Scope 3 emissions in purchased goods and basic materials is further explored in relation to governance and procurement strategies (GHG Protocol, 2011; Hettler et al., 2024).

The different roles and decarbonisation influence of supply chain actors are summarised in Table 2.

Table 2. Roles and decarbonisation influence across supply chain tiers

Supply chain actor	Main activities	Role in decarbonisation
OEM	Product design, system integration, final assembly	Define sustainability requirements and procurement criteria
Tier-1 suppliers	Development of complex subsystems	Introduce low-carbon technologies and innovations
Tier-2 / Tier-3 suppliers	Component manufacturing	Major contributors to Scope 3 emissions
Material producers	Production of steel, aluminium and polymers	Highest emission intensity in the value chain

1.1.3 Structural characteristics of the supply chain

The supply chain in the off-highway sector displays a number of features that distinguish it markedly from that of traditional automotive. These characteristics stem both from the highly specialised nature of the machines and from the way production is organised at global level. The main distinguishing elements are outlined below.

1.1.3.1 Globalisation

As noted earlier, one of the most visible features of the off-highway supply chain is its wide geographical dispersion.

The sector is embedded within global value chains in which production stages are distributed across multiple regions according to cost structures, technological specialisation and market proximity (Gereffi, 2018). Many mechanical components and raw materials are sourced from Eastern Europe, China, India or other parts of South-East Asia. Energy-intensive processing activities are frequently located in regions where energy costs are comparatively lower, while OEMs typically operate assembly plants in several geographical areas in order to serve local markets more effectively and reduce logistics lead times (McKinsey & Company, 2021).

The physical distance between actors in the value chain significantly complicates the management of Scope 3 emissions. Geographic fragmentation makes it more difficult to trace upstream emission flows accurately, to apply consistent methodologies for calculating the carbon footprint of components and, above all, to monitor the sustainability performance of second- and third-tier suppliers in a systematic manner. The challenges associated with data availability, comparability and verification are widely recognised in the Scope 3 accounting literature (GHG Protocol, 2011; Hettler et al., 2024).

Moreover, differences in regulatory frameworks, energy mixes and reporting maturity across countries contribute to considerable heterogeneity in environmental performance among supply chain actors. In globalised industrial supply chains, transparency gaps and uneven decarbonisation trajectories tend to persist unless supported by coordinated governance mechanisms and standardised reporting practices (World Economic Forum & Boston Consulting Group, 2021).

1.1.3.2 Product customisation and production variety

A further distinctive feature of the off-highway sector is the high degree of product customisation. Unlike automotive manufacturing, where production is typically organised around high volumes and standardised platforms, off-highway production is characterised by lower volumes, higher configuration variability and a stronger orientation towards application-specific requirements (Shekarian et al., 2023; Zils et al., 2023).

Machines are frequently configured in a modular manner in order to accommodate heterogeneous operational needs. Requirements vary not only according to functional application — for example agriculture, construction or mining — but also across geographical markets, environmental conditions and local regulatory frameworks. As a result, product architectures must allow for multiple combinations of subsystems, powertrains and control solutions within the same machine family.

This production logic results in comparatively smaller batch sizes than those observed in the automotive sector, combined with a very large number of possible configurations. The structural variability inherent in such systems limits the full exploitation of economies of scale and increases coordination requirements along the supply chain (Koberg & Longoni, 2019; Shekarian et al., 2023).

From a decarbonisation perspective, high product variety complicates the standardisation and diffusion of low-carbon solutions. Each configuration may require specific materials, components or manufacturing processes, thereby reducing the feasibility of uniform substitution strategies or rapid technological roll-out across the entire product portfolio (McKinsey & Company, 2021).

1.1.3.3 Demand volatility

The off-highway sector is characterised by highly cyclical demand, shaped by macroeconomic and sector-specific dynamics that are inherently variable. Demand for machinery is closely linked to public infrastructure investment, developments in agricultural markets — influenced by seasonality, climate variability and commodity prices — and fluctuations in construction, mining and heavy industry activity (IEA, 2022; McKinsey & Company, 2023).

This structural exposure to economic cycles generates significant variability in order intake and production volumes. Compared with more stable, high-volume industries, such volatility complicates long-term capacity planning and increases uncertainty in capital allocation decisions. In the context of decarbonisation, this uncertainty may constrain investments in low-carbon technologies, production process upgrades or long-term supplier development programmes, particularly where such investments require multi-year amortisation horizons (McKinsey & Company, 2023; World Economic Forum & Boston Consulting Group, 2021).

Demand fluctuations also affect supply chain coordination. Tier-1 and Tier-2 suppliers may experience abrupt volume increases or sharp contractions, with consequences for capacity utilisation, inventory management and upstream procurement planning. In complex, multi-tier supply chains, such instability can amplify coordination challenges and increase sustainability risks, especially when environmental requirements are introduced without sufficient alignment across tiers (Wilhelm et al., 2021; Both & Wilhelm, 2025).

Overall, demand volatility reinforces the structural tension between short-term operational responsiveness and long-term sustainability investment, adding another layer of complexity to Scope 3 emission management in the off-highway context.

1.1.3.4 Technological complexity

The increasing integration of digital technologies — including IoT architectures, advanced telematics platforms and predictive maintenance systems — introduces an additional layer of technological and organisational complexity into off-highway products. These technologies require the integration of mechanical engineering, embedded electronics, data analytics and software development capabilities, thereby reinforcing the interdisciplinary nature of the sector (Ma et al., 2024; Zaoui et al., 2026).

This evolution is further amplified by the gradual diffusion of automation and operator-assistance systems, which are reshaping how machines are deployed in construction, agriculture and mining environments. Electrified powertrains, advanced control systems and digital monitoring solutions alter not only product architecture but also supplier configurations and knowledge requirements along the value chain (McKinsey & Company, 2021; Shen et al., 2026).

Each technological subsystem must be designed, manufactured and integrated coherently within the machine architecture. This process involves a broad set of specialised suppliers and increases the number of interfaces that must be managed across the supply chain. As a consequence, technological interdependencies intensify, coordination requirements expand and governance challenges become more pronounced. In the context of net-zero transition strategies, this complexity has direct implications: decarbonisation initiatives must be aligned with evolving digital and technological trajectories, rather than treated as isolated interventions (Zaoui et al., 2026).

1.1.4 Environmental impact along the supply chain

Analyses conducted by the World Economic Forum and Boston Consulting Group (2021), together with guidance provided by the GHG Protocol, highlight a particularly significant pattern for understanding emission dynamics in mechanical industries and industrial mobility: the majority of product-related emissions are typically generated upstream in the supply chain and fall within Scope 3, particularly Category 1 (purchased goods and services) (World Economic Forum & Boston Consulting Group, 2021; GHG Protocol, 2011). While the exact percentage varies depending on system boundaries, product architecture and the degree of vertical integration, the structural predominance of upstream emissions in complex industrial value chains is consistently observed.

In practical terms, this implies that most emissions do not originate from the direct operations of OEMs, but from earlier stages of the value chain — including raw material extraction and processing, primary material production, component manufacturing and international logistics. For heavy industrial systems, upstream material production often represents the single largest emission hotspot.

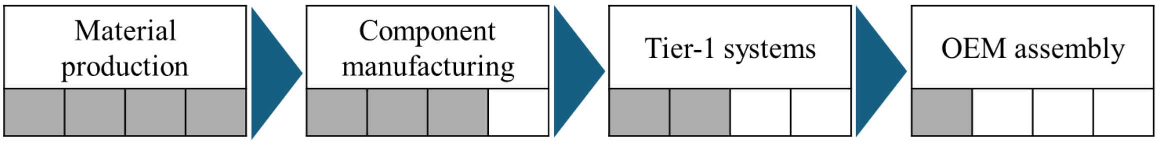
Within the off-highway sector, this pattern is particularly pronounced. Machines rely extensively on structural steel, cast iron and aluminium, materials that are intrinsically carbon-intensive in their primary production phases. Steelmaking and primary aluminium production remain among the most emission-intensive industrial processes globally, due to the use of fossil-based reduction routes and electricity-intensive electrolysis (Arens et al., 2021; Material Economics, 2019).

The downstream transformation processes required to convert these materials into high-performance components — including casting, forging, extrusion, heat treatment and large-scale machining — further add to embodied emissions, as they involve substantial energy consumption (IEA, 2022). In addition, the physical characteristics of off-highway components — often large, heavy and bulky — necessitate complex logistics chains. Maritime transport and heavy road freight contribute additional emissions, particularly in globally dispersed supply networks (McKinsey & Company, 2024).

Upstream impacts are further amplified by the precision and durability requirements typical of the sector. Components are frequently manufactured with tight tolerances and high safety margins, increasing material input per unit of output and therefore embodied energy. Moreover, the deeply globalised and multi-tier structure of the supply chain complicates emissions tracing beyond Tier-1 suppliers, reinforcing information asymmetries and measurement challenges (GHG Protocol, 2011).

Taken together, these characteristics indicate that the off-highway sector is structurally predisposed to a carbon footprint that is largely generated upstream. Consequently, any credible decarbonisation pathway cannot be confined to improvements in direct operations (Scope 1) or purchased energy (Scope 2). It must instead address material choices, supplier practices and early-stage production processes, where the bulk of emissions is embedded and where strategic procurement and supply chain governance become central levers of transition (World Economic Forum & Boston Consulting Group, 2021).

Figure 2 shows the conceptual distribution of emissions across the off-highway supply chain, while highlighting the predominance of upstream Scope 3 emissions.



Scope 3 emissions dominate upstream stages

Figure 2. Conceptual distribution of emissions across the off-highway supply chain

1.2 Regulatory pressures and global decarbonisation targets

The need to decarbonise the off-highway supply chain does not stem solely from companies' voluntary commitment to sustainability or from competitive positioning considerations. It is increasingly driven by a regulatory landscape that has become progressively more structured and demanding at both international and regional levels. Governments, supranational institutions and multilateral organisations are defining climate targets, disclosure obligations and policy instruments that require structural adjustments across industrial value chains, directly affecting production models, sourcing strategies and governance systems.

In this context, decarbonisation is no longer framed exclusively as a strategic option, but as a response to evolving institutional expectations and regulatory frameworks. For sectors characterised by material intensity and complex supply chains, such as off-highway manufacturing, these pressures extend beyond direct operations and increasingly encompass upstream emissions embedded in purchased goods and services (GHG Protocol, 2011).

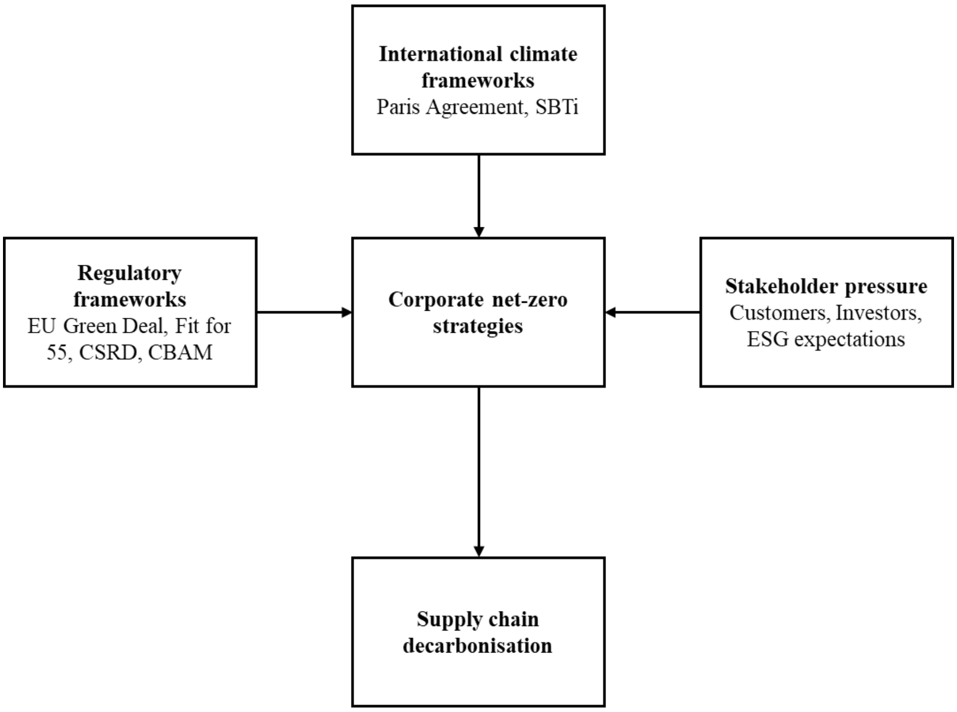


Figure 3. Main drivers of decarbonisation in the off-highway supply chain

1.2.1 Global framework: regulations and international agreements

At global level, the principal reference point is the Paris Agreement, adopted under the United Nations Framework Convention on Climate Change (UNFCCC, 2015). The Agreement establishes the overarching framework within which national and regional climate policies are subsequently developed. It sets the objective of limiting global temperature increase to well below 2°C above pre-industrial levels, while pursuing efforts to limit it to 1.5°C, thereby requiring rapid and sustained reductions in greenhouse gas emissions and the progressive achievement of climate neutrality over the medium to long term (UNFCCC, 2015).

Although the Paris Agreement does not impose direct obligations on individual companies, it has reshaped the regulatory and policy environment within which industrial actors operate. The translation of national commitments into sectoral decarbonisation strategies has intensified scrutiny on energy- and material-intensive industries, including heavy manufacturing and machinery production (IEA, 2022). For the off-highway sector, this implies a reassessment of production processes, material choices and sourcing models in light of long-term decarbonisation trajectories.

Within this broader framework, voluntary but widely recognised international standards have gained prominence, particularly the Corporate Net-Zero Standard developed by the Science Based Targets initiative (Science Based Targets initiative, 2021). This framework provides methodological guidance for setting science-based emission reduction targets aligned with 1.5°C pathways. It requires companies to quantify and report Scope 1, Scope 2 and Scope 3 emissions; to establish time-bound reduction targets; and to adopt credible action plans covering the entire value chain.

For sectors characterised by long and multi-tier supply chains, such as off-highway manufacturing, alignment with science-based targets implies extending decarbonisation efforts beyond direct suppliers. Upstream engagement becomes necessary, especially where Tier-2 and Tier-3 suppliers account for a substantial share of embedded emissions (World Economic Forum & Boston Consulting Group, 2021). This shift reinforces the strategic importance of supply chain governance mechanisms capable of influencing actors over which OEMs do not exercise direct hierarchical control.

1.2.2 European regulatory pressures

The European Union represents one of the most advanced and stringent regulatory environments with regard to industrial decarbonisation. Over recent years, the EU has introduced a comprehensive policy architecture aimed at aligning economic activity with long-term climate neutrality objectives. These initiatives combine binding emission reduction targets, reporting obligations, financial incentives and market-based mechanisms, thereby exerting structural pressure on energy- and material-intensive industries (European Commission, 2021).

For sectors such as off-highway manufacturing, which depend heavily on carbon-intensive materials and complex supply chains, European regulatory developments affect not only direct operations but also sourcing strategies, supplier relationships and data governance practices.

1.2.2.1 Fit for 55 and the European Green Deal

The Fit for 55 package forms part of the broader European Green Deal and operationalises the EU's legally binding target of reducing net greenhouse gas emissions by at least 55% by 2030 compared with 1990 levels (European Commission, 2021). Rather than constituting a single legislative act, Fit for 55 is a comprehensive set of policy measures revising existing climate and energy legislation.

The package includes strengthened provisions under the EU Emissions Trading System (EU ETS), more ambitious energy efficiency and renewable energy targets, and regulatory measures designed to accelerate industrial decarbonisation. These measures directly affect manufacturing companies by tightening emission constraints, encouraging process electrification and promoting the integration of renewable energy sources into industrial operations (European Commission, 2021).

For actors across the off-highway supply chain, this policy framework requires a reassessment of the entire production cycle. Material selection, plant energy management and process technologies must increasingly be evaluated not only on cost and performance criteria, but also on their carbon intensity and long-term regulatory exposure.

1.2.2.2 CSRD – Corporate Sustainability Reporting Directive

The Corporate Sustainability Reporting Directive (CSRD) aims to expand and harmonise sustainability reporting obligations for companies operating within the European Union (European Commission, 2023). Compared with the previous Non-Financial Reporting Directive, the CSRD broadens the scope of companies subject to reporting requirements and introduces more detailed and standardised disclosure obligations.

Under the CSRD framework, companies are required to provide comprehensive information on environmental, social and governance (ESG) matters, including material climate-related risks and impacts. Crucially, this includes systematic disclosure of Scope 1, Scope 2 and Scope 3 emissions in accordance with recognised standards, as well as alignment with the European Sustainability Reporting Standards (ESRS) (European Commission, 2023; GHG Protocol, 2011).

For the off-highway supply chain, these requirements have direct operational implications. OEMs and Tier-1 suppliers must obtain more accurate and structured emissions data from their upstream partners in order to ensure compliance. This increases the importance of traceability systems, standardised data collection processes and robust governance mechanisms for emissions reporting. The regulatory obligation thus reinforces the strategic relevance of supply chain transparency and supplier engagement.

1.2.2.3 CBAM – Carbon Border Adjustment Mechanism

The Carbon Border Adjustment Mechanism (CBAM) introduces a carbon pricing mechanism on embedded emissions in selected goods imported into the European Union from jurisdictions with less stringent climate policies. After an initial transitional phase focused on reporting, CBAM will become fully operational from 1 January 2026 (European Commission, 2021).

The mechanism initially covers carbon-intensive sectors such as steel, aluminium, cement, fertilisers, electricity and hydrogen. Importers will be required to purchase CBAM certificates corresponding to the embedded emissions of these products, thereby reducing the risk of carbon leakage and creating a more level playing field between EU and non-EU producers.

For the off-highway sector, CBAM represents a structural shift. A substantial share of the steel and aluminium used in frames, structural components and heavy-duty subsystems may originate from non-EU markets. As carbon costs are progressively internalised, the economic attractiveness of high-emission materials is likely to decline. This strengthens the business case for sourcing lower-carbon steel and aluminium, recycled inputs or materials produced using decarbonised processes (European Commission, 2021; Arens et al., 2021).

Over time, CBAM is expected to influence procurement strategies and supplier selection criteria, reinforcing the integration of carbon considerations into sourcing decisions across the value chain.

Table 3. Key regulatory and institutional frameworks influencing industrial decarbonisation

Framework / Policy	**Scope**	**Main objective**	**Implications for companies**
Paris Agreement	Global	Limit global warming to 1.5–2°C	Long-term decarbonisation pathways
SBTi Net-Zero Standard	Global	Science-based emission targets	Full value-chain emissions reduction
EU Green Deal / Fit for 55	European Union	Reduce emissions by 55% by 2030	Industrial decarbonisation and energy transition
CSRD	European Union	Mandatory sustainability reporting	Increased transparency on Scope 1–3 emissions
CBAM	European Union	Carbon pricing on imports	Incentives for low-carbon materials

1.2.3 Stakeholder pressures

Beyond the regulatory landscape, the off-highway sector is facing mounting pressure from a wide range of stakeholders who increasingly shape corporate decision-making.

Industrial customers — particularly large OEMs and system integrators — are progressively demanding products with a lower carbon footprint and are embedding sustainability criteria into tendering procedures and supplier evaluation processes. In practice, this translates into requests for life-cycle emissions data, science-based targets and documented reduction pathways across Scope 1, Scope 2 and Scope 3 categories (GHG Protocol, 2011).

Institutional investors are placing growing emphasis on climate-related financial risk and transition exposure. ESG ratings, climate scenario analyses and alignment with net-zero trajectories are increasingly used as indicators of long-term robustness and strategic resilience (McKinsey & Company, 2023). Companies perceived as lagging in decarbonisation efforts may face higher capital costs or reduced access to sustainable finance instruments.

Environmental non-governmental organisations and civil society actors are also exerting greater scrutiny, calling for enhanced transparency in emissions reporting and for credible, verifiable transition plans (World Economic Forum & Boston Consulting Group, 2021). This scrutiny is amplified by evolving reporting standards and by the broader public debate on industrial responsibility in climate mitigation.

In parallel, end users — particularly in agriculture, construction and infrastructure — are showing increasing sensitivity to environmental performance. While total cost of ownership remains a primary decision criterion, efficiency improvements, fuel savings and lower-emission solutions are gradually gaining strategic relevance, especially in markets exposed to carbon pricing mechanisms or sustainability-driven public procurement frameworks (McKinsey & Company, 2021; McKinsey & Company, 2023).

The combined effect of regulatory, financial and societal pressures makes a passive or reactive approach to decarbonisation increasingly untenable for companies operating in the off-highway sector. Under these conditions, embedding emissions reduction strategies across the entire supply chain becomes a prerequisite for maintaining industrial competitiveness, preserving attractiveness to customers and investors, and safeguarding resilience over the medium to long term (McKinsey & Company, 2023).

When considered alongside the structural characteristics of the supply chain discussed in Section 1.1, these pressures reinforce the conclusion that net-zero is not merely a strategic aspiration, but a systemic requirement for the sector.

Section 1.3 further develops this argument.

1.3 Why net zero is critical in the off-highway supply chain

Considering the structural characteristics of the value chain and the regulatory environment discussed above, the shift towards net zero has become a strategic necessity for the off-highway sector. It reflects the combined impact of environmental constraints, tightening regulation and broader industrial transformations that are redefining how professional machinery is designed, produced and managed (World Economic Forum & Boston Consulting Group, 2021; McKinsey & Company, 2023).

Compared with other manufacturing industries — and particularly with traditional automotive — the off-highway sector is structurally more complex and less advanced in its net-zero transition. This condition is largely attributable to its high material intensity, the strong degree of product customisation and the limited standardisation of low-carbon solutions across the supply chain. The embedded emissions associated with steel, aluminium and other carbon-intensive materials remain a dominant component of the overall carbon footprint, reinforcing the centrality of upstream decarbonisation (IEA, 2022; Arens et al., 2021; GHG Protocol, 2011).

At the same time, net zero has become central not only from an environmental standpoint, but also in economic and competitive terms (McKinsey & Company, 2023). From an industrial perspective, decarbonisation is increasingly influencing inter-firm relationships, effectively becoming a differentiating factor in procurement processes. Many OEMs are integrating ESG criteria into supplier selection and evaluation mechanisms, directing demand towards partners able to demonstrate credible, measurable commitments to emissions reduction and transparent Scope 3 reporting (Hettler et al., 2024).

In this context, companies that fail to embark on structured decarbonisation pathways risk progressively losing access to strategically important market opportunities or facing less favourable financing conditions, partly due to weaker ESG assessments and growing scrutiny from investors. Conversely, the integration of decarbonisation strategies can enhance operational efficiency, facilitate access to higher value-added segments and strengthen competitive positioning within an industrial landscape undergoing rapid structural change (McKinsey & Company, 2023).

The regulatory pressures described in Section 1.2 should therefore not be interpreted merely as compliance obligations. For off-highway firms, they translate into tangible strategic risks, with direct implications for competitiveness, supply chain stability and market access. In complex and globally dispersed value chains, decarbonising the supply chain becomes not only a climate objective but also a mechanism for managing sustainability-related risks and strengthening governance across multiple tiers (Both & Wilhelm, 2025).

Companies that delay the adoption of net-zero strategies increase their exposure to regulatory tightening, volatility in energy and material costs, and rising expectations from customers and investors (McKinsey & Company, 2023). In addition, inadequate engagement with upstream suppliers may compromise the credibility of Scope 3 targets and weaken climate performance reporting, which is increasingly scrutinised under emerging reporting frameworks (GHG Protocol, 2011; Hettler et al., 2024).

Finally, the net-zero pathway is reshaping the governance logic of supply chains in the off-highway sector. It requires closer collaboration with suppliers, greater transparency in emissions measurement and enhanced capabilities in sustainable procurement and inter-organisational coordination. In a sector characterised by deep technological interdependencies and multi-tier supply networks, decarbonisation thus operates as a lever for organisational transformation — not only reducing environmental impact but also fostering shared value creation and reinforcing the long-term resilience of the industrial ecosystem (Koberg & Longoni, 2019; World Economic Forum & Boston Consulting Group, 2021).

1.3.1 Real environmental impact

As outlined in Section 1.1, the environmental footprint of the off-highway sector is largely concentrated in the upstream stages of the supply chain, particularly in the production and processing of materials and components (GHG Protocol, 2011). This section revisits that evidence from a strategic perspective, clarifying why supply chain decarbonisation constitutes a core pillar of credible net-zero strategies.

Materials such as steel, cast iron and aluminium — extensively used in the manufacture of off-highway machinery — are associated with high levels of embedded emissions. Conventional steel production remains heavily dependent on coal-based blast furnace processes, while primary aluminium production relies on electricity-intensive electrolytic smelting. Both processes are among the most emission-intensive activities within heavy industry (Arens et al., 2021).

Given the material intensity of off-highway equipment — driven by requirements for robustness, load-bearing capacity and long service life — the emissions associated with this upstream production stages represent a substantial share of the total carbon footprint of the final machine (IEA, 2022).

These materials are essential for ensuring structural strength and durability under severe operating conditions; however, their extraction, transformation and primary processing entail a significant carbon burden. As a consequence, meaningful reductions in the sector's total emissions cannot be achieved solely through improvements in direct operations (Scope 1) or purchased energy (Scope 2). Instead, effective decarbonisation strategies must address upstream supply chain emissions, which predominantly fall within Scope 3 categories related to purchased goods and services (GHG Protocol, 2011; World Economic Forum & Boston Consulting Group, 2021).

Targeted interventions at this level — including the uptake of lower-carbon materials, supplier engagement and process innovation in heavy industry — therefore represent the most structurally relevant lever for achieving substantial decarbonisation in the off-highway sector (Arens et al., 2021).

1.3.2 Strategic and competitive relevance

The transition to net zero is not solely an environmental undertaking; it has become an increasingly decisive competitive factor within industrial value chains (McKinsey & Company, 2023).

As outlined in Section 1.2 on stakeholder pressures, companies that fail to implement credible decarbonisation strategies risk progressive marginalisation in procurement processes. Many OEMs are incorporating ESG criteria and emissions transparency requirements into supplier qualification and tendering procedures, effectively reshaping competitive dynamics along the supply chain.

In parallel, the absence of a structured emissions reduction pathway may negatively influence sustainability assessments and investor perception. As capital markets increasingly integrate climate-related risks into valuation models, companies that lag in their net-zero transition may face higher financing costs or reduced attractiveness to investors focused on long-term resilience (McKinsey & Company, 2023).

Conversely, firms that embed sustainability strategies within their operations and supply chains can gain tangible advantages. They are better positioned to access customers and markets in which transparency on carbon footprint performance is becoming a practical operational requirement rather than a voluntary disclosure (World Economic Forum & Boston Consulting Group, 2021).

These strategic benefits are often accompanied by operational improvements. Efficiency gains in energy use, process optimisation and material management — frequently associated with decarbonisation initiatives — can contribute to cost reductions and enhanced productivity over the medium term (McKinsey & Company, 2023). In addition, the transition stimulates technological innovation, including the electrification of powertrains, the integration of digital monitoring systems and the development of more efficient hydraulic and control architectures. Such technological shifts are increasingly reshaping competitive positioning in industrial machinery sectors (McKinsey & Company, 2021).

Table 4. Strategic implications of the net-zero transition for off-highway companies

Dimension	**Implications for companies**
Market competitiveness	ESG criteria increasingly integrated into supplier selection
Access to capital	Investors consider climate risk and transition readiness
Operational efficiency	Energy and material efficiency improvements
Innovation	Electrification, digital monitoring and new technologies

1.3.3 Risk management

Failing to decarbonise the off-highway supply chain exposes companies to significant risks across several dimensions. From a regulatory standpoint — as outlined in Section 1.2 — non-compliance with evolving sustainability requirements may lead to legal exposure, increased reporting burdens and restricted market access. The tightening of European climate regulation and reporting obligations, particularly under the Fit for 55 framework and the Corporate Sustainability Reporting Directive (CSRD), progressively reduces the feasibility of operating without structured emissions management systems (European Commission, 2021; European Commission, 2023).

Hence, structural dependence on carbon-intensive materials such as steel and aluminium increases exposure to transition risks. These materials are both emission-intensive and sensitive to climate-related regulatory instruments, including carbon pricing and border adjustment mechanisms. As decarbonisation policies intensify, price volatility and regulatory constraints affecting upstream heavy industry may translate into cost and supply vulnerabilities for downstream manufacturers (Arens et al., 2021). From a supply chain governance perspective, sustainability-related risks increasingly extend beyond first-tier suppliers, requiring more structured monitoring and risk management capabilities across multiple tiers (Both & Wilhelm, 2025).

Financial risks are equally relevant. As carbon pricing mechanisms expand and investor scrutiny of climate exposure deepens, companies with a high emissions footprint may face additional cost burdens and reduced access to favourable financing conditions. Capital markets are progressively integrating transition risks into valuation and risk assessment frameworks, reinforcing the link between emissions performance and financial resilience (McKinsey & Company, 2023).

Reputational exposure further amplifies these dynamics. Organisations unable to demonstrate credible and measurable progress towards net-zero objectives risk losing legitimacy in the eyes of customers, investors and broader stakeholder groups, particularly in sectors where transparency and supply chain accountability are becoming normative.

In this context, decarbonisation should not be interpreted merely as an environmental aspiration. It increasingly functions as a strategic instrument for strengthening business resilience, safeguarding operational continuity and protecting long-term competitiveness. In a sector structurally dependent on energy-intensive materials and globally fragmented supply networks, the capacity to manage upstream emissions and associated transition risks is becoming a decisive determinant of sustainable industrial performance.

Table 5. Main transition risks associated with delayed decarbonisation

Risk category	Description
Regulatory risk	Stricter climate regulations and reporting requirements
Supply chain risk	Dependence on carbon-intensive materials and suppliers
Financial risk	Higher capital costs and reduced investor attractiveness
Reputational risk	Loss of legitimacy among stakeholders

1.4 Research Questions e Research Objectives

The analysis developed in the previous sections has shown that the off-highway sector is undergoing a profound structural transformation. This shift is driven by mounting regulatory pressure, significant exposure to upstream emissions and the need to reconsider production models traditionally reliant on carbon-intensive materials and energy-intensive processes. In a context characterised by complex, global and highly interdependent supply chains, it becomes essential to understand how companies are responding to these challenges and which solutions are emerging to accelerate the transition towards net zero (IEA, 2022).

To structure the discussion and provide analytical direction, this thesis is organised around two research questions designed to capture both the strategic dimension of corporate initiatives and the more technical and operational aspects of emissions reduction within the supply chain.

The first research question (RQ1) focuses on the strategies adopted by high-tech companies and firms operating in the off-highway sector to reduce the carbon footprint of their processes and products. The aim is to examine which approaches, frameworks and governance mechanisms are effectively used to define credible net-zero pathways, to identify the main strategic levers being activated, and to assess how these are implemented across the different tiers of the value chain.

The second research question (RQ2) addresses the technical solutions and enabling technologies that allow more direct intervention on Scope 3 emissions, which account for the largest share of the sector's overall environmental impact (GHG Protocol, 2011; World Economic Forum & Boston Consulting Group, 2021). In this case, the analysis seeks to identify the key innovations — whether material, digital, production-related or organisational — capable of reducing upstream emissions, as well as the barriers that hinder their large-scale adoption.

Building on these research questions, the following Research Objectives (ROs) define the analytical and applied goals of the thesis:

RO1: to map and analyse the main net-zero strategies adopted by high-tech and off-highway companies, with particular attention to initiatives involving the supply chain.

RO2: to identify the most relevant technologies and operational solutions for reducing Scope 3 emissions, assessing their level of maturity, potential impact and implementation conditions.

RO3: to examine the principal organisational, economic, technical and regulatory barriers limiting the diffusion of such solutions across the value chain.

RO4: to apply the theoretical findings to the Bosch Mobility case study, evaluating how the identified strategies and technologies are implemented in a real industrial context.

RO5**:** to develop a decarbonisation roadmap to 2030, translating the analytical results into operational and time-based guidelines applicable to the off-highway supply chain.

Taken together, these research questions and objectives provide the conceptual backbone of the thesis and guide the development of the subsequent chapters, enabling an analysis of the off-highway sector's net-zero transition from both a strategic and a technological-operational perspective.

1.5 Methodology

The methodological approach adopted in this study is based on a semi-systematic literature review, considered more suitable for examining a complex and multidimensional topic such as the decarbonisation of the off-highway supply chain.

A strictly systematic literature review would be less appropriate in this context, as the off-highway sector is characterised by a limited number of academic studies specifically addressing it, while much of its evolution is driven by industrial initiatives, regulatory developments and institutional contributions. For this reason, it is necessary to integrate industry reports and institutional sources in a structured manner—materials that would be difficult to incorporate within a purely systematic review.

Compared with traditional systematic reviews, which rely on highly standardised procedures, a semi-systematic approach makes it possible to combine academic, industrial and institutional sources in a coherent way. This flexibility is particularly valuable in a field shaped by rapid technological, regulatory and market developments.

1.5.1 Methodological objective

The primary aim of the methodology is to provide a solid theoretical foundation for addressing the defined Research Questions. It supports the mapping of corporate net-zero strategies identified in the literature (RQ1), the identification of enabling technologies and operational barriers relevant to Scope 3 emissions reduction (RQ2), and the development of the final roadmap and case study analysis.

1.5.2 Phases of the literature review

The methodological process is structured into several consecutive stages, each designed to ensure the completeness, relevance and quality of the selected sources.

1.5.2.1 Definition of keywords

The literature search was guided by a set of keywords derived from the core concepts of the thesis. These included: net-zero strategies, corporate decarbonisation, Scope 3 emissions, sustainable supply chain management, off-highway, low-carbon materials, manufacturing decarbonisation, digital manufacturing, circular economy.

Combining these terms enabled the identification of both well-established academic contributions and up-to-date industry reports.

1.5.2.2 Selection of sources

The source selection relied on a diverse range of contributions, chosen according to their relevance to the decarbonisation of the off-highway supply chain. The review included peer-reviewed academic articles identified through the Scopus and Web of Science databases, alongside key institutional publications such as the GHG Protocol, the SBTi framework and relevant ISO standards.

These were complemented by reports from international consulting firms and think tanks—including McKinsey, Boston Consulting Group and the World Economic Forum—widely referenced in applied literature on industrial decarbonisation. In addition, official documents, sustainability reports and position papers from companies operating in the sector were considered, with particular attention to the Bosch Mobility case study.

This combination of sources made it possible to capture both the scientific dimension of the topic and its most recent industrial applications.

1.5.2.3 Inclusion criteria

Publications were considered eligible if they demonstrated clear alignment with the research objectives and were relevant to the analysis of off-highway supply chain decarbonisation. In particular, sources were included if they addressed decarbonisation and supply chain management directly and provided meaningful insights into net-zero strategies or enabling technologies.

Additional selection criteria included methodological robustness, transparency in data presentation and relevance within academic debate or established industrial practice.

1.5.2.4 Exclusion criteria

Sources were excluded where methodological transparency was lacking or where data were not verifiable, as these would not support a rigorous analysis. Studies considered outdated and therefore insufficient to reflect current industrial decarbonisation dynamics were also excluded. Finally, purely descriptive or non-analytical contributions were omitted, as they did not provide the level of rigour required for the research objectives.

1.5.2.5 Analysis and synthesis of findings

Once the sources had been selected, they were analysed and organised according to analytical dimensions directly linked to the Research Questions. The review examined corporate strategies, guidelines and approaches used to define net-zero pathways, as well as key technologies, materials and processes with significant potential for Scope 3 emissions reduction.

Particular attention was paid to identifying the economic, technical and organisational barriers hindering implementation across the supply chain, together with future perspectives and emerging trends likely to shape the sector's evolution over the medium to long term.

This stage made it possible to construct an interpretative framework that informed the structure of subsequent chapters and clarified how the different elements interact within the off-highway context.

1.5.2.6 Methodological limitations

The chosen approach entails certain limitations that should be considered when interpreting the findings. The limited availability of academic research specifically dedicated to the off-highway segment required the inclusion, by analogy, of studies from the broader automotive or industrial sectors.

Moreover, the quality and depth of information provided in corporate reports can vary significantly, potentially affecting the consistency of the available evidence.

2. Corporate net-zero strategies in high-tech and off-highway automotive companies (RQ1)

2.1 Strategic frameworks for net-zero: introduction and methodological references

This chapter addresses Research Question 1 (RQ1), which examines the net-zero strategies adopted by high-tech companies and firms operating in the off-highway sector across their supply chains. The corresponding objective, defined in Chapter 1 as RO1, is to map and analyse the principal decarbonisation strategies implemented at both corporate and supply chain level, identifying their underlying logic, priorities and recurring approaches.

To answer RQ1, this section introduces the main international methodological frameworks on which companies base the definition of their net-zero pathways. These frameworks establish criteria, metrics, governance responsibilities and reporting requirements, providing a shared reference system that enables corporate strategies to be scientifically grounded, comparable and externally verifiable (Science Based Targets initiative, 2021; GHG Protocol, 2011).

In the high-tech and off-highway sectors, however, the application of these frameworks presents specific challenges. The structural predominance of Scope 3 emissions, combined with the fragmented and multi-tiered nature of the supply chain, makes the translation of methodological prescriptions into operational practice particularly complex.

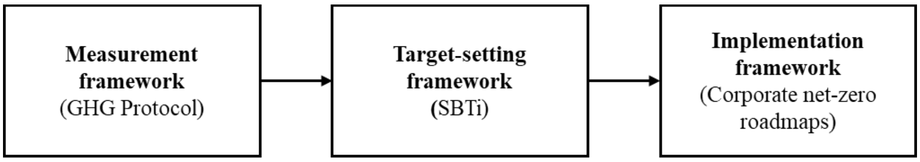


Figure 4. Methodological architecture supporting corporate net-zero strategies

2.1.1 SBTi Net-Zero Standard

The Science Based Targets initiative (SBTi) was established in 2015 as a partnership between CDP, the United Nations Global Compact, the World Resources Institute and the Worldwide Fund for Nature. Its purpose is to support companies in aligning corporate emission reduction targets with climate science and the temperature goals outlined in international climate agreements.

Originally focused on near-term emission reduction targets, the initiative introduced the SBTi Net-Zero Standard in 2021. This represented the first globally recognised framework defining consistent criteria for corporate net-zero commitments. The development of the standard responded to increasing ambiguity surrounding corporate “net-zero” pledges, which until 2020 were often based on heterogeneous definitions and varying levels of methodological rigour. The Net-Zero Standard clarified the conditions under which a company can credibly claim alignment with global climate objectives (Science Based Targets initiative, 2021).

At its core, the framework establishes that emission reductions must be real, measurable and prioritised overcompensation mechanisms. Companies are required to address emissions across Scopes 1, 2 and 3, covering the entire value chain. The use of carbon offsets is permitted only for residual emissions that remain after deep decarbonisation efforts have been implemented.

The standard distinguishes between near-term and long-term targets. Near-term targets, typically set over a five-to-ten-year horizon, are designed to ensure immediate alignment with 1.5°C pathways. Long-term targets require companies to reduce emissions by approximately 90–95% by 2050 (or earlier), leaving only a limited volume of residual emissions to be neutralised (Science Based Targets initiative, 2021).

The framework also recognises sectoral specificities. In manufacturing and high-tech industries, emission intensity pathways may be applied where appropriate, while in hard-to-abate sectors such as steel and cement, decarbonisation trajectories are assessed against sectoral transition scenarios consistent with global carbon budgets. These sectoral considerations reflect the structural constraints and technological maturity of different industries.

Another defining element of the SBTi approach is its validation process. Targets are subject to independent methodological review, and companies obtaining approval are listed as “Targets Approved”. Periodic reassessment is required, typically every five years, ensuring that commitments remain aligned with evolving climate science.

Particular emphasis is placed on Scope 3 emissions. In sectors characterised by complex, multi-tier supply chains and high material intensity—such as off-highway manufacturing—upstream emissions often represent the majority of the total footprint. The SBTi therefore requires companies to set Scope 3 targets where these emissions are material and to demonstrate progress in engaging suppliers and reducing value chain emissions (Science Based Targets initiative, 2021).

By limiting the role of offsets to residual emissions and requiring deep structural reductions, the standard aims to prevent superficial neutrality claims and to anchor corporate net-zero strategies in measurable and science-based transformation pathways.

2.1.2 GHG Protocol

The Greenhouse Gas Protocol (GHG Protocol) is the most widely adopted international framework for the measurement and reporting of greenhouse gas emissions. Developed by the World Resources Institute and the World Business Council for Sustainable Development, it emerged in response to the need for methodological consistency in corporate carbon accounting following the growing institutionalisation of global climate policy (GHG Protocol, 2011).

Prior to its diffusion, emission reporting practices were heterogeneous and often non-comparable, limiting transparency and reducing the credibility of corporate disclosures. The GHG Protocol established a common structure that enabled comparability across firms and sectors. Since its introduction, it has become the reference framework for corporate inventories and the basis for most climate-related disclosure systems (GHG Protocol, 2011).

The framework introduced the three-scope classification that continues to underpin contemporary carbon accounting. Scope 1 covers direct emissions from owned or controlled sources. Scope 2 refers to indirect emissions from purchased electricity and energy. Scope 3 encompasses all other indirect emissions along the value chain, including upstream material production, component manufacturing, logistics, product use and end-of-life treatment. This structure provides the analytical foundation for corporate decarbonisation strategies and is explicitly incorporated into science-based target-setting approaches (GHG Protocol, 2011; Science Based Targets initiative, 2021).

Beyond defining emission categories, the GHG Protocol provides detailed methodological guidance. It addresses the definition of organisational and operational boundaries, the selection of emission factors, the use of primary and secondary data, and the management of uncertainty. These principles are operationalised through dedicated standards, including the Corporate Standard and the Scope 3 Standard, enabling companies to develop inventories aligned with different reporting objectives and analytical levels.

The framework also clarifies boundary-setting approaches — such as equity share, financial control and operational control — which are critical for ensuring consistency and avoiding double counting (GHG Protocol, 2011). A robust emissions inventory constructed on these principles is a prerequisite for any credible net-zero commitment.

In high-tech and off-highway sectors, however, implementation presents significant challenges. Supply chains are multi-tiered and geographically dispersed, and primary data from upstream suppliers are often unavailable or incomplete. Many Tier-2 and Tier-3 suppliers lack structured environmental reporting systems, leading companies to rely on secondary datasets or generic emission factors. This reduces precision and limits the effectiveness of reduction strategies (Hettler et al., 2024).

Further complexity arises from the variability of energy-intensive processes such as casting, heat treatment and precision machining, where actual emissions depend heavily on local energy mixes and production technologies. In the absence of harmonised data-sharing mechanisms, traceability across the value chain remains partial, constraining Scope 3 transparency.

For this reason, the GHG Protocol should be understood as a necessary foundation rather than a complete solution. It enables companies to establish baselines, identify material emission categories and structure reporting systems. However, effective Scope 3 reduction also requires supply chain coordination, data governance mechanisms and structured supplier engagement beyond the measurement phase.

The complementarity between the GHG Protocol and the SBTi is therefore central. The former defines how emissions are measured and reported; the latter defines the level and trajectory of reductions required to align corporate strategies with climate science (Science Based Targets initiative, 2021). Together, they constitute the methodological architecture underpinning corporate net-zero strategies.

Table 6. Complementary roles of the GHG Protocol and the SBTi Net-Zero Standard

Framework	Main function	Key elements
GHG Protocol	Emissions measurement and reporting	Scope 1–2–3 classification, emission inventories, reporting standards
SBTi Net-Zero Standard	Target setting aligned with climate science	Near-term targets, long-term net-zero targets, limited use of offsets

2.1.3 Corporate net-zero roadmaps

Corporate net-zero roadmaps have become one of the principal instruments through which companies translate climate commitments into structured action plans.

While standards such as the SBTi define what it means to be aligned with global climate objectives, and the GHG Protocol establishes how emissions should be measured, roadmaps clarify how a company intends to achieve those objectives in practice. They coordinate internal functions, capital allocation, technological innovation and supply chain initiatives within a coherent transition pathway (Science Based Targets initiative, 2021; GHG Protocol, 2011).

The growing prominence of roadmaps reflects two parallel developments. On the one hand, the rapid increase in corporate net-zero commitments—often formalised through SBTi validation—has required a level of planning far more detailed than in the past. On the other hand, regulatory developments such as the CSRD have introduced reporting obligations that demand transparent evidence of transition pathways and measurable progress. In this context, the roadmap has emerged as a central governance tool for operationalising decarbonisation (Science Based Targets initiative, 2021; European Commission, 2023).

The primary function of a roadmap is to link long-term strategic targets with short- and medium-term operational measures. A structured roadmap typically begins with an analysis of the corporate emissions baseline, identifying major hotspots and the most material emission sources. In high-tech and off-highway sectors, this assessment consistently highlights a strong concentration of emissions in carbon-intensive materials and upstream production processes, placing the supply chain at the core of the decarbonisation challenge (GHG Protocol, 2011; World Economic Forum & Boston Consulting Group, 2021).

Building on this analytical foundation, the roadmap sets out priority interventions. These may include energy efficiency measures, process innovation, the adoption of low-carbon materials and the development of circular solutions such as remanufacturing. Increasingly, roadmaps also incorporate digital initiatives, including real-time emissions monitoring systems and the use of digital twins to optimise production processes and resource consumption (McKinsey & Company, 2021).

In high-tech and off-highway contexts, a distinctive feature of net-zero roadmaps is the central role of the supply chain. Since the majority of emissions fall under Scope 3, companies cannot rely solely on internal measures. Instead, they must establish structured collaboration programmes with suppliers across multiple tiers. This often involves progressive engagement mechanisms—ranging from basic emissions reporting requirements to joint adoption of low-carbon technologies—and targeted support for smaller suppliers in data collection and technical capability building.

Beyond technical measures, an effective roadmap also integrates organisational and financial dimensions. Clear internal accountability, dedicated transition budgets, risk assessment processes and the identification of funding opportunities are essential to ensure both feasibility and credibility. In this sense, a roadmap is not merely a planning document but a coordination mechanism that aligns corporate functions and enables continuous monitoring of progress against defined targets (Both et al., 2025; McKinsey & Company, 2023).

In general, corporate net-zero roadmaps can be understood as the structural backbone of the decarbonisation journey. They connect methodological and regulatory requirements with day-to-day operational decisions, making it possible to convert strategic commitments into tangible changes in products, processes and supply chain configurations.

In line with the applied analysis developed in Chapter 5, this chapter adopts a temporal structure anchored in the current context (2026), distinguishing between short-term actions (2026–2028), medium-term measures (2028–2030) and a longer-term horizon beyond 2030. This framing ensures conceptual continuity between the theoretical discussion and the empirical roadmap proposed later in the thesis.

The following sections use these roadmap frameworks as a reference point to examine how high-tech and off-highway companies operationalise net-zero strategies across the entire value chain.

The typical structure of a corporate net-zero roadmap is illustrated in Figure 5.

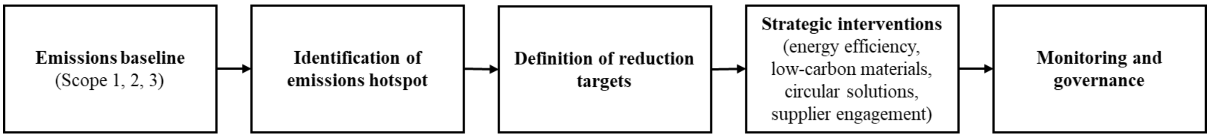


Figure 5. Conceptual structure of a corporate net-zero roadmap

2.2 Overview of net-zero strategies across the supply chain

The methodological consolidation introduced by the SBTi and the GHG Protocol has progressively shifted corporate decarbonisation strategies beyond the boundaries of direct operations. In high-tech and off-highway sectors, companies are increasingly structuring net-zero pathways that extend across the entire value chain, reflecting the predominance of Scope 3 emissions and the need for coordinated action among supply chain actors (Science Based Targets initiative, 2021; GHG Protocol, 2011).

As discussed in Chapter 1, upstream activities account for the largest share of the sector's carbon footprint. Net-zero strategies therefore cannot focus solely on improvements in manufacturing efficiency or purchased energy. They must also address material sourcing, product architecture, logistics configurations and the data systems that enable emissions monitoring across tiers (IEA, 2022).

In operational terms, companies are organising their decarbonisation initiatives along several complementary directions. These typically correspond to the distribution of emission hotspots within the supply chain and to the varying degrees of influence firms can exercise. Some levers — such as internal energy management or product design choices — fall under direct managerial control. Others, particularly those linked to upstream material production and lower-tier suppliers, require governance mechanisms based on coordination, incentives and long-term engagement (World Economic Forum & Boston Consulting Group, 2021).

The result is an integrated strategic approach in which direct operational interventions coexist with structured forms of supply chain orchestration. This configuration reflects the structural complexity of the off-highway sector and the systemic nature of its net-zero transition.

Table 7 aims to summarise the main strategic levers through which companies structure net-zero strategies across the supply chain.

Table 7. Main decarbonisation levers across the off-highway supply chain

Strategic lever	Main objective	Supply chain level	Example actions
Energy & Operations	Reduce direct operational emissions	Manufacturing sites	Energy efficiency, electrification, renewable procurement
Materials & Product Innovation	Reduce embodied emissions in products	Product design & suppliers	Low-carbon materials, lightweighting, eco-design
Circularity	Reduce demand for virgin materials	Entire value chain	Remanufacturing, recycling, life extension
Logistics	Reduce transport-related emissions	Distribution networks	Modal shift, transport optimisation
Digital enablers	Improve measurement and coordination	Entire supply chain	Carbon tracking systems, digital twins

2.2.1 Energy & Operations

The decarbonisation of operational activities represents a foundational component of corporate net-zero strategies. It is typically the starting point of transition pathways, as it concerns emission sources that fall under direct managerial control and can be addressed through internal investment and process optimisation.

In high-tech and off-highway manufacturing environments, operational decarbonisation is particularly relevant. Production facilities host energy-intensive processes — including precision machining, heat treatment, casting preparation and hydraulic system testing — which contribute significantly to Scope 1 and Scope 2 emissions (IEA, 2022).

Energy and operations strategies generally develop along three interconnected directions: improving energy efficiency, electrifying industrial processes and decarbonising energy procurement. These interventions are consistent with the principles embedded in corporate carbon accounting and target-setting frameworks, which prioritise direct emission reductions before reliance on offsetting mechanisms (Science Based Targets initiative, 2021; GHG Protocol, 2011).

2.2.1.1 Energy efficiency and process optimisation

Energy efficiency is often the most immediate lever available and, in many cases, offers the most favourable cost–benefit profile. Manufacturing environments frequently contain improvement potential both in installed technologies and in operational practices (McKinsey & Company, 2021).

Typical measures include upgrading electric motors to high-efficiency models, deploying variable-speed drives, improving thermal insulation, optimising compressed air systems and modernising lighting infrastructure. In facilities dedicated to off-highway components — where machining operations and heat treatment phases are common — further gains can be achieved through heat recovery systems, enhanced furnace performance and predictive maintenance strategies aimed at reducing energy losses and unplanned downtime (IEA, 2022).

Beyond reducing energy consumption, these interventions often generate operational co-benefits, including greater process stability and extended equipment lifespan. Such complementarities reinforce the economic rationale for early investment in operational decarbonisation (McKinsey & Company, 2021).

2.2.1.2 Electrification of industrial processes

A second strategic area concerns the gradual substitution of fossil fuel-based thermal and mechanical processes with electrified alternatives. This intervention is particularly relevant for reducing Scope 1 emissions in facilities where natural gas boilers, direct combustion systems or fuel-based heat generation remain in use (IEA, 2022).

Electrification allows companies to progressively eliminate on-site fossil fuel consumption. Its decarbonisation potential, however, depends on the carbon intensity of the electricity mix. Where electricity is sourced from renewable generation, electrification can enable substantial reductions in operational emissions over the medium term (Science Based Targets initiative, 2021).

In off-highway manufacturing environments, this transition is technically demanding. Certain production stages — including heat treatment, surface processing and continuous mechanical operations — require high and stable temperature levels or uninterrupted 24-hour functioning. These characteristics limit the immediate substitutability of combustion-based systems and necessitate phased implementation strategies.

As a result, electrification is typically integrated into long-term asset renewal cycles. Companies align process conversion with planned capital expenditure, combining equipment replacement with upgrades to internal electrical infrastructure. This may include reinforcement of grid connections, installation of higher-capacity switchgear, deployment of digital energy management systems and, in some cases, battery storage solutions to mitigate peak loads and stabilise consumption patterns (McKinsey & Company, 2021).

2.2.1.3 Decarbonisation of energy procurement

The decarbonisation of energy procurement constitutes the third component of operational transition strategies. While electrification reduces direct fossil fuel use, the climate impact of such a shift ultimately depends on the carbon intensity of the electricity supplied. Securing renewable electricity therefore becomes a structural requirement for credible Scope 2 reduction pathways (IEA, 2022).

Companies increasingly adopt a combination of instruments to achieve this objective. Among these, long-term Power Purchase Agreements (PPAs) have gained prominence. Through contractual arrangements with renewable energy producers, firms can secure stable electricity prices while contributing to the expansion of renewable generation capacity. From a corporate decarbonisation perspective, PPAs provide both accounting benefits — in line with market-based Scope 2 reporting — and strategic advantages related to price predictability and long-term supply security (Science Based Targets initiative, 2021).

In parallel, many industrial companies invest directly in on-site renewable generation. Rooftop or ground-mounted photovoltaic installations, battery storage systems and local energy management infrastructures are increasingly integrated into manufacturing sites. Beyond emission reduction, these investments strengthen operational continuity and reduce exposure to energy price volatility — an aspect of growing relevance for energy-intensive production environments (IEA, 2022; McKinsey & Company, 2021).

2.2.1.4 Intelligent energy management and digital infrastructure

Supporting the operational measures discussed above, intelligent energy management systems increasingly function as enabling infrastructure for industrial decarbonisation. The integration of digital Energy Management Systems (EMS), IoT-based monitoring platforms and real-time consumption analytics allows firms to identify inefficiencies at process level and to optimise the performance of production assets with greater accuracy (IEA, 2022; Ma et al., 2024).

In energy-intensive manufacturing environments, digital technologies enable more dynamic control of electricity consumption, linking production planning with load management and internal grid flexibility. Advanced data architectures make it possible to track performance indicators continuously, simulate optimisation scenarios and evaluate the impact of specific decarbonisation measures before large-scale deployment (Ma et al., 2024; McKinsey & Company, 2021).

Digital infrastructure therefore goes beyond measurement and reporting. When embedded in operational decision-making, it becomes a coordination mechanism between energy strategy and production management, facilitating the systematic integration of climate objectives into day-to-day manufacturing activities (Zaoui et al., 2026).

2.2.1.5 Strategic implications for high-tech and off-highway sectors

For high-tech and off-highway companies, Energy & Operations strategies extend beyond technical optimisation; they represent a foundational pillar of the net-zero transition. Reducing direct and indirect site-level emissions is a prerequisite for the credibility of any decarbonisation pathway and for alignment with the methodological expectations embedded in internationally recognised frameworks (Science Based Targets initiative, 2021; GHG Protocol, 2011).

Operational measures also generate structural effects along the supply chain. Improved transparency in energy consumption, greater cost efficiency and enhanced process reliability reinforces <both environmental and industrial performance. In energy- and material-intensive sectors, upgrading the energy mix and modernising production systems are not only environmental actions but strategic investments that support long-term competitiveness and resilience (IEA, 2022).

In this sense, operational decarbonisation contributes to shaping industrial models that are simultaneously more efficient, more robust and more consistent with emerging climate governance standards.

Operational decarbonisation		
Energy efficiency	*Electrification*	*Renewable energy*
Process optimisation	Industrial systems	PPAs & on-site generation

Figure 6. Operational decarbonisation pathway in manufacturing environments

2.2.2 Materials & Product Innovation

Innovation in materials and product design constitutes one of the most decisive levers for decarbonising high-tech and off-highway supply chains. In these sectors, the material intensity of components — and the extensive use of steel, aluminium, cast iron and specialised alloys — accounts for a substantial share of upstream Scope 3 emissions.

Across energy- and material-intensive industries, embodied emissions in materials frequently represent the dominant portion of a product's life-cycle footprint. While the exact percentage varies depending on system boundaries and design configurations, multiple industrial analyses confirm that materials constitute the primary source of upstream emissions within heavy manufacturing value chains. For companies seeking alignment with science-based net-zero pathways, this implies that meaningful emission reductions cannot be achieved without addressing material-related impacts across the supply base (Science Based Targets initiative, 2021).

Innovation in this domain develops along two complementary directions: the adoption of lower-carbon materials and the redesign of products according to eco-design and circularity principles. The latter includes strategies such as lightweighting, modularity, durability optimisation and improved end-of-life recoverability (König et al., 2024; Geissdoerfer et al., 2020). These approaches are mutually reinforcing: the environmental benefits of alternative materials are maximised when product architectures are conceived to minimise material use, extend service life and enable reuse or remanufacturing (Zils et al., 2023).

In structurally complex sectors such as off-highway manufacturing, materials and product innovation therefore represent not only a technical intervention, but a structural transformation of how environmental value is embedded into product architecture.

2.2.2.1 Introduction of low-carbon materials

In recent years, material-producing industries have initiated substantial technological transformations aimed at reducing the emissions intensity of primary metals and other energy-intensive inputs. Steelmakers are investing in electric arc furnace (EAF) technologies powered by renewable electricity and in hydrogen-based direct reduced iron (H-DRI) processes, which have the potential to significantly lower emissions compared with conventional blast furnace routes (Material Economics, 2019). These pathways are central to long-term industrial decarbonisation scenarios.

Aluminium production is also evolving. The increasing use of recycled aluminium, which requires considerably less energy than primary production, plays a decisive role in reducing embodied emissions. Emerging innovations, including inert anode technologies, further contribute to lowering the carbon intensity of smelting processes. In parallel, progress in engineering polymers and composite materials is driven by the development of bio-based alternatives and improvements in advanced recycling systems, although these technologies remain uneven in terms of maturity and scalability (IEA, 2022).

For high-tech and off-highway companies, the integration of lower-carbon materials represents not merely a technological option but a structural component of supply chain decarbonisation strategies. Securing access to such materials often requires long-term collaboration with Tier-1 and Tier-2 suppliers, forward purchasing agreements and coordinated investment signals that support upstream innovation (Hettler et al., 2024). In this context, material substitution and process innovation become closely intertwined with governance mechanisms capable of aligning incentives along the value chain.

2.2.2.2 Design optimisation through eco-design and lightweighting

Alongside innovation in material production, a second fundamental pillar of supply chain decarbonisation lies in eco-design, understood as the systematic integration of environmental considerations into product development across the entire life cycle. In the off-highway sector, where machines must deliver robustness, long service life and high performance under severe operating conditions, eco-design requires a careful balance between sustainability objectives, reliability constraints and functional requirements.

One of the primary strategies is lightweighting, namely the reduction of overall component mass through structural optimisation, improved geometries and the selective use of lighter alternative materials. When implemented at early design stages, lightweighting can reduce the quantity of carbon-intensive materials embedded in the product while maintaining structural integrity (König et al., 2024). In heavy industrial applications, this design approach must be carefully validated to avoid compromising safety margins and durability standards.

Lightweighting also delivers a dual emissions benefit. Beyond lowering material demand in production, reduced mass may decrease operational energy consumption over the machine's lifetime, particularly in mobile or fuel-dependent equipment (IEA, 2022).

In parallel, increasing attention is being paid to durability-oriented and circular design solutions. Designing modular systems with components that can be easily replaced, upgraded or remanufactured extends product service life and limits the demand for virgin materials. Standardisation of components and design for disassembly further facilitate recycling and value retention strategies within the supply chain (Geissdoerfer et al., 2020; Zils et al., 2023). These approaches are consistent with broader industrial decarbonisation frameworks that emphasise material efficiency and circularity as structural levers for reducing upstream emissions (Material Economics, 2019).

2.2.2.3 Powertrain innovation and integration of emerging technologies

Innovation in powertrain systems is playing an increasingly central role in corporate decarbonisation strategies, in particular in off-highway segments where high-powered diesel engines continue to represent the dominant technological standard. The transition away from conventional internal combustion engines constitutes one of the most technically demanding dimensions of the net-zero pathway, given the energy intensity and duty-cycle requirements of heavy machinery.

Corporate roadmaps tend to increasingly include investments in hybrid architectures, battery-electric configurations and hydrogen-based solutions, often accompanied by pilot projects aimed at testing operational feasibility in high-load and continuous-duty applications. The transition to alternative powertrains typically entails a comprehensive redesign of the machine, also affecting component layout, thermal management systems, structural integration and energy management architecture. These transformations require coordination across multiple engineering domains and close collaboration with Tier-1 technology suppliers.

Such developments pose substantial engineering and infrastructural challenges. However, they also offer transformative potential, as they enable significant reductions in operational emissions associated with the use phase (Scope 3, Category 11) and create opportunities to reconsider the full life-cycle configuration of the machine (IEA, 2022). From a value-chain perspective, the electrification and diversification of powertrains may also alter upstream material demand patterns and supplier structures, reinforcing the systemic character of decarbonisation strategies.

Besides propulsion systems, advanced manufacturing technologies are gaining increasing relevance. Additive manufacturing, for example, enables the production of components with optimised internal geometries, reducing material input while maintaining or enhancing functional performance. In material-intensive sectors, such optimisation can contribute to lowering embedded emissions associated with purchased goods (Ma et al., 2024). Over the longer term, additive and digitally enabled production technologies may also increase manufacturing flexibility and reduce tooling requirements, which is particularly relevant in high-variety, lower-volume off-highway contexts (World Economic Forum & Boston Consulting Group, 2021).

2.2.2.4 Strategic and supply chain implications

The adoption of innovative materials and the redesign of products have significant implications for supply chain management. The transition towards low-carbon materials rarely involves a simple substitution. It often requires adjustments to manufacturing processes, the acquisition of new technical qualifications and certifications, and the alignment of specifications between OEMs and suppliers. In sectors characterised by strict safety and performance requirements, harmonising standards across the value chain can represent a substantial coordination effort.

Moreover, the introduction of low-carbon inputs frequently entails higher short-term costs compared with conventional alternatives. Managing these cost differentials requires contractual and organisational adaptations, including multi-year procurement agreements, strategic partnerships with material producers and, in some cases, the introduction of internal carbon pricing mechanisms to guide investment decisions. Empirical evidence suggests that first movers in supply chain decarbonisation tend to combine technological change with long-term relational strategies in order to reduce uncertainty and distribute transition costs across partners (Zhang et al., 2022).

For high-tech and off-highway sectors, the capacity to innovate in materials and product design is increasingly emerging as a source of competitive differentiation. Firms that integrate lower-carbon solutions into their product portfolios not only reduce upstream Scope 3 emissions but also strengthen their resilience to regulatory tightening and carbon-related cost exposure. In addition, transparent reporting and structured supplier engagement — particularly with regard to Scope 3 emissions — can reinforce credibility towards customers and investors, contributing to more stable and strategically aligned value chain relationships (Hettler et al., 2024).

2.2.3 Circularity

Circularity constitutes a key lever within net-zero strategies in the high-tech and off-highway sectors, as it enables companies to address multiple dimensions of their carbon footprint simultaneously, by retaining value from existing sources (Geissdoerfer et al., 2020): reducing waste generation, limiting the extraction and processing of virgin raw materials, extending product lifecycles and retaining value embedded in components and materials.

Whereas energy-related initiatives primarily affect Scope 1 and Scope 2 emissions, circular strategies are particularly relevant for upstream Scope 3 emissions, which are largely associated with purchased goods and materials (GHG Protocol, 2011; Material Economics, 2019). In material-intensive industries, reducing primary material demand through reuse, remanufacturing and recycling can generate substantial emission reductions along the value chain.

From a strategic perspective, circularity goes beyond environmental compliance. It implies a reconfiguration of business models, supply chain relationships and product architectures. The literature on circular business models emphasises how value retention mechanisms — such as remanufacturing, refurbishment and modular design — can simultaneously reduce environmental impact and strengthen long-term competitiveness (Geissdoerfer et al., 2020; Zils et al., 2023).

In off-highway applications, where products are capital-intensive, durable and often designed for extended service lives, the potential of circular approaches is particularly significant. The technical feasibility of remanufacturing and component recovery, combined with structured aftermarket service networks, creates favourable conditions for integrating circular principles into industrial practice (Burggräf et al., 2021; König et al., 2024). Under these conditions, circularity becomes not only a support mechanism for net-zero alignment but also a structural element of supply chain resilience and long-term value creation.

2.2.3.1 Extension of the life cycle: remanufacturing, refurbishment and repair

The most advanced form of circularity in the sector is remanufacturing, namely the industrial regeneration of complex components restored to a condition equivalent to, or in some cases exceeding, that of a new product. Remanufacturing typically involves systematic disassembly, inspection, replacement of worn parts, reassembly and testing according to defined quality standards.

This approach is particularly relevant for engines, hydraulic systems, electronic control units and transmissions, which are characterised by high economic value and significant material intensity. By preserving the core structural elements of these components, remanufacturing substantially reduces the need for virgin material extraction and primary processing. Studies on industrial circularity highlight that such value-retention strategies can significantly lower energy demand and associated emissions compared with full replacement manufacturing (Material Economics, 2019; Burggräf et al., 2021).

Alongside remanufacturing, refurbishment and specialised repair activities also contribute to extending product service life. These approaches reduce demand for newly manufactured components and limit upstream material flows, thereby mitigating Scope 3 emissions associated with purchased goods and material production (GHG Protocol, 2011; Geissdoerfer et al., 2020).

In many corporate transition pathways, these circular models are supported by structured reverse logistics systems, take-back schemes and dedicated collection networks for used components. Effective implementation requires coordination across OEMs, Tier-1 suppliers and service networks, as well as the integration of circular principles into supply chain management and business model design (Zils et al., 2023).

2.2.3.2 Advanced recycling and resource management

Recycling represents a further structural pillar of circular strategies. In high-tech and off-highway sectors — where steel, aluminium and specialised alloys account for a substantial share of product mass — the substitution of primary materials with secondary inputs can significantly reduce embedded emissions. The production of recycled steel through electric arc furnaces and the use of secondary aluminium, for instance, require substantially less energy than primary production routes, leading to markedly lower carbon intensities (IEA, 2022; Material Economics, 2019).

However, capturing the full decarbonisation potential of recycling requires upstream integration at the design stage. Intervening only at end of life is insufficient if products are not conceived to facilitate disassembly, material separation and recovery. Design for disassembly and modular architectures therefore become enabling conditions for effective resource loops. These principles are consistent with broader circular economy frameworks that emphasise the retention of material value across multiple life cycles (Geissdoerfer et al., 2020; Zils et al., 2023).

In parallel, digital tools such as material passports and traceability systems are increasingly explored to enhance transparency regarding product composition and to improve the efficiency of reverse logistics and recycling operations. These solutions are particularly relevant in mechatronic and electronic subsystems, where heterogeneous material combinations and high levels of integration can complicate separation and recovery processes (World Economic Forum & Boston Consulting Group, 2021).

2.2.3.3 Circular business models

Alongside technical interventions in materials and design, circularity is progressively reshaping business models in high-tech and off-highway industries. The shift from transactional product sales towards service-oriented or performance-based models — including pay-per-use schemes, operating leasing and advanced maintenance contracts — alters the incentives embedded in the value chain. When manufacturers retain ownership or responsibility for long-term performance, product durability, upgradeability and maintainability become economically aligned with environmental objectives (Geissdoerfer et al., 2020; Zils et al., 2023).

In such configurations, OEMs often maintain closer control over the use phase, maintenance cycles and end-of-life management. Digital platforms supported by IoT technologies enable continuous monitoring of machine performance, predictive maintenance scheduling and data-driven optimisation. These capabilities facilitate life extension strategies, improve resource efficiency and support structured reverse logistics systems.

In off-highway applications, where equipment is capital-intensive and typically operates in high-utilisation professional contexts, circular business models can be particularly effective. They allow firms to maintain long-term customer relationships, generate recurring revenue streams and collect operational data that feeds back into product redesign and efficiency improvements. In this way, circular models combine environmental gains with industrial advantages, reinforcing competitiveness while contributing to supply chain decarbonisation (World Economic Forum & Boston Consulting Group, 2021).

2.2.3.4 Circularity and the supply chain: collaboration as a prerequisite

The effectiveness of circular strategies depends strongly on the degree of coordination and collaboration established across the supply chain. Many circular initiatives — including reverse logistics for used components, material standardisation, modular design alignment and shared recovery infrastructures — cannot be implemented unilaterally by OEMs. They require the active involvement of Tier-1 and Tier-2 suppliers, as well as structured governance mechanisms capable of aligning incentives and responsibilities (Hettler et al., 2024; Zils et al., 2023).

In high-tech and off-highway sectors, this coordination is often demanding due to supply chain fragmentation, technological interdependencies and the presence of numerous highly specialised actors operating across different geographical regions. These structural characteristics increase transaction complexity and make the harmonisation of circular standards more challenging (Koberg & Longoni, 2019).

Nevertheless, companies that manage to integrate circular practices in a systemic manner tend to generate benefits that extend beyond emission reductions alone. Strengthened collaboration enhances visibility over material flows, reduces exposure to supply disruptions and lowers dependence on critical or price-volatile raw materials. In addition, structured circular partnerships can reinforce transparency in Scope 3 emissions reporting and support broader ESG positioning, which is increasingly relevant in relations with customers, investors and regulators.

2.2.3.5 Barriers and enabling factors

Despite their potential, circular models face several structural and organisational barriers. Technical complexity is one of the most relevant constraints: highly integrated mechanical and electronic systems may be difficult to disassemble, refurbish or recycle efficiently. In addition, the absence of common standards across the supply chain complicates component interoperability and material traceability. High upfront investment requirements for dedicated recovery infrastructures, together with the need to establish reliable reverse logistics systems, further increase implementation costs. Cultural resistance also plays a role, as industrial customers often display a preference for new products over remanufactured or refurbished alternatives (World Economic Forum & Boston Consulting Group, 2021; Zils et al., 2023).

From a supply chain perspective, fragmentation and asymmetries in capabilities between large OEMs and smaller suppliers may hinder the systemic adoption of circular practices. These challenges reflect broader governance issues typical of global value chains, where coordination costs and misaligned incentives can slow the diffusion of sustainability-oriented innovations (Koberg & Longoni, 2019; Hettler et al., 2024).

To address these obstacles, companies are increasingly adopting complementary enabling mechanisms. These include the establishment of structured industrial partnerships, incentivised take-back schemes for used components, the deployment of digital platforms to track product life cycles and material flows, and the integration of circular performance indicators into supplier evaluation and procurement processes. When embedded within broader net-zero strategies, such measures contribute to reducing Scope 3 emissions while simultaneously strengthening supply chain resilience and transparency.

2.2.3.6 Impact and strategic value

Circularity has strategic implications that extend well beyond emission reductions alone.

In high-tech and off-highway sectors, products designed to be more durable, reconditionable and recyclable are becoming an increasingly relevant competitive factor, particularly in markets where professional customers — such as those operating in agriculture and construction — are progressively more attentive to the environmental performance and life-cycle efficiency of the capital goods they deploy.

From an industrial perspective, circularity contributes to strengthening supply security, reducing exposure to price volatility in carbon-intensive raw materials and improving long-term cost structures through higher material efficiency. These dynamics are particularly significant in sectors characterised by heavy reliance on steel, aluminium and specialised alloys, where upstream decarbonisation pathways remain capital-intensive and uncertain.

More broadly, circularity increasingly intersects with innovation in operations and supply chain management. Firms that successfully integrate circular principles into product design, procurement strategies and reverse logistics systems tend to reinforce supply chain resilience and enhance their strategic positioning in global markets undergoing structural transition (Zils et al., 2023).

Overall, circularity should not be interpreted merely as an environmental lever. It represents a core dimension of industrial innovation, a driver of supply chain robustness and an integral component of credible net-zero strategies, whose implications will be examined in greater depth in the subsequent chapters.

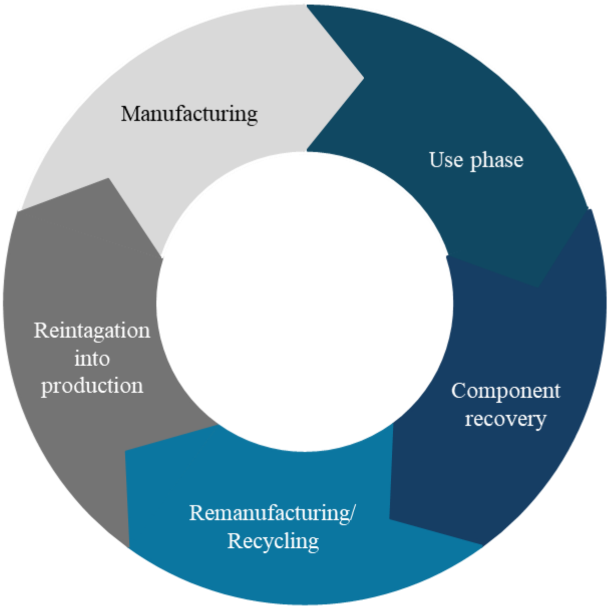


Figure 7. Circular value loops in the off-highway supply chain

2.2.4 Logistics

Logistics constitutes one of the most sensitive areas within the net-zero strategies of high-tech and off-highway companies, not only because of its operational complexity, but also due to its contribution to Scope 3 emissions. In sectors characterised by globalised supply chains and heavy, bulky components, the movement of materials can represent a significant share of upstream emissions, particularly when logistics flows span multiple continents or rely on high-emission transport modes. For this reason, decarbonisation roadmaps increasingly recognise logistics as a relevant field of intervention, where operational efficiency and environmental performance are closely interconnected (GHG Protocol, 2011).

A first area of intervention concerns the optimisation of transport flows. The growing diffusion of digital planning systems enables companies to reduce redundant shipments, optimise vehicle loading rates and improve synchronisation between production, warehousing and deliveries. The objective is to decrease the number of journeys required while maximising the utilisation of transport capacity. This is particularly relevant in off-highway contexts, where the size and weight of components make each shipment economically and environmentally costly. Packaging design also plays a role: modular and reusable packaging solutions reduce transported volumes and limit waste generation, contributing to more resource-efficient logistics systems (World Economic Forum & Boston Consulting Group, 2021; McKinsey & Company, 2021).

A second strategic area concerns modal shift. Companies are progressively prioritising lower-carbon transport options, such as maritime shipping for long-distance intercontinental flows and rail for intra-continental connections, where feasible. Shifting from road to rail or from air freight to sea transport is widely recognised as one of the most effective short-term levers for reducing logistics-related emissions, provided that service levels and supply reliability can be maintained. In practice, however, this transition requires greater visibility over demand and more stable planning horizons — conditions that are not always easily met in the off-highway sector, where demand volatility and product customisation complicate logistics coordination.

Electrification of short- and medium-distance transport is also gaining traction. Electric trucks are increasingly viable for urban deliveries and inter-plant transport within limited radii, while alternative fuels — including advanced biofuels, hydrogen and biomethane — are being explored for heavier or longer-distance routes. Nevertheless, the scalability of these solutions remains strongly dependent on the availability of charging and refuelling infrastructure, as well as on the evolution of vehicle technology and total cost of ownership (IEA, 2022; McKinsey

& Company, 2024). As a result, logistics decarbonisation often progresses unevenly across different segments of the transport network.

Beyond operational optimisation, some firms are reassessing the geographical configuration of their supply chains. Processes of regionalisation or nearshoring are increasingly considered as a means to shorten transport distances, reduce exposure to international disruptions and lower transport-related emissions. From a global value chain perspective, however, such reconfiguration entails trade-offs between efficiency, specialisation and proximity to markets (Gereffi, 2018). Empirical evidence suggests that first movers in supply chain decarbonisation often combine selective regionalisation with strengthened supplier collaboration, rather than pursuing a full retreat from global sourcing (Zhang et al., 2022). In the off-highway sector, where many components are highly specialised, the feasibility of nearshoring depends on the availability of adequate technical capabilities at regional level.

It is important to note that, in most off-highway supply chains, logistics does not constitute the primary driver of Scope 3 emissions. Upstream material production and component manufacturing typically account for a larger share of total emissions (Material Economics, 2019). Nonetheless, logistics remains strategically relevant. Decarbonising transport flows requires coordination with logistics providers, the integration of environmental criteria into transport contracts and, in some cases, joint investments in low-emission fleets or dedicated infrastructure. Company-level sustainability reports increasingly document such initiatives as part of broader supply chain transition programmes (Bosch, 2023; Bosch, 2024).

Digitalisation performs an enabling role in this transformation. Advanced tracking systems, IoT sensors and integrated fleet management platforms increase visibility over transport flows and support more accurate measurement of logistics-related emissions, in line with GHG Protocol requirements (GHG Protocol, 2011). Improved data transparency allows companies to identify inefficiencies, compare modal options and integrate environmental considerations into tactical and strategic logistics decisions.

Logistics in the high-tech and off-highway sector is evolving from a function traditionally centred on cost and delivery performance to one that contributes directly to climate strategy. Although its relative emission impact may be lower than that of upstream materials, its integration into net-zero roadmaps strengthens supply chain resilience, enhances transparency and supports the credibility of corporate decarbonisation pathways (World Economic Forum & Boston Consulting Group, 2021; McKinsey & Company, 2024).

2.2.5 Digital enablers

Digitalisation constitutes a cross-cutting enabler within the net-zero strategies of high-tech and off-highway companies. Whereas initiatives related to energy systems, material substitution or logistics optimisation target specific emission sources, digital technologies provide the infrastructure that allows these interventions to be measured, coordinated and scaled across complex supply chains. In industries characterised by global sourcing, multiple supplier tiers and high product complexity, the availability of reliable and granular data is a prerequisite for credible decarbonisation pathways (GHG Protocol, 2011; Hettler et al., 2024).

The growing relevance of digital enablers is closely linked to the evolution of methodological frameworks. The GHG Protocol establishes detailed requirements for emission accounting, while the SBTi demands measurable, science-aligned reduction trajectories. Translating these methodological requirements into operational practice requires robust digital systems capable of integrating heterogeneous datasets, defining organisational boundaries and tracking performance over time (GHG Protocol, 2011; Science Based Targets initiative, 2021).

A first area of transformation concerns carbon measurement and reporting. Companies are increasingly adopting digital carbon accounting platforms that consolidate data from production sites, logistics operators and upstream suppliers. These systems automate the application of emission factors, reduce manual reporting errors and enhance transparency in Scope 3 calculations. In sectors such as off-highway, where upstream emissions dominate, digital platforms are particularly relevant for improving data comparability and enabling structured supplier engagement (Hettler et al., 2024; Zaoui et al., 2026).

Beyond reporting, digitalisation directly supports operational optimisation. Industry 4.0 technologies — including IoT sensors, real-time monitoring systems and advanced analytics — allow firms to measure energy consumption, machine utilisation and process performance at high levels of detail. The integration of data analytics and artificial intelligence facilitates predictive maintenance, dynamic parameter adjustment and early identification of inefficiencies. In energy-intensive manufacturing contexts, these capabilities contribute not only to reduced emissions but also to improved operational stability and cost control (Ma et al., 2024; IEA, 2022).

Digital twins represent a further development in this trajectory. By creating virtual replicas of production systems, components or even entire supply chains, companies can simulate alternative configurations, evaluate logistics scenarios and test product design changes prior to physical implementation. In off-highway contexts, characterised by low production volumes and high product variety, simulation-based optimisation reduces material waste, shortens development cycles and improves energy performance at system level (Ma et al., 2024; Zaoui et al., 2026).

Digitalisation also plays a critical role in supply chain governance. Collaborative platforms increasingly enable suppliers to share environmental data in more structured and standardised formats, improving the quality of Scope 3 information and supporting coordinated reduction efforts. Research on digital supply chain orchestration highlights how the diffusion of digital tools across tiers can strengthen transparency, reduce information asymmetries and facilitate alignment of sustainability objectives (Shen et al., 2026; Zaoui et al., 2026). In this context, technologies such as distributed ledgers are being explored to enhance traceability of materials and components, although large-scale adoption remains uneven.

Finally, digital systems support organisational integration. Emission dashboards, scenario modelling tools and decision-support systems make environmental performance more visible to managers and facilitate the incorporation of climate-related criteria into procurement, design and operations decisions. The ability to link carbon metrics to financial and operational indicators contributes to embedding decarbonisation within routine management processes rather than treating it as a parallel reporting exercise (Hettler et al., 2024; Shen et al., 2026).

Overall, digital enablers should not be understood merely as technical add-ons to sustainability strategies. In high-tech and off-highway industries, they constitute the connective tissue that links measurement frameworks, operational processes and supply chain coordination. Their contribution lies not only in improving data quality, but in enabling the systematic integration of net-zero objectives into industrial decision-making across multiple organisational and geographical boundaries.

Table 8. Digital technologies enabling supply chain decarbonisation

Digital technology	Function	Decarbonisation impact
Carbon accounting platforms	Emission measurement	Improved Scope 3 transparency
IoT monitoring systems	Real-time energy tracking	Operational optimisation
Digital twins	Simulation of processes	Material and energy efficiency
Supply chain data platforms	Supplier collaboration	Better emissions reporting

2.3 Expected Impact and Maturity of the Strategies

The net-zero strategies adopted by high-tech and off-highway companies differ significantly in terms of expected emission impact and degree of maturity. These differences depend both on the nature of the intervention and on the segment of the supply chain involved. While all the levers discussed in the previous section contribute to decarbonisation, they vary in implementation complexity, diffusion across the sector and time horizon of impact.

Initiatives focused on energy and operations generally represent the most mature set of strategies. Energy efficiency measures, process electrification and renewable electricity procurement are already widely implemented in OEM and Tier-1 facilities, largely because they rely on consolidated technologies and often generate predictable economic returns (IEA, 2022). Their emission impact is particularly relevant for Scope 1 and Scope 2 categories, whereas their influence on Scope 3 emissions is mainly indirect, for example through improved upstream energy demand or supplier benchmarking (GHG Protocol, 2011). From a maturity perspective, these measures can be considered advanced within large firms, although their extension to Tier-2 and Tier-3 suppliers remains uneven.

Strategies related to materials and product innovation display a different profile. Their potential impact on overall emissions is substantial, given the structural weight of carbon-intensive materials such as steel and aluminium in off-highway systems (Material Economics, 2019; IEA, 2022). Low-carbon materials, lightweighting and product redesign can significantly reduce embedded emissions across the product life cycle. However, diffusion remains heterogeneous. Technological readiness, cost premiums, supply availability and stringent reliability requirements limit rapid adoption, particularly in heavy-duty applications. Empirical evidence from manufacturing case studies shows that early movers tend to concentrate on pilot projects or selected product lines rather than full portfolio transformation (Zhang et al., 2022; Shekarian et al., 2023). As a result, although the long-term emission potential is high, maturity remains moderate and uneven across tiers.

Circularity strategies occupy an intermediate position in both impact and maturity. Remanufacturing, refurbishment and recycling are well established for specific mechanical components with high residual value, especially in capital-intensive equipment sectors (Material Economics, 2019; Shekarian et al., 2023). However, scaling these models across the entire supply chain requires adjustments in product architecture, contractual arrangements and reverse logistics infrastructures. Literature reviews on Scope 3 management highlight that circularity often remains fragmented or limited to selected categories rather than systematically embedded across value chains (Borchardt et al., 2025). Consequently, while circular approaches offer structural reductions in demand for primary materials, their full decarbonisation potential depends on organisational transformation and cross-tier coordination.

Logistics strategies present a comparatively high technological maturity but a more limited relative impact. Measures such as modal shift, route optimisation and electrification of short-distance transport are technically available and increasingly implemented (IEA, 2022; McKinsey & Company, 2024). Nevertheless, in the off-highway sector their contribution to total emissions reduction is often secondary to upstream material production and component manufacturing. Logistics therefore functions primarily as a complementary lever within broader Scope 3 strategies rather than as a dominant decarbonisation driver.

Digital enablers occupy a distinctive position. Their technological maturity is high, but their emission impact is indirect. Digital platforms for carbon accounting, supplier data integration and process optimisation enhance the measurability and coordination of decarbonisation initiatives rather than generating reductions autonomously (GHG Protocol, 2011; Hettler et al., 2024). Reviews of Scope 3 governance underline that improvements in data quality and transparency represent necessary preconditions for structural emission reductions, yet they do not automatically translate into immediate quantitative results (Borchardt et al., 2025). The maturity of digital systems is therefore advanced at corporate level but still constrained by limited data reliability in upstream tiers.

Overall, the evidence suggests that net-zero strategies in the high-tech and off-highway sector do not evolve in a linear manner. Measures under direct organisational control tend to reach higher maturity earlier, whereas strategies with the greatest long-term emission impact—particularly those targeting upstream materials and systemic redesign—require deeper collaboration and longer implementation cycles. This creates a structural tension between climate ambition and execution capacity, especially in supply chains characterised by fragmentation and heterogeneous technological capabilities (World Economic Forum & Boston Consulting Group, 2021; Zhang et al., 2022).

Strategic planning must therefore combine short-term operational measures with medium- and long-term structural interventions. Recognising these differentiated maturity levels is essential for designing credible and realistic transition pathways. The issue of sequencing and timing of implementation is addressed in the following section.

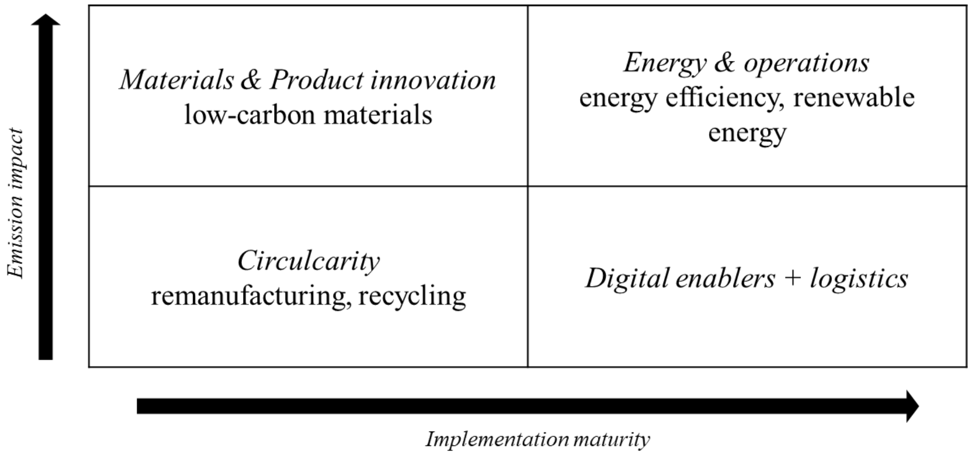


Figure 8. Maturity and emission impact of net-zero strategies in the off-highway supply chain

2.4 Implementation timelines

The definition and implementation of net-zero strategies in the high-tech and off-highway sector require explicit temporal planning, structured across short-, medium- and long-term horizons. This articulation is not merely descriptive. It reflects the need to align climate ambition with technological feasibility, capital allocation cycles and the adaptive capacity of a fragmented supply chain. In industrial systems characterised by high material intensity and strong interdependencies among actors, sequencing becomes a governance tool: it determines how investments are prioritised, how suppliers are engaged and how credibility towards regulators and investors is maintained.

2.4.1 Short term (2026–2028)

In the short term (2026–2028), strategies concentrate on measures that are technologically mature and organisationally manageable. The focus is on actions capable of generating measurable emission reductions without requiring structural redesign of products or supply networks.

Energy efficiency in production plants represents the primary lever. Optimisation of existing processes, upgrading of equipment and elimination of energy losses remain among the most cost-effective interventions in manufacturing environments (IEA, 2022). In parallel, renewable electricity procurement is typically accelerated, including the use of long-term purchasing agreements, so to reduce Scope 2 emissions and stabilise energy exposure.

On the materials side, short-term interventions usually involve increasing the share of recycled inputs where technical and regulatory constraints allow it. In heavy industrial applications, substitution possibilities are limited by performance requirements, but incremental improvements remain feasible (Material Economics, 2019).

At the same time, companies strengthen emission accounting systems in line with the GHG Protocol and prepare their targets for validation under the Science Based Targets initiative (GHG Protocol, 2011; Science Based Targets initiative, 2021). In this phase, investments in digital carbon management tools and structured engagement with Tier-1 suppliers to improve Scope 3 data quality are often included. Literature on Scope 3 reporting confirms that early stages of decarbonisation are frequently characterised by improvements in data transparency before large-scale emission reductions materialise (Hettler et al., 2024).

Hence, the short term serves as a consolidation phase: it delivers tangible results while building the organisational infrastructure required for more transformative interventions.

2.4.2 Medium term (2028–2030)

The medium term marks a shift from incremental optimisation to structural change. During this phase, companies begin to address the main emission drivers embedded in materials, product architecture and supply chain configuration.

Electrification of energy-intensive processes becomes more widespread where technically feasible, especially in facilities with stable production volumes (IEA, 2022). At the same time, collaboration with Tier-1 suppliers and material producers intensifies to secure access to lower-carbon steel and aluminium, whose decarbonisation pathways are already being industrially piloted (Material Economics, 2019).

Circularity strategies also tend to become more systematic in this period. Remanufacturing, advanced recycling and design for disassembly require coordinated adjustments in product development, contracts and reverse logistics. Case-based evidence suggests that such transformations demand multi-year alignment between OEMs and suppliers, particularly in capital goods sectors (Zhang et al., 2022).

Logistics strategies may also evolve beyond optimisation, including partial regionalisation of sourcing and initial deployment of low-emission transport solutions where infrastructure allows it (IEA, 2022). However, their quantitative impact typically remains secondary compared with upstream material decarbonisation.

Digitalisation expands from measurement to integration. Carbon data platforms, collaborative systems and advanced monitoring tools begin to cover a broader share of the supply chain, although upstream data reliability continues to present challenges (Hettler et al., 2024).

This phase is closely linked to the 2030 interim targets embedded in SBTi-aligned pathways (Science Based Targets initiative, 2021). Achieving these milestones depends not only on corporate ambition but also on supplier investment capacity and regulatory stability.

2.4.3 Long term (post 2030)

The post-2030 horizon corresponds to the consolidation of structural transformation. At this stage, strategies rely on the large-scale deployment of technologies that are currently emerging but considered essential for deep decarbonisation.

Among the most relevant developments is the diffusion of near-zero-carbon materials, including steel produced through low-emission routes and aluminium manufactured with renewable electricity (Material Economics, 2019). The availability and cost competitiveness of these materials will largely determine the feasibility of substantial Scope 3 reductions in heavy industrial sectors.

On the product side, a broader transition towards electric, hydrogen-based or advanced hybrid powertrains is expected in segments where operational constraints can be addressed (IEA, 2022). Such transitions imply not only technological substitution but redesign of machine architecture and energy infrastructure.

Logistics decarbonisation in the long term is likely to depend on systemic changes in transport fuels and infrastructure, rather than solely on firm-level optimisation.

Finally, residual emissions that cannot be eliminated through technological or organisational measures are neutralised in accordance with the criteria defined by the Science Based Targets initiative, which restricts compensation to a limited share of structurally unavoidable emissions (Science Based Targets initiative, 2021).

In this horizon, net zero ceases to be a project and becomes an embedded industrial configuration. Achieving it requires coordination across firms, suppliers, energy systems and policy frameworks. The timeline therefore reflects not only corporate planning cycles but the broader pace of technological and infrastructural transformation.

Table 9. Implementation timeline of net-zero strategies in the off-highway supply chain

Time horizon	Strategic focus	Main actions
Short term (2026–2028)	Operational optimisation	energy efficiency, renewable electricity, recycled materials, Scope 3 accounting
Medium term (2028–2030)	Supply chain transformation	low-carbon materials, electrification, circularity, supplier engagement
Long term (post-2030)	Technological transition	hydrogen powertrains, near-zero materials, systemic logistics decarbonisation

3. Innovative supply chain solutions and technologies to reduce Scope 3 emissions (RQ2)

3.1 Scope 3 emissions in the off-highway sector

As highlighted in the concluding part of Chapter 2, achieving net-zero objectives in the high-tech and off-highway sector depends to a decisive extent on companies' ability to address indirect emissions along the value chain (World Economic Forum & Boston Consulting Group, 2021; Borchardt et al., 2025).

Scope 3 emissions typically represent the largest share of corporate carbon footprints and constitute the most complex dimension of decarbonisation due to their multi-actor nature and governance challenges (GHG Protocol, 2011; Hettler et al., 2024). The management of Scope 3 therefore constitutes a critical test of the credibility and effectiveness of corporate decarbonisation roadmaps, as it involves processes and actors beyond firms' direct operational control (Hettler et al., 2024).

In the off-highway sector, Scope 3 emissions are strongly influenced by the material-intensive nature of products and by the complexity of their systems architecture. Agricultural, construction and mining machinery rely on massive load-bearing structures and energy-intensive metallic components. The production of primary steel and other carbon-intensive materials represents a major upstream emission hotspot (IEA, 2022; Arens et al., 2021; Poschmann et al., 2023). Unlike other manufacturing sectors, emission reductions cannot rely solely on miniaturisation or standardisation but require structural redesign and material innovation.

A distinctive feature of the off-highway sector is the strong interdependence between product design and supply chain configuration. Engineering decisions in early development phases – including material selection, tolerances and subsystem integration – shape supplier processes and embedded emissions over extended product lifecycles (McKinsey & Company, 2021; König et al., 2024). Scope 3 is therefore largely determined ex ante through design and sourcing choices that configure the value chain for years (Hettler et al., 2024).

The structure of the off-highway supply chain further amplifies complexity. Global value chains in capital goods industries are characterised by multi-tier fragmentation and specialised suppliers performing energy-intensive processing activities (Gereffi, 2018; Shekarian et al., 2023). Tier-2 and Tier-3 suppliers often remain partially invisible to OEMs while embedding significant shares of product emissions (Borchardt et al., 2025). Engaging these actors in decarbonisation programmes is particularly challenging where technical specificity limits rapid supplier substitution (Zhang et al., 2022).

Geographical heterogeneity further complicates emission reduction strategies. Suppliers frequently operate in regions with carbon-intensive electricity systems, which significantly influences embedded emissions in materials and components (Arens et al., 2021; IEA, 2022). As a consequence, uniform global decarbonisation approaches may produce uneven results across supply networks.

From an operational perspective, high product customisation and relatively low production volumes constrain economies of scale in decarbonisation investments. Case studies in the heavy vehicle and equipment industry confirm that sector-specific production models limit rapid diffusion of low-carbon materials and technologies (Shekarian et al., 2023). This constraint is reinforced by long product lifecycles and technological path dependencies that slow supply chain reconfiguration.

Data availability constitutes an additional barrier. Although the GHG Protocol provides structured Scope 3 accounting guidance (GHG Protocol, 2011), empirical evidence shows persistent gaps in supplier data quality, methodological consistency and digital integration (Hettler et al., 2024; Borchardt et al., 2025). Limited digital maturity among upstream actors further restricts traceability and transparency (Zaoui et al., 2026).

Overall, Scope 3 emissions in the off-highway sector represent not only a quantitative challenge linked to emission magnitude, but a structural challenge embedded in industrial organisation and supply chain governance (Gereffi, 2018; Hettler et al., 2024). Their reduction requires systemic integration of design innovation, material transition and coordinated multi-tier collaboration. In this perspective, Scope 3 becomes a proxy for the sector's capacity to transform its industrial model while preserving performance and reliability.

3.2 Enabling technologies and operational solutions

Reducing Scope 3 emissions in the off-highway sector requires coordinated technological and operational interventions addressing upstream emission drivers. In material-intensive industries, the majority of emissions originate along the value chain rather than within organisational boundaries (GHG Protocol, 2011; Borchardt et al., 2025). Consequently, approaches confined to direct operations are structurally insufficient.

Recent literature emphasises that effective Scope 3 mitigation depends on integrated strategies combining technological innovation, structured supplier collaboration and governance mechanisms capable of influencing multi-tier networks (Hettler et al., 2024). Isolated initiatives generate limited impact where emission sources are embedded in complex supply structures.

The solutions analysed below reflect the main technological trajectories relevant for off-highway supply chains, with attention to industrial feasibility and scalability across global value chains.

3.2.1 Low-carbon materials

The adoption of low-carbon materials constitutes one of the most significant levers for reducing upstream Scope 3 emissions in material-intensive industries. Heavy industrial value chains are characterised by high emission intensities in primary steel, aluminium and other structural metals (Arens et al., 2021; IEA, 2022).

Steel, cast iron and aluminium account for the majority of mass in off-highway machinery. Decarbonisation pathways for these materials include electrification with renewable energy, hydrogen-based direct reduction and carbon capture technologies (Material Economics, 2019; Arens et al., 2021). Empirical pathway modelling in automotive supply chains confirms that material substitution and process innovation in steel production represent central emission reduction hotspots (Poschmann et al., 2023).

Despite high theoretical potential, adoption in off-highway applications remains constrained. Mechanical robustness, fatigue resistance and long-term stability under extreme operating conditions impose strict qualification requirements. Industrial diffusion is further limited by scale availability and cost differentials relative to conventional materials (IEA, 2022).

Increasing recycled content represents an additional intervention pathway. Secondary aluminium and ferrous materials exhibit substantially lower embodied emissions compared to primary production. However, high-performance applications impose technical constraints related to material consistency, traceability and mechanical reliability. The transition toward higher recycled shares therefore requires coordinated design adaptation and supply chain integration.

Design optimisation complements material substitution strategies. Reducing total material demand through structural redesign, functional integration and geometry optimisation enables indirect and persistent Scope 3 reduction. Early-phase product development decisions determine long-term material flows and embedded emissions (König et al., 2024). Circular business model research further emphasises that product architecture redesign is a prerequisite for enabling resource efficiency and material loop closure (Geissdoerfer et al., 2020; Zils et al., 2023).

In the off-highway context, however, lightweighting and cross-section reduction are bounded by safety regulations and severe load conditions. This limits direct transferability of strategies developed in less demanding sectors and requires context-specific engineering solutions.

Low-carbon materials present high emission reduction potential but are subject to significant technological, economic and supply chain constraints. Their large-scale implementation depends on technological maturation in primary material production (Arens et al., 2021), systemic supply chain collaboration (Zhang et al., 2022) and alignment between design, sourcing and industrial validation cycles.

3.2.2 Advanced manufacturing

Advanced manufacturing technologies constitute a relevant lever for reducing Scope 3 emissions in material-intensive industries, as they enable improvements in energy and material efficiency across upstream production stages. In energy-intensive sectors, incremental gains in process efficiency can generate substantial cumulative emission reductions along supply chains (IEA, 2022; Ma et al., 2024).

In the off-highway context, advanced manufacturing primarily involves optimisation of machining operations, heat treatments, forming and assembly processes. Empirical studies in the heavy vehicle and equipment industry indicate that production systems are frequently configured around robustness and reliability, with limited historical focus on energy optimisation (Shekarian et al., 2023). The integration of high-efficiency machine tools, digital monitoring systems and data-driven process control can reduce material scrap, shorten cycle times and decrease energy consumption in critical stages (Ma et al., 2024; Zaoui et al., 2026).

Heat treatment processes represent a particularly energy-intensive phase in metallic component production. Industrial decarbonisation analyses emphasise that electrification, improved furnace efficiency and optimised thermal cycle management can significantly reduce unit energy consumption in heavy manufacturing (IEA, 2022; Arens et al., 2021). In the off-highway sector, however, metallurgical property requirements constrain process modification and necessitate extensive validation to preserve fatigue resistance and structural integrity (Shekarian et al., 2023).

Additive manufacturing represents an additional, though still selective, pathway. While large structural components typically remain unsuitable for additive production due to size and load constraints, the technology offers advantages for secondary or geometrically complex parts.

Advanced manufacturing literature highlights that additive approaches enable functional integration, reduced material waste and design-driven material efficiency (Ma et al., 2024; König et al., 2024). These characteristics may indirectly reduce Scope 3 emissions through lower raw material demand and simplified production chains.

Potential logistics benefits may also arise where distributed production reduces transport distances. However, empirical evidence in the heavy vehicle and equipment industry indicates that such applications are currently limited to specific components and pilot initiatives, rather than representing a systemic shift in production models (Shekarian et al., 2023).

Beyond direct efficiency gains, advanced manufacturing contributes through enhanced production flexibility. In highly customised, low-volume environments such as the off-highway sector, digitally enabled and reconfigurable systems allow adaptation to product variability without proportional increases in energy use (Zaoui et al., 2026; Shen et al., 2026). Digital orchestration across supply chains further facilitates alignment of production planning and sustainability objectives.

Despite tangible technical potential, diffusion remains gradual. Barriers include high capital requirements, limited digital capabilities among upstream suppliers and risk aversion in quality-critical industries (Koberg & Longoni, 2019).

Hence, advanced manufacturing represents a medium-term Scope 3 lever characterised by incremental but scalable improvements in upstream efficiency. Its impact depends on the integration of cleaner production technologies with sector-specific engineering constraints and on coordinated capability development across multiple supply chain tiers.

3.2.3 Logistics optimisation

Logistics constitutes a relevant contributor to Scope 3 emissions in globally dispersed supply chains, particularly in sectors characterised by heavy and volumetric goods. Transport-related emissions are amplified in capital goods industries where materials and semi-finished components move across multiple tiers and geographical regions (McKinsey & Company, 2024; Borchardt et al., 2025).

In the off-highway sector, logistics involves large structural elements and complex mechanical assemblies, which limit optimisation opportunities based solely on load densification or packaging efficiency. As a result, emission reduction strategies focus primarily on organisational and planning interventions rather than radical modal shifts.

Operational optimisation includes rationalisation of logistics flows, reduction of redundant routes and improved coordination across procurement, production and assembly nodes. Digital supply chain integration enhances visibility and planning accuracy, reducing urgent or fragmented shipments that are typically associated with disproportionate emission intensity (Zaoui et al., 2026; Shen et al., 2026). Logistics decarbonisation studies confirm that improved network design and planning discipline can generate measurable short-term emission reductions without structural redesign of transport systems (McKinsey & Company, 2024).

Recent debate also emphasises the potential role of regionalisation and sourcing adjustments. Global value chain research shows that supplier location patterns often reflect historical cost optimisation and capability clustering rather than environmental considerations (Gereffi, 2018). Where technically feasible, partial localisation of suppliers closer to assembly operations may reduce transport distances and exposure to carbon-intensive intercontinental freight (IEA, 2022; Zhang et al., 2022).

However, in the off-highway sector, high supplier specialisation and dependence on niche competences constrain rapid relocation strategies (Shekarian et al., 2023). Governance literature further highlights that restructuring sourcing networks requires careful risk management and due diligence alignment (Both & Wilhelm, 2025).

Technological interventions in transport assets offer additional but more limited opportunities. The electrification of intra-plant logistics and short-distance regional transport represents one of the most immediately applicable measures (IEA, 2022). By contrast, long-distance freight decarbonisation remains constrained by technological maturity, infrastructure availability and cost considerations (McKinsey & Company, 2024).

Alternative fuels for heavy-duty transport are gaining strategic attention, yet their diffusion remains conditional on systemic infrastructure development and fleet compatibility (IEA, 2022). Consequently, in the short to medium term, the most realistic contribution of logistics to Scope 3 reduction derives from process optimisation and network efficiency rather than full technological substitution.

Logistics optimisation represents a complementary lever capable of delivering incremental Scope 3 reductions while simultaneously enhancing operational resilience and coordination. Nevertheless, its structural mitigation potential remains lower than that associated with material and production transformations, reinforcing the need for integrated, multi-lever decarbonisation strategies across the off-highway supply chain (Borchardt et al., 2025; Hettler et al., 2024).

3.2.4 Digital tracking and data platforms

Digital tracking and data management platforms constitute the enabling infrastructure through which Scope 3 emission reduction measures can be operationalised across complex supply chains. While they do not directly reduce emissions, they are essential for rendering emissions measurable, comparable and governable in accordance with international reporting standards (GHG Protocol, 2011; Hettler et al., 2024).

Scope 3 literature consistently identifies limited visibility beyond Tier-1 suppliers as a central obstacle to effective decarbonisation (Borchardt et al., 2025). In multi-tier industrial networks such as the off-highway sector, emission-relevant data are distributed across heterogeneous actors with differing digital maturity and reporting capabilities. Structured digital platforms enable aggregation and harmonisation of data on materials, production processes and logistics flows, thereby supporting environmentally informed procurement and sourcing decisions (GHG Protocol, 2011; Praeger et al., 2025).

A distinctive feature of the off-highway sector lies in the technical specificity of emission-relevant data. Material grades, surface treatments, heat cycles and customised product configurations directly influence embodied emissions. Bottom-up accounting research demonstrates that granular, process-level data are necessary for accurate Scope 3 quantification, yet difficult to standardise across actors (Praeger et al., 2025). This technical complexity limits the applicability of generic digital solutions and necessitates tailored integration approaches.

Digital platforms further enable new forms of supply chain coordination. Data transparency supports joint target setting, performance monitoring and identification of emission hotspots requiring collaborative intervention (Hettler et al., 2024). In sectors characterised by high supplier specialisation and limited substitutability, collaborative governance mechanisms are more effective than purely prescriptive compliance approaches (Both & Wilhelm, 2025).

Digital supply chain literature highlights that orchestration mechanisms and shared data infrastructures facilitate sustainability diffusion across tiers (Shen et al., 2026; Zaoui et al., 2026). However, inter-firm power asymmetries and dependence structures may influence willingness to share data and invest in transparency, affecting the effectiveness of digital platforms (Bag et al., 2024).

The integration of advanced analytical tools, including predictive modelling and digital twins applied to supply chain configurations, represents a further evolution. Such tools enable simulation of alternative sourcing or design scenarios and ex ante evaluation of emission implications (Ma et al., 2024; Shen et al., 2026). Their practical effectiveness, however, depends on data completeness, interoperability and methodological consistency—conditions that remain unevenly fulfilled in complex industrial contexts.

In conclusion, digital tracking platforms constitute an indispensable enabling layer for Scope 3 management. By reducing information asymmetries and supporting coordinated decision-making, they enhance the effectiveness of material, production and logistics interventions. Nevertheless, their diffusion depends not only on technological investment but also on the development of shared standards, governance structures and supplier capabilities across the value chain (Hettler et al., 2024; Borchardt et al., 2025).

Table 10. Scope 3 reduction technologies and operational solutions

Solution category	Example technologies	Scope 3 relevance
Low-carbon materials	green steel, recycled aluminium	Very high
Advanced manufacturing	energy-efficient machining, additive manufacturing	Medium
Logistics optimisation	route optimisation, modal shift	Low-medium
Digital tracking platforms	carbon accounting platforms, supply chain data systems	Enabling

3.3 Barriers to adoption and critical constraints

Despite the increasing availability of technological and operational levers for Scope 3 reduction, diffusion within the off-highway sector remains uneven. While several solutions display substantial theoretical mitigation potential, their large-scale implementation is constrained by structural, technological and governance-related barriers.

Understanding these constraints is essential for assessing the practical feasibility of net-zero strategies and explaining heterogeneity in maturity across supply chain tiers (Hettler et al., 2024; Borchardt et al., 2025).

3.3.1 Barriers related to low-carbon materials

In the off-highway sector, the adoption of low-carbon materials is primarily constrained by technological and performance-related requirements inherent to heavy-duty applications. Structural components must ensure high mechanical strength, fatigue resistance and durability under extreme operating conditions. Decarbonisation pathways in hard-to-abate material sectors such as steel and aluminium remain technologically demanding and unevenly mature (IEA, 2022; Arens et al., 2021).

Although modelling studies demonstrate significant emission reduction potential through low-carbon steel pathways (Poschmann et al., 2023), industrial readiness varies across production technologies and geographical contexts. In applications characterised by high cyclic loads and safety-critical performance, OEMs exhibit risk aversion toward materials lacking long-term validation.

A distinctive constraint in the off-highway domain concerns extended validation cycles. The introduction of alternative materials requires multi-year laboratory testing, field validation and qualification procedures. Empirical evidence from the heavy vehicle and equipment industry indicates that product reliability considerations substantially slow the diffusion of process and material innovations (Shekarian et al., 2023). Global value chain research further highlights that upgrading trajectories in capital-intensive industries are path-dependent and resistant to abrupt technological shifts (Gereffi, 2018).

Economic barriers compound technological constraints. Low-carbon materials currently entail cost premiums due to limited production capacity, incomplete economies of scale and high capital investment in new production technologies (Material Economics, 2019; IEA, 2022). In supply chains characterised by margin pressure and cost sensitivity, these differentials create adoption reluctance. Studies on supply chain decarbonisation barriers confirm that cost allocation and uncertain return on investment represent major obstacles, particularly for upstream suppliers with limited bargaining power (Bag et al., 2024).

Availability and supply continuity constitute additional concerns. Production of low-emission materials remains geographically concentrated and capacity-constrained, generating uncertainty regarding long-term volume stability (Arens et al., 2021). In sectors characterised by long product platform cycles, such uncertainty increases perceived operational risk and discourages binding long-term commitments.

Organisational and contractual complexities further inhibit diffusion. Adoption of alternative materials requires coordinated specification alignment, risk-sharing mechanisms and contractual adaptation across OEMs, Tier-1 suppliers and material producers. Literature on supply chain sustainability governance indicates that reallocating technological and financial risk across tiers is institutionally complex and dependent on trust, power balance and regulatory pressure (Both & Wilhelm, 2025; Hettler et al., 2024).

Finally, measurement uncertainty affects the business case for adoption. Variability in carbon accounting methodologies and limited availability of primary process-level data complicate comparison between material alternatives (GHG Protocol, 2011; Praeger et al., 2025). Scope 3 management studies emphasise that inconsistent data quality across suppliers weakens investment incentives in low-carbon materials (Borchardt et al., 2025).

Low-carbon materials then represent a strategically central but structurally constrained decarbonisation lever in the off-highway sector. Technological maturity gaps, economic premiums, governance complexity and informational uncertainty jointly explain their gradual and selective diffusion. Large-scale adoption is therefore likely to depend on continued technological development, expansion of industrial capacity and strengthened coordination mechanisms across supply chain tiers.

3.3.2 Barriers related to advanced manufacturing

In the off-highway sector, the diffusion of advanced manufacturing technologies is primarily constrained by implementation complexity and high upfront capital requirements. Although such technologies offer improvements in energy efficiency and waste reduction, their integration frequently requires upgrading or replacing existing production assets. In capital-intensive industries, asset specificity and sunk costs create structural resistance to technological substitution (Gereffi, 2018).

Many Tier-2 and Tier-3 suppliers operate with highly customised equipment tailored to specific processes and product requirements. Empirical evidence from the heavy vehicle and equipment industry indicates that production systems are often optimised for robustness and reliability rather than energy efficiency, and that existing assets are frequently fully amortised (Shekarian et al., 2023). Under these conditions, investments in advanced manufacturing are difficult to justify without long-term volume guarantees or contractual stability.

Quality assurance and reliability constraints further limit adoption. Off-highway components must meet stringent standards in terms of precision, durability and performance under extreme operating conditions. The introduction of alternative production processes therefore entails extensive validation and qualification procedures. Sector-specific studies highlight that reliability considerations significantly slow the implementation of novel manufacturing technologies in safety-critical applications (Shekarian et al., 2023).

Economic uncertainty compounds these barriers. Decarbonisation literature identifies uncertain return on investment and lack of clear cost allocation mechanisms as central obstacles to supply chain-level innovation (Zhang et al., 2022; Koberg & Longoni, 2019). In multi-tier supply chains, upstream suppliers may lack incentives to invest where emission reduction benefits accrue primarily to downstream OEMs.

Competence-related constraints also emerge. Advanced manufacturing and digitally integrated processes require skilled personnel, data integration capabilities and organisational adaptation. Industry 4.0 literature emphasises that successful implementation depends on technological readiness and workforce capabilities (Ma et al., 2024). In supply chains characterised by a high share of SMEs, resource and capability gaps may significantly slow diffusion (Zaoui et al., 2026; Koberg & Longoni, 2019).

Product variability and low production volumes constitute additional structural constraints. The off-highway sector is characterised by high customisation and frequent product variants, limiting economies of scale associated with process standardisation. Empirical analyses in heavy equipment manufacturing confirm that low-volume production reduces the economic attractiveness of large-scale process optimisation investments (Shekarian et al., 2023).

Finally, limited coordination capacity across tiers constrains systemic adoption. While OEMs may recognise the emission reduction potential of advanced manufacturing, they primarily exercise indirect influence over upstream suppliers. Governance research on supply chain sustainability indicates that diffusion of innovation depends on incentive alignment, contractual mechanisms and orchestration capacity (Hettler et al., 2024; Both & Wilhelm, 2025). Digital orchestration mechanisms can facilitate coordination, yet require trust, data sharing and aligned strategic priorities (Shen et al., 2026).

Overall, advanced manufacturing technologies constitute a relevant but structurally constrained lever for Scope 3 reduction in the off-highway sector. Asset specificity, economic uncertainty, competence gaps and coordination challenges jointly explain why diffusion remains incremental rather than systemic.

3.3.3 Barriers Related to logistics optimisation

In the off-highway sector, logistics decarbonisation is constrained by infrastructural, structural and operational barriers. The transport of large, heavy and often non-standardised components limits flexibility in modal choice and reduces applicability of certain low-emission logistics solutions common in lighter manufacturing sectors (Shekarian et al., 2023; McKinsey & Company, 2024).

A first constraint concerns infrastructure availability. The diffusion of electric and alternative fuel vehicles depends on charging networks, refuelling systems and compatibility with heavy-duty transport requirements. Analyses of industrial decarbonisation pathways indicate that infrastructure for low-emission freight remains unevenly developed across regions (IEA, 2022). Consequently, adoption is frequently confined to intra-plant logistics or short-distance regional routes rather than long-haul transport (McKinsey & Company, 2024).

Global value chain configuration further constrains regionalisation strategies. Off-highway supply networks are shaped by long-term specialisation patterns, clustering of technical competences and access to raw materials (Gereffi, 2018). Reconfiguring sourcing geography for environmental reasons alone may compromise cost efficiency, quality consistency or supply continuity. Empirical case studies on supply chain decarbonisation confirm that relocation strategies face structural and contractual barriers (Zhang et al., 2022).

Operational complexity constitutes an additional limitation. High product customisation, low volumes and frequent configuration changes complicate transport planning and reduce opportunities for load consolidation. Sector-specific evidence from heavy equipment manufacturing shows that flexibility and delivery reliability often prevail over environmental optimisation in made-to-order contexts (Shekarian et al., 2023; Koberg & Longoni, 2019).

Economic barriers reinforce these constraints. Transitioning to lower-emission logistics solutions frequently entails additional costs related to vehicle acquisition, fuel premiums or specialised services. Studies on supply chain sustainability adoption highlight that cost allocation and uneven distribution of benefits discourage upstream actors from investing in decarbonisation measures (Bag et al., 2024). In the absence of structured incentive mechanisms or contractual support, logistics transformation remains limited.

A further structural factor concerns the relative contribution of logistics to total Scope 3 emissions. Scope 3 literature indicates that, in material-intensive industries, upstream material production often dominates the emission profile, while transport represents a smaller share (Borchardt et al., 2025). Logistics decarbonisation studies similarly suggest that while transport emissions are significant, they rarely constitute the primary hotspot compared with energy-intensive material processes (McKinsey & Company, 2024). This distribution may reduce the strategic priority assigned to logistics interventions relative to material or production transformations.

Logistics optimisation in the off-highway sector presents tangible but structurally bounded mitigation potential. Infrastructural gaps, global value chain rigidity, operational complexity and economic disincentives limit rapid and systemic transformation. Consequently, logistics should be considered a complementary lever within an integrated Scope 3 decarbonisation strategy rather than a standalone solution capable of addressing the sector’s principal emission drivers.

3.3.4 Barriers related to digital tracking and data platforms

Despite their enabling role in Scope 3 emission management, digital tracking platforms face significant technical, organisational and governance-related barriers in the off-highway supply chain.

A primary constraint concerns data availability and quality in deeper supply chain tiers. Scope 3 literature consistently identifies limited transparency beyond Tier-1 suppliers as a major obstacle to effective decarbonisation (Hettler et al., 2024; Borchardt et al., 2025). Many Tier-2 and Tier-3 suppliers operate with heterogeneous or insufficiently structured information systems, which are not designed for systematic environmental data collection. As a result, primary emission data are frequently incomplete or inconsistent.

These difficulties are amplified by the technical specificity of off-highway products. Emission intensity depends on detailed production parameters, including machining cycles, heat treatments and customised configurations. Bottom-up accounting research demonstrates that accurate Scope 3 calculation requires granular process-level data, yet such data are rarely standardised across supply chain actors (Praeger et al., 2025). In practice, companies often rely on secondary emission factors and proxies, reducing analytical precision and limiting the strategic usefulness of digital platforms (GHG Protocol, 2011; Borchardt et al., 2025).

Interoperability challenges further constrain implementation. Supply chain actors employ diverse ERP systems and digital infrastructures that are seldom designed for seamless integration. Digital supply chain research emphasises that sustainability diffusion requires interoperable data architectures and coordinated orchestration mechanisms (Shen et al., 2026; Zaoui et al., 2026). In their absence, data aggregation and validation become resource-intensive, particularly in relationships with smaller suppliers.

Governance and confidentiality concerns represent additional barriers. Sharing detailed process and emission data may expose sensitive operational information. Studies on supply chain sustainability governance indicate that data transparency depends on trust, contractual safeguards and balanced power relationships (Both & Wilhelm, 2025). Power asymmetries and opportunistic behaviour can further inhibit voluntary data disclosure (Bag et al., 2024). In highly specialised off-highway supply networks, such concerns may slow adoption of shared digital infrastructures.

Organisational capacity constitutes another limiting factor. Effective use of digital platforms requires competences in environmental accounting, data analytics and cross-functional coordination. Scope 3 research highlights that internal capability gaps frequently undermine the translation of data collection into concrete emission reduction actions (Hettler et al., 2024). Finally, alignment with external reporting frameworks increases complexity. Data generated by digital systems must be consistent with established methodologies such as the GHG Protocol (2011) and target-setting requirements defined by the Science Based Targets initiative (Science Based Targets initiative, 2021). In sectors characterised by heterogeneous data sources and multi-tier supply chains, ensuring methodological consistency entails substantial managerial effort.

Overall, digital tracking platforms are a necessary but not self-sufficient condition for effective Scope 3 management. Their effectiveness depends on digital maturity, standardisation, governance alignment and supplier capability development across the supply chain (Borchardt et al., 2025; Shen et al., 2026). Without progress in these areas, digitalisation risks remaining confined to reporting functions rather than enabling structural decarbonisation.

3.3.5 Cross-cutting constraints and systemic challenges

Beyond solution-specific barriers, the decarbonisation of the off-highway supply chain is shaped by systemic constraints rooted in value chain governance structures, economic incentives and organisational dynamics.

A central cross-cutting constraint concerns the asymmetry between responsibility and intervention capacity. OEMs and major Tier-1 suppliers are accountable for Scope 3 reporting and target setting, yet a substantial share of emissions originates in upstream tiers over which they exert limited direct control. Scope 3 governance literature identifies this structural asymmetry as a core challenge in multi-tier supply chains (Hettler et al., 2024; Borchardt et al., 2025). From a global value chain perspective, governance power is distributed unevenly, and coordination mechanisms depend on contractual arrangements and relational capabilities rather than hierarchical control (Gereffi, 2018).

A second systemic constraint relates to temporal misalignment between decarbonisation objectives and investment horizons. Supply chain emission reduction often requires substantial upfront investment in technologies, materials and coordination mechanisms, while benefits materialise over extended timeframes. Studies on supply chain decarbonisation barriers emphasise uncertainty regarding return on investment and risk allocation as critical deterrents (Zhang et al., 2022). In cyclical capital goods industries, where market volatility influences investment decisions, such temporal asymmetry further limits willingness to commit long-term resources.

Heterogeneity across supply chain actors constitutes an additional structural barrier. Suppliers differ significantly in technological maturity, financial capacity and environmental awareness. Research on sustainable supply chain management highlights that uneven capabilities impede coordinated implementation and reduce scalability of sustainability initiatives (Koberg & Longoni, 2019; Shen et al., 2026). As a result, progress tends to be fragmented, with advanced actors moving faster than less mature tiers.

Organisational and cultural dimensions further shape diffusion dynamics. Scope 3 reduction requires a shift from transactional supplier management towards collaborative and strategically aligned relationships. Circular business model research underscores that sustainability integration necessitates reconfiguration of value creation logics and inter-organisational relationships (Geissdoerfer et al., 2020). Governance studies indicate that effective transformation depends on incentive alignment, trust and regulatory pressure (Both & Wilhelm, 2025). Power asymmetries and dependence structures may either facilitate or hinder such transformation (Bag et al., 2024).

Internal alignment also represents a critical success factor. The integration of environmental objectives into procurement, engineering and operations requires cross-functional coordination and strategic consistency. Scope 3 literature emphasises that fragmented organisational structures and misaligned incentives reduce the effectiveness of emission reduction initiatives (Hettler et al., 2024; Borchardt et al., 2025).

Cross-cutting constraints demonstrate that Scope 3 decarbonisation in the off-highway sector cannot be achieved solely through isolated technological interventions. Structural transformation of governance mechanisms, incentive systems and organisational processes is required to translate technical potential into systemic impact. Recognising these systemic limitations provides a necessary foundation for the critical synthesis developed in Section 3.4.

Table 11. Barriers affecting Scope 3 decarbonisation solutions

Solution	Technological barriers	Economic barriers	Governance barriers
Low-carbon materials	validation cycles	cost premium	supplier coordination
Advanced manufacturing	asset specificity	capital investment	supplier capabilities
Logistics optimisation	infrastructure limits	fuel cost	supply network rigidity
Digital platforms	data gaps	implementation cost	data governance

3.4 Synthesis of findings

The combined analysis of technological and operational solutions, together with the barriers constraining their adoption, reveals a structural tension between climate ambition and industrial feasibility in the off-highway sector. While significant emission reduction potential exists across upstream material production, manufacturing and logistics processes, implementation remains uneven and strongly conditioned by technological maturity, governance structures and economic constraints.

A first key element emerging from the synthesis concerns the inverse relationship between theoretical mitigation potential and short-term implementability. Interventions with the highest expected impact—particularly low-carbon material substitution and transformation of energy-intensive upstream production processes—are also those most constrained by technological readiness, cost premiums and long industrial validation cycles (Arens et al., 2021; Poschmann et al., 2023; Shekarian et al., 2023). Decarbonisation pathways in hard-to-abate material sectors require structural shifts that cannot be rapidly scaled across multi-tier supply chains.

Conversely, solutions characterised by higher maturity and lower implementation barriers—such as logistics optimisation and digital monitoring systems—tend to generate more incremental reductions. Although their individual mitigation potential is limited relative to material transformation, they contribute to cumulative progress and enable improved coordination across the supply chain (Borchardt et al., 2025; McKinsey & Company, 2024).

This pattern is particularly pronounced in the off-highway sector, where dependence on carbon-intensive structural materials, safety-critical performance requirements and long product life cycles slow the diffusion of radical innovations. From a global value chain perspective, such sectors exhibit path dependency and high asset specificity, which moderate transition speed (Gereffi, 2018). As a result, Scope 3 reduction pathways are non-linear and distributed over time, requiring differentiated strategies across supply chain tiers (Hettler et al., 2024).

A second central element concerns the systemic nature of Scope 3 emissions. Emission reduction does not derive from isolated technological interventions but from interdependent decisions involving design, material selection, process configuration, logistics structures and governance mechanisms (Borchardt et al., 2025). Digital platforms perform a crucial enabling function by enhancing transparency and coordination, yet their effectiveness depends on supplier engagement and organisational alignment rather than purely technological deployment (Shen et al., 2026).

The synthesis further highlights the strategic role of OEMs and major Tier-1 suppliers as orchestrators of transition processes. Although emissions are largely embedded upstream, downstream actors shape specifications, sourcing criteria and investment signals. Governance literature emphasises that effective decarbonisation depends on incentive alignment, risk-sharing mechanisms and collaborative relationships across tiers (Gereffi, 2018; Both & Wilhelm, 2025; Hettler et al., 2024).

From a temporal perspective, the interaction between high-impact but slow-moving levers and rapidly deployable incremental measures underscores the need for multi-horizon strategies. Early-stage actions can generate immediate improvements and build organisational capabilities, while long-term investments in material and process transformation are indispensable for achieving net-zero trajectories (Zhang et al., 2022; Arens et al., 2021).

Scope 3 emission reduction in the off-highway sector cannot be framed as a purely technical optimisation problem. It requires coordinated transformation of industrial models, governance structures and inter-organisational relationships. Technological solutions are progressively maturing, yet their systemic impact depends on the capacity of supply chain actors to address structural barriers and align incentives across tiers.

This interpretative framework provides the conceptual bridge toward the empirical analysis developed in Chapter 4, where the case of Bosch Mobility will be examined to assess how a leading sector actor navigates the trade-offs between ambition and feasibility within the constraints identified in this chapter.

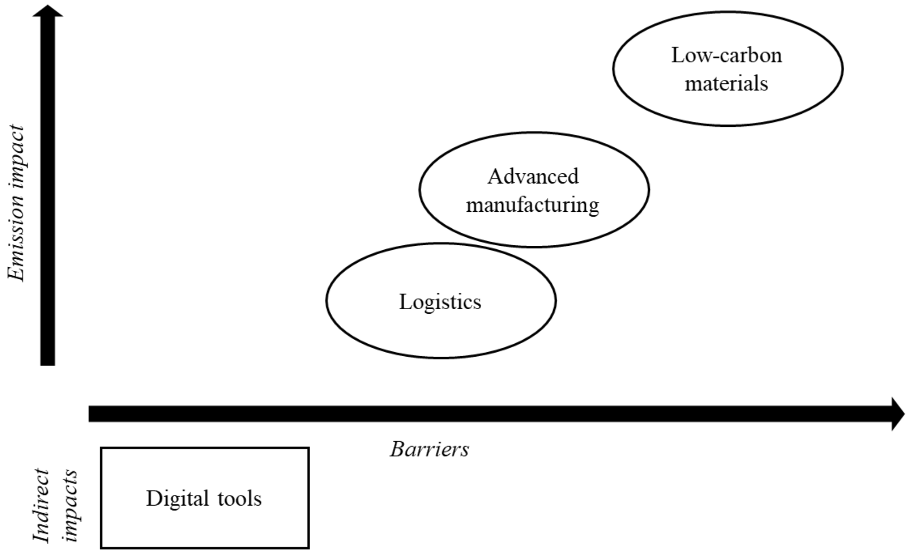


Figure 9. Scope 3 solutions: impact vs implementation barriers

4. Case Study: Bosch Mobility

4.1 Bosch Mobility’s Sustainability Framework

Bosch Mobility’s sustainability framework is embedded within the broader climate strategy of the Bosch Group, which has articulated long-term objectives oriented towards carbon neutrality and the progressive extension of decarbonisation initiatives along the value chain (Bosch, 2023).

The present analysis does not focus on declarative commitments, but rather on the structural configuration of the framework and the mechanisms through which climate objectives are governed and operationalised within the Mobility division. Particular attention is devoted to the implications for Scope 3 emission management in the off-highway supply chain (Bosch, 2023; Hettler et al., 2024).

4.1.1 Strategic intent and scope of application

From a strategic perspective, Bosch Mobility aligns its climate targets with established international standards, using recognised accounting and target-setting frameworks as methodological references (Bosch, 2023; GHG Protocol, 2011; Science Based Targets initiative, 2021). Consistent with broader corporate decarbonisation patterns, initial emphasis is placed on Scope 1 and Scope 2 reductions, followed by a progressive extension toward Scope 3 categories (Hettler et al., 2024).

In the off-highway context, this extension appears selective and gradual. Although indirect emissions represent a substantial share of the total carbon footprint in material-intensive sectors (Borchardt et al., 2025), the operational scope of intervention is initially delimited to categories considered both material and comparatively manageable. This prioritisation reflects a staged implementation logic frequently observed in supply chain decarbonisation strategies, where feasibility constraints influence sequencing of action (Zhang et al., 2022).

The resulting framework thus reveals a pragmatic orientation: long-term climate ambition is maintained at corporate level, while operational deployment in complex supply chains proceeds incrementally, balancing environmental objectives with technological maturity, governance capacity and economic constraints (Bosch, 2023; Both & Wilhelm, 2025).

4.1.2 Governance and decision-making processes

Sustainability governance within Bosch Mobility follows a hybrid configuration. Strategic guidelines, climate targets and reporting requirements are defined at Group level, while implementation responsibilities are distributed across operational divisions and corporate functions, particularly procurement and supply chain management (Bosch, 2023; Bosch, 2024). This structure preserves strategic coherence while allowing contextual adaptation. However, it also generates heterogeneity in implementation practices. In the off-highway context, governance is shaped by a structural asymmetry: downstream actors define and report Scope 3 targets, yet a substantial share of emissions originates upstream, beyond their direct operational control. Scope 3 literature identifies this asymmetry as a central governance challenge in multi-tier supply chains (Hettler et al., 2024; Borchardt et al., 2025).

From a global value chain perspective, coordination in fragmented industrial networks relies less on hierarchical authority and more on relational and contractual governance mechanisms (Gereffi, 2018). Consequently, Bosch Mobility's framework must operate within structural limits: while strategic responsibility is concentrated downstream, intervention capacity depends on negotiation, incentives and collaboration with specialised upstream suppliers.

4.1.3 Structure of instruments and implementation logic

Bosch Mobility's sustainability framework comprises instruments designed to integrate environmental criteria into existing decision-making structures rather than substitute them. Corporate policies, ESG criteria and transparency requirements embed sustainability considerations into procurement and supply chain processes (Bosch, 2023; Bosch, 2024). These mechanisms primarily function as coordination and influence tools rather than direct command-and-control instruments.

This configuration is particularly salient in the off-highway sector, where supplier specialisation and limited substitutability constrain coercive leverage. Empirical studies in the heavy vehicle and equipment industry confirm that high technical specificity reduces the feasibility of rapid supplier replacement (Shekarian et al., 2023). Global value chain theory further highlights how asset specificity and capability concentration shape power relations and limit unilateral intervention (Gereffi, 2018).

Under such conditions, sustainability governance tends to rely on collaborative mechanisms and incentive alignment. Research on supply chain sustainability governance indicates that long-term relational approaches and shared value creation logics are more effective than purely prescriptive compliance models (Both & Wilhelm, 2025; Hettler et al., 2024). Power asymmetries and dependence structures may influence the effectiveness of these mechanisms, requiring careful design of incentives and engagement strategies (Bag et al., 2024).

Accordingly, the framework adopted by Bosch Mobility reflects a progressive implementation logic: rather than imposing abrupt requirements, it seeks to integrate environmental criteria into existing supplier relationships through gradual alignment of expectations, monitoring and strategic coordination.

4.1.4 Control, influence and structural limitations

The analysis of Bosch Mobility's framework reveals a clear distinction between areas subject to direct managerial control and those governed primarily through influence. Emissions generated within organisational boundaries can be addressed through operational decisions and direct capital allocation, whereas Scope 3 emissions depend on supplier practices and multi-tier coordination mechanisms (Bosch, 2023).

Scope 3 governance literature identifies this structural asymmetry as a defining characteristic of supply chain decarbonisation: reporting responsibility lies downstream, while emission sources are frequently embedded upstream (Hettler et al., 2024; Borchardt et al., 2025). From a global value chain perspective, such asymmetry reflects distributed governance structures and limited hierarchical authority over specialised suppliers (Gereffi, 2018).

In the off-highway sector, these constraints are intensified by structural characteristics including long product life cycles, high material intensity and reliance on energy-intensive industrial processes (Arens et al., 2021; Poschmann et al., 2023; Shekarian et al., 2023). These features limit the speed and scope of radical transformation.

The framework implicitly reflects these structural limits by adopting a gradual implementation logic, prioritising technological maturity, operational continuity and risk mitigation over abrupt intervention. Empirical research on supply chain decarbonisation barriers highlights that path dependency, investment risk and asset specificity frequently slow large-scale technological substitution in heavy industrial contexts (Zhang et al., 2022; Gereffi, 2018).

4.1.5 Trade-offs and managerial Implications

Bosch Mobility's sustainability framework embodies the trade-offs inherent in sustainability management within complex industrial systems. Integrating climate objectives into decision-making requires balancing environmental ambition with technical performance, safety standards and economic competitiveness. Sector-specific research confirms that in heavy equipment industries such trade-offs are particularly acute due to stringent reliability requirements and cost pressures (Shekarian et al., 2023; Koberg & Longoni, 2019).

Decarbonisation in this context therefore unfolds as a progressive transformation rather than a disruptive shift. Investment uncertainty, long validation cycles and inter-organisational coordination challenges moderate the pace of change (Zhang et al., 2022).

Taken as a whole, the framework provides a coherent structure for guiding the transition toward net-zero objectives, while simultaneously exposing intrinsic limitations—particularly in Scope 3 management, where intervention capacity remains structurally mediated by supplier relationships (Hettler et al., 2024; Borchardt et al., 2025).

These considerations provide the foundation for the subsequent sections. Section 4.2 examines how strategic intent is translated into operational supply chain practices, while Section 4.3 analyses the concrete technologies and initiatives deployed to address indirect emissions. The empirical insights derived from this analysis will inform the roadmap proposed in Chapter 5.

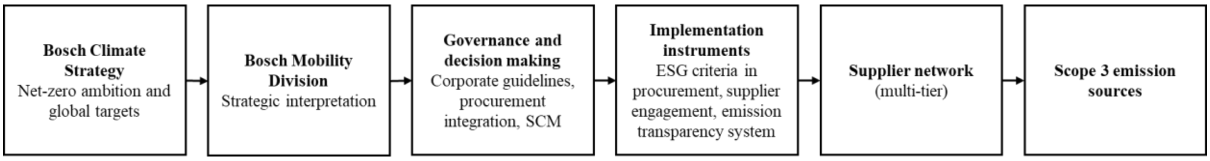


Figure 10. Bosch Mobility sustainability governance framework

4.2. Application of RQ1: Bosch net-zero strategy in the supply chain

This section applies the first research question to the Bosch Mobility case, analysing how the corporate-level net-zero strategy is translated into supply chain governance within the off-highway context.

The focus is not on evaluating technical performance of specific solutions, but on examining the strategic and organisational logics through which climate objectives are extended along a multi-tier industrial value chain characterised by limited direct control over emission sources.

4.2.1 Strategic intent: adaptation of net-zero standards to the off-highway context

From a strategic standpoint, Bosch Mobility aligns its climate targets with established international standards, using recognised accounting and target-setting frameworks as methodological references (GHG Protocol, 2011; Science Based Targets initiative, 2021).

However, case evidence indicates that adherence to these frameworks does not result in uniform and prescriptive implementation across the supply chain. Instead, the approach reflects progressive adaptation to sector-specific constraints. Scope 3 governance literature highlights that companies frequently interpret international standards as directional frameworks, sequencing implementation according to feasibility and control capacity (Hettler et al., 2024; Borchardt et al., 2025).

The strategy reveals a distinction between long-term ambition—encompassing life-cycle emission reduction—and short- to medium-term trajectories shaped by technological maturity, asset specificity and economic constraints. Research on industrial decarbonisation in hard-to-abate sectors confirms that structural characteristics such as material intensity and capital intensity necessitate staged transition pathways (Arens et al., 2021; Zhang et al., 2022).

From a global value chain perspective, such adaptation reflects path-dependent industrial structures in which radical transformation cannot be imposed uniformly across tiers (Gereffi, 2018). Net-zero frameworks therefore function less as rigid compliance templates and more as strategic orientation devices, whose operationalisation depends on sectoral feasibility and governance capacity (Hettler et al., 2024).

4.2.2 Governance: translation of climate targets into supply chain strategy

The translation of climate objectives into supply chain strategy reflects the hybrid governance architecture outlined in Section 4.1. Corporate-level targets provide strategic direction, while procurement and supply chain management functions operationalise these objectives within business divisions (Bosch, 2023; Bosch, 2024).

Scope 3 governance literature emphasises that such distributed implementation structures are typical in multi-tier supply chains, where downstream actors define targets but rely on relational governance to influence upstream emission sources (Hettler et al., 2024; Borchardt et al., 2025). From a global value chain perspective, coordination occurs through a combination of contractual arrangements, capability alignment and strategic interdependence rather than direct hierarchical control (Gereffi, 2018).

In the off-highway context, climate objectives are progressively embedded into existing sourcing and supplier management processes. Sustainability criteria are incorporated alongside cost, quality and reliability considerations, reflecting the integration of environmental dimensions into core procurement decision-making (Koberg & Longoni, 2019; Both & Wilhelm, 2025). This indicates that sustainability is treated as a strategic parameter within supply chain governance rather than as a parallel or peripheral initiative.

4.2.3 Operational levers: strategic logic of intervention instruments

At the operational level, Bosch Mobility relies primarily on influence-based instruments to extend climate objectives across the supply chain. Supplier engagement, incorporation of ESG criteria into procurement practices and requirements for transparency and emission reporting constitute the main levers of intervention (Bosch, 2023; Hettler et al., 2024).

Tier-1 suppliers occupy a pivotal intermediary position. In multi-tier value chains, lead firms frequently cascade sustainability requirements through direct contractual partners, who in turn transmit expectations to deeper tiers (Gereffi, 2018; Borchardt et al., 2025). This configuration acknowledges structural limits in directly engaging Tier-2 and Tier-3 suppliers and seeks to amplify impact through actors with established relational proximity to the OEM.

Operational levers are therefore conceived as mechanisms of alignment and coordination rather than unilateral impositions. Governance research suggests that in complex industrial supply chains, collaborative approaches and incentive alignment mechanisms are more effective than purely prescriptive enforcement strategies (Both & Wilhelm, 2025; Bag et al., 2024). In this sense, Bosch Mobility's approach reflects an influence-based model consistent with structural characteristics of the off-highway value chain.

4.2.4 Control vs influence: effective capacity to steer the supply chain

A central dimension in applying RQ1 concerns Bosch Mobility's effective capacity to steer supplier behaviour in relation to decarbonisation objectives. The case analysis reveals a distinction between domains subject to direct managerial control and those governed through influence mechanisms.

Scope 3 governance literature emphasises that downstream firms frequently bear reporting responsibility while lacking direct authority over upstream emission sources (Hettler et al., 2024; Borchardt et al., 2025). From a global value chain perspective, such arrangements reflect distributed governance structures in which coordination relies on contractual and relational mechanisms rather than hierarchical command (Gereffi, 2018).

In the off-highway sector, supplier technical specialisation, high component customisation and switching costs further constrain unilateral intervention. Empirical evidence from heavy equipment manufacturing indicates that supplier replacement is often limited by asset specificity and long-standing capability alignment (Shekarian et al., 2023).

Consequently, Bosch Mobility's net-zero strategy within the supply chain relies predominantly on collaborative influence mechanisms, including structured supplier engagement, communication of medium- to long-term objectives and alignment of reporting practices. Governance research suggests that in complex industrial supply chains, such relational coordination approaches are more viable than command-and-control models (Both & Wilhelm, 2025; Bag et al., 2024).

Supply chain decarbonisation thus appears less as a hierarchical imposition and more as a coordination process among interdependent actors embedded within stable industrial relationships.

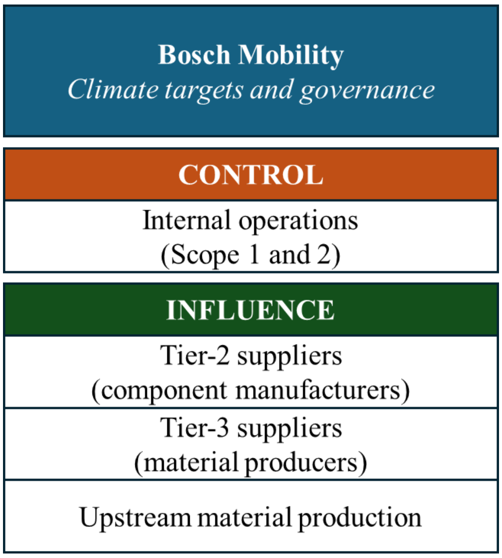


Figure 11. Control and influence in Bosch Mobility's supply chain decarbonisation

4.2.5 Limits and trade-offs: climate ambition, costs and reliability

The implementation of net-zero objectives within the off-highway supply chain entails structural trade-offs. Emission reduction must be reconciled with requirements for reliability, safety and high technical performance, which are particularly stringent in heavy-duty industrial applications. Sector-specific studies confirm that performance constraints and risk aversion moderate the pace of technological substitution in heavy equipment industries (Shekarian et al., 2023; Koberg & Longoni, 2019).

Economic considerations further shape implementation dynamics. The integration of climate criteria into procurement and sourcing decisions introduces cost pressures across supply chain tiers. Research on supply chain decarbonisation barriers identifies investment uncertainty and uneven cost-benefit distribution as major constraints (Bag et al., 2024). In capital-intensive sectors with limited margins, such pressures directly influence the speed and scope of adoption. As a result, Bosch Mobility's approach appears to prioritise operational stability and technological maturity, favouring incremental implementation over abrupt transformation.

Industrial transition literature indicates that in hard-to-abate and low-volume sectors, decarbonisation pathways typically unfold progressively, reflecting asset specificity and path dependency (Arens et al., 2021; Gereffi, 2018).

This configuration suggests that climate ambition is operationalised through staged alignment rather than rapid systemic disruption, consistent with the structural characteristics of the off-highway supply chain.

4.2.6 Synthesis

The application of RQ1 to the Bosch Mobility case reveals a net-zero supply chain strategy that is structurally coherent yet significantly conditioned by the industrial and organisational characteristics of the off-highway sector. Structural constraints—such as supplier specialisation, asset specificity and distributed governance—shape the extent to which climate objectives can be operationalised across tiers (Gereffi, 2018; Shekarian et al., 2023).

The strategy reflects a pragmatic adaptation of international decarbonisation standards, implemented through a distributed governance model and influence-based mechanisms rather than direct hierarchical control. Scope 3 literature confirms that such configurations are typical in multi-tier supply chains where reporting responsibility exceeds direct intervention capacity (Hettler et al., 2024; Borchardt et al., 2025).

The analysis further demonstrates that strategic alignment alone is insufficient to ensure effective supply chain decarbonisation. Governance frameworks require technological and operational instruments capable of translating climate ambition into actionable measures. Research on supply chain decarbonisation emphasises that the effectiveness of strategic intent depends on the availability and scalability of concrete levers across material, production and logistics domains (Zhang et al., 2022).

Accordingly, the following section (4.3) examines how Bosch Mobility addresses Scope 3 emissions through the deployment of enabling technologies and targeted initiatives along the value chain, providing an applied response to the second research question of the thesis.

4.3 Application of RQ2: Bosch technologies and Scope 3 initiatives

Chapters 2 and 3 established that reducing Scope 3 emissions in the off-highway sector requires coordinated technological and operational interventions across a fragmented multi-tier supply chain. Scope 3 governance research highlights that emission sources are frequently embedded upstream, beyond direct organisational control, requiring influence-based coordination mechanisms (Hettler et al., 2024; Borchardt et al., 2025; Gereffi, 2018).

Against this background, the second research question investigates which enabling technologies and operational solutions can effectively contribute to Scope 3 decarbonisation and how feasible their implementation is within a capital-intensive and material-intensive industrial context. Empirical research on industrial decarbonisation emphasises that the translation of technical potential into measurable emission reduction depends on sector-specific constraints, including technological maturity, investment risk and supplier capability (Arens et al., 2021; Zhang et al., 2022; Shekarian et al., 2023).

This section applies that analytical perspective to the Bosch Mobility case, examining how the solution categories identified in Chapter 3 are operationalised within the company's supply chain strategy. The objective is not to assess Bosch as a normative benchmark, but to analyse how a large industrial actor navigates the practical challenges of implementing Scope 3 initiatives under structural constraints.

In continuity with Section 4.2, technologies and initiatives are treated as instruments embedded within governance structures rather than as autonomous solutions. Research on digital and supply chain orchestration indicates that technological tools enhance coordination capacity but require complementary governance mechanisms and supplier engagement to generate systemic impact (Shen et al., 2026; Hettler et al., 2024).

The analysis follows the conceptual structure developed in Chapter 3, organising discussion around four principal solution categories: low-carbon materials, production-related initiatives, logistics optimisation and digital data platforms. For each category, attention is directed not only to emission reduction potential but also to governance mechanisms, scalability constraints and trade-offs shaping implementation (Borchardt et al., 2025; Both & Wilhelm, 2025).

Section 4.3 therefore constitutes the empirical bridge between the theoretical framework on Scope 3 solutions and their practical deployment within an industrial context. The insights derived here will subsequently be compared with broader sectoral developments in Section 4.4 and will inform the roadmap articulated in Chapter 5.

4.3.1 Strategic intent: role of technologies in Bosch's net-zero strategy

Within Bosch Mobility's net-zero strategy, technologies are not treated as autonomous solutions capable of resolving Scope 3 complexity in isolation. Instead, they function as enabling instruments embedded within a broader supply chain governance framework (Hettler et al., 2024; Borchardt et al., 2025). The strategic intent emerging from the case analysis indicates that technological initiatives support the implementation of supply chain strategy rather than acting as standalone decarbonisation drivers.

This orientation reflects the structural characteristics of the off-highway sector. Empirical research in heavy equipment manufacturing highlights that reliability, safety requirements and long validation cycles constrain the rapid introduction of disruptive innovations (Shekarian et al., 2023). Industrial decarbonisation studies further show that in hard-to-abate sectors, technological transitions tend to unfold incrementally due to capital intensity and asset specificity (Arens et al., 2021; Zhang et al., 2022).

Accordingly, Bosch Mobility prioritises technologies that are compatible with existing industrial systems, scalable over time and capable of gradual integration into established processes. From a global value chain perspective, such incrementalism reflects path-dependent industrial structures and interdependencies among supply chain actors (Gereffi, 2018).

In this configuration, Scope 3-related technologies assume a facilitating role. They enhance emission visibility, support supplier engagement and enable progressive alignment of lower-carbon practices along the value chain. Digital and traceability solutions in particular strengthen coordination capacity by creating shared informational infrastructures across tiers (Shen et al., 2026; Hettler et al., 2024).

A further element of Bosch Mobility's strategic intent concerns the prioritisation of industrial robustness over speed of transformation. Technologies are assessed not solely on emission reduction potential but also on maturity, reliability and compatibility with product performance requirements. Sectoral evidence confirms that in heavy-duty industrial contexts, operational risk minimisation significantly shapes decarbonisation pathways (Shekarian et al., 2023).

Overall, technologies within Bosch Mobility's net-zero strategy function as facilitators of progressive and coordinated change rather than disruptive instruments. While this orientation may moderate short-term emission reductions, it appears aligned with the structural characteristics of the off-highway supply chain and with the need to balance environmental ambition, industrial reliability and economic viability. The following section examines how this technological orientation is translated into governance and organisational choices for implementing Scope 3 initiatives.

4.3.2 Governance of technological initiatives for Scope 3 emission reduction

The governance of technological initiatives aimed at reducing Scope 3 emissions constitutes a critical determinant of Bosch Mobility's effective decarbonisation capacity. Scope 3 literature emphasises that the principal challenge lies less in the absence of technical solutions than in the coordination of their adoption across multi-tier supply chains characterised by heterogeneous capabilities and incentives (Hettler et al., 2024; Borchardt et al., 2025; Both & Wilhelm, 2025).

Organisationally, governance follows a hybrid configuration. Corporate-level strategic guidelines and reporting principles ensure alignment with international standards, while implementation of technological and operational initiatives is delegated to business divisions and procurement functions interacting directly with suppliers (Bosch, 2023; Bosch, 2024). Such distributed governance structures are consistent with global value chain dynamics in which lead firms coordinate but do not directly control upstream actors (Gereffi, 2018).

Procurement functions operate as a key interface between climate strategy and supplier relationships. Research on sustainable supply chain management highlights procurement's central role in embedding environmental criteria into sourcing decisions (Koberg & Longoni, 2019; Both & Wilhelm, 2025). Within Bosch Mobility, digital tools for emission data collection and traceability primarily support sourcing evaluation and supplier dialogue rather than functioning as coercive enforcement mechanisms.

The absence of direct hierarchical control over Tier-2 and Tier-3 suppliers reinforces reliance on non-coercive coordination instruments. Multi-tier governance studies demonstrate that cascading requirements through direct suppliers and fostering relational alignment are more feasible than imposing unilateral mandates in fragmented supply chains (Gereffi, 2018; Borchardt et al., 2025). Digital reporting platforms enhance transparency but cannot alone guarantee adoption of high-impact solutions, as supplier capabilities and incentive structures remain decisive (Shen et al., 2026).

Technological initiatives are introduced progressively. Mature and low-risk solutions tend to be piloted first, often in collaboration with strategically important suppliers, whereas technologies associated with higher uncertainty undergo phased experimentation. Industrial transition literature confirms that such staged diffusion reduces operational risk but slows systemic transformation in capital-intensive sectors (Arens et al., 2021; Zhang et al., 2022; Shekarian et al., 2023).

Governance of Scope 3 technologies within Bosch Mobility resembles an orchestration model rather than direct command-and-control. The company defines reference frameworks, provides coordination tools and establishes incentive structures, while recognising that implementation depth depends substantially on supplier capacity and structural sector constraints (Hettler et al., 2024; Shen et al., 2026).

This configuration underscores the central role of governance in translating technological potential into tangible emission reductions, while simultaneously revealing the structural limits inherent in the off-highway supply chain.

4.3.3 Operational levers: Scope 3 technologies and initiatives in practice

The operational levers through which Bosch Mobility addresses Scope 3 emissions operate at the intersection of strategic intent, governance architecture and supplier execution capacity. Scope 3 literature emphasises that indirect emissions require influence-based coordination mechanisms rather than direct managerial control (Hettler et al., 2024; Borchardt et al., 2025). From a global value chain perspective, such mechanisms reflect distributed governance structures across interdependent actors (Gereffi, 2018).

A primary operational lever concerns the integration of environmental criteria into procurement processes. Research on sustainable supply chain management highlights procurement's role in embedding environmental considerations into sourcing decisions (Koberg & Longoni, 2019; Both & Wilhelm, 2025). Within Bosch Mobility, ESG criteria and emission transparency expectations are progressively incorporated into supplier evaluation systems. Digital tools support this process by enabling comparison of sourcing alternatives, identification of emission-intensive components and structured supplier dialogue (Shen et al., 2026).

These criteria are applied selectively rather than uniformly, calibrated according to component criticality and strategic relevance. Such differentiated implementation aligns with governance findings indicating that rigid enforcement in complex industrial supply chains may compromise reliability and supply continuity (Shekarian et al., 2023).

Supplier engagement and development programmes constitute a further operational lever. In heavy equipment industries characterised by technological specialisation and long-term relationships, collaborative engagement mechanisms are often more effective than coercive enforcement (Both & Wilhelm, 2025; Bag et al., 2024). Shared reporting platforms, benchmarking tools and pilot collaborations facilitate progressive learning and capability building across tiers (Shen et al., 2026).

Technological influence also extends to design and engineering phases. Although Bosch Mobility does not directly control upstream material production, it can shape emission trajectories through specification setting and early-stage design decisions. Research on design for circularity and resource conservation demonstrates that early product development decisions significantly determine upstream material demand and associated emissions (König et al., 2024; Poschmann et al., 2023).

Logistics optimisation represents an additional lever, albeit with comparatively limited reduction potential. Initiatives focus on flow optimisation, route rationalisation and gradual introduction of lower-impact logistics solutions. Digital visibility tools enhance monitoring of transport flows and identification of inefficiencies, consistent with analyses of logistics decarbonisation pathways (McKinsey & Company, 2024; IEA, 2022).

Bosch Mobility's operational levers reflect an incremental and systemic approach. Technologies are embedded within procurement practices, supplier development and product design processes rather than deployed as isolated interventions. Industrial transition research confirms that in capital-intensive and hard-to-abate sectors, such gradual integration is characteristic of feasible decarbonisation pathways (Arens et al., 2021; Zhang et al., 2022; Shekarian et al., 2023).

This configuration enables steady progress while recognising that substantial Scope 3 reductions depend on coordinated technological and organisational evolution across the value chain. The following section examines more closely the effective balance between control and influence in implementing these initiatives.

Table 12. Scope 3 technologies and operational initiatives in the Bosch Mobility case

Solution category	Example initiatives	Governance mechanism	Expected impact
Low-carbon materials	collaboration with suppliers on material specifications	procurement alignment	high but long-term
Production-related initiatives	process efficiency and manufacturing optimisation	supplier development programmes	medium
Logistics optimisation	transport flow optimisation and route rationalisation	coordination with logistics providers	limited
Digital data platforms	emission reporting and traceability systems	transparency and supplier engagement	enabling

4.3.4 Control vs influence: effective capacity to intervene along the supply chain

The analysis of technological and operational initiatives highlights a structural distinction between domains subject to direct managerial control and those governed primarily through influence mechanisms. In Scope 3 management, emission sources are largely embedded upstream, beyond the organisational boundaries of the OEM. Scope 3 governance literature identifies this asymmetry as a defining structural feature of multi-tier supply chains (Hettler et al., 2024; Borchardt et al., 2025).

Direct control is exercised primarily through internal decision-making processes and boundary-setting mechanisms, including technical specifications, reporting requirements and supplier evaluation criteria. Through these instruments, Bosch Mobility can shape sourcing decisions and progressively embed environmental criteria into procurement and product development. Digital technologies strengthen this capacity by enhancing transparency and decision-support capabilities across functions (Shen et al., 2026).

Beyond these domains, intervention capacity shifts from control to influence. Technological and production choices at Tier-2 and Tier-3 levels depend on supplier-specific investment priorities, cost structures and technological maturity. From a global value chain perspective, such dynamics reflect distributed governance structures in which lead firms coordinate rather than command upstream actors (Gereffi, 2018).

In the off-highway sector, this asymmetry is reinforced by supplier specialisation and asset specificity. Empirical studies in heavy vehicle and equipment industries show that limited substitutability and long-standing technical interdependencies constrain the feasibility of imposing abrupt decarbonisation requirements (Shekarian et al., 2023). As a result, Bosch Mobility relies predominantly on relational and collaborative mechanisms, favouring long-term alignment over short-term coercion.

This configuration reflects broader patterns observed in sustainable industrial transitions, where balancing environmental ambition with reliability and operational continuity necessitates gradual and negotiated change (Arens et al., 2021; Zhang et al., 2022). The asymmetry between reporting responsibility and effective intervention capacity thus remains a central structural limitation of Scope 3 strategies.

Overall, decarbonisation of the off-highway supply chain cannot be achieved through command-and-control mechanisms alone. It requires an orchestration model grounded in coordination, incentive alignment and information sharing, in which technologies function as enabling tools rather than substitutes for governance (Shen et al., 2026; Hettler et al., 2024). The following section further examines the trade-offs and structural tensions shaping the adoption of Scope 3 solutions within Bosch Mobility's industrial context.

4.3.5 Limits & trade-offs: climate ambition, costs and industrial reliability

The analysis of Scope 3 initiatives within Bosch Mobility reveals structural trade-offs characteristic of decarbonisation in complex industrial supply chains. Scope 3 governance research emphasises that emission reduction in multi-tier systems requires balancing environmental ambition with economic viability and operational feasibility (Hettler et al., 2024; Borchardt et al., 2025).

A primary trade-off concerns environmental ambition versus product reliability. In the off-highway segment, equipment operates under extreme mechanical and environmental conditions over extended life cycles. Empirical studies in heavy vehicle and equipment industries demonstrate that reliability and safety constraints significantly moderate the pace of technological substitution (Shekarian et al., 2023). Industrial transition research further shows that in capital-intensive and hard-to-abate sectors, risk aversion and long validation cycles limit rapid deployment of immature low-carbon solutions Bosch Mobility's prioritisation of technological maturity and performance compatibility reflects these sectoral constraints.

A second trade-off relates to economic sustainability. Solutions with the highest upstream mitigation potential—such as low-carbon materials and process transformation—are often associated with substantial cost premiums and investment requirements. Sectoral analyses indicate that uneven cost distribution and investment uncertainty constrain rapid diffusion, particularly in supply chains characterised by tight margins and competitive pressure (Arens et al., 2021; Zhang et al., 2022; IEA, 2022). In this context, selective and phased implementation emerges as a rational strategy rather than a lack of ambition.

A further tension concerns standardisation versus customisation. Decarbonisation benefits from scale and replicability, whereas the off-highway sector is characterised by high product configuration variety and application-specific adaptation. Research on heavy equipment manufacturing confirms that low volumes and high customisation complicate uniform implementation of sustainability solutions (Shekarian et al., 2023). From a global value chain perspective, asset specificity and capability concentration further moderate scalability (Gereffi, 2018).

At the organisational level, a trade-off emerges between speed and depth of transformation. Accelerated imposition of environmental requirements may generate resistance and disrupt established supplier relationships. Transition studies highlight that gradual, learning-based implementation enhances long-term adoption and systemic integration in complex industrial contexts (Arens et al., 2021; Hettler et al., 2024).

Overall, these trade-offs indicate that Bosch Mobility's Scope 3 strategy should be interpreted as an exercise in managing structural complexity rather than maximising short-term emission reduction metrics. Decarbonisation becomes one dimension within a multi-objective optimisation problem integrating performance, cost, reliability and supply chain stability. In the off-highway sector, the pathway toward net-zero is therefore inherently gradual and shaped by compromises reflecting industrial realities (Shekarian et al., 2023; Gereffi, 2018).

The following section synthesises the key findings of RQ2 and situates them within broader industry trends.

4.3.6 Synthesis

The analysis of Scope 3 technologies and initiatives adopted by Bosch Mobility provides insight into how a large industrial actor operationalises supply chain decarbonisation under structural constraints. Consistent with findings from Scope 3 governance research, the availability of technological solutions alone does not ensure emission reduction; effective outcomes depend on their integration into coordinated governance mechanisms and multi-tier alignment structures (Hettler et al., 2024; Borchardt et al., 2025).

The case confirms that technologies function primarily as enabling instruments. Their impact is mediated by supply chain fragmentation, supplier specialisation and limited direct control over upstream production stages. From a global value chain perspective, such distributed governance structures constrain hierarchical intervention and reinforce coordination-based approaches (Gereffi, 2018). Empirical studies in heavy equipment supply chains similarly emphasise that asset specificity and long-standing technical interdependencies moderate the pace of systemic transformation (Shekarian et al., 2023).

A clear pattern emerges between theoretical mitigation potential and implementation complexity. High-impact interventions—such as low-carbon material substitution and upstream process transformation—are associated with elevated costs, technological uncertainty and industrial risk. Research on hard-to-abate sectors confirms that such characteristics slow large-scale diffusion despite high decarbonisation potential (Arens et al., 2021; Zhang et al., 2022). By contrast, initiatives such as digital tracking systems and logistics optimisation are more readily implementable but generate predominantly incremental reductions. Nevertheless, these initiatives contribute to building transparency, coordination capacity and organisational learning, which are prerequisites for deeper transformation (Shen et al., 2026).

A recurring feature of the Bosch Mobility case is the orchestration role of the OEM. Rather than imposing unilateral technological mandates, the company relies on procurement integration, supplier development programmes and digital coordination tools to progressively align upstream actors. Governance research indicates that such orchestration mechanisms are characteristic of decarbonisation efforts in multi-tier supply chains where formal authority is limited (Both & Wilhelm, 2025; Shen et al., 2026).

Taken together, the findings confirm that Scope 3 decarbonisation in the off-highway sector is shaped by a persistent tension between climate ambition and industrial feasibility. Solutions are technically available, yet their implementation depends on gradual capability development, supplier alignment and risk management. The Bosch case therefore illustrates not a radical transformation model, but a structured and adaptive pathway consistent with industrial transition dynamics observed in other capital-intensive sectors (Arens et al., 2021; Shekarian et al., 2023).

These conclusions provide the analytical foundation for the benchmarking analysis in Section 4.4, which will assess Bosch Mobility's positioning relative to broader industry developments and inform the transformation roadmap proposed in Chapter 5.

4.4. Benchmarking Bosch against industry trends

4.4.1 Objective and methodology of the benchmarking

The objective of this section is to position Bosch Mobility's supply chain decarbonisation approach within broader industry trajectories observable in technologically complex and material-intensive sectors. Rather than constructing quantitative rankings, the benchmarking aims to assess strategic and organisational alignment relative to prevailing governance patterns in multi-tier supply chains.

From a methodological standpoint, the analysis adopts a qualitative and interpretative comparison between empirical findings from the Bosch case and patterns identified in academic literature on sustainable supply chain governance and Scope 3 implementation (Hettler et al., 2024; Borchardt et al., 2025; Both & Wilhelm, 2025). This approach reflects the recognition that differences across firms are often less visible in formal climate commitments than in the mechanisms through which such commitments are operationalised.

The comparison focuses on four analytical dimensions:

- the approach to Scope 3 emission management.
- the role of technologies as enabling factors.
- the governance configuration for supply chain decarbonisation.
- the balance between control and influence across tiers.

This framing is consistent with global value chain theory, which emphasises governance structures and coordination mechanisms as key differentiators among lead firms (Gereffi, 2018), as well as with recent research on digital orchestration in sustainable supply chains (Shen et al., 2026).

A central methodological distinction concerns the gap between formal commitment and effective implementation capacity. Scope 3 research demonstrates that companies may declare similar net-zero targets while diverging substantially in perimeter definition, sequencing of initiatives and integration into procurement and product development processes (Hettler et al., 2024; Borchardt et al., 2025). The benchmarking therefore concentrates on implementation logics rather than the existence of declared climate objectives.

Particular attention is devoted to sectoral specificity. Empirical studies in heavy vehicle and equipment industries highlight structural characteristics—such as long product life cycles, asset specificity and low production volumes—that significantly influence decarbonisation pathways (Shekarian et al., 2023). Research on hard-to-abate sectors similarly underscores the importance of contextualising transition strategies within industrial constraints (Arens et al., 2021). Avoiding inappropriate comparisons with sectors characterised by high volumes and standardisation ensures analytical validity.

This benchmarking hence provides a contextualised assessment of Bosch Mobility's strategic maturity and coherence relative to sector trends. The objective is not evaluative ranking, but identification of convergences, differentiating elements and potential gaps. This interpretative step establishes the analytical foundation for the transformation roadmap proposed in Chapter 5, ensuring consistency with industrial constraints and governance realities.

4.4.2 Industry trends in Scope 3 management in the off-highway sector

Emerging trends in Scope 3 management within the off-highway sector reveal increasing convergence toward gradual, coordination-based decarbonisation pathways shaped by structural industrial constraints. In capital-intensive and hard-to-abate sectors, transition trajectories are typically characterised by incremental implementation and risk mitigation rather than rapid systemic shifts (Arens et al., 2021; Shekarian et al., 2023; Zhang et al., 2022). This pattern reflects the technological specificity, long product life cycles and asset intensity typical of off-highway industries.

A first prominent trend concerns the growing strategic centrality of Scope 3 emissions, accompanied by selective prioritisation of intervention areas. Scope 3 governance research indicates that firms frequently focus initially on emission categories perceived as both materially significant and comparatively governable—particularly purchased goods and direct suppliers (Hettler et al., 2024; Borchardt et al., 2025). Such prioritisation reflects practical constraints related to data availability, supplier capabilities and governance complexity rather than purely theoretical emission hierarchies (Both & Wilhelm, 2025).

A second major trend relates to the emphasis on low-carbon materials as a primary upstream mitigation lever. In material-intensive sectors relying heavily on steel and aluminium, attention is shifting from internal operational efficiency to embodied emissions in purchased inputs

(IEA, 2022; Poschmann et al., 2023). However, diffusion remains gradual due to cost premiums, limited production capacity and technological uncertainty, particularly in heavy industry contexts (Arens et al., 2021; Material Economics, 2019). This confirms the structural pattern identified earlier: the highest-impact interventions are also those associated with the greatest implementation complexity.

Digitalisation constitutes a further enabling trend. Investment in emission tracking platforms and data integration systems is increasingly recognised as foundational for effective Scope 3 governance (Hettler et al., 2024; Borchardt et al., 2025). Digital tools enhance traceability and comparability across tiers, yet their primary contribution lies in enabling coordination and informed decision-making rather than directly reducing emissions (Shen et al., 2026).

From a governance perspective, hybrid models combining central target-setting with decentralised operational implementation are widely observed. Global value chain theory emphasises that lead firms coordinate complex networks without exercising full hierarchical control (Gereffi, 2018). In off-highway supply chains characterised by high customisation and heterogeneous suppliers, such distributed governance structures balance strategic coherence with necessary operational flexibility (Shekarian et al., 2023).

Finally, a consistent cross-cutting trend is the recognition of OEMs as orchestrators rather than unilateral enforcers of decarbonisation. Multi-tier supply chain research demonstrates that effective Scope 3 reduction depends on relational coordination, supplier capability development and incentive alignment (Shen et al., 2026; Hettler et al., 2024). Coercive approaches alone are generally insufficient in fragmented and technically specialised value chains.

To resume, industry trends depict Scope 3 management in the off-highway sector as a long-term and coordination-intensive process shaped by selective prioritisation, gradual diffusion of high-impact technologies and persistent trade-offs between ambition and feasibility. This framework provides the contextual basis for comparing Bosch Mobility's approach with prevailing sectoral trajectories in the following subsection.

4.4.3 Bosch's positioning relative to industry trends

The comparison between Bosch Mobility's approach and emerging patterns in Scope 3 management within the off-highway sector indicates broad alignment with prevailing governance trajectories, characterised by gradual implementation and selective prioritisation. Scope 3 governance research shows that firms in complex supply chains increasingly adopt pragmatic and capability-based decarbonisation strategies rather than uniformly aggressive deployment across all tiers (Hettler et al., 2024; Borchardt et al., 2025).

Regarding ambition and perimeter definition, Bosch Mobility mirrors the broader tendency to prioritise emission categories that are both materially significant and operationally governable, particularly purchased goods and strategic first-tier suppliers. Empirical reviews confirm that such prioritisation reflects realistic assessments of influence capacity rather than purely declarative climate positioning (Both & Wilhelm, 2025; Hettler et al., 2024). This suggests alignment with sectoral norms rather than symbolic overextension.

In terms of implementation pace, Bosch Mobility follows the incremental pathways observed in capital-intensive and hard-to-abate sectors. Research on industrial transition demonstrates that diffusion of high-impact solutions—such as low-carbon materials and upstream process transformation—is moderated by technological uncertainty, cost premiums and industrial risk (Arens et al., 2021; Shekarian et al., 2023; Material Economics, 2019). Pilot-based experimentation and phased integration, as observed in the Bosch case, therefore correspond to dominant sectoral practice.

Digital enablement similarly reflects mainstream trends. Scope 3 literature emphasises that reliable emission data and cross-tier transparency are prerequisites for effective governance, even if digital tools do not directly reduce emissions (Hettler et al., 2024; Borchardt et al., 2025). From a supply chain orchestration perspective, digital platforms facilitate coordination and alignment across distributed actors (Shen et al., 2026). Bosch's emphasis on traceability and data integration thus aligns with prevailing governance patterns.

From a structural viewpoint, Bosch Mobility's hybrid governance configuration is consistent with global value chain dynamics in which lead firms coordinate rather than hierarchically control upstream actors (Gereffi, 2018). Centralised target-setting combined with decentralised implementation reflects a widely observed configuration in technologically complex supply chains (Both & Wilhelm, 2025).

Bosch Mobility's general positioning appears pragmatic and coherent rather than disruptive. The company does not emerge as an outlier in ambition or technological experimentation, but rather as representative of the structural constraints and negotiated trade-offs shaping Scope 3 management in heavy industrial sectors (Arens et al., 2021; Shekarian et al., 2023). Its strategy reflects alignment with sectoral transition dynamics rather than deviation from them.

The following subsection extends the benchmarking by examining how Bosch's operational levers—procurement mechanisms, supplier engagement instruments and coordination practices—compare with broader industry practices.

Table 13. Bosch Mobility's positioning relative to industry trends in Scope 3 management

Dimension	Industry trend	Bosch Mobility approach	Alignment assessment
Scope 3 prioritisation	focus on purchased goods and direct suppliers	prioritisation of strategic suppliers and material categories	aligned
Technology deployment	gradual diffusion of low-carbon materials and digital tools	pilot-based implementation and digital traceability systems	aligned
Governance structure	hybrid governance with central targets and decentralised execution	corporate targets combined with procurement-driven implementation	aligned
Supply chain coordination	relational engagement and supplier development	supplier dialogue, ESG criteria in procurement, collaborative initiatives	aligned

4.4.4 Comparison of operational levers: procurement, engagement and coordination instruments

The most relevant benchmarking dimension concerns not the isolated adoption of technologies, but the operational levers through which companies steer decarbonisation along fragmented supply chains. In contexts where Scope 3 emissions lie largely outside direct organisational boundaries, differentiation emerges primarily in procurement integration, supplier engagement mechanisms and coordination architectures (Both & Wilhelm, 2025; Borchardt et al., 2025).

A first key area concerns procurement as a strategic interface. Research on sustainable supply chain management highlights procurement's central role in embedding environmental objectives into sourcing decisions (Koberg & Longoni, 2019; Both & Wilhelm, 2025). Bosch Mobility's integration of ESG criteria and emission transparency into supplier evaluation reflects a practice increasingly observed among industrial OEMs. However, consistent with empirical findings, such criteria typically function as enabling and orienting mechanisms rather than rigid prescriptive constraints—particularly for technically critical components where reliability considerations remain paramount (Shekarian et al., 2023).

A second area relates to supplier engagement strategies. In heavy industrial sectors characterised by asset specificity and long-term relationships, collaborative and relational governance structures tend to outperform purely transactional models (Gereffi, 2018; Bag et al., 2024). Bosch Mobility's emphasis on dialogue, transparency and pilot-based collaboration aligns with research indicating that capability development and shared learning are prerequisites for effective Scope 3 reduction (Hettler et al., 2024; Shen et al., 2026).

Digital coordination tools represent another point of convergence. Rather than being positioned as direct emission reduction instruments, digital platforms function primarily as mechanisms enhancing traceability, comparability and coordination across tiers. Scope 3 literature consistently emphasises that reliable and granular data constitute a foundational condition for systemic intervention (Hettler et al., 2024; Borchardt et al., 2025). Digitalisation thus acts as an enabling infrastructure rather than a standalone solution.

A further comparison concerns the balance between experimentation and large-scale diffusion. Studies of decarbonisation in hard-to-abate and capital-intensive sectors show that firms often adopt phased and pilot-based implementation strategies to mitigate technological and operational risks (Arens et al., 2021; Zhang et al., 2022). Empirical evidence from heavy vehicle and equipment industries confirms similar gradual scaling patterns (Shekarian et al., 2023). Bosch Mobility's cautious diffusion trajectory therefore reflects broader structural dynamics rather than company-specific conservatism.

The benchmarking of operational levers indicates that Bosch Mobility's approach aligns closely with prevailing sectoral governance configurations. Sustainability-oriented procurement, collaborative supplier engagement and digitally enabled coordination constitute recurring patterns across complex industrial supply chains addressing Scope 3 emissions (Both & Wilhelm, 2025; Hettler et al., 2024).

In this perspective, the Bosch case illustrates the systemic tensions and coordination challenges characteristic of heavy industrial Scope 3 management, rather than representing an exceptional or outlier pathway. The following subsection further examines whether the observed limitations stem primarily from firm-level strategic choices or from structural sector conditions.

4.4.5 Control vs influence: comparison with Tier-1 suppliers

The comparison between Bosch Mobility Tier-1 suppliers in the off-highway sector indicates that limited direct control over Scope 3 emissions constitutes a structural condition rather than a company-specific constraint. Global value chain research demonstrates that lead firms coordinate extended supplier networks without exercising full hierarchical authority over upstream production stages (Gereffi, 2018). Scope 3 governance studies similarly emphasise that emission responsibility often exceeds direct intervention capacity in multi-tier supply chains (Hettler et al., 2024; Borchardt et al., 2025).

Across the sector, OEMs are required to report and reduce emissions generated in production contexts shaped by suppliers' investment priorities, cost pressures and technological capabilities. Empirical evidence suggests that Tier-2 and Tier-3 suppliers operating in competitive and margin-constrained environments may exhibit limited willingness or capacity to invest autonomously in decarbonisation without supportive incentives (Bag et al., 2024; Shekarian et al., 2023). Consequently, relationships are configured predominantly through indirect influence mechanisms, including contractual requirements, incentive structures and collaborative engagement rather than unilateral mandates (Both & Wilhelm, 2025).

This structural dynamic appears particularly pronounced in the off-highway segment. High supplier specialisation, asset specificity and long product life cycles significantly reduce substitutability of supply sources (Shekarian et al., 2023; Gereffi, 2018). Under such conditions, OEMs typically prioritise continuity and reliability over abrupt switching strategies driven solely by environmental considerations. Bosch Mobility's approach therefore reflects sector-wide governance constraints rather than exceptional conservatism.

Benchmarking further indicates that the most impactful initiatives across the sector focus on strengthening influence capacity rather than expanding formal control. Joint supplier development programmes, long-term material agreements and collaborative technology investments represent recurrent mechanisms aimed at gradually aligning upstream actors (Both & Wilhelm, 2025; Shen et al., 2026). Bosch Mobility's strategy of coordinated engagement aligns closely with this broader governance orientation.

A related dimension concerns stakeholder expectations and credibility management. Scope 3 literature underscores the importance of aligning declared targets with realistic intervention capacity to avoid reputational risks associated with overextension (Borchardt et al., 2025; Hettler et al., 2024). Explicit recognition of structural limitations may therefore enhance strategic coherence rather than weaken environmental commitment.

Overall, the benchmarking confirms that the tension between reporting responsibility and limited direct control is systemic within the off-highway sector. Scope 3 decarbonisation emerges primarily as a challenge of inter-organisational governance and orchestration rather than expansion of traditional control-based mechanisms (Gereffi, 2018; Both & Wilhelm, 2025). This conclusion provides the basis for the final synthesis of the benchmarking, integrating convergences and structural gaps to inform forward-looking strategic implications.

Table 14. Control vs influence in supply chain decarbonisation

Dimension	Bosch Mobility	Typical tier-1
Direct operational control	Scope 1 and 2 emissions	Scope 1 and 2 emissions
Influence on Tier-1 suppliers	through procurement requirements	through contractual governance
Influence on upstream tiers	indirect via supplier engagement	indirect via cascading mechanisms

4.4.6 Conclusions and overall evaluation of the Bosch Mobility case

The benchmarking synthesis indicates that Bosch Mobility's supply chain decarbonisation strategy reflects a level of maturity broadly aligned with structural constraints characteristic of the off-highway segment. Rather than signalling radical deviation, the case exemplifies a governance configuration typical of capital-intensive and technologically specialised industries, where decarbonisation unfolds incrementally under industrial risk constraints (Arens et al., 2021; Shekarian et al., 2023).

A first observation concerns convergence in formal alignment. Like many OEMs and Tier-1 suppliers, Bosch aligns with international frameworks and places Scope 3 emissions at the centre of its climate strategy. However, Scope 3 research demonstrates that differentiation emerges primarily in implementation logics—particularly in prioritisation mechanisms, sequencing of initiatives and management of trade-offs—rather than in declared targets (Hettler et al., 2024; Borchardt et al., 2025).

A distinctive feature of the Bosch case lies in its explicit delimitation of intervention perimeter. Concentration on Tier-1 suppliers and strategic material categories reflects a governance approach grounded in realistic leverage assessment. Global value chain theory supports this prioritisation, highlighting that influence capacity diminishes significantly beyond direct contractual relationships (Gereffi, 2018). This orientation enhances coherence between ambition and execution capacity and mitigates divergence between declared objectives and practical implementation (Both & Wilhelm, 2025).

Digital technologies are treated as enabling infrastructure rather than standalone mitigation tools. Scope 3 governance literature consistently emphasises that reliable and granular data are necessary conditions for systemic intervention, though insufficient without complementary organisational alignment (Hettler et al., 2024; Shen et al., 2026). Bosch Mobility's investment in digital traceability therefore reflects sectoral best practice rather than differentiation.

From a managerial standpoint, the benchmarking reinforces the relevance of progressive and cumulative transformation pathways. Industrial transition research in hard-to-abate sectors demonstrates that structural emission reductions typically require phased implementation combining incremental short-term measures with longer-term structural investments (Arens et al., 2021; Zhang et al., 2022). Bosch's roadmap logic corresponds to this pattern.

With regard to RQ1, the case confirms that net-zero strategies in the off-highway segment are closely aligned with global frameworks but operationalised selectively to reflect industrial constraints. Corporate roadmaps function as adaptive governance instruments rather than fixed prescriptions (Hettler et al., 2024; Borchardt et al., 2025).

Concerning RQ2, the case illustrates that technological and operational solutions only generate impact when embedded within coherent governance architectures and structured supplier relationships. Research on sustainable supply chain management confirms that procurement integration, supplier orchestration and relational coordination are decisive for translating technological potential into measurable outcomes (Koberg & Longoni, 2019; Both & Wilhelm, 2025; Shen et al., 2026).

Recognition of structural trade-offs—technological, economic and organisational—emerges as a precondition for credible strategy. Studies of industrial transition caution against linear representations of decarbonisation pathways and instead emphasise negotiated, phased transformation processes (Arens et al., 2021; Shekarian et al., 2023).

In terms of relevance for sustainable business management, the Bosch case illustrates how net-zero transition is fundamentally a governance and organisational challenge. Procurement systems, supplier engagement mechanisms and coordination capabilities become central strategic levers rather than auxiliary functions. Empirical SSCM research supports this interpretation, demonstrating that decarbonisation effectiveness depends on integration across organisational functions and supply chain actors (Koberg & Longoni, 2019; Borchardt et al., 2025).

Overall, Chapter 4 consolidates the thesis by linking theoretical insights from previous chapters with empirical evidence from a representative industrial actor. The Bosch Mobility case does not present an exceptional transformation model; instead, it provides a grounded illustration of how Scope 3 decarbonisation unfolds within the structural realities of the off-highway sector. This realism forms the analytical basis for the operational roadmap developed in Chapter 5.

5. Roadmap to 2030

5.1 Proposed roadmap for off-highway supply chain decarbonisation

Given that the present analysis is developed in 2026, the proposed roadmap adopts a forward-looking perspective, structuring supply chain decarbonisation actions in the off-highway sector across three time-horizons: short term (2026–2028), medium term (2028–2030) and long term (post-2030). This temporal articulation reflects the progressive and staged nature of industrial decarbonisation in hard-to-abate sectors, where technological maturation, investment cycles and supply chain coordination evolve over extended timeframes (IEA, 2022; Geissdoerfer et al., 2020).

In the off-highway sector, the definition of a supply chain decarbonisation roadmap must necessarily account for structural characteristics that significantly condition its applicability and effectiveness. Empirical research on heavy vehicle and equipment manufacturers highlights relatively low production volumes, high product customisation and stringent safety requirements as key constraints affecting sustainability transitions (Shekarian et al., 2023). In addition, the strong dependence on carbon-intensive structural materials and energy-intensive upstream processes further limits the feasibility of rapid technological substitution (IEA, 2022; Material Economics, 2019). These characteristics render decarbonisation models based on accelerated standardisation or immediate large-scale substitution unrealistic. Instead, they require selective prioritisation and gradual integration of solutions within established industrial architectures, consistent with systemic transition literature (Geissdoerfer et al., 2020; Hettler et al., 2024).

Considering these constraints, the proposed roadmap does not take the form of a rigid operational plan but rather of a structured strategic orientation intended to support off-highway companies in defining priorities, sequencing interventions and allocating resources along the supply chain. The framework explicitly acknowledges the governance asymmetries and coordination challenges typical of multi-tier value chains (Gereffi, 2018; Borchardt et al., 2025) and aims to facilitate the transition through choices consistent with the sector's structural characteristics, balancing climate ambition, industrial feasibility and operational continuity.

5.1.1 Short term (2026–2028): building operational foundations and enabling Scope 3 reduction

In the short term, the roadmap for off-highway supply chain decarbonisation should prioritise the creation of operational and informational conditions necessary to render subsequent phases credible and scalable. Within this time horizon, the primary objective is not the maximisation of absolute Scope 3 emission reductions, but the strengthening of companies' analytical capacity, selective prioritisation and coordination along the most material nodes of the value chain. Literature on Scope 3 governance emphasises that effective upstream intervention depends on progressive capability building and structured engagement rather than immediate comprehensive transformation (Hettler et al., 2024; Borchardt et al., 2025).

A first area of intervention concerns the improvement of Scope 3 emissions data quality. In the off-highway sector, characterised by high material intensity and a heterogeneous supplier base, expanding reporting boundaries indiscriminately is less effective than concentrating on emission categories and suppliers with the highest material impact. Research on Scope 3 management confirms that reliable primary data from strategically relevant suppliers constitutes a prerequisite for credible decarbonisation pathways (GHG Protocol, 2011; Hettler et al., 2024). Accordingly, firms should progressively transition from aggregated secondary estimates towards structured primary data collection for critical materials and components. This shift requires investments not only in digital systems but also in internal analytical competences capable of translating data into sourcing and design decisions (Zaoui et al., 2026).

Procurement assumes a central role during this phase. Without fundamentally altering sourcing structures, firms can begin to integrate environmental criteria more systematically into supplier evaluation and selection processes. Empirical studies in sustainable supply chain management show that gradual integration of ESG criteria, particularly when aligned with risk management and supplier development logic, tends to produce more durable outcomes than abrupt prescriptive mandates, especially in contexts characterised by limited supplier substitutability and asset specificity (Both & Wilhelm, 2025; Koberg & Longoni, 2019). The short-term objective is therefore to formalise expectations regarding transparency, measurement and commitment, thereby initiating progressive alignment across Tier-1 suppliers.

Pilot initiatives represent another key lever during this phase. In the off-highway context, such projects may include the introduction of lower-carbon materials in non-critical components, targeted optimisation of specific upstream production processes, or the rationalisation of selected logistics flows. Evidence from first movers in supply chain decarbonisation indicates that pilot projects primarily reduce technological and organisational uncertainty, enabling learning and gradual scaling rather than delivering immediate systemic impact (Zhang et al., 2022; Geissdoerfer et al., 2020).

Finally, the short term should strengthen collaborative relationships along the value chain. Scope 3 research highlights the asymmetry between reporting responsibility and intervention capacity, emphasising the importance of structured dialogue and capability development among suppliers (Hettler et al., 2024; Borchardt et al., 2025). In the off-highway sector, where supplier specialisation is high, sustained engagement reduces the risk of contractual tensions and supports joint identification of barriers related to low-carbon materials, process innovation and data transparency.

The period 2026–2028 thus constitutes a phase of consolidation and preparation. Although emission reductions may initially remain incremental, this stage establishes the organisational, informational and relational foundations required for more structural medium-term interventions. Without such preparatory measures, net-zero commitments risk remaining declarative rather than operationally embedded within supply chain decision-making processes (Geissdoerfer et al., 2020).

5.1.2 Medium term (2028–2030): selective implementation and operational integration

In the medium term, the roadmap for off-highway supply chain decarbonisation enters a phase of structured implementation, in which the analytical and organisational capabilities developed previously are translated into measurable Scope 3 emission reductions. This stage marks the transition from experimentation to selective scaling, consistent with heavy-industry transition pathways that emphasise staged adoption aligned with investment cycles and technological maturity (IEA, 2022; Material Economics, 2019).

A first area of intervention concerns the progressive integration of lower-carbon materials into off-highway applications. Between 2028 and 2030, the adoption of low-carbon steels and aluminium is likely to prioritise components for which safety and durability constraints allow greater design flexibility. Research on automotive and heavy supply chains confirms that diffusion of low-carbon materials in material-intensive sectors typically proceeds through gradual integration into non-critical applications, supported by medium-term supplier agreements, due to constraints related to cost, availability and technological maturity (Poschmann et al., 2023; IEA, 2022). This approach reduces industrial risk while enabling progressive expansion towards more structurally relevant components.

Concurrently, advanced production technologies can be diffused more systematically along strategically relevant supply chain nodes. In highly heterogeneous sectors, selective transformation at key suppliers tends to produce more effective results than uniform large-scale programmes (Shekarian et al., 2023; Borchardt et al., 2025). Accordingly, interventions during this period should focus on improving energy efficiency and reducing embodied emissions in critical upstream processes, while preserving the flexibility required to manage product customisation and demand variability.

From a logistics perspective, this period enables consolidation of optimisation measures initiated in the short term. Selective regionalisation and broader adoption of lower-impact transport modes can be more firmly embedded in industrial planning. Although the heavy and bulky nature of off-highway components limits the magnitude of achievable reductions, logistics improvements contribute to cumulative efficiency gains, consistent with evidence positioning logistics among levers with moderate reduction potential but relatively high feasibility (McKinsey & Company, 2021).

A distinctive feature of this phase is the evolution of digital tracking platforms into integrated decision-support systems. Between 2028 and 2030, digital infrastructures should move beyond compliance-oriented reporting and become embedded within sourcing, design and planning processes. Literature on Scope 3 management highlights that reliable, granular and comparable data constitute a necessary enabling condition for systematic decarbonisation integration, even though data systems alone do not directly reduce emissions (GHG Protocol, 2011; Zaoui et al., 2026).

In general, the medium term represents a decisive transition phase in which supply chain decarbonisation becomes an operational component of industrial strategy rather than a primarily exploratory initiative. Decisions taken during this period significantly influence the feasibility of long-term structural transformation, reducing the risk that net-zero objectives remain temporally distant and disconnected from present industrial choices (IEA, 2022; Borchardt et al., 2025).

5.1.3 Long term (post-2030): structural integration and systemic transformation

The long term represents the horizon in which the initiatives launched in earlier phases can consolidate into a structural transformation of the off-highway supply chain. Decarbonisation in this stage is no longer addressed as a set of dedicated programmes but becomes embedded within industrial architectures, governance models and competitive strategies. Heavy-industry transition literature emphasises that systemic change requires extended timeframes aligned with technological maturation, capital renewal cycles and evolving regulatory environments (IEA, 2022; Material Economics, 2019).

A first structural shift concerns the integration of Scope 3 emission considerations into early-stage product design. In material-intensive sectors such as off-highway equipment, design decisions strongly determine embodied emissions through material selection, system architecture and functional integration. Research on circular and resource-efficient design demonstrates that early-phase decision-making offers disproportionate leverage over long-term environmental impacts (König et al., 2024; Zils et al., 2023). As low-carbon materials and process technologies mature, their integration into primary structural components becomes progressively feasible, allowing more systematic influence on upstream emissions.

In parallel, the long term enables the standardisation and diffusion of solutions validated during the medium term. Structural integration of lower-carbon materials, optimised production technologies and improved logistics configurations reduces technological uncertainty and facilitates adoption across a broader supplier base. Studies on heavy-industry transition highlight that learning effects, scaling and policy alignment progressively reduce cost differentials and diffusion barriers, including among small and medium-sized enterprises (IEA, 2022; Material Economics, 2019).

Supply chain relationships are also expected to evolve towards more systemic forms of coordination. As Scope 3 management matures, governance configurations shift from bilateral buyer–supplier interactions towards multi-actor coordination involving material producers, logistics providers and, in some cases, regulatory stakeholders. Literature on global value chains and Scope 3 governance underscores that structural decarbonisation depends on orchestrated inter-organisational alignment rather than unilateral control (Gereffi, 2018; Hettler et al., 2024).

Regulatory and market frameworks further shape this long-term transformation. The progressive strengthening of climate policy instruments, carbon pricing mechanisms and mandatory disclosure requirements alters the economic conditions under which supply chain decisions are made. In the European context, policy initiatives such as Fit for 55 and enhanced sustainability reporting requirements contribute to internalising carbon considerations into industrial strategy (European Commission, 2021; European Commission, 2023). Such developments reduce part of the structural asymmetry between climate ambition and industrial feasibility identified in earlier phases.

The period beyond 2030 therefore represents a maturation stage rather than a final milestone. Organisations that have invested in digital infrastructure, supplier capability development and governance alignment are better positioned to navigate evolving regulatory and market conditions. In this configuration, sustainability ceases to be treated as a parallel agenda and becomes embedded within core business logic, supporting long-term resilience and competitive positioning in structurally transforming industrial systems (IEA, 2022; Gereffi, 2018).

Table 15. Roadmap for off-highway supply chain decarbonisation to 2030

Dimension	Short term (2026–2028)	Medium term (2028–2030)	Long term (post-2030)
Governance & data infrastructure	Improve Scope 3 data quality; expand primary supplier data collection; develop internal analytical capabilities	Integrate digital tracking systems into sourcing and planning processes; improve data comparability across suppliers	Full digital integration across the supply chain enabling real-time monitoring and strategic decision support
Supply chain engagement	Introduce ESG criteria in procurement; initiate structured dialogue with Tier-1 suppliers; establish supplier reporting expectations	Expand supplier capability development programmes; strengthen collaboration with strategic suppliers	Multi-tier coordination across material producers, suppliers and logistics actors
Technological initiatives	Pilot projects with lower-carbon materials in non-critical components; initial optimisation of selected upstream processes; targeted logistics optimisation	Selective integration of low-carbon materials; diffusion of advanced production technologies among strategic suppliers	Structural integration of low-carbon materials and optimised production technologies across the supply chain
Strategic objective	Build organisational, informational and relational foundations for supply chain decarbonisation	Achieve measurable Scope 3 emission reductions through selective scaling of solutions	Enable systemic transformation and structural integration of decarbonisation into industrial strategies

5.2 Governance, KPIs and implementation priorities

The effectiveness of the proposed roadmap depends on the ability of off-highway companies to establish governance mechanisms consistent with the structural characteristics of Scope 3 emissions. Supply chain decarbonisation in this sector develops predominantly through coordination and influence rather than direct hierarchical control, requiring governance configurations capable of aligning heterogeneous actors across multiple tiers (Hettler et al., 2024; Gereffi, 2018).

From an organisational perspective, implementation requires explicit allocation of responsibilities across procurement, supply chain management and product engineering functions. Sustainability objectives cannot remain confined to specialised units but must be embedded within routine sourcing and design decisions. Research on sustainable supply chain management highlights that interfunctional integration constitutes a decisive enabler of coherent implementation in complex manufacturing environments (Koberg & Longoni, 2019; Both & Wilhelm, 2025). In sectors characterised by long product life cycles and high material intensity, alignment between engineering and procurement is particularly critical.

Hybrid governance models—combining centralised strategic direction with decentralised operational execution—offer a pragmatic response to this complexity. Such configurations allow alignment with corporate climate objectives while preserving operational flexibility across diverse applications and supplier structures (Borchardt et al., 2025; Hettler et al., 2024).

A central component of roadmap governance concerns the definition of appropriate performance indicators. In the context of Scope 3 emissions, reliance exclusively on absolute CO_2 reductions may produce distorted interpretations due to volume fluctuations, product mix changes and cyclical demand patterns. Methodological standards for corporate emission accounting explicitly caution against such interpretative risks (GHG Protocol, 2011; Science Based Targets initiative, 2021). A coherent monitoring framework should therefore combine outcome-based indicators with process-oriented and maturity-related KPIs.

Outcome indicators include absolute Scope 3 emissions and intensity metrics normalised per unit of output or economic value. These measures ensure alignment with formal net-zero frameworks but may insufficiently capture short-term structural progress (GHG Protocol, 2011; Science Based Targets initiative, 2021).

Process-oriented KPIs are particularly relevant in early roadmap phases. Indicators such as the proportion of emissions calculated using primary supplier data, the coverage of supplier reporting and the granularity of available information reflect measurement system maturity. Empirical research confirms that improvements in data quality constitute a necessary precondition for effective Scope 3 reduction, even when immediate emission impacts remain limited (Hettler et al., 2024; Borchardt et al., 2025).

Supplier engagement indicators represent another critical dimension. Metrics such as the share of procurement spend linked to suppliers with decarbonisation targets, participation in structured engagement programmes and formal integration of ESG criteria into sourcing processes assess the extent to which climate objectives permeate supply chain relationships.

Studies on sustainability governance emphasise that such influence-based metrics are essential in multi-tier supply chains where direct control is structurally constrained (Both & Wilhelm, 2025; Gereffi, 2018).

A final category of KPIs relates to operational implementation, including the proportion of lower-carbon materials in purchased volumes, adoption rates of energy-efficient processes among strategic suppliers and coverage of logistics optimisation initiatives. While these indicators provide a closer link to expected emission outcomes, their interpretation requires caution due to uncertainties in quantifying the real-world impact of individual interventions (IEA, 2022; Poschmann et al., 2023).

Implementation priorities must also account for trade-offs between environmental ambition, reliability requirements and economic viability. In hard-to-abate sectors such as off-highway equipment, governance must incorporate structured trade-off management rather than purely formal performance monitoring. Literature on industrial transition highlights that the ability to balance climate targets with operational continuity and financial sustainability constitutes a decisive success factor in long-term net-zero strategies (Geissdoerfer et al., 2020; IEA, 2022).

Effective governance of the roadmap to 2030 therefore requires a continuous balance between strategic direction, operational adaptability and multi-layered monitoring systems. The integration of outcome and process KPIs transforms the roadmap from a declarative reporting instrument into a managerial tool embedded within procurement, design and supply chain coordination decisions. In this way, decarbonisation can evolve progressively and credibly, aligned with the structural constraints of the off-highway sector and supported by robust governance mechanisms.

Table 16. Key KPIs for monitoring supply chain decarbonisation

KPI category	Example indicators	Purpose
Outcome indicators	absolute Scope 3 emissions, emission intensity	alignment with net-zero targets
Process indicators	share of primary supplier data, supplier reporting coverage	measurement system maturity
Supplier engagement indicators	suppliers with decarbonisation targets	governance effectiveness
Operational indicators	share of low-carbon materials, logistics optimisation coverage	operational implementation

5.3 Implications for management practice and research

The proposed roadmap and the empirical evidence emerging from the off-highway sector generate relevant implications for both managerial practice and academic research. The analysis confirms that Scope 3 emission reduction cannot be addressed as a purely technical optimisation problem or as a matter of compliance with reporting standards. Rather, it constitutes a governance and coordination challenge embedded in complex global value chains (Hettler et al., 2024; Gereffi, 2018).

From a managerial perspective, the development of supply chain orchestration capabilities emerges as a decisive competence. In fragmented and multi-tier supply networks typical of the off-highway domain, managers rarely exercise hierarchical control over upstream emission sources. Instead, influence is exerted through coordination mechanisms, relational governance and alignment of incentives across independent actors. Research on global value chain governance and sustainability confirms that such relational and network-based coordination mechanisms are central where formal control is structurally limited (Gereffi, 2018; Both & Wilhelm, 2025). In this context, sustainability management requires negotiation, long-term relationship building and capability development across organisational boundaries.

A second managerial implication concerns the design of transition pathways. The findings suggest that attempts to replicate decarbonisation models developed in sectors characterised by higher volumes and greater standardisation may be inappropriate for the off-highway context. Sector-specific constraints—including long product life cycles, high material intensity and strong reliability requirements—necessitate differentiated and gradual approaches (IEA, 2022; Geissdoerfer et al., 2020). Rather than applying uniform templates, firms must define prioritised and phased interventions aligned with industrial feasibility. Managing trade-offs between climate ambition, technical performance and economic viability therefore becomes a core managerial capability in hard-to-abate industrial segments.

The research also highlights the need to reconsider traditional functional separations within firms. Decisions relating to product design, procurement and supply chain management are deeply interdependent when Scope 3 emissions are considered. Literature on sustainable supply chain management emphasises that interfunctional integration significantly enhances the coherence and effectiveness of environmental strategies in complex manufacturing contexts (Koberg & Longoni, 2019; Both & Wilhelm, 2025). For managers in the off-highway sector, this implies embedding climate considerations within mainstream decision processes while safeguarding safety, reliability and performance standards.

From an academic perspective, this thesis contributes to the literature by focusing on the off-highway sector, which remains comparatively less examined than the on-road automotive industry and other manufacturing domains. Existing research on supply chain decarbonisation tends to concentrate on sectors with higher standardisation and shorter innovation cycles (Poschmann et al., 2023). By contrast, the present analysis underscores how structural characteristics such as low volumes, technological specialisation and limited supplier substitutability intensify governance asymmetries and elevate the importance of influence-based coordination mechanisms (Hettler et al., 2024).

Moreover, the findings reinforce the interpretation of Scope 3 emissions as embedded within industrial relationships rather than reducible to measurement or reporting practices. Decarbonisation emerges as a transformative process affecting governance structures, supplier relationships and strategic decision-making logics (Geissdoerfer et al., 2020). This systemic perspective extends beyond incremental efficiency improvements and situates supply chain decarbonisation within broader debates on sustainable industrial transformation.

Taken together, these implications indicate that the transition towards lower-carbon off-highway supply chains constitutes not only an environmental necessity but also an arena for managerial innovation. The evolution of governance models, relational capabilities and inter-organisational coordination mechanisms becomes central to long-term competitiveness in complex industrial ecosystems. These reflections provide the basis for a critical discussion of the study's limitations and for identifying directions for future research.

5.4 Methodological boundaries and future research perspectives

As with any research work, this thesis presents limitations that must be explicitly acknowledged and which simultaneously open avenues for further research. These boundaries relate primarily to the methodological design, the time horizon considered and the sectoral focus of the analysis.

First, the thesis is based predominantly on secondary sources — academic literature, institutional reports and corporate documentation — complemented by the in-depth analysis of a single case study. This approach enables a structured reconstruction of net-zero strategies and Scope 3 reduction solutions in the off-highway domain, offering a systemic interpretation of the phenomenon. However, the reliance on documentary evidence and the focus on a single case limit the statistical generalisability of the findings and confine their validity to an interpretative level. While consistent with qualitative research designs applied to complex supply chains, this methodological choice implies that the conclusions should be understood as analytically transferable rather than universally generalisable. Future research could complement this analysis through primary data collection, including qualitative interviews with

OEM and supplier managers or survey-based investigations across multiple tiers of the supply chain, thereby strengthening empirical robustness and enabling comparative validation.

A second limitation concerns the temporal scope of the proposed roadmap, which focuses primarily on the period up to 2030. Although aligned with prevailing corporate climate targets and regulatory milestones, deep industrial decarbonisation — particularly in material-intensive sectors — typically unfolds over longer technological and infrastructural cycles (IEA, 2022; Geissdoerfer et al., 2020). Extending the analytical horizon beyond 2030 would allow exploration of structural transformations in material production, large-scale circular economy integration and systemic shifts in energy infrastructures. Future research could therefore adopt scenario-based or longitudinal approaches to assess how emerging technologies and evolving regulatory frameworks reshape supply chain decarbonisation trajectories over extended time frames.

A further limitation relates to the sectoral focus of the study. Concentrating on the off-highway domain allows for a detailed examination of its structural constraints, yet it does not provide direct cross-sector comparison with other capital-intensive and technologically complex industries. Comparative studies across sectors such as aerospace, energy equipment or infrastructure manufacturing could help identify which challenges are sector-specific and which derive from more general characteristics of complex global supply chains. Research in sustainable supply chain management highlights that sectoral context significantly shapes governance models, supplier relationships and implementation dynamics (Koberg & Longoni, 2019; Poschmann et al., 2023). Such comparative designs would contribute to refining theoretical generalisations about Scope 3 decarbonisation.

At a conceptual level, the analysis demonstrates that the challenges of supply chain decarbonisation are not reducible to technological constraints alone. Organisational structures, governance arrangements and coordination dynamics play a decisive role in shaping feasible transition pathways. This interpretation aligns with research emphasising the governance dimension of Scope 3 emissions and the asymmetry between reporting responsibility and intervention capacity within global value chains (Hettler et al., 2024; Gereffi, 2018). Integrating management, strategy and organisational perspectives therefore appears essential for advancing both academic understanding and practical implementation of net-zero transitions.

Taken together, these reflections indicate that decarbonising the off-highway supply chain does not constitute a linear or immediate objective, but rather a progressive and structurally constrained process. The roadmap proposed in this thesis does not claim to offer definitive solutions; instead, it provides a structured framework for translating theoretical insights and empirical evidence into actionable orientations. By explicitly recognising methodological and contextual boundaries, the study contributes to an evolving debate and establishes a foundation for further research capable of deepening both analytical precision and practical relevance.

6. References

Arens, M., Åhman, M. & Vogl, V. (2021). Which countries are prepared to green their coal-based steel industry with electricity? - Reviewing climate and energy policy as well as the implementation of renewable electricity. *Renewable and Sustainable Energy Reviews*, 143, https://doi.org/10.1016/j.rser.2021.110938

Bag, S., Rahman, M.S., Srivastava, A.K., Shrivastav, S.K., Naude, P., (2024) Investigating the overdependence on supply chain partners, exploitation, and willingness to focus on sustainability performance in business-to-business firms. *Organization & Environment*, 37(4). https://doi.org/10.1177/10860266241268155

Borchardt, M., Pereira, G., Milan, G., Pereira, E., Lima, L., Bianchi, R., Scavarda do Carmo, A., (2025) Are Sustainable Supply Chains Managing Scope 3 Emissions? A Systematic Literature Review. *Sustainability*, 17(13). https://doi.org/10.3390/su17136066

Bosch (2022) Code of Conduct for Business Partners of the Bosch Group. https://assets.bosch.com/media/en/global/bosch_group/compliance/code-of-conduct-for-business-partners.pdf

Bosch (2023), Sustainability Report. https://assets.bosch.com/media/global/sustainability/reporting_and_data/2023/bosch-sustainability-report-2023.pdf

Bosch (2024), Sustainability Report. https://assets.bosch.com/media/global/sustainability/reporting_and_data/2024/bosch-sustainability-report-2024.pdf

Both, C. M. & Wilhelm M. (2025). Supply chain sustainability risk management in the era of mandatory due diligence: A literature review. *Journal of Purchasing and Supply Chain Management*. https://doi.org/10.1016/j.pursup.2025.101083

Burggräf, P., Wagner, J., Heinbach, B., Wigger, M. (2021), Design of a Methodological Framework for Adaptive Remanufacturing-based Business Models. *Procedia CIRP*, 98, 547-552. https://doi.org/10.1016/j.procir.2021.01.149

European Commission. (2023). *Corporate sustainability reporting directive (CSRD)*. European Union. https://finance.ec.europa.eu/regulation-and-supervision/financial-services-legislation/implementing-and-delegated-acts/corporate-sustainability-reporting-directive_en

European Commission. (2021). *Fit for 55 package*. European Union. https://www.consilium.europa.eu/en/policies/fit-for-55/

Geissdoerfer, M., Pieroni, M., Pigosso, D., Soufani, K. (2020), Circular business models: A review. *Journal of Cleaner Production*, 277, https://doi.org/10.1016/j.jclepro.2020.123741

Gereffi, G., (2018), *Global Value Chains and Development: Redefining the Contours of 21st Century Capitalism*. https://doi.org/10.1017/9781108559423

GHG Protocol. (2011). *Corporate value chain (Scope 3) accounting and reporting standard*. World Resources Institute & World Business Council for Sustainable Development. https://ghgprotocol.org/standards/scope-3-standard

Hettler, M. & Graf-Vlachy, L. (2024). Corporate scope 3 carbon emission reporting as an enabler of supply chain decarbonization: A systematic review and comprehensive research agenda. *Business Strategy and the Environment*, 33(2), 263-282. https://doi.org/10.1002/bse.3486

Internation Energy Agency (IEA) (2022), Achieving Net Zero Heavy Industry Sectors in G7 Members. https://www.iea.org/reports/achieving-net-zero-heavy-industry-sectors-in-g7-members

Koberg, E. & Longoni A. (2019). A systematic review of sustainable supply chain management in global supply chains. *Journal of Cleaner Production*, 207, 1084-1098. https://doi.org/10.1016/j.jclepro.2018.10.033

König, K., Mathieu, J., Vielhaber, M. (2024), Resource conservation by means of lightweight design and design for circularity—A concept for decision making in the early phase of product development. *Resources, Conservation & Recycling*, 201, https://doi.org/10.1016/j.resconrec.2023.107331

Material Economics (2019), *Industrial Transformation 2050 - Pathways to Net-Zero Emissions from EU Heavy Industry.* https://materialeconomics.com/node/13

McKinsey & Company. (2024). *Decarbonizing logistics: Charting the path ahead*. McKinsey & Company. https://www.mckinsey.com/capabilities/operations/our-insights/decarbonizing-logistics-charting-the-path-ahead

McKinsey & Company. (2021). *Making supply-chain decarbonization happen*. McKinsey & Company. https://www.mckinsey.com/capabilities/operations/our-insights/making-supply-chain-decarbonization-happen

McKinsey & Company. (2023). *The net-zero transition: What it would cost, what it could bring*. McKinsey & Company. https://www.mckinsey.com/capabilities/sustainability/our-insights/the-net-zero-transition-what-it-would-cost-what-it-could-bring

Poschmann, J., Bach V. & Finkbeiner M. (2023). Decarbonization Potentials for Automotive Supply Chains: Emission-Intensity Pathways of Carbon-Intensive Hotspots of Battery Electric Vehicles. *Sustainability*, 15(15), https://doi.org/10.3390/su151511795

Praeger, L., Woytcowicz, J., Reitber, R., Lang, W., (2025), LCA-based calculation of GHG Protocol Scope 3: A bottom-up approach to determine GHG emissions of the construction activity of municipalities. *Building and Environment*, 285. https://doi.org/10.1016/j.buildenv.2025.113502

Science Based Targets initiative (SBTi). (2021). *Corporate net-zero standard*. Science Based Targets initiative. https://sciencebasedtargets.org/net-zero

Shekarian, E., Prashar, A., Majava, J., Khan, I.S., Ayati, S.M., Sillanpaa, I., (2023) Sustainable supply chains in the heavy vehicle and equipment industry: a multiple-case study of four manufacturers. *Benchmarking: An International Journal*, 31(6), 1853-1875. https://doi.org/10.1108/BIJ-07-2022-0474

Shen L., Shi, Q., Panda, D., Parida, V., (2026), Digital technology diffusion through supply chain orchestration. *Technological Forecasting and Social Change*, 225. https://doi.org/10.1016/j.techfore.2026.124554

UNFCCC. (2015). *Paris Agreement*. United Nations Framework Convention on Climate Change. https://unfccc.int/process-and-meetings/the-paris-agreement

World Economic Forum & Boston Consulting Group. (2021). *Net-Zero Challenge: The Supply Chain Opportunity*. World Economic Forum. https://www3.weforum.org/docs/WEF_Net_Zero_Challenge_The_Supply_Chain_Opportunity_2021.pdf

Zaoui, H., Kamsu-Foguem, B., Tchuente, D. (2026), Exploring the digital supply chain in the Industry 5.0 era: A literature review and empirical study of sustainability. *Digital Engineering*, 8. https://doi.org/10.1016/j.dte.2025.100074

Zhang, A., Alvi, M.F., Yu Gong, Wang, J.W., (2022) Overcoming barriers to supply chain decarbonization: Case studies of first movers. *Resources, Conservation and Recycling*, 186. https://doi.org/10.1016/j.resconrec.2022.106536

Zils, M., Howard, M. (2023), Circular economy implementation in operations & supply chain management: Building a pathway to business transformation. *Production Planning & Control*, 36(4), 501-520. https://doi.org/10.1080/09537287.2023.2280907